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Magnetostrictive hypersound generation by spiral magnets in the vicinity of magnetic field induced phase transition

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ABSTRACT

In present work we have investigated magnetostrictive ultrasound generation by spiral magnets in the vicinity of magnetic field induced phase transition from spiral to collinear state. We found that such magnets may generate transverse sound waves with the wavelength equal to the spiral period. We have examined two types of spiral magnetic structures: with inhomogeneous exchange and Dzyaloshinskii–Moriya interactions. Frequency of the waves from exchange-caused spiral magnetic structure may reach some THz, while in case of Dzyaloshinskii–Moriya interaction-caused spiral it may reach some GHz. These waves will be emitted like a sound pulses. Amplitude of the waves is strictly depends on the phase transition speed. Some aspects of microwaves to hypersound transformation by spiral magnets in the vicinity of phase transition have been investigated as well. Results of the work may be interesting for investigation of phase transition kinetics as well, as for various hypersound applications.

1. Introduction

Nowadays, ideas on nanoscale heat control attract great researcher"s attention. It is well known that heat transfer in solids occurs mainly by high-frequency phonons (with frequencies more than 0.1 THz), so, these ideas have lead to formation of such cutting-edge physics area like phononics [1–4]. Lower-frequency phonons (in frequency range from 100 MHz up to 0.1 THz), hypersound, cannot to propagate in solids on macroscopic scales due to large damping. For the same reason it is difficult to investigate these waves experimentally. Efforts to generate and detect such phonons are justified by the possibility of submicron scale and nanosecond time-scale investigation of materials properties. Inaccessible to the human ear sound vibrations with frequencies approximately from 20 kHz to 100 MHz, ultrasound, become the basis of a vast number of diagnostic and research technologies [5,6].

Due to great number of application, new ways of generating of ultra- and especially hyper- sound may be very useful. In present work we show the possibility of ultra- and hyper- sound generation by magnets with spiral spin structure during and in the vicinity of magnetic field induced phase transition into collinear state.

Recently, electromagnetic waves radiation by Heusler"s alloy at structural phase transition has been experimentally observed [7]. Some possible mechanisms of this radiation have been proposed and theoretically investigated as well. In general, material"s energy changes to minimal value during phase transition. This change of energy may be released like electromagnetic waves, heat, sound etc. In magnetic materials spin, electromagnetic and acoustic waves are coupled. Excitation any of them leads to energy redistribution between all subsystems. One of manifestations of this effect is a well-known phenomenon of electromagnetic sound generation in magnetic materials (see, for example, review [8]). The features associated with electromagnetic-acoustic transformation became the basis for some methods of study and detection of phase transitions in magnetic materials [9–14]. In spiral magnets such hybridization of the oscillations has a number of features and may be controlled by external magnetic field [15,16]. In [17] authors experimentally observed and theoretically explained intensive electromagnetic-acoustic transformation and anomalies in transverse sound velocity in erbium single crystal at different phase transitions (including state with spiral magnetic structure). These features may be explained by resonant subsystems interaction in the vicinity of phase transition. Electromagnetic-sound transformation should take a place even far from resonances. It will be less efficiently, but may be more convenient for practical

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implementation. Features of such transformation are investigated in this paper. The possibility of sound generation by spiral magnets during phase transition has never been investigated. This issue is also covered in this paper.

2. Theory and calculations

Let us consider spiral magnet crystal. For definiteness, we will assume that it has a hexagonal symmetry. It's properties may be described phenomenologically by the following free energy density

$$F = \frac{\alpha}{2}\left(\frac{\partial \mathbf{M}}{\partial x_i}\right)^2 + F_{in} + \frac{\beta_1}{2}M_z^2 + \frac{\beta_2}{2}M_z^4 - HM_z + b_{ijlm}M_iM_ju_{lm} + c_{ijlm}u_{ij}u_{lm,}, \quad (1)$$

