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Control of magnetoelastic waves in structure containing thin antiferromagnetic films on an elastic substrate

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In this work we present a model explaining the properties of magnetoelastic waves propagation in the heterostructure containing an antiferromagnetic layer on a non-magnetic elastic substate. The dispersion characteristic of magnetoelastic waves in such structure was obtained, and the effect of variation of the thickness of the antiferromagnetic layer and the external magnetic field on the frequency of the magnetoelastic resonance on the elastic structure was also studied. It was found that an increase in the magnetic field magnitude leads to the increase with pressure of the magnetoelastic resonance frequency, and, on the contrary, with an increase in the thickness of the AFM layer the magnitude of the magnetoelastic resonance frequency decreases. The results obtained can be used to create devices for generating and processing signals in the gigahertz and terahertz frequency ranges

Keywords: spin waves, Love waves, magnetoelastic resonance, sigma model, films, pressure.

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1. Introduction

Recently the possibility is considered to expand the range of operating frequencies for electronic devices through application of new technologies and materials using achievements of spintronics and magnonics [1–3]. Within these areas the spin transfer processes or magnetic moment are researched in the structures containing magnetic materials. Besides, it is proposed to use spin waves to build element base of instruments for information processing and storage [2,4].

In particular, antiferromagnetics (AFM) attract high attention in connection with the possibility to develop high speed devices for processing signals of terahertz (THZ) range of frequencies [2,4,5]. In AFM-materials the superfast spin dynamics is due to strong exchange interaction between magnetic sublattices.

AFM may be divided into two classes, where magnetic sublattices have compensated magnetic moments (full magnetization is equal to 0), and also materials with non-compensated sublattices, namely, having low ferromagnetism. For the first time AFM-materials with non-zero full magnetization were described by Dzyaloshinski and Moriya [6,7]. Ratio of fields of Dzyaloshinski−Moriya to the exchange one determines the angle of skew between magnetic sublattices and makes 0.2%. Dynamics of magnetizations of sublattices for AFM-materials with weak ferromagnetism is described using standard Landau−Lifshitz equations. However, in virtue of low value of magnetization vector $|\bar{m}| \ll |\bar{l}|$ and $\bar{l}^2 = 1-\bar{m}^2 \approx 1$, where $\bar{m} = \frac{\bar{M}_1+\bar{M}_2}{2M_0}$ and $\bar{l} = \frac{\bar{M}_1-\bar{M}_2}{2M_0}$, the system of sublattice magnetization vector equations may be reduced to motion equation only of the antiferromagnetic vector $\bar{l}$ (Neel vector) [8–10].

Spin waves in AFM may exist in a wide range of frequencies, from units of gigahertz to several dozens of terahertz. Since AFM materials have low total magnetization vector, this makes it possible to apply magnetic fields of lower order for generation of spin waves. Such properties make AFM good candidates for development of microwave devices and potential applications for magnetic storage [11], generators [12–14], waveguides [15] etc., since research in this area is relevant [16–18].

The possibility to control properties of spin waves in AFM with the help of elastic stresses [19,20] is also of interest. So far, however, the question remains open on the impact of mechanical deformations at frequency of antiferromagnetic mode, having higher frequencies that ferromagnetic mode.

This article considers the properties of the propagating magnetic elastic waves in the structure containing the AFM layer placed on an elastic non-magnetic substrate. A mathematical model is described for propagation of related magnetic elastic waves in the structure of AFM-film—elastic substrate; a numerical calculation is presented for the dispersion ratio of magnetic elastic waves with specific selected materials of AFM and elastic substrate, and also the questions are considered regarding the impact of the external magnetic field and various thickness of AFM-film with fixed pressure at the frequency of magnetic elastic resonance.

2. Model

Let us consider the propagation of surface elastic Love waves [21,22] in a heterostructure containing a thin layer on an elastic substrate. Love waves are shear elastic waves. For their existence it is necessary that the speed of transverse acoustic waves in a layer is lower than in the substrate:

$$S_{t1} < S_{t2}, \tag{1}$$

where S_{t1} — speed of body shear waves in a layer, S_{t2} — speed of body shear waves in a substrate.

