Measurement of the spin-wave instability threshold h_{crit} in microwave ferrites

Y. T. Zhang,[a] C. E. Patton, G. Srinivasan, G. O. White,[b] C. J. Brower,[c] and C. A. Edmondson[d]

Department of Physics, Colorado State University, Fort Collins, Colorado 80523

(Received 13 August 1986; accepted for publication 8 December 1986)

Several improvements for a previously described semiautomated system for spin-wave instability threshold measurement in microwave ferrites are described. The effects of sample size, sample position in the microwave cavity, and method of data interpretation on the threshold field h_{crit} are also reported. The data were obtained by the parallel pumping technique at 8.92 GHz. Sphere-shaped samples of polycrystalline yttrium iron garnet were used for the measurements. The results show that the initial, "exact" instability onset, the "extrapolated" onset from the loss increase above threshold, and the "visual" onset estimate from the above threshold response can vary by more than 0.5 Oe for h_{crit} values of 3 Oe or so. Large samples, above 1 mm in diameter, lead to an overestimation of h_{crit} due to errors in the microwave cavity perturbation theory analysis which forms the basis of the measurement. The amount of overestimation is about 0.1 Oe for a diameter of 2 mm and 0.2 Oe at 3 mm. Sample position relative to the cavity end wall does not appear to be critical. Imaging effects are small for h_{crit} measurements in the YIG-like materials of interest here.

INTRODUCTION

The spin-wave instability threshold h_{crit} is an important parameter for microwave ferrite materials. The h_{crit} value corresponds to the microwave field amplitude (typically for a linearly polarized field) at which the power into the ferrite exceeds the ability of the spin system to relax by normal channels. This threshold places a fundamental limitation on the microwave power handling capability of ferrite radar devices. It also provides a rather direct measurement of the intrinsic microwave losses, or spin-wave linewidth, for the material.

Spin-wave thresholds have been studied extensively for three decades, following the theoretical work of Suhl.[1,2] There has been a renewed interest in such measurements in recent years because of developments in phased array radar and new microwave ferrite materials, among others. Accurate h_{crit} data are crucial for the quantitative comparison of different materials, different processing techniques, etc. This paper is concerned with two aspects of h_{crit} measurements. The first has to do with instrumentation. A semiautomated system for instability threshold measurements was developed and documented some years ago.[3] Some recent modifications and improvements to this type of system are reported herein. The second aspect has to do with the problem of accurate threshold measurements on ferrite materials. We have examined the effects of data interpretation method, sample size, and sample position in the microwave cavity on the experimentally determined value obtained for h_{crit}. The data were obtained on sphere-shaped samples of polycrystalline yttrium iron garnet (YIG) by the parallel pumping technique at 8.92 GHz (X-band). In parallel pumping, the microwave field is applied parallel to the static field.[4] Polycrystalline YIG, X-band microwaves, and parallel pumping represent a fairly typical situation for routine high-power ferrite characterization.

Sample size effects for h_{crit} have been examined previously by Ollom *et al.*[5] The motivation for this new study of size effects was twofold. First, the linewidths of many polycrystalline spinel and garnet ferrite materials of current interest are somewhat smaller than for the materials considered in Ref. 5, and there was some expectation that size effects might be larger for the narrow linewidth materials. Second, over two decades have elapsed since the study in Ref. 4 and the techniques for h_{crit} measurement have evolved considerably.[3] Several questions concerning measurement accuracy and repeatibility as well as size effects come up on a regular basis in this laboratory and in others. It appeared that a fresh look at this problem was in order.

I. EXPERIMENT

The experiments were carried out using a semiautomatic system for determining the spin-wave instability threshold in ferromagnetic materials at 8.92 GHz and room temperature which is similar to the system described in Ref. 3. The experimental apparatus is shown schematically in Fig. 1. The basic system consists of pulsed 2J51 magnetron source which feeds a conventional TE_{101} rectangular cavity through a series of high-power attenuators and a high-power isolator. Reference arms A and B sample the incident power and the reflected power, respectively. A microwave power meter is used to monitor the average power level in the reference arm. The microwave switch is driven so that the crystal

