Light-scattering observation of anomalous parametric spin-wave character in subsidiary absorption

W. D. Wilber
U. S. Army Electronics Technology and Devices Laboratory, Fort Monmouth, New Jersey 07703-5000
J. G. Booth
Department of Physics, Salford University, Salford, M5 4WT, England
C. E. Patton, G. Srinivasan, and R. W. Cross
Colorado State University, Fort Collins, Colorado 80521

The technique of Brillouin light scattering has been used for the characterization, in terms of wave number and direction of propagation, of parametric spin waves associated with subsidiary absorption in thin films of yttrium iron garnet. Measurements at 7.99, 8.47, and 9.90 GHz have revealed a spin-wave character consistent with theory, with two notable exceptions. First, the data show no evidence for a predicted flip in the azimuthal propagation angle. Second, the measured magnon wave numbers at high fields are inconsistent with the theoretical values. The wave number and polar angle results imply that the change to low-k spin waves is not a discontinuous transition as indicated by the model.

INTRODUCTION

In some early ferromagnetic resonance (FMR) measurements,[1,2] it was noticed that for microwave powers above a certain level, a broad absorption peak would appear at fields well below FMR. The mechanism responsible for this subsidiary absorption peak was described by Suhl[3] as the annihilation of a uniform mode magnon and the parametric excitation of two magnons with wave vectors $\mathbf{k}$ and $-\mathbf{k}$ and frequency $\omega_p/2$ (half the pump frequency). The Suhl theory was able to explain the available microwave absorption data, but could not be verified in terms of the specific spin waves which should be parametrically excited. Fortunately, the development of high-contrast Fabry–Perot interferometry[4] has made Brillouin light scattering (BLS) a useful technique for studying the character of magnetic excitations.[5] BLS measurements of subsidiary absorption reported here show general agreement with theory, except for two particular aspects. In order to understand these results, brief summaries of the theoretical parametric spin-wave character and of BLS are presented below.

SUBSIDIARY ABSORPTION AND BLS

From subsidiary absorption theory, a general magnon state will be parametrically excited by a microwave field greater than the threshold field[4]

$$h_t = \omega_p \Delta H_k / [\gamma 4\pi M_s \sin\theta_k \cos\theta_k F(\theta_k, \phi_k, \omega_p)]. \quad (1)$$

In Eq. (1), γ is the gyromagnetic ratio (2.8 MHz/Oe), $4\pi M_s$ is the saturation magnetization, and ΔH_k is the spin-wave linewidth. The lengthy expression for the function F can be found in Ref. 4, but is not necessary for this discussion. Figure 1 shows that the polar angle θ_k is measured between the magnon wave vector $\mathbf{k}_m$ and the applied static field $\mathbf{H}$, while the azimuthal angle ϕ_k is measured between the x axis and the projection of $\mathbf{k}_m$ onto the x-y plane (for this particular field/sample geometry). The expression used here for the spin-wave linewidth is

$$\Delta H_k = A_0 + A_1 \sin^2 2\theta_k + B_1 L(k_m/B_2), \quad (2a)$$

where

$$L(x) = 0.72 \ln[1 + 8x^2(1 + 2x^2)/(1 + 8x^2)], \quad (2b)$$

and A_0, A_1, B_1, and B_2 are used as fitting parameters. Equation (2) has a theoretical basis[4] but is also somewhat empirical.[5] For a given static magnetic field and pump frequency, a minimum threshold field (h_{crit}) can be determined by minimizing Eq. (1) with respect to θ_k, ϕ_k, and k_m. One is restricted, however, to those magnon states available at $\omega_p/2$. The important point of this discussion is that the calculation of the minimum threshold field leads to very specific θ_k, ϕ_k, and k_m values for the parametric spin waves excited by microwave fields just above h_{crit}.

