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Tunable permeability of magnetic wires at microwaves

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ABSTRACT

This paper presents the analysis into microwave magnetic properties of magnetic microwires and their composites in the context of applications in wireless sensors and tunable microwave materials. It is demonstrated that the intrinsic permeability of wires has a wide frequency dispersion with relatively large values in the GHz band. In the case of a specific magnetic anisotropy this results in a tunable microwave impedance which could be used for distributed wireless sensing networks in functional composites. The other range of applications is related with developing the artificial magnetic dielectrics with large and tunable permeability. The composites with magnetic wires with a circumferential anisotropy have the effective permeability which differs substantially from unity for a relatively low concentration (less than 10%). This can make it possible to design the wire media with a negative and tunable index of refraction utilising natural magnetic properties of wires.

1. Introduction

This paper discusses the high frequency permeability and impedance of magnetic microwires and the applications based on these properties. It is well known that soft magnetic wires exhibit the magnetoimpedance effect owing to a helical magnetic structure and large dynamic permeability (see, for example, reviews [1–3]). At MHz frequencies, MI is successfully used in low field magnetic sensors [4,5] and stress sensors [6,7]. Here, the emphasis is placed on the permeability behaviour at MHz and GHz frequencies in the presence of the external factors such as a magnetic field, stress and temperature. The intrinsic permeability spectra in wires are very wide and the values differs substantially from unity in the GHz frequency band [8,9]. This could be attractive to design artificial magnetic dielectrics with enhanced and tunable permeability. Large permeability values at GHz also allow the MI to remain very high in the range of tens of per cent at such frequencies [10–12]. The wires showing MI at GHz frequencies, which is also sensitive to stress or temperature, may find applications in wireless sensing networks within functional materials [13–15]. In composites with magnetic wires, a variable MI may also provide a tuning of the dielectric losses and transmission modulation [8,9,16–19].

Here we investigate the permeability spectra in magnetic wires which can be easily tuned by changing the magnetisation direction. The wires with a circumferential anisotropy have a large permeability in response to a high frequency magnetic field applied along the wire, which can be changed by a moderate dc axial field due to magnetisation re-orientation. The wires embedded in composite matrix will provide tunable magnetic properties at microwaves. The applications include controllable absorbing or shielding systems. The other range of applications is related with left handed materials. It is known that high frequency magnetic properties can be generated by electric current loops in structures such as split- ring resonators [20,21] and cut-wire pairs [22,23]. In this case the permeability spectra are of a resonance type but limited to a very narrow frequency band. Typically ferrite composites are used to realise wideband and tuneable permeability spectra [24,25]. However, thin ferromagnetic conductors having a higher saturation magnenetisation can be preferable to design diluted artificial magnetics (5–10% of volume concentration). Owing to low concentration of ferromagnetic components, this structure could be easily integrated with other systems as arrays of metallic wires providing a specific dielectric function. For example, using Co-rich magnetic wires having a negative magnetostriction it is possible to achieve a negative index of refraction at GHz frequencies [26,27]. Very wide permeability spectra typical of magnetic wires may also help to minimise losses at certain frequencies which is a problem for metamaterials without an active phase [3,4].

The other range of application of high frequency magnetic properties in wires is related with the development of smart

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composites which are expected to have integrated sensors to monitor potential damage to the structure. The majority of work in this area has been investigating the use of optical fibre sensors (see review in [28]) for stress and temperature detection within a material or structure. However, there remains a problem of diameter mismatch between reinforcing and optical fibres, that affects the structural integrity and detection sensitivity. Novel sensing elements for use within composite structures are highly desired. Magnetic wires with microwave MI which is sensitive to mechanical stress and temperature have a high potential for such applications. The stress-sensitive MI and its application to smart composites is investigated in a number of recent works [7–9, 29–31]. Here we focus on MI in wires with a relatively low Curie temperature T_c (100–200 °C) demonstrating its high temperature sensitivity in the vicinity of T_c for a wide frequency range. In this case, wires with an axial anisotropy are preferable.

Tunable high frequency behaviour of microwires and their composites are available by a specific dc magnetic structure in wires and production technology offering a wide room for manipulation. In amorphous wires, the magnetostriction and internal stress play the main role in determining the effective anisotropy and domain structure. Thus, for negative magnetostriction ($\lambda < 0$) the anisotropy is circumferential (excluding small inner region) and for $\lambda > 0$ the wire has an axial anisotropy. The value and sign of the magnetostriction depend on the alloy composition which can be widely varied. For example, in the $(Co_{1-x}Fe_x)_{75}Si_{15}B_{10}$ series, λ is positive for $x > 0.06$ [30,32] and around this compositional point, excellent soft magnetic properties can be realised. For a circumferential anisotropy, the wire dynamic permeability is large up to GHz range and also strongly depends on the dc axial magnetic field. This is also a condition for large and sensitive MI and the tuning mechanism involves a linear dc remagnetisation by the dc magnetic field. The dominant role of the magnetostrictive anisotropy makes it possible to achieve stress-sensitive MI.