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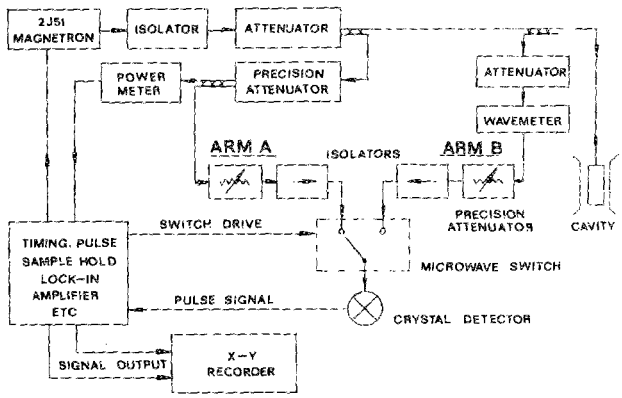

FIG. 1. Schematic diagram of the experimental apparatus used to measure the spin-wave instability threshold.

detector alternately samples the incident power pulse through reference arm A and the pulse reflected from the cavity through cavity arm B.

With proper attention to cavity calibration for the microwave field at the sample position near the cavity end wall versus the input peak power level and the power meter output voltage, one can use various signal processing techniques to obtain data on the ferrite loss versus the microwave field amplitude. Measurement details are described in Ref. 3. The essential aspects of the perturbation theory approach which is used to analyze the cavity response are described in Ref. 6. A useful procedure for precise cavity Q measurement is described in Ref. 7.

The system presently in operation is similar to the one described in Ref. 3, but with several modifications. First, the hard tube modulator which drives the magnetron source is a modified MIT-Model 3/Mark II unit from the MIT Radiation Laboratory radar program of the 1940's. The basic unit is obtainable on the surplus electronics market at nominal cost. This unit has been mounted in a standard instrument rack, and fitted with panel switches, a solid-state 800-Hz power supply, and various other accessories to make an operational laboratory high-power microwave pulse generator. The present unit can produce pulses with selectable widths of 1, 2, and 4 μs, with a peak power level of about 40 kW. Under normal operation, a high-power isolator is inserted backwards in the output arm of the magnetron system to reduce the maximum output power to the spectrometer to 1 kW.

Second, a countdown circuit has been designed to synchronize the high-voltage pulses which drive the magnetron to some selectable subharmonic of the power supply frequency. This synchronization serves to reduce the jitter in the observed crystal detector output pulses. The reduction of such jitter is extremely important, since various adjustments and measurements must be made on the incident and reflected microwave pulse signals over a rather wide range of pulse amplitudes. For a range of microwave field from 1 to 10 Oe, for example, the power must be changed by a factor of 100. Under normal operation, the countdown factor is set at four, so that the pulses are at a repetition rate of 200 Hz and synchronized to the 800-Hz power supply output as well.

Third, a special analog signal processing system has been designed to take the microwave power meter output and the pulse signal from the crystal detector and use these signals to derive two outputs. One of these outputs is a voltage proportional to the square root of the power meter output which is used to drive the x-axis of a conventional x–y recorder. This axis on the recorder is the "field axis" for the raw data, since this signal is proportional to the microwave field amplitude at the ferrite sample position in the cavity. This field axis is usually calibrated according to the procedure in Ref. 3 to yield a voltage which is simply related to the microwave field amplitude at the sample position, e.g., 100 mV/Oe. The second output is a square wave at one-half the magnetron pulse frequency and with an amplitude which is proportional to the *change* in the microwave cavity reflection coefficient that occurs above the instability threshold of the ferrite test sample. This square-wave signal is processed through a lock-in amplifier (as in Ref. 3) to provide a dc voltage for display on the x–y recorder y axis.

With all the requisite adjustments and calibrations, one obtains raw data in the form of x–y recorder traces similar to the one shown in Fig. 2. Figure 2 reproduces an actual recorder trace of the lock-in amplifier output, a signal proportional to the change in the cavity reflection coefficient as the power increases above the spin-wave threshold level, versus the microwave field amplitude at the position of the cavity end wall. The low-field portion of the trace is simply a horozontal line (base line), corresponding to *no* change in the cavity reflection coefficient. The trace breaks away from the base line at a field of about 2.5 Oe, corresponding to the onset of instability, and then increases in a more-or-less linear fashion for some range of fields above the threshold.

