Light Scattering from Parallel-Pump Instabilities in Yttrium Iron Garnet

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Brillouin light scattering has been observed from parametrically excited magnons by parallel pumping in a 4-μm yttrium-iron-garnet film at 9.4 GHz. Scattering from the spin waves could be observed continuously from the thermal level through the nonlinear region of parametrically excited magnons. Magnons with small wave vectors propagating perpendicular to the static field are seen to have the lowest critical field as predicted theoretically. The spectra of these parametric excitations show a pronounced structure.

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In Brillouin light scattering from magnetic excitations, magnons with specific wave vectors may be selectively observed. This feature has been used to characterize directly the nonlinear behavior in yttrium iron garnet (YIG) under the influence of a strong microwave field. Inelastic light scattering from parametric spin waves has been reported by Jotikov and Kreines[1,2] for the transparent weak ferromagnet $CoCO_3$, and by Venitsky, Eremenko, and Matyushkin[3,4] for yttrium iron garnet. The former work involved transverse microwave pump fields. The latter work demonstrated the feasibility of light scattering from parallel-pumped paramagnetic magnons in YIG, but only for rather high microwave power levels which were well above the spin-wave instability threshold. In the present study, it was possible to observe magnon scattering continuously from the thermal-level excitations into the parametric magnon region, and to study the angle and wave-number characteristics of the pumped magons directly. This allows a detailed study of the parametric processes at all levels of microwave power.

The process of parallel pumping in YIG has been extensively studied, both theoretically[5-8] and experimentally by microwave techniques.[9-11] In these microwave experiments, the critical microwave field amplitude h_{crit} for the onset of spin-wave instability was determined as a function of static field H_{dc} by monitoring the reflected power from a microwave cavity as the static field was slowly scanned. The instability onset was characterized by an abrupt increase in reflected power. The resulting plots of h_{crit} vs H_{dc} are generally called butterfly curves. Reasonable theoretical fits to these curves were made based on phenomenological equations for magnon lifetime as a function of wave-vector magnitude and direction.[9-11] In all of these experiments, the details of magnon instability processes are inferred only indirectly from changes in the microwave-cavity reflection coefficient as a function of static field and microwave power. With the light scattering experiment, instabilities for specific magnon wave vectors can now be examined. This makes it possible to characterize directly the nature of the parametrically excited magnons under parallel pumping.

The experimental apparatus consists of a stabilized multipass tandem Fabry-Perot interferometer,[12] and an X-band reflection-cavity spectrometer. Details of the instrumentation and experimental procedures will be given elsewhere.[13] The 4.15-μm-thick epitaxial film of YIG on gadolinium gallium garnet was mounted in a cavity tuned to 9.4 GHz, as shown in Fig. 1(a). Figure 1(b) shows the incident and scattered wave vectors, $\vec{k}_{\text{inc}}$ and $\vec{k}_{\text{sc}}$, respectively, and the resulting magnon wave vector $\vec{k}$ in the film plane. The maximum detectable magnon wave number in this geometry was

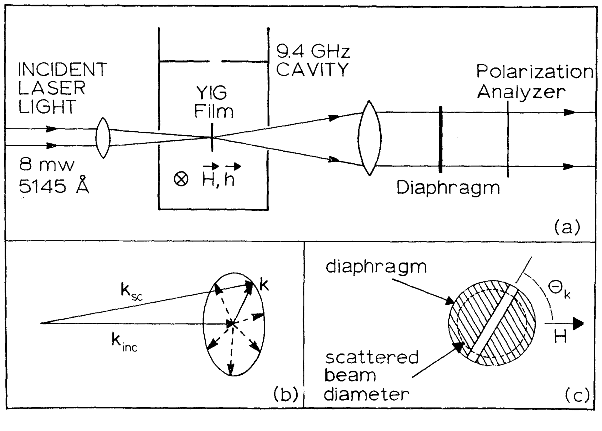

FIG. 1. Scattering geometry showing (a) the incident beam, cavity, sample, orientation, static (H_{dc}) and microwave (h) fields, scattered beam, and collection optics; (b) the incident, scattered, and magnon wave-vector geometry; and (c) the θ_k selection by means of a diaphragm in the collection optics.