It is not possible, with conventional microwave experiments, to selectively detect specific spin waves. However, measurements of θ_k, ϕ_k, and k_m can be performed using Brillouin light scattering (BLS). In the BLS experiment, laser light interacts with the magnetic excitations and a small fraction of the scattered light is shifted in frequency by an amount equal to the spin-wave frequency. A high-contrast Fabry–Perot interferometer[6,7] is used to measure this frequency shift. To fully characterize the spin wave, the wave vector $\mathbf{k}_m$ can be determined from the scattering geometry.[8] Figure 1 shows the forward scattering geometry of this experiment, and illustrates the simple vector analysis used to

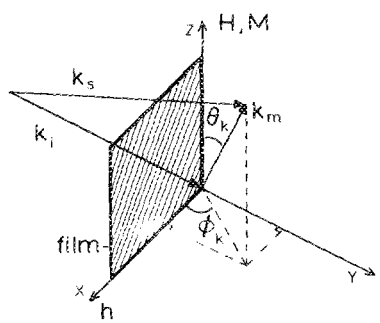

FIG. 1. Forward light-scattering geometry showing film orientation, polar angle θ_k, azimuthal angle ϕ_k, microwave field $\mathbf{h}$, static field $\mathbf{H}$, magnetization $\mathbf{M}$, and incident light, scattered light, and magnon wave vectors $\mathbf{k}_i$, $\mathbf{k}_s$, and $\mathbf{k}_m$, respectively.

 0021-8979/88/225477-03$02.40 © 1988 American Institute of Physics

Downloaded 26 Dec 2001 to 129.82.140.114. Redistribution subject to AIP license or copyright, see http://ojps.aip.org/japo/japcr.jsp

determine $\mathbf{k}_m$ from the incident- and scattered-light wave vectors ($\mathbf{k}_i$ and $\mathbf{k}_s$, respectively). BLS measurements obtained for subsidiary absorption are described in the following section.

RESULTS AND DISCUSSION

The sample used for the measurements reported here was a 9.8-μm-thick yttrium-iron-garnet film on a gadolinium gallium garnet substrate. Microwave absorption data taken at 8.47 GHz for this sample yielded the critical microwave fields shown in Fig. 2 (filled circles). The solid line in Fig. 2 indicates the fit obtained with Eqs. (1) and (2). The parameters from Eq. (2a) used for this figure, along with the results for 7.99 and 9.90 GHz, are listed in Table I. Efforts to improve the fit at low fields in Fig. 2 resulted in a high-field curve that did not diverge as rapidly as the experimental data. Although a closer fit was achieved for the 7.99 and 9.90 GHz data, only the results at 8.47 GHz are discussed here because the ϕ_k flip described below should occur in the middle of the accessible field range for this frequency.

The fit to the critical field shown in Fig. 2 yields the θ_k, ϕ_k, and k values expected for the parametric spin waves excited by microwave fields exceeding $h_{\rm crit}$. The static field dependence of the polar and azimuthal angles for 8.47 GHz is shown as the solid and broken lines, respectively, in Fig. 3, and the wave-vector magnitude is shown as the solid line in Fig. 4. Notice in Fig. 3 that for low static fields, the polar angle is roughly 35°. This is intuitively reasonable since the $\sin\theta_k \cos\phi_k$ term in the denominator of Eq. (1) would favor 45°. The function $F(\theta_k,\phi_k,\omega_p)$ has a polar angle term that shifts the preferred value from 45° to 35°. Between 900 and 1000 Oe, the polar angle jumps from 35° to almost 85°, and there is a corresponding drop in k from 2.5×10^5 to 0 $\rm cm^{-1}$. This sudden change in the spin-wave character occurs because of competition in the expression for $h_{\rm crit}$ between the θ_k terms and the k-dependent terms. At a pump frequency of 8.47 GHz and for fields above approximately 950 Oe, the critical field is lower for the zero-k, high-polar angle magnon modes than it is for the nonzero-k modes with θ_k near 35°. As the field is further increased and the spin-wave manifold moves higher in frequency, the polar angle decreases toward zero and the critical field begins to diverge for very small angles because of the term in the denominator of Eq. (1).

TABLE I. Spin-wave linewidth variables as determined by fitting theoretical critical field to microwave absorption data.

