Frequency dependence of the FMR Linewidth in Single Crystal Barium Ferrite Platelets

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***Abstract*-Measurements of the frequency dependence of the room temperature ferromagnetic resonance (FMR) linewidth have been performed in well characterized barium hexaferrite single crystals at millimeter wave frequencies. A shorted waveguide measurement technique was used to obtain very clean FMR profiles in the frequency range of 55 to 90 GHz. FMR field values versus frequency determined from these profiles show good agreement with theoretical values for uniform mode precession. The FMR linewidth increases linearly with frequency at a rate of 0.54±.02 Oe/GHz and has a zero frequency extrapolation close to zero. These data yield a Landau-Liftshitz damping frequency of 4.6 X 10^6 rad/sec.**

I. Introduction

The use of barium hexaferrite in millimeter wave devices such as resonance filters and isolators has been limited because of its large loss rate at high frequencies [1,2]. The exact origins of this loss rate are not precisely known, but have been attributed to loss processes such as two magnon scattering, Kasuya-LeCraw relaxation, and eddy current dissipation [3,4]. One key to understanding the origin of these losses lies in studying the frequency dependence of their FMR linewidths. Measurements to date of the FMR linewidth in barium ferrite provide no definite conclusion as to the linewidth frequency dependence. For example, reported room temperature values of ΔH are 6 - 53 Oe at 55 GHz, and 10 - 35 Oe at 70 GHz [5]. In another study, the FMR linewidth was reported to be constant at 30 Oe over the frequency range 50-100 GHz [6].

The present work was performed in order to quantitatively measure the room temperature FMR linewidth in barium ferrite as a function of frequency from 55 to 90 GHz. Values of ΔH were obtained for thin disk samples of single crystal barium ferrite using a field-swept shorted-waveguide technique. These measurements indicate that in the frequency range from 55 to 90 GHz, ΔH increases linearly with frequency at 0.54±.02 Oe/GHz and extrapolates to near zero at zero frequency.

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II. Experiment

The single crystal barium ferrite material used in this study was prepared by standard flux-melt growth methods [7]. Single crystal platelets were cut and polished to the shape of thin disks 0.5 mm in diameter and 0.04 mm thick, with the crystal c-axis perpendicular to the disk plane. The disks were made as thin as possible. The demagnetizing factors parallel and perpendicular to the disk plane were 0.06 and 0.88, as calculated by the Osborn method [8]. Values of the saturation induction $4\pi M_s$ and the anisotropy field H_A were measured with a vibrating sample magnetometer and determined to be 4.7 kG and 16.3 kOe, respectively [3]. The barium ferrite samples were found to have a moderate conductivity. The microwave conductivity at 10 GHz ranged from 5 to 7 Ohm-cm and the dc conductivity was 20 Ohm-cm [3]. The 0.04 mm thickness value was sufficient to minimize conductivity contributions to the FMR losses in these moderately conductive materials [3].

Carefully prepared thin disks were chosen because sample shape and edges have significant effects on the FMR absorption profiles and linewidth measurements. FMR measurements on spherical samples, for example, are usually complicated by a large number of magnetostatic mode absorption lines [5] which make interpretation and accurate linewidth determination difficult. Irregular platelets or poorly prepared disks also show complicated spectra. In contrast, the present thin disk samples show very clean and simple FMR profiles. Higher order modes are weak and well separated from the main FMR line.

FMR measurements were made from 55 to 90 GHz in 5 GHz steps. Samples were placed in a shorted waveguide one half wavelength away from the shorting plate, and oriented with the applied static field applied perpendicular to the disk plane. The reflected power from the short was then monitored as the applied static field was swept through the resonance region. The incident microwave power was held constant at about 1.5 mW for all the measurements. This power level is sufficient to avoid linebroadening due to nonlinear processes or sample heating. An example absorption curve, obtained at 85 GHz, is shown in Fig. 1. The FMR profile is quite clean, with little distortion or additional structure. The full-width half-power linewidth, ΔH, can be measured from such curves to within 1 Oe. For the example profile in Fig. 1, the FMR linewidth is 44 Oe.

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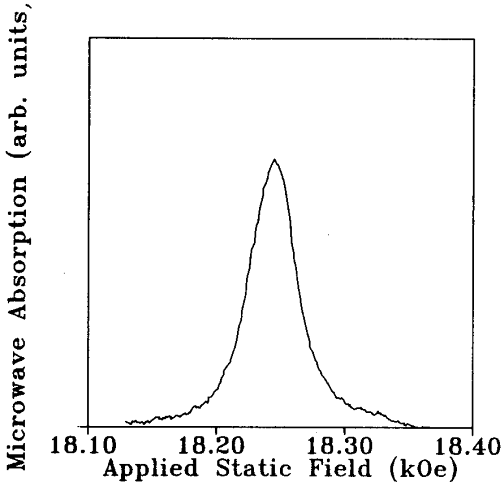

Fig. 1. FMR profile for a single crystal barium ferrite c-axis thin disk at 85 GHz with the external field applied parallel to the c-axis and perpendicular to the disk plane.

