Tunable microwave electric polarization in magnetostrictive microwires

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Abstract. In this work, the induced electric dipole moment of ferromagnetic microwires dependent on the wire magnetic structure is investigated with the aim of sensing applications. The wire behaves as micro antenna exhibiting a resonance at half wavelength condition. At the vicinity of the resonance the wire polarization is sensitive to all the losses including magnetic losses. The transfer mechanism is based on the magnetoimpedance effect (MI) which requires a specific magnetic structure of a helical type. We demonstrate that scattering from a ferromagnetic microwire showing large MI effect at microwaves can be modulated with a low frequency magnetic field and the amplitude of this modulation near the antenna resonance can sensitively change in the presence of the external stimuli such as a dc magnetic field. The modelling is based on solving the scattering problem from a cylindrical wire with the impedance boundary conditions. The modelling results agree well with the experimental data.

1. Introduction.
Miniature sensors with remote wireless operation are required in many technological areas including structural health monitoring, smart composites, embedded biosensors, etc. Microwave technologies have a high potential for remote sensing applications. Recently, the research topic on microwaves interacting with ferromagnetic structures is intensively developing [1] and one of the main areas of applications is identified as sensor materials [2-3]. Here we investigate the performance of magnetic microwires as embedded sensors operating at microwave frequencies. The sensor operation is based on tunable electric polarization due to large change of the wire surface impedance (known as magnetoimpedance (MI) effect [4-6]).

In order to realize efficient tunable properties, magnetic microwires of CoFeSiB composition in amorphous state are considered. The absence of the crystalline structure is very useful since it is possible to induce a required magnetic anisotropy through the magnetoelastic interaction. For microwave sensing applications, the magnetic structure in the outer shell of a circumferential or helical type is preferable, which can be established in Co-rich alloys with negative magnetostriction. For such wires, the remagnetisation behaviour in an axial magnetic field less than the effective anisotropy field is almost linear, without a hysteresis and with a very high susceptibility. The external stress and temperature can substantially modify the magnetic anisotropy and the magnetization processes.
The use of metal inclusions in microwave applications is often justified by their larger electric polarisability in comparison with dielectrics. This enables a strong response even from a single inclusion. Here we demonstrate theoretically that scattering from a ferromagnetic microwire showing large MI effect at microwaves can be modulated with low frequency magnetic field and the amplitude of this modulation near the antenna resonance can sensitively change in the presence of the external stimuli. The modelling is based on solving the scattering problem from a cylindrical wire with the impedance boundary conditions [7-8]. The modelling results agree well with the available experimental data [9-10].

2. Electric polarization of a ferromagnetic wire

The wire of finite length is interrogated by the microwave field with the electric field $e_0$ along the wire ($z$-axis). The field $e_0$ induces the current $i$ in the wire with some distribution along the wire length $l$. Zero boundary conditions must be imposed at the wire ends: $i(\pm l/2) = 0$. This condition means the concentration of electric charge at the ends and the generation of a dipole moment $\mathcal{P}$ in the wire, which can be calculated using the continuity equation: $\partial i(z)/\partial z = j\omega \rho(z)$ and integrating by parts ($\rho$ is a charge density per unit length, $\omega$ is a frequency, $j$ is imaginary unit). The dipole moment is calculated as:

$$\mathcal{P} = j\frac{\omega}{2} \int_{-l/2}^{l/2} i(z) dz$$

The current distribution in a thin wire can be found in the antenna approximation [11]. However, this approach should be further developed when considering a ferromagnetic metallic wire and the effect of its magnetic structure on $i(z)$ and dipole moment [7-8]. The scattering problem is solved imposing the impedance boundary conditions at the wire surface

$$\bar{e}_z = \xi (\hat{h}_\varphi \times \mathbf{n})$$

Here $\xi$ is the surface impedance tensor, $\mathbf{n}$ is the unit radial vector directed inside the wire, $\bar{e}_z$ and $\hat{h}_\varphi$ are the longitudinal electric field and circumferential magnetic field at the wire surface, which include both the scattered and external fields.

The scattering problem is formulated in terms of the vector potential $\mathbf{A}$ which obeys the Helmholtz equation:

$$\Delta \mathbf{A} + k^2 \mathbf{A} = \mathbf{i}, \quad k = (\omega/c)\sqrt{\varepsilon_d}$$

$c$ is the velocity of light and $\varepsilon_d$ is the permittivity of the dielectric medium around the wire. The solution of Eq. (3) can be represented using the convolution of $i(z)$ with the Green function $G(r) = \exp(jkr)/4\pi r$, $r$ is radial coordinate. Then, the electric and magnetic fields are expressed in terms of integro-differential operators using the convolutions with the current. Imposing boundary condition (2) we obtain the integro-differential equation for the current density in the ferromagnetic wire (generalized antenna equation):

$$\frac{\partial^2 (G * i)}{\partial z^2} + k^2 (G * i) + \frac{j\omega \epsilon_d Szz}{2\pi ac} (G_\varphi * i) = \frac{j\omega \epsilon_d}{4\pi} e_0$$

