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Tuneable Composites Containing Magnetic Microwires

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1. Introduction

This chapter provides a comprehensive review on tuneable electromagnetic properties of magnetic wire composites. In these systems, the microwave permittivity and permeability (response to the electric and magnetic field in the wave, respectively) can be controlled by a weak magnetic field, mechanical stress, and temperature. The underlying physics involves the combination of collective frequency dispersive effects and giant magnetoimpedance (GMI) effect in amorphous microwires. In particular, the emphasis is placed on specific magnetic structures in amorphous magnetic wires, which makes it possible to achieve high sensitivity of the surface impedance to external stimuli; modelling the microwave spectra in magnetic wire composites with different microstructure, and experimental results on tuneable impedance and scattering spectra.

In order to face future developments in microwave technology with applications in such vital areas as wireless communication, antenna engineering, non-destructive testing of civil structures, multifunctional structural materials, and biomedical engineering, the investigations into innovative designs of electromagnetic materials continue to be an important issue. The problems difficult to overcome are related with unbalanced electric and magnetic properties of conventional matters, the lack of needed relationships between the refractive index and wave impedance and between the quality factor and tunability ratio. Here, we are examining diluted composites with magnetic metallic wires that can have both effective permittivity ε_{ef} and permeability μ_{ef} at microwave frequencies. A special feature of these composites is that both parameters can demonstrate a strong tunability with respect to varying magnetic structure in wires with such external stimuli as magnetic field, mechanical load and heat. Furthermore, incorporating arrays of magnetic wires in fibre-reinforced polymer composites has also a potential to engineer materials with required structural and electromagnetic functionalities.

Large values of permittivity can be engineered utilising ferroelectric or conducting elements. The latter could be preferable since very large values of ε_{ef} are obtained for small volume concentrations and various frequency and spacial dispersions of permittivity are realised. Another advantageous feature of metallic composites is that due to a low concentration of the metallic phase it could be combined with other subsystems to obtain, for example, magnetic and structural integrity properties. Metallic wire systems as artificial dielectrics were recognized as early as in 1960s (Brown, 1960) and were used in such applications as beam shaping systems and broadband absorption systems. Recently arrays of continuous wires gained much attention as systems with negative real part of the effective permittivity to constitute the materials with left-handed properties by combining the wire arrays and ring resonators (Pendry et al, 1998; Smith et al, 2000). In composites with short-cut wires the length of which is comparable with the wavelength, the effective permittivity may have a resonance dispersion in the GHz range due to induced dipole moments of wires resonating at half wavelength condition (Lagarikov & Sarychev, 1996). This differs greatly from natural dielectrics, where the charge oscillation resonances become important only at optical frequencies.

The magnetic properties of composites materials could be originated by incorporating a ferromagnetic phase. A constraint here is commonly related to response-bandwidth product known as Snoek's relationship (Snoek, 1948). To avoid this limitation, it was proposed to design magnetic activity from conducting elements, which is based on magnetic moments of electric currents. However, the ferromagnetic-like behaviour in systems of current-loops can be realised in rather narrow frequency band. Yet, this approach allows the magnetic activity to exist at very high frequencies up to infrared and visible spectral bands (Panina et al, 2000). At frequencies of 1-10 GHz, ferromagnetic components in the form of thin-films often provide an optimal response due to their high magnetisation saturation, reduced demagnetisation effects and weak skin effect. Similar performance could be achieved utilising magnetic wires with special circumferential magnetic anisotropy. Then, this magnetic subsystem could be easily integrated with the conducting wire arrays generating the electrical properties. The difference between these two subsystems is that the magnetic one should be much dense. Here we consider the use of magnetic wires for both electric and magnetic subsystems. It is demonstrated, that the effective permittivity of magnetic wire arrays shows strongly tunable behaviour. Such composites could be of interest for reconfigurable microwave devices as well as for sensory materials (Reynet et al, 2002; Makhnovskiy et al, 2003; Panina et al, 2005; Makhnovskiy et al, 2006).

Adjustability of electromagnetic properties is important for many applications, especially in communication, defence and non-destructive testing. This will be highly needed in realization of reconfigurable local network environment, beam steering antennas, and microwave methods of remote sensing and control. Several methods were proposed based on biased ferroelectric, ferrite or magnetic composite substrates (Adenot et al, 2000; Yashchyshyn & Modelski, 2000) and reconfigurable resonant elements implementing active devices (Sievenpiper et al, 2002) or a system of micro actuators such as the divergent dipoles (Barlevy, 1999). These technologies each have its advantages and limitations such as high power consumption, low operational speed, limited frequency band and high cost. Here we introduce a relatively new technology of magnetic wire arrays to manipulate the collective electric response from composite systems. Therefore, the overall response will be decided by interplay between structural design and magnetic behaviour of individual wires.

In thin conducting wires the currents that are responsible for effective permittivity are constrained with the associated resonances determined by the geometrical parameters. The current resonances are damped due to the wire impedance which may increase greatly when the wire magnetisation is changed. This is known as giant magnetoimpedance (GMI) effect (Panina & Mohri, 1994; Beach, & Berkowicz, 1994). In soft magnetic amorphous wires subjected to an external magnetic field GMI is in the range of 100% even at frequencies of few GHz. Increase in magnetic losses results in increase in the relaxation parameter which

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determines the frequency dispersion of the effective permittivity. In the case of plasmonic wire arrays, this will result in considerable decrease in the absolute value of the permittivity and will enhance the wave propagation. Similarly, in cut-wire composites, the increase in relaxation broadens the permittivity dispersion which may even show transformation from resonance to relaxation behaviour. Therefore, in composites containing ferromagnetic wires exhibiting GMI effect at GHz frequencies the effective permittivity will depend on the wire magnetic properties via the corresponding dependence of its impedance. Applying a magnetic field H_{ex} larger than the magnetic anisotropy field H_K in wires which is just in the range of few Oersted (fraction of mTesla), rotates the magnetisation towards the axis, and strongly increases its impedance (for frequencies from MHz towards 10 GHz). Then the permittivity behaviour is damped. This will result in dramatic changes in the wave propagation through this material. Thus, in composites with $Co_{68}Fe_4Cr_3B_{14}Si_{11}$ glass coated amorphous wires a change in transmission spectra of nearly 15 dB by applying a field of just 5.8 Oe was reported (Makhnovsky et al, 2006). Furthermore, this concept was demonstrated by investigating magnetic field dependent permittivity of Co-based magnetic microwires and fibre-reinforced 913 E-glass prepreg (Peng et al, 2009).

Another benefit of using magnetic microwires is that it will be possible to engineer low density materials with relatively high values of the effective magnetic permeability originated from natural magnetic properties of the wires with a circumferential magnetic anisotropy. The magnetic field in the incident wave along the wire will generate substantial magnetic activity as it will be in the orthogonal position with respect to a static magnetisation. The demagnetising effects will not deteriorate the axial permeability as the ac magnetisation could lay in the tangential position to the wire surface. Integrating electric and magnetic wire arrays, composites with relatively large values of both ε_{ef} and μ_{ef} could be realised. For example, it will be possible to achieve a negative index of refraction. As comparing to other types of left handed materials, an enhanced performance in terms of tunability, simple internal structure, reduced losses and low cost is anticipated.

This chapter is organised as following. In Section 2, the analysis of the effective permittivity and permeability in magnetic-wire media – random or periodic arrays of ferromagnetic wires is given. Emphasis is placed on such effects as permittivity dispersion dependent on the wire magnetic structure, and tunable negative refraction. Section 3 deals with the science and technology of thin magnetic wires with a diameter 10-50 microns (microwires). Emphasis is placed on tailoring their magnetic structure to achieve high dynamic permeability tensor and high sensitivity of GMI at microwave frequencies (few GHz). Here as constituent elements of wire metamaterials we consider amorphous magnetic wires of CoFe-based alloy possessing a specific helical magnetic anisotropy and microwave GMI. In amorphous materials, the magnetoelastic effects determine the magnetic behaviour via the coupling between magnetostriction and stress frozen in during the fabrication or annealing treatments. Following this, we will consider magnetoimpedance in wires with a specific magnetic anisotropy. In Section 4, the discussion on the experimental methods for measurement of magnetic field-dependent effective permittivity in the GHz frequency band on the basis of free space techniques and results on tuneable electromagnetic response in the wire composites are given. Section 5 briefly discusses the possible applications.

2. Electromagnetic spectra of magnetic wire composites

Composites containing elongated metallic inclusions can be designed to have specific frequency spectra. In particular, composites with metallic wires can have effective permittivity of plasmonic type (continuous wires), resonant type (wire length is comparable with the wavelength) or relaxation type (wire length is much smaller than the wavelength). Typically, it is considered that the wire radius is small compared to the wavelength. Then, every wire can be described in terms of effective linear current referred to the wire axis, the polarization properties of which determine the effective permittivity. It is further assumed that the wires are ideally conductive; therefore, the field distribution inside them is ignored. This is justified when the skin effect is strong. Here we are interested in realizing the conditions when the losses may become relatively large. Therefore, the approximations utilizing infinite conductivity cannot be used here. In magnetic wires, if the skin effect is essential the loss parameter is enhanced by the wire dynamic permeability. This will make it possible to change the dispersion of the effective permittivity by changing the wire magnetic properties (Makhnovskiy et al, 2003). However, the skin effect should not be too strong when the relaxation is indeed small and the internal properties of constituent wires have little effect on the permittivity spectra. For electrical systems, two main configurations are of interest as shown in Fig.1: periodic arrays of continuous wires (Brown, 1960; Rotman, 1962; Pendry et al, 1998; Belov et al, 2002) and short-cut wires arranged randomly or periodically (Lagarikov & Sarychev, 1996 ; Liu et al, 2005) . In the first case, the effective permittivity is of a plasmonic type with the plasma frequency determined by the spacing between the wires b and the wire radius a. In the second case, the permittivity is of a resonance type in the frequency band within which the half wave length condition is realized: $f_{res} = c/2l\varepsilon_d$ where l is the wire length, c is the velocity of light and ε_d is the permittivity of matrix. The volume concentration of wires should be below 0.02%. To design composite with magnetic properties, it is needed to add a magnetic subsystem with much larger concentration (~5-10%) of magnetic wires which should be placed parallel to the magnetic field of the incident electromagnetic wave and perpendicular to the electrical subsystem.

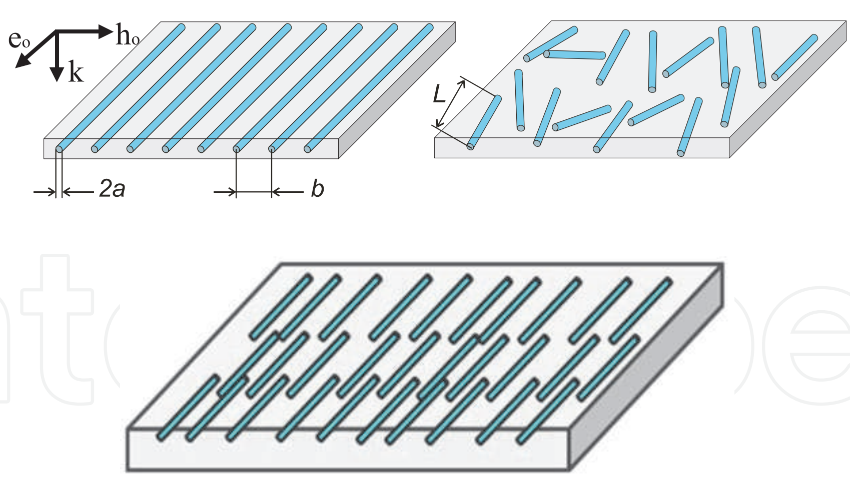

Fig. 1. Sketch of wire composites to engineer permittivity spectra. In periodic arrays, the electric field in the incident wave is parallel to the wires.

2.1 Electromagnetic field distribution in magnetic wires

Here we are interested in possible effects of the wire magnetic properties on the electromagnetic spectra of wire composites. Therefore, the electromagnetic field distribution inside magnetic wires has to be considered. The dynamic magnetic response of wires is characterized by the susceptibility tensor $\hat{\chi}$ which has the simplest form in the coordinate system with the z-axis parallel to the static magnetization $\boldsymbol{M}$ which in general has some angle θ with the wire axis as shown in Fig. 2.

$$\hat{\chi} = \begin{pmatrix} \chi_1 & -i\chi_a & 0 \\ i\chi_a & \chi_2 & 0 \\ 0 & 0 & 0 \end{pmatrix} \tag{1}$$

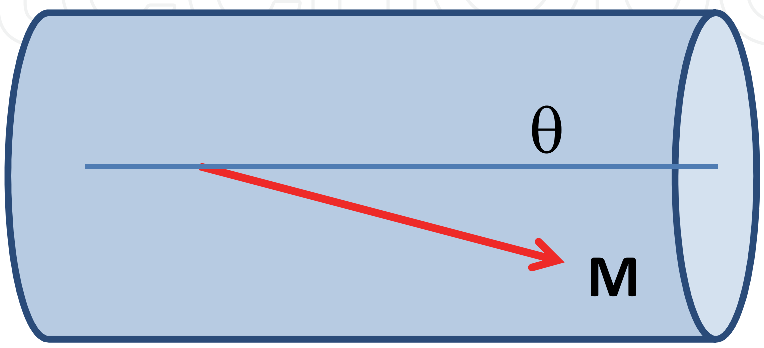

Fig. 2. Magnetic configuration in wires

In the quasi-static approximation, the Maxwell equations inside the wires can be written in terms of electric or magnetic fields. In cylindrical coordinates (r, φ, z) the magnetic induction $\boldsymbol{b}$ and magnetic field $\boldsymbol{h}$ are related as

$$b_\varphi = \mu_1 h_\varphi + \mu_3 h_z\,. \tag{2}$$

$$b_z = \mu_3 h_\varphi + \mu_2 h_z\,. \tag{3}$$

Here the parameters μ_i are related to the susceptibility tensor (1):

$$\mu_1 = 1 + 4\pi \cos^2\theta\,\chi,\;\; \mu_2 = 1 + 4\pi \sin^2\theta\,\chi,\;\; \mu_3 = -2\pi \sin 2\theta\,\chi. \tag{4}$$

$$\chi = \chi_2 - \frac{4\pi\chi_a^2}{1+4\pi\chi_1}. \tag{5}$$

The method of finding the solutions for (h_φ, h_z) for any frequencies is described in (Makhnovskiy et al, 2001). Here we are interested in the case of a moderate skin effect ($\beta = a/\delta < 1,\; \delta = c/\sqrt{2\pi\sigma\omega}, \sigma$ is the conductivity). In this case, neglecting terms proportional to the powers of β it is obtained

$$h_\varphi = h_\varphi(a)\frac{J_1(k_1 r)}{J_1(k_1 a)}, \qquad k_1^2 = \mu_1 \frac{i4\pi\omega\sigma}{c^2}. \tag{6}$$

$$h_z = h_z(a)\frac{J_0(k_2 r)}{J_0(k_2 a)}, \qquad k_2^2 = \mu_2 \frac{i4\pi\omega\sigma}{c^2}. \tag{7}$$

Using equations (6) and (7) it is possible to find the distribution of electric field $\boldsymbol{e}$ in magnetic wires, and hence, the surface impedance which relates the tangential components of electric $\boldsymbol{e}$ and magnetic $\boldsymbol{h}$ fields at the wire surface. For magnetic subsystems, equations (3) and (7) determine the effective permeability with respect to magnetic field parallel to the wires. In the approximation used, the longitudinal component of the surface impedance ς_{zz} is expressed as

$$\varsigma_{zz} = \frac{k_1 c}{4\pi\sigma}\frac{J_0(k_1 a)}{J_1(k_1 a)} \ . \tag{8}$$

It is possible to demonstrate that the surface impedance increases when the wire magnetization is rotated towards the axis (when the magnetization angle becomes zero and $\cos^2\theta = 1$). Certainly the effect of magnetic structure in wires on ς_{zz} will be essential if the dynamic permeability $\mu = 1 + 4\pi\chi$ differs from unity. Coupling between the high frequency impedance (8) and the magnetization direction depends on the value of μ.

