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LETTER TO THE EDITOR

Magnon generation by laser beam scanning along a ferromagnet surface

I V Baryakhtar†§ and A E Chubykalo‡

† Institute for Low Temperature Physics and Engineering, 47 Lenin Avenue, Kharkov 310164, USSR

‡ Department of Theoretical Physics, Kharkov State University, Kharkov 310007, USSR

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Abstract. A new method of spin wave generation by laser beam scanning along a ferromagnet surface is proposed. It is shown that due to the action of the beam a local magnetic inhomogeneity appears that can be considered as a source of Cherenkov radiation. Depending on the form of the beam cross section and properties of the ferromagnet, the formation of a one-, two- or three-dimensional source is possible.

It is well known that laser radiation action on a solid body is accompanied by the generation of acoustic waves. It has been shown both theoretically [1, 2] and experimentally [3–5] (for the case of a low-power beam) that the generation is most effective when the beam moves along the surface of a solid with the velocity V close to the velocity of sound. In other words, the intensity of the generation is maximal if the Cherenkov radiation condition is satisfied. It is obvious that if a solid body is magneto-ordered we can expect the radiation of not only acoustic but also spin waves. The Cherenkov mechanism is a rather effective means of spin wave generation. A charged particle propagating in the ferromagnet [6] as well as the moving domain wall [7] are examples of Cherenkov radiation sources.

In the present letter we consider a local magnetic inhomogeneity (LMI) stimulated by thermal action of a laser beam scanning along the ferromagnet surface. We consider a moving inhomogeneity of this type to be a source of Cherenkov generation of spin waves (magnons) and propose a simple way of calculating the power of this source.

Let us consider the following problem. Suppose that a laser beam scans a hard semi-infinite ferromagnet. As a result a local change in the ferromagnet's temperature $\Delta T(x)$ arises. According to Bloch's law a local change of magnetization $\Delta M(x)$ takes place and a LMI appears. Then $\Delta M(x)$ can be written as follows,

$$\Delta M(x) = -\tfrac{3}{2} M_0 (T^{1/2}/T_c^{3/2}) \Delta T(x) \qquad (1)$$

where M_0 is the saturation magnetization, T is the temperature in the ferromagnet and T_c is the Curie temperature. When a laser beam is scanning along the surface, a LMI moves parallel to it with the velocity V. Therefore, a moving LMI can be considered as a Cherenkov source of spin waves (magnons) since the characteristic velocity of the heat

§ The author to whom any correspondence should be forwarded.

propagation from the local thermal source is sufficiently smaller than the velocity V of the source. Let us assume that a laser beam follows a line perpendicular to the ferromagnet surface. Then, since the problem is symmetric with respect to the surface, we may consider the problem of magnon generation not in semi-infinite geometry but in infinite geometry. In the present letter we are not interested in surface effects, i.e. we assume, below, that the characteristic size of the LMI is sufficiently larger than the length of surface waves. In this way the formation of a one-, two- or three-dimensional source of magnons is possible depending on the form of the cross section of the laser beam and on the depth of its penetration into the ferromagnet. For example, if the penetration depth of a beam with a circular cross section is of the order of the beam diameter we have a three-dimensional source. If the cross section is in the form of a narrow strip and the body is transparent, then a one-dimensional source is formed.

To describe the process of magnon radiation by means of a LMI we need a proper Hamiltonian of interaction. Taking into account all the remarks above we consider a Hamiltonian for the interaction between LMI and magnons in the following form

$$H_{\text{int}} = \frac{1}{\Omega^{1/2}} \sum_q u_q c_q^+ \exp(\mathrm{i}\boldsymbol{q} \cdot \boldsymbol{v}t) + \text{HC}. \tag{2}$$

Here Ω is the system's volume, c_q^+ and c_q are operators of creation and annihilation of magnons, $\boldsymbol{v}$ is the velocity of the LMI and $\boldsymbol{q}$ is the wave vector. The amplitude U_q is determined by a Fourier component of magnetization, i.e. $U_q \sim \Delta M(\boldsymbol{q})$.