One can make a determination of h_{crit} directly from the recorder trace. There are several options in making this determination. The simplest procedure is to extrapolate the linear increasing part of the trace back to the base-line extension part of the trace, and use that intersection to define an "extraploated" h_{crit}. A second option is to closely examine the region of the trace where the response actually breaks away from the base line, and use this as a measure of the "exact" onset field. Of course, one may invent other options to extract h_{crit} values from the data traces. The main point to be made here is that, unless the break in the response from the base line is extremely sharp, there will always be some ambiguity in the actual numerical value that one assigns to h_{crit}. For comparative measurements, it is particularly important to be consistent in the procedure one uses to determine h_{crit}. When considering h_{crit} data from various sources, it is also important to be cognizant of the differences which can occur between different procedures. For the data in Fig. 2, for example, the "extrapolated" h_{crit} value is about 3.0 Oe, while the "exact" value is about 2.5 Oe, a difference on the order of 25%! It is clear that h_{crit} determinations can be rather dependent on the way in which one interprets the raw onset data. The results presented in the following section are based on the "extrapolated" option.

In line with this discussion on the subjectivity of h_{crit} measurements, we note that one basic industry standard for

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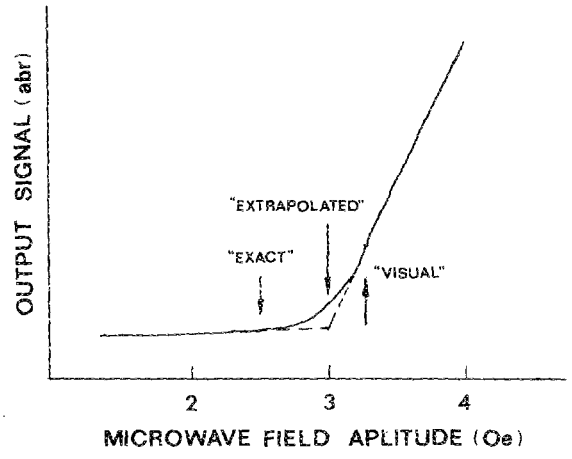

FIG. 2. Typical x–y recorder output trace of lock-in amplifier output vs the microwave field amplitude at the sample position. The lock-in output is proportional to the change in the cavity reflection coefficient as the power is increased. The threshold behavior is manifested by the break in the recorder trace from the horizontal base line. The specific convention one uses to obtain *the* threshold field h_{crit} is somewhat arbitrary. Three possible options, indicated by the arrows labeled "exact," "extrapolated," and "visual," are discussed in the text.

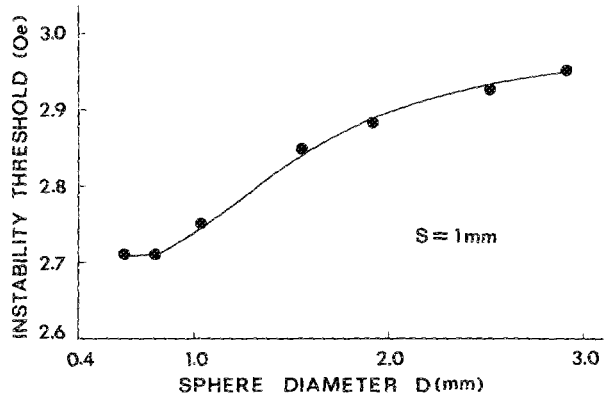

FIG. 3. The experimental threshold field h_{crit} for parallel pumping at 8.92 GHz and a static field of 1450 Oe as a function of sphere diameter. The ferrite material was commercial polycrystalline YIG. The spheres were placed 1 mm away from the cavity end wall for these measurements.

this measurement involves a visual determination of the threshold from the distortion in the microwave pulse reflected from the cavity containing the sample as viewed on an oscilloscope.[8] Such a visual technique is probably adequate for relatively low threshold materials, for which the distortion in the pulse shape becomes quite severe right above threshold. For larger h_{crit} values, however, the pulse distortions are not so pronounced (and sometimes not apparent at all!), and the visual technique would tend to overestimate the threshold value. The "visual" h_{crit} value for the situation in Fig. 2 is about 3.25 Oe.

