Automatic System for Determining the Spin Wave Instability Threshold in Ferromagnetic Materials at Microwave Frequencies

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A system has been developed which allows spin wave thresholds in ferromagnetic materials to be determined extremely rapidly. Curves of the change in cavity reflection coefficient as a function of the microwave field amplitude are generated on an X–Y recorder. The thresholds are read directly off the calibrated recorder plot.

INTRODUCTION

ALTHOUGH experimental techniques for determining the spin wave instability threshold in ferromagnetic insulators are well known, the actual procedure is quite tedious.[1] The basic approach is to measure the imaginary part of the diagonal component χ_e'' of the microwave susceptibility tensor as a function of the microwave magnetic field amplitude h_0. At low field, χ_e'' is quite small and field independent. When h_0 exceeds the threshold value h_{crit}, χ_e'' increases sharply.[2] The standard experimental procedure is as follows: (1) Make point-by-point measurements of the reflection or transmission coefficient Γ_s for a suitable microwave cavity containing the sample as a function of the microwave power incident on the cavity; (2) calculate χ_e'' and h_0 from Γ_s and the other cavity parameters; (3) plot χ_e'' vs h_0 and determine h_{crit} as the break in the curve. Such a procedure is extremely time consuming. Considerable data are required to determine a single value of h_{crit}. An automatic system has been developed which simplifies the above procedure considerably. The system allows analog curves of the change in cavity reflection coefficient Γ_s as a function of the microwave field amplitude h_0 to be obtained directly on an X–Y recorder. The threshold fields are simply read off the calibrated recorder plot.

I. INSTRUMENTATION

The system is designed around a standard reflection cavity spectrometer for high power measurements such as described in Ref. 1. The microwave instrumentation is indicated schematically in Fig. 1. The specific system described here operates at 9.1 GHz, although the techniques have also been applied at other frequencies. The basic system consists of a 2J51 magnetron source operated in a pulsed mode which feeds a TE_{102} rectangular reflection cavity through a series of high power attenuators and a high power isolator. Directional couplers sample the incident power into reference arm A and the reflected power into cavity arm B. A commercial self-balancing microwave power meter with a temperature compensated thermistor mount[3] was used to monitor the average power level in the reference arm and provide a voltage proportional to the power incident on the cavity. A directional coupler in the reference arm feeds the crystal detector through one side of a microwave switch.[4] The detector monitors the reflected power in the cavity arm through the other side of the switch. Attenuators are provided in both the reference and cavity arms to adjust the signal levels and to facilitate point-by-point measurements when the automatic feature is not desired. The electronic circuits provide appropriate pulses to control the magnetron output and to drive the microwave switch. A block diagram of the electronic instrumentation is shown in Fig. 2. The various circuits are used to derive a dc voltage proportional to the change in the cavity reflection coefficient (vertical axis drive) and a voltage proportional to h_0 (horizontal axis drive).

Vertical Axis-Drive Reflection Coefficient

The basic approach was to use sample–hold and divide circuits to derive a square wave signal with an amplitude proportional to the change in the cavity reflection coefficient. The basic components are shown in Fig. 2. The 60 Hz trigger initiates 4 μsec pulses to modulate the magnetron and 1 μsec gate pulses to provide the sample command for the sample–hold circuit.[5] It also drives a bistable divider to provide a 30 Hz square wave output to operate the microwave switch. The gate pulse delay (2 μsec) causes the sample command to occur during the middle of the magnetron pulse so that the transients which occur at the leading and trailing edges of the reflected microwave pulse

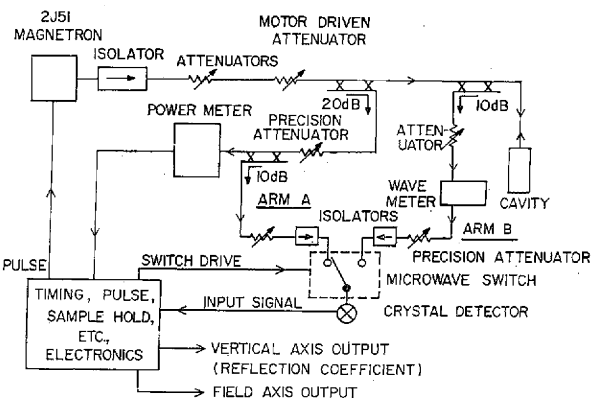

FIG. 1. Block diagram of microwave instrumentation.