Guided magnetic elastic waves may propagate in a heterostructure containing a thin magnetic AFM layer on an elastic substrate [23,24]. In Figure 1 there is such structure of a thin AFM-layer *1* on an elastic non-magnetic substrate *2*. To transfer external deformations, one can select a piezoelectric substrate and apply voltage through electrodes. Then, whenever the electric field is applied, mechanical stresses in the substrate will impact the magnetic subsystem of the AFM-layer.

The paper used the equation for dynamics of Neel's vector $\bar{l}$ [8,9,10]. In this case vector $\bar{m}$ is determined by vector $\bar{l}$ and its derivative in time $\partial\bar{l}/\partial t$. Equations for such model may be produced directly from Lagrangian operator using magnetic symmetry of AFM [9]. Lagrangian operator variation produces closed equations for the Neel's vector. Using Lagrangian operator variation, the general equation was produced [9]:

$$\left(\frac{\partial^2}{\partial t^2} - V_m^2\nabla^2\right)\bar{l}\times\bar{l} = 2g(\bar{l}\bar{H})\frac{\partial\bar{l}}{\partial t} - g^2\Big\{l_z(l_y\bar{e}_x - l_x\bar{e}_y)H_{\mathrm{D}}$$
$$+ 2bl_z(\bar{l}\times\bar{e}_z)M_0H_e\Big\} + g^2\left(\bar{l}\frac{\partial(F_{\mathrm{me}}+F_{\mathrm{ms}})}{\partial L}\right)H_e, \tag{2}$$

where $\bar{L} = \bar{M}_1 - \bar{M}_2 = 2\bar{l}M_0$ — antiferromagnetic vector, V_m — phase speed of spin wave, g — gyromagnetic ratio, b — heterogeneous exchange constant, H_{D} — Dzyaloshinski–Moriya field, H_e — exchange field, $\bar{e}_{x,y,z}$ — single vector along the corresponding axis, F_{me} — magnetic elastic energy and F_{ms} — induced magnetostriction energy. Calculations are made in approximation of isotropy of elastic and magnetic elastic properties of antiferromagnetic.

To account for induced magnetostriction, this paper used a model that takes into account the impact of the external elastic pressure [25]. If, for example, a substrate — is piezoelectric, the electric field applied thereto causes elastic stresses therein. Such stresses induce additional magnetic anisotropy in the crystal plane. Since antiferromagnetic is subjected to deformations, energy of elastic stresses is added to its full energy. Equation expressing dependence of energy on the value of deformation and direction of spontaneous magnetization is the following [25]:

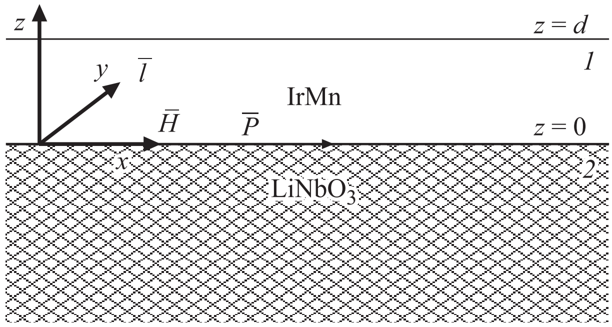

Figure 1. Geometry of thin AFM layer (IrMn) structure with thickness of $d = 6\,\mu$m on elastic substrate ($LiNbO_3$).

$$F_{\mathrm{ms}} = -\frac{3}{2}\lambda\sigma\left(\cos^2(\varphi) - \frac{1}{3}\right), \tag{3}$$

where λ — magnetostriction constant, the value of which depends on the crystallographic direction; σ — normal component of the mechanical stresses tensor; and φ — angle between the vector of spontaneous magnetization and direction of the stressed state axis.

Hooke's law was used to describe the elastic wave properties in the following form:

$$\rho\frac{\partial^2 u_i}{\partial t^2} = \frac{\partial\sigma_{i\kappa}}{\partial x_\kappa}, \tag{4}$$

where $\sigma_{i\kappa}$ — tensor of mechanical stresses. Let us find the solution for the longitudinal and transverse wave numbers in the form of $l_x = \exp[i(ky - \omega t) + qz]$ and for $u_x = \exp[i(ky - \omega t) + \kappa z]$ motion equation, and we get the following conditions:

