SPINWAVE LINEWIDTHS IN POLYCRYSTALLINE YIG

L. M. Silber and C. E. Patton

Abstract - Values of spinwave linewidths derived from measured instability fields for parallel, perpendicular, and oblique pumping butterfly curves in polycrystalline yttrium iron garnet are compared to the theory of Sawado for spinwave scattering by nonmagnetic pores. Reasonable agreement is obtained for a spinwave linewidth of the form $\Delta H_k = A + B\Delta H_k(p)$, where A and B are parameters which depend on both the pumping angle and the sample microstructure, and $\Delta H_k(p)$ is the normalized, wavevector dependent pore scattering linewidth of Sawado. A model based on grain boundary scattering is not consistent with the data.

INTRODUCTION

There has been considerable interest in the origin of the spinwave linewidth in polycrystalline ferrites for both fundamental and technical reasons. In this paper, some observations of spinwave linewidth in polycrystalline yttrium iron garnet (YIG) are presented and discussed in relation to recent theories. These linewidths are obtained from measured instability threshold fields as a function of static field. Plots of such data, termed "butterfly curves", have the general shape shown in Fig. 1, with a minimum or knee at about 1500 - 2000 Oe at 9 GHz, depending on the pump configuration.

First consider a pumping configuration with the microwave and static fields parallel. The relationship between the critical microwave field amplitude for spinwave instability, h_c, and the spinwave linewidth, ΔH_k, is given by

$$h_c = (\omega/\omega_M)\ \Delta H_k(k,\ \theta_k)/\mathrm{Sin}^2\theta_k, \qquad (1)$$

where ω is the frequency of the excitation, ω_M is $\gamma 4\pi M_S$ with γ the magnetogyric ratio and M_S the magnetization, and ΔH_k is the spinwave linewidth of the unstable spinwave of wavenumber k propagating at an angle θ_k to the static field. This ΔH_k may be a function of both the magnitude and direction of the spinwave k-vector. The objective of the experiment is to determine values of ΔH_k from the measured values of h_c. This critical field will be determined by the values of ΔH_k and θ_k which minimize the right hand side of (1). Where all values of θ_k are allowed by the spinwave dispersion relation, the minimum will normally occur for a θ_k of 90°. Previous observers have generally assumed a θ_k of 90° at static fields below the knee of the butterfly curve and calculated values of ΔH_k as a function of k. The region above the butterfly curve minimum, corresponding to fields for which θ_k = 90° is not allowed, has not been extensively investigated.

In polycrystalline materials with small porosity and large grain size, ΔH_k may be written as a sum of a constant term and a term proportional to k. Since the group velocity of a spinwave with θ_k = 90° is also proportional to k, this observation has suggested a "transit time" or mean-free-path model; that is, the generated spinwave at $\omega_k = \omega/2$ travels a distance ℓ at a group velocity v_g before being destroyed. This gives the spinwave a lifetime $\tau = \ell/v_g$ and a spinwave linewidth $\Delta H_k = 1/\gamma\tau = v_g/\gamma\ell = 2Dk/\ell$, where D is the exchange constant. The question of interest is then the physical origin of the mean-free-path ℓ. Vrehen et al [1] have suggested that ℓ should be given by the grain size. This idea was supported by the observation of an inverse grain size dependence of the extrapolated k = 0 spinwave linewidth in fine grain samples [1,2], but the slopes of the experimental curves of ΔH_k vs k were far smaller than the theoretical curves.