The wires with $\lambda > 0$ of Fe-rich compositions exhibit a rectangular hysteresis loop of a bistable type. Typically, they are not suitable for MI. Recently, bistable wires with relatively low Curie temperatures T_c in the range of 75–200 °C have been designed [33,34]. When approaching T_c, the permeability spectra and MI become highly temperature-sensitive. Near T_c there is a decrease in magnetisation saturation and magnetostriction. As a result, the ferromagnetic resonance shifts towards lower frequencies leading to a decrease in high frequency impedance. Therefore, these wires can serve as embedded temperature sensors within composites, operating in a moderate temperature range which is of interest for composite curing.

1.1. Theoretical analysis

Tunable electromagnetic response from magnetic wires is described in terms of the surface impedance tensor $\hat{\varsigma}$ and the averaged permeability μ_{ef} and permittivity ε_{ef}. In both cases, the radial distribution of ac electric $\boldsymbol{e}(r)$ and magnetic $\boldsymbol{h}(r)$ fields and the dynamic magnetisation $\boldsymbol{m}$ inside the wire are needed. The surface impedance relates the tangential components of $\boldsymbol{e}$ and $\boldsymbol{h}$ at the wire surface (a is the wire radius):

$$\boldsymbol{e}(a) = \hat{\varsigma}(\boldsymbol{h}(a) \times \boldsymbol{n}) \tag{1}$$

The induced voltage in the wire and its dependence on the magnetic structure are determined by the tensor $\hat{\varsigma}$. If magnetic wires are used as the component of a composite system, the surface impedance determines the relaxation due to resistive and magnetic losses. Therefore, it enters the effective permittivity of wire composites [17]. The effective permeability can be defined by the ratio of the averaged magnetic induction and external magnetic field. A large response is possible to the field h_0 directed along the wires. Then,

$$\mu_{ef} = \langle b_z \rangle / h_0 \tag{2}$$

Here b_z is the axial component of the magnetic induction, $\langle \ldots \rangle$ means volume averaging.

A proposed approach is to consider a local relationship between $\mathbf{m}$ and $\mathbf{h}$: $\mathbf{m} = \hat{\chi}\,\mathbf{h}$ and to solve the Maxwell equations inside the wire with a given ac permeability tensor $\hat{\mu} = 1 + 4\pi\hat{\chi}$ [34]. The boundary conditions at the wire surface correspond to the excitation conditions.

This is certainly a strong assumption. Firstly, the domain structure is ignored and a uniform precession of the magnetisation is considered. This can be reasonable in the presence of the bias magnetic fields eliminating the domains. It is assumed that the static magnetisation $\boldsymbol{M}_0$ is lying along a helical pass making a constant angle θ with the wire axis. In this case, $\hat{\mu}$ is spatially independent. This approximation is justified as follows. The practical interest is related with two limiting cases: a strong skin effect when the surface impedance shows a high sensitivity to the magnetic properties and a weak skin effect when the average permeability is large. For a high frequency case, the permeability is predominantly a surface permeability. In the low frequency case an averaged value of the permeability can be used.

It is convenient to consider a prime coordinate system with the axis z' along the static magnetisation $\boldsymbol{M}_0$. The linearised Landau–Lifshitz equation for $\boldsymbol{m}$ is written in the form (assuming the time dependence as $\exp(-j\omega t)$):

$$-j\omega\,\mathbf{m} + (\omega_H - j\tau\omega)(\mathbf{m} \times \mathbf{n}_{z'}) + \gamma M_0((\hat{N}\,\mathbf{m}) \times \mathbf{n}_{z'}) = \gamma M_0(\mathbf{h} \times \mathbf{n}_{z'}) \tag{3}$$

where $\boldsymbol{n}_{z'}$ is a unit vector along z', $\omega_H = \gamma(\partial U/\partial \mathbf{M}_0)_{z'}$, U is the magnetic energy, τ is the spin-relaxation parameter, $\widehat{N}$ is the tensor of the effective anisotropy factors in the prime coordinate system, γ is the gyromagnetic constant. Assuming a helical uniaxial anisotropy defined by an angle α with respect to the wire axis and presence of external magnetic fields: H_{ex} along the wire and H_b along circumference (due to dc bias current), the magnetic energy is

$$U = -K\cos^2(\alpha - \theta) - M_0 H_{ex}\cos\theta - M_0 H_b \sin\theta \tag{4}$$

