FERROMAGENTIC RESONANCE FOLDOVER IN SINGLE CRYSTAL YIG FILMS--SAMPLE HEATING OR SUHL INSTABILITY

Y. T. Zhang, C. E. Patton, and M. V. Kogekar

ABSTRACT

Foldover and linebroadening effects have been observed in 500 μm diameter, 7.9 μm thick yttrium iron garnet single crystal films at 9.18 GHz and room temperature. The distortions in lineshape and field shifts of the prominent FMR curve features were a strong function of the microwave power level and duty cycle. At high duty cycles, distortions and shifts were quite similar to those reported by previous authors and attributed to sample heating. As the duty cycle is reduced, however, the characteristic foldover profiles evolve into a simple line broadening without appreciable foldover. This linebroadening occurs at power levels which are on the order of the expected Suhl threshold.

INTRODUCTION

Suhl first predicted the existance of foldover effects in ferromagnetic resonance (FMR) due to spin-wave excitations.[1] Since then, nonlinear effects in FMR have been studied by a number of investigators.[2-9] Masters observed a foldover effect in single crystal yttrium iron garnet (YIG) due to sample heating at resonance.[7] McKinstry et al.[8] have reported further experimental results on foldover due to sample heating in YIG spheres under continuous wave (CW) and pulsed microwave power excitation conditions. Seagle et al.,[9] however, have interpreted foldover effects in small diameter single crystal YIG films in terms of Suhl instability processes.

This paper reports some new experimental foldover results for small diameter single crystal YIG films. FMR profiles versus applied static field were measured for CW microwave power and various pulsed microwave power configurations so that profiles for different pulse widths, peak powers, and duty cycles could be compared in detail. As the CW power was increased, one could see large shifts and distortions of the narrow low power FMR absorption peak, much like the results in Refs. 8 and 9. By going to a low duty cycle, the narrow FMR profile could be regained at moderate power levels; at large powers, the low duty cycle profiles are simply broadened with no foldover. The onset power for this low-duty-cycle linebroadening is on the order expected from the Suhl theory.

EXPERIMENT

These experiments were carried out using a conventional microwave reflection cavity at 9.18 GHz and room temperature. The single crystal 7.9 μm thick, 500 μm diameter YIG films were prepared by liquid phase epitaxy on gadolinium gallium garnet substrates and photolithographic etching procedures, courtesy of Westinghouse Research Laboratories. The sample was mounted on a low loss microwave dielectric rod at the center of a critically coupled TE_{102} cavity with a loaded Q of about 2500 and the microwave field perpendicular to the film plane. The static magnetic field was applied in the plane of the film. For this field configuration, the low power FMR linewidth was 2.1 Oe. The power incident on the sample was controlled by a precision variable attenuator. The maximum peak power was 300 mW, corresponding to a microwave field amplitude of about 1040 mOe at the sample position. A precision attenuator in the detector arm of the spectrometer was used in a complimentary fashion so that all FMR absorption curves could be obtained with approximately the same power at the detector. For the pulse experiments, a diode switch was used to obtain pulsed microwave power with different pulse widths (10 μsec-10 msec), and a range of duty cycles (1%-100%). The pulse power FMR profiles were obtained by standard signal averaging techniques. All curves were obtained by sweeping the applied static field at a fixed rate of 40 Oe/min. The arrows on the absorption curves in Figs. 1-3 indicate direction of the sweep.