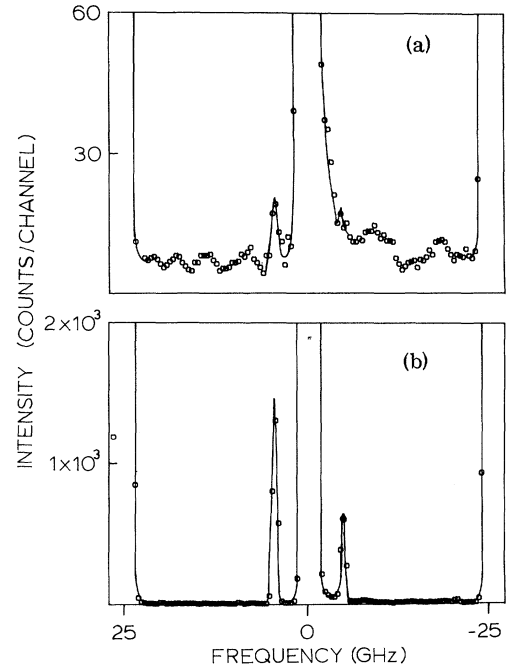

FIG. 2. Fabry-Perot spectra, intensity vs frequency, for (a) thermally exicted magnons at $k = 1.7 \times 10^4$ cm^{-1} and $\theta_k = 90°$ obtained with $H_{dc} = 1030$ Oe, and for (b) the same static field as in (a) but with an applied microwave field at 9.4 GHz with an amplitude of 0.37 Oe, 10 mOe above threshold. The static field was carefully adjusted so that the thermal and parallel-pumped magnons would be at the same frequency, 4.7 GHz.

2.9×10^4 cm^{-1}. Magnon wave vectors with specific magnitudes and angles of propagation with respect to the static field (θ_k) could be selected by placing various diaphragms behind the collecting lens, similar to Refs. 3 and 4. Figure 1(c) shows a diaphragm that allows the detection of all k vectors between 0 and 2.9×10^4 cm^{-1} propagating at a specific θ_k. Figure 2(a) shows a thermal magnon spectrum taken with no applied microwave field for $k = 1.7 \times 10^4$ cm^{-1}, $\theta_k = 90°$, and $H = 1030$ Oe. The spectrum in Fig. 2(b) was taken under the same conditions except for an applied microwave field 10 mOe above the instability onset (threshold). Scattering from the thermal magnons is two orders of magnitude less intense than scattering at the instability threshold.

A method was developed to record the magnon scattered light intensity (total intensity, both Stokes and anti-Stokes peaks) as a function of the external static field H_{dc}. Spectra taken in this manner are shown in Fig. 3 for $k = 1.7 \times 10^4$ cm^{-1} and $\theta_k = 90°$, for microwave field amplitudes from 0.38 Oe (just above threshold, bottom trace) to 0.56 Oe. At the lowest microwave field amplitude of 0.38 Oe, one relatively sharp instability peak is observed at H_b, the minimum threshold field. This corresponds to the conventional parallel-pump butterfly-curve minimum obtained by microwave techniques. As the microwave power is increased the region of instability widens, as indicated by the arrows in Fig. 3. Additionally, a pronounced structure is observed with the number of peaks increasing with microwave power.