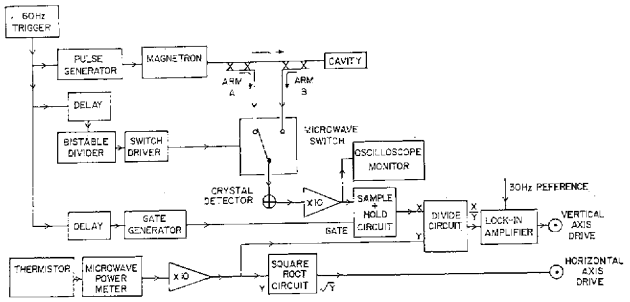

FIG. 2. Block diagram of the electronic instrumentation.

do not influence the sample–hold output. The sample–hold output feeds the numerator input of a divide circuit.[6] The denominator input comes from the recorder output of the microwave power meter. With suitable adjustments, the divider output consists of a 30 Hz square wave with an amplitude equal to the difference between the reflected and incident pulse amplitudes divided by the incident microwave power. Additional sensitivity is achieved by using a lock-in amplifier to derive a dc voltage proportional to the square wave amplitude.

The relative timing for the various signals is shown in Fig. 3. The reflected pulse is shown for a power level slightly above threshold. The microwave switch drive is such that the crystal detector alternately samples the incident power pulse through reference arm A and the pulse reflected from the cavity through cavity arm B. The sample–hold gate command occurs every cycle so that the sample–hold output is alternately V_A (incident pulse amplitude) for 1/60 sec and then V_B (reflected pulse amplitude) for 1/60 sec. The sample–hold output, then, consists of a dc level $(V_A+V_B)/2$ and a 30 Hz square wave of amplitude (V_B-V_A). The waveguide attenuators are adjusted so that $V_A=V_B$ at low power (h_0 less than h_{crit}). As the power is increased, V_A and V_B track each other as

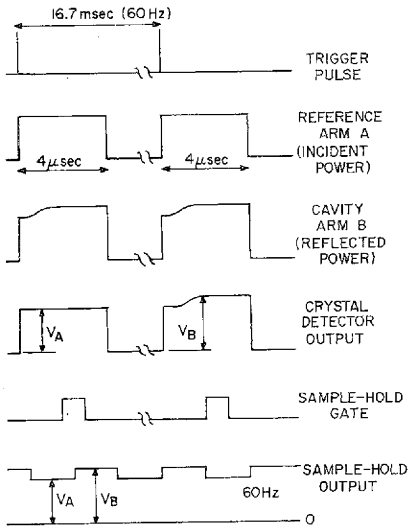

FIG. 3. Timing for the signals at various points in the automatic system.

long as $h_0<h_{crit}$ is satisfied. When h_0 exceeds the threshold, the cavity reflection coefficient increases, V_B exceeds V_A, and the square wave amplitude becomes nonzero. The divide circuit output amplitude, which is essentially $|V_B-V_A|/V_A$, is then proportional to the change in the cavity reflection coefficient above threshold.

Horizontal Axis Drive-Microwave Field Amplitude

The field axis drive voltage was derived from the power meter output and a square root circuit,[7] since $h_0 \propto$ (incident power)$^{\frac{1}{2}}$. The response time of the power meter was slow enough so that the output was essentially dc and indicative of the average power incident on the cavity.

II. ADJUSTMENT AND CALIBRATION

Since the determination of the change in the cavity reflection coefficient is reduced to the measurement of a 30 Hz square wave amplitude, the adjustments required to obtain the appropriate vertical axis response are extremely simple. The only critical adjustment is in setting the attenuators in the reference and cavity arms to give equal pulse amplitudes for $h_0<h_{crit}$. Otherwise, the small deviations of the detector from a square law response will result in a square wave divider output which is a function of incident power, even below threshold. Once this adjustment has been made, the square wave output is zero for $h_0<h_{crit}$. Crystal tracking problems are eliminated by using a single detector for both the incident and reflected microwave pulses. For a typical measurement the incident power may be swept over a range as large as 30 dB to obtain the recorder plot of $\delta\Gamma_s$ vs h_0. Care must be taken to ensure that the power levels at the detector do not exceed the maximum limits for the particular diode in use. The various attenuators were usually adjusted so that V_A did not exceed 500 mV at maximum power. The detector voltage levels at the low power end of the sweep were typically 2–3 mV. Other than retuning the magnetron to the cavity resonance, the above are the only frequent adjustments required for the vertical axis instrumentation. Initial adjustments, such as pulse widths, delay times, reference phase for the lock-in, etc., are required only infrequently.

The accuracy of the h_{crit} determination made from the recorder curve depends, to a large degree, on the accuracy of the horizontal axis calibration. From standard microwave theory,[1] the relation between the peak microwave field amplitude in a rectangular TE_{101} reflection cavity and the power incident on the cavity is given by

$$h_0^2=40[(1-\Gamma_s)/f_0](Q_L/gV_c)P_{inc}, \qquad (1)$$

where f_0 is the cavity frequency (GHz), Q_L is the loaded Q of the cavity, V_c is the cavity volume (mm^3), P_{inc} is the power incident on the cavity (W), and h_0 is the microwave

field amplitude (Oe). The g term relates the stored energy W in the cavity to the microwave field amplitude h_0,

$$W=(h_0^2V_c/4\pi)g \text{ (cgs units)}. \quad (2)$$

$$g=\tfrac{1}{8}[1+(l/a)^2]. \quad (3)$$

In Eq. (3) l and a are the cavity length and width, respectively. The reflection coefficient (dB) is related to Γ_s by $\Gamma_s=10^{-(\Gamma_{dB}/20)}$. For $f_0=9.1$ GHz, $Q_L\approx 2500$, and $\Gamma_{dB}\approx 16$ dB, the calibration is about 7 Oe^2/W incident on the cavity.