Frequency (GHz)	A_0 (Oe)	A_1 (Oe)	B_1 (Oe)	B_2 (10^6 $\rm cm^{-1}$)
7.99	0.152	0.152	0.12	1.0
8.47	0.175	0.175	0.12	1.0
9.90	0.210	0.210	0.25	0.5

Light-scattering measurements of the polar angle were made by collecting the scattered light from one narrowly defined region that corresponded to, for example, scattering from magnons with $\theta_k = 50° \pm 5°$. Spectra of scattered light intensity versus static field were measured for the full range of θ_k in 2° increments. The field value for the maximum intensity was found from these spectra, and these field values for each angle are plotted as the filled circles in Fig. 3. The overall agreement is quite good, especially at the higher fields. From about 1050 to 1450 Oe, the theoretical curve lies well within the experimental uncertainty of the light scattering data. For the fields near 1000 Oe, the data fall somewhat below the theoretical polar angle. This feature is important relative to the following wave-number data.

The magnitude of the wave vector for the parametric spin waves was measured in a manner similar to that described above for θ_k, and the results are shown by the filled circles in Fig. 4. The nonzero value for k_m, although not shown by the theoretical results of Fig. 4, is not surprising since the theory does not account for a finite sample size. The zero-k magnon modes for the thin film used here are magnetostatic modes with wave numbers on the order of $n\pi/$(film thickness), where n is an integer. Previous measurements of subsidiary absorption and parallel pumping (static and microwave fields applied parallel) have shown that wave numbers in the range of $(1.5\text{–}2.5)\times10^4$ $\rm cm^{-1}$ can

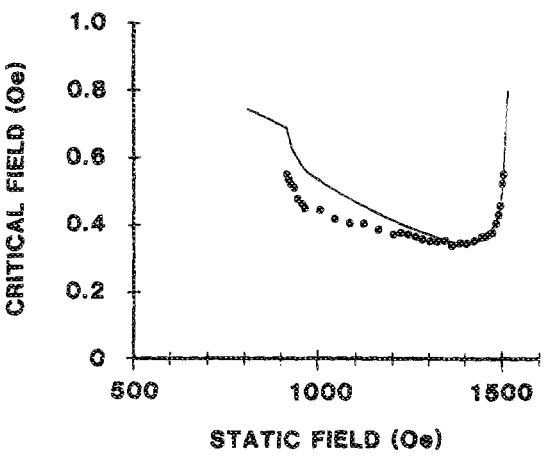

FIG. 2. Critical microwave field $h_{\rm crit}$ as a function of static field for subsidiary absorption at 8.47 GHz.

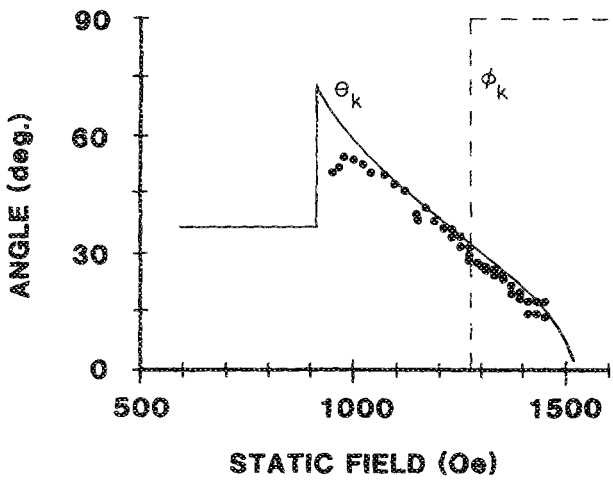

FIG. 3. Polar angle θ_k and azimuthal angle ϕ_k from theoretical fit to critical microwave field results at 8.47 GHz (shown in Fig. 2). Filled circles are experimental results obtained by light scattering.

Downloaded 26 Dec 2001 to 129.82.140.114. Redistribution subject to AIP license or copyright, see http://ojps.aip.org/japo/japcr.jsp

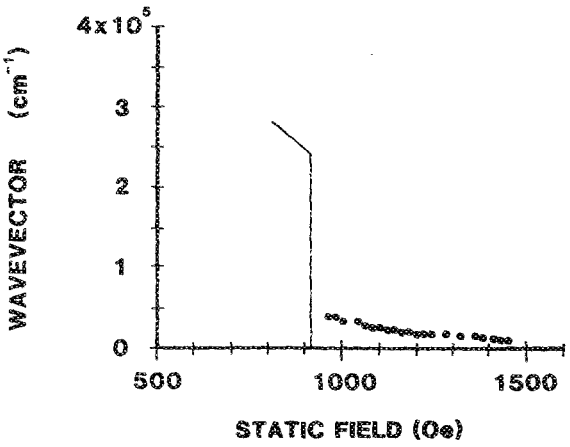

FIG. 4. Theoretical fit (solid line) and light-scattering measurements (filled circles) of wave vector as a function of field for parametric spin waves.

