OFF RESONANCE LOSS MEASUREMENTS IN FERRITES AT 35 GHz

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ABSTRACT

The effective linewidth technique at 35 GHz has been applied to polycrystalline YIG and single crystal Zn_2-Y hexagonal ferrite with planar anisotropy. Because of static field limitations, it was necessary to use low field rather than high field extrapolations to obtain the baseline cavity parameters for the loss determinations. The results show that the low-field off-resonance effective linewidth of these materials is 12 Oe for YIG and 30 Oe for Zn_2-Y. The results are consistent with estimated values of the intrinsic losses in these materials.

INTRODUCTION

Off-resonance losses in hexagonal ferrites are of current interest because of (1) the need to better understand the limits of intrinsic losses in these materials and (2) potential millimeter wave applications. Past work on hexagonal ferrites, however, has generally focused on ferromagnetic resonance (FMR) losses (e.g., FMR linewidth). There has been only very limited work on effective linewidth or off-resonance losses [1,2]. This work presents the first effective linewidth results at 35 GHz for polycrystalline YIG and single crystal Zn_2-Y hexagonal ferrite with planar anisotropy.

The effective linewidth technique was originally developed to separate intrinsic losses from inhomogeneity related and two-magnon scattering losses in ferrites [3,4]. The basic concept derives from the realization that the high frequency magnetic losses can be field dependent [5]. The presence of inhomogeneities and/or two magnon scattering processes can cause these losses to be large over a field region for which certain portions of the spin-wave manifold are degenerate with the excitation frequency, the so called manifold region. Outside of this region, the losses can be much smaller, sometimes approaching intrinsic values, even though the actual material is very far from being a perfect single crystal [6]. Off-resonance effective linewidth measurements, therefore, can provide a quantitative estimate of intrinsic microwave or millimeter wave losses in new materials.

EFFECTIVE LINEWIDTH TECHNIQUE

The basic effective linewidth technique is described in Ref. 7. Specific modifications for use at 35 GHz are described in Ref. 2. In essence, the technique involves the measurement of cavity Q and resonance frequency versus applied static field for a cylindrical TE011 transmission cavity containing the material of interest. Then, in conjunction with cavity perturbation theory and an analysis of the dynamic magnetic response of the material, these data are used to obtain the real and imaginary parts of the high frequency susceptibility as a function of field. The susceptibility data are related to the relaxation rate (or effective linewidth, ΔH_{eff}, when expressed in linewidth units) through the application of an appropriate model for the high frequency response.

High Frequency Susceptibility

The high frequency susceptibility can be modeled in terms of a uniform mode response derived from the the magnetic torque equation of motion,

$$\frac{d\vec{M}}{dt} = -\gamma (\vec{M} \times \vec{H}) , \qquad (1)$$

where γ is the gyromagnetic ratio, $\vec{M}$ is the magnetization vector in the material and $\vec{H}$ is the internal magnetic field. Both $\vec{M}$ and $\vec{H}$ are composed of static and high frequency components. The linearized small-signal equation of motion is solved in a straightforward manner to obtain the real and negative imaginary components of the high frequency susceptibility, given by $\chi = \chi' - i\chi''$.

Magnetic losses are included by replacing the resonance frequency ω_o [which appears in the expressions for χ' and χ'' derived from Eq. (1)] by a complex frequency,

$$\omega_r = \omega_o + i\eta_o , \qquad (2)$$

where η_o is a phenomenological relaxation rate. The effective linewidth ΔH_{eff} is given by

$$\Delta H_{eff} = 2 \eta_o / \gamma, \qquad (3)$$

and simply expresses η_o in equivalent linewidth units.

