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High-frequency magnetoimpedance in nanocomposites

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Abstract

The transmission of millimeter-range electromagnetic waves (30–50 GHz) through a magnetic nanocomposite thin film exhibiting tunnel magnetoresistance (TMR) is calculated. The relative change of transmission coefficient in an applied magnetic field due to the magnetorefractive effect is approximately linear with TMR and strongly depends on nanocomposite resistivity and film thickness. The obtained results are in a good agreement with experiment.

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1. Introduction

Recently, it has been observed that the transmission of millimeter-range electromagnetic waves through magnetic nanocomposites exhibiting tunnel magnetoresistance (TMR) strongly depends on magnetic field [1]. It was found that the relative change of transmission coefficient

$$\frac{\Delta D(H)}{D} = \frac{D(0) - D(H)}{D(0)}, \tag{1}$$

also called as the magnetoimpedance (MI) parameter, is linear with TMR

$$\frac{\Delta \rho}{\rho} = \frac{\rho(0) - \rho(H)}{\rho(0)} \tag{2}$$

and strongly depends on the thin film composition, its thickness d and resistivity ρ [1]. The effect was attributed to the high-frequency spin-dependent tunneling and can be viewed as a manifestation of the magnetorefractive effect (MRE) [2,3]. Calculations of the MI parameter in Ref. [1] were carried out for the oversimplified model "air–magnetic nanocomposite–air" in the framework of the MRE theory [2,3] for dielectric permittivity $\varepsilon(\omega, H)$, neglecting possible influence of field dependence of magnetic permeability $\mu(\omega, H)$ at millimeter and micrometer-range waves. Besides, quantitative estimations in Ref. [1] were done for the nanocomposites with the metal volume fraction corresponding to the metallic type conductivity that does not strictly correlate with experiment.

In this paper we present results of theoretical investigations of the transmission of millimeter-range electromagnetic waves (30–50 GHz) through magnetic nanocomposites possessing TMR for more practical model "air–magnetic nanocomposite–semi-infinite lossless substrate", taking into account that both dielectric permittivity $\varepsilon(\omega, H)$ and magnetic permeability $\mu(\omega, H)$ are responsible for the MI in magnetic nanocomposites.

The transmission coefficient D through the three-layer structure under consideration is as follows [1,4]:

$$D = \frac{4Z_2Z_3}{(Z_1 - Z_2)(Z_2 - Z_3)e^{-i\alpha_2 d} + (Z_1 + Z_2)(Z_2 + Z_3)e^{i\alpha_2 d}}, \tag{3}$$

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where $Z_j = \sqrt{\mu_j/\varepsilon_j}$ is the characteristic impedance of the jth layer, $\alpha_2 = \omega(\varepsilon_2\mu_2)^{1/2}/c$. We consider the case of normal incidence of waves and assume that (i) substrate is lossless and semi-infinite, (ii) magnetic field is applied in the film plane, (iii) magnetic permeability of nanocomposite thin film can be described by the well-known relations of the theory of ferromagnetic resonance for homogeneous films, (iv) dielectric permittivity of nanocomposites with TMR is linear with frequency-dependent conductivity and changes under magnetization due to the MRE like in Ref. [5].

Numerical calculations were done for the set of parameters corresponding to Co-based nanocomposites with compositions close to the percolation threshold. Fig. 1 shows some results for the MI parameter when $\mu(\omega, H) = 1$ and therefore the MI is due to the MRE. In this case the MI parameter (1) is positive, linear with TMR if $\Delta\rho/\rho$ less than 5–8%, and strongly depends on the film thickness. All these features are consistent with experiment [1]. Both the transmission coefficient D and the MI parameter depends also on the nanocomposite resistivity because the skin-depth δ increases with resistivity. In fact, the MI parameter depends on the ratio d/δ. Large resistivity corresponds to the case of small thickness shown in Fig. 1. It means that for fixed d and $\Delta\rho/\rho$ the MI parameter significantly differs for compositions below and above the percolation threshold. Thus, nanocomposites with rather large TMR do not exhibit noticeable MI if their resistivity is much greater than for metallic samples [1]. The theory is in a good qualitative agreement with experiment [1] and the MI can be rather large for a quite reasonable set of parameters.

