ON THE BROADENING OF THE SPIN-WAVE RESONANCE LINES IN FERROMAGNETS BY DISLOCATIONS

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Broadening of the long-wavelengths magnon modes due to two-magnon scattering on dislocations is considered. The calculations were performed for the geometry corresponding to the one used in the spin wave resonance experiments in thin films with dislocations perpendicular to the plane of the film. Attention is paid to the anisotropy of the broadening due to dislocations.

1. Introduction

The influence of dislocations on the ferromagnetic resonance line-width was recently a subject of theoretical [1–7] and experimental [8–10] investigations. Three aspects of the broadening of the ferromagnetic resonance line were discussed so far, namely its dependence on static magnetic parameters of the material studied, its dependence on dislocation density and its anisotropy with respect to geometrical configuration of dislocations.

The theory predicts [1] that the broadening of the resonance line-widths due to dislocations ΔH is proportional to B_1^2/M^3, where B_1 is the magneto-elastic coupling constant and M is the spontaneous magnetization. Perhaps the most elegant verification of the dependence ΔH on B_1^2/M^3 is provided by a series of experiments on nickel and iron [10], which gave a well-resolved contribution from dislocations to the ferromagnetic resonance line in nickel whereas no detectable broadening by dislocations was found in iron under the same experimental conditions. This finding reflects the fact that B_1^2/M^3 is by two orders of magnitude larger in nickel than in iron.

The dependence of the broadening ΔH on the dislocation density n is not universal but is influenced by details of distribution of dislocations. For low dislocation densities ($n \lesssim 10^8$ cm^{-2}), in the additivity regime, ΔH is proportional to the dislocation density n([1, 9]). At higher dislocation densities, corresponding to the second stage of work

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hardening, for a system of parallel dislocations, the dependence is roughly $\Delta H \sim n^{1/2}$ ([4, 5, 8]).

Of special interest is the high anisotropy of ΔH predicted by theory [1] — the contribution to ΔH from a single dislocation line strongly depends on the angle between the magnetization and the direction of the dislocation line, the dependence being different for various types of dislocations. The anisotropy of ΔH could in principle be used as a tool for investigating dislocation structure of ferromagnetic materials having large value of the ratio B_1^2/M^3 by means of measuring ΔH. Therefore it is important, and in fact necessary for such a program, to have an experimental check of the anisotropy of ΔH calculated for simple dislocation structures. It is not an easy task to produce experimentally simple dislocation structures at reasonable high dislocation density, needed for having ΔH of detectable value.

Geometry of thin film could be useful for studying well defined dislocation structures. Thin films of YIG are particularly suitable for this purpose because of low intrinsic line--width of ferromagnetic resonance in YIG but high value of the ratio B_1^2/M^3. In principle the most direct way of studying the anisotropy of the dislocation broadening at resonance would be the case of a thin film with a system of dislocations parallel to each other and to the plane of the film, and the magnetization confined also to the plane of the film (but with varying angle between the dislocations and the magnetization). Such a case was discussed recently [11]. However, for materials like YIG it is much easier to produce thin films with dislocations perpendicular to the plane of the film[1]. A model with such geometry will be discussed in the present paper. The anisotropy of the dislocation broadening will be now reflected, somewhat indirectly, in the dependence of the broadening on the angle between the magnetization and the normal to the film.

2. *Model*

The broadening of the line-width will be calculated here for a geometry corresponding to the one used in the spin wave resonance experiments at varying angle between dc magnetic field and the normal to the film. Let us take the plane of the film as the plane (x_1, x_2) of the coordinate system and consider dislocations perpendicular to this plane, i. e. dislocation lines are parallel to the x_3 axis, see Fig. 1. The magnetic field $\vec{H}$ direction with respect to the normal to the plane is defined by the angle ϑ. For simplicity we neglect effects of magnetocrystalline anisotropy and assume that the magnetization is parallel to the magnetic field.