Here K is the effective anisotropy constant. Solving Eq. (3) for $\boldsymbol{m} = \hat{\chi}\boldsymbol{h}$ determines the susceptibility tensor $\hat{\chi}$ which has the simplest form in the prime coordinate system:

$$\hat{\chi} = \begin{pmatrix} \chi_1 & -j\chi_a & 0 \\ j\chi_a & \chi_2 & 0 \\ 0 & 0 & 0 \end{pmatrix} \tag{5}$$

For the considered magnetic configuration, the parameters χ_1, χ_2, χ_a are expressed as

$$\begin{aligned} \chi_1 &= \omega_M(\omega_1 - j\tau\omega)/\Delta, \\ \chi_2 &= \omega_M(\omega_2 - j\tau\omega)/\Delta, \\ \chi_a &= \omega\omega_M/\Delta, \\ \Delta &= (\omega_2 - j\tau\omega)(\omega_1 - j\tau\omega) - \omega^2, \\ \omega_1 &= \gamma[H_{ex}\cos\theta + H_b\sin\theta + H_K\cos 2(\alpha - \theta)], \\ \omega_2 &= \gamma[H_{ex}\cos\theta + H_b\sin\theta + H_K\cos^2(\alpha - \theta)], \\ H_K &= 2K/M_0 \quad \omega_M = \gamma M_0. \end{aligned} \tag{6}$$

The solution of the Maxwell equations in a magnetic wire with a spatially independent permeability is based on the expansion in asymptotic series with respect to a parameter $\beta = a/\delta$, where

$\delta = c/\sqrt{2\pi\sigma\omega}$ is the non-magnetic penetration depth [35]. It is also assumed that the radial magnetic induction is zero. In the law frequency case ($\beta \ll 1$) the field distribution inside the wire (up to the terms ~β^2), written in cylindrical coordinates (r, φ, z) is

$$h_\varphi = h_{\varphi 0}\frac{J_1(k_1 r)}{J_1(k_1 a)} + h_0\left(\frac{a}{\delta}\right)^2 \frac{2j\mu_3}{3}\frac{r}{a}\left(1 - \frac{r}{a}\right) \quad (7)$$

$$h_z = h_0\frac{J_0(k_2 r)}{J_0(k_2 a)} + h_{\varphi 0}\left(\frac{a}{\delta}\right)^2 \frac{2j\mu_3}{9}\left(1 - \frac{r^3}{a^3}\right) \quad (8)$$

Here $h_{\varphi 0} = 2i/ca$ is the circumferential field at the wire surface due to ac current i, c is the velocity of light, $k_i^2 = \mu_i\ (4\pi j\omega\sigma/c^2)$, i=1,2, σ is the conductivity, and the permeability parameters are

$$\mu_1 = 1 + 4\pi\cos^2(\theta)\,\tilde{\chi},$$
$$\mu_2 = 1 + 4\pi\sin^2(\theta)\tilde{\chi},$$
$$\mu_3 = -4\pi\ \sin(\theta)\cos(\theta)\tilde{\chi} \quad (9)$$

In (9) the apparent susceptibility $\tilde{\chi}$ is composed of the components of tensor $\hat{\chi}$ (5) and has a form [34,35]

$$\tilde{\chi} = \chi_2 - \frac{4\pi\chi_a^2}{1 + 4\pi\chi_1} \quad (10)$$

It is seen, that the magnetic field distribution inside the wire depends only on a single dynamic susceptibility parameter $\hat{\chi}$ and the direction of the dc magnetisation.

The asymptotic expansion is built such that the first terms in (7) and (8) correspond to the exact solutions for the uncoupled equations for fields h_z, h_φ. As it was proven in [34] that the area of validity of low frequency approximation is much wider: a/δ_m~1, where δ_m is the magnetic skin depth. For amorphous Co-based wires with effective anisotropy of 5 Oe, δ_m changes from 12.5 to 4.8 μm in the frequency range of 1–10 GHz. Therefore, for wires with a radius of smaller than 5 μm the low frequency approximation is valid in the GHz range. This is especially important to get large values of the averaged wire permeability. The axial permeability μ_w of the wire with respect to the external ac magnetic field h_0 averaged over the wire volume is found integrating Eqs. (7) and (8) with the corresponding permeability parameters:

$$\mu_w = \frac{\mu_2 < h_z > + \mu_3 < h_\varphi >}{h_0} = \mu_2\frac{2J_1(k_2 a)}{J_0(k_2 a)k_2 a} + \mu_3^2\frac{j}{9}\beta^2 \quad (11)$$

The second term in (11) is due to cross-magnetisation processes: a circumferential magnetic field generates an axial magnetisation as seen from (8).