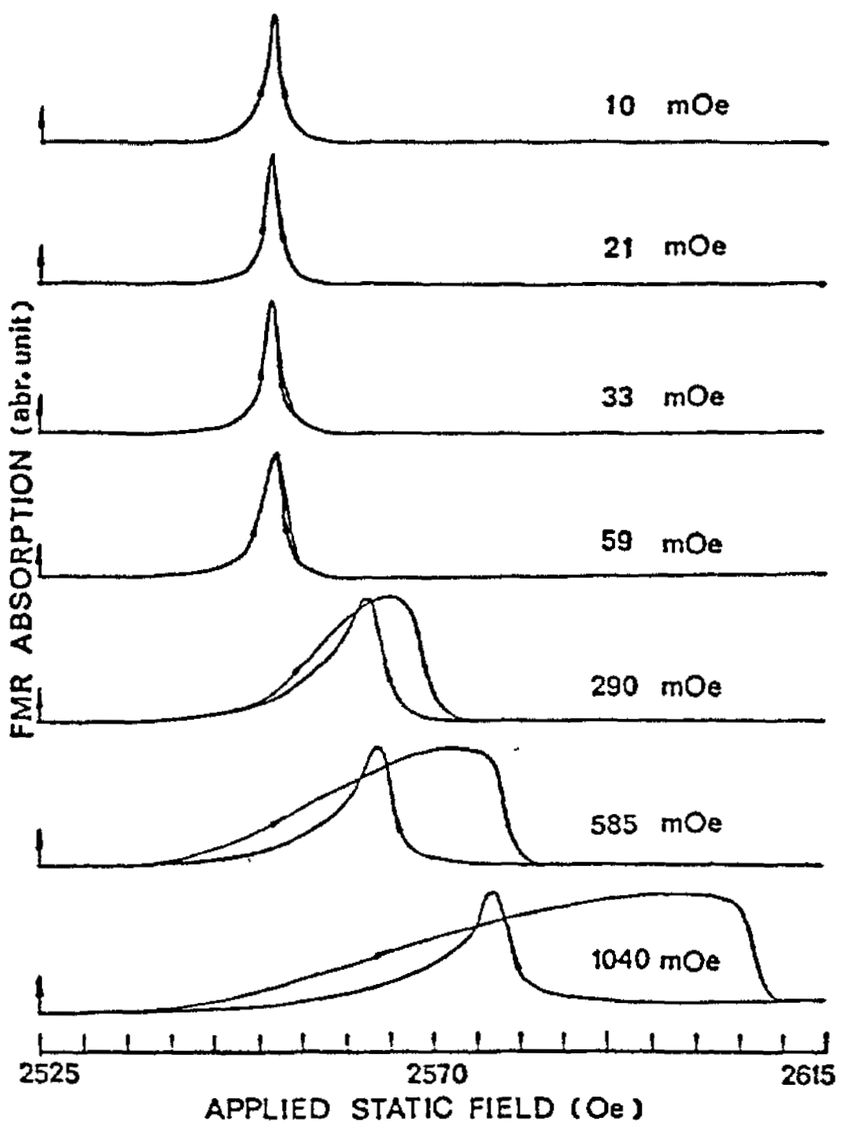

Fig. 1. Upsweep and downsweep FMR curves vs. incident power for the single crystal YIG film at room temperature and 9.18 GHz. The number given for each set of curves indicates the microwave field amplitude at the sample position in mOe. The sweep rate is 40 Oe/min.

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The influence of increasing mocrowave field amplitude on the FMR profiles for CW power is shown in Fig. 1. The onset of the foldover is at a microwave field amplitude of about 30 mOe. As the microwave power incident on the YIG film is increased further, a series of extremely distorted FMR profiles are observed and the peaks of the FMR absorption profiles for both increasing and decreasing field are shifted to higher field. At the highest power, the upsweep curve (increasing field) has evolved into an extended sharp shoulder above the low power FMR peak position by about 50 Oe. The evolution of the downsweep curves (decreasing field) is rather different. The downsweep FMR profile is somewhat broadened. At the highest power the peak is still prominent, but is shifted by 25 Oe from the low power FMR peak position.

An explanation of a similar foldover effect in single crystal YIG spheres based on sample heating was initially presented by Masters.[7] In that work and in Ref. 8, field shifts were possible in both directions, relative to the low power FMR position, because of the dominant role of magnetocrystalline anisotropy in determining the precise FMR position. For thin films, the important magnetic parameter is the magnetization $4\pi M_S$. Heating causes a decrease in $4\pi M_S$ and a corresponding increase of the FMR field. The shoulder position in the bottom trace in Fig. 1 implies a decrease in $4\pi M_S$ of about 50 Oe, corresponding to a temperature rise of about 10°C. This level of heating for the YIG film at FMR is not unreasonable.