Equations (3) and (8) determine the effective permeability μ_{ef} of the wire system in the direction parallel to the wire axis :

$$\mu_{ef} = 1 + p(\mu_2 f(k_2 a) - 1), \ f(k_2 a) = \frac{2J_1(k_2 r)}{J_0(k_2 a)(k_2 a)^2} \ . \tag{9}$$

Here p is the volume concentration of metallic wires. It follows from (9) that the effective permeability could be essential if the static magnetization has some angle with the wire axis. The largest values of μ_{ef} will be for the case of the circumferential magnetization ($\sin^2\theta = 1$ in equation (4)). Figure 3 shows the spectra of the permittivity parameter $\mu = 1 + 4\pi\chi$ for different values of the dc bias field H_{ex} applied along the wires. Relatively large values of H_{ex} are needed to cause substantial changes in the permeability at frequencies larger than 1 GHz ($H_{ex}/H_K > 3$, where H_K is the anisotropy field). On the other hand, the dc magnetization may be rotated from circular to axial direction by applying $H_{ex} \sim H_K$. Therefore, sensitive tuning will be realized if the external stimuli cause the reorientation of the magnetization. For circular magnetization ($H_{ex} \sim 0$), the real part of the permeability is about -20 for frequencies 1 -1.5 GHz. This suggests that it is possible to realize diluted magnetic composites ($p \sim 5\%$) with a negative effective permeability. Such wire system could be attractive for use as a component of left-handed metamaterials.

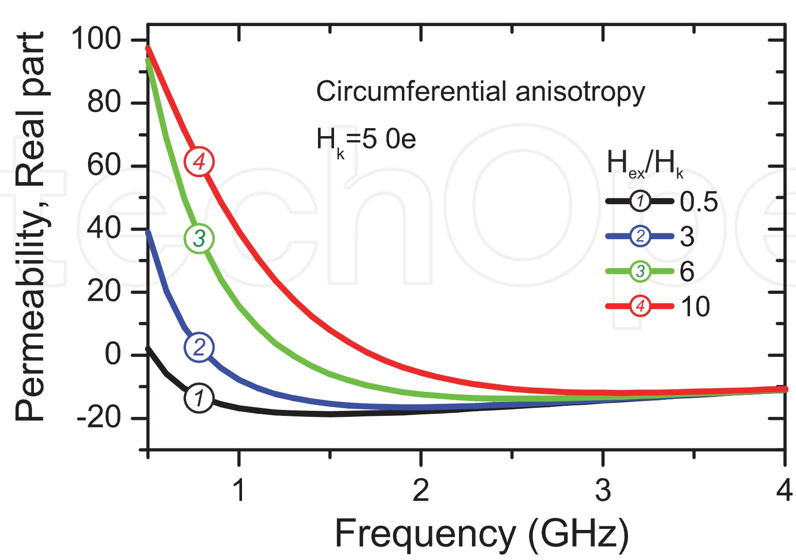

Fig. 3. Spectra of the circular permeability of a wire having a circumferential anisotropy with the axial field as a parameter. The parameters used for calculations are: $M = 500$ G, $H_K = 5$ Oe, the anisotropy deviation from circular direction is 5 degrees.

2.1 Effective permittivity of magnetic wire systems

In a system of short-cut wires, the incident wave induces the dipole electrical moments $\boldsymbol{\mathcal{P}}$ which can be found by solving the scattering problem. If the interactions between the induced dipoles are neglected (diluted system) the effective permittivity ε_{ef} is expressed as

$$\varepsilon_{ef} = \varepsilon_d + 4\pi p\alpha, \tag{10}$$

Where ε_d is the permittivity of matrix and α is the electric polarization ($\alpha = \mathcal{P}/Ve,\ \ V$ is the wire volume). We are considering the case when the losses in metallic wires are important. This can be taken into account by solving the scattering problem with the impedance boundary conditions. The incident electrical field $\boldsymbol{e}$ creates a circular magnetic field $\boldsymbol{h}$ within the wire and at the surface of the wire these fields are related as

$$e_z = \varsigma_{zz}\, h_\varphi, \tag{11}$$

where the surface impedance ς_{zz} is determined by Eq.(9). For non-magnetic wires, ς_{zz} determines resistive losses and for magnetic wires this parameter also includes the relaxation due to magnetization dynamics as was discussed above. If the relaxation in the system is relatively large, the dispersion of ε_{ef} broadens and even can show a transition to a relaxation type. In composites with magnetic wires the relaxation can be controlled by the magnetic properties of wires and very large changes in the effective permittivity can be realized by applying external fields (magnetic or mechanical).
The wire polarization is expressed in a simple analytical form in the case of relatively strong skin effect when the radiation losses are neglected:

$$\alpha = \frac{1}{2\pi \ln(l/a)(\tilde{k}a)^2}\left(\frac{2}{\tilde{k}l}\tan(\frac{\tilde{k}l}{2}) - 1)\right) \tag{12}$$

Here $\tilde{k}$ is the renormalized wave number depending on the surface impedance in the following way:

$$\tilde{k} = k\left(1 + i\frac{\gamma_0}{\ln(l/a)}\right), \qquad k = \frac{\omega\sqrt{\varepsilon_d}}{c}. \tag{13}$$

$$\gamma_0 = \frac{c\varsigma_{zz}}{\omega a}\ . \tag{14}$$

It turns out that the renormalization of the wave number in (14) is essential in the case of a moderate skin effect, which is also consistent with the condition of relatively large losses.
In the case of composites with continuous wires, the dispersion of the effective permittivity corresponds to that for a diluted plasma:

$$\varepsilon_{ef} = 1 - \frac{\omega_p^2}{\omega^2(1+i\gamma)} \tag{15}$$

Different approaches to calculate ε_{ef} give slightly varying results for the plasma frequency, ω_p. Customarily, ω_p is written as

$$\omega_p^2 = \frac{2\pi c^2}{b^2\ lnb/a} \tag{16}$$

A rigorous approach allowing the determination of ε_{ef} was proposed in (Sarychev and Shalaev, 2002), which is based on the solution of the Maxwell equations in the elementary cell and the consequent homogenization procedure to find the averaged electric field and displacement. We extended the method for magnetic wires demonstrating that γ is given by (Panina, et al, 2011)

$$\gamma = \frac{\gamma_0}{lnb/a} \tag{17}$$

Therefore, for both types of magnetic wire composites the relaxation parameter in the effective permittivity spectra depends on the wire impedance. To better understand the dependence of the wire impedance on magnetic permeability, it is useful to express the surface impedance in the approximation of a strong skin effect:

$$\varsigma_{zz} = (1-i)\frac{\omega\delta}{2c}(\sqrt{\mu}cos^2\theta + sin^2\theta)\,. \tag{18}$$

Substituting (18) into (14) shows that γ_0 increases as a square root of the permeability. It is also seen that γ_0 depends on the static magnetisation angle. However, with increasing the frequency well beyond the frequency of the ferromagnetic resonance the permeability tends to be unity and the dependence on θ vanishes. Therefore, we demonstrated that the dispersion properties of permittivity in magnetic wire media depend on the wire internal magnetic structure following the magnetic behavior of the wire impedance. Combining the dispersion properties of wire media and GMI effect it is possible to actively tune the permittivity spectra of arrays of magnetic microwires by application of a small magnetic field and a stress which is now demonstrated in a number of experimental studies (as will be discussed in Section 4). However, to realize large and sensitive tuning requires the existence of very special magnetic structures in wires as that with a circular anisotropy. The methods of tailoring magnetic structure in amorphous wires will be discussed in Section 3. Here we give the results of the permittivity modeling made for amorphous Co-based wires with negative magnetostriction and nearly circular magnetic anisotropy which is presented in Fig. 4. It is seen that in the presence of the external bias field the dispersion region broadens since the losses are increased in high impedance state of the wires.

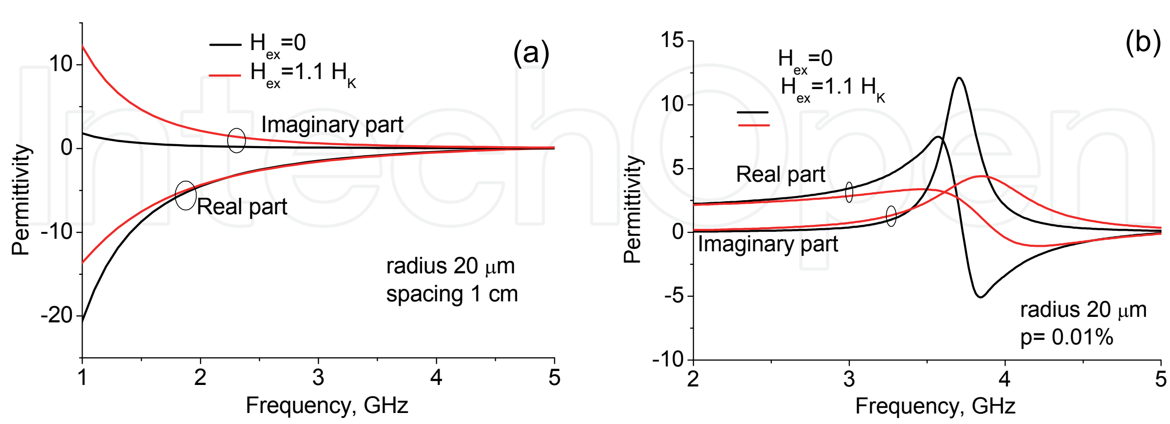

Fig. 4. Effective permittivity spectra in composites depicted in Fig.1 with the external field as a parameter. Modelling is performed for wires with a circumferential anisotropy (anisotropy field H_k=500A/m). The other parameters are: resistivity 130 μΩ·cm, magnetization 0.05T, wire radius 20 μm. For (a), *b*=1cm. For (b), *l*=4cm, *p*=0.01%.

3. Science and technology of thin magnetic wires

In this part, static and dynamic magnetic properties of amorphous magnetic wires in glass coating are reviewed in relation to their application in composites with electromagnetic functionalities.

3.1 Fabrication method of magnetic microwires

There are a number of methods of producing magnetic fibres and wires that may suit particular applications. Here we are discussing the one widely referred to as modified Taylor-Ulitovsky method or quenching-and-drawing method (Zhukov & Zhukova, 2010; Zhukov et al, 2004; Zhukov et al, 2000; Chiriac & Ovari, 1996), which is most suitable for composite technology. The method, as described elsewhere (Larin et al, 2002; Badinter et al, 1973; Ulitovski & Avernin 1964; Ulitovsky et al, 1960; Ulitovsky 1951; Taylor 1931; Taylor 1924), essentially consists of simultaneous drawing of the composite microwire (metallic nucleus inside the glass capillary) through the quenching liquid (water or oil) jet onto rotating bobbins, as schematically depicted in Fig. 5.

