Materials Science Forum
ISSN: 1662-9752, Vol. 845, pp 185-188
doi:10.4028/www.scientific.net/MSF.845.185

Submitted: 2015-09-08
Revised: 2015-11-10
Accepted: 2015-11-16
Online: 2016-03-03

Waves Generation by Spiral Magnets at Phase Transitions

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Keywords: electromagnetic waves, acoustic waves, spiral magnets, phase transitions

Abstract. The possibility of electromagnetic and acoustic waves generation by magnets with spiral spin structure at phase transition to collinear state has been shown. Intensities and frequencies of generated waves have been calculated. It has been shown that intensities of both electromagnetic and acoustic waves strictly depend on the phase transition kinetics.

Introduction

In recent years new effects of electromagnetic waves generation under nonequilibrium processes in condensed media attract researcher's attention. During phase transition the medium is active, i.e. it may emit the energy as electromagnetic and/or acoustic waves. The jumps of magnetization ΔM or polarization ΔP of the sample, which may have a place at phase transition, may lead to generation of electromagnetic and acoustic fields pulses [1]. During structural phase transition a nuclei of a new phase, defects, dislocations, etc. may lead to generation of electromagnetic and acoustic pulses [2]. Recently, electromagnetic waves radiation by Heusler's alloy at structural phase transition has been experimentally observed [3].

There is a class of magnetic materials with non-uniform magnetization distribution in the ground state, the so-called spiral (or helical) magnets, or magnets with incommensurate magnetic structure [4]. During phase transitions, magnetic structure is rearranged in such materials. This fact may lead to generation of electromagnetic radiation due to change in the sample magnetization. Withal, such materials have non-zero equilibrium deformations in the spiral state. Emergence/vanishing of these deformations during phase transition may lead to acoustic waves generation. In this work we study electromagnetic and acoustic waves generation by spiral magnets at phase transitions.

Electromagnetic Waves Generation

Generally, electromagnetic radiation processes may be described by the following equation

$$\Delta \mathbf{E} - c^{-2}\,\partial^2 \mathbf{E}\big/\partial t^2 = 4\pi c^{-2}\left[\partial\left(\mathbf{j} + \partial\mathbf{P}/\partial t + c\,\mathrm{rot}\,\mathbf{M}\right)\big/\partial t + c^2\,\mathrm{grad}\,\mathrm{div}\left(\mathbf{P}\right)\right]. \quad (1)$$

In (1) **E** is electric field strength, **P** and **M** are polarization and magnetization of the medium, consequently, **j** is the current density, c is speed of light in the vacuum. We will assume that magnetic material is non-conductive, and has a dielectric constant ε. Equation (1) can be simplified:

$$\Delta \mathbf{E} - \varepsilon c^{-2}\,\partial^2 \mathbf{E}\big/\partial t^2 = 4\pi c^{-2}\,\partial \mathbf{j_M}\big/\partial t \quad (2)$$

In (2) magnetic current density has been introduced: $\mathbf{j_M} = c\cdot\mathrm{rot}(\mathbf{M})$. Such form of radiation equation allows one to see that time-varying non-uniform magnetization distribution is equivalent to time-varying distributed conductive currents. Generally, this equation should be solved together with the magnetization motion equation in Landau-Lifshitz-Gilbert form, for example. This system of equations can be solved only numerically. However, it is known that the frequency of precession of the magnetization vector in ferromagnetic materials (ferromagnetic resonance frequency) is about 10-100 GHz, and the relaxation of magnetization to equilibrium state is of the order of few microseconds at usual conditions. In this case, if we are interested in processes with characteristic frequencies far from resonance, the motion of magnetization can be neglected, and one can assume that magnetization has always ground state value.

The ground state of spiral magnet may be determined by minimization of the free energy density F, which has a form

$$F = \alpha\left(\partial \mathbf{M}/\partial x_i\right)^2/2 + F_{in} + \beta_1 M_z^2/2 + \beta_2 M_z^4/2 - HM_z + b_{ijlm}M_iM_ju_{lm} + c_{ijlm}u_{ij}u_{lm}, \tag{3}$$

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} 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.