One simple test of the heating hypothesis, as opposed to foldover due to a Suhl instability, is to obtain data similar to those shown in Fig. 1 for reduced duty cycle values. A reduced duty cycle will lead to a reduced heating. Any shifts or distortions which are due to heating should disappear. The results of such measurements are presented in Figs. 2 and 3.

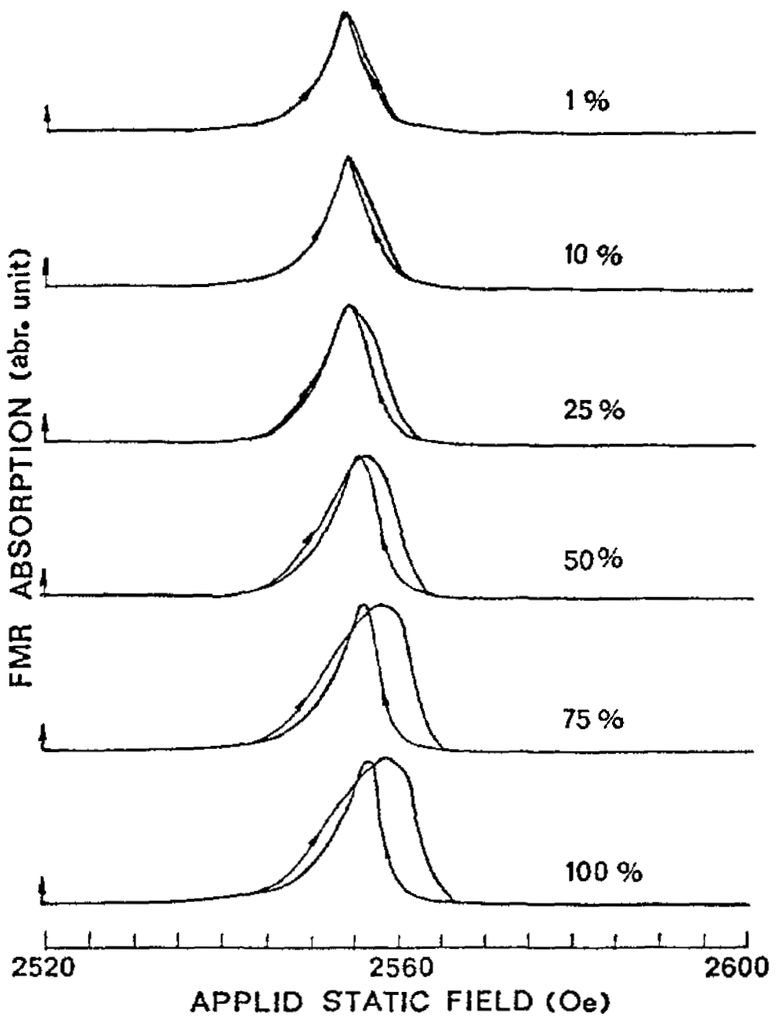

Fig. 2. Upsweep and downsweep FMR absorption curves as in Fig. 1, but vs. duty cycle for a peak microwave field amplitude of about 290 mOe. The number given for each set of curves indicates the duty cycle.

Figure 2 shows a series of FMR absorption curves for a pulse width of 100 μsec and a range of duty cycles from 1% to 100%. The peak microwave field was about 290 mOe. At the lowest duty cycle of 1%, one sees a moderately broadened but essentially unshifted profile (upper trace). This broadening effect under low duty cycle conditions will be considered in more detail in Fig. 3. As the duty cycle is increased, the curves are further broadened and shifted. The high duty cycle FMR profiles (bottom two traces) are essentially the same as the CW absorption curve in Fig. 1 for the same 290 mOe microwave field.