The series representation for the electric field $\mathbf{e} = (e_z,\ e_\varphi)$ is found using (7) and (8) directly from the Maxwell equation. Representing the surface values of the electric field as a linear combination of (h_0, $h_{\varphi 0}$), the surface impedance tensor is calculated from Eq. (1). Its axial component ς_{zz} is expressed as

$$\varsigma_{zz} = \frac{k_1 c}{4\pi\sigma}\frac{J_0(k_1 a)}{J_1(k_1 a)} + \frac{1}{54}\beta^4\frac{c\,\mu_3^2}{\pi\sigma a} \quad (12)$$

High frequency asymptote for the impedance gives [34]

$$\varsigma_{zz} = \frac{c(1-j)}{4\pi\sigma\delta}\left(\sqrt{\tilde{\mu}}\ \cos^2\theta + \sin^2\theta\right) \quad (13)$$

$$\tilde{\mu} = 1 + 4\pi\tilde{\chi} \quad (14)$$

Eq. (13) can be also obtained by considering a local plane geometry [36,37]. However, this method is restricted to a zero-order approximation only. The higher-order terms can be important to determine the validity conditions. Thus, strictly speaking a strong skin-effect approximation yielding (13) requires $\delta/a \ll 1$ which is much stronger than that involving the magnetic skin-depth $\delta_m/a \ll 1$. The asymptotic series analysis demonstrates that for many cases the latter condition is sufficient and it also makes it possible to accurately join together the low and high frequency asymptotes for the impedance.

The important conclusion which follows from Eqs. (11)–(13) for the averaged permeability and impedance is that the dependence on the magnetic properties involves two parameters: dynamic susceptibility $\tilde{\chi}$ (or permeability $\tilde{\mu}$) and the static magnetisation angle θ. In the case of the circumferential anisotropy, tuning effect is easier to realise by changing the magnetisation direction since much larger external forces are required to cause noticeable changes in the behaviour of $\tilde{\mu}$ entering (11)–(13). This low magnetic field effect is responsible for giant magnetoimpedance effect in magnetic wires and is also known as low magnetic field absorption [38,39].

2. Permeability dispersion for wires with nearly circumferential anisotropy

Soft magnetic wires with nearly circumferential anisotropy find applications in sensors since they have a high sensitivity of the impedance to the external magnetic and mechanical forces. At GHz frequencies this sensitivity is mainly related with the change in the dc magnetisation caused by the external factors. However, the magnitude of the permeability parameter $\tilde{\mu} = 1 + 4\pi\tilde{\chi}$ where $\tilde{\chi}$ is given by Eq. (10), which defines the electromagnetic characteristics in wires must substantially differ from unity to observe the impedance sensitivity to the magnetic structure. The parameter $\tilde{\mu}$ for this case has a wide resonance dispersion and the GHz band lies past the resonance for moderate values of H_{ex}. For Co-rich wires with the magnetisation saturation of about 500 G and the anisotropy field of few Oe, the ferromagnetic resonance frequency f_{res} is in the range of 300–800 MHz for moderate external fields of 1–10 Oe. Therefore, at GHz frequencies the real part of $\tilde{\mu}$ is negative but retains a large magnitude (about 10–20). The spectra of $\tilde{\mu}$ calculated from (6) and (10) are shown in Fig. 1. The real part crosses unity at $f_{res} = \gamma\sqrt{4\pi M_0|H_k - H_{ex}|}/2\pi$ $(\alpha = 90°)$ which is 564 MHz at $H_{ex} = 2.5$ Oe and 805 MHz at $H_{ex} = 15$ Oe ($H_K = 5$ Oe). It is seen that in both cases the frequency where the imaginary part has a maximum is considerably smaller than f_{res} and the dispersion region is very wide. At frequencies past the resonance the values of $\tilde{\mu}$ for moderate fields of few times larger than H_K are very close. This confirms, that high sensitivity of microwave MI is related with changing the direction of the dc magnetisation.