Magnetization distribution in ground state is folowwing

$$M_x = M_0\cos(qz)\sin\theta, M_y = M_0\sin(qz)\sin\theta, M_z = M_0\cos\theta \tag{4}$$

where $q = 2\pi/L$ is the spiral wavenumber, L is the period of spiral. Angle θ is dependent on the external magnetic field value H and may be determined from equation [5] $M_0\cos\theta\left[\tilde{\beta}_1 + h_{me} + \left(\tilde{\beta}_2 - h_{me}/M_0^2\right)M_0^2\cos^2\theta + \alpha q^2 + \tilde{\Delta}\right] + H = 0$, where $\tilde{\beta}_1$ and $\tilde{\beta}_2$ are renormalized by magnetostriction anisotropy constants [5]. For exchange interaction-caused spiral structure we have $\gamma > 0$, $\alpha < 0$, $q = (-\alpha/2\gamma)^{1/2}$, $h_{me} = (b_{11} - b_{12})^2 M_0^2/(c_{11} - c_{12})$, $\tilde{\Delta} = \gamma q^4$. In Dzyaloshinskii-Moriya interaction-caused case $\alpha_1 \neq 0, \alpha > 0$, $q = \alpha_1/\alpha$, $h_{me} = b^2 M_0^2/2\mu$, $\tilde{\Delta} = -2\alpha_1 q$.

One may calculate magnetic current density $\mathbf{j_M} = (j_0\cos(qz), j_0\sin(qz), 0)$, $j_0 = -cqM_0\sin(\theta)$.

Let us consider an infinite crystal. We will assume also that at initial time there was no electromagnetic radiation, i.e., we should solve the equation (2) with zero initial conditions. In this case, the solution of Eq. (2) can be obtained from the Duhamel's principle [6].

To begin with, let us consider the simplest case, when $\sin[\theta(t)] = \Theta(-t)$; $\Theta(t)$ is the step-like Heaviside function; $\partial\Theta(-t)/\partial t = -\delta(t)$; $\delta(t)$ is the Dirac delta function. This situation corresponds to instantaneous turning on of magnetic field with the value H_{cr} at time $t = 0$, and collapse of the spin spiral. Such a process is quite unreal since the magnetization requires finite relaxation time to get to the final collinear ferromagnetic state. However, despite unreality of the case, its analysis allows us to estimate an upper limit of emitted wave's amplitude. Calculations show that electromagnetic field has form:

$$E_\pm(z,t) = E_x(z,t) \pm iE_y(z,t) = \mp 4\pi i M_0 \varepsilon^{-1/2}\sin(qvt)\exp[\mp iqz] \tag{5}$$

In case of linearly time dependence of $\sin[\theta(t)]$: $\sin[\theta(t)] = Pt$, at $t \le P^{-1}$, $P = const$, we will have:

$$E_\pm(z,t) = \pm 4\pi i M_0 P (qc)^{-1}\left[1 - \cos(qvt)\right]\exp[\mp iqz], t \le P^{-1} \tag{6}$$

It is seen that in contrast to the fast turning on of the magnetic field, in addition to the standing wave a constant component of the electric field appears as well. The amplitude and the constant component are directly proportional to the speed of the state change P.

Solutions (5) and (6) are superposition of waves travelling to the left and to the right, which, due to unbounded periodic source, give a standing wave by adding each other. In the real material multiple reflections of the excited waves from the borders and emission of energy beyond the material will take a place. If refractive index of the environment is the same as for crystal with thickness d, two electromagnetic wave pulses with wave number q and frequency qv from each sample's side.

Acoustic Waves Generation

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

$$\rho \ddot{u}_i = \partial \sigma_{ij} / \partial x_j ,\ \sigma_{ij} = \partial F / \partial u_{ij} . \tag{7}$$

Let us consider only waves propagating along z-axis. Equations (7) may be transformed to wave equations with non-zero source functions, which in general may depend from both coordinate and time. We will consider only some simple for analysis ideal cases without solving of the phase transition kinetics problem. It is convenient to introduce a 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. Calculations show that only transverse sound will be excited. We will have

$$\ddot{u}_\pm - v_t^2\, \partial^2 u_\pm / \partial z^2 = \pm iq\rho^{-1} b_{44} M_0^2 \sin(2\theta) \exp(\pm iqz). \tag{8}$$

Solution of (8) can be also obtained by the Duhamel's principle.