be accounted for by the magnetostatic mode dispersion of a 9.8-μm film.[9] This is consistent with the results shown here in Fig. 4 for fields above 1100 Oe. For fields below 1100 Oe, and particularly from 950 to 1050 Oe, the wave number is greater than 2.5×10^4 cm^{-1} and is increasing for decreasing fields. These results, together with the polar angle results of Fig. 3, indicate that the abrupt transition indicated by the theory may not actually be as discontinuous as expected. The changes in wave number and polar angle are consistent with a more gradual change as the applied magnetic field approaches the transition field. Further increases in wave number could not be measured because of optical restraints in the forward scattering geometry.

The light-scattering results presented above provide information on the azimuthal angle of the parametric spin waves, although in a less obvious manner than for the polar angle and the wave number. Figure 3 shows that the azimuthal angle ϕ_k should switch from 0° to 90° at a field of about 1270 Oe (for an 8.47-GHz pump frequency). Notice in Fig. 1 that for the geometry of this experiment, an azimuthal angle of 0° implies in-plane spin-wave propagation for all polar angles while $\phi_k = 90°$ leads to out-of-plane propagation for all polar angles except zero. This point is important because the BLS selection rules can be satisfied only for in-plane spin-wave propagation; for magnons with wave vectors perpendicular to the film plane, the BLS selection rules require that the magnitude of $\mathbf{k}_s$ must change by nearly 10% while the frequency would change by less than one part in 10^5. However, the light-scattering results of Figs. 3 and 4 clearly show that parametric excitations other than the $\phi_k = 90°$ modes exist for fields above 1270 Oe. Similar results were obtained for a pump frequency of 7.99 GHz for which the change in ϕ_k should occur at 1110 Oe. One possible explanation for this apparent discrepancy is that since the threshold fields for the two modes differ by about 0.1 Oe, parametric excitations may exist for azimuthal angles of 0° *and* 90°. Evidence for the excitation of magnons other than those corresponding to $h_{\rm crit}$ has been observed elsewhere,[9] but only for microwave fields 4–5 dB above the minimum critical field. One might expect a sudden change in the scattered-light intensity as a function of static field if spin waves with $\phi_k = 90°$ are excited above some particular field, however, no such change was observed.

CONCLUSIONS

Light-scattering measurements of parametric excitations in a YIG film have been made for subsidiary absorption and, in general, confirm the spin-wave parameters expected from the theoretical model. However, two BLS results inconsistent with the model are (1) the transition from moderate to low-k magnons may not be as discontinuous as originally thought, and (2) the anisotropy-induced change in ϕ_k was not observed.

ACKNOWLEDGMENT

The authors wish to thank Dr. J. D. Adam, Westinghouse, for kindly providing the YIG films used in this study.

[1]R. W. Damon, Rev. Mod. Phys. **25**, 239 (1953).
[2]N. Bloembergen and S. Wang, Phys. Rev. **93**, 72 (1954).
[3]H. Suhl, J. Phys. Chem. Solids **1**, 209 (1957).
[4]C. E. Patton, Phys. Status Solidi B **92**, 211 (1979); **93**, 63 (1979).
[5]Y. H. Liu and C. E. Patton, J. Appl. Phys. **53**, 5116 (1982).
[6]J. R. Sandercock, *Proceedings of the 2nd International Conference on Light Scattering in Solids*, edited by M. Balkanski (Flammarion, Paris, 1971).
[7]M. G. Cottam and D. J. Lockwood, *Light Scattering in Magnetic Solids* (Wiley, New York, 1986).
[8]W. D. Wilber, W. Wettling, P. Kabos, C. E. Patton, and W. Jantz, J. Appl. Phys. **55**, 2533 (1984).
[9]W. D. Wilber, Ph.D. thesis, Colorado State University, 1987.

Downloaded 26 Dec 2001 to 129.82.140.114. Redistribution subject to AIP license or copyright, see http://ojps.aip.org/japo/japcr.jsp