Scotter [3] suggested that the mean-free-path was limited by scattering from nonmagnetic pores rather than grain boundaries, and developed a simple model in which the scattering cross-section of a pore is given just by its geometric size. This approach gave somewhat better agreement with experiment. The pore scattering model was developed further by Sawado [4], who calculated the scattering cross-section of a spherical nonmagnetic pore in a magnetic medium as a function of the wavenumber and direction of the incident spinwave. From this, one obtains the mean-free-path and the spinwave linewidth. Sawado's expression for the scattering cross-section of a pore for an incident spinwave at k and θ_k is given by

$$\sigma(\theta_k) = (4/9)(\omega_M\beta/4\pi\gamma D)^2 I(\theta_k), \qquad (2)$$

where $I(\theta_k)$ is an integral which sums over all the angles into which the spinwave may be scattered and β is the pore volume. Since all the spinwaves which are candidates for instability have a frequency $\omega_k = \omega/2$, for any fixed static field k and θ_k are related by the dispersion relation. Therefore, σ may be written as a function of the one variable θ_k as indicated in (2). The mean-free-path for a spinwave at k and θ_k becomes $\ell = \beta/[p\,\sigma(\theta_k)]$, where p is the porosity of the sample. The linewidth is then

$$\Delta H_k = p v_g(\theta_k)\,\sigma(\theta_k)/\gamma\beta. \qquad (3)$$

The object of this paper is to show that the Sawado model, with certain modifications, gives good agreement with the present data over the entire range of static fields for first-order instability processes and different pumping configurations.

RESULTS

Measurements of instability fields were made on three samples of polycrystalline YIG at 8.9 GHz using standard techniques. Data were obtained for parallel pumping on three samples of 30, 20, and 5μ grain size. The 30μ and 5μ grain size samples were also studied under perpendicular pumping. The 30μ grain size sample was examined under oblique pumping at 45° as well. From the parallel pump data, values of ΔH_k were calculated from the measured h_c values below the minimum of the butterfly curve, assuming θ_k = 90°. It was found that the spinwave linewidth could be expressed in the form $\Delta H_k = A + Ck$. Characteristics of the three samples and values for the A and C parameters, as well as the derived mean-free-path ℓ, are given in Table I. Typical parameters for single crystal YIG are also given for comparison.

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TABLE I

SAMPLE	POROSITY (%)	GRAIN SIZE (μ)	A (Oe)	C (10^{-6}Oe-cm)	ℓ (μ)
S.C.			0.14	1	
CF30	0.25	30	0.9	2.7	45
G113	1	20	2.2	3.4	40
p1.9	1.9	5	2.6	4.5	30

The most striking difference between the polycrystals and the single crystal is in the size of the A parameter. In addition, the C parameter which reflects the k-dependence of ΔH_k increases as the porosity increases and the grain size decreases. This is consistent with the idea of a constant mean-free-path, but gives no clue as to whether ℓ is limited by grain boundary or pore scattering. However, the fact that the fitted ℓ-values decrease by only 33% as the grain size changes by a factor of six indicates that the mean-free-path is not determined by the grain size. Furthermore, the constant mean-free-path model does not fit the data at fields above the butterfly curve minimum. Therefore, the scattering of spinwaves at grain boundaries cannot be the only mechanism which limits the spinwave lifetime in polycrystals.

The Sawado model permits one to calculate the contribution of pore scattering to the spinwave linewidth as a function of spinwave direction and, therefore, the critical field h_c as well. Since agreement with the data could not be obtained from a grain boundary scattering model, an attempt was made to fit the data with a pore scattering approach. It was assumed that the spinwave linewidth has the form

$$\Delta H_k = A + B\Delta H_k(p), \qquad (4)$$

where $\Delta H_k(p)$ is the normalized pore scattering linewidth from (2) and (3). A porosity of 1% and a pore radius of 0.014μ were used for the numerical calculations. The butterfly curve fits were quite good, as will be discussed shortly. The fits showed that at all static fields such that $\theta_k = 90°$ is allowed, $\Delta H_k(p)$ is a minimum at this angle. Sawado has shown that σ may be minimum at some θ_k less that 90°. This suggests the possibility of a minimum h_c at some θ_k less that 90° as well. The present results show that this is not the case. The threshold for 90° spinwaves is still the minimum threshold, because of the sharp minimum in v_g at this angle. Values of A and B for parallel pumping were determined by setting the theoretical h_c equal to the measured value at two static fields below the butterfly curve minimum, where $\theta_k = 90°$ is allowed. The values of A and B thus obtained were assumed to be valid at fields above the butterfly curve knee so that theoretical h_c values could also be obtained in this field regime. The dependence of $\Delta H_k(p)$ is such that the maximum allowed θ_k does not give the minimum h_c value.

