Effective Linewidth due to Conductivity Losses in Barium Ferrite at 10 GHz

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***Abstract*-The effective linewidth technique has been applied at 10 GHz and room temperature to single crystal barium ferrite with uniaxial anisotropy. Effective linewidths were obtained from measurements of the positive field tails of the FMR absorption and dispersion curves for circular disks barium ferrite ranging in thickness from 0.33 to 1.75 mm. The effective linewidths ranged from 125 to 2850 Oe, and vary linearly with the square of the disk thickness. This linear relation is consistent with an eddy current loss process. A fit of the data to rudimentary eddy current theory yields a resistivity of 0.8 Ω cm. This result for the resistivity is consistent with a resistivity of 1 - 4 Ω cm determined from 10 Ghz dielectric measurements and 20 Ω cm from dc resistivity measurements. The effective linewidth vs sample thickness extrapolated to zero thickness indicates an intrinsic linewidth of 60 ± 45 Oe. The results indicate that for barium ferrite samples thicker than about 0.3 mm, the effective linewidth losses are dominated by losses due to eddy currents in the material.**

I. INTRODUCTION

The standard technique to study losses in hexagonal ferrites is ferromagnetic resonance (FMR). The analysis of losses by FMR techniques, however, is limited to microwave fields that can satisfy the FMR resonance condition for positive fields and saturated samples. FMR in barium ferrite (Ba-M) with a static external field applied along the uniaxial axis requires a minimum frequency of 42 GHz. The effective linewidth technique [1,2] can be used to study losses in Ba-M at lower frequencies than is possible with FMR methods, and also to analyze losses for a range of external fields. The above resonance high field effective linewidth technique is discussed in detail in [2]. Here, the technique is applied to perpendicularly magnetized single crystal Ba-M disks at 10 GHz and room temperature.

The material used for this work consisted of high purity single crystal c-plane barium ferrite platelets obtained from Purdue University [3]. Thin disks 3 mm in diameter were ground and polished. Hysteresis loop measurements with a vibrating sample magnetometer yielded saturation induction and intrinsic anisotropy values of $4\pi M_s = 4.73$ kG and $H_A = 16.3$ kOe, respectively.

At a frequency of 10 GHz, the FMR field for Ba-M is negative and on the order of -10 kOe. The effective linewidth technique, therefore, measures the microwave losses of the positive field tails of the FMR absorption and dispersion curves. The FMR absorption and dispersion curves are directly related to the real and negative imaginary parts of the microwave susceptibility, χ, defined by, $\chi = \chi' - i\chi''$. For c-plane barium ferrite disks saturated along the disk axis, the susceptibility relations are given by

$$4\pi\chi' = \frac{4\pi M_s H_o [H_o^2 - (\omega/|\gamma|)^2]}{[H_o^2 - (\omega/|\gamma|)^2]^2 + [2H_o(\Delta H/2)]^2} \tag{1}$$

and

$$4\pi\chi'' = \frac{4\pi M_s (\Delta H/2) [H_o^2 + (\omega/|\gamma|)^2]}{[H_o^2 - (\omega/|\gamma|)^2]^2 + [2H_o(\Delta H/2)]^2}, \tag{2}$$

where H_o is an effective stiffness field given by

$$H_o = H_{ext} + H_A - 4\pi M_s(N_x - N_z). \tag{3}$$

In (1) - (3), $4\pi M_s$ is the saturation magnetization of the material, H_{ext} denotes the applied external static field, and the parameter ΔH corresponds to the half-power linewidth of the absorption curve described by $4\pi\chi''$ vs. field. N_X and N_Z are the demagnetizing factors parallel and perpendicular to the disk plane.