Scattering of magnons on dislocations results from the magneto-elastic coupling between magnetization and strains

$$\mathscr{H}_{\text{me}} = \int d\vec{r}\{(B_1/M^2)\,[M_x^2 e_{xx} + M_y^2 e_{yy} + M_z^2 e_{zz}] + (B_2/M^2)\,[(M_x M_y) e_{xy} + (M_y M_z) e_{yz} + (M_z M_x) e_{zx}]\}. \tag{1}$$

where $M_i = M_i(\vec{r})$ and $e_{ij} = e_{ij}(\vec{r})$ are the components of the magnetization and the strain

[1] I am indebted to P. E. Wigen for this remark, which actually motivated the present investigation.

tensor, respectively. B_1, B_2 are the magnetoelastic constants and (M_iM_j) is the symmetrized product $\frac{1}{2}(M_iM_j+M_jM_i)$. The matrix elements for the scattering process of magnons $\vec{k} \to \vec{k}'$ are given by (see [1])

$$W_k = (2\mu_B B_1/MV) \int d\vec{r}(e_{xx}+e_{yy}-2e_{zz})e^{i\vec{k}\cdot\vec{r}}. \quad (2)$$

The relaxation time of magnons $\vec{q}$ for two-magnon scattering processes is calculated from [13]

$$1/\tau_q = (2\pi/\hbar) \sum_k |W_{k-q}|^2 \delta(\varepsilon_q - \varepsilon_k), \quad (3)$$

where ε_q is the energy of magnon $\vec{q}$, given by the standard expression [13] $\varepsilon_q = \{(2\mu_B H + D_0 q^2)(2\mu_B H + D_0 q^2 + 4\pi M \sin^2 \theta_q)\}^{1/2}$. For a system of parallel dislocations of density

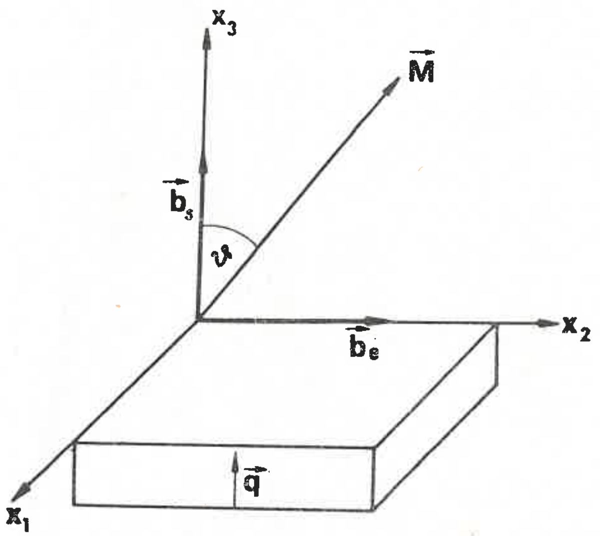

Fig. 1. Dislocations are assumed perpendicular to the plane (x_1, x_2) of the thin film. $\vec{b}_s$ and $\vec{b}_e$ denote the Burgers vector for the screw and edge dislocations, respectively

n, under the assumption of independent scattering, the broadening of the magnon line-width is determined by [1]

$$\Delta H_q = (\hbar/2\mu_B\tau_q)(V/L)n, \quad (4)$$

where L is the thickness of the film, V is its volume. For the discussion of limits of validity of the assumption of independent scattering see [3–5].

3. *Broadening of the Spin Wave Resonance by screw dislocations*

We shall calculate the dislocation broadening ΔH_q for conditions of the spin wave resonance. ΔH_q will be given for fixed energy of magnons, determined by the frequency of microwave field $\varepsilon_q/2\pi\hbar$, but for varying values of the magnon wave vector q. The anisotropy of ΔH_q is reflected in its dependence on the angle between the magnetization (or applied magnetic field) and the normal to the plane.

For screw dislocations the Burgers vector $\vec{b}$ is parallel to the dislocation line whence it is parallel to the x_3 axis. The scattering matrix element calculated from (2) is (see [1])

$$W_k = i(6\mu_B B_1 b/MV) \sin 2\vartheta[k_1/(k_1^2+k_2^2)]$$
$$\times[\sin(k_3L/2)/k_3][1-J_0(R\sqrt{k_1^2+k_2^2})], \qquad (5)$$

where k_i are the components of the wave vector $\vec{k}$ in the coordinate system (x_1, x_2, x_3) and $J_n(x)$ denotes the Bessel function. The range of the deformation field of a single