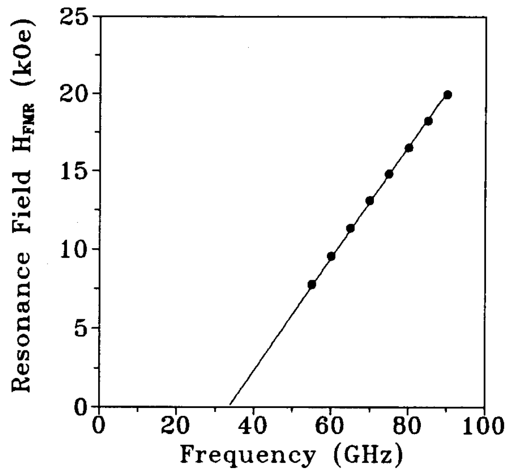

Fig. 2. Plot of FMR resonance field vs. frequency for a single crystal barium ferrite disk. The solid line is calculated from theory with H_A = 16.3 kOe and $4\pi Ms$ = 4.7 kOe.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The two basic parameters of interest are the FMR position and the FMR linewidth. Fig. 2 shows the measured FMR resonance field as a function of frequency. The experimental data are indicated by filled circles. The resonance position, H_{FMR} , shows a linear increase with frequency, at .35 kOe/GHz. The data extrapolate to $H_{FMR}=0$ frequency of 32.39±.05 GHz. A plot of the measured FMR linewidth vs. frequency is shown in Fig. 3. The FMR linewidth increases linearly with frequency at 0.54±.02 Oe/GHz and extrapolates to near zero at zero frequency. The linewidth increase of 0.54 Oe/GHz is lower than previously reported increases for single crystal hexagonal ferrites which typically range from 1 to 3 Oe/GHz [9].

For barium ferrite with the static field parallel to the c-axis and disk normal, the uniform mode FMR resonance field H_{FMR} is given by

$$H_{FMR} = f/|\gamma| - H_A - 4\pi M_s (N_x - N_z), \qquad (1)$$

where f is the frequency, γ is the gyromagnetic ratio, H_A is the anisotropy field, $4\pi M_s$ is the saturation induction, and N_x and N_z are the sample demagnetizing factors perpendicular and parallel to the applied static field, respectively. Note that H_{FMR} increases linearly with frequency. A plot of H_{FMR} vs. frequency from equation (1), based on the values of H_A, $4\pi M_s$, N_x, N_z cited above and a γ value of 2.81 GHz/kOe is shown by the solid line in Fig. 2. The agreement with the data is extremely good. It should be emphasized that there is only one adjustable parameter, γ, in this fit. The other values of the material and sample shape parameters are derived from independent static measurements. Our fitted γ value corresponds to a g-value of 2.01, which is consistent with literature values which range from 1.98 to 2.05 for barium ferrite single crystals [9]. These results support the operational assumption in this analysis of uniform mode FMR.

The variation of the FMR linewidth with frequency can be analyzed based on the phenomenological Landau-Liftshitz damping model [10]. In this model one starts with an equation of motion given by

$$\frac{dM}{dt} = -|\gamma|(\vec{M} \times \vec{H}) - \frac{\lambda}{M^2} \vec{M} \times (\vec{M} \times \vec{H}), \qquad (2)$$

where λ is the Landau-Liftshitz relaxation frequency in rad/sec, $\vec{H}$ is the total internal magnetic field vector and $\vec{M}$ is the total vector magnetization. In the standard small signal analysis for barium ferrite, one obtains an absorption profile peaked at the FMR field given by equation (1). The halfwidth of the profile, which corresponds to the FMR linewidth ΔH, is given by [10]

$$\Delta H = \frac{2\lambda\omega}{M|\gamma|^2}, \qquad (3)$$

where ω is the angular frequency in rad/sec. From (3) it is clear that the theoretical Landau-Liftshitz linewidth increases linearly with frequency. The slope of the observed linear experimental response discussed above, 0.5 Oe/GHz, corresponds to a Landau-Lifshitz damping frequency λ of

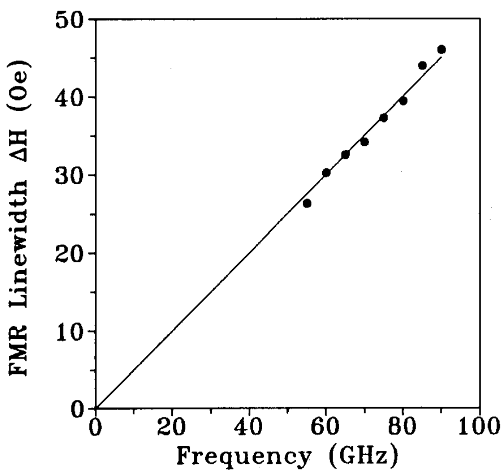

Fig. 3. Plot of FMR linewidth vs. frequency for a single crystal barium ferrite disk. The solid line through the origin is a fit of the data to Landau-Liftshitz damping theory.

