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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):

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

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,

$$\mu_{ef} = \langle b_z \rangle / h_0 \quad (2)$$

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 $\exp(-j\omega t)$):

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

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

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

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:

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

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

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

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