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Hybridization of electromagnetic, spin and acoustic waves in magnetic having conical spiral ferromagnetic order

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ABSTRACT

The spectrum of hybrid electromagnetic–spin–acoustic waves for magnetic having conical spiral ferromagnetic structure defined by heterogeneous exchange and relativistic interactions has been received. The possibility of resonant interaction of spin, electromagnetic and acoustic waves has been shown. The electromagnetic waves reflectance from the half-infinity layer of magnetic having conical spiral ferromagnetic order has been calculated for different values of external magnetic field (angle of spiral). The acoustic Faraday effect has been considered.

1. Introduction

Recently, helicoidal (spiral) magnetic materials have attracted researchers' attention for their unusual physical properties [1,2]. The spiral magnetic structures contribute a number of features in the spectrum and dynamics of spin excitation in magnetic materials: band structure is observed, the nonreciprocity effect is manifested, i.e. difference between the velocity of wave transmission along and against the spiral axis. Previously, the spin–wave spectrum was calculated without taking into account of the effects of the electromagnetic retardation, and the electromagnetic wave spectrum was calculated without taking into account of the effects of the dynamic interaction of the electromagnetic field with the oscillations of the spins in the ferromagnetic spiral structure [3,4]. Earlier had been investigated the hybrid electromagnetic–spin, electromagnetic–spin–acoustic waves in the magnetic having simple spiral structure [5,6], and the hybrid electromagnetic–spin waves in the magnetic having conical spiral ferromagnetic structure, also termed "ferromagnetic spiral" [7]. However the spectrum and dynamic properties of magnets in a phase ferromagnetic spiral are not studied enough. In the present work the spectrum of the hybrid electromagnetic–spin–acoustic waves in spiral magnetic structure of type ferromagnetic spiral is investigated. Also the reflection of electromagnetic waves from a surface of half-infinity magnetic material with a ferromagnetic spiral depending on the angle of spiral determined by an external magnetic field and Faraday effect are considered. Researches of spectrum of the coupled fluctuations in the modulated magnetic structures are spent in approach $L \gg a$, where $L = 2\pi/q$ the spiral period, q the wave number of spiral, a the lattice constant.

2. The spectrum of hybrid spin, acoustic and electromagnetic waves

The ground state of a crystal is described by a vector of magnetization with components:

$$M_{0x} = M_0 \sin\theta \cos qz, \quad M_{0y} = M_0 \sin\theta \sin qz, \quad M_{0z} = M_0 \cos\theta, \tag{1}$$

where M_0 is the magnetization of saturation, q the wave number of a spiral, θ an angle between a direction of magnetization and a spiral axis z. θ is defined by the value of an external magnetic field. When $\theta = \pi/2$ the magnetic transforms from the phase of the ferromagnetic spiral into simple spiral, when $\theta = 0$ in the ferromagnetic phase.

The free energy of the crystal phase of ferromagnetic spiral has the form:

$$F = \frac{\alpha}{2}\left(\frac{d\vec{M}}{dx_i}\right)^2 + F_{in} + \frac{\beta_1}{2}M_z^2 + \frac{\beta_2}{2}M_z^4 - HM_z + b_{ijlm}M_iM_ju_{lm} + c_{ijlm}u_{ij}u_{lm}, \tag{2}$$

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where $\vec{M}$ the magnetization of the crystal, $u_{ij}=(\partial u_i/\partial x_j+\partial u_j/\partial x_i)/2$ the tensor of deformations; $\vec{u}$ the displacement vector, α,β,b,c the constants of inhomogeneous exchange, anisotropy, magnetostriction and elastic constant.

The term F_{in}, which causes inhomogeneous magnetization in the ground state for crystals with exchange spiral structure is

$$F_{in}=\frac{\gamma}{2}\left(\frac{d^2\vec{M}}{dx_i^2}\right)^2 \tag{3}$$

and for magnetics with a relativistic helicaloidal structure

$$F_{in}=\alpha_1\vec{M}\ rot\ \vec{M}, \tag{4}$$

where γ and α_1 are constants of inhomogeneous exchange interaction and inhomogeneous relativistic interaction. In (2) it is taken into account that the external magnetic field is directed along the axis of symmetry.