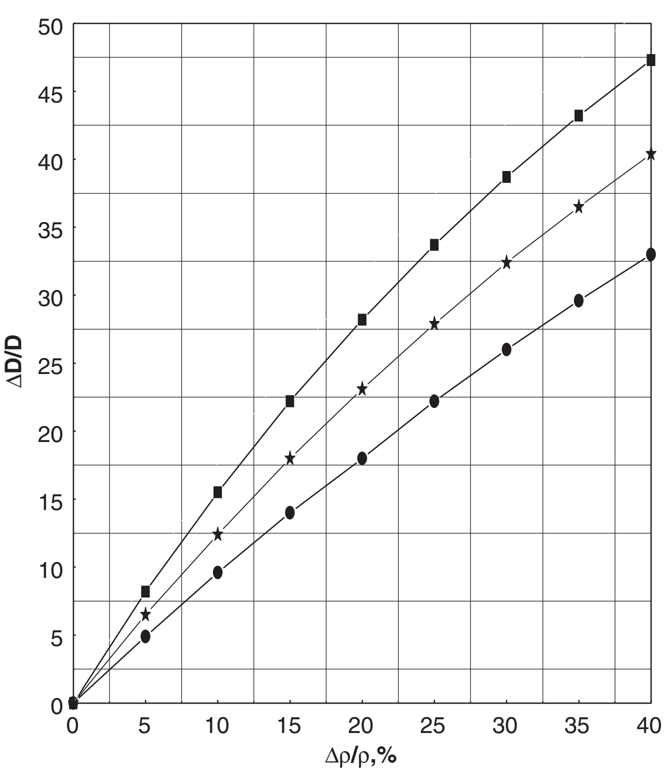

Fig. 1. The relative change of the transmission coefficient under magnetization of nanocomposite versus magnetoresistance ($\mu(\omega, H) = 1$, $\varepsilon(\omega, H = 0) = -50$ to 6000i, $f = 44\,\mathrm{GHz}$) (squares—$d = 3\,\mu\mathrm{m}$; stars—$d = 1\,\mu\mathrm{m}$; circles—$d = 0.5\,\mu\mathrm{m}$).

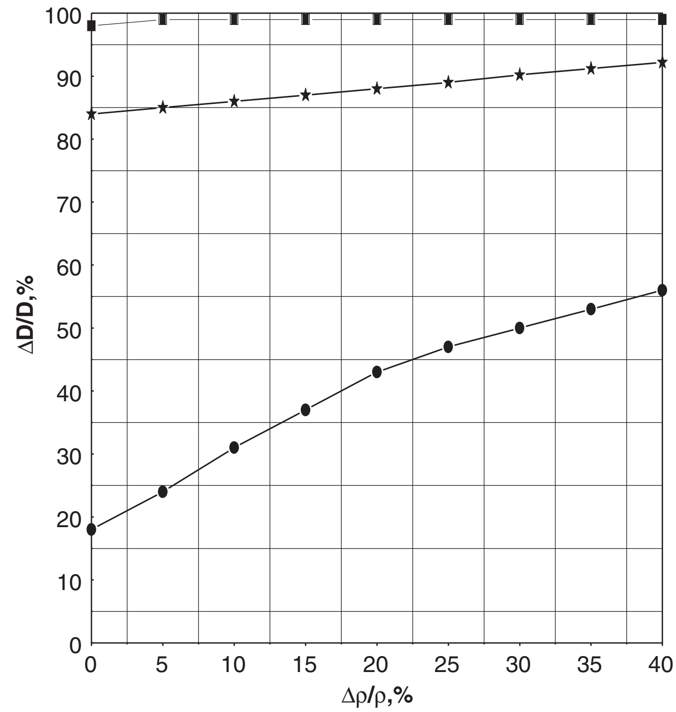

Fig. 2. The relative change of the transmission coefficient under magnetization of nanocomposite versus magnetoresistance if $\mu(\omega, H) \neq 1$ ($\mathrm{Re}\,\mu(\omega, H) = 5$, $\varepsilon = -50$ to 6000i, $d = 3\,\mu\mathrm{m}$ (nanocomposite), squares—$\mathrm{Im}\,\mu(\omega, H) = 100$, stars—$\mathrm{Im}\,\mu(\omega, H) = 100$, circles—$\mathrm{Im}\,\mu(\omega, H) = 10$).

The MI behavior becomes much more complicated when $\mu(\omega, H) \neq 1$ (Fig. 2). Close to the ferromagnetic resonance the MI parameter is also positive and can be very large because of damping strongly increases in an external magnetic field. As a result the transmission coefficient becomes negligibly small. It should be underline that the field dependence of $\mu(\omega, H)$ affects the MI parameter even for frequencies or for magnetic field amplitudes, which do not satisfy ferromagnetic resonance conditions (Fig. 2). But in this case the MI parameter slightly depends on TMR. Such behavior was not found in Ref. [1] because of too small magnetic field used for MI measurements.

2. Conclusions

Our calculations demonstrate that the MI parameter $\Delta D/D$ depends on both $\varepsilon(\omega, H)$ and $\mu(\omega, H)$. Far from the ferromagnetic resonance the MI for nanocomposites with the metal volume fraction close to and larger than the percolation threshold is of the same order of magnitude as TMR. In this case the MI is linear with TMR and strongly depends on magnetic nanocomposite thin film thickness and resistivity.

The most of obtained results are consistent with the experimental data obtained for Co–(Al–O), CoFe–MgF, Co–(Ti–O), Co–(Si–O) nanocomposites [1].

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