Let us consider infinitely fast phase transition, corresponding to the spiral suppression. This process may be modeled by step-like time dependence of spiral angle θ. From (8) 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 phase transition from $\theta = \pi/4$ to collinear ferromagnetic state. Mathematically, it may be expressed as $\sin[2\theta(t)] = \Theta(t)$, where $\Theta(t)$ is Heaviside step function. In such case solution may be easily calculated:

$$u_\pm(z,t) = \pm i\, b_{44} M_0^2 \exp[\pm iqz]\left[1 - \cos(qv_t t)\right] / \rho q v_t^2 . \tag{9}$$

Let us consider now the model process, when $\sin[2\theta(t)] = \eta t$, $t < \eta^{-1}$ (i.e. linear time-dependence of source function). Calculations show, that the following sound oscillations will be excited:

$$u_\pm(z,t) = \pm \eta i b_{44} M_0^2 \rho^{-1} q^{-2} v_t^{-3} \left[qv_t t - \sin(qv_t t)\right] \exp[\pm iqz],\ t < \eta^{-1}. \tag{10}$$

Summary

For numerical estimations we will use following constants values [4]: $b_{ij} \sim 20$ erg/(Oe×cm^4), $\rho \sim 10$ g/cm^3, $v_t \sim 3\times10^5$ cm/s, $v_l \sim 5\times10^5$ cm/s, $M_0 \sim 500$ Oe. Period of the structure for Dzyaloshinskii-Moriya interaction-caused spiral magnets is usually much more that in case of exchange-caused spiral structures. 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 ($q \sim 3\times10^5$ cm^{-1}) [7]. Other examples of the magnets with Dzyaloshinsky-Moria interaction-caused spiral structures are FeGe ($L = 70$ nm, $q \sim 8\times10^5$ cm^{-1}) [8] and MnSi ($L = 18$ nm, $q \sim 3\times10^6$ cm^{-1}) [9]. 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) [10], i.e. $q \sim 3\times10^7$ cm^{-1}. We will use $q \sim 10^5$ cm^{-1} and $q \sim 10^8$ cm^{-1}, consequently.

The frequency of standing electromagnetic waves in formulas (7) and (8) is $\omega = qv \sim 10^{15}$ - 10^{16} s^{-1}. At "slow" change of the state, in mode determined by formula (8), signal amplitude is proportional to P. For $P \sim 10^7$ s^{-1}, the amplitude of emitted waves is small: $E \sim 10^{-2}$ CGSE (energy density is about 10^{-11} J/cm^3). For ultrafast magnetization reversal processes the time of magnetization switching is usually about 10^{-12} s, or $P \sim 10^{12}$ s^{-1}, and we $E \sim 10^2$ CGSE (energy density is about 10^{-3} J/cm^3). The maximal radiation corresponding to the situation of the instantaneous change of the state has amplitude of electric field $E \sim 10^3$ CGSE (energy density is about 0.1 J/cm^3). This radiation will be emitted like a pulse. Characteristic time length of this pulse is $d/v + P^{-1}$. For sample with $d \sim 1$ μm, we will have $d/v \sim 10^{-14}$ s. This time is much smaller than usual magnetization switching time, so in real experiments characteristic time length of the pulse should be comparable with switching time for $d << vP^{-1}$. Despite low energy density of the pulse, it may have valuable power density. In case of $P = 10^{12}$ s^{-1} this value may reach about 1 GW/cm^3.

For acoustic waves generation we will have in case of infinitely fast phase transition the oscillations frequency $\omega = qv_t$. For Dzyaloshinskii-Moriya interaction-caused spiral magnets linear frequency $f = \omega/(2\pi) \sim 5$ GHz, and amplitude is $u_{\pm} \sim 10^{-5}$ cm. In exchange-caused case $f \sim 5$ THz, $u_{\pm} \sim 10^{-8}$ cm. Both cases correspond to hypersound oscillations. In case of "slow" phase transition sound oscillations with the same frequency are excited. Amplitude of exited oscillations linearly depends on the "phase transition speed" η. We may calculate, that $u_{\pm} \sim 10^{-21}\times\eta$ cm and $u_{\pm} \sim 10^{-27}\times\eta$ cm for Dzyaloshinskii-Moriya and exchange interaction-caused spiral magnets, respectively. For example, ultrafast magnetization reversal processes have a time of magnetization switching about 10^{-12} s, or $\eta \sim 10^{12}$ s^{-1}. The amplitudes will have large values $u_{\pm} \sim 10^{-9}$ cm and $u_{\pm} \sim 10^{-15}$ cm for Dzyaloshinskii-Moriya and exchange interaction-caused spiral magnets, consequently. In experiments it is possible to detect pulse of sound with characteristic time length of about $\tau \sim d/v_t$, where d is the sample size. For sample size $d \sim 1$ mm we will have time length $\tau \sim 10^{-6}$ s.

Acknowledgements

Investigation of electromagnetic waves generation has been supported by RFBR grants ## 13-07-00462, 15-07-99654, investigation of acoustic waves generation has been supported by RScF grant # 14-22-00279.

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10.4028/www.scientific.net/MSF.845

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10.4028/www.scientific.net/MSF.845.185