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FERROMAGNETIC RELAXATION IN POROUS POLYCRYSTALLINE FERRITES

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Résumé. — On a mesuré la largeur de raie effective \( W \) d'échantillon de YIG polycristallin de porosité comprise entre 0.006 et 0.04. Les mesures ont été effectuées à la fréquence de 9 GHz pour des champs appliqués \( H_e \) compris entre 1.5 et 8 kOe. Les valeurs de \( W \) en dehors du domaine d'existence des ondes de spin sont plus élevées que le prévoit la théorie. Une modification de la théorie est proposée pour tenir compte de la perturbation des ondes de spin elles-mêmes par la porosité. L'accord entre la théorie et l'expérience est bon.

Abstract. — The effective linewidth \( W \) has been measured in polycrystalline YIG with porosities between 0.006 and 0.04, at a frequency of 9 GHz and for external magnetic fields \( H_e \) between 1.5 kOe and 8 kOe. The values of \( W \) outside the spinwave manifold are much larger than predicted by existing spin wave theories. A new treatment is proposed, in which secondary scattering of the spin waves is taken into account, by considering the spin waves to be broadened over a field range of \( 4 \pi M \). Fair agreement is obtained between theory and experiment.

I. Introduction. — The measurement of the effective linewidth \( W \), as described by Vrehen [1], allows the study of ferromagnetic relaxation both inside and outside the spin wave (SW) manifold. Experimental data (see section II) on porous ferrites show that porosity induced relaxation exists over a wide range of fields above and below the manifold. This field range is of the order of \( 4 \pi M \) (\( M \) saturation magnetization). The original SW theory by Sparks et al. [2] predicts relaxation only within the manifold. According to a modified theory by Motizuki et al. [3] losses can extend over a field range of the order of \( 0.4 \pi M \) on both sides of the manifold (\( p \) is the porosity), as a result of secondary scattering, i.e., the perturbation of the manifold itself by the porosity. In section III we explain why the effects of secondary scattering are more serious than assumed by Motizuki et al. [3], and we propose a modification of the theory which describes our experiments fairly well.

II. Experimental results. — We measured

\[
W = 2M \text{Im}(1/\chi_{\perp})
\]

at 9 GHz as a function of the applied magnetic field \( H_e \) and at room temperature. In figure 1 results are presented for polycrystalline YIG with \( p = 0.006, 0.015 \) and 0.04. For \( H_e > 5 \) kOe, \( W \) has a constant intrinsic value of 3 Oe. For \( 2.4 \) kOe \(< H_e < 5 \) kOe one observes additional relaxation, a small part of which results from anisotropy broadening and the remainder from porosity broadening. The contribution from anisotropy broadening can be calculated on the basis of recent work by Schloëmnn [4], Patton [5] and the present authors [6, 7]; it explains in particular the peak near 3 100 Oe in the curve for \( p = 0.006 \). The porosity induced part of \( W \) extends from 2.4 kOe up to nearly 5 kOe for all values of \( p \), and it is proportional to \( p \) for all values of \( H_e \). Note that the SW manifold extends from 3 kOe up to 3.8 kOe.

III. Theoretical considerations and discussion. — III.1 The spin wave model. — We consider the model of a spherical cavity at the center of a spherical sample, and we assume \( M \) and \( H_e \) to be parallel to the z-axis. \( H_y \) is the internal field that would be present without the pore. Sparks et al. [2] obtained the following expression for \( W \) in this model:

\[
W = \frac{1}{\gamma T} = \int_0^1 B^2(\theta) \delta(\omega - \omega(\theta)) \, d \cos \theta \tag{1}
\]

where

\[
B^2(\theta) = p\gamma(\pi/2) (4 \pi M)^2 (3 \cos^2 \theta - 1)^2
\]

and

\[
\omega(\theta) = \gamma \left[ H_y (H_y + 4 \pi M \sin^2 \theta) \right]^{1/2}.
\]

In the expression (1) the factor \( B^2(\theta) \) measures the strength of the coupling of the uniform precession (UP) to spin waves that propagate under an angle \( \theta \) with the z-axis. The delta function measures the density of states of the spin waves. In the limit \( H_y > 4 \pi M \) the integral of \( W \) over \( H_y \), \( N_{SW} \), equals \( p(2 \pi/5) (4 \pi M)^2 \), in good agreement with our experimental result for YIG. However, the expression (1) does not predict any relaxation outside the SW manifold. To improve the theory one must consider secondary scattering.