Since we do not know the exact structure of the LMI we use the following assumptions in order to proceed with calculations. We assume that the local heating is fast, i.e. $\Delta t \gg \Delta\tau \gg \tau_t$, where $\Delta t = s/r_0$. s is the threshold velocity at which the Cherenkov resonance condition is satisfied, r_0 is the radius of the LMI, $\Delta\tau = k\Delta T/I_0$, k is the Boltzmann constant, I_0 is the laser radiation power and τ_t is the characteristic temperature propagation time. Here we assume that all emitted energy is converted to heat. Consequently, we may suppose that the temperature distribution in a LMI is determined by the intensity distribution in the laser beam cross section which is known to be described by the formula

$$J \sim J_0 \exp(-r^2/r_0^2) \qquad r^2 = x^2 + y^2.$$

As follows from the Bloch law, the magnetization in the LMI is distributed according to the same formula. The Fourier component of magnetization can easily be obtained then in the case of a one-dimensional source, and the amplitude of interaction can be presented as follows

$$U_q = (3x_0/2)(\pi\mu_B TM_0^3/\Omega T_c^3)^{1/2}\Delta T_0 \exp(-q^2x_0^2/4) \tag{3}$$

where x_0 is the width of the cross section of the beam (in the form of a narrow strip) and μ_B is the Bohr magneton. For a three-dimensional source the result is

$$U_q = (3r_0^3/2)(\pi^3\mu_B TM_0^3/\Omega T_c^3)^{1/2}\Delta T_0 \exp(-q^2r_0^2/4) \tag{4}$$

where r_0 is radius of the cross section of the beam and $q = |\boldsymbol{q}|$.

Magnon generation by any source leads to a change in the energy of the magnon subsystem. The radiation power can be determined as a rate of change of magnon energy, $\dot{E}$, induced by its interaction with a moving source. It is obvious that the radiation is possible if the frequency of the emitted magnon is sufficiently larger than its relaxation frequency. Assuming that this condition is satisfied, and using equation (2), the expression for $\dot{E}$ can be presented as follows

$$\dot{E} = [\Omega/(2\pi\hbar)^3](2\pi/\hbar) \int |U_q|^2 \varepsilon_k \delta(\varepsilon_k - \boldsymbol{k}\cdot\boldsymbol{v})\, \mathrm{d}\boldsymbol{k} \tag{5}$$

where ε_k is the magnon energy and $\boldsymbol{k} = \hbar\boldsymbol{q}$ is its quasimomentum. Equation (5) can be obtained by means of thermodynamical perturbation theory [8].

To obtain the concrete form of $\dot{E}$ we use the long-wave approximation for the magnon spectrum:

$$\varepsilon_k = \hbar\omega_q = \hbar\omega_0(1 + l_0^2 q^2) \tag{6}$$

where l_0 is the characteristic ferromagnetic length. In the case of a one-dimensional source, substituting equation (3) into equation (5), we obtain the following expression for $\dot{E}$:

$$\dot{E}_{1\mathrm{D}} = \tfrac{9}{4}[\pi M_0^3 \mu_\mathrm{B} T \Delta T_0^2/\hbar(2\pi)^2 T_\mathrm{c}^3](x_0^2\omega_0/s) I_{1\mathrm{D}}(\alpha). \tag{7}$$

Here

$$I_{1\mathrm{D}}(\alpha) = \begin{cases} (\alpha^2-1)^{-1/2}[(1+G_{(+)}^2)\exp(-AG_{(+)}^2) \\ \quad + (1+G_{(-)}^2)\exp(-AG_{(-)}^2)] & \alpha \geqslant 1 \\ 0 & \alpha < 1 \end{cases}$$

where

$$\alpha = v/s \qquad s = 2l_0\omega_0 \qquad A = x_0^2/2l_0^2 \qquad G_{(\pm)} = \alpha \pm (\alpha^2-1)^{1/2}. \tag{8}$$

As follows from equation (7), at $\alpha = 1$ the radiation power becomes infinite and for $\alpha \to \infty$ the value of $\dot{E}$ tends to zero. This result is connected with the fact that the system is one-dimensional, more exactly with the absence of Mach's cone. It is not possible to avoid this within the framework of the model proposed. The situation can be changed if we introduce the relaxation of the system.