4.6×10^6 rad/sec.

The identification of the physical relaxation mechanisms responsible for the present linewidth response of .5 Oe/GHz is as yet incomplete. The main such process for single crystal YIG, the so-called Kasuya-LeCraw (KL) process [11], yields a room temperature response of about 0.02 Oe/GHz for barium ferrite. Tsantes and Silber [4] have argued that the KL linewidth in barium ferrite might be larger than this estimate by a factor of ten or more, due to a combination of effects involving anisotropy, lattice distortions and optical phonons. Rare earth impurities , even at very low levels, and Fe^{2+} - Fe^{3+} valence exchange also yields a linear increase of linewidth with frequency. This response can be large. Terbium, for example, yields an estimated room temperature linewidth increase of a few tenths Oe per GHz at an impurity level of 10 ppm [11]. Effective linewidth measurements have shown that two-magnon scattering effects are also important for hexagonal ferrites [1,12,13].

IV. Conclusion

The dependence of the FMR linewidth in barium ferrite single crystals on frequency was measured in the 55-90 GHz range, at room temperature. The measured FMR profiles consisted of a single large mode which was very clean with little distortion. The FMR resonance position was found to have a linear dependence on the applied field and fitted well with the dependence predicted from uniform mode theory. This dependence confirmed that the measured absorption was due to uniform precession FMR.

The FMR linewidth versus frequency measurements indicate that the linewidth in single crystal barium ferrite scales linearly with frequency in the 55-90 GHz range. This frequency dependence is in accordance with the Landau-Liftshitz damping model and many other established loss processes. The linewidth was found to increase at about 0.5 GHz/Oe, which corresponds to a Landau-Liftshitz damping frequency, λ, of 4.6×10^6 rad/sec.

References

[1] K.M. McKinstry, C.E. Patton, M.A. Wittenauer, M. Sankarraman, J. Nyenhuis, F.J. Friedlander, H. Sato and A. Schindler, "Off resonance loss measurements in ferrites at 35 GHz," *IEEE Trans. Mag.* MAG-25, 3482 (1989).

[2] C. Vittoria, "Ferrites at millimeter wavelengths," *J. Magn. Magn. Mater.* 21, 109 (1980).

[3] J.R. Truedson, C. Patton, R. Karim. " Effective linewidth due to conductivity losses at 10 GHz in barium ferrite," *J. Appl. Phys.*, in press.

[4] E. Tsantes and L.M. Silber, " A contribution to the ferromagnetic resonance linewidth of M-phase barium ferrite" *J. Appl. Phys.* 63, No. 8, 3350 (1988).

[5] M. Labeyrie, J.C. Mage, W. Simonet, J.M. Desvignes and H. Le Gall, " FMR linewidths of barium hexaferrite at millimeter wavelengths" *IEEE Trans. Mag.*, MAG-20, 1224 (1984).

[6] M. EL Rayess, J.B. Sokolov and C. Vittoria, "Frequency dependence of the FMR linewidth in barium ferrite" *J. Appl. Phys.* 67, 5527 (1990).

[7] M.A. Wittenauer, J.A. Nyenhuis, A.I. Schindler, H. Sato, F.J. Friedlander, J.R. Truedson, R. Karim, C. Patton. " Growth characterization of high purity single crystals of barium ferrite" *J. Appl. Phys.*, in press.

[8] J.A. Osborn, "Demagnetization factors of the general ellipsoid" *Phys. Rev.* 67, No. 11-12, 351 (1945).

[9] W.H. von Aulock, *Handbook of Microwave Ferrite Materials*. New York: Academic, 1965, Secs. III & IV.

[10] B. Lax and J. K. Button, *Microwave Ferrites and Ferromagnetics*. New York: McGraw-Hill, 162, (1962).

[11] M. Sparks, *Ferromagnetic-Relaxation Theory*. New York: McGraw-Hill (1964).

[12] M.V. Kogekar and C.E. Patton, "Off resonance relaxation in hexagonal ferrites" *J. Magn. and Magn. Mater.*, 54-57, 1139 (1986).

[13] M. Labeyrie, J.C. Mace and T.M. Robinson, "Characterization of strontium hexaferrite for millimeter wave applications" *IEEE Trans. Mag.* MAG-22, 976 (1986).