$$\kappa_1 = \left[\frac{\omega^2}{S_{t1}^2} - \kappa^2\right]^{-1/2}, \tag{5}$$

$$\kappa_2 = \left[-\frac{\omega^2}{S_{t2}^2} + \kappa^2\right]^{-1/2}, \tag{6}$$

$$q = \frac{\begin{array}{r}[\omega^4 + (k^2+\kappa^2)(\omega^2 S_t^2 + V_m^2 S_t^2 - V_m^2 S_t^2 - \omega_{sk} S_t^2)\\ -V_m^2 k^2 - \omega_{\mathrm{me}}\omega_e\omega_{tk}^2]\end{array}}{V_m^2\omega^2\left[1 + \frac{S_t^2}{\omega^2}(k^2+\kappa^2)\right]}, \tag{7}$$

where k — wave number, $S_t = \left[\frac{C_{44}}{\rho}\right]^{1/2}$ — transverse sound velocity, ω_{me}, ω_e — magnetic elastic and elastic frequencies, accordingly,

$$\omega_{sk} = [V_m^2 k^2 + \omega_H(\omega_H - \omega_{\mathrm{D}}) + \omega_e\omega_{\mathrm{me}}]^{1/2},$$

$\omega_{tk} = S_t k$. To find dispersion, let us use the harmonic form of function

$$l_x = \left[A\sin(qz) + B\cos(qz)\right]\exp[i(ky - \omega t)]$$

for exponential attenuation of elastic waves in the substrate. Produced forms of functions are added to the boundary conditions. Boundary conditions consist in the conditions of spin fixation at the boundary of the magnetic layer with the substrate, equality of elastic stresses tensor components to zero at the free boundary and equality of normal stresses components between the layers. As a result, we get the following equations

$$\sigma_1 + 4bM_0^2 l_x = 0, \quad z = d; \tag{8}$$

$$\sigma_1 + 4bM_0^2 l_x = \sigma_2, \quad z = 0; \tag{9}$$

$$u_{z1} = u_{z2}, \quad z = 0; \tag{10}$$

$$l_y \frac{\partial l_x}{\partial z} - l_x \frac{\partial l_y}{\partial z} = 0, \quad z = d; \tag{11}$$

$$l_y \frac{\partial l_x}{\partial z} - l_x \frac{\partial l_y}{\partial z} = 0, \quad z = 0. \tag{12}$$

To find dispersion dependence of magnetic elastic waves in AFM heterostructure on an elastic substrate set by expressions (8–12), it is necessary to find the solution for the determinant of matrix 5×5.

3. Numerical computation

For numerical computation we used the following parameters of IrMn layer and elastic substrate $LiNbO_3$:

$$d = 6\,\mu\text{m}, \quad \rho_1 = 15.6\,\text{g/cm}^3, \quad \rho_2 = 4.65\,\text{g/cm}^3,$$

$$C_{44}^1 = 5.02 \cdot 10^{11}\,\text{dyn/cm}^3, \; C_{44}^2 = 6.1 \cdot 10^{11}\,\text{dyn/cm}^3,$$

$$M_0 = 970\,\text{G}, \quad D_z = 1.01 \cdot 10^{-9}\,\text{Oe/cm}^3,$$

$$b = 7 \cdot 10^8\,\text{erg/cm}^3, \quad \gamma = 1.78 \cdot 10^7\,\text{g/cm}^2$$

$$\text{and } H_\text{E} = 1.4 \cdot 10^3\,\text{Oe}.$$

Numerically computed dispersion characteristic (8–12) is given in Figure 2. For AFM the spectrum of purely spin waves consists of two branches (low frequency and high frequency). As a rule, the low frequency branch is in the gigahertz range, and high-frequency one — in terahertz one.

Frequency of magnetic elastic resonance, as shown in Figure 2, *a*, is equal to

$$\frac{\omega_\text{GHz}}{2\pi} \approx 7.87\,\text{GHz}$$

for the lowest mode. In terahertz range (Figure 2, b) the frequency of magnetic elastic resonance is

$$\frac{\omega_\text{THz}}{2\pi} \approx 0.7895\,\text{THz}.$$

Such accuracy of frequency ω_THz is caused by narrow resonance in the terahertz branch.