The dispersion curves, considered above, look similar to a relaxation spectrum typical of polycrystalline multidomain ferrites. In the present case, a wide dispersion of the permeability is caused by a special form of the circumferential susceptibility (10). This type of dispersion is often observed in experiments with ferromagnetic conductors [40].

In the GHz frequency band the impedance shows high sensitivity to the applied magnetic field only for $H_{ex} < H_K$ when there is change in the magnetisation direction since the sensitivity of $\tilde{\mu}$ with respect to variation in H_{ex} and H_K is very small. This tendency could be also observed in microwave stress–impedance. Fig. 2 shows the experimental plots of the impedance vs. tensile stress in wires with a negative magnetostriction and circumferential anisotropy [7].

A tensile stress σ_{ex} in negative magnetostrictive wires increases the circumferential anisotropy and does not change the magnetisation direction. As a result no change in impedance with σ_{ex} is seen at GHz frequencies. However, this sensitivity can be

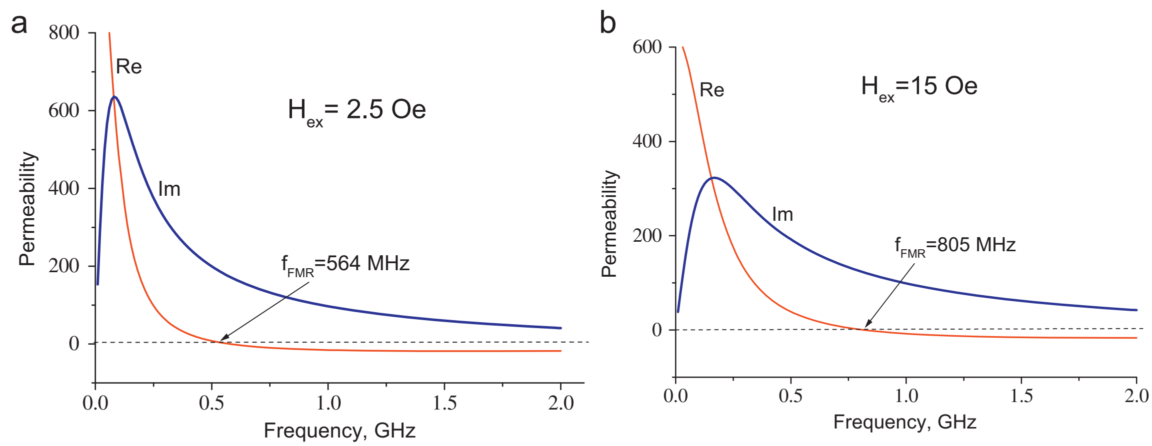

Fig. 1. Spectra of the permeability parameter $\tilde{\mu}$ defined by Eq. (10) in wires with a circumferential anisotropy. Parameters used for calculations: anisotropy field H_K = 5 Oe, M_0 = 500 G, spin relaxation parameter is 0.2. Small deviations of the anisotropy angle α are used to avoid permeability divergence near a critical field of the rotational magnetisation flip.

established in the presence of a dc magnetic bias H_{ex} which rotates the magnetisation towards the axis so the applied stress will rotate it back. The largest sensitivity (about 60% per 180 MPa) with respect to σ_{ex} in Fig. 2 is seen for H_{ex} of 3 Oe which is around the anisotropy field for this case. Further increase of the field is not necessary and results in the sensitivity decrease since the magnetic hardness in the axial direction is increased. If the use of the magnetic bias is not desirable, a helical anisotropy is needed to realise tuning with an external tensile stress. The role of the bias field on the stress-sensitive MI could be utilised to detect stress gradients in composites with amorphous wires. In this case, measuring MI or electromagnetic response in the presence of a non-uniform magnetic bias or a scanning local magnetic field will provide the stress distribution inside the composite matrix [30].

Magnetic wires with a circumferential anisotropy could be attractive to design artificial magnetic dielectrics with large and tunable effective permeability at GHz frequencies. In this case, the static magnetisation in the absence of the external dc magnetic field is orthogonal to the high frequency magnetic field h_0. Along with this, the demagnetising factor is small. These are the most favourable conditions to increase the apparent wire permeability μ_w (see Eq. (11)) and the effective permeability. In composites with ordered wires μ_{ef} defined by (2) can be written in the form

$$\mu_{ef} = 1 + p\left(\mu_w - 1\right) \tag{15}$$

Here p is the wire volume concentration. With appropriate choice of magnetic, resistive and geometrical parameters the real part of μ_{ef} is negative in the frequency band of 1–3 GHz for concentrations below 10%. Such diluted wire composites could be attractive as a component of left-handed metamaterials with natural magnetic activity [24,25].

