Observation of auto-oscillations and chaos in subsidiary absorption in yttrium iron garnet

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Auto-oscillations of the dynamic magnetization and routes to chaos for the first-order transverse pump spin-wave instability have been studied in single-crystal yttrium-iron-garnet (YIG) films. The measurements reported here were made on a 20.8-μm-thick YIG film at 9.4 GHz with the static and microwave fields in the plane of the film. Auto-oscillations at 100–400 kHz were observed in the power absorbed by the film over a relatively narrow static field range of 1100–1460 Oe, compared to the first-order instability (FOI) range of 0–1630 Oe. The auto-oscillation frequency and threshold microwave field amplitude were both strongly field dependent. The threshold amplitudes were about a factor of 2 larger than the FOI threshold amplitudes. At even higher power levels and for an even narrower field range of 1300–1380 Oe, the auto-oscillations showed frequency changes indicative of chaotic behavior. Several different subharmonic bifurcation routes to chaos were observed for different fields within the chaotic region.

I. INTRODUCTION

Low-frequency oscillations in the microwave power absorbed by yttrium-iron-garnet (YIG) samples for microwave field amplitudes somewhat above the threshold for spin-wave instability processes are well known.[1] Such oscillations were attributed to the excitation of standing spin waves in the sample[2] or nonlinear interactions between the parametric spin waves.[3] Recent ferromagnetic resonance (FMR) experiments on YIG spheres have shown that these auto-oscillations exhibit a chaotic character.[4] The frequency power spectra of the auto-oscillations revealed the existence of various routes to chaos for FMR saturation,[4] parallel pumping,[5] and subsidiary absorption.[6]

The objective of this work was to study in detail the auto-oscillations and routes to chaos for first-order instability (FOI) processes and subsidiary absorption (SAB) in single-crystal YIG films. Measurements at room temperature and x-band frequencies show high-power auto-oscillations in the frequency range 100–400 kHz, but only for a limited static field interval within the SAB field range. For an even more limited field interval, these auto-oscillations manifest characteristics of chaos and exhibit various routes to chaos at high microwave power levels.

II. EXPERIMENT

The experiments were performed using a modified 9.4-GHz Varian microwave spectrometer. The microwave power was provided by a klystron which was frequency stabilized using an external crystal oscillator. A 20.8-μm-thick (111) YIG film on a gadolinium gallium garnet substrate was used for the results presented here. The sample was placed at the bottom of an undercoupled, TE 102 reflection type cavity with a loaded Q of 3100. The measurements were done with cw power. The peak power was 400 mW, corresponding to a peak-to-peak maximum microwave field amplitude of 1.5 Oe at the sample position. A static magnetic field was applied parallel to the film plane and perpendicular to the in-plane microwave field. The reflected power from the cavity was monitored with a diode detector. A spectrum analyzer was used for frequency analysis of the power reflected from the cavity after detection.

III. AUTO-OSCILLATIONS AT HIGH MICROWAVE POWER LEVELS

As the microwave driving field amplitude was increased beyond the FOI threshold h_{crit}, the expected increase in the reflection coefficient of the cavity and the corresponding relative increase in the reflected power was observed. Measured values for h_{crit} versus the static magnetic field H are shown by the lower set of data points in Fig. 1. These data map out the usual so-called "butterfly curve" for subsidiary absorption in narrow linewidth single-crystal ferrites.[7]

As the microwave power was increased further, the reflected power after detection generally remained dc, except for a static field interval from about 1100 to 1460 Oe, located in the bottom portion of the butterfly curve. For this interval, a second threshold, H_{osc}, was found. For microwave field amplitudes above h_{osc} (in this H interval), the detected power was found to change abruptly from purely dc to dc with a superimposed ac component at a base frequency f_{osc} in the 100–400-kHz range. These ac signals are the so-called auto-oscillations cited in the introduction. The middle set of data points in Fig. 1 maps out the measured auto-oscillation threshold amplitude H_{osc} vs H. The upper graph and data show the observed variation in f_{osc} with static field.