where α and β_i are exchange and anisotropy constants, b_{ijlm} and c_{ijlm} are the tensors of magnetostriction and elasticity, $\mathbf{M}$ is the crystal magnetization, H is the value of external magnetic field directed along z-axis (spiral axis), $u_{ij} = \left(\partial u_i/\partial x_j + \partial u_j/\partial x_i\right)/2$ are the components of the strain tensor, u_i are the components of displacement vector. Term F_{in} corresponds to inhomogeneous magnetic interaction. In case of exchange-caused spiral this is $F_{in} = \gamma\left(\partial^2\mathbf{M}/\partial x_i^2\right)^2/2$, while in Dzyaloshinskii–Moriya interaction-caused case $F_{in} = \alpha_1\mathbf{M}rot\mathbf{M}$, γ and α_1 are the constants of inhomogeneous exchange and Dzyaloshinskii–Moriya interaction, consequently. Ground state of such system corresponds to the minimum of free energy density. In case under consideration (i.e. when both anisotropy and external magnetic field distinguish z-axis) magnetization in ground sate will rotate in xy-plane. Magnetization may be expressed in the form

$$M_{0x} = M_0 \sin\theta\cos qz, \quad M_{0y} = M_0\sin\theta\sin qz,$$
$$M_{0z} = M_0\cos\theta, \quad (2)$$

where M_0 is saturation magnetization, $q=2\pi/L$ is wavenumber of the spiral, L is spiral period, θ is angle between spiral axis and magnetization direction. When $\theta=\pi/2$, magnetic is in simple spiral phase, $\theta=0$ correspond to collinear ferromagnetic state. When $0<\theta<\pi/2$ magnetic is in conical (ferromagnetic) spiral phase. Spiral angle θ depends on external magnetic field value and may be calculated by solving of equation

$$M_0 \cos\theta\left[\tilde{\beta}_1 + h_{me} + \left(\tilde{\beta}_2 - \frac{h_{me}}{M_0^2}\right)M_0^2\cos^2\theta + \alpha q^2 + \tilde{\Delta}\right] + H = 0 \quad (3)$$

where $\tilde{\beta}_1$ and $\tilde{\beta}_2$ are renormalized by magnetostriction anisotropy constants [15,16]. For exchange interaction-caused spiral structure we have $\gamma > 0$, $\alpha < 0$, $q = (-\alpha/2\gamma)^{1/2}$, $h_{me} = (b_{11} - b_{12})^2M_0^2/(c_{11} - c_{12})$, $\tilde{\Delta} = \gamma q^4$. In Dzyaloshinskii–Moriya interaction-caused case $\alpha_1 \neq 0$, $\alpha > 0$, $q = \alpha_1/\alpha$, $h_{me} = b^2M_0^2/2\mu$, $\tilde{\Delta} = -2\alpha_1 q$. Magnetosriction is small enough and not affects the ground state configuration of magnetic subsystem.

Equilibrium deformations tensor has been calculated in [16]. It's components u°_{xx} , u°_{yy}, and u°_{zz} are homogeneous and depend on the spiral angle θ, while the components u°_{xz}, and u°_{yz} are inhomogeneous.

For investigation of sound waves generation we should to solve equation of motion for elastic medium

$$\rho\ddot{u}_i = \partial\sigma_{ij}/\partial x_j, \quad \sigma_{ij} = \partial F/\partial u_{ij}. \quad (4)$$

Let us consider only waves propagating along z-axis. Eq. (4) with (1) lead to the following wave equations

$$\ddot{u}_\pm - v_t^2\partial^2u_\pm/\partial z^2 = 2\rho^{-1}b_{44}M_z\partial M_\pm/\partial z;$$
$$\ddot{u}_z - v_l^2\partial^2u_z/\partial z^2 = 4\rho^{-1}b_{13}\left(M_x\partial M_x/\partial z + M_y\partial M_y/\partial z\right). \quad (5)$$