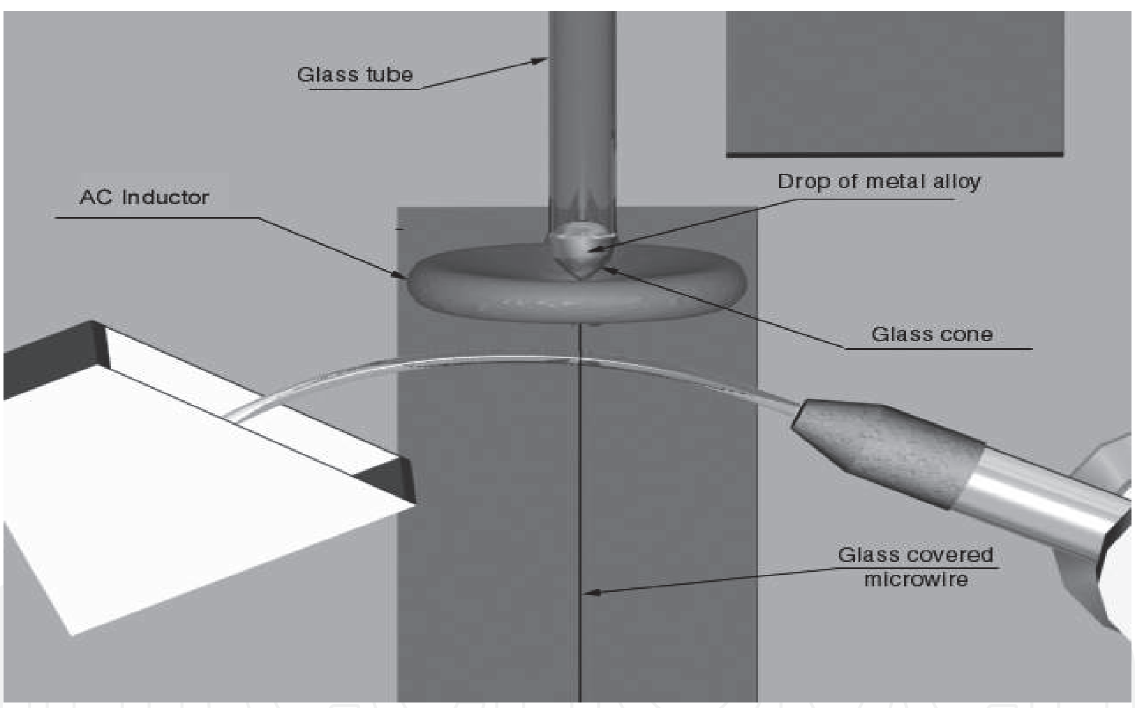

Fig. 5. Schematic drawing of microwire fabrication process by the Taylor–Ulitovsky method. Reprinted with permission from V. S. Larin et al., "Preparation and properties of glass-coated microwires", J. Magn. Magn. Mater. 249(1-2) pp.39-45 (2002). © 2002, Elsevier Science (Fig.1)

Magnetic properties of a microwire essentially determined by the structure which depends mainly on the cooling rate and the chemical composition of the alloy. Some advantages of this method of microwire fabrication important for composite technology (Larin et al, 2002) are: repeatability of microwire properties at mass-production; vast range of variation in parameters (geometrical and physical); fabrication of continuous long pieces of microwire up to 10 000 m/per bobbin; control and adjustment of geometrical parameters (inner core diameter and glass thickness) during the fabrication process. There could be some complexities related with the rapid quenching process of thin composite material subjected during the casting to the mechanical stress arising from different thermal expansion coefficients of solidifying metallic alloy and the glass coating. This potentially influences the reproducibility and homogeneity of properties along the microwire length. Another problem is a possibility of formation of the intermediate layer between the metallic nucleus and the glass coating because of the interaction between the alloy and the glass coating. The character of this interaction depends on chemical composition of the ingot as well as on type of glass used for the casting (Zhukov & Zhukova, 2010).

The other source of instability of properties of cast microwires is related with gas content inside the microwire. The sources of the gas are: the atmosphere, the gas impurities in the alloy and the glass. Some content of oxygen and/or hydrogen (in the range of 5 cm^3/100 g) and even nitrogen has been detected. Gaseous precipitations can cause the metallic nucleus deformation and cracks. Chemical reactions of hydrogen with the oxides of the metals can result in appearance of water bubbles inside the metallic nucleus. The electro-dynamic interaction determining the shape of the molten ingot and temperature regimes significantly affects the casting process and should be also taken into account. In general, the thermal conditions affect greatly the microwire properties, in particular, thermal phenomena inside the molten ingot under effect of electromagnetic field of the inductor and thermal conditions related with solidification of cast microwire. Much effort has been made to determine the temperature distribution inside the ingot and its dependence on the metallic bar dimensions. It was found that for Cu, increasing the diameter of the bar from 2 to 6 mm resulted in decrease in temperature inside the ingot by 10-35% (Badinter et al, 1973).

The method allows pure metals such as Ag, Au, Cu, Ni, Sn, Pb, Pt to be used. Semiconductors such as Ge, Si, or Bi can also be cast. Then, it is possible to process the alloys of these metals, but not over the whole range of compositions. For example, the content of Cr in Ni and Co based alloys can be up to 20%, the content of Mo, W, V in Ni, Co, and Fe based alloys can be up to 8 – 10 at. %. These limitations are related to the melting temperature, which must not be too high. On the other hand, rare earth metals and metals which react with the glass and atmosphere (Ti, Cr, Mo, W, Nb, Al, Na, La, Nd) are not suitable for this technology (Zhukov & Zhukova, 2010; Badinter et al, 1973).

Our prime interest here is the fabrication of magnetic microwires with soft magnetic characteristics for which Fe, Ni and Co are the main elements in alloys. Soft magnetic properties are typical for amorphous state. To prepare amorphous microwires such elements as Si, B, C, and Al are added to enable the amorphicity of the alloys. Mixed crystalline-amorphous and nanocrystalline-amorphous structure can be also obtained by thermal annealing of initially amorphous microwires (Vazquez et al, 2011; García et al 2009; Zhukov et al, 2007; Dudec et al, 2006) as well as in-prepared state using specially designed mixed compositions like (FeSiB)-Cu, (CoFeSiB)-Cu. These compositions exhibit unusual magnetic properties with irregular hysteresis loops. Additionally, recently novel magnetically soft compositions with small additions of Cr based on Ni with ferromagnetic-paramagnetic phase transitions near room temperature have been introduced (Zhukova et al, 2009; Zhukova et al, 2006).

Metastable supersaturated solid solutions can be obtained for immiscible metal systems in a solid and even liquid state, such as Cu-Co, Cu-Co–Ni, Ag-Fe, Ag-Co. As-cast microwire can exhibit a structure of a supersaturated solid solution of transition metals in Cu or Ag. After suitable thermal treatments small single domain particles of Co or Fe can precipitate. Recently giant magnetoresistance (GMR) effect attributed to the scattering of the electrons on grain boundaries between ferromagnetic grains and paramagnetic matrix has been observed in such compositions (Zhukova et al, 2009; Zhukov et al, 2004).

3.2 Magnetic properties of amorphous microwires

It is worth mentioning, that studies of magnetic properties of amorphous glass coated microwires started even in 70-th (Kraus et al, 1976), although they have been limited to Fe-Ni compositions, measurements of hysteretic properties and ferromagnetic resonance (FMR). Recently these tiny glass-coated ferromagnetic microwires newly attracted considerable attention mainly due to a number of unusual magnetic properties and their potential applications in sensors (Zhukova et al, 2009; Mohri & Honkura, 2007, Ripka, 2001, Vazquez & Hernando, 1996) and multifunctional composites (Qin et al, 2010; Panina 2009; Phan & Peng, 2008).

Generally, the magnetic properties including the shape of hysteresis loops of amorphous microwires depend on the composition of metallic nucleus as well as on the composition and thickness of glass coating. This can be illustrated by hysteresis loops in Figs. 6 & 7. The hysteresis loops of three main groups of amorphous microwires: Fe-rich, Co-rich and Co-Fe-rich with positive, negative and vanishing magnetostriction constant, respectively, show very different magnetisation reversal process. Figure 6 shows how the shape of hysteresis loops changes from rectangular typical of amorphous Fe-rich compositions to inclined typical of Co-rich compositions. The magnetisation loops of amorphous microwires with the same composition ($Co_{67}Fe_{3.85}Ni_{1.45}B_{11.5}Si_{14.5}Mo_{1.7}$ in Fig. 7) but with different ρ-ratio defined as $\rho = d/D$ (d and D are the metallic nucleus diameter and total microwire diameter, respectively) also demonstrate significant difference in anisotropy fields. Comparing the hysteresis loops in Fig.6b and Fig.6c, it can be concluded that the microwires with vanishing magnetostriction show very soft magnetic behaviour with the anisotropy field H_K being in the range of 100-400 A/m, where as the anisotropy field of Co-based wires with negative magnetostriction is about 8000 A/m. The value of H_K can be tuned by changing ρ – ratio. Therefore, magnetic microwires demonstrate large variety of magnetic behaviours which is important for sensing applications.

Strong dependence of the hysteresis behaviour on the value and sign of the magnetostriction constant, and on the glass thickness is attributed to the dominant effect of the magnetoelastic anisotropy K_{me} in the absence of the crystalline anisotropy:

$$K_{me} = \frac{3}{2}\lambda_s \sigma_i (\boldsymbol{n}_\sigma \cdot \boldsymbol{n}_m)\,. \tag{19}$$

In (19), λ_s is the saturation magnetostriction, σ_i is the internal stress, $\boldsymbol{n}_\sigma$ and $\boldsymbol{n}_m$ are unit vectors along the stress and magnetization, respectively. The magnetostriction constant depends mostly on the chemical composition and is as small as 10^{-7} in amorphous Fe-Co based alloys with Co/Fe content about 70/5 (Zhukova et al, 2009; Fujimori et al, 1976). The estimated values of the internal stresses in these glass coated microwires arising from the difference in the thermal expansion coefficients of metal and glass are of the order of 100-1000 MPa, depending strongly on the parameter ρ and generally increasing with the increase in the glass coating thickness (Vazquez et al, 2011; Zhukova et al, 2009; Chiriac & Ovari, 1996).

This allows tailoring the magnetic properties of glass-coated microwires through the change of magnetic anisotropy by tailoring the internal stresses (by using thermal treatment, chemical etching, etc.) and chemical composition of the metallic nucleus. As a confirmation, the investigations of the effect of the progressive elimination of the glass insulating coating by chemical etching on magnetic properties showed considerable improvements in soft magnetic behavior as the thickness of glass coating has been diminished (Garcia Prieto et al, 2000; Catalan et al, 1997).

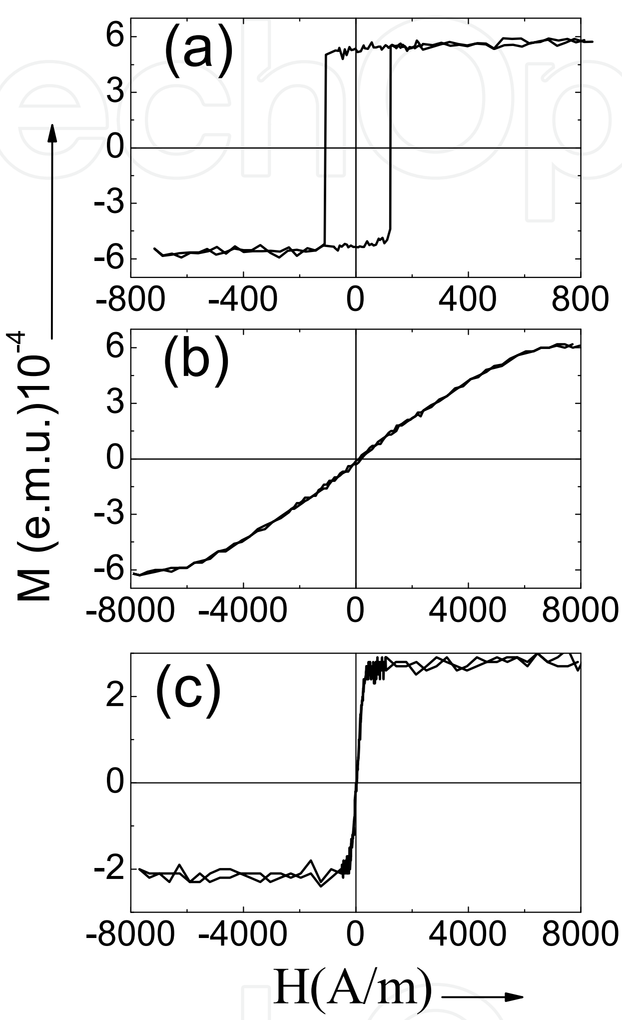

Fig. 6. Hysteresis loops of thin glass coated Fe-rich (a), C-rich (b) and Fe-Co-rich (c) microwires. Reprinted with permission from A. Zhukov et al., J. Mater. Res. 15, 2107 (2000). © 2000, Materials Research Society (Fig. 1).

Two types of microwires distinguished by the sign of the magnetostriction find quite different applications. Bistable magnetization reversal at $\lambda_s > 0$ (Fe-rich alloys) with rectangular hysteresis loops is of great interest for magnetic surveillance (Zhukova et al, 2009; Vazquez & Hernando, 1996). Possessing strongly non-linear magnetic properties, such wires generate specific high frequency harmonics, detection of which may provide information on the state of environment. Therefore, these wires can be used as local non-contact sensors of stress and temperature within composite material (Ong & Grimes, 2002). However, our prime interest here is related with wires made of nearly-zero magnetostriction alloys with good magnetic softness (Co-rich compositions). These wires exhibit almost linear and high magnetic permeability, good high frequency properties and giant magnetoimpedance (GMI) effect . Large number of magnetic sensors was proposed based on these properties alone, and in particular, based on GMI effect. Typically, for magnetic sensor applications, the interrogation frequencies are in tens MHz range. Realizing GMI at GHz frequencies, the wires can be used as embedded sensors within composite matrix. Therefore, the concept of sensory and tunable microwave composites based on magnetic microwires was put forward.

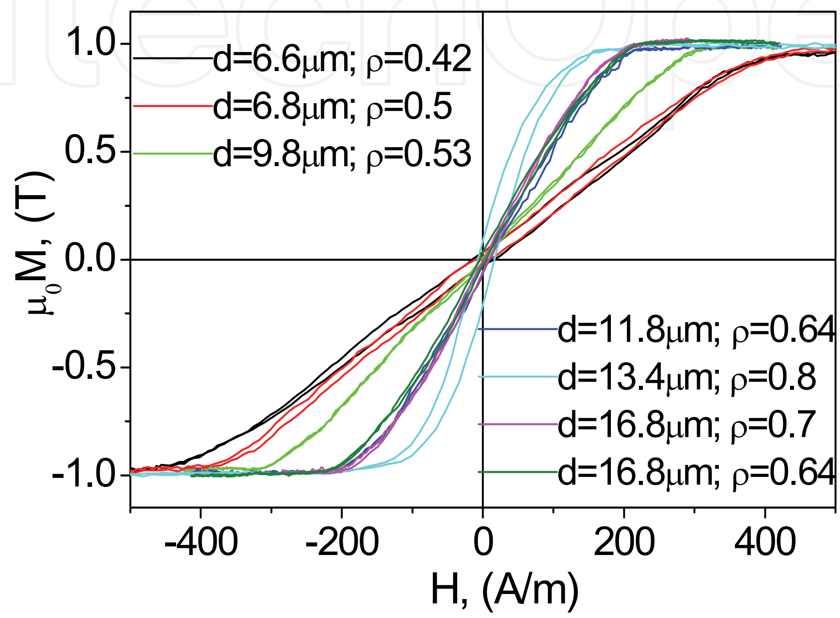

Fig. 7. Hysteresis loops of $Co_{67.1}Fe_{3.8}$ $Ni_{1.4}Si_{14.5}B_{11.5}Mo_{1.7}$ microwires with different geometry. Reprinted with permission from A. Zhukov et al., J. Magn. Magn. Mater. 321 (2009) 822–825 Copyright Elsevier B.V (2008) (Fig. 1).