The large values for h_{osc}, relative to h_{crit}, and the very distinct field dependencies for both h_{osc} and f_{osc} may be noteworthy. The h_{osc} values reported for parallel pumping and subsidiary absorption in YIG spheres[3,5,6] were only a factor of 1.02–1.5 larger than h_{crit}. The present h_{osc} values are larger than h_{crit} by a factor of 2 or more. The early references[1,2] reported an auto-oscillation frequency which was either independent of H or a simple decreasing function of H. The present data show a very complicated f_{osc} vs H dependence. The abrupt jump in f_{osc} at 1265 Oe is quite distinct. This jump appears to correlate with the distinct kink in the

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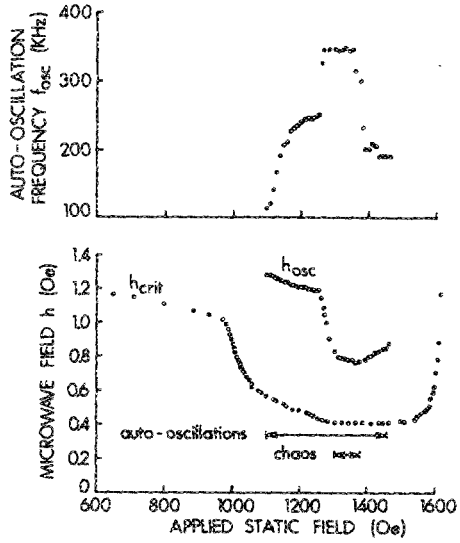

FIG. 1. Static applied field dependence of the threshold microwave field amplitude h_{crit} for subsidiary absorption, the threshold field amplitude h_{osc} for auto-oscillations, and the auto-oscillation frequency f_{osc} for a 20.8-μm-thick yttrium-iron-garnet film at 9.4 GHz. The horizontal arrow bars indicate the static field ranges for the observation of auto-oscillations and chaos.

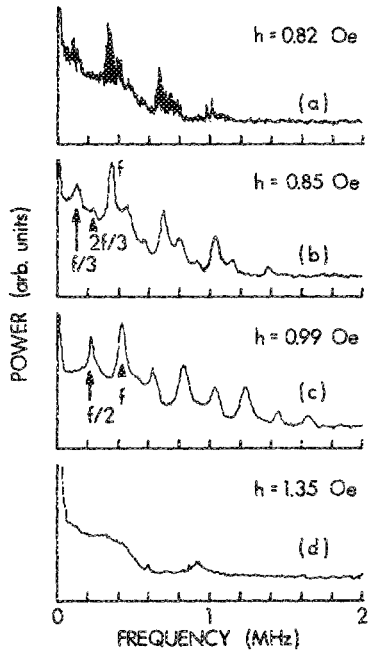

FIG. 2. Power vs frequency spectra for the detected reflected microwave power for subsidiary absorption in the YIG film at $H = 1350$ Oe. The vertical axis represents the power in logarithmic units. The parameter h denotes the amplitude of the microwave field for each spectrum shown.

h_{osc} vs H curve at the same H value. The flat plateau in f_{osc} and the gradual falloff at the high field end of the auto-oscillation region are also distinct. These behaviors are probably correlated in some way with the observed minimum in h_{osc} over the same H range. There is, at present, no satisfactory theory for these auto-oscillations. Any viable theory should account for the present observations: (i) the narrow field interval for the oscillations; (ii) the distinct field dependencies for the threshold h_{osc} and the base auto-oscillation frequency f_{osc}.

The data in Fig. 1 do present one clue concerning the nature of the unstable modes which produce the auto-oscillations. The H region for the oscillations is located within the broad minimum h_{crit} portion of the butterfly curve which corresponds to parametric spin waves of low wave number in the range from zero to about 10^3 cm^{-1}.[7] It is clear, therefore, that relatively low wave number and long wavelength modes are involved.

IV. CHAOS AND ROUTES TO CHAOS

Over most of the auto-oscillation H range discussed above, an increase in the microwave field amplitude above h_{osc} has no big effect other than a slight shift in the auto-oscillation base frequency and in the harmonics at $2f_{osc}$, $3f_{osc}$, etc., to higher values. There is no important change in the frequency content of the ac component of the detected power.

For a relatively narrow field interval within the auto-oscillation range, however, there is a rather spectacular change in the frequency content of the ac signal in which additional peaks appear in the frequency spectrum at various subharmonics. These multiple peaks in the power-frequency spectra then evolve into a broad continuous spectrum characteristic of chaos. The specific ways in which the evolution occurs are termed "routes to chaos."