The evolution of the FMR profile with increasing power is quite different from Fig. 1 if a low duty cycle is used. Figure 3 shows a set of FMR absorption curves vs. pulsed power for a 1% duty cycle and pulse width of 100 μsec. A sharp, narrow profile characteristic of low power FMR is obtained for a very low average power (incident microwave field about 30 mOe). If the peak microwave power is now increased at this low duty cycle, only broadening of the FMR curve is observed. While there is some difference between the profiles for upsweep and downsweep field, the main effect is an overall broadening, coupled with a small shift in peak position at the highest average power. The evolution of the FMR profile with peak power in Fig. 3 is clearly reminiscent of Suhl linebroadening, rather than the extreme foldover effects due to heating.

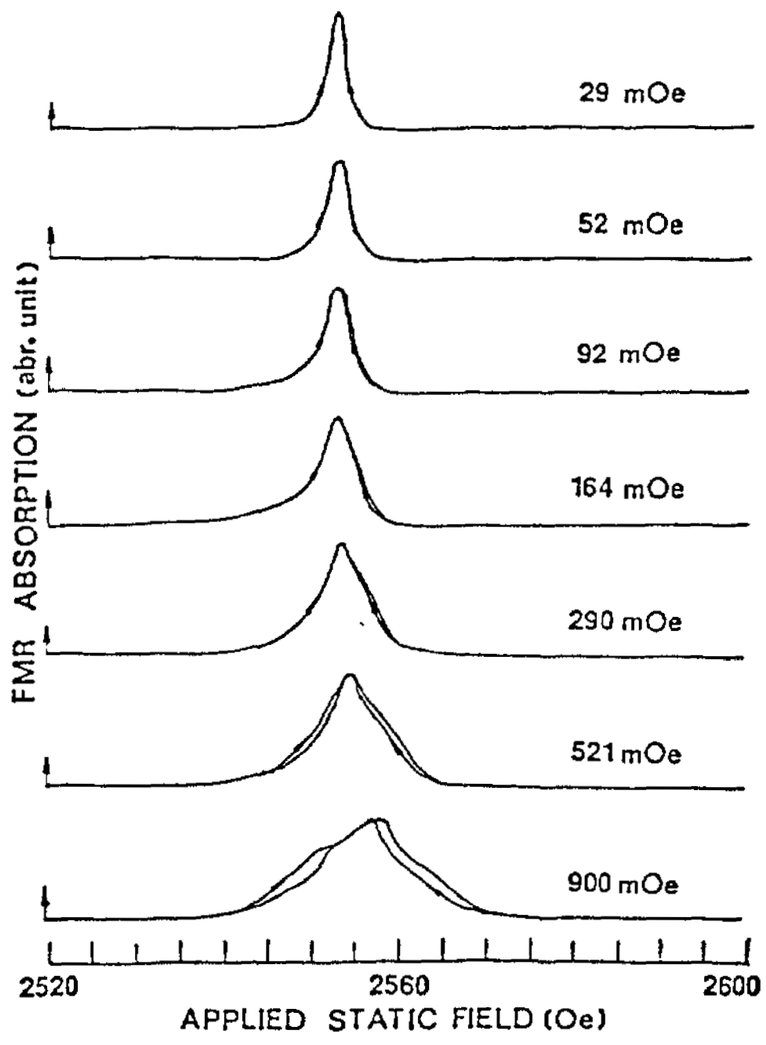

Fig. 3. Upsweep and downsweep FMR absorption curves as in Fig. 2, but vs. the peak power incident on sample for a fixed duty cycle of 1%. The number given for each set of curves indicates the incident microwave field amplitude in mOe.

DISCUSSION

The above results clearly demonstrate a change from foldover to linebroadening as the microwave power

duty cycle is decreased. Following the usual procedure for FMR linebroadening due to Suhl processes, one can estimate the instability threshold from a plot of the inverse linewidth (essentially the peak microwave susceptibility at FMR) vs. the inverse microwave field amplitude. Such a plot, shown in Fig. 4, reveals a reasonably sharp threshold of about 30 mOe.