3.3 Giant magneto-impedance effect and enhanced magnetic softness

Since its discovery in 1994 (Panina &Mohri, 1994; Beach & Berkowicz, 1994) the GMI effect has become a topic of great interest in the field of applied magnetism owing to the large sensitivity of the total impedance to the applied DC field at low field magnitudes and high frequencies. Vast literature exists on this topic, and here we mention just few more relevant to this review (Zhukova et al, 2009; Mohri & Honkura, 2007; Knobel & Pirota 2002). For practical application, GMI is characterized by the relative change in impedance $\Delta Z/Z$:

$$\frac{\Delta Z}{Z} = \frac{Z(H_{ex}) - Z(H_{max})}{Z(H_{max})} \tag{20}$$

where H_{max} is the value of the external magnetic field where the impedance has a maximum which typically does not exceed few kA/m. In GMI experiments, H_{ex} is usually supplied by a long solenoid or Helholtz coils. It has been recognized that the sensitivity of the impedance change occurs due to sharp dependence of the circular permeability on axial magnetic field at a condition of a strong skin effect (see Eq.(18)). Improvements in magnetic softness allowed the GMI ratio $\Delta Z/Z$ to be increased up to 600% at few MHz in glass coated wires (Zhukova et al, 2009; Zhukova et al, 2002), as shown in Fig. 8.

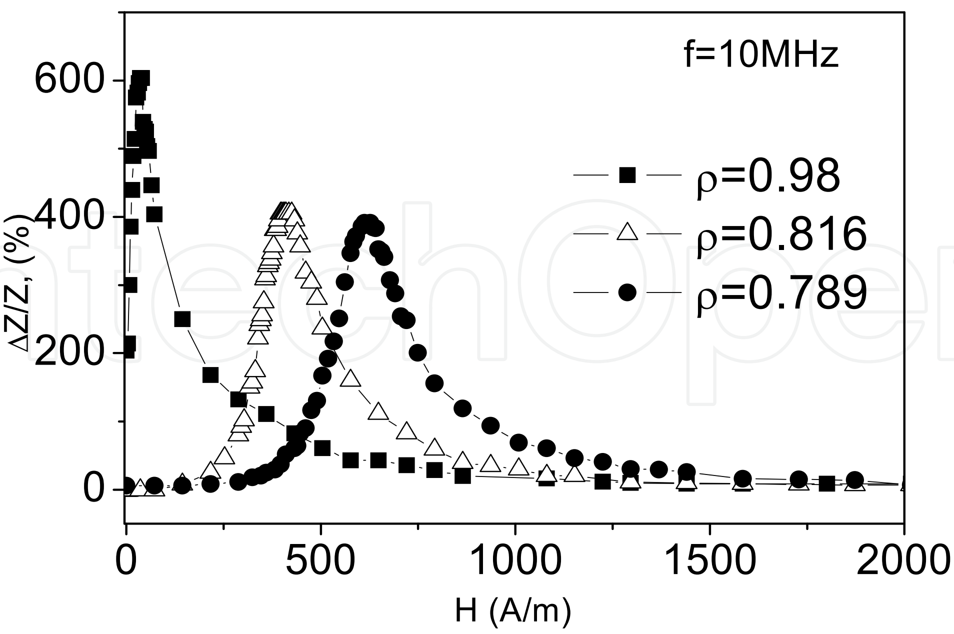

Fig. 8. Axial field dependence of $\Delta Z/Z$ measured at $f = 10$ MHz and current magnitude of 0.75 mA in microwire of composition $Co_{67}Fe_{3.85}Ni_{1.45}B_{11.5}Si_{14.5}Mo_{1.7}$ with ρ as a parameter. Reprinted with permission from V. Zhukova et al. "Optimization of Giant Magnetoimpedance in Co-Rich Amorphous Microwires" IEEE Trans. Magn., V 38, 5 part I, 2002 pp. 3090-3092. Copyright IEEE Magnetic Society (2002). (Fig. 4)

Additionally, stress-impedance (SI) and torsion impedance (TI) effects showing high sensitivity of the impedance to the applied stress with a strain gauge factor of 2000-4000 have been found in amorphous wires (Zhukova et al, 2009; Zhukov, 2006; Panina et al, 2005; Tejedor et al, 2001; Shen et al, 1997). For MI sensor applications, a CMOC IC circuitry with pulse current operation has been developed (Zhukov et al, 2008; Sandacci et al, 2004; Mohri et al, 2002). As a result, the GMI and SI sensors with the CMOC IC circuitry with advantageous features comparing with conventional magnetic sensors have been developed by different companies (Zhukova et al, 2009; Vazquez et al, 2011; Mohri et al, 2001; Honkura, 2002). Main applications of GMI effect are related with the detection of the magnetic fields, small weights, vibrations, acceleration, and recently, in microwave sensory and tunable composites.

Enhanced GMI ratios in amorphous wires were explained by a specific domain structure existing in negative magnetostrictive amorphous wires (Makhnovsky et al, 2001; Panina &Mohri, 1994; Beach & Berkowicz, 1994). Negative magnetostriction coupled with tensile stress creates alternative left and right handed circular domains in the outer sheath of wires. Such domain configuration was observed in wires produced by various method including in-rotating water developed by Unitika LTD (Takajo at el, 1993) and in glass-coated microwires (Chizhik et al, 2004; Chizhik et al, 2001). Such domain structure preserves even in wires with very small but negative magnetostriction (Vazquez et al, 2011; Zhukova et al, 2009; Chiriac & Ovari, 1996) and they demonstrate the highest sensitivity of GMI.

Strong influence of the internal stress on the magnetization behavior suggests that the magnetic structure as well as GMI can be tailored through the heat treatment using conventional annealing (CA), magnetic field annealing (MFA), or even stress annealing (SA)

(Zhukov & Zhukova, 2010; Zhukova et al, 2009; Garcia Prieto et al, 2000; Zhukov, 2006). As expected, the performed heat treatment strongly affects both the hysteresis loops and the GMI characteristics. Figure 9 shows, that both CA and MFA annealing results in considerable change in hysteresis loops. Soft magnetic behavior is improved due to stress relaxation during annealing.

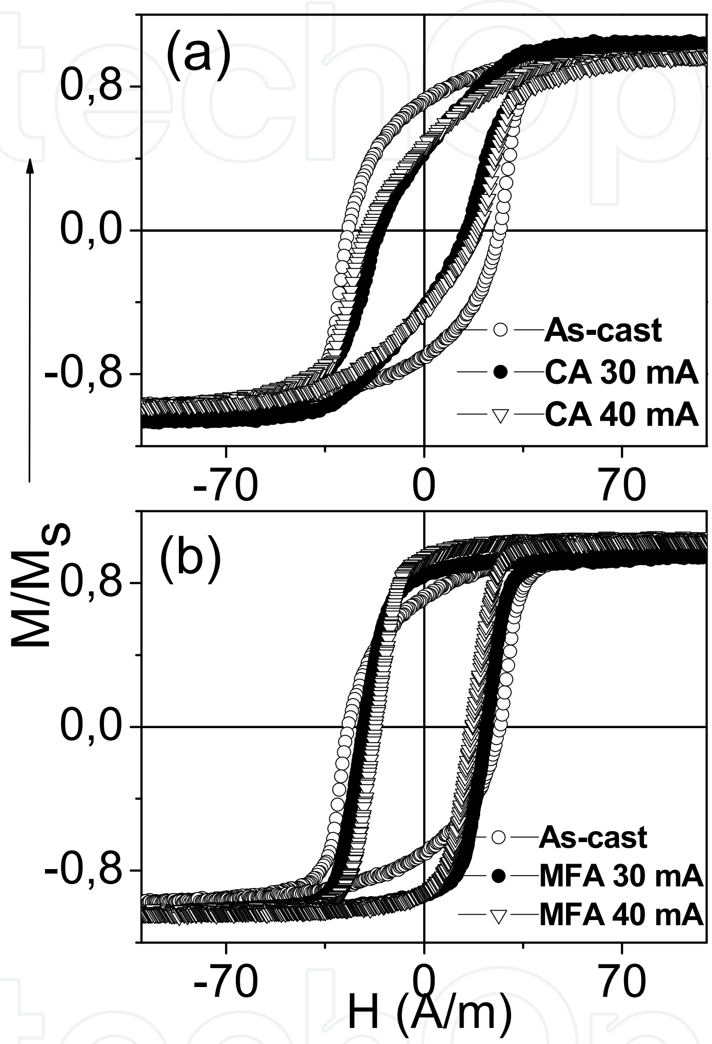

Fig. 9. Effect of CA (a) and MFA (b) treatments on bulk hysteresis loops of $Co_{67}Fe_{3.85}Ni_{1.45}B_{11.5}Si_{14.5}Mo_{1.7}$ microwires. Reprinted with permission from V.Zhukova et al., "Development of Ultra-Thin Glass-Coated Amorphous Microwires for High Frequency Magnetic Sensors Applications" Open Materials Science Reviews, 2007, 1, 1-12. Copyright 2007 Bentham Science Publishers Ltd. (Fig. 7).

Figure 10 shows the plots of relative change in impedance vs. field measured for as-prepared and annealed $Co_{67}Fe_{3.85}Ni_{1.45}B_{11.5}Si_{14.5}Mo_{1.7}$ microwires subjected to Joule heating for different annealing time (annealing current 30 mA and 40 mA). As can be seen, the value of $\Delta Z/Z$ strongly decreases at zero field resulting in much larger impedance change ratios due to annealing. However, the value of H_{max} also increases due to annealing.

One of the most important effects occurring due to stress annealing is enhancement of stress sensitivity of magnetic properties and stress- impedance (Zhukov & Zhukova, 2010;

Zhukova et al, 2009; Garcia Prieto et al, 2000; Zhukov, 2006). In particularly, it was demonstrated, that stress annealing, performed at certain annealing conditions results in induction of stress-sensitive transverse magnetic anisotropy and observation of significant (up to 60%) stress-impedance effect (Zhukov, 2006; Zhukova et al, 2003), as shown in Fig. 11. This result is of special interest for developing stress-sensitive composites with the use of magnetic microwires. The origin of this creep annealing induced anisotropy has been attributed to redistribution of the residual stresses during the stress annealing which results in drastic decrease in the longitudinal stress component and even in the appearance of the compressive longitudinal stresses (so-called "back stresses").

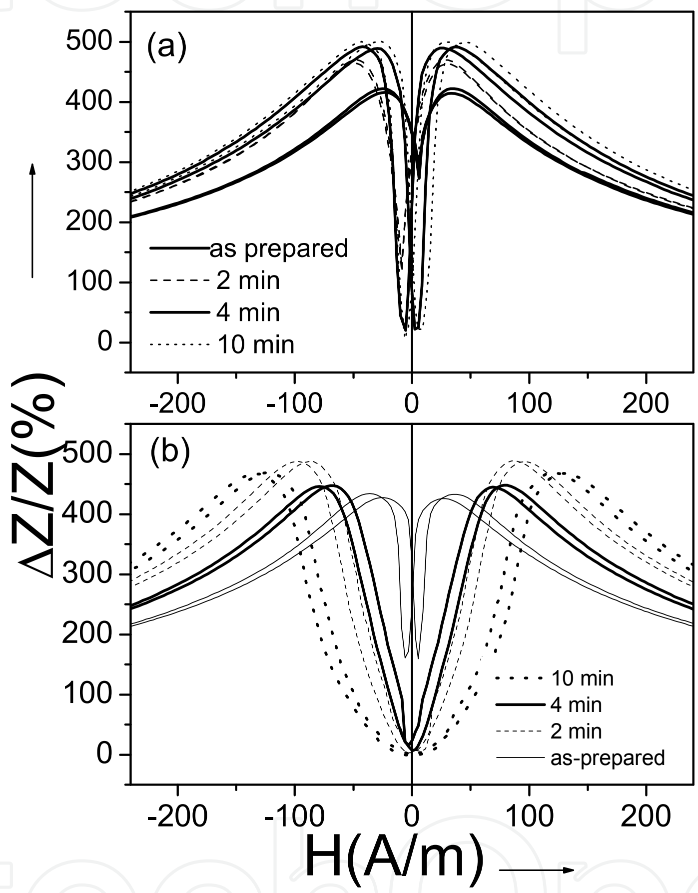

Fig. 10. Relative impedance change plots vs. external field measured at $f = 30$ MHz and current of 1 mA in microwire subjected to CA annealing at 30 mA (a) and at 40 mA (b). Reprinted with permission from A. Zhukov "Recent research on magnetic properties of glass-coated microwires" J. Magn. and Magn., Mater. 294 (2005) 182-192. Copyright Elsevier (2005). (Fig. 8).

Typically, the Curie temperature of Fe and Co-rich amorphous microwires is about 300-400 °C. Additions of Ni and Cr in the alloys make it possible to substantially decrease the Curie temperature (Trémolet de Lacheisserie, et al 2005, Zhukova et al 2006, Zhukova et al 2007). For example, the Curie temperature between 75 and 90 °C was reported for microwires with composition $Co_{60.51}Fe_{3.99}Cr_{12.13}B_{13.53}Si_{9.84}$ and $Co_{23.67}Fe_{7.14}Ni_{43.08}B_{13.85}Si_{12.26}$. This suggest a potential to develop magnetically soft microwires showing large temperature dependence of magnetization, anisotropy, magnetic permeability etc. (Fig.12) and, hence, GMI effect. Then, the microwires would be suitable for remote temperature detection in the range of moderate temperatures from room temperature to about 400 °C.