In situations for which the angle ψ between the microwave magnetic field and the static field is not zero, the relation between h_c and ΔH_k is given by [5]

$$h_c = (\omega/\omega_M)[\Delta H_k(k,\theta_k)/W(H_{dc}, \theta_k, \psi)]_{min}. \qquad (5)$$

where W is a pumping factor which accounts for the coupling between the microwave field and the spinwaves, and H_{dc} is the static field. As before, the θ_k which minimizes the right hand side yields the observed h_c. Experimental butterfly curves of h_c vs H_{dc} were obtained for perpendicular pumping ($\psi = 90°$) and oblique pumping ($\psi = 45°$), and compared with fitted theoretical curves. The fits were made using the same form for ΔH_k as in (4). Initially, the pore scattering contribution to the linewidth was calculated at the angle which maximized W, and values of A and B were determined by comparison with the experimental results at static fields such that all θ_k values were allowed. The θ_k was then varied around this starting angle until the minimum h_c was obtained. Then, values of ΔH_k and h_c were calculated for the entire range of static fields used in the experiments.

In Table II values of the coefficients A and B which were used in calculating the spinwave linewidths for the various samples and pumping configurations are given. The values of A are comparable to those in Table I. It seems that a large part of the spinwave linewidth in polycrystals is not due to pore or grain boundary scattering but to some other mechanism which is microstructure related.

TABLE II

SAMPLE	PUMP ANGLE	A(Oe)	B
CF30	0	0.56	3.86
	45	0.96	3.47
	90	0.86	2.76
G113	0	1.91	4.57
P1.9	0	2.35	5.69
	90	2.28	4.61

The pore scattering contribution in (4) was written as $B\Delta H_k(p)$, where $\Delta H_k(p)$ was calculated from the Sawado theory using a fixed porosity of 1 % and a fixed pore radius of 0.014μ. One would therefore expect the values of B to be proportional to the sample porosity. The values in Table II do increase with porosity, but a small variation in pore size would completely mask the porosity dependence.

The Sawado model predicts that the functional dependence of the pore scattering on wavenumber k and angle θ_k is the same for all pore sizes and porosities. This model, therefore, will not account for the inverse k dependence of ΔH_k observed in high porosity samples, 6.5 % and higher [6]. In these samples, however, the grain size was 2μ or less and grain boundary scattering may be the dominant contribution to the linewidth.

Figures 1, 2, and 3 present experimental butterfly curve data (symbols) and theoretical fitted butterfly curves (lines) obtained as described above. Figure 1 contains results for parallel pumping for all three polycrystalline samples. The agreement is good. The experimental h_c values at the butterfly curve minimum are somewhat higher that the theoretical fits. At static fields above the minimum, the fits show the same rapid increase in h_c which is observed experimentally. At the highest static fields, the data are more uncertain because the onset of absorption is not sharp. Figure 2 shows the results for perpendicular pumping. Again, the theoretical fits reproduce well the trend of the data. Similarly, Fig. 3 shows the results for oblique pumping at 45° in the 30μ sample.

The agreement between theory and experiment could undoubtedly be improved by a more sophisticated method of determining the A and B parameters. The results presented here certainly suggest that in these samples, at least, pore scattering contributes a large part to

the spinwave linewidth, and that a modified Sawado theory accounts reasonably well for the effects of porisity. This theory is termed modified because the approach in [4] is somewhat different than used above. First, Sawado suggests that the effective spinwave linewidth should be obtained by integrating (3) over all allowed values of θ_k. This is believed to be incorrect. The critical field will be determined by the spinwave which minimizes h_c. Indeed, an integration over all spinwave angles, and hence over all allowed values of k, yields a wavevector-independent linewidth. This is not supported by the experimental observations. Second, since the scattered field due to a pore, and hence the scattering cross-section, depends on the permeability of the medium around the pore, Sawado suggests that the effective scattering volume of the pore should be given by $\beta = 3\beta_o/(2\mu + 1)$, where β_o is the geometrical pore volume and μ is the permeability of the medium. This idea is correct in calculating the scattering cross-section, but not in the calculation of the mean-free-path. In addition, Sawado used the static permeability. Rather, the permeability of the medium for the scattered spinwave should be the microwave permeability at the spinwave frequency. This is very close to unity.