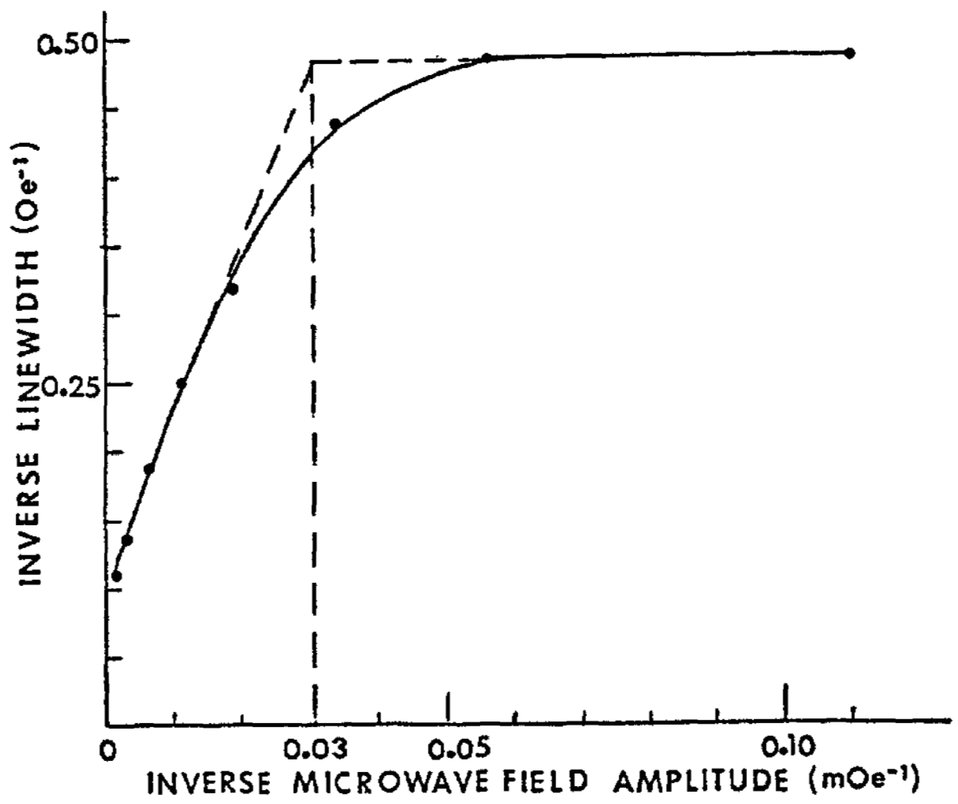

Fig. 4. The inverse linewidth vs. inverse microwave field amplitude.

The Suhl theory for the situation in which the microwave field is in-plane and the static field is perpendicular to the film plane yields a threshold field given by[10]

$$h_{crit} = \Delta H \sqrt{\frac{1.54\ \Delta H_K}{4\pi M_s}}, \qquad (1)$$

where ΔH is the half power FMR linewidth, ΔH_K is the spin-wave linewidth, and $4\pi M_S$ is the saturation induction. The linewidth parameter under the square root in Eq. (1) is ΔH_K, rather than ΔH (as in Ref. 10), to account for the fact that the power balance in the Suhl theory involves the spin-wave relaxation rate, not the FMR linewidth. For ΔH = 2.1 Oe, as measured experimentally at low power, and ΔH_K = 0.5 Oe, typical for YIG single crystal materials, Eq. (1) yields a theoretical h_{crit} estimate of 40 mOe. Because of the perpendicular microwave field orientation in the present experiment, the theoretical h_{crit} which is applicable here is probably somewhat higher than 40 mOe, due to the reduced uniform mode response. In any case, the calculated Suhl threshold is in reasonable agreement with the onset data of Fig. 4.

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