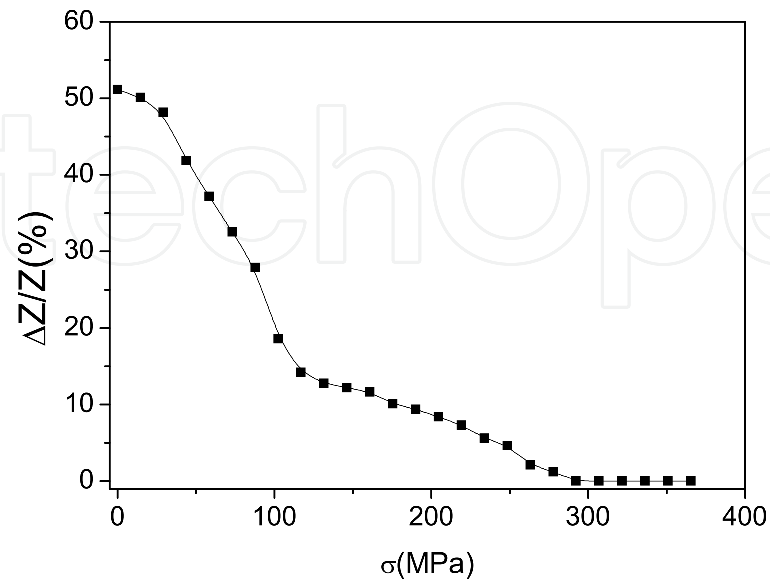

Fig. 11. Stress impedance effect in stress annealed $Fe_{74}B_{13}Si_{11}C_2$ glass-coated microwire measured at 10 MHz and driving current amplitude of 2 mA. The annealing conditions are: 468 MPa at 275°C for 0.5h for. Reprinted with permission from A. Zhukov et al. "Design of the Magnetic Properties of Fe-Rich, Glass-Coated Microwires for Technical Applications" Adv. Funct. Mater. 2006, 16, 675–680. Copyright WILEY-VCH (2006). (Fig. 6)

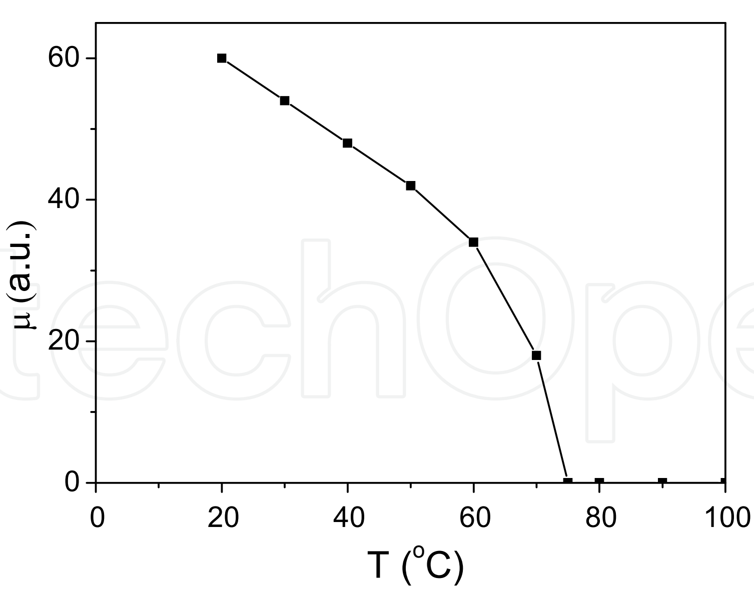

Fig. 12. Temperature dependence of permeability (given in arbitrary units) measured in $Co_{60.51}Fe_{3.99}Cr_{12.13}$ $B_{13.53}Si_{9.84}$ microwire. Reprinted with permission from Ref. [193], V. Zhukova et al. "Development of thin microwires with low Curie temperature for temperature sensors applications" Sensors and Actuators B 126 (2007) 318–323 Copyright Elsevier (2007). (Fig. 4)

The developed magnetic field, stress, and temperature -sensitive microwires have been proposed for completely new range of applications as constituent elements of wire-composites for tunable microwave systems, and non-destructive remote control of stress, strain and temperature (Panina et al, 2011; Makhnovskiy et al, 2006; Makhnovskiy & Panina, 2005). The wires can be regarded as embedded sensors and their impedance sensitive to the wire magnetic structure will be responsible for producing a controlled microwave dielectric response, as explained in Section 2. This will be demonstrated in the next Section, where the experimental results on the microwave scattering spectra of magnetic wire composites are discussed.

4. Scattering properties of glass-coated magnetic wire composites.

4.1 Free space experimental method for composite characterization

The material parameters in microwaves frequencies usually are found from the measurement of the reflection and/or transmission coefficients from which the complex permittivity and permeability are calculated. The measurement methods can be divided in two categories: (i) transmission line methods (coaxial lines probes, rectangular waveguides, cavity resonators) and (ii) antenna techniques in free space. The methods in the first category require cutting a piece of a sample to be placed inside the transmission line or cavity making a close contact with the probe. The transmission line methods work best for homogeneous materials that can be precisely machined to fit inside the sample holder.

At microwaves, the measurement of the effective permittivity of composite materials with the inhomogeneity scale comparable with the wavelength requires large sample dimensions. In this case, the method of spot localized measurement area, such as conventional coaxial line and waveguide methods cannot be used. A free-space method is more appropriate. Generally, it is used to characterize large flat solid materials, although granular and powdered materials can also be measured in a fixture.

Free-space techniques for material property measurements have several advantages (Chen et al, 2004). Firstly, materials such as ceramics and composites are inhomogeneous due to variations in manufacturing processes. Because of inhomogeneities, the unwanted higher-order modes can be excited at an air-dielectric interface in hollow metallic waveguides, while this problem does not exist in free-space measurement. Secondly, the measurements using free-space techniques are non-destructive and contactless, so free-space methods can be used to measure samples under special conditions, such as high temperature. Thirdly, in hollow metallic waveguide methods, it is necessary to machine the sample so as to fit the waveguide cross section with negligible air gaps. This requirement limits the accuracy of measurements for materials that cannot be machined precisely; in free-space method, this problem does not exist. Finally, waveguides have a rather narrow operating frequency range. Therefore, to characterized material in a wide frequency range, a number of waveguides is required. Moreover, every waveguide, having different cross-section, will required preparation of separate sample.

Further we consider the free space method for measurement of the electromagnetic parameter of the composites as the most suitable for both laboratory investigation and *in situ* non-destructive testing and remote structural health monitoring. In free space method, materials are placed between antennas for a non-contacting measurement allowing much flexibility in studying materials under different conditions such as high temperatures and hostile environments. A key component of any free space system is antenna that is a

transition element between transmission line and free space radiating and/or receiving the electromagnetic energy into/from free space.
The experimental setup for the reflection/transmission microwave free-space measurements basically consists of vector network analyzer (VNA), a pair of broadband horn antennas and an anechoic chamber as shown in Fig. 13. A composite sample is placed in the middle of the chamber with the wire orientation along the electric-field of the incident electromagnetic wave. The desired frequency range, in which the scattering parameters will be investigated, determines the requirements to the operating frequency of the VNA, antennas and to the chamber size (distance between antennas and sample). The lens can be applied to focus the radiation pattern and minimize the effect of sample boundaries and measuring environment. It is essential to place the sample outside the reactive near-field region where the wave is not polarized and the electromagnetic interaction between the sample and the antenna can arise. The reactive near-field terminates at the distance of the order of wavelength λ from antennas.

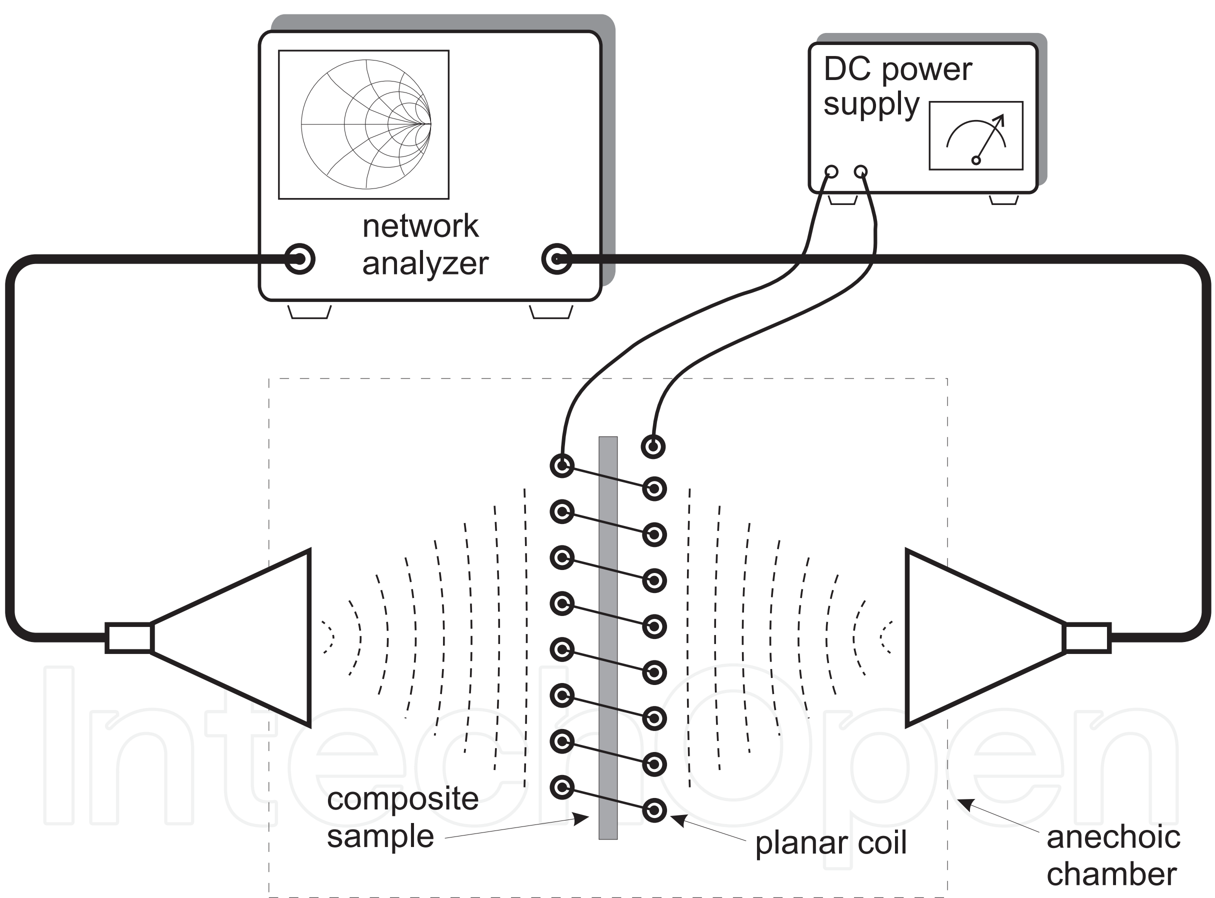

Fig. 13. Sketch of the free space microwave measurement setup.

Free space method imposes a limit on the minimal sample size. If the sample size is much smaller than the wavelength, the response of the sample to electromagnetic waves will be similar to those of a particle object. To achieve convincing results, the size of the sample should be larger than the wavelength of the electromagnetic wave. To further minimize the effects of the scatterings from the sample boundary, the sample size should be at least twice larger than the wavelength (Chen et al, 2004). Therefore if the lowest measurement frequency is 1 GHz, then the sample size should be 2λ = 60 cm.

The free space technique requires precise calibration. The Thru-Rreflect-Line (TRL) and Thru-Reflect-Match (TRM) calibration techniques, that were commonly used until recently, are being widely replaced with the Gated Reflect Line (GRL) calibration (Bartley & Begley, 2005). The GRL calibration, based on the time domain gating, allows enhancing the calibration accuracy and elimination of the the need for expensive spot focusing antennas and micro positioning fixturing. Time-domain technique is important not only for calibration of the free-space measurement path but also during the measurements as it makes it possible to effectively eliminate the effects of multipath reflection to which the measurements in free-space are subjected. The main source of the reflection is the inevitable mismatch between the antenna and free space. The other error sources such as reflection from chamber's walls and noise could be also essential. The time domain procedure "gates out" these error terms and also reduces the requirements for the quality of the anechoic chamber or even allowing conducting the measurements without the chamber.

The free space setup, shown in Fig.13 is applied for the wire composite characterisation. It consists of Agilent 0.01 – 20 GHz two port VNA with time domain option, two broadband horn antennas with the operating range 0.9 – 17.0 GHz and the anechoic chamber with dimensions 80 x 80 x 80 cm^3 covered inside with a microwave absorber. The composite sheets are placed at a distance of 40 cm from each horn antenna, appearing in the radiating near-field region in the whole range of operating frequencies. 85071E Material Measurement Software (Agilent) and "Reflection/Transmission Epsilon Fast Model" can be used for calculating the complex permittivity of the composites from the experimental S-parameters.

To study the influence of magnetic field on the dispersion characteristics of the composite samples a special planar magnetic coil was constructed as described in (Makhnovskiy et all 2006). A thin planar composite sample is placed inside the magnetic coil so that the microwires were along the direction of magnetic field. The coil having the field coefficient 90 [A/m]/A creates a homogeneous along the sample surface DC magnetic field. A 35 Ampere Agilent 6674A DC power supply is used to feed the coil and permits to reach the magnetic field as high as 3000 A/m with resolution below 1 A/m. The coil turns are set perpendicular to the electrical field so there is no effect of the coil on scattering.