The narrow H interval over which subharmonics and chaos were found is indicated in Fig. 1. This narrow interval from 1300 to 1380 Oe covers part of the minimum h_{osc} H region and part of the plateau-shoulder H region for f_{osc}. The narrowness of this interval is consistent with the summary results in Fig. 1 of Ref. 6.

Figure 2 gives a representative example of the evolution of the power-frequency spectrum for the ac component of the detected signal as the microwave field amplitude is increased above h_{osc} for the H interval over which subharmonics and routes to chaos are observed. The spectra in Fig. 2 are for a static field $H = 1350$ Oe. The spectrum for a microwave field amplitude $h = 0.82$ Oe (upper graph), barely above h_{osc}, shows a fundamental ac signal centered at about 180 kHz, along with higher harmonics. The peaks all exhibit a distinct fine structure; there appears to be a series of sharp excitations (in frequency) distributed around f_{osc}, $2f_{osc}$, and $3f_{osc}$, rather than simple peaks at these frequencies. This fine structure, with the very narrow spectral peaks, is reminiscent of the fine structure in field initially reported by Jantz and Schneider[8] for subsidiary absorption in YIG spheres.

The next spectrum, for a slightly higher power ($h = 0.85$ Oe), demonstrates the disappearance of the fine structure and the appearance of the first subharmonics at $f_{osc}/3$ and $2f_{osc}/3$, along with higher harmonics. The appearance of these peaks is termed "$f/3$ bifurcation." As the power is further increased ($h = 0.99$ Oe), the $f/3$ bifurcation changes to $f/2$ bifurcation, with the single subharmonic now at $f_{osc}/2$. The lower spectrum in Fig. 2 is for a relatively large h value of 1.35 Oe. At this power, the power-frequency spectrum is relatively structureless, with a more-or-less continuum distribution. This continuum spectrum for the ac component represents the "chaotic" nature of the absorbed microwave power in the present context. The "route to chaos" shown by the series of spectra in Fig. 2 could be classified as "f-$f/3$-$f/2$-C", corresponding to an "f to $f/3$" bifurca-

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tion, followed by an "$f/3$ to $f/2$" bifurcation, and then chaos.

Similar series of spectra for different H values within the static field interval for chaos yielded different routes to chaos, including a direct "f-$f/2$-C" route and an "f-$f/2$-$f/4$-C" route. A systematic map of the change in the route to chaos with field has not been found.

The background noise evident in Fig. 3 was found to be present even at microwave power levels below the threshold for auto-oscillations. Given this background, it is important to note that the chaoticlike spectrum at the bottom of Fig. 3 is mostly noise upon which the chaotic response is superimposed. It is also important to note that the relatively broad f, $f/3$, and $f/2$ peaks in Fig. 3 must be intrinsic to the YIG films, since the very sharp fine structure peaks are resolved. Single-crystal YIG spheres yield much sharper peaks.

V. DISCUSSION

The above results provide a fairly detailed description of the auto-oscillations and chaotic dynamics in the detected microwave power for subsidiary absorption in a YIG film at power levels above the spin-wave threshold. This work compliments and, in some aspects, contrasts with recently published experimental and theoretical results for subsidiary absorption in YIG spheres.[6] In that study, auto-oscillations and chaotic dynamics were also over the relatively flat region of the butterfly curve. Reference 6 also makes important connections with the fine structure effects of Jantz and Schneider[8] and intuitive considerations on bifurcations and chaotic dynamics due to the interaction of different parametric spin waves.

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[1]S. Wang, G. Thomas, and T. L. Hsu, J. Appl. Phys. **39**, 2719 (1968).
[2]G. Thomas and Goh Komoriya, J. Appl. Phys. **46**, 883 (1975).
[3]V. E. Zakharov, V. S. L'vov, and S. S. Starobinets, Sov. Phys. Usp. **17**, 896 (1975).
[4]G. Gibson and C. Jeffries, Phys. Rev. A **29**, 811 (1984).
[5]F. M. de Aguiar and S. M. Rezende, Phys. Rev. Lett. **56**, 1070 (1986).
[6]P. Bryant, C. Jeffries, and K. Nakamura, Phys. Rev. Lett. **60**, 1185 (1988).
[7]C. E. Patton and W. Jantz, J. Appl. Phys. **50**, 7082 (1979).
[8]W. Jantz and J. Schneider, Phys. Status Solidi A **31**, 595 (1975).

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