Temperature dependence of the parallel-pump spin-wave instability in porous yttrium iron garnet[a]

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The parallel-pump spin-wave instability threshold has been measured at 8.88 GHz in porous polycrystalline YIG at temperatures ranging from 88 K to 368 K. Sample porosities ranged from $<0.5\%$ to 16.3%. The shapes of the low-temperature butterfly curves suggest that the previously inferred inverse wavenumber dependence of the spin-wave linewidth ΔH_k may not be valid in porous YIG. The temperature dependences of the ΔH_k are incongruous with those predicted by the various transit-time models of spin-wave relaxation. They are also markedly different from those reported for the off-resonance effective linewidth ΔH_{eff}, which suggests that different mechanisms determine ΔH_{eff} and ΔH_k.

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INTRODUCTION

The relaxation mechanisms which determine the off-resonance effective linewidth ΔH_{eff} and the spin-wave linewidth ΔH_k in polycrystalline ferrites have yet to be positively identified. Previous analyses of room temperature spin-wave linewidth data have been tentatively interpreted in terms of spin-wave transit-time models [1,2]. The most detailed transit-time calculation of Sawado [3], predicts curves of ΔH_k vs. wavenumber k which are in reasonable agreement with the room-temperature data of Patton [4]. Borghese, however, has recently made a detailed study of spin-wave group velocity constraints, which indicates that a transit-time concept cannot reasonably account for existing data [5].

The temperature dependence of the high-field effective linewidth in porous and fine grain polycrystalline yttrium iron garnet has been recently reported [6]. The ΔH_{eff} increases with both porosity and inverse grain size, and increases with decreasing temperature. The temperature dependence of ΔH_{eff} resembles a Curie-Weiss curve with a Curie temperature of about 330 K for all samples.

In this study, the temperature dependence of the parallel-pump spin-wave instability has been studied for a series of porous YIG samples from 88 K to 368 K at 8.88 GHz, for comparison with predictions of various models and with the recent effective linewidth data. The observed shapes of the parallel-pump butterfly curves indicate that a previously inferred inverse k dependence of ΔH_k at low k for porous samples may not be valid. The temperature dependences of ΔH_k indicate that a transit-time relaxation mechanism is not operative. Moreover, the data are very different from those on ΔH_{eff} vs. temperature, and indicate that different processes are responsible for these two linewidths.

EXPERIMENT

Data were obtained on polycrystalline YIG prepared by conventional sintering techniques as described in Ref. 4. A dense sample with a porosity p below 0.5%, and porous samples with p approximately 1.9%, 6.5%, and 16.3% were studied. These are nominal values based on careful volume and weight measurements on the individual samples. They are accurate to about 0.5%. It is to be noted that higher porosities are obtained by reducing the sintering time. Hence the grain size generally decreases as p increases. Estimated average grain sizes are 30 μ, 5 μ, 2 μ, and 1 μ for the dense, 1.9%, 6.5%, and 16.3% porous materials, respectively.

The actual data were obtained in a variable-temperature high-power microwave spectrometer utilizing a pulsed magnetron source. The evacuated TE_{101} cavity was held at 77 K in a liquid nitrogen bath. The sample was mounted on a diamond rod inserted approximately one sample diameter above the bottom of the cavity. The sample temperature was controlled by a heater-thermocouple feedback arrangement.

The general shapes of the experimental butterfly curves of parallel-pump threshold h_{crit} vs. static applied field H vary with both porosity and temperature. The evolution in curve shape is more or less continuous with temperature. Representative data at 88 K and 368 K are shown in Figs. 1 and 2. Data at 298 K (not shown) are consistent with those previously reported [4]. At 88 K, only the dense and 1.9% porous samples evidence parallel-pump butterfly curves with a sharp break. The behavior for the porous samples is more rounded. At 368 K all samples have a relatively sharp break in their butterfly curves (hereafter referred to as BC).

ANALYSIS

The spin-wave linewidth ΔH_k can be inferred from the well known relationship [7]

$$\Delta H_k = \left(\frac{\omega_m}{\omega}\right) h_{crit} \sin^2 \theta_k ,$$

where $\omega_m \equiv 4\pi\gamma M$, γ is the gyromagnetic ratio, $4\pi M$ is the saturation induction, ω is the pump frequency, and θ_k is the spin-wave polar angle referred to the direction of H. The angle θ_k for minimum threshold spin-waves is generally taken as $\pi/2$ for external fields less than a critical field H_c at which the unstable spin-wave modes have wavenumber k near zero. In this range k can be determined from the dispersion relation. At fields above H_c, k is assumed to be zero, and θ_k is assumed to decrease with H as determined by the dispersion relation. Values of H_c are indicated in Figs. 1 and 2 by vertical arrows.

The wavenumber dependences of ΔH_k, determined from the BC data of Figs. 1 and 2 are shown in Figs. 3 and 4 for 88 K and 368 K respectively. At both temperatures, the ΔH_k for the dense and 1.9% porous samples exhibit weak linear k dependences. At 88 K, the ΔH_k for the more porous samples pass through a minimum at $k = 2 - 3 \times 10^5$ cm^{-1}. This minimum is less marked at 368 K.