Eq. (11) for μ_w demonstrates that this parameter strongly depends on the static magnetisation direction. Therefore, similar to the microwave impedance behaviour a sensitive tuning of the effective permeability μ_{ef} requires the modification in the magnetisation angle θ. In the case of a circumferential anisotropy tuning can be achieved by applying a magnetic field H_{ex}.

Fig. 3 shows the spectra of μ_w and demonstrates a strong suppression of the wire permeability in the presence of a magnetic field of about the anisotropy field. At a frequency of 2 GHz, the real part reaches −12 when no field is applied. Therefore, the effective permeability will be negative in this frequency range for a volume concentration of just about 10%. For thinner wires, even smaller concentrations can be used.

This analysis is confirmed experimentally. Fig. 4 shows the permeability spectra measured by a co-axial transmission line method for composites with amorphous glass-coated wires of the composition CoFeNiSiB with a negative magnetostriction and having 5 μm in diameter [41]. The permeability spectra are very wide, and just 8% of the volume concentration is sufficient to obtain the negative values of the real part of the permeability at GHz frequencies. The application of the axial bias field strongly reduces the permeability.

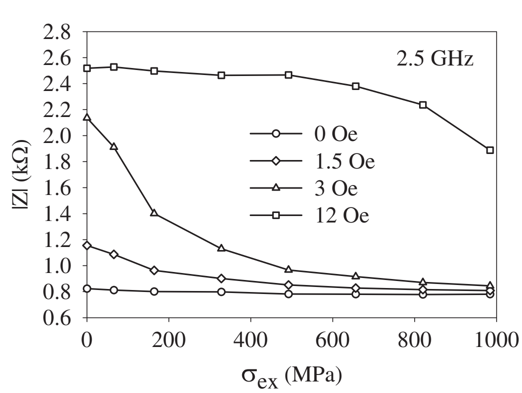

Fig. 2. Experimental spectra of the impedance magnitude vs. external tensile stress in $Co_{68.5}Mn_{6.5}Si_{10}B_{15}$ amorphous glass-coated wires having the total diameter of 14.5 μm and the metallic core diameter of 10.2 μm. The frequency is 2.5 GHz [7].

3. Effect of temperature on the permeability spectra in wires with axial anisotropy

The permeability in amorphous wires made of low Curie temperature T_c alloys can demonstrate a strong temperature dependence in moderate temperature range. The addition of Ni and Cr in Co/Fe amorphous alloys results in a decrease in T_c ranging between the room temperature and 400 °C. For example, alloy systems $Co_{57.33}Fe_{4.7}Cr_{13.4}B_{13.02}Si_{11.09.84}Mo_{0.62}$ and $Co_{23.67}Fe_{7.14}Ni_{43.08}B_{13.85}Si_{12.26}$ have T_c = 75–100 °C [34]. Near T_c the magnetic properties such as saturation magnetisation and anisotropy experience considerable variations. Thus, the magnetisation changes as $(1 - T/T_c)^{\gamma}$, where γ is a critical exponent. Considering that the magnetostriction constant is proportional to the cube of the magnetisation, the initial rotational susceptibility M_0/H_k will increase near T_c resulting in a shift of the frequency dispersion of the permeability towards lower frequencies. Therefore, in this case high temperature sensitivity of the wire permeability $\tilde{\mu}$ can be realised. Considering possible applications of this effect in remote