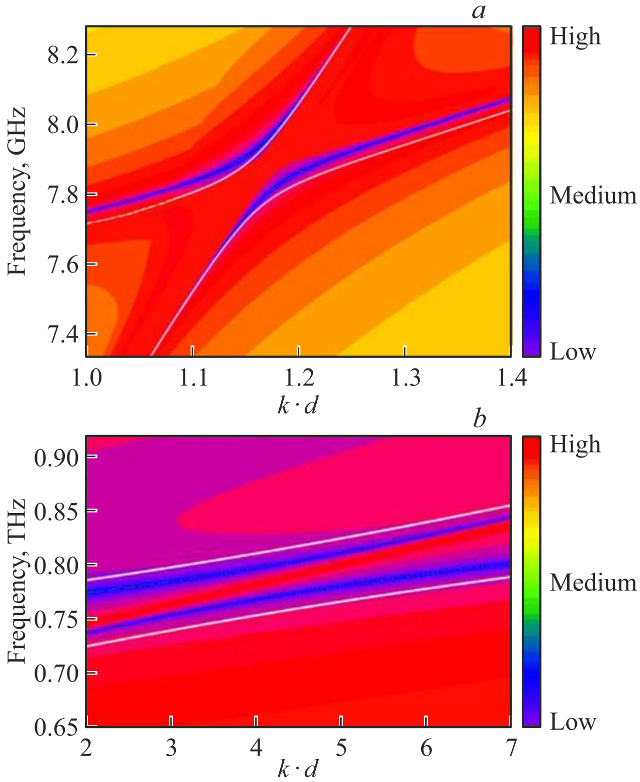

Figure 2. Dispersion characteristic of magnetic elastic waves in the structure containing AFM on an elastic non-magnetic substrate in the external magnetic field 190 Oe: *a*) magnetic elastic slot in GHz-range ω_GHz, *b*) magnetic elastic slot in THz-range ω_THz.

Figures 3 and 4 show in blue — non-interacting spin waves, red — non-interacting elastic Love waves, black — solution for matrix determinant (8–12) and green — solution with account of pressure.

Figure 3 shows dispersion dependence of magnetic elastic waves at various pressures for the lower mode. As external pressure increases, the frequency of magnetic elastic resonance changes. Please note that resonance moves to a longer-wave area.

Figure 4 presents dispersion characteristic of magnetic elastic surface Love waves for a heterostructure containing an antiferromagnetic layer on an elastic substrate, with various pressure for the upper mode. By nature of pressure impact at resonance properties it is possible to see that increased pressure leads to wider spectrum and changes resonance frequency. It is noticeable that nature of pressure interaction at lower and upper modes differs. It is related to the fact that in the terahertz area the resonance is narrower, and to shift the resonance frequency to a longer-wave area, higher pressure values are required.

In Figure 5, *a* it is shown that as external field increases, the resonance frequency of surface spin waves also increases. In case of zero magnetic field the value of the resonance frequency must be proportionate to value $\sqrt{\omega_\text{E}\omega_\text{A}}$, where ω_E — frequency of effective exchange field,

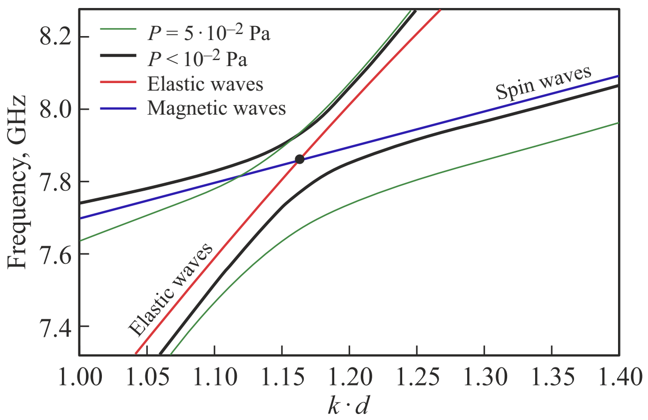

Figure 3. Dispersion characteristic for the heterostructure containing a layer of AFM on an elastic substrate in the external field and at different external pressure in the gigahertz range. Thin blue line — comparative curve for magnetic subsystem, red — comparative curve for elastic Love waves.