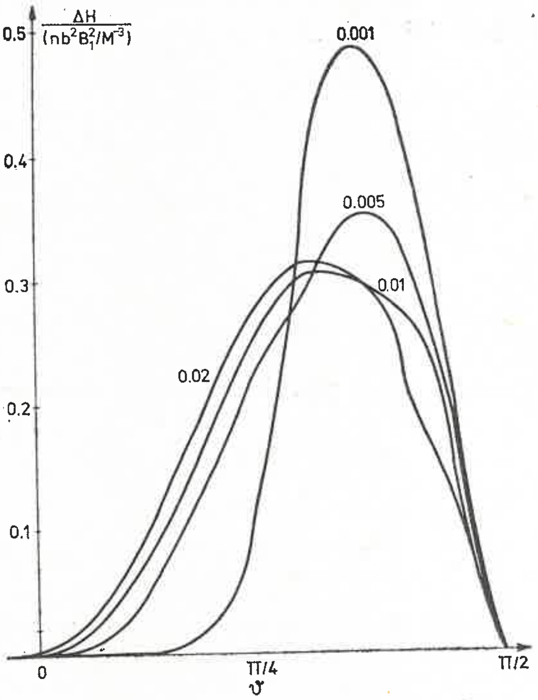

Fig. 2. The broadening of magnon modes by a system of parallel screw dislocations versus the angle ϑ between the magnetization and the dislocation line, calculated for YIG, for the frequency 9 GHz and for specified values of the magnon wave-vector q (measured in units of the inverse lattice constant)

dislocation is determined by R, for not too low dislocation density R is correlated with the dislocation density, $n = 1/R^2$. The contribution to W_k from the dislocation core is negligible (cf. [12]).

The broadening ΔH_q of magnons $\vec{q}$ by screw dislocation can be calculated from (3), (4) and (5) resulting in the expression

$$\Delta H_q = (3/2\pi)^2(B_1^2 b^2/M^3)n\omega \sin\vartheta\cos^2\vartheta\int_0^\pi dx[x^2u(h+Dk^2)]^{-1}$$
$$\times[1-J_0(Rx)]^2\{[x^2\sin^2\vartheta \mp (q\cos\vartheta+ku)^2]^{1/2}\Theta(x^2\sin^2\vartheta$$

$$-(q\cos\vartheta+ku)^2)+[x^2\sin^2\vartheta-(q\cos\vartheta-ku)^2]^{1/2}\Theta(x^2\sin^2\vartheta$$
$$-(q\cos\vartheta-ku)^2)\}. \qquad (6)$$

The domain of integration in (6) is restricted by the condition $(h+Dk^2)(h+Dk^2+1) > \omega^2$. The following notation was used in (6):

$$k = (x^2+q^2)^{1/2},$$
$$u = [h+Dk^2+1-\omega^2/(h+Dk^2)]^{1/2},$$
$$h = (\omega^2+\tfrac{1}{4}\sin^4\vartheta)^{1/2}-\tfrac{1}{2}\sin^2\vartheta-Dq^2,$$
$$h = H/4\pi M, \qquad \omega = \varepsilon_q/8\pi\mu_B M, \qquad D = D_0/(8\pi\mu_B Ma^2). \qquad (7)$$

a is the lattice constant and $\Theta(x)$ denotes the step function.