The relations for the real and negative imaginary components of the susceptibilty thus obtained are

$$\chi' = \frac{\gamma M \omega_\alpha (\omega_o^2 - \omega^2 - \eta_o^2)(\omega_\alpha + \omega_\beta) + 4\eta_o^2\omega_o^2}{(\omega_\alpha + \omega_\beta)[(\omega_o^2 - \omega^2 - \eta_o^2)^2 + 4\eta_o^2\omega_o^2]} \qquad (4)$$

and

$$\chi'' = \frac{2\gamma M \eta_o \omega_o (\omega_\alpha^2 + \omega^2 + \eta_o^2)}{(\omega_\alpha + \omega_\beta)[(\omega_o^2 - \omega^2 - \eta_o^2)^2 + 4\eta_o^2\omega_o^2]} \qquad (5)$$

The parameter M is the saturation induction $4\pi M$ divided by 4π. The ω_α and ω_β parameters correspond to magnetic stiffness fields in frequency units, and are related to the resonance frequency ω_o through the expression

$$\omega_o = (\omega_\alpha \omega_\beta)^{1/2} \qquad (6)$$

Equation (6) represents a general form of the well known Kittel resonance condition. The resonance frequency ω_o is simply the geometric mean of the two stiffness frequencies. For a spherical sample with no magnetocrystalline anisotropy these frequencies are given by

$$\omega_\alpha = \omega_\beta = \gamma H_o , \qquad (7)$$

where H_o is the applied static magnetic field. For a planar hexagonal ferrite thin platelet with the ap-

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plied field in plane, ω_α and ω_β are given by

$$\omega_\alpha = \gamma(H_o + 4\pi M - H_A) \tag{8}$$

and

$$\omega_\beta = \gamma H_o \ . \tag{9}$$

The H_A parameter in Eq. (8) is the planar anisotropy field. Note that ω_α/γ is the effective stiffness field for the magnetization vector tipping out of the film plane, and ω_β/γ is the stiffness field for tipping in plane.

Cavity Parameters and Effective Linewidth

The high frequency components of the susceptibility are related to the cavity quality factor Q and resonance frequency ω through the microwave perturbation theory expressions

$$\chi' = -2K[(\omega - \omega_\infty)/\omega] \tag{10}$$

and

$$\chi'' = K[1/Q - 1/Q_\infty] \ . \tag{11}$$

The ω_∞ and Q_∞ parameters correspond to the cavity resonance frequency and quality factor extrapolated to infinite field. The coefficient K is a cavity calibration parameter given by

$$K = 2V_c g/V_s \ , \tag{12}$$

where g is the cavity mode/size factor (see below), and V_c and V_s are the cavity and sample volumes, respectively.

Based on the form of the χ' expression given in Eq. (4) and the perturbation theory result in Eq. (10), one may obtain the infinite field frequency ω_∞ from plots of ω versus a "1/H" parameter p given by

$$p = \omega_\alpha\omega/[\omega_o^2 - \omega^2] \ . \tag{13}$$

Such plots are linear at high field and extrapolate to ω_∞ at $p = 0$ (or $H_o = \infty$). Similarly, Q_∞ may be obtained from plots of 1/Q versus a "$1/H^2$" parameter q given by

$$q = \frac{\omega_o(\omega^2_\alpha + \omega^2)}{(\omega_\alpha + \omega_\beta)(\omega_o^2 - \omega^2)^2} \ . \tag{14}$$

Such plots are also linear at high field and extrapolate to $1/Q_\infty$ at $q = 0$ (or $H_o = \infty$). Once ω_∞ and Q_∞ have been determined from the $Q(H_o)$ and $\omega(H_o)$ data, it is a straightforward matter to determine $\eta_o(H_o)$ and hence ΔH_{eff} versus field.

Millimeter Wave Modifications

For this work at 35 GHz, the basic effective linewidth method has been modified in two ways. First, because of static field limitations, cavity data below the FMR peak (in field) was used to determine the cavity parameters ω_∞ and Q_∞. This modification corresponds essentially to finding the extrapolations to $p = 0$ and $q = 0$ for the limit $H_o \to -\infty$. Care must be taken when making these extrapolations to avoid the low field regime for which the ferrite is not magnetized to saturation.

The second modification involves the mode/size factor g in Eq. (12). This factor can be obtained directly from the microwave field distributions in the cavity in the perturbation theory limit, which assumes that the mode is essentially the same as for the empty cavity with no sample. However, perturbation theory is accurate only for very small sample-cavity volume ratios. The error for workable sample sizes and typical 35 GHz cavities is large, on the order of 10% or greater, depending on the loading.