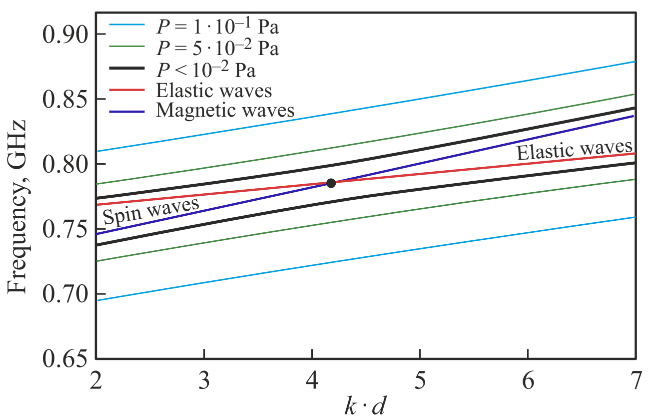

Figure 4. Dispersion characteristic for the heterostructure containing a layer of AFM on an elastic substrate in the external field and at different external pressure in the terahertz range. Thin blue line — comparative curve for magnetic subsystem, red — comparative curve for elastic Love waves.

and ω_A — frequency of anisotropy field. In Figure 5, *b* there are results of resonance frequency change with change of AFM layer thickness. It can be seen that the value of the resonance magnetic elastic frequency reduces with the increased thickness of the AFM layer. Therefore, by changing the thickness of AFM-layer or the external static magnetic field, it is possible to control the resonance frequency.

4. Conclusion

This paper considered propagation of the magnetic elastic Love waves in a thin layer of antiferromagnetic on an elastic substrate, when the film is exposed to external pressure. The following materials were used for numerical estimates: AFM-layer — IrMn and elastic substrate — $LiNbO_3$, and also dispersion characteristic of magnetic elastic waves in such structure was obtained. It was established that the frequency of the magnetic elastic resonance of the first mode for structure IrMn—$LiNbO_3$ makes 7.87 GHz, resonance frequency in the terahertz range becomes 0.79 THz, and under pressure the spectrum widens in the terahertz area and in the gigahertz area — frequency shift to a longer-wave area. As pressure is applied to the AFM-structure, the internal frequency substantially increases regarding oscillations of magnetic sublattices of AFM ferromagnetic mode.

Study of the structures containing a thin AFM layer expands the prospects of using and developing the magnetic elastic sensors, magnetic media for information recording and memory devices.

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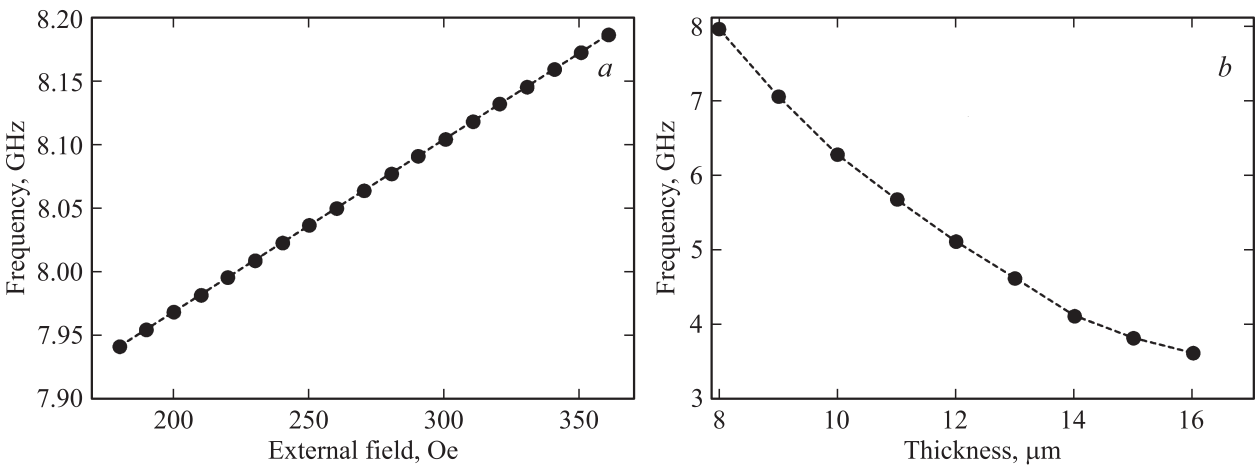

Figure 5. Dependence of resonance frequency on external conditions: *a*) on external field under pressure, and *b*) on thickness of AFM-layer under pressure.

Conflict of interest

The authors declare that they have no conflict of interest.

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