In a simple way, the wire composites can be prepared by gluing them on paper to form wire-lattices of needed dimensions. Firstly, 1D wire-lattices of plasmonic type with continuous wires (as shown in Fig. 1a) are arranged. Composites with short- wire pieces forming ordered electrical dipoles (seen in Fig. 1c) could be obtained by cutting the continuous wire arrays in stripes of different size to be able to change the dipole resonance frequencies. The wires used for these experiments were glass coated microwires of the composition $Co_{66}Fe_{3.5}B_{16}Si_{11}Cr_{3.5}$, with magnetic core diameter of 20 microns. These wires have small but negative magnetostriction and show GMI in the range of 100% at few GHz (Panina et al, 2011).

4.2 Tunable scattering spectra

Figure 14 shows the spectra of the reflection R and transmission T for composites with continuous wires having spacing $b = 1$cm with the magnetic field H_{ex} as a parameter. The relative change of T (Figure of Merit $FOM = (T(0) - T(H_{max})/T(0))$ is about 25% at 1.8 GHz while the phase of transmission shifts about 40 degrees with the field change from 0 to 500 A/m. Figure 15 shows the absorption parameter $A = 1 - R^2 - T^2$, which changes by 4 times from 10 % to 40 %.

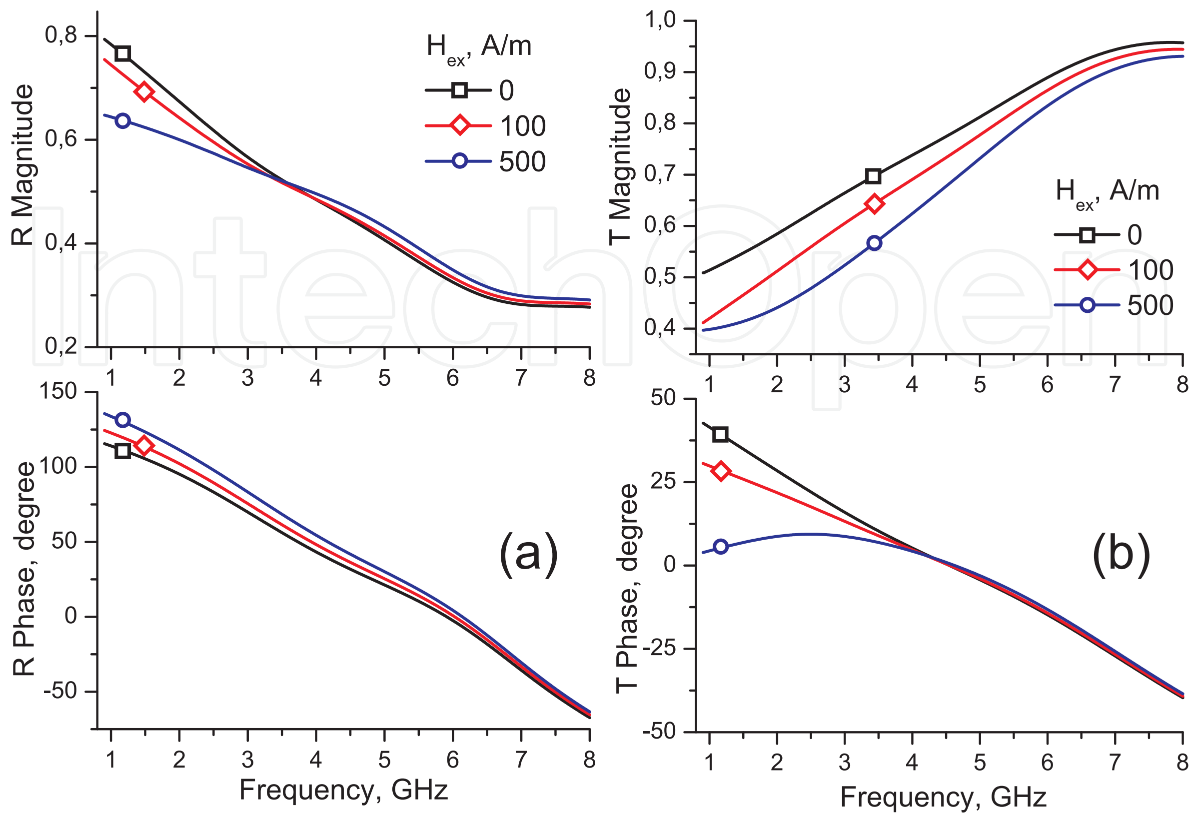

Fig. 14. Spectra of R and T for composites with continuous wire arrays with H_{ex} as a parameter.

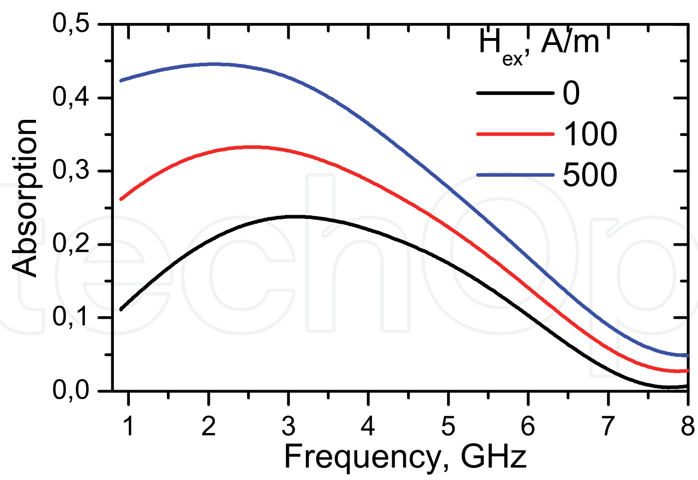

Fig. 15. Absorption spectra for composites with continuous wire arrays H_{ex} as a parameter.

The permittivity spectra shown in Fig. 16 were calculated from R and T coefficients. The effective thickness was taken equal to the lattice period b although the real composites thickness is much smaller and is defined by the host matrix thickness. The real part of ε_{ef} has a negative value below the plasma frequency which is equal to 4.7 GHz. Application of the field decreases the value of the real part (compare with theoretical plots shown in Fig. 4) as the wire impedance increases and so does the relaxation. The imaginary part of the permittivity, that directly demonstrates the losses or absorption, increases with the field. This results in reduced transmitted and reflected signals.

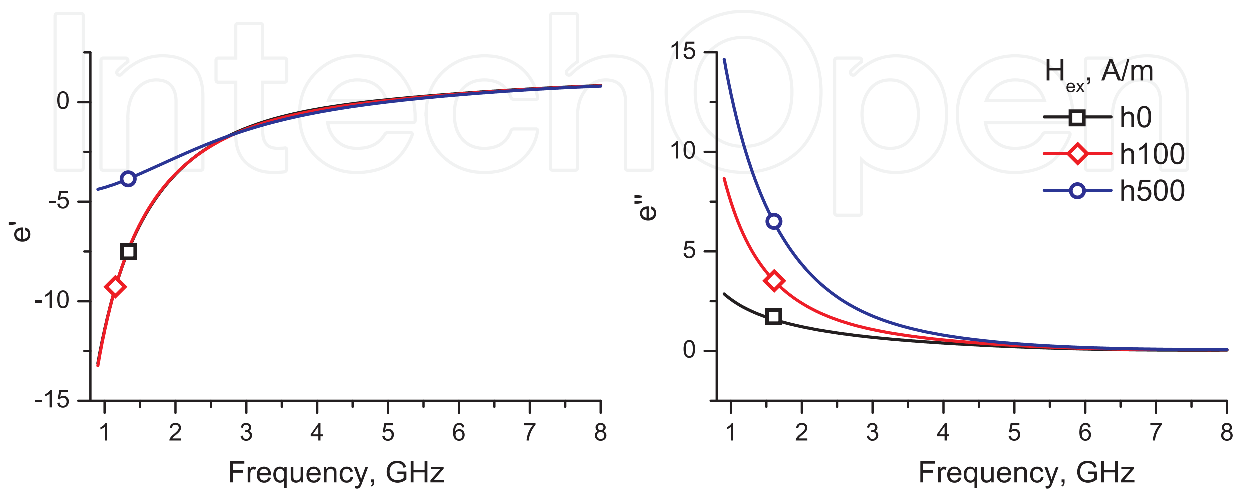

Fig. 16. Effective permittivity spectra for composites with continuous wire arrays with H_{ex} as a parameter.

The *R* and *T* spectra for the cut-wire composites with different wire length *l* of 40, 20 and 10 mm are shown in Fig. 17. The transmission spectra have a deep minimum near a resonance

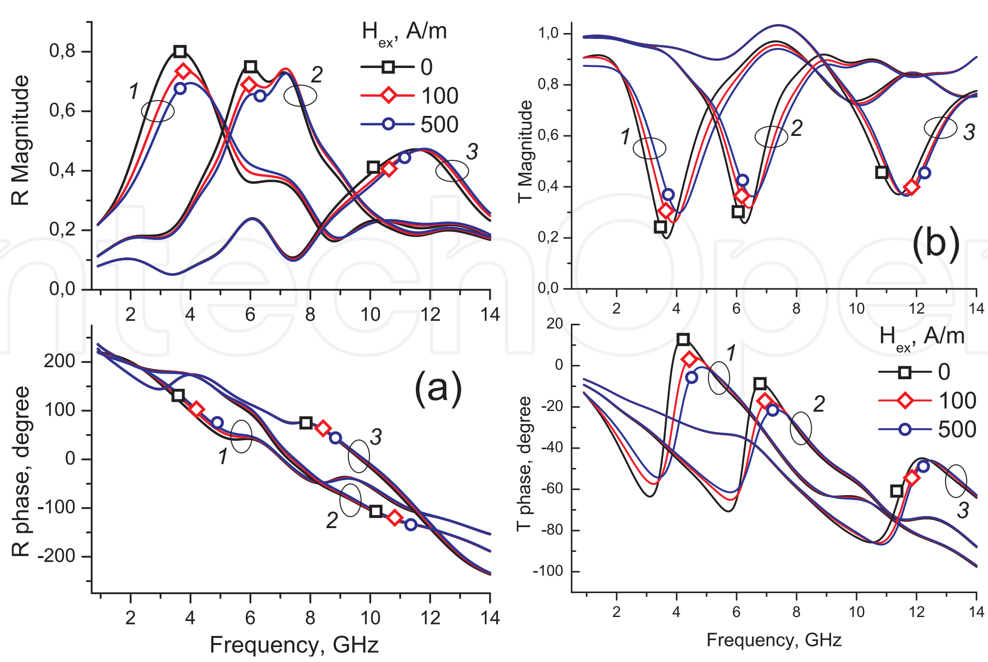

Fig. 17. Spectra of *R* and *T* of composites with cut wires of length 40 (1), 20 (2) and 10 (3)mm with the field as a parameter.

demonstrating stop-filter behaviour. The magnitude of this minimum depends strongly on the field for longer wires with lower resonance frequency. For 40 mm long-wire composites, FOM = 102 % at 3.57 GHz and for 20 mm long wires FOM=57% at 6.18 GHz. For shorter wires with the dispersion region 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, as explained in Section 2. The phase of transmission component exhibits a phase reversal and negative grope delay in the stop band region.
Fig. 18 shows the real and imaginary parts of the effective permittivity. For making comparison between the two composites, the calculation of the effective permittivity was done with the same effective thickness of 1 cm. The frequency where the real part of the permittivity is zero depends on the external magnetic field which can be useful for constructing tunable *Epsilon-Near-Zero* materials.

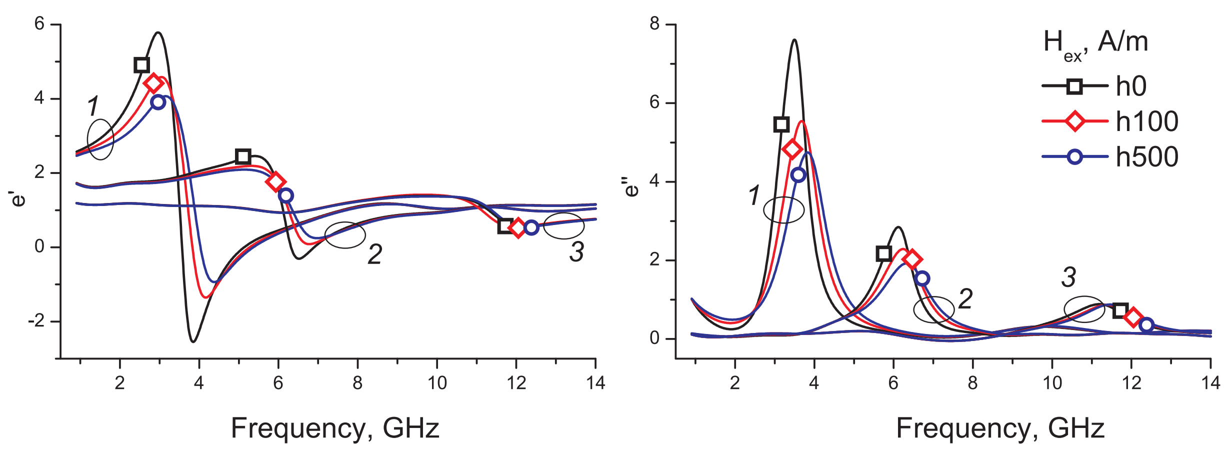

Fig. 18. Effective permittivity spectra for composites with cut wires of length 40 (1), 20 (2) and 10 (3)mm with the field as a parameter

5. Applications

Ferromagnetic microwire based composites with tuneable electromagnetic characteristics represents a new technology with potentially wide applications. These composites gain additional functionalities while their mechanical properties (mechanical strength, geometrical dimensions, weight, density and other) are defined by the host material matrix and not altered by the inclusion as they are thin and their concentration is very small, less than 0.01% for electric composites. As the wire is very inexpensive to manufacture, the overall composite cost keeps almost unchanged.
The potential applications for composite based on microwires with large and sensitive magneto-impedance effect can be divided in two categories. In the first one, the MI effect in wires is used to control the composite's electromagnetic characteristics. The application of a magnetic field or other stimuli will cause change in reflection, transmission and absorption in the composite material. For example, an "active microwave window" can be realized, the state of which can be changed from transparent (open) to opaque (close) for the microwaves. Other applications are transmission signal modulation, deferent frequency selective surfaces and reconfigurable absorbers.