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Spin-wave linewidths extrapolated to k = 0 for the four samples are shown as functions of temperature in Fig. 5. The somewhat arbitrary choice of ΔH_k ($k \to 0$) was made to facilitate comparison. One could presumably just as well choose to compare, for example, minimum values of ΔH_k. The extrapolated values, however, are representative of the qualitative nature of the temperature dependences. The spin-wave linewidth is essentially temperature independent for the dense and 1.9% porous samples. It shows a tendency to increase with decreasing temperature for the 6.5% porous sample, and, except for a small upturn below 125 K, increases with increasing temperature for the 16.3% porous sample.

DISCUSSION

The present data on the parallel-pump instability vs. temperature provide several new inputs to the search for the elusive origins of microwave loss in polycrystalline ferrites. They call into question the conventional interpretation of BC data, and disfavor the transit-time relaxation model. The data also suggest that single-ion relaxation is not important. Although no presently known relaxation mechanism is clearly evident in these data, it is clear that different mechanisms predominate in the determination of ΔH_{eff} and ΔH_k.

Because of the differences shown in Figs. 1 and 2 between the H_c and the fields H_b at which the butterfly curves break, some caution is prudent in the inference of ΔH_k vs. k. In these and previous room temperature data [4], H_b is nearly equal to H_c for the dense samples, and falls below H_c as p increases. This was interpreted in terms of a porosity induced inverse k dependence of ΔH_k at low k. The present low-temperature data of Fig. 1 also show $H_c > H_b$ for the 16.3% porous sample. However, for the dense and 1.9% porous samples, H_c is notably less than H_b. Interpreted within the

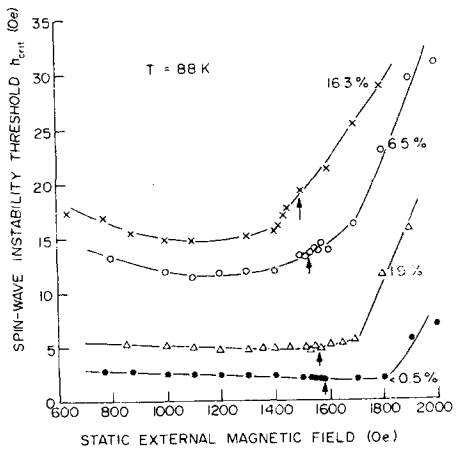

Figure 1. Microwave threshold field h_{crit} as a function of static external magnetic field H at 88 K. Vertical arrows indicate the theoretical field H_c at which the unstable spin-wave has wavenumber $k \to 0$ and a polar angle θ_k of $\pi/2$.

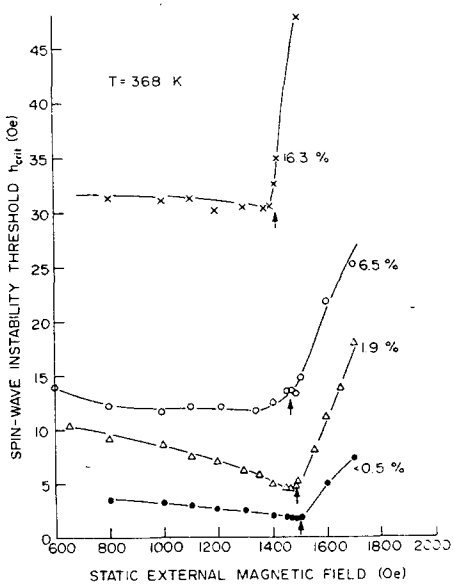

Figure 2. Microwave threshold field h_{crit} as a function of static external magnetic field H at 368 K. Vertical arrows indicate the theoretical field H_c at which the unstable spin-wave has wavenumber $k \to 0$ and a polar angle θ_k of $\pi/2$.

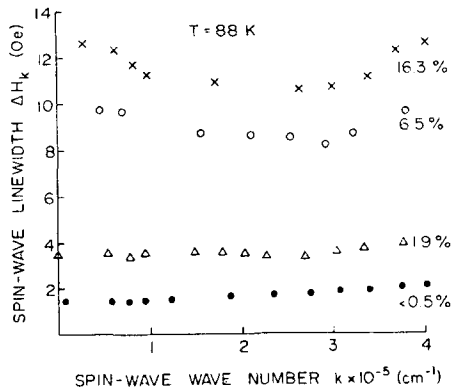

Figure 3. Spin-wave linewidth ΔH_k as a function of spin-wave wavenumber k at 88 K.

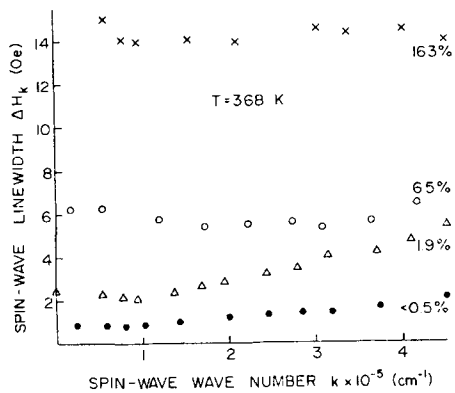

Figure 4. Spin-wave linewidth ΔH_k as a function of spinwave wavenumber k at 368 K.