Fig. 1 shows theoretical curves of $4\pi\chi'$ and $4\pi\chi''$ vs. external static field H_{ext} for a linewidth of ΔH of 300 Oe and a frequency of 10 GHz for a typical thin disk with N_X and N_Z equal to 0.1 and 0.8, respectively. The FMR field H_{res} is -8.7 kOe. For saturated Ba-M crystals the accessible region is for fields between 5 to 11 kOe. This field region is very far from H_{res}. In this field region the ΔH term in the denominator of (1) and (2) can be neglected to obtain the far field susceptibility components, $4\pi\chi'_{FF}$ and $4\pi\chi''_{FF}$. The linewidth ΔH can then be treated as an average high field effective linewidth ΔH^{FF}_{eff}. The high field effective linewidth ΔH^{FF}_{eff} is then calculated from measurements of the far field microwave susceptibility components for the static field range of 5 - 11 kOe, as discussed below.

Manuscript received February 17, 1992. The work was supported in part by the United States Office of Naval Research, Contract N00014-90-J-4078.

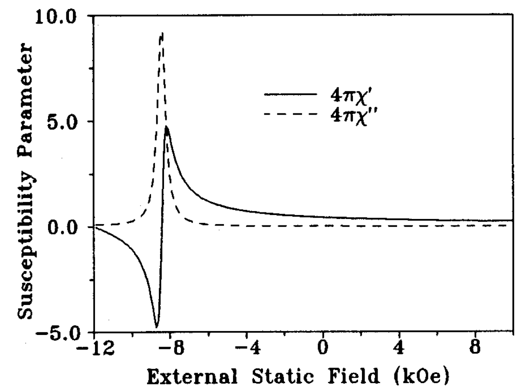

Fig. 1. Plot of susceptibility parameters $4\pi\chi'$ and $4\pi\chi''$ versus external static field for a thin barium ferrite disk at 10 GHz. The external static field is along the c-axis.

II. EFFECTIVE LINEWIDTH ANALYSIS

The starting point for the analysis is the connection between the measured cavity parameters and the microwave susceptibility relations for the sample, obtained from microwave perturbation theory [4]. The cavity frequency, ω, and cavity quality factor, Q, are measured for a given applied static field. The susceptibility relations obtained from perturbation theory are used to relate the measured cavity parameters ω and Q with the far field susceptibility components $4\pi\chi'_{FF}$ and $4\pi\chi''_{FF}$. These relations are given as

$$\left[\frac{\omega - \omega_\infty}{\omega}\right] = -K_{cav} 4\pi\chi'_{FF} = \frac{-K_{cav}}{\omega}\cdot X_F \tag{4}$$

and

$$\left[\frac{1}{Q} - \frac{1}{Q_\infty}\right] = 2K_{cav}\cdot 4\pi\chi''_{FF} = +[K_{cav}\cdot\Delta H^{FF}_{eff}]\cdot X_Q, \tag{5}$$

where X_F and X_Q are given by

$$X_F = \frac{4\pi M_s \omega H_o}{[H_o^2 - (\omega/|\gamma|)^2]} \tag{6}$$

and

$$X_Q = \frac{4\pi M_s (H_o^2 + (\omega/|\gamma|)^2)}{[H_o^2 - (\omega/|\gamma|)^2]^2}. \tag{7}$$

The parameters Q_∞ and ω_∞ are the cavity Q and frequency ω values extrapolated to infinite external field. The parameter K_{cav} is a dimensionless cavity value based on the cavity dimensions and sample volume. The parameter X_F is a parameter with units of frequency and X_Q is a parameter with units of inverse field. Both X_F and X_Q are completely determined in terms of measured parameters. One plots ω vs. X_F and obtains K_{cav} from the slope. One plots 1/Q vs. X_Q and obtains $K_{cav}\bullet\Delta H^{FF}_{eff}$. The ratio of the two slopes gives the average high field effective linewidth ΔH^{FF}_{eff}. Note that this analysis is based on the explicit assumption of a field independent high field effective linewidth. The effective linewidth results for the Ba-M disks are presented in the next section.

III. EFFECTIVE LINEWIDTH RESULTS

Effective linewidths were measured for 11 disks ranging in thickness from 0.28 to 1.75 mm. Microwave measurements were made on the disks over a static field range of 5 - 11 kOe. The lower limit on the static field was chosen to ensure saturated samples. The ω vs. X_F and 1/Q vs. X_Q results for all samples were extremely linear, indicative of a field independent ΔH^{FF}_{eff}. The effective linewidths for the disks over the static field range of 5 - 11 kOe varied from 120 ± 10 Oe for the 0.28 mm thick disk to 2870 ± 50 Oe for the 1.75 mm thick disk.

