PROCEEDINGS OF THE INTERNATIONAL CONFERENCE
NANOMATERIALS: APPLICATIONS AND PROPERTIES
Vol. **2**No 1, 01NFPMM05(3pp) (2013)

Effective Conductivity and Magnetic Permeability of Nanostructured Materials in Magnetic Field

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(Received 10 Juny 2013; published online 02 September 2013)

The problem of homogenization the nanostructured materials placed in DC magnetic field has been discussed. The experimental data are obtained using metallic superlattices, metal-dielectric thin films and 3D-nanostructured materials. All these materials contain ferro- or ferrimagnetic component. The transmission and reflection coefficients were measured on the waves of millimeter waveband. It has been shown that the experimental frequency spectra of the coefficients in zero magnetic field can be described by the effective conductivity and dielectric permittivity. The spectra of ferromagnetic resonance, however, cannot be calculated correctly with the averaged magnetization.

Keywords: Layer Structures, Opal Matrix, Metamaterials, Microwave Properties.

PACS number: 75.81

1. INTRODUCTION

Nanostructured media such as magnetic superlattices, metal-dielectric thin films and photonic crystals became fashionable objects of investigation on microwaves. Description of electromagnetic properties of these kinds of media using the averaged material constants looks very attractive but the possibility to introduce the effective parameters has to be carefully analyzed. A lot of works have been carried out by now where the methods of calculation the effective parameters is developed. Metamaterials where the period of structure could be of the order of the wavelength are the class of materials representing especial difficulties [1]. A method to homogenize arbitrary nonmagnetic periodic metamaterials has been outlined in work [2]. An accurate homogenized description of metamaterials made of magnetodielectric inclusions has been derived [3]. A review of current state of the homogenization problem is presented [4]. The bianisotropic effects in the left-handed metamaterials is investigated [5]. A composite medium consisting of insulating magnetodielectric spherical particles embedded in a matrix is studied [6]. The validity of retrieval methods that assign bulk electromagnetic properties, from calculations of the scattering S parameters has been verified [7].

The experimental data which allow introduce the effective magnetic permeability and dielectric permittivity for the several types of nanomaterials placed in magnetic field are discussed here. Only long wavelength approximation is under discussion where the wavelength is much greater than the scale of inhomogeneities.

Most valuable feature of magnetic nanocomposite or metamaterial lies in the fact that these materials obey not only the Maxwell's equations with boundary conditions but also the Landau-Lifshitz equation complemented with the boundary condition for spins. The key point is the off-diagonality of the material constant tensors in magnetic field. Because of demagnetizing fields the inner DC magnetic field differs from the outer one. All these circumstances influence the possibility to use the effective material constants. We will show the data on the frequency and magnetic field dependences of transmission and reflection coefficients measured for metallic nanostructures, metal-dielectric film nanostructures and 3D-nanocomposites based on opal matrices with the particles of magnetic metals or ferrites embedded. The examples of the effective conductivity, dielectric permittivity and magnetic permeability will be presented.

2. RESULTSANDDISCUSSION

Let us discuss at first the case when the transmission and reflection coefficients have been measured in zero magnetic field. Our experimental data confirm the possibility to use the effective conductivity of metal or metal-dielectric nanostructure on microwaves or waves of millimeter wavelength.

The frequency dependences of transmission and reflection coefficients for metallic Fe/Cr and FeNi/V nanostructures as well as for the film $Co_x(SiO_2)_{1-x}$ and $Co_x(Al_2O_3)_{1-x}$ structures were measured. The procedure of the effective conductivity reconstruction has been developed from the frequency spectra of transmission coefficient. The effective conductivity of the Fe/Cr superlattices with the layer thickness from 0.45 to 7.6 nm and the total thickness of the nanostructure from 38 to 114 nm was obtained. Cluster-layered Fe/Cr nanostructures are also discussed. In the frequency range from 26 to 38 GHz the frequency dependences of transmis-

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sion and reflection coefficients are fairly good be described by the effective conductivity. The conductivity σ in different Fe/Cr samples varies from 0.74 to 1.22 MSim/m. Further, the effective conductivity of metallic nanostructure reconstruction was carried out in DC magnetic field. In the fields far from the magnetic resonance condition the using of the effective conductivity permits to adequately describe the microwave magnetoresistive effect for Fe/Cr and FeNi/V nanostructures.