From the minimum of free energy with (1) we obtain expressions for determining the angle θ through an external magnetic field H.

$$H=M_0\cos\theta[\tilde{\beta}_1+h_{me}+(\tilde{\beta}_2+h_{me}/M_0^2)M_0^2\cos\theta^2+\alpha q^2+\tilde{\Delta}], \tag{5}$$

where $\tilde{\beta}_1$ and $\tilde{\beta}_2$-the constants of anisotropy renormed by magnetostriction:

$$\tilde{\beta}_1=\beta_1-\frac{c_{33}c_{11}-c_{13}^2}{\Delta(c_{11}-c_{12})}(b_{11}-b_{12})^2M_0^2-\frac{c_{13}}{\Delta}(b_{33}-b_{31})(b_{11}-b_{12})M_0^2 +\frac{c_{33}}{\Delta}(b_{13}-b_{12})(b_{11}-b_{12})M_0^2+\frac{b_{44}^2M_0^2}{2c_{44}},$$

$$\tilde{\beta}_2=\beta_2-\frac{c_{33}c_{11}-c_{13}^2}{\Delta(c_{11}-c_{12})}(b_{11}-b_{12})^2+\frac{c_{11}-c_{12}}{2\Delta}(b_{33}-b_{31})^2 +\frac{c_{33}}{\Delta}(b_{33}-b_{31})(b_{11}-b_{12})-\frac{c_{11}}{\Delta}(b_{13}-b_{12})(b_{11}-b_{12}) -\frac{b_{44}^2}{2c_{44}}-\frac{2c_{13}}{\Delta}(b_{33}-b_{31})(b_{13}-b_{12}),$$

$$\Delta=c_{33}(c_{11}+c_{12})-2c_{13}^2.$$

For a spiral with the exchange interaction we have, $\gamma>0$, $\alpha<0$, $h_{me}=(b_{11}-b_{12})^2M_0^2/(c_{11}-c_{12})$, $q=(-\alpha/2\gamma)^{1/2}$, $\tilde{\Delta}=\gamma q^4$.

In the case of relativistic spiral, $\alpha_1\neq 0$, $\alpha>0$, $h_{me}=b^2M_0^2/2\mu$, $q=\alpha_1/\alpha$, $\tilde{\Delta}=-2\alpha_1 q$.

Note that the magnetoelastic coupling is not affected by the value of the wave number of the spiral q.

The tensor of the equilibrium deformations is

$$u_{xx}^0=M_0^2\left(-\frac{c_{33}}{2\Delta}(b_{11}-b_{12})\sin^2\theta\frac{1}{\Delta}[c_{33}(b_{13}-b_{12})-c_{13}(b_{33}-b_{31})]\cos^2\theta\right),$$

$$u_{yy}^0=u_{xx}^0,\quad u_{zz}^0=-\frac{2c_{13}}{c_{33}}u_{xx}^0-\frac{1}{c_{33}}(b_{33}-b_{31})M_0^2\cos^2\theta,$$

$$u_{xz}^0=-\frac{b_{44}}{4c_{44}}M_0^2\sin 2\theta\cos qz,\quad u_{yz}^0=-\frac{b_{44}}{4c_{44}}M_0^2\sin 2\theta\sin qz,\quad u_{xy}^0=0. \tag{6}$$

For solving a problem of getting the spectrum of hybrid waves one have to take into account the system of Maxwell's, Landau–Lifshitz and motion of an elastic medium equations:

$$\partial\vec{M}/\partial t=g[\vec{M}\vec{H}^{eff}],\quad \vec{H}^{eff}=-\delta F/\delta\vec{M},$$

$$\rho\ddot{u}_i=\partial\sigma_{ik}/\partial x_k,\quad \sigma_{ik}=\partial F/\partial u_{ik},$$

$$rot\ \vec{E}=-\frac{1}{c}\frac{\partial}{\partial t}(\vec{H}+4\pi\vec{M}),\quad rot\ \vec{H}=\frac{\varepsilon}{c}\frac{\partial\vec{E}}{\partial t},$$

$$div(\varepsilon\vec{E})=0,\quad div(\vec{H}+4\pi\vec{M})=0. \tag{7}$$

The linearized system of Eq. (7) for Fourier components is

$$\pm\omega m_\pm(k)=\cos\theta[\omega_{2k}^\pm+\tfrac{1}{2}\omega_{me4}\sin^2\theta]m_\pm(k) +\tfrac{1}{2}\omega_{me4}\sin^2\theta\cos\theta m_\pm(k\mp 2q)-\omega_{1k\pm q}\sin\theta m_z(k\mp q) +igb_{44}M_0^2k[\tfrac{1}{2}-\tfrac{3}{2}\sin^2\theta]u_\pm(k)-\tfrac{i}{2}gM_0^2b_{44}\sin^2\theta(k\pm 2q)u_\pm(k\mp 2q) -ig(b_{33}-b_{31})M_0^2\sin 2\theta(k\pm q)u_z(k\mp q)+gM_0\sin\theta h_z(k\mp q) -gM_0\cos\theta h_\pm(k),$$

