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ON THE NECESSITY OF ACCOUNTING THE PONDEROMOTOR MOMENT OF FORCES WHEN STUDYING NONLINEAR FERROMAGNETIC RESONANCE IN ANISOTROPIC SAMPLES

It is shown that a large ponderomotive moment of forces arises at resonance as a result of the dependence of the resonance frequency on the orientation of the anisotropic sample relative to the external magnetic field. For calculations, the definition of the moment of forces from the expression of energy was used. As an example, we obtained formulas for a single-domain spherical sample of a single crystal of a cubic system. A model is proposed to explain the significant hysteresis of the excitation of magnetoacoustic resonance in the field in unattached anisotropic samples.

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On the need to take into account the ponderomotive moment of forces in the study of nonlinear ferromagnetic resonance in anisotropic samples

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The ponderomotive effect of a resonant electromagnetic field can be significant not only on the molecular [1], but also at the macroscopic level [2]. Therefore, it becomes necessary to take it into account when interpreting some features of the NFMR. These features include slow (frequency ~ 1-2u Hz) ariations in the magnetoacoustic resonance (MAP) signal in spherical loose samples from a YIG single crystal, significant hysteresis of MAP excitation over the field, intricate sample displacements, etc. [2-6].

Earlier, the reasons for the emergence of large ponderomotive forces in an inhomogeneous magnetic field at resonance and their consequences were clarified. [2]. In turn, a significant hysteresis of MAP excitation in the field for unattached samples [3-6] can be explained taking into account the anisotropy and ponderomotive moment of forces. Since until now the question of an unambiguous determination of the force and moment of forces in macroscopic electrodynamics has not been resolved [7,8], to estimate we use the definition of the moment of forces from the expression of energy [9].

Consider an anisotropic single-domain spherical sample with magnetization M, placed in a uniform external magnetic field $\vec{H} = (H_1 cos\omega t, H_1 sin\omega t, H_0)$. We will neglect the sample size in comparison with the wavelength. Then, in the magnetostatic approximation, the effective magnetic field inside the sample is determined as [10]

$$\vec{H}_{eff} = \vec{H} + \vec{H}_a - \frac{4\pi}{3}\vec{M}, (1)$$

where $\vec{H}_a = -\hat{N}_a \vec{M}$ - anisotropy field (for simplicity, we do not consider the exchange interaction, magnetoelastic). The expression for the magnetic free energy (without entropy) is written in the form [10]

$$U = -\vec{M} \cdot \vec{H} - \frac{1}{2}\vec{M}1 \cdot \vec{H}_a + \frac{4\pi}{6} M^2/V, (2)$$

where $\vec{M} = \vec{M}V$- magnetic moment, V - sample volume. Its minimum is the condition for the equilibrium of the ferromagnet at a given field $\vec{H}$ [10].

The energy of the magnetic field (2), in this case, plays the role of potential energy in the sense of analytical mechanics, the methods of which we can use. Let U - be the function of "generalized coordinates" q_i. Then, in the terminology of analytical mechanics

$$g_i = -\frac{\partial v}{\partial q_i}, (3)$$

- are the "generalized forces" acting "in the direction" of the coordinates q_i. Quite often, such a definition turns out to be incomparably simpler than a direct definition by the formulas [7,8]. Accordingly, the moment applied to the dipole $\vec{M}$ forces

$$K_i = -\frac{\partial U}{\partial \Phi_i}, (4)$$

where, in our case, determine the orientation of the crystallographic axes relative to the field $\vec{H}$.

As an example, consider single crystals of a cubic system. This case is of the greatest interest for practice, since YIG, in particular, belongs to cubic crystals. In the general case, the problem of finding the dependence $U(\Phi_i)$ with considering $(\omega_{\text{pe3}}(\phi_i))$ я is complicated, since the equations of motion for the magnetization become essentially nonlinear. Therefore, to estimate K_i it is advisable to simplify it by sloping $H_0 \gg |H_a|, M_0, \Delta H;\ -\Delta M_z = M_0 - M_z < \Delta H$, where M_o - equilibrium value of static magnetization, ΔH - magnetic resonance half-width.

As a result, for ω_{pe3} we get the formula [10]

$$\frac{\omega_0}{\gamma} = H_0 + H_a\left(2 - \frac{5}{2}sin^2\theta - \frac{5}{2}sin^4\theta sin^2 2\varphi\right), (5)$$

Where the anfle $\theta = (\widehat{\vec{\iota}_z, [001]}), \varphi = (\widehat{[100], (yoz)})$, - γ gyromagnetic ratio.

As an approximation, we use the solution of the Bloch equation for M_z (disregarding the anisotropy) [11], taking into account the anisotropy indirectly through the dependence $\omega_0(\theta, \varphi, H_a)$:

$$M_z \approx M_0\{1-\gamma^2 H_1^2\tau^2/[1+\tau^2(\omega_0-\omega)^2]\}, (6)$$

where $\tau^2 = T_1 T_2 = 1/(\gamma \Delta H)^2$, $T_{1,2}$ - relaxation times. Discarding the terms of the second order of smallness in ΔM_z, get from (2, 4-6)

$$K_i = \frac{M_0 H_0 \gamma^2 H_1^2 \tau^4 2(\omega_0-\omega)}{[1+\tau^2(\omega_0-\omega)^2]^2}\frac{\partial\omega_0}{\partial\phi_i}, (7)$$

$$K_0 = |K_i|_{max,(\omega_0-\omega)=\pm(2\tau)^{-1}} = \left(\frac{16}{25}\cdot\gamma^2\cdot H_1^2\cdot\tau^3\cdot\left|\frac{\partial\omega_0}{\partial\phi_i}\right|\right) M_0 H_0, (8)$$

n an experimental study of ferromagnetic resonance in cubic single crystals, spherical samples are usually oriented so that the axis of rotation perpendicular to the magnetic field coincides with the axis [110]. Then $\vec{H}_0$ lies in the (110) plane and, when the sample (or magnet) rotates, coincides alternately with all the symmetry axes of the crystal $(\varphi = \pi/4)$. Resonance formula (7) for this case has the form

$$K_0 = \frac{5\gamma^2 H_1^2 \tau^4(\omega_0-\omega)H_\Delta}{[1+\tau^2(\omega_0-\omega)^2]^2} sin2\theta\cdot(1+2sin^2\theta)M_0 H_{0,}(9)$$

Loose anisotropic sample placed in a magnetic field $\vec{H}$ at $H_1 = 0$, the axis of easy magnetization will be oriented along the field (for YIG $H_a < 0$, axis [111]). In this case, the value of energy (2) is minimal and the classical moment of forces, usually taken into account,

$$\vec{K}_{\text{клас}} = [\vec{M}\times\vec{H}_{eff}], (10)$$

is zero. Under resonance conditions, the value K_0 (9) is non-zero and numeric substitution [2-6] in (8) at$|\Delta M_z| \approx \Delta H$ gives assessment $K_0/V \approx 2|H_a|H_0 \approx 10^5$ dyne/cm^2, which exceeds the value taken into account at resonance [12] of moment of strength (10), $K_{\text{клас}}/V = \Delta H\cdot|\Delta M_z| \approx 0{,}1$ dyne/cm^2 for YIG with $\Delta H \approx 0{,}3\ e$.

Thus, the appearance of a significant moment of forces (7, 9) at resonance must be taken into account when interpreting the phenomenon of MAP hysteresis and the absorption line over the field when observing NFMR in unfixed samples with anisotropy [2-6]. Taking into account the moment of forces may also be useful for explaining the mechanisms of MAP excitation, along with the previously known effect of magnetostriction.

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