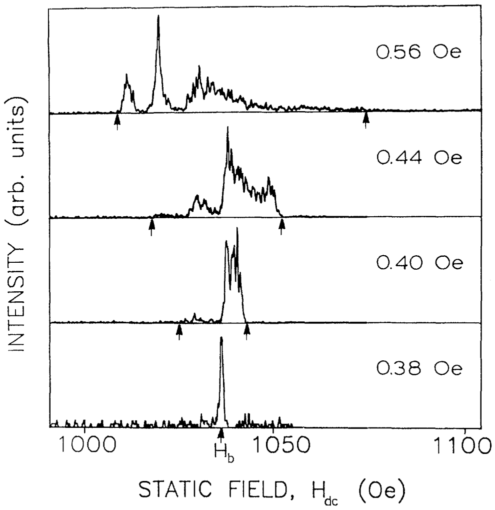

FIG. 3. Intensity of the scattered light from magnons with $k = 1.7 \times 10^4$ cm^{-1} and $\theta_k = 90°$ as a function of the static field H_{dc}, with the 9.4-GHz microwave field amplitude h as a parameter. The arrows designate the breaks in scattered intensity above the background which characterize the onset of spin-wave instability.

With the spectra ordered by increasing microwave field this way, a light-scattering butterfly curve can be obtained by following the static field limits for the region of instability from H_b up through higher microwave fields. This butterfly curve is then analogous to the one obtained from microwave measurements described above except that this curve is for the instability of magnons with *one specific wave vector*. Figure 4 shows the light-scattering butterfly curve for the field range $850 < H_{dc} < 1150$ Oe, obtained from data similar to Fig. 3. This result shows that the light scattering from parametrically excited magnons with $\theta = 90°$ and magnitudes $k = 1.1 \times 10^4$ cm^{-1} and $k \approx 0$ is observed only in a small range $H_b \pm 50$ Oe. The corresponding microwave butterfly curve is indicated in Fig. 4 by the dotted line.

The critical parallel-pump microwave field in

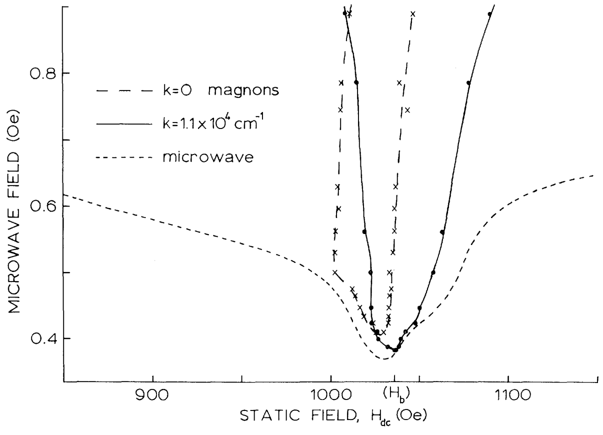

FIG. 4. Light-scattering butterfly curve of threshold microwave field amplitude $h_c^{\min}$ vs static field for magnons with $k = 1.1 \times 10^4$ cm^{-1}, $\theta_k = 90°$, and for $k \approx 0$. The microwave butterfly curve is shown by the dotted line.

an isotropic material is given by[6]

$$h_c = (\omega/\omega_m)(\Delta H_k/\sin^2\theta_k), \qquad (1)$$

where ω is the microwave pump frequency, ω_m is the saturation magnetization $4\pi M_s$ multiplied by the gyromagnetic ratio γ, and ΔH_k is the spin-wave linewidth. For a given static field and pump frequency, the observed critical field or threshold $h_c^{\min}$ corresponds to that spin wave at frequency $\omega_k = \omega/2$ with the lowest h_c from Eq. (1). This theory predicts that at or slightly below H_b, magnons of small wave number, $0 \leqslant k \leqslant 10^4$ cm^{-1}, and $\theta_k = 90°$ will have the lowest microwave threshold amplitude $h_c^{\min}$ and, hence, may be excited well above their thermal levels when the microwave field exceeds this threshold. At lower static fields, magnons with larger k and $\theta_k = 90°$ will be excited. At higher fields, $k \simeq 0$ and $\theta_k < 90°$ magnons will be generated because of the dispersion limitations on the available spin-wave states.