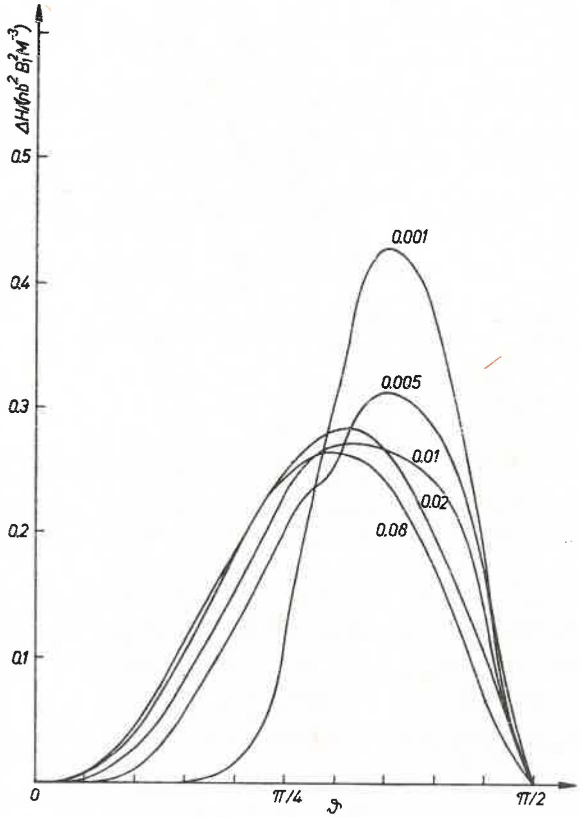

Fig. 3. The broadening of magnon modes by screw dislocations at 35 GHz

Numerical results were obtained from (6) for the case of films of yttrium iron garnet. The following values of material parameters for YIG at room temperature were taken [13]: M = 135 G, $D_0 = 8.1\times10^{-27}$ erg cm^2. Computations were done for fixed resonance frequency and for fixed range of the deformation field R. Plots of the dislocation broad-

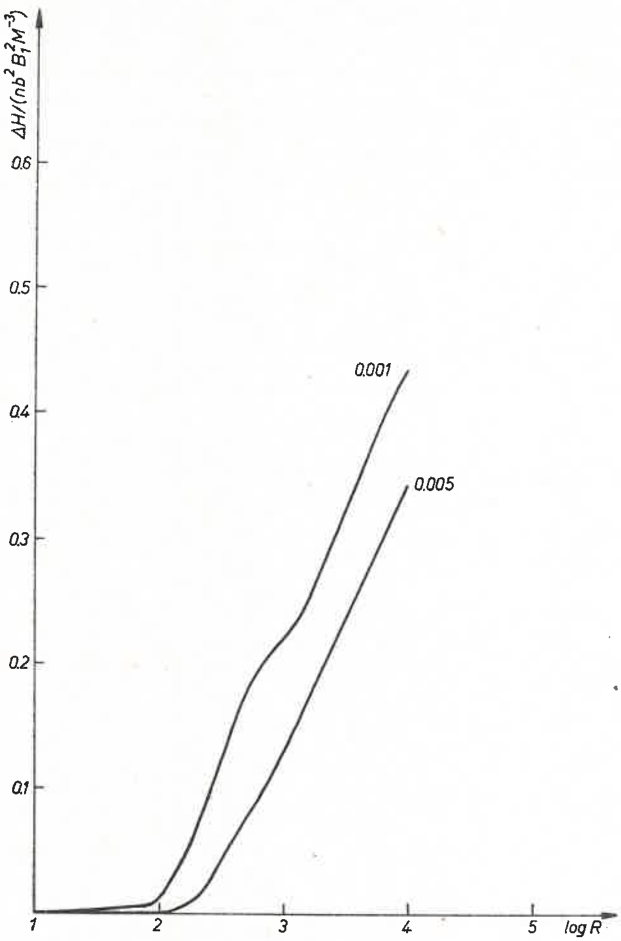

Fig. 4. The dependence of the dislocation broadening on the range R of the deformation field, for screw dislocations in YIG, for 9 GHz and for specified value of q

ening ΔH_q versus the angle ϑ are given in Figs 2 and 3, for the resonance frequency 9 GHz and 35 GHz, respectively. For convenience, ΔH_q was plotted in units $(B_1^2 b^2/M^3)\ n$. For YIG at room temperature, taking $b = 3$ Å as a typical value of the Burgers vector we have $B_1^2 b^2/M^3 = 3.1 \times 10^{-9}$ cm^2 Oe. For the range of deformation field R the typical value 1000 lattice constants was taken (see [14]). The dependence of ΔH_q on R is presented in Fig. 4.

4. *Edge dislocations*

The case of edge dislocations perpendicular to the film plane is perhaps not highly relevant to the actual SWR experiments since it does not seem easy to induce in practice such a system of dislocations. However, it is worthwhile to quote briefly some results as an example of completely different behaviour of anisotropy of ΔH_q as compared with the case of screw dislocations.