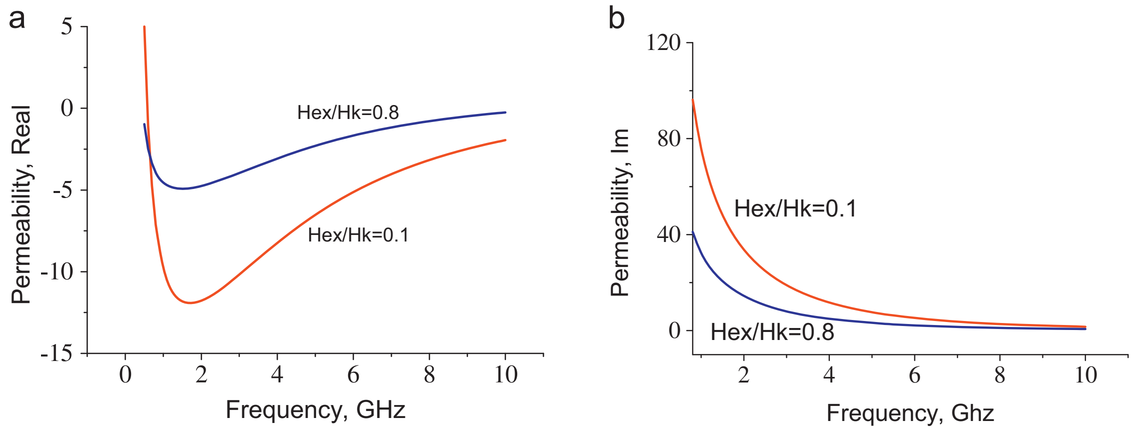

Fig. 3. Modelled permeability spectra of a wire with a circumferential anisotropy: (a) real part, and (b) imaginary part. The effect of a dc magnetic field H_{ex} is demonstrated. The magnetic parameters for calculation are the same as for Fig. 1. The wire resistivity is 130 μΩ cm, the wire radius $a = 5$ μm.

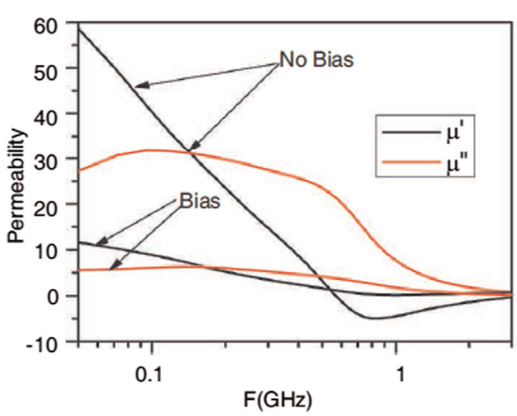

Fig. 4. Experimental spectra of the effective permeability of composites with 8% concentration of CoFeNiSiB amorphous wires having a diameter of 5 μm [41]. The measurements were done with co-axial transmission line method. The effect of a bias dc magnetic field of about 200 G applied along the wires is shown. Measurements are performed in a co-axial waveguide (reproduced courtesy of The Electromagnetics Academy).

temperature sensors based on magnetoimpedance, the axial anisotropy is preferable. Such anisotropy could be easily established in many low T_c amorphous alloys including the first alloy mentioned above. Fig. 5a presents the hysteresis loop for microwire with this composition which shows a bistable behaviour [34]. The impedance characteristic in Fig. 5b at 100 MHz has a central peak which is typical of an axial anisotropy. With increasing temperature, the value of the impedance sharply decreases.

Fig. 6 presents the modelled spectra of the permeability parameter $\tilde{\mu}$ for axial anisotropy calculated from (6) and (10) with $\alpha = 0$ and without any bias field applied. The change in magnetisation with a temperature far from T_c is considered according to a classical model (spin orientation is unrestricted)

$$\frac{M_0(T)}{M_s} = \coth \kappa - \frac{1}{\kappa}, \quad \kappa = \frac{3T_c}{T}\frac{M_0(T)}{M_s} \tag{16}$$

Here M_s is the saturation magnetisation at zero temperature. Eq. (16) could be regarded as a reasonable approximation at temperatures not lying in the immediate vicinity of T_c. When approaching T_c Eq. (16) gives a critical exponent of 0.5 but the calculations were done with $\gamma = 0.42$ which was found experimentally [34]. It is seen that far from T_c the resonance frequency is about 270 MHz and it decreases down to 130 MHz for $T/T_c = 0.9$. Such behaviour of the permeability will result in decrease in high frequency impedance with increasing temperature as demonstrated in Fig. 7 where the absolute value of the axial impedance at two frequencies is shown. The relative change of the impedance with temperature at $H_{ex} = 0$ is 32% at 50 MHz and 41% at 0.5 GHz. The modelling agrees with the experimental data.

4. Conclusion

We have demonstrated that the intrinsic dynamic permeability in soft magnetic amorphous wires has a very wide dispersion region with relatively large values past the resonance. Taking advantage of tunable magnetic configuration in wires, this gives the opportunity to develop various microwave sensors based on magnetoimpedance modulated with external magnetic,