Let us discuss the conductivity and dielectric permittivity reconstruction for the film metal-dielectric structures. We will compare the experimental and calculated frequency dependences of transmission coefficients for the thin film $Co_x(SiO_2)_{1-x}$ samples.The dashed line in Fig. 1 shows the measured frequency dependence for the film $Co_{0.65}(SiO_2)_{0.35}$ with the thickness of 100 nm. The solid line presents the calculated dependence obtained with the mentioned above procedure. The effective conductivity is equal to $\sigma = 7.6 \cdot 10^4$ Sim/m. The experimental dependences are good approximated with the calculated dependences obtained for one fixed value of conductivity. This fact means that frequency dispersion of conductivity is negligible in the frequency range discussed.

Now we will reconstruct the conductivity and dielectric permittivity of metal-dielectric 3D-nanocosites based on opal matrices. These nanocomposites consist of closely packed lattices of submicron spheres 0.25 μm in diameter with the metal or ferrite nanoparticles embedded in the inter-sphere voids. Comparison between the experimental and calculated frequency dependences of transmission and reflection coefficients for the 3D-nanocomposite sample with metallic cobalt particles has been drown in Fig. 2. Estimation of effective parameters of nanocomposite gave the following values: $\sigma = 0.36$ Sim/m, real part of dielectric permittivity $\varepsilon' = 3.29$.

Let us discuss in detail the effective parameters of media in magnetic field. The magnetic permeability and conductivity are tensors in general. We will believe that the media under study is an electrically isotropic media. The media obeys the Landau-Lifshitz equation for the magnetization movement.

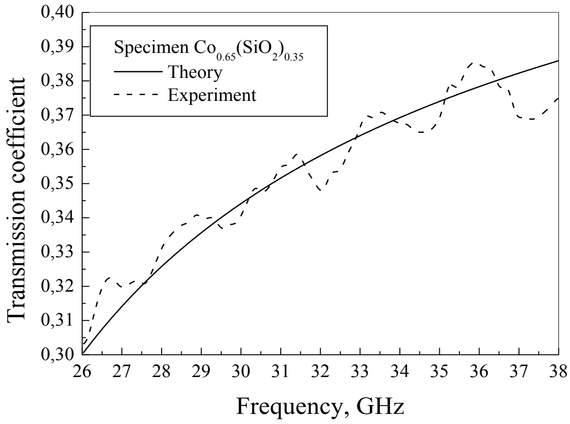


Fig. 1 – Comparison between the experimental and calculated frequency dependences of transmission coefficient for the thin film sample $Co_{0.65}(SiO_2)_{0.35}$. The calculated dependency is drawn for σ $7.6 \cdot 10^4$ Sim/m

The high-frequency magnetic permeability tensor contains diagonal μ and off-diagonal μ_a components. What is more important, the resonance peculiarities do not fit the peculiarities for the magnetic permeability components μ and μ_a but they obey the Kittel's equation [8]:

$$\left(\frac{\omega_0}{\gamma}\right)^2 = \left[H_0 + (N_x - N_z)M_s\right]\left[H_0 + (N_y - N_z)M_z\right], \qquad (1)$$

where ω_0 is the resonance frequency, H_0 is the DC magnetic field, M_s is the saturated magnetization, N_i are the components of diagonalized tensor of demagnetizing factors.