II. SPHERE SIZE AND POSITION RESULTS

The spin-wave instability threshold field h_{crit} and the related spin-wave linewidth parameter ΔH_k are materials parameters. While they may depend on various experimental variables, such as the static field, frequency, sample shape, etc., they should not depend on sample size (within sensible limits, of course) or sample position in the measurement cavity. In practice, however, size and position effects can introduce errors into the experiment. Too large a sample leads to problems with the microwave perturbation theory analysis used to calibrate the microwave field in the cavity. Sample placement too close to the cavity wall can lead to image effects which may affect the apparent threshold. Even though various laboratories involved in such measurements have developed "rules of thumb" to avoid such errors, recent work on a variety of polycrystalline spinel and garnet materials has raised questions about these effects.

We selected a more-or-less standard commercial material, Trans-Tech G-113 polycrystalline YIG, and examined the effect of sphere size and position on the measured h_{crit} for parallel pumping at X band, with an operating frequency of 8.92 GHz. All data were obtained at the static field for minimum h_{crit}, approximately 1450 Oe. The data were obtained with a TE_{101} rectangular cavity of moderate $Q(\simeq 2000)$. Samples were mounted on the end of a small, low-loss microwave dielectric rod and inserted through a small hole in the center of the cavity end wall. The measurement procedure was similar to that in Ref. 3. The threshold field determinations were made by the extrapolation procedure described above for x–y recorder traces of the type shown in Fig. 2.

The experimental results are summarized in Fig. 3. The instability threshold h_{crit} is shown as a function of sample diameter for a specific sample end-wall distance of 1 mm. The data show that there is a clear sphere diameter dependence for the apparent threshold. One would infer from these results that a sphere diameter below approximately 1 mm or so is needed in order to measure the true h_{crit} value for the YIG material under test. For this particular situation, larger samples lead to an overestimation of h_{crit} by approximately 0.1-Oe/mm increase in the sphere diameter beyond the 1-mm limit. For accurate measurements on h_{crit} in YIG-like materials with threshold fields in the 1–10-Oe range, a sphere size of 1 mm or smaller would appear prudent.

Some comments are in order concerning size effects for thresholds above 10 Oe or below 1 Oe. When the threshold field is large, the actual onset behavior becomes even more gradual than shown in Fig. 2 and differences between the "exact" and the "extrapolated" thresholds become even larger. The ambiguity in h_{crit} due to the gradual nature of the onset can easily exceed 1 Oe under these circumstances and the smaller effects due to size, etc. become unimportant. For threshold fields below 1 Oe, one is moving into the range for narrow linewidth single crystals. Here, the narrow ferromagnetic resonance linewidths and other considerations necessitate the use of very small samples, lower powers, long pulses, reduced pulse repitition rates, and a host of other changes in the experiment that are outside the focus of this paper.

It is well known that the sample position relative to the cavity or waveguide end wall can affect the measured ferromagnetic resonance linewidth under some circumstances. It was decided to use the occasion of the present work to exam-

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ine the effect of sample position for h_{crit} as well. The "rule of thumb" generally followed in this laboratory (and others) is to place the sample about one sphere diameter, more-or-less, from the end wall. We have found that moving the sample from a location flush with the cavity end wall to one 2 mm away causes an increase in h_{crit} by only 0.02 Oe! Image effects may be significant for conditions in which the materials are more strongly excited, as in ferromagnetic resonance, for example. They do not appear to be important for the kind of below resonance processes (e.g., parallel pumping) of interest here. We note in passing that there is an apparent (and false) size effect in the h_{crit} experiment if one does not take into account the decrease in the field amplitude as one moves away from the cavity wall. This decrease was properly taken into account in the present work.

ACKNOWLEDGMENTS

The authors gratefully acknowledge R. G. West, Trans-Tech, Inc., for the polycrystalline YIG G-113 material which is used in this study. The work was supported in part by the U. S. Army, Contracts DAHCO4-75-G-0010 and DAAG29-77-G-209, and by grants from Ampex, Inc., and TRW, Inc. One of the authors (CEP) gratefully acknowledges Dr. J. J. Green, Raytheon Research Division, for help with various aspects of the high-power microwave instrumentation development.

[a] Visiting scholar from Shanghai University of Science and Technology, Shanghai, Peoples Republic of China.
[b] Present address: Boeing Aerospace Company, Seattle, Washington 98124.
[c] Present address: Iomega, Inc., Roy, Utah 84067.
[d] Present address: Department of Navy Studies, University of Colorado, Boulder, Colorado 80303.

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