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Numerical investigation of the surface impedance of ferromagnetic manganite thin films

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Abstract

The surface impedance and the microwave characteristics of conductive ferromagnetic (FM) films with the parameters similar to those of $La_{0.7}Sr_{0.3}MnO_3$ (LSMO) films deposited on a dielectric substrate were modeled with respect to linearly polarized planar transverse electromagnetic waves, incident normally to the structure. It was shown that the microwave losses caused by the film conductivity dominate the losses due to the ferromagnetic resonance (FMR) if the film is thin enough. The FMR is more clearly observed in FM films deposited on substrates of higher permittivity due to smaller microwave losses, caused by the film conductivity in this case. The peculiarities of the surface impedance and the absorption, reflection and transmission coefficients caused by the film conductivity and FMR are simultaneously observed in thicker films.

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1. Introduction

The successes in the technology and the science of thin-film materials in the last decade have renewed great interest in magnetic oxides. A large part of the recent studies has been devoted to mixed-valence manganese oxides (or manganites), which exhibit so-called colossal magneto-resistance at the metal–insulator transition temperatures [1,2]. The ferromagnetic resonance (FMR) and the magneto–impedance effects can be observed in these materials at microwave frequencies if the material is in a ferromagnetic (FM) state [3,4]. The microwave measurements in manganites can give information about the module, the orientation of the magnetization vector and about the effective magnetic fields that affect the magnetization vector [3–7]. The thin films of FM manganites have attracted great attention for their importance in fundamental physics and in potential applications in spintronics [8,9].

Although great progress in the investigation of the structure and the electric and magnetic characteristics of magnetic manganite materials has been achieved in the last decade, to the best of our knowledge the microwave characteristics of manganite thin films have not been investigated in detail. This prompted us to investigate through a modeling the main microwave characteristics of FM manganite thin films, which could be observed in experiments. The modeling was performed by taking into account the normal conductivity and the complex dynamic permeability of the magnetic film and the electrodynamics boundary conditions. The results concern tangentially magnetized FM films with parameters similar to those of the $La_{0.7}Sr_{0.3}MnO_3$ (LSMO) film.

2. Specification of the magnetic medium

Let us consider a structure (Fig. 1) placed in free space (medium 1) and consisting of a magnetic manganite film (medium 2) deposited on a dielectric substrate (medium 3). The OZ-axis of the co-ordinate system XYZ is assumed to be perpendicular to the plane of the layered structures and

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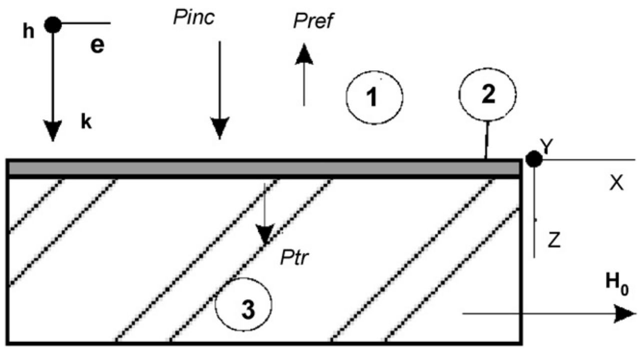

Fig. 1. A sketch of the layered structure and the coordinate system. The scheme demonstrates the orientations of the microwave electric ***e*** and magnetic ***h*** fields, of the wavevector ***k*** in the incident waves, and the propagation directions of the incident P_{inc}, transmitted P_{tr} and reflected P_{ref} microwave powers as well.

the external DC magnetic field $\boldsymbol{H_0}$ is applied parallel to the OX-axis of the co-ordinate system. We assume that the saturation magnetization $\boldsymbol{M}$ of the magnetic medium is parallel to the external field $\boldsymbol{H_0}$. A linearly polarized planar transverse electromagnetic wave propagating along the Z-axis impinges normally on the structure. The microwave electric ***e*** and magnetic ***h*** fields are assumed to be parallel to the OX- and OY- axes of the co-ordinate system, respectively, and are perpendicular to the wavevector ***k***, i.e. $\boldsymbol{H_0} \| \boldsymbol{e} \perp \boldsymbol{h} \perp \boldsymbol{k}$.