In (5) we have introduced circular components $(u, M)_\pm = (u, M)_x \pm i(u, M)_y$, transversal and longitudinal sound velocities $v_t = (2c_{44}/\rho)^{1/2}$ and $v_l = (c_{33}/\rho)^{1/2}$, consequently. Right-hand sides of Eq. (5) mean the sound source functions, and in general may depend from both coordinate and time. Indeed, computation of time dependence of magnetization vector"s components during phase transition (i.e. phase transition kinetics) is an individual problem. It may be modeled, for example, by time-dependent Ginzburg–Landau, Landau–Khalatnikov, or Landau–Lifshitz equations with different damping terms. We will consider only some simple for analysis ideal cases without solving of the phase transition kinetics problem. Our calculations are valid for processes when characteristic time of magnetization change is much larger than time of local quasi-equilibrium setting up in material. In real magnets local quasi-equilibrium distribution of magnetic moments is reached quickly due to strong exchange interaction [18].

For numerical estimations we will use following constants values [19]: b_{ij}~20 erg/(Oe × cm^4), ρ~10 g/cm^3, v_t~3 × 10^5 cm/s, v_l~5 × 10^5 cm/s, M_0~500 Oe. Period of the structure for Dzyaloshinskii–Moriya interaction-caused spiral magnets is usually much more that in case of exchange-caused spiral structures [20]. For example, $Fe_xCo_{1-x}Si$ alloys, which symmetry allows Dzyaloshinsky–Moria interaction, for x=0.3 in spiral state has a modulation period L=230 nm (q~3 × 10^5 cm^{-1}) [21]. Other examples of the magnets with Dzyaloshinsky–Moria interaction-caused spiral structures are FeGe (L=70 nm, q~8 × 10^5 cm^{-1}) [22] and MnSi (L=18 nm, q~3 × 10^6 cm^{-1}) [23]. Different modulated states exist in erbium single crystal due to the competing exchange interaction. In conical state wavenumber of the structure is $5c^*/21$ ($c^* = 2\pi/c$ is inverse lattice constant, c=0.56 nm is lattice constant) [24], i.e. q~3 × 10^7 cm^{-1}. We will use q~10^5 cm^{-1} and q~10^8 cm^{-1}, consequently.

During phase transition, spin waves (or magnons) may also be excited. So, components of magnetization vector M_i should have the form $M_i(z,t)=M_{i0}(z,t)+m_i(z,t)$, where term $M_{i0}(z,t)$ means change of the ground state during the phase transition, while $m_i(z, t)$ correspond to excited spin waves. We will consider only sound waves excited by $M_{i0}(z,t)$ because usually, change of the ground state magnetization during the phase transition is much more than excited spin waves amplitude. In such a case it is easy to show, that only transverse sound will be excited. From (5) we will have

$$\ddot{u}_\pm - v_t^2\partial^2u_\pm/\partial z^2 = \pm iq\rho^{-1}b_{44}M_0^2\sin(2\theta)\exp(\pm iqz). \quad (6)$$

Solution of (6) can be obtained by the Duhamel's principle [25]

$$u_\pm(z, t) = (2v_t)^{-1}\int_0^t\int_{z-v(t-s)}^{z+v(t-s)} f_\pm(\xi, s)d\xi ds, , \quad (7)$$

where $f_\pm(z, t)$ is right-hand side of Eq. (6).

First of all let us consider infinitely fast phase transition, corresponding to the spiral suppression. Despite an evident nonreality of such a process, this situation corresponds to the maximum change of sound source function and, thus, to maximum amplitude of the emitted sound. We will consider such process only for estimation of fundamentally maximal value of amplitude of emitted sound. This process may be modeled by step-like time dependence of spiral angle θ. From (6) one can see, that source function is equal to zero for both simple spiral phase ($\theta=\pi/2$) and collinear ferromagnetic state ($\theta=0$), and has a maximum at $\theta=\pi/4$. So, if we will have infinitely fast phase transition from simple spiral phase to collinear ferromagnetic one, sound waves will not be emitted. Maximum sound waves generation will take a place at