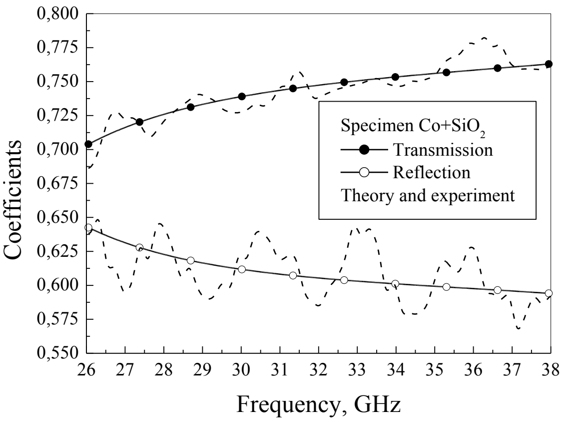
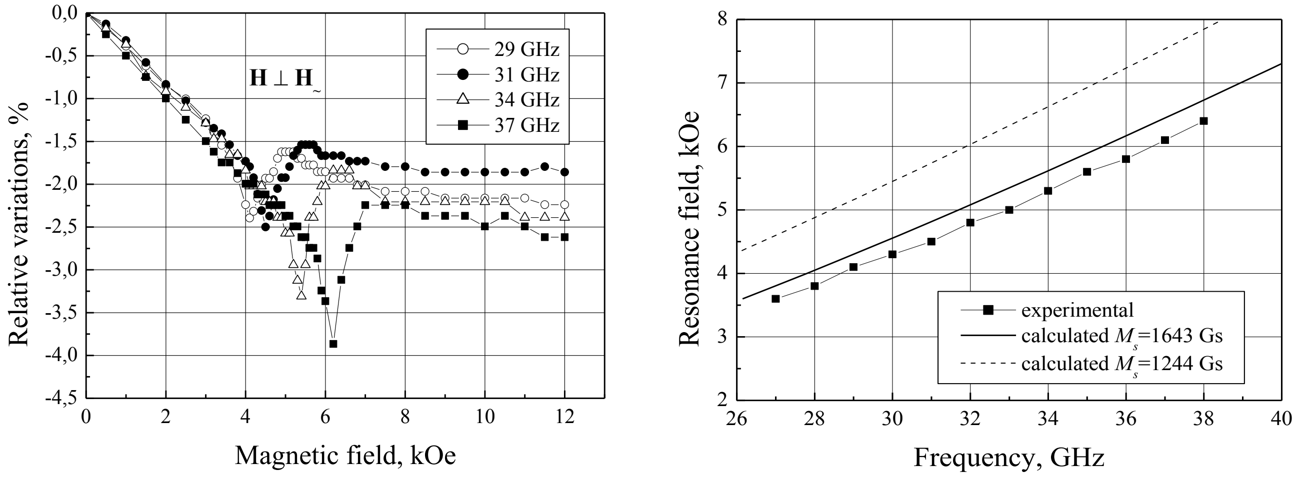


Fig. 2 – Experimental (dashed lines) and calculated (solid lines) frequency dependences of transmission and reflection coefficient for the nanocomposite with Co particles

The magnetic field dependences of transmission coefficient through the $[Cr(7,1)/Fe(26)]_{12}/Cr(65)/Al_2O_3$ superlattice are shown in Fig. 3a. They include the monotonically decreased component combined with the resonant peculiarity which position moves to higher fields if the frequency increases. The resonance spectrum for this superlattice is shown in Fig. 3b. Following to (1), the calculated spectrum depends on the magnetization M_s. The spectra are presented in Fig. 3b calculated both for the averaged magnetization of the sample 1244 Gs and measured magnetization of the Fe layer in this sample 1643 Gs. It is clear that the spectrum calculated for the layer's magnetization is close to the experimental spectrum. Similar results were obtained for the Fe/Cr and FeNi/V superlattices and for the cluster-layered Fe/Cr nanostructures.

The averaged magnetization of the nanostructured media does not describe the field of magnetic resonance and therefore the magnetic field dependences of transmission and reflection coefficients. As a consequence, in the general case it is impossible to introduce correctly the effective magnetic permeability for the inhomogeneous media in which the magnetic resonance can be realized. There exists however the exception to this general rule. If the components of the demagnetizing factor are equal each other, $N_x = N_y = N_z$, then the position of resonance does not depends on magnetization. It comes to be for the particles of spherical shape, for example.



a b

Fig. 3 – Magnetic field dependences of transmission coefficient measured on different frequencies for the [Cr(7,1)/Fe(26)]$_{12}$/Cr(65)/Al$_2$O$_3$ superlattice (a); experimental and calculated spectra of magnetic resonance (b)

3. CONCLUSIONS

We can conclude as a whole that the effective conductivity correctly describes the zero-field frequency dependences of transmission and reflection coefficients for metallic nanostructures, metal-dielectric film materials and 3D-nanocomposites based on opal matrices under study on frequencies of millimeter waveband. The averaged magnetization of the nanostructured media (metamaterial) does not describes the magnetic resonance spectrum. The correct spectrum can be obtained by using the magnetization of nanolayer or nanoparticles. High frequency and radiofrequency magnetic properties of nanoparticles ensembles are quite specific.

The application of microwave research method sappears as effective since these methods make it possible to easily estimate the dynamic and relaxation parameters of such materials. Applying waveguides and cavities operating with various types of waves, it is possible to obtain various mutual orientations of microwave fields and the external magnetic field and, in this way, to create favorable conditions for the strongest interaction between the nanoparticles of the embedded substance and the fields.

Opal matrices are considered as the class of materials suitable for producing media with a negative refractive index. The so called “left” medium with a negative real part of permeability can be produced in the region of magnetic resonances. The possibility of microwave radiation beam focusing was discussed in [3]. The focusing is performed in the near radiation field in a metalized photon structure with a negative refractive index.

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