The effective linewidth clearly increases as the disk thickness increases. This increase is found to be quadratic. The effective linewidth data are plotted in Fig. 2 vs. the square of the disk thickness. The fitted straight line has a slope of 898 Oe/mm^2. The intercept for the data at zero thickness is 60 ± 45 Oe. This result for the intrinsic linewidth is consistent with previous results for barium ferrite at higher frequencies [5]. The quadratic dependence of the effective linewidth on disk thickness is suggestive of an eddy current loss mechanism. The intercept indicates a relatively

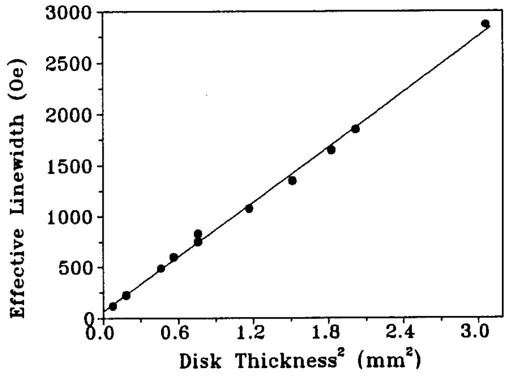

Fig. 2. Plot of effective linewidth vs. disk thickness squared for the barium ferrite disks at 10 GHz.

large intrinsic linewidth.

IV. DISCUSSION

As indicated above, the quadratic relation between effective linewidth and disk thickness suggests an eddy current loss process. The eddy current linewidth ΔH_{ec} can be calculated for the barium ferrite material for a given resistivity ρ with the use of a simple model [6,7] based on energy losses due to currents induced by the precessing magnetization. The effective linewidth result for perpendicularly saturated c-plane barium ferrite disks is

$$\Delta H_{ec} = \frac{4\pi^2 M_s \omega^2 \sigma D^2}{3c^2 |\gamma| H_o}. \tag{8}$$

This result demonstrates the expected quadratic thickness dependence for eddy current relaxation. The inverse H_o dependence, however, suggests an eddy current linewidth which decreases somewhat with increasing field. The data clearly show a constant ΔH_{eff}^{FF}. Equation (8) has been modified to obtain an estimate of the average eddy current linewidth ΔH_{ec}^{av} for comparison with experiment. The factor of $5\omega/(\gamma H_o)$ in (8), which ranges from from 0.8 to 1.2 for the field range used for the measurements, has been replaced by unity. The result obtained in practical units is

$$\Delta H_{ec}^{av}[\mathrm{Oe}] \approx \left[\frac{4\pi^2(4\pi M_s[\mathrm{kG}])(f[\mathrm{GHz}])}{3(\rho[\Omega \mathrm{cm}])}\right] D^2[\mathrm{mm}^2], \tag{9}$$

where f is the nominal cavity frequency in GHz, D is the disk thickness in mm, and ρ is the resistivity in Ω cm. The quantity in brackets corresponds to the linear dependence of the effective linewidth on disk thickness squared in Fig. 2. The fitted slope of 898 Oe/mm^2 for the 10 GHz data and (9) yield a resistivity of 0.8 Ω cm.

This microwave resistivity is comparable to microwave resistivities of 1 - 4 Ω cm obtained from dielectric measurements on 5 barium ferrite disks. The dc measured resistivity was 20 Ω cm. The measured resistivities are close to the resistivity obtained from the effective linewidth technique. The results indicate that in Ba-M samples thicker than about 0.3 mm, the effective linewidth is dominated by losses due to eddy currents.

ACKNOWLEDGMENTS

M. A. Wittenauer at Purdue University is acknowledged for producing the barium ferrite material used in this work. Dr. J. A. Nyenhuis at Purdue University is acknowledged for his helpful comments in the determination of the intrinsic anisotropy of the barium ferrite material. Dr. E. Schlömann, Raytheon Company, Lexington, MA. is acknowledged for his helpful comments in the eddy current analysis.

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