The present experimental findings are in partial agreement with these results. The $k \approx 0$ magnons in Fig. 4 are found in a narrow field interval of less than 40 Oe around H_b even at the highest powers. The 1.1×10^4 cm^{-1} magnons are observed in a field interval more than twice as wide. No parametric magnons with $0 \leqslant k \leqslant 2.9 \times 10^4$ cm^{-1} were observed below 990 Oe. The steep low-field character is due to the dispersion constraints; at low fields only high-k magnons ($k > 10^5$ cm^{-1}) may be generated at $\omega/2$. These magnons are not observable in the present forward-scattering arrangement. The $k = 1.1 \times 10^4$ cm^{-1} magnons are observable at higher static fields than are the $k \approx 0$ magnons. This behavior is contrary to what is expected theoretically. Parametrically excited magnons (4 dB above minimum threshold) were observed to propagate mainly perpendicular to H_{dc}. A measurement of intensities versus θ_k gave a bell-shaped distribution centered at 90° with intensity decreasing to zero at 90° ± 35°. Magnons with $\theta_k = 75°$ were observed at higher values of H_{dc} than for magnons with $\theta_k = 90°$, as expected from the preceding discussion.

The distinct structure seen in the spectra of Fig. 3 at the higher powers presents an interesting feature which is not fully understood at present. It is possible that the structure corresponds to the parametric excitation of dipole-exchange magnon modes proposed by Wolfram and DeWames.[14] This feature is being investigated further.

In conclusion, the technique of inelastic light scattering from parametrically excited magnons, in contrast to microwave measurements, permits the observation of instability processes for specific, selectable magnons. The Letter presents the first results on excitations observed continuously from the level of thermal magnon occupation numbers into the nonlinear region of parametrically excited magnons. Fundamental theoretical predictions have been confirmed with some interesting exceptions. Future work will focus on measurements of excited magnons with larger wave number and on a detailed analysis of the pronounced structure in the spectra, as well as microwave pump configurations other than parallel.

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[1] V. G. Jotikov and N. M. Kreines, Zh. Eksp. Teor. Fiz. 77, 2486 (1979) [Sov. Phys. JETP 50, 1202 (1979)].

[2] V. G. Jotikov and N. M. Kreines, J. Magn. Magn. Mater. 15, 809 (1980).

[3] V. N. Venitsky, V. V. Eremenko, and E. V. Matyushkin, Pis'ma Zh. Eksp. Teor. Fiz. 27, 239 (1978) [JETP Lett. 27, 222 (1978)].

[4] V. N. Venitsky, V. V. Eremenko, and E. V. Matyushkin, Zh. Eksp. Teor. Fiz. 77, 1965 (1979) [Sov. Phys. JETP 50, 934 (1979)].

[5] J. Suhl, J. Phys. Chem. Solids 1, 209 (1957).

[6] E. Schloemann, Raytheon Technical Report No. R-48, Research Division, Raytheon Company, 1959 (unpublished); E. Schloemann, J. J. Green, and V. Milano, J. Appl. Phys. 31, 3865 (1960).

[7] W. Haubenreisser, D. Linzen, and E. Glauche, Phys. Status Solidi 1, 764 (1961).

[8] C. E. Patton, Phys. Status Solidi (b) 92, 211 (1979), and 93, 63 (1979).

[9] W. Jantz, J. Schneider, and B. Andlauer, Solid State Commun. 10, 937 (1972).

[10] C. E. Patton and W. Jantz, IEEE Trans. Magn. 14, 698 (1978).

[11] Y. H. Liu and C. E. Patton, J. Appl. Phys. 53, 5116 (1982).

[12] J. R. Sandercock, Top. Appl. Phys. 51, 173 (1982)

[13] W. D. Wilber, W. Wettling, C. E. Patton, P. Kabos, and W. Jantz, to be published.

[14] T. Wolfram and R. E. DeWames, Phys. Rev. Lett. 24, 1489 (1970).