The second category includes different sensing applications that use a high sensitivity of the wire impedance to external stimuli. They include non-destructive testing and structure health monitoring for detection of invisible structural damages and defects, monitoring stress concentrations and temperature distribution. The measurement can be conducted in the waveguide and in the free-space. The later being a non-contact remote method is of special interest as it allows *in-situ* health monitoring of objects such as infrastructure (bridges, buildings, etc.), pipeline and pressure vessels.

As the permittivity ε_{ef} depends on the wire surface impedance (see Eq.(14) for the relaxation parameter), which in turn is a function of the magnetic permeability of the wire (Eg.(18)), then any physical phenomenon that affects the permeability will affect ε_{ef}. Applying a stress or a torque to amorphous wires causes the change in the wire transverse magnetisation and very large variations in impedance (SI) (Garcia et al, 2005). At GHz frequencies, however, sensitive SI effect requires a special magnetic anisotropy (Panina et al, 2005; Makhnovsky et al, 2006). For example, in the case of negative magnetostrictive wires the anisotropy should be nearly axial (customarily, it is circumferential). Only in this case the applied tensile stress may produce large effect on impedance through the change in static magnetisation direction (see Eq. (18)). Such reverse anisotropy can be induced by special stress-annealing as explained in Section 3. The SI effect is promising for constructing composites with stress-sensitive dispersion of ε_{ef}. The stress applied to the composite matrix will be transmitted to each wire inclusion through matrix strain. As reported in (Sandacci et al 2005, Panina et al, 2005), the application of the tensile stress resulted in increase of the impedance up to 100% at GHz frequencies. In (Makhnovskiy et all 2006) the stress sensitivity of composite media containing amorphous microwires was demonstrated experimentally.

The magnetic structure and GMI of the ferromagnetic wires can be made highly temperature dependent for moderate temperature regions (50-200 °C) that gives a possibility to construct the composites with thermally tuneable microwave response and can find applications in remote temperature monitoring by free-space method, e.g., for composite curing control. The high sensitivity to the temperature can be achieved in the vicinity of the compensation point where the magnetostriction changes its sign. Thus, in $Fe_{73}Cu_1Nb_3Si_{16}B_6$ nanocrystalline alloy the compensation point existing due to high volume fraction of bcc-FeSi is about 170 °C (Hong Duong et al. 1996). The magnetisation of wires produced from such alloy will change from axial to circumferential direction when the temperature is increased beyond the compensation point resulting in decrease in the high frequency impedance.

The other approach to realise temperature sensitive composites is based on the ferromagnetic-paramagnetic transition at Curie temperature T_c. This transition is characterized by the drastic change of properties such as magnetization, magnetic susceptibility, anisotropy etc. It could be expected that GMI ratio will also change near T_c, constituting basis for remote temperature detection. The addition of Ni and Cr in Co/Fe amorphous alloy systems results in a decrease in T_c down to the room temperature (See Section 3). In this way a wide variety of temperature-sensitive composites based on microwires with the T_c ranging between the room temperature and 400 °C can be realized. At approaching T_c, the magnetisation saturation M_s scales with $(1 - T/T_c)^{\beta}$ and the magnetostriction scales as ${M_s}^3$. It will result in increase in the initial rotational permeability proportional to the ratio of the magnetisation and magnetostrictive anisotropy field. However, high frequency properties will deteriorate. Then, the high frequency impedance is expected to decrease near the Curie temperature.

In both proposed approaches, the decrease in the wire impedance as the temperature increases produces substantial changes in the frequency dispersion of the effective permittivity and scattering parameters from such composites. For example, in the case of cut wire composites, the resonance type dispersion of the permittivity and band gap propagation regimes will become more pronounce with increasing temperature. These investigations require modification of the microwave setup such as a construction of special thermo chamber which is quite realistic to be realised.

6. Conclusion

Here we have discussed the electromagnetic properties of composites with magnetic wires showing giant magnetoimpedance effect. A striking property of these materials is that the spectra of the effective electromagnetic parameters (permittivity and permeability) can be actively tuned by applying an external magnetic field. Similar effect could be achieved with proper wire systems by applying a stress or changing a temperature. To realize large tunability, the magnetic wires need to possess a rather unique magnetic structure. Technology of glass coated amorphous and nanocrystalline microwires allows the fabrication of continuous wires having various helical magnetic configurations sensitive to a particular magnetic or mechanical stimuli. It is also possible to vary the Curie temperature of magnetic microwires for temperature sensitive behavior.

The magnetic wire composites may either change the electromagnetic response in a desirable way or provide information about the material's properties (stress, strain, temperature). Then, they can be used as free space filters for secure wireless systems to obtain the desired band-pass or band-gap result or as sensory materials for non-destructive tests. The overall technology of magnetic wire composites is cost-effective and is suitable for large-scale applications.

7. Acknowledgment

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8. References

Adenot, A.L.; Acher, O.; Taffary, T.; Queffelec, P. & Tanne, G. (2000). Tuneable microstrip device controlled by a weak magnetic field using ferromagnetic laminations. J.Appl. Phys, Vol. 87, No. 9, May 2000, pp. 6914-6916, ISSN 0021-8979

Agilent 85071E Materials Measurement Software Available from www.agilent.com/find/materials.

Badinter, E.Ya.; Berman, N.R.; Drabenko, I.F.; Zaborovsky, V.I.; Zelikovsky, Z.I. & Cheban, V.G. (1973) Cast micwories and its properties, Shtinica, Kishinev, USSR.

Barlevy, A. & Rahmat-Samii, Y. (1999). Control of Resonant bandwidth in frequency selective surfaces by tilting the periodic elements. Microwave and Optical Technology Letters, Vol. 21, No. 2, April 1999, pp. 114-117, ISSN 0895-2477

Bartley P. & Begley S., (2005). Improved Free-Space S-Parameter Calibration, Proceedings of the IEEE Instrumentation and Measurement Technology Conference, ISBN 0-7803-8879-8, Ottawa, Canada, May 2005.

Beach, R.S. & Berkowicz, A.E. (1994). Giant magnetic field dependent impedance of amorphous FeCoSiB wire. Appl.Phys.Lett., Vol. 64, No. 26, Jun 1994, pp. 3652-3654, ISSN 0003-6951.

Belov, P. A.; Tretyakov, S. A. & Viitanen, A. J. (2002). Dispersion and Reflection Properties of Artificial Media Formed By Regular Lattices of Ideally Conducting Wires J. Electromagn. Waves Applic. Vol. 16, No. 8, January 2002, pp 1153-1170, ISSN 0920-5071

Brown, J. (1960). Artificial dielectrics. Progress in Dielectr., Vol. 2, 1960, pp. 195-225, ISSN.

Catalan, C.F.; Prida, V.M.; Alonso, J.; Vazquez, M.; Zhukov, A.; Hernando, B. & Velazquez (1997). Effect of glass coating on magnetic properties of amorphous microwires, Rapidly Quenched and Metastable Materials J. Materials Science and Engineering A, Supplement 1997, pp. 438-441. ISSN 0921-5093

Chen, L. F.; Ong C. K.; Neo, C. P.; Varadan, V. V. & Varadan, V. K. (2004). Microwave Electronics Measurement and Materials Characterization, John Wiley & Sons, ISBN 0-470-84492-2, Chichester, England

Chiriac, H. & Ovari, T.A. (1996). Amorphous glass-covered magnetic wires: preparation properties, applications. Progress in Material Science, Vol. 40, No. 5, February 1999, pp. 333-407, ISSN: 0079-6425

Chizhik, A.; Gonzalez, J.; Zhukov, A. &Blanco, J.M. (2004). Vortex-type domain structure in Co-rich wires. J. Appl. Phys. Vol. 95, No. 5, Mart 2004 pp. 2933-2935, ISSN 0021-8979

Chizhik, A.; Zhukov, A.; Balnco, J.M; & Gonzalez J. (2001). Magneto-optical investigation of the magnetization reversal in Co-rich wires, Physica B: Condensed Matter Vol. 299, No. 3-4, June 2001, pp. 314-321, ISSN 0921-4526

Dudek, C.; Adenot-Engelvin, A . L. & Acher, O. (2006). Static and Dynamic Properties of Fe-Si-B-Nb-Cu Nanocrystallized Ferromagnetic Glass-Coated Microwires From 20 C to 350 C. IEEE Trans. Magn., Vol. 42, No. 10, October 2006, pp. 2787-2789, ISSN 0018-9464

Fujimori, H.; Arai, K.I.; Shirae, H.; Saito, H.; Masumoto, T. & Tsuya, N., (1976). Magnetostriction of Fe-Co Amorphous Alloys. Jpn. J. Appl. Phys. Vol. 15, No. 4, April 1976, pp. 705-706, ISSN 0021-4922

Garcia, C.; Zhukov, A.; Zhukova, V.; Ipatov, M.; Blanco, J. M. & Gonzalez, J. (2005). Effect of tensile stresses on GMI of Co-rich amorphous microwires. IEEE Trans Magn, Vol. 41, No. 10, October 2005, pp. 3688 - 3690, ISSN 0018-9464

Garcia, C.; Zhukov, A.; Gonzalez, J.; del Val, J.J.; Blanco, J.M.; Knobel, M. & Zhukova, V. (2009) Fabrication, structural and magnetic characterization of thin microwires with novel composition Cu70(Co70Fe5Si10B15)30. Journal of Alloys and Compounds Vol. 483, No. 1-2, August 2009, pp. 566-569, ISSN 0925- 8388

Garcia Prieto, M.J.; Pina, E.; Zhukov, A.P.; Larin, V.; Marin, P.; Vazquez, M. & Hernando, A. (2000). Glass-coated Co-rich amorphous microwires with enhanced permeability. Sensors and Actuators A: Physical, Vol. 81, No. 1, April 2000, pp. 227-231, ISSN 0924-4247

Garcia, C.; Zhukov, A.; Zhukova, V.; Ipatov,M.; Blanco, J.M. & Gonzalez, J. (2005). Effect of Tensile Stresses on GMI of Co-rich Amorphous Microwires. IEEE Trans Magn. Vol. 41, No. 10, pp. 3688-3690, October 2005, ISSN 0018-9464

Hong Duong, V.; Sato Turtelli, R.; Grossinger, R.; Hiebl, K. & Rogl, P. (1996). Magnetostriction in Fe76.5-xCu1NbxSi13.5B9. IEEE Transactions on Magnetics, Vol. 32, No. 5, September 1996, pp. 4821 - 4823, ISSN 0018-9464

Honkura, Y. (2002) Development of amorphous wire type MI sensors for automobile use. J. Magn. Magn. Mater. Vol. 249, No. 1-2, August 2002, pp. 375-381, ISSN 0304-8853

Knobel, K. & Pirota K. R. (2002) Giant magnetoimpedance: concepts and recent progress, J Magn Magn Mater, Vol. 242-245, No. 1, April 2002, pp. 33-40, ISSN 0304-8853

Kraus, L.; Schneider, J.; & Wiesner H. (1976) Ferromagnetic resonance in amorphous alloys prepared by rapid quenching from the melt. Czech. J. Phys. Vol. 26, No. 5. May 1976, pp. 601-602, ISSN: 0011-4626

Kraus, L.; Knobel, M.; Kane, S.N.; & Chiriac, H. (1999). Influence of joule heating on magnetostriction and giant magnetoimpedance effect in a glass covered CoFeSiB microwire, J. Appl. Phys., Vol. 85, No. 8, April 1999, pp. 5435–5437, ISSN 0021-8979

Lagarkov, A. N. & Sarychev, A. K. (1996). Electromagnetic properties of composites containing elongated conducting inclusions. Phys. Rev. B, Vol. 53, No. 10, March 1996, pp. 6318-6336, ISSN 1098-0121

Larin, V. S.; Torcunov, A. V.; Zhukov, A. P.; Gonzalez, J.; Vazquez, M. & Panina, L. V. Preparation and properties of glass-coated microwires. J. Magn. Magn. Mater., Vol. 249, No.1-2, August 2002, pp 39-45, ISSN 0304-8853

Liu, L.; Matitsine, S. M.; Gan, Y. B. & Rozanov, K. N. (2005). Effective permittivity of planar composites with randomly or periodically distributed conducting fibers. J. App. Phys. Vol. 98, No. 6, September 2005, pp. 063512-7, ISSN 0021-8979

Lofland, S. E.; Bhagat, S. M.; Dominguez, M.; Garcia-Beneytez, J. M.; Guerrero, F. & Vazquez ,M. Low-field microwave magnetoimpedance in amorphous microwires, J. Appl. Phys., Vol. 85, No. 8, April 1999, pp. 4442-4444, ISSN 0021-8979

Makhnovskiy, D.P.; Panina, L. V. & Mapps, D. J. (2001) Field-dependent surface impedance tensor in amorphous wires with two types of magnetic anisotropy: helical and circumferential, Phys. Rev. B, Vol. 63, No. 14, April 2001, pp. 144424-17, 2001, ISSN 1098-0121

Makhnovskiy, D.P; Panina, L.V. & Maps D. J. (2001). Field-dependent surface impedance tensor in amorphous wires with two types of magnetic anisotropy: Helical and circumferential. Phys. Rev. B Vol. 63, No. 14, March 2001, pp.144424-17, ISSN 1098-0121

Makhnovskiy, D.P & Panina, L.V. (2003). Field Dependent Permittivity of Composite Materials Containing Ferromagnetic Wires. J. Appl. Phys., Vol. 93, No. 7, April 2003, pp. 4120-4129, ISSN 0021-8979

Makhnovskiy, D. P. & Panina L. V. (2005) Field and stress-tunable microwave composite materials based on ferromagnetic wires, in Progress in Ferromagnetism Research, Murray V. N. (Ed.) pp. 255-292, Nova Science Publishers Inc., ISBN 1-59454-335-6 Hauppauge, NY, USA