The details of the field axis calibration based on Eq. (1) will vary somewhat, depending on the range of thresholds expected. The two basic steps are: (1) Adjust the precision attenuator in the reference arm so that the maximum rating of the thermistor is not exceeded at the high power end of the sweep and (2) adjust the recorder sensitivity to give the correct X deflection for known values of peak incident power. The present 9.1 GHz system was usually calibrated at $h_0=30$ Oe [$P_{\text{inc}}\approx 130$ W from Eq. (1)] with a recorder X-axis calibration of 1 cm/Oe. It was found that tracking could be improved by using the power meter zero to touch up the calibration at $h_0=0.5$ Oe. The tracking was accurate to a few tenths of an oersted over the range $0.50<h_0<30$ Oe.

III. OPERATION

After the initial adjustments and calibration described above, the measurement of instability curves and the determination of threshold fields can be done extremely rapidly. The sample is mounted in the microwave cavity at a point of maximum rf magnetic field and the magnetron is tuned to cavity resonance while observing the detector output pulse on the oscilloscope. Fine tuning can be done by observing the lock-in amplifier output and tuning the magnetron for a minimum output level at low power (below threshold). The attenuator in the cavity arm is then adjusted to zero the lock-in output, corresponding to equal detected amplitudes for the reflected pulse in the cavity arm and the incident pulse in the reference arm.

Typical data are shown in Fig. 4 for transverse pumping at 9.1 GHz. The curves were obtained for polycrystalline yttrium iron garnet with a minimum threshold of about 3 Oe. The vertical response corresponding to a 0.5 dB change in Γ_s is indicated in the figure. The noise in the base line corresponds to a change in Γ_s of about 0.02 dB, which is nearly the same as the usual measurement error encountered in point-by-point data taking. Figure 4 shows

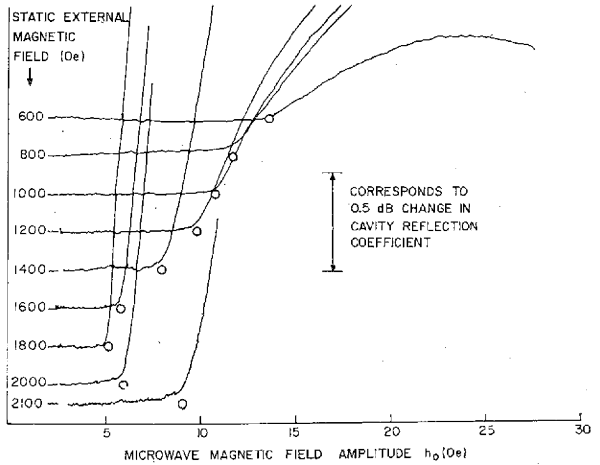

FIG. 4. Recorder plots of threshold curves for yttrium iron garnet 2 mm diam spheres at 9.1 GHz with the static magnetic field as a parameter. The change in cavity reflection coefficient is shown as a function of the microwave field amplitude h_0.

how butterfly curves of h_{crit} vs static field can be constructed on the graph used to obtain the threshold curves. The data are shown with the static magnetic field as a parameter from 600 to 2600 Oe in 200 Oe steps. By determining thresholds from the individual curves (open circles) and rotating the graph 90°, one has a plot of the threshold h_{crit} as a function of the static magnetic field. Such results can now be obtained in a matter of minutes, compared to several hours of tedious measurements, data reduction, and plotting required using previous point-by-point techniques.

ACKNOWLEDGMENT

The authors are indebted to J. Hiller for much of the circuit design incorporated in the automatic system.

[1] See, for example, J. J. Green and T. Kohane, Semicond. Prod. 7, No. 8, 46 (1964).

[2] The present discussion is limited to first order instability processes such as parallel pumping [E. Schlömann, J. J. Green, and U. Milano, J. Appl. Phys. 31, 386S (1960)]. For second order processes such as the premature saturation of the uniform precession resonance [H. Suhl, J. Phys. Chem. Solids 1, 207 (1957)] χ_e'' decreases from its low power resonance value when h_0 exceeds the threshold.

[3] Hewlett-Packard model X486A thermistor mount and model 431B power meter.

[4] Hewlett-Packard model 33006A solid state spdt microwave switch.

[5] Intronics model FS101 sample-hold module.

[6] Intronics model D401 divide module.

[7] Princeton Applied Research model 230 multiplier unit operated in a square root mode.