The coupled time-harmonic Maxwell and Landau–Lifshitz equations [4,6,10,11] govern the behavior of the electromagnetic waves in a magnetic medium. The solutions of these equations, which correspond to the situation presented in Fig. 1, will include the effective complex permeability μ_n and permittivity ε_n (indexes $n = 1, 2, 3$ correspond to the number of the media) of the media

$$\varepsilon_n = \varepsilon_{rn}\varepsilon_0, \tag{1}$$

$$\mu_n = \mu_{rn}\mu_0, \tag{2}$$

where μ_{rn} and ε_{rn} are the effective values of the relative complex permeability and permittivity of the media, and $\varepsilon_0 = (36\pi)^{-1}10^{-9}$ F/m and $\mu_0 = 4\pi\ 10^{-7}$ H/m are the dielectric and magnetic constants of free space.

The relative complex permittivity of conductive magnetic medium 2 is

$$\varepsilon_{r2} = \varepsilon_{r'2} - i\sigma_2/(\varepsilon_0\omega), \tag{3}$$

where σ_2 is the normal conductivity of the magnetic medium, $\varepsilon_{r'2}$ is the real part of the relative permittivity of the medium, ω is the angular frequency of the incident electromagnetic wave, and $i^2 = -1$. When the external magnetic field $\boldsymbol{H_0}$ (note that $\boldsymbol{M} \| \boldsymbol{H_0}$), the wave vector ***k*** and the microwave magnetic field ***h*** are perpendicular to each other, the following expression can be obtained for the relative effective permeability of the magnetic medium μ_{r2} (see Refs.[10,11], for example):

$$\mu_{r2} = \mu - (\mu_a^2/\mu), \tag{4}$$

$$\mu = 1 + \omega_H\omega_M(\omega_H^2 - \omega^2)^{-1}, \tag{5}$$

$$\mu_a = \omega\omega_M/(\omega_H^2 - \omega^2), \tag{6}$$

where $\omega_H = 2\pi\gamma_e H + i\alpha_1\omega$; $\omega_M = 2\pi\gamma_e M$; M, γ_e and α_1 are the saturation magnetization, the gyromagnetic ratio and a coefficient for the damping term in the magnetic layer, respectively. The relative permeability $\mu_{r2} = 1$ when the microwave magnetic field ***h*** is parallel to the external magnetic field $\boldsymbol{H_0}$ and is perpendicular to the propagation direction. It can be noted that the saturation magnetization M and the conductivity σ_2 of the magnetic manganites depend significantly on ambient temperature.

3. Transverse waves incident perpendicularly to the structure

The characteristic impedance of the medium Z_n and the wavevector k_n of the electromagnetic waves propagating in the nth medium are expressed in terms of the effective complex permeability μ_n, and the permittivity ε_n, as follows:

$$Z_n = Z_0\sqrt{\mu_{rn}/\varepsilon_{rn}}, \tag{7}$$

$$k_n = k_0\sqrt{\varepsilon_{rn}\mu_{rn}}, \tag{8}$$

where $Z_0 = \sqrt{\mu_0/\varepsilon_0}$ and $k_0 = \omega\sqrt{\varepsilon_0\mu_0}$ are the impedance and the wavevector for free space, respectively. The total field of the planar electromagnetic wave in the medium with the number n consists of the incident field and the scattered field:

$$e_{xn}(z) = A_n \exp(-ik_n z) + B_n \exp(ik_n z),$$
$$e_{zn} = 0\ ,\quad e_{yn} = 0,\quad n = 1, 2, 3, \tag{9}$$

$$h_{yn}(z) = [A_n \exp(-ik_n z) - B_n \exp(ik_n z)]/Z_n, h_{xn} = 0, \tag{10}$$

where A_n and B_n are unknown coefficients associated with the incident and scattered fields.

The electromagnetic boundary conditions for the tangential (parallel to the boundary) components of the electric and magnetic fields are given as follows:

$$e_{\tau,n} = e_{\tau,n+1},\quad h_{\tau,n} = h_{\tau,n+1} \text{ at } z = 0 \text{ and } z = t_2, \tag{11}$$

where t_2 is the magnetic film thickness.

The normal ($z-$) component of the electric and magnetic fields in the dielectric media and in free space are zero

$$e_{z,n} = 0 \tag{12}$$

for the transverse waves. The perpendicular (to the surface, Fig. 1) component of the microwave field $h_{z,2}$ exists in medium 2 because of the anisotropy of magnetic materials. However, the boundary conditions for this component are automatically satisfied due to the magnetic field of the magnetic "charges" induced in the boundary of the magnetic thin film [10,11].

Substituting expressions (9), (10) to the boundary conditions (11) one can obtain a linear system of algebraic equations with respect to the unknown coefficients A_n, B_n. The following solution of this system of equations was