Makhnovskiy, D.P.; Panina, L. V.; Garcia, C.; Zhukov, A. P. & Gonzalez, J. (2006). Experimental demonstration of tunable scattering spectra at microwave frequencies in composite media containing CoFeCrSiB glass-coated amorphous ferromagnetic wires and comparison with theory, Phys. Rev. B, Vol. 74 No. 6, August 2006, pp. 064205-11, ISSN 1098-0121

Matitsine, S. M.; Hock, K. M.; Liu, L. ; Gan, Y. B.; Lagarikov, A.N. & Rozanov, K.N. (2003) Shift of resonance frequency of long conducting fibers embedded in a composite, J. Appl. Phys., Vol. 94No. 2, July 2003, pp. 1146-1154, ISSN 0021-8979

Mohri, K.; Uchiyama, T.; Shen, L.P.; Cai, C.M. & Panina, L.V. (2001). Sensitive micro magnetic sensor family utilizing magneto-impedance (MI) and stress-impedance (SI) effects for intelligent measurements and controls. Sensors and Actuators, A: Physical, Vol. 91 No. 1-2, June 2001, pp. 85-90, ISSN: 0924-4247

Mohri, K.; Uchiyama, T.; Shen, L. P.; Cai, C. M.; Panina, L. V. & Honkura Y. (2002). Amorphous wire and CMOS IC-based sensitive micromagnetic sensors utilizing magnetoimpedance (MI) and stress-impedance (SI) effects, IEEE Trans. Magn., Vol. 38, No.5, September 2002, pp. 3063–3068, ISSN 0018-9464

Mohri K. & Honkura Y. (2007). Amorphous wire and CMOS IC based magneto-impedance sensors --- Orign, topics, and future. Sensor Letters, Vol. 5, No. 2, March 2007 pp. 267-270, ISSN 1546-198X

Ong, K .G. & Grimes, C. A. (2002). Tracking the harmonic response of magnetically-soft sensors for wireless temperature, stress, and corrosive monitoring. Sensors and Actuators A: Physical, Vol. 101, No. 1-2, September 2002, pp. 49-61, ISSN 0924-4247

Panina, L.V. & Mohri, K. (1994). Magneto-impedance effect in amorphous wires. Appl.Phys.Lett, Vol. 65, No. 9, August 1994, pp. 1189-1191, ISSN 0003-6951

Panina, L. V.; Sandacci, S.I. & Makhnovskiy, D.P. (2005). Stress effect on magnetoimpedance in amorphous wires at gigahertz frequencies and application to stress-tunable microwave composite materials. J. Appl. Phys, Vol. 97, No. 1, January 2005, pp. 013701-07, ISSN 0021-8979

Panina, L.V. (2009). Magnetoimpedance (MI) in amorphous wires: new materials and applications. Phys. Status Solidi A, Vol. 206, No. 4, April 2009, pp. 656–662, ISSN 1862-6300

Panina, L. V.; Ipatov, M.; Zhukova, V.; Zhukov, A. & Gonzalez J. (2011). Magnetic field effects in artificial dielectrics with arrays of magnetic wires at microwaves, J. Appl. Phys., Vol. 109, No. 5, March 2011, pp. 053901-8, ISSN 0021-8979

Qin, F. X. ; Peng, H. X.; Pankratov, N.; Phan, M. H. ; Panina, L. V. ; Ipatov, M.; Zhukova, V.; Zhukov, A.; & Gonzalez J. (2010). Exceptional electromagnetic interference shielding properties of ferromagnetic microwires enabled polymer composites. J. Appl. Phys., Vol. 108, No. 4, August 2010, pp. 044510-044515, ISSN 0021-8979

Ripka P. (Ed). (2001). Magnetic sensors and magnetometers, Artech House Publishers, ISBN 1-58053-057-5, Norwood, USA

Pendry, J. B.; Holden, A. J.; Robbins, D. J. & Stewart, W. J. (1998). Low frequency plasmons in thin-wire structures. J. Phys.:Condens. Matter., Vol. 10, No. 22, (June 1998), pp. 4785-4809, ISSN 0953-8984

Peng, H.X.; Qin, M.H.; Phan, F.X.; Tang Jie, Panina, L.V.; Ipatov, M.; Zhukova, V.; Zhukov, A. & Gonzalez J. (2009). Co-based magnetic microwire and field-tunable multifunctional macro-composites. J. Non-Crystalline Solids, Vol. 355, No. 24-27, August 2009, pp. 1380-1386, ISSN: 0022-3093

Reynet, O.; Adent, A.-L.; Deprot, S.; Acher, O. & Latrach, M. (2002). Effect of the magnetic properties of the inclusions on the high-frequency dielectric response of diluted composites. Phys. Rev. B, Vol. 66, No. 9, (Septembertember 2002), pp. 94412-9, ISSN 1098-0121

Phan, M. & Peng, H. (2008). Giant Magnetoimpedance Materials: Fundumentals and Applications. Progress in Materials Science, Vo.53, No 2, February 2008, pp. 323-420, ISSN 0079-6425

Rotman, W. (1962). Plasma simulation by artificial dielectrics and parallel-plate media. IRE Trans. Antennas Propag., Vol. 10, No. 1, January 1962, pp. 82-95 1962. ISSN 0096-1973

Sandacci, S. I.; Makhnovskiy, D. P.; Panina, L. V.; Mohri, K. & Honkura, Y. (2004a) Off-diagonal impedance in amorphous wires and its application to linear magnetic sensors. IEEE Trans Magn., Vol. 40, No. 6, November 2004, pp. 3505 – 3511, ISSN: 0018-9464

Sandacci, S.; Makhnovskiy, D.P.; Panina, L. V. & Larin, V. (2004b) Valve-like behavior of the magnetoimpedance in the GHz range. J. Magn. Magn. Mat., Vol. 272-276, No. 3, May 2004, pp. 1855-1857, ISSN 0304-8853

Sandacci, S.; Makhnovskiy, D.; Panina, L. & Larin, V. (2005). Stress-dependent magnetoimpedance in Co-based amorphous wires with induced axial anisotropy for tunable microwave composites. IEEE Transactions on Magnetics, Vol. 41, No. 10, October 2005, pp. 3553 - 3555, ISSN 0018-9464

Sarychev, A.K. & Shalaev, V.M. (2000) Electromagnetic field fluctuations and optical nonlinearities in metal-dielectric composites. Physics Reports, Vol. 335, No. 6, September 2000, pp. 275-371, ISSN 0370-1573, (see equation 7.67)

Shen, L.P.; Uchiyama, T.; Mohri, K.; Kita, E. & Bushida, K. (1997). Sensitive Stress-Impedance Micro Sensor Using Amorphous Magnetostrictive Wire. IEEE Transactions on Magnetics, Vol. 33, No. 5, September1997, pp. 3355 – 3357, ISSN 0018-9464

Sievenpiper, D.; Schaffner, J.; Loo, R.; Tangonan, G.; Ontiveros, S. & Harold R. (2002). A tunable impedance surface performing as a reconfigurable beam steering reflector. IEEE Trans. Antennas Propagat., Vol. 50, No. 3, March 2002, pp. 384-390, ISSN 0018-926X

Sievenpiper,D. F.; Sickmiller, M. E. & Yablonovitch, E. (1996), 3D wire mesh photonic crystals. Phys. Rev. Lett., Vol. 76, No. 14, April 1996, pp 2480-2483, ISSN 0031-9007

Smith, D. R.; Padilla, W. J.; Vier, D. C.; Nemat-Nasser, S. C. & Schultz, S. (2000). Composite Medium with Simultaneously Negative Permeability and Permittivity. Phys. Rev. Lett., Vol. 84, No. 18, May 2000, pp. 4184-4187, ISSN 0031-9007

Snoek, J.L. (1948). Dispersion and Absorption in Magnetic Ferrites at Frequencies above 1 Mc/s. Physica, Vol. 14, No. 4, May 1948, pp. 207-217, ISSN

Takajo, M.; Yamasaki, J.; Humphrey, F.B.;(1993). Domain observations of Fe and Co based amorphous wires, IEEE Trans. Magn., Vol. 29, No 6, pp. 3484-3486, ISSN 0018-9464

Taylor G.F. (1924) A Method of Drawing Metallic Filaments and a Discussion of their Properties and Uses. Phys. Rev., Vol. 23, No. 5, May 1924, pp. 655-660, ISSN 0031-899X

Taylor, G.F. Process and apparatus for making Filaments, Patented Feb. 24, 1931, United States Patent Office, 1, 793, 529.

du Trémolet de Lacheisserie, E.; Gignous, D. & Schlenker, M. (2005). Magnetism: Materials and Applications, Vol. 2 Springer, ISBN 0-387-23000-9, New York

Tejedor, M.; Hernando, B.; Sanchez, M. L.; Prida V. M.; & Vazquez, M. (2001). Magneto-impedance effect in amorphous ribbons for stress sensor application, Sensors and Actuators A: Physical ,Vol. 81, No. 1-3, 1 April 2000, pp. 98-101, ISSN 0924-4247

Ulitovsky, A.V. & Avernin, N.M. Method of fabrication of metallic microwire Patent No161325 (USSR), 19.03.64. Bulletin No7, p.14.

Ulitovsky, A.V. Micro-technology in design of electric devices, Leningrad, 1951, No.7, p.6.

Ulitovsky, A.V.; Maianski, I.M. & Avramenco, A.I. Method of continuous casting of glass coated microwire Patent No128427 (USSR), 15.05.60. Bulletin. No10, p.14.

Vazquez, M.; Chiriac, H.; Zhukov, A; Panina, L. & Uchiyama T., On the state-of-the-art in magnetic microwires and expected trends for scientific and technological studies. Phys. Status Solidi A, Vol. 208, No. 3, March 2011, pp. 493–501, ISSN 1862-6300

Vazquez, M. & Hernando, A. (1996). A soft magnetic wire for sensor applications, J Phys D: Appl Phys, Vol. 29, No. 4, April 1996, pp. 939–949

Yashchyshyn Y. & Modelski, J. (2002). The Leaky-Wave Antenna with Ferroelectric Substrate., Proceedings of XIV International Conference on Microwaves, Radar and Wireless Communications (MIKON-2002), Vol.1, p.21, ISBN 83-906662-5-1, Poland, Gdansk, May 2002

Zhukov, A.; Gonzalez, J.; Blanco, J.M.; Vazquez, M. & Larin, V. (2000). Microwires coated by glass: A new family of soft and hard magnetic materials. J. Mat. Res., Vol. 15, No. 10, October 2000, pp. 2107-2113, ISSN: 0884-2914

Zhukov, A.; Gonzalez, J.; Vazquez, M.; Larin, V. & Torcunov, A. (2004) Nanocrystalline and Amorphous Magnetic Microwires, In: Encyclopedia of Nanoscience and Nanotechnology, ed. Nalwa H. S., pp. 365-387), American Scientific Publishers, ISBN: 1-58883-001-2, Valencia, USA

Zhukov, A. (2006). Design of magnetic properties of Fe-rich glass - coated magnetic microwires for technical applications. Adv. Func. Mat., Vol. 16, No. 5, January 2006, pp.675-680, ISBN 1616-3028

Zhukov, A.; Garcia, C.; Zhukova, V.; Larin, V.; Gonzalez J.; del Val, J.J.; Knobel, M. & Blanco, J.M. (2007). Fabrication and magnetic properties of Cu50(Fe69Si10B16C5)50 thin microwires. J. Non-Cryst. Solids, Vol. 353, No. 8-10, April 2007, pp. 922-924, ISBN 0022- 3093

Zhukov, A.; Ipatov, M.; Zhukova, V.; Garcia, C.; Gonzalez, J. & Blanco, J. M. (2008). Development of ultra-thin glass-coated amorphous microwires for HF magnetic sensor applications. Phys. Stat. Sol. (A), Vol. 205, No. 6, June 2008, pp. 1367-1372, ISSN 1862-6300

Zhukov A. & Zhukova V. (2009). Magnetic properties and applications of ferromagnetic microwires with amorphous and nanocrystalline structure, Nova Science Publishers, ISBN: 978-1-60741-770-400, Hauppauge, NY, USA

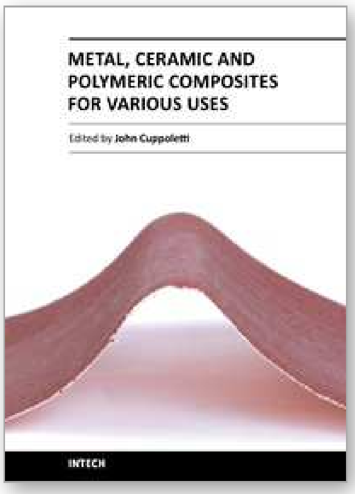
Zhukova, V.; Chizhik, A.; Zhukov, A.; Torcunov, A.; Larin, V. & Gonzalez, J. (2002), Optimization of giant magnetoimpedance in Co-rich amorphous microwires. IEEE Trans. Magn., Vol. 38 No. 5, September2002, pp. 3090-3092, ISSN: 0018-9464

Zhukova, V.; Larin. V.S. & Zhukov A. (2003). Stress induced magnetic anisotropy and giant magnetoimpedance in Fe-rich glass/coated magnetic microwires. J.Appl. Phys. Vol. 94, No. 2 July 2003, pp. 1115-1118, ISSN 0021-8979

Zhukova, V.; Ipatov, M.; Zhukov, A.; Varga, R.; Torcunov, A.; Gonzalez, J. & Blanco J.M. (2006). Studies of magnetic properties of thin microwires with low Curie temperatures. J. Magn. Magn. Mater., Vol. 300, No.1, May 2006, pp. 16-23, ISSN 0304-8853

Zhukova, V.; Blanco, J.M.; Ipatov, M.; Zhukov, A.; Garcıa, C.; Gonzalez, J.; Varga, R. & Torcunov, A. (2007) Development of thin microwires with low Curie temperature for temperature sensors applications Sensors and Actuators B: Chemical, Vol. 126, No. 1, September 200), pp. 318-323, ISSN 0925-4005

Zhukova, V; Ipatov, M. & Zhukov A., (2009) Thin Magnetically Soft Wires for Magnetic Microsensors. Sensors Vol. 9, No. 11, November 2009, pp. 9216-9240, ISSN 1424-8220



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