The formula for broadening due to edge dislocations is

$$\Delta H_q^e = [2\pi(1-\nu)]^{-2}(B_1^2 b^2/M^3)n(\omega/\sin\vartheta)\int_0^\pi dx[x^2u(h+Dk^2)]^{-1}$$
$$\times\{(q\cos\vartheta+ku)^2 f_1^{-1/2}[(1-2\nu+3\nu\sin^2\vartheta-3f_1x^{-2})(1-J_0(Rx))$$
$$+(6f_1x^{-2}-\tfrac{3}{2}\sin^2\vartheta)J_2(Rx)]^2\Theta(f_1)$$
$$+(q\cos\vartheta-ku)^2 f_2^{-1/2}[(1-2\nu+3\nu\sin^2\vartheta-3f_2x^{-2})(1-J_0(Rx))$$
$$+(6f_2x^{-2}-\tfrac{3}{2}\sin^2\vartheta)J_2(Rx)]^2\Theta(f_2)\}, \quad (8)$$

where ν is the Poisson ratio ($\nu = 0.29$ for YIG),

$$f_1, f_2 = x^2\sin^2\vartheta-(q\cos\vartheta\pm ku)^2, \quad (9)$$

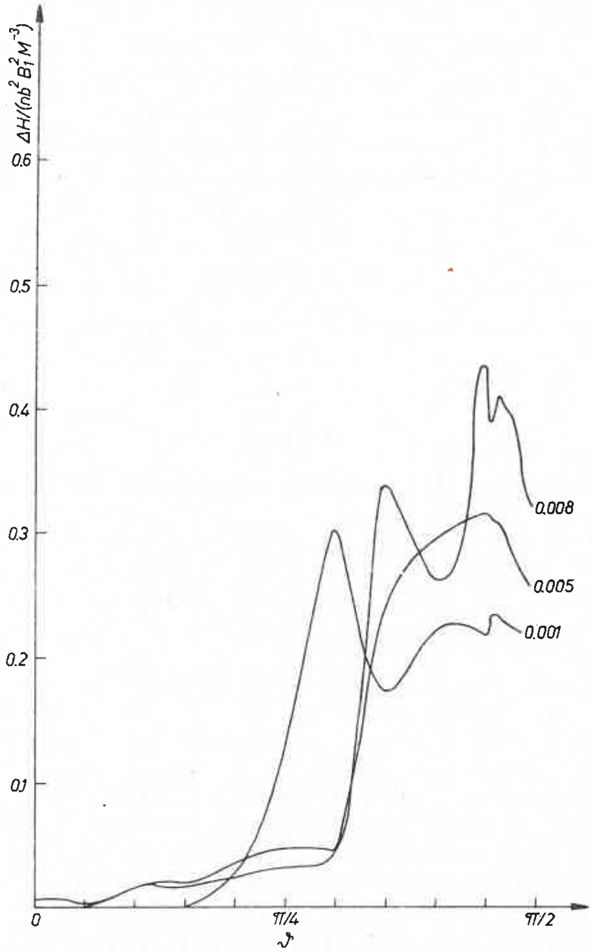

Fig. 5. The broadening of magnon modes by edge dislocations for YIG, at 9 GHz and for specified values of q

and the remaining notation is defined by (7). The Burgers vector of the edge dislocations was taken along the x_2 axis for the sake of definiteness, see Fig. 1.

Numerical results for the frequency 9 GHz and for several values of the magnon wave vector are presented in Fig. 5. The range of the deformation field R was taken equal to 1000 lattice constants, as in the previous Section.

5. *Conclusions*

In the spin wave resonance experiments in ferromagnetic thin films magnon modes with wave vectors perpendicular to the plane of the film are excited. We have calculated damping of these magnon modes by dislocations perpendicular to the plane of the film. For low values of q, say $q \sim 10^{-3}\,a^{-1}$ (corresponding to the first few modes $q = n\pi/L$, $n = 1, 3, \dots$ of the spin wave resonance in YIG films of a typical thickness $L \sim 1$ μm, see e. g. [15]) damping of magnon modes by dislocations perpendicular to the plane of the film is, at the same dislocation density, roughly by one order of magnitude weaker than for the previously considered [11] case of dislocations parallel to the plane of the film. This feature is a result of conservation of the components parallel to the dislocation line of wave vector of an incoming magnon and a magnon scattered on the dislocation (see [1]), and properties of the density of states in the degenerate magnon spectrum.

The anisotropy of ΔH_q with respect to the angle ϑ between the dislocation line and the magnetization is similar for screw dislocations both perpendicular and parallel to the plane of the film. For edge dislocations the anisotropy is different in both cases, presumably due to a dependence of ΔH_q on the direction of the Burgers vector.

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