$$\omega m_z(k)=\tfrac{1}{2}\sin\theta[\omega_{2k-q}^-m_-(k-q)-\omega_{2k+q}^+m_+(k+q)] +\tfrac{1}{2}gM_0\sin\theta[h_+(k+q)-h_-(k-q)] -\tfrac{i}{4}gb_{44}M_0^2\sin 2\theta[(k-q)u_-(k-q)-(k+q)u_+(k+q)],$$

$$[\omega^2-s_t^2k^2]u_\pm(k)=\tfrac{i}{\rho}kb_{44}M_0[\sin\theta m_z(k\mp q)+\cos\theta m_\pm(k)],$$

$$[\omega^2-s_l^2k^2]u_z(k)=-2i(b_{33}-b_{31})kM_0\cos\theta m_z(k)/\rho,$$

$$[\omega^2-k^2v^2]h_\pm(k)=-\omega^2 4\pi m_\pm(k),\quad h_z(k)=-4\pi m_z(k). \tag{8}$$

Here, we introduce the following notation: $v=c/\sqrt{\varepsilon}$ velocity of propagation of electromagnetic waves in a magnetic, ε dielectric constant, $s_t=\sqrt{c_{44}/\rho}$, $s_l=\sqrt{c_{33}/\rho}$ velocity of propagation of transversal and longitudinal acoustic waves, respectively,

$$\omega_{1k}=\omega_{10}+gM_0\sin^2\theta L_\parallel(k),\ \omega_{2k}^\pm=\omega_{20}+gM_0L_\perp(k),$$

$$L_\perp^\pm(k)=-\alpha(q^2-k^2)-\gamma(q^4-k^4)+2\alpha_1(q\mp k),$$

$$L_\parallel(k)=-\alpha(q^2-k^2)-\gamma(q^4-k^4)+2\alpha_1 q,$$

$$\omega_{me4}=gM_0h_{me4}=gb_{44}^2M_0^3/c_{44},\quad \omega_{20}=\omega_{me4}\cos^2\theta,$$

$$\omega_{10}=gM_0[h_{me4}-\sin^2\theta(\tilde{\beta}_1+M_0^2\cos^2\theta(\tilde{\beta}_2+2\beta_2)+h_{me}\sin^2\theta)]. \tag{9}$$

In system of Eq. (8) we have to add the condition of constancy of the modulus of the magnetization $|\vec{M}|=const$, what for the Fourier components of the magnetization is

$$\sin\theta[m_-(k-q)+m_+(k+q)]+2m_z(k)\cos\theta=0. \tag{10}$$

Using the ordinary values of the constants for magnetic with exchange spiral ($TbMn_2O_5$) $g=2\times 10^7\ s^{-1}\ erg^{-1}$, $M_0\sim 10^3$ Oe, $\alpha_1\sim 10^{-28}\ cm^4$, $\alpha\sim -10^{-14}\ cm^2$, $q\sim 10^7\ cm^{-1}$, and in the case of relativistic spiral ($CsCuCl_3$) $\alpha\sim 10^{-12}\ cm^2$, $\beta\sim 1$, $a\sim 10^{-8}$ cm, $q\sim 10^4\ cm^{-1}$, from Eq. (8), we obtain the spectrum of coupled electromagnetic–spin–acoustic waves.

Changing θ the range $0\le\theta\le\pi/2$, we can calculate the spectrum for the ferromagnetic spiral. Fig. 1 shows the dependence $\omega(k)$ for $\theta=\pi/4$ in the case of relativistic spiral.

To get more details and study the dynamic of changing band gaps width with changing external magnetic field value let us consider the dependence $\omega(k)$ for different values of θ near $k=0$ (Fig. 2).

It is seen that all spectra have a band structure. At certain frequencies the gap (window opacity) is observed as for electromagnetic such for acoustic waves. These band gaps appear due to the resonant interaction of spin, acoustic and electromagnetic waves in a magnet. From Fig. 2 we can see that with decreasing angle the electromagnetic band shifts toward lower frequencies and its width decreases. Calculations show that in the case of exchange spiral, a band of opacity is much narrower than in the case of relativistic one. Note also that the magnitude of the interaction of spin, acoustic and electromagnetic waves depends on the angle θ.