Here $a$ is the wire radius, $G_\varphi$ is a sort of a Green function occurring due to the induced circular magnetic field:

$$G_\varphi = \frac{a^2(1 - jkr)}{2r^3} \exp(jkr)$$

Equation (4) is completed with the zero boundary condition for the current at the wire ends. The internal losses are given by the impedance $\zeta_{zz}$ and the convolution $(G_\varphi * i)$, whereas the imaginary part of $(G * i)$ determines the radiation losses. The solution of equation (4) can be obtained by the iteration method. We have compared the current distribution calculated in zero approximation and in the first approximation. If the skin effect is not very strong ($a \sim \delta_m$, $\delta_m$ is the skin-depth) the difference between
the two approximations is less than few percent. The zero approximation obtained by putting imaginary parts of $G$ and $G_\phi$ to zero corresponds to neglecting the radiation losses which are small for a moderate skin effect. Similar condition of a moderate skin-effect is needed to realize magnetic tuning of the electric polarization. Therefore, in further analysis a simplified analytical solution obtained in zero approximation is used.

The formalism for calculating the matrix $\hat{\varsigma}$ for a ferromagnetic wire with an arbitrary helical anisotropy was developed in [12]. In the case of a sufficiently strong skin-effect which is expected at GHz frequencies and considering that the surface layer of the wire has a helical magnetization with the constant angle $\theta$ (with respect to the wire axis), the component $\varsigma_{zz}$ is defined as:

$$
\varsigma_{zz} = \frac{c(1 - j)}{4\pi\sigma\delta} \left( \sqrt{\mu} \cos^2 \theta + \sin^2 \theta + \frac{\delta(1 + j)}{4a} \right), \quad \delta = \frac{c}{2\pi\sigma\omega} \tag{6}
$$

In equation (6) $\sigma$ is the wire conductivity, $\theta$ is the angle between the dc magnetization and the wire axis, $\mu$ is a permeability parameter composed of the components of internal permeability tensor and has a meaning of a circular permeability with respect to the dc magnetization.

3. Result and discussion

As it follows from Equation (6) the impedance may be sensitive to the change in the dc magnetization and ac permeability. For soft amorphous wires at GHz frequencies the parameter $\mu$ weekly depends on the moderate external magnetic field since this range of parameters corresponds to the tail of the ferromagnetic resonance. In the case of a circumferential anisotropy the impedance shows strong variations in the range of small magnetic field $H_{ex}$ applied along the wire when the static magnetization changes its direction from circumferential to axial (the magnetization angle $\theta$ changes from $\pi/2$ to 0), as shown in Figure 1. The experimental results for MI at GHz frequencies confirm such behavior.

The dependence of the impedance on the magnetic properties makes it possible to tune the scattering from a single ferromagnetic wire as follows from Equation (4). Figure 2 presents the current distribution along the wire of finite length near the antenna resonance without a field and in the presence of the field of about the anisotropy field $H_K$ ($H_K$ corresponds to the field needed to magnetize the wire along the axis). The calculation is done neglecting the radiation losses which is justified if the skin effect is not very strong. A very large difference is observed. It should be noted that the antenna resonance frequency defined by the half wavelength condition is chosen such that the skin effect is not very strong ($a\sqrt{\mu/\delta} \sim 1$) and the permeability parameter $\mu$ substantially differs from unity. For a wire with a diameter of 10-20 micron the frequency range is within few GHz. The antenna resonance frequency $f_{res} = c/(2l\sqrt{\varepsilon_d})$ can be adjusted by varying the wire length $l$ and the permittivity of the surrounding medium $\varepsilon_d$. If the proper conditions are realised, the induced electric dipole moment of ferromagnetic wire becomes magnetic field dependent as shown in Figure 3.

![Figure 1: Plots of the surface impedance of amorphous wires with a circumferential anisotropy. The wire has 10 µm diameter, conductivity $\sigma = 7.6 \cdot 10^{15} \text{ s}^{-1}$, anisotropy field $H_{ex} = 2$ Oe, saturation magnetization $M_0 = 500$ G, and gyromagnetic constant $\gamma = 2 \cdot 10^7 \text{ (rad/s)/Oe}$.](image-url)
Scattering from a ferromagnetic wire showing MI effect at GHz frequencies can be used for contactless sensing of external parameters such as magnetic field (or mechanical stress) as was proposed in [9-10]. The procedure is as following.

Figure 2: Current distribution along the wire for frequency f=1.9 GHz (near the resonance). Imaginary part is shown. Parameters are the same as for Figure 1.

Figure 3: Spectra of real part of dipole moment. Parameters are the same as for Figure 1.

Figure 4: Modulation of the dipole moment with ac bias field as a function of the measured field $H_{ex}$. This parameter is defined as

$$\Delta P/P = \max \left| \frac{P(H_{ex}+H_b) - P(H_{ex})}{P(0)} \right|.$$

The wire is placed in a microwave field and is subjected to low frequency bias field $H_b$ which modulates the amplitude of the scattered output signal. The magnitude of these modulations will depend on the external dc magnetic field $H_{ex}$, as shown in Figure 4. This result agrees with the experiment [10]. A similar effect can be expected in the presence of a mechanical stress.

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