REFERENCES

[1] Q. H. F. Vrehen, H. G. Beljers, and J. G. M. DeLau, IEEE Trans. Magnetics 5, 619 (1969).
[2] C. E. Patton, J. Appl. Phys. 41, 1637 (1970).
[3] D. G. Scotter, J. Phys D6, L93 (1972).
[4] E. Sawado, Ferrites - Proc. of the ICF3, Center for Academic Publications, Japan, 1981, pp. 818-821.
[5] C. E. Patton, J. Appl. Phys. 40, 2837 (1969).
[6] C. E. Patton, Ferrites - Proc. of the Int. Conf., Univ. of Tokyo Press, Tokyo, Japan (1971), pp. 524-526.

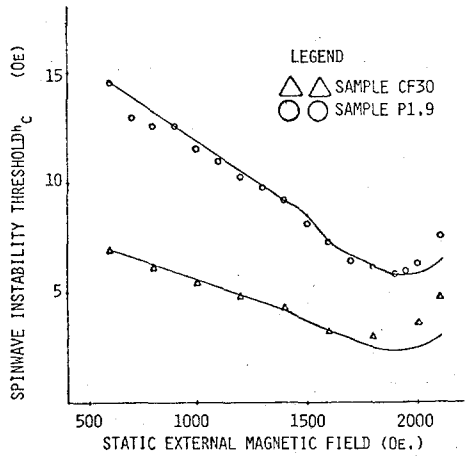

Fig. 2. Spinwave instability threshold h_c as a function of the static external field for perpendicular pumping. Data points and fitted theoretical curves are shown for two samples, CF30 and P1.9.

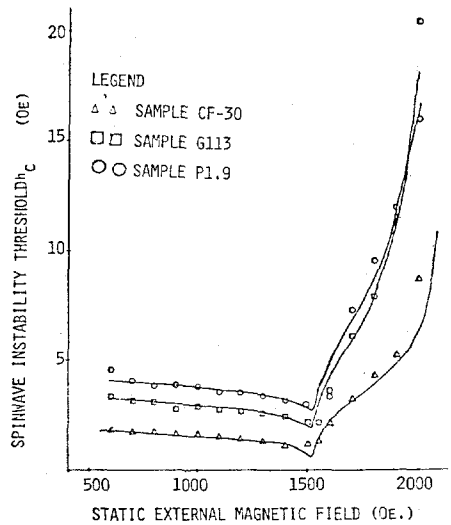

Fig. 1. Spinwave instability threshold h_c as a function of the static external field for parallel pumping. Data points and fitted theoretical curves are shown for three samples, CF30, G113, and P1.9.

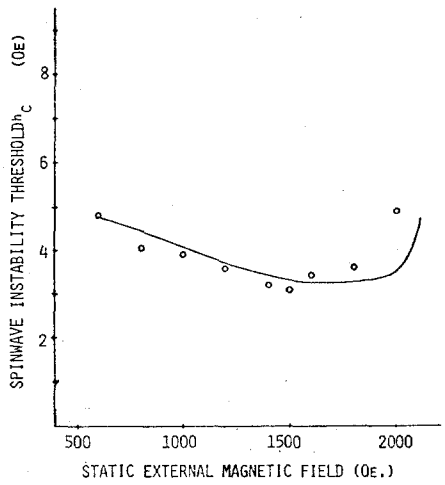

Fig. 3. Spinwave instability threshold h_c as a function of the static external field for oblique pumping at 45° in CF30.