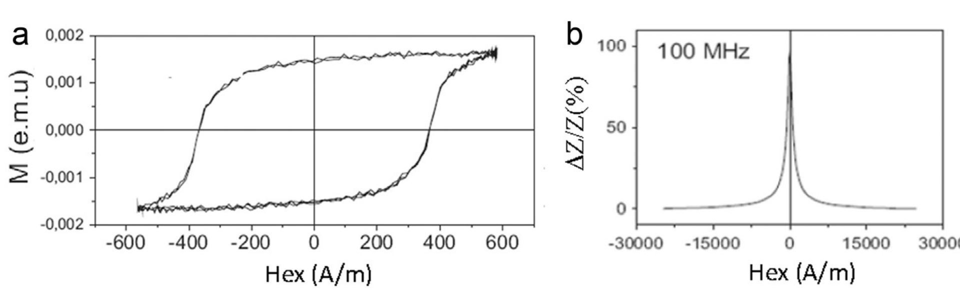

Fig. 5. Hysteresis loops (a) and the impedance vs. H_{ex} at 100 MHz (b) for a microwire of the composition $Co_{57.33}Fe_{4.7}Cr_{13.4}B_{13.02}Si_{11.09.84}Mo_{0.62}$ with $T_c \approx 100$ °C. The total diameter is 34.2 μm and the metal core diameter is 30 μm.

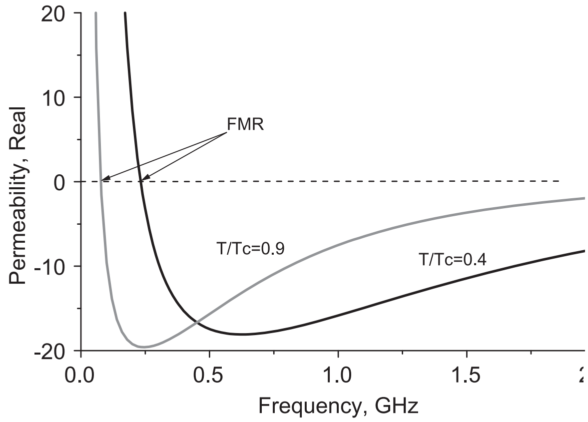

Fig. 6. Modelled permeability spectra (real part) for different temperatures in wires with axial anisotropy. the parameters for calculation: $M_s = 435$ G, the anisotropy field at zero temperature $H_K(T = 0) = 5$ Oe.

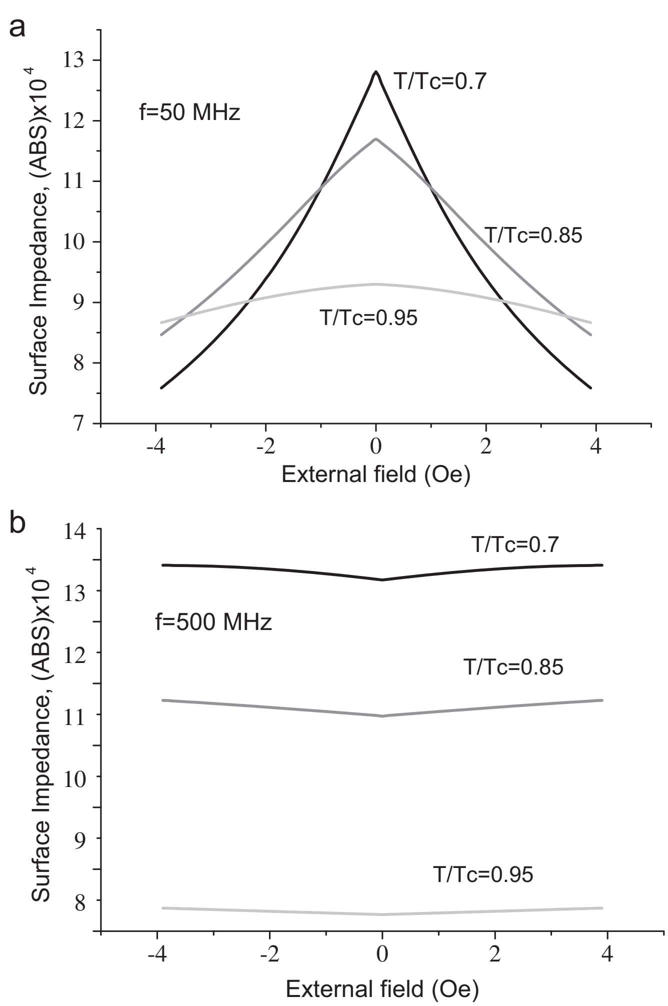

Fig. 7. Absolute value of the axial component of the surface impedance vs. H_{ex} for frequencies of 50 MHz (a) and 0.5 GHz (b) with a temperature as a parameter. The magnetic parameters of calculation are the same as for Fig. 6. $a = 10$ μm.

mechanical and thermal stimuli. The wires can be also used to obtain artificial magnetic dielectrics with tuneable spectra at microwaves.

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