In the three-dimensional case, substituting equation (4) into equation (5) and using a spherical coordinate system, we obtain the following expression for $\dot{E}$:

$$\dot{E}_{3\mathrm{D}} = \tfrac{9}{4}(M_0^3\mu_\mathrm{B} T\Delta T_0^2/\pi\hbar T_\mathrm{c}^3)(r_0^4\omega_0/s) I_{3\mathrm{D}}(\alpha). \tag{9}$$

Here

$$I_{3\mathrm{D}}(\alpha) = \begin{cases} \pi^3(2B)^{-1}\alpha^{-1}[(2BG_{(-)}^2 + 2 + 2B)\exp(-BG_{(-)}^2) \\ \quad - (2BG_{(+)}^2 + 2 + 2B)\exp(-BG_{(+)}^2)] & \alpha \geqslant 1 \\ 0 & \alpha < 1 \end{cases}$$

where $B = r_0^2/2l_0^2$ and α and $G_{(\pm)}$ are defined in equation (8). The function $I_{3\mathrm{D}}(\alpha)$ is plotted in figure 1. It is interesting that in this case the radiation power tends to zero in both limiting cases $\alpha \to 1$ and $\alpha \to \infty$ and therefore certainly has a maximum.

The radiation is generated in the continuum spectrum of the magnon wave vector. The angle between the direction of the source motion and the direction of emission is varied in the region $1/\alpha \leqslant \cos\theta \leqslant 1$. Every value of θ corresponds to emission at some definite value of q:

$$\cos\theta = [\omega_0(1 + l_0^2 q^2)]/s\alpha q. \tag{10}$$

The results obtained allow us to estimate the value of the radiation power $\dot{E}_{3\mathrm{D}}$. First

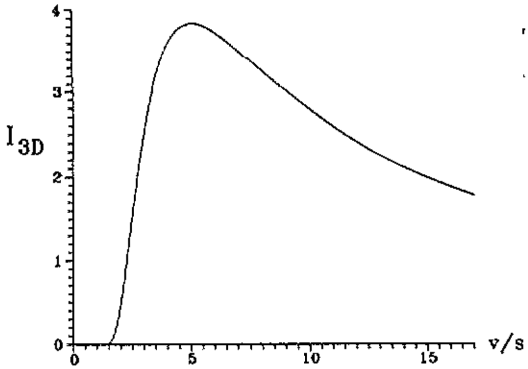

Figure 1. The plot of the function I which is proportional to the radiation power $\dot{E}$ (see equation (9)) plotted against $\alpha = v/s$.

of all, in both one- and three-dimensional cases, the value $\dot{E}$ tends to zero as $1/v$ for $\alpha \to \infty$. This fact confirms that it is possible to employ the linear theory (2) for the case of rather large α. If we suppose that equation (9) is valid for all α (at least, that real values are close to what we can obtain from it) we can estimate the maximal value of $\dot{E}_{3D}$. Assuming that $M_0 = 100\,\mathrm{G}$, $r_0 = 10^{-1}\,\mathrm{cm}$ and $l_0 = 10^{-4}\,\mathrm{cm}$, we have $\dot{E}_{3D} \approx 0.2 \times 10^{-4}\,\mathrm{erg\,s^{-1}}$. The estimated value is obviously a little larger than the real one since we do not take the relaxation into account. In this way, we propose a new means of spin wave generation.

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