III.2. Secondary scattering: the density of states. — The perturbation by the pore mixes the
spin waves and affects both the density of states of the nonuniform modes and the strength of their coupling to the UP. Motizuki, Sparks and Seiden (MSS) [3] replaced the delta function in (1) by a normalized distribution function

\[ \rho_{1}(\omega, \theta, H_{\parallel}) = \frac{1}{\gamma} w_{1}(H_{\parallel}, H_{\perp}(\theta)) \]

where

\[ H_{\perp}(\theta) = -b + \left\{ \frac{\omega}{\gamma} \right\}^{2} + b^{2} \]

and

\[ b = 2 \pi M \sin^{2} \theta. \]

The function \( w_{1}(H_{\parallel}, H_{\parallel}) \) describes the distribution of the z-component of the static internal field \( H_{\parallel}(r) \) in the sample. This function has been considered by Schömann [8] and Pointon et al. [9]. It is presented in figure 2 for \( p = 0.10 \). Although the function \( w_{1} \)

is non-zero over a field range \( 4 \pi M \) around the unperturbed field value, corresponding to those parts of the sample that are not too close to the pore. The curve for \( W \) calculated according to the MSS theory for YIG with \( p = 0.04 \) is presented in figure 3. At the edges of the SW manifold \( W \) falls off to zero over a field range of the order of \( 4 \pi M \). The MSS theory allows one to take into account a possible non-sphericity of the pores by a modification in \( B^{2}(\theta) \) which contains an adjustable parameter \( c \). Sage [10] has shown that \( c \) is restricted to the values \( -1 < c < 2 \). The curve of figure 3 has been calculated with \( c = 2 \). The modification introduced into the theory by MSS reflects the change in the density of states, but it overlooks the change in the coupling due to the secondary scattering.

III. 3 SECONDARY SCATTERING: THE COUPLING. — Close to the pore the wave functions of the nonuniform modes will be strongly perturbed. Since the coupling of these modes to the UP takes place through the demagnetizing fields which are concentrated around the pore, it will be modified considerably. Outside the SW manifold the nonuniform modes will be «local resonances», which may be strongly coupled to the UP and thus lead to large values of \( W \), even though the density of states is small. It would be very complicated to calculate how the factor \( B^{2}(\theta) \) should be modified. However, for anisotropy broadening [6, 7] we found that all effects of secondary scattering could be described fairly well by replacing the delta function in (1) by an effective distribution function, proportional to the effective linewidth \( W_{\text{IB}} \) as calculated in the inhomogeneous broadening (IB) model. In that model [8] one has

\[ \chi_{+} = 4 \pi^{2} M w_{1}(H_{\parallel}, \omega/\gamma). \]

We computed \( \chi_{+} \) with the Kramers-Kronig relations and obtained for \( W_{\text{IB}} \) in the limit of very small \( p \):

\[ W_{\text{IB}}(H_{\parallel}, \omega/\gamma) = \frac{8 \pi^{2} M \sqrt{3}}{27} (2 - \beta) \sqrt{1 + \beta} \]

where \( \beta = 3(H_{\parallel} - \omega/\gamma)/4 \pi M \). The integral \( N_{\text{IB}} \) of \( W_{\text{IB}} \) over \( H_{\parallel} \) is only 4/9 as large as \( N_{\text{GW}} \), a result of the fact that dynamic demagnetizing fields are neglected in the IB model. A similar situation was met in nuclear magnetic resonance (see e.g. Abragam [11]). The function \( w_{2}(H_{\parallel}, \omega/\gamma) \equiv W_{\text{IB}}(H_{\parallel}, \omega/\gamma)/N_{\text{IB}} \) is shown in figure 2. It gives much weight to the regions directly around the pore, where the field deviations are large, as required by our arguments about the coupling. We define the distribution function

\[ \rho_{2}(\omega, \theta, H_{\parallel}) = \frac{1}{\gamma} \frac{\omega/\gamma}{\sqrt{\omega/\gamma}^{2} + b^{2}} w_{2}(H_{\parallel}, H_{\perp}(\theta)) \]

which is normalized with respect to \( \omega \). The curve for \( W \) calculated with the expression (1) in which \( \delta(\omega - \omega(\theta)) \) is replaced by \( \rho_{2}(\omega, \theta, H_{\parallel}) \) is shown in figure 3, together with the experimental results (YIG, \( p = 0.04 \)) and the MSS result. Our theory describes very well the magnitude of \( W \) inside and above the manifold (i.e. for 2.4 kOe \(< H_{\parallel} < 3.8 \text{ kOe} \)). Below the manifold (3.8 kOe \(< H_{\parallel} < 5 \text{ kOe} \)) the range over which the losses exist is calculated correctly, but the experimental values are a factor of two smaller than the calculated ones.

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