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SPIN-WAVE RESONANCE IN GRADIENT FERROMAGNETS WITH A PARABOLIC BARRIER OF MAGNETIC PARAMETERS

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The theory of spin-wave resonance (SWR) in gradient films for two profiles of smooth variation of the magnetic moment through the film thickness was developed in the 60s of the last century. The development of the theory was stimulated by experimentally detected deviations of the dependence of the resonant frequencies ω_n (or resonant fields H_n) on the mode number n, from the quadratic law predicted by Kittel's theory [1]. It was supposed [2] that these deviations are due to the smooth inhomogeneity of the static magnetization across the film thickness caused by various technological factors. The theory of SWR was developed for models with a parabolic decrease of $M(z)$ from the center of the film to its surfaces [3] and the linear variation of the magnetization along the z axis [4]. The parabolic increase of the effective magnetic field to the film surfaces (potential well) corresponds to the first model. For the first model the law $\omega_n \sim n$ and for the second one $\omega_n \sim (1/4+n)^{2/3}$ were obtained. In subsequent years, the authors of experimental investigations of the SWR described their results within the framework of these models. In the paper [5], the authors developed a technology for creating layered films in which the magnetic parameters of the layers smoothly vary over the thickness of the film, simulating a predetermined dependence of the magnetization $M(z)$, and investigated the SWR in such gradient films. The creation of artificial gradient films poses the problem of developing the theory of SWR for a wider range of profiles of the dependences of magnetic parameters on z. The aim of our work is to investigate the spectrum of SWR in gradient ferromagnets with a parabolic potential barrier of the magnetic parameters.

We consider the case of SWR in a field H directed along the z axis perpendicular to the surface of the film. In a gradient film, when the magnetization or the uniaxial anisotropy along the film thickness is a function of the coordinate z, we introduce the effective magnetic field $H^{eff}(z) = H - [4\pi - \beta(z)]M(z)$ and represent it in the form $H^{eff}(z) = H_0^{eff} - \Delta H^{eff}(2z/d)^2$, where H_0^{eff} is a value of the effective field in the middle of the film, and ΔH^{eff} is a barrier height. The wave equation for the resonance circular projection of the magnetization $m(z,\omega)$ has the form

$$\frac{d^2m}{dz^2} + \frac{1}{\alpha M_0}\left[\frac{\omega}{g} - H_0^{eff} + \Delta H^{eff}\left(\frac{2z}{d}\right)^2\right] m = 0, \tag{1}$$

where α is the exchange parameter, β is the constant of uniaxial anisotropy, whose axis is directed along z axis, ω is the frequency, g is the gyromagnetic ratio, and d is thickness of the film. It should be noted that equation (1) for the case of the gradient of the uniaxial anisotropy constant $\beta(z)$ is exact, but for the magnetization gradient $M(z)$ is approximate. The authors of [6] obtained the solution of the Schrödinger equation for the parabolic potential barrier, which we used in our work. Symmetric $m_s(\zeta)$ and antisymmetric $m_a(\zeta)$ solutions of equation (1) are expressed in terms of Kummer's functions (confluent hypergeometric functions), respectively

$$m_s = \exp\left(\frac{-i\zeta^2}{4}\right) M\left(\frac{i\Omega}{2}+\frac{1}{4},\ \frac{1}{2},\ \frac{i\zeta^2}{2}\right), m_a = \zeta \exp\left(\frac{-i\zeta^2}{4}\right) M\left(\frac{i\Omega}{2}+\frac{3}{4},\ \frac{3}{2},\ \frac{i\zeta^2}{2}\right). \tag{2}$$

Here the dimensionless frequency Ω and coordinate ζ are entered

$$\Omega = \frac{1}{4}\left(\Delta H q^2 \alpha M_0\right)^{-1/2}\left(\frac{\omega}{g} - H^{eff}(0)\right), \quad \zeta = 2\left(\frac{\Delta H}{q^2\alpha M_0}\right)^{1/4} qz, \tag{3}$$

where $q = 1/d$. The cases of pinned and unpinned boundary conditions are considered. The discrete frequency spectrum ω_n (Fig. 1*b* and *c*) is obtained from the numerical solution of transcendental dispersion equations corresponding to these boundary conditions.

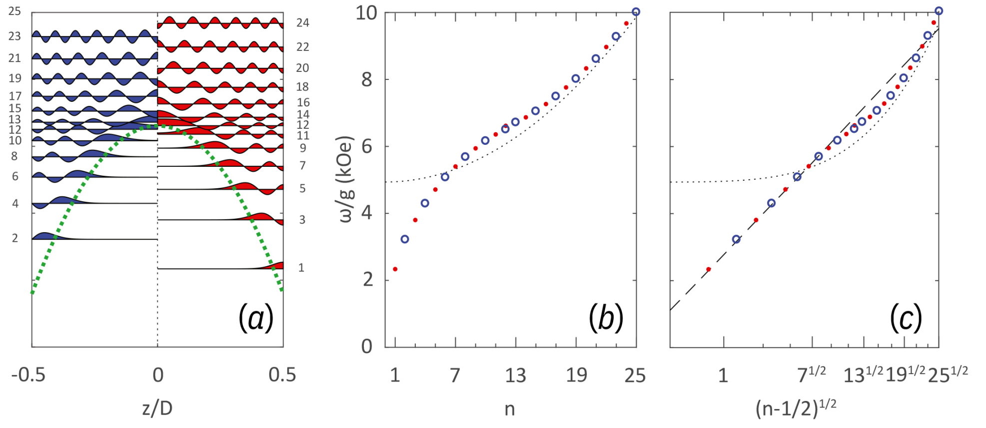

Figure 1. The normalized spin oscillations $m''(z)$ for pinned ($z < 0$) and unpinned ($z > 0$) boundary conditions (*a*). The energy potential barrier (*a*, dotted green curve). Spin-wave resonance frequencies ω_n *vs* the mode number n (*b*) and the value $(n - 1/2)^{1/2}$ (*c*) for pinned (blue circles) and unpinned (red dots) boundary conditions. Asymptote for $n << n_c$ (*c*, dashed straight line, and ω_n *vs* n for a homogeneous film (*b* and *c*, black dotted curves)

The form of eigenmodes $m_n(z)$ corresponding to these frequencies is calculated (Fig.1*a*). The relative high-frequency susceptibility χ_n was also calculated. Spin-wave oscillations at energy levels $n \leq n_c$, where n_c is the energy level nearest the top of the barrier, occur in two potential wells between the boundaries of the barrier and the film surfaces. We obtained the law of the dependence of the frequencies of the first resonance peaks on n at $n \leq n_c$ for the parabolic potential barrier as

$$\omega_n \sim (n - 1/2)^{1/2}. \tag{4}$$

Indeed, the frequencies of the first peaks ω_n are located along a straight line in the corresponding coordinates (Fig.1*c*). When $n >> n_c$, the discrete frequency spectrum tends to $\omega_n \sim n^2$, corresponding to the spectrum of a homogeneous film. Changing the shape of the function $\omega_n(n)$ when $n = n_c$, as well as a sharp decrease in χ_n at the same point, makes it possible to experimentally determine the frequency of the height of the potential barrier.

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