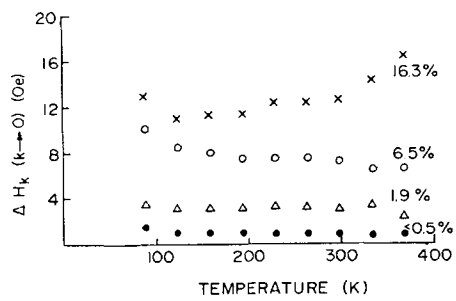

Figure 5. Spin-wave linewidth ΔH_k ($k \to 0$) as a function of temperature.

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above framework, this implies some sort of strong θ_k dependence of ΔH_k for $H > H_c$. Such implications are a priori rather implausible, and call into question the previously inferred inverse k dependence as well.

Rather than signifying specific relaxation processes, it is possible that the rounded shapes of the BC for the 6.5% and 16.3% porous samples at low temperatures, and the observation of $H_c < H_b$ for the dense and 1.9% porous samples at low temperatures, are simply different manifestations of demagnetizing effects. Magnetization data for the dense material at 88 K indicate that saturation occurs for external fields between 1500 and 2000 Oe. Hence, the material is not actually saturated at the theoretical H_c. This could account for the shift of the butterfly curve minimum to a higher external field for the dense and 1.9% porous samples. Saturation at temperatures above 220 K was observed to occur at somewhat lower fields, so that the lack of saturation would not be a problem at high temperatures. This is consistent with the concidence of H_c and the butterfly curve minima for these two samples at 368 K in Fig. 2.

The rounded shapes of the curves for the 6.5% and 16.3% porous samples could be due to the complicated distribution of internal static and microwave fields due to dipolar interactions. The rounded butterfly curve shapes may simply represent a composite of many different localized curves for regions with different internal field distributions. It is to be noted that the actual onset of instability in the more porous materials at 88 K was very gradual, which is one more indication of inhomogeneous internal fields. At higher temperatures, $4\pi M$ is reduced and these porous samples are also more easily saturated. Hence, the 368 K data exhibit little of the rounded character evident at 88 K.

Of course, if the above demagnetizing effects are affective, the validity of the ΔH_k vs. k curves in Fig. 3, as well as similar results previously reported [4], is doubtful, since the nature of the unstable modes is more ambiguous. One could speculate that the dense and 1.9% porous results are qualitatively correct since the butterfly curves are reasonably flat at low field. The ΔH_k for the 6.5% and 16.3% samples, however, can only be taken as some value averaged over the k values for the pumped modes.

Previous room temperature parallel-pump data in polycrystalline YIG have been tentatively explained by some form of transit-time model [2-4]. In these models, the transit time for spin-waves between scattering centers such as grain boundaries, pores, or nonmagnetic inclusions is considered to constitute an effective lower limit on ΔH_k, if the mean free path is sufficiently small. Where the mean free path is determined by grain boundary scattering, this model predicts a spin-wave linewidth which is proportional to $|v_g|/a_o$, where v_g is the spin-wave group velocity and a_o is the grain size, in agreement with experimental data in fine-grain YIG [8].

The temperature dependence of ΔH_k shown in Fig. 5, however, is inconsistent with transit-time relaxation. Depending on the details of the particular model, ΔH_k should vary as $4\pi M$, or some higher power of $4\pi M$, and hence decrease with increasing temperature. Of the four samples, only the 6.5% material evidences a ΔH_k which decreases with increasing temperature, but even here the decrease is too weak to be due to a transit-time effect. Thus, the present temperature dependent data pose problems for the transit-time model not previously evident from room-temperature data.

It may be tempting to associate the low-temperature increase in ΔH_k, for the 6.5% and 16.3% porous samples, with a temperature peak impurity process. It is to be noted however, that all samples were made from starting powders of the same purity. Hence, any impurity process which is observed for one sample should be observed for all. As significant increases in ΔH_k at low temperature are conspicuously absent for the dense and 1.9% porous samples, impurity relaxation can be eliminated from consideration.

Aside from discounting the importance of a transit time relaxation mechanism, probably the most significant aspect of these data is the marked difference between the temperature dependences of the ΔH_k, and those previously reported for ΔH_{eff}. As shown in Fig. 5, the ΔH_k are constant, or increase with temperature above 200 K. The ΔH_{eff} on the other hand, decrease sharply with temperature above 250 K [6]. Therefore, the mechanisms which determine H_{eff} and ΔH_k in polycrystalline ferrites are almost certainly different.

CONCLUSION

Data on the parallel-pump spin-wave instability threshold in porous YIG provide several new inputs concerning the origin of microwave losses in polycrystalline ferrites. (1) The very different variations in the spin-wave linewidth and effective linewidth with temperature strongly indicates that the mechanisms are also different. (2) The temperature dependence of ΔH_k does not appear consistent with the transit-time mechanism previously invoked to explain room temperature data. (3) The qualitative evolution of the butterfly curve shapes with porosity at low temperature appears to be consistent with demagnetization effects.

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