The approach used here was to take advantage of the form of the perturbation theory relations in Eqs. (10) and (11) to determine χ''/χ' ratios empirically, and use theoretical estimates of χ' from Eq. (4) to obtain χ'' and (thereby) η_o and ΔH_{eff}. The use of a χ''/χ' ratio causes the calibration parameter K to cancel out, so that a purely empirical value of χ''/χ' is obtained. This ratio depends on the form of the perturbation analysis but not on the specific mode assumptions. Equation (2) is then used to calculate χ' in terms of known values of γ, H_o, $4\pi M$, and H_a, by neglecting η_o effects. Under off-resonance conditions, $(\omega_\alpha\omega_\beta - \omega^2)^{1/2} \gg \eta_o$ is satisfied, and χ' is essentially independent of loss. With χ' obtained in this way, the emperical χ''/χ' ratio yields χ'', and hence η_o and ΔH_{eff} as well. As with the χ''/χ' ratio, the ΔH_{eff} value thus obtained depends on the form of the perturbation analysis but not on the details of the cavity mode.

RESULTS AND DISCUSSION

Figure 1 shows the 35 GHz effective linewidth vs. external field for a polycrystalline YIG sphere of commercial Trans-Tech material. FMR occurs in this material at approximately 12.5 kOe at 35 GHz, as shown. The upper and lower edges of the spin-wave manifold region are indicated by the arrows at 12.2 and 13.1 kOe, respectively.

The effective linewidth is relatively constant for dc fields up to 11 kOe or so, and then begins to increase. This increase occurs as the field approaches the lower edge of the spin-wave manifold region. At fields 1000 Oe or so above the upper edge of the manifold region, the effective linewidth has dropped back down to low values, values which are somewhat below the low field results. This difference has also been observed in X-band effective linewidth measurements [6]. The lack of data points for the manifold region is due to extreme degradation in the cavity Q because of the high losses at resonance. The FMR linewidth for this material is about 200 Oe at 35

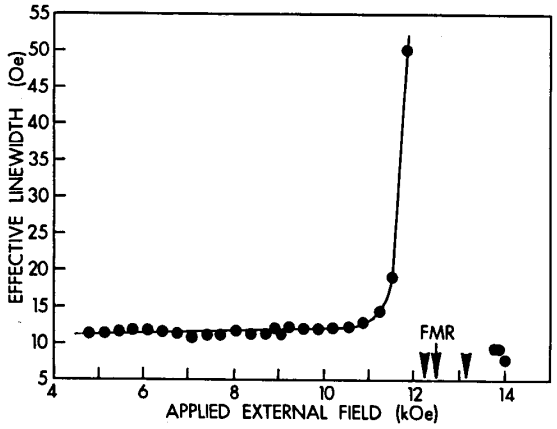
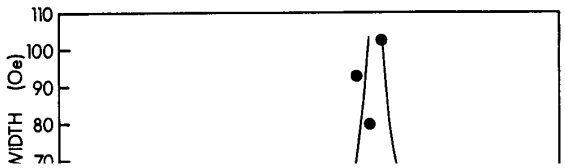


Fig. 1. Plot of effective linewidth vs. external static field at 35 GHz for a polycrystalline YIG sphere. The FMR field position is 12.5 kOe. The lower and upper spin-wave manifold limits are indicated by the arrows at 12.2 and 13.1 kOe.

GHz. This linewidth gives a rough estimate of the expected magnitude of ΔH_{eff} in the manifold region, about 4 times higher than the scale of Fig. 1.

It is to be emphasized that the increase in ΔH_{eff} in the manifold region does not represent an absorption profile. Rather, the increase reflects a growing relaxation rate due to inhomogeneities and two-magnon scattering over the manifold region for which such broadening processes can be operative. The actual FMR peak would be relatively narrow (less than 200 Oe) on the field scale of this figure. At fields below FMR the effective linewidth is about 12 Oe, a factor of 3-4 times larger than typical X-band off-resonance effective linewidths in dense polycrystalline YIG [6]. This increase is consistent with the expected linear scaling of the intrinsic loss with frequency.

Effective linewidth vs. external field data for a single crystal Zn_2-Y platelet are shown in Fig. 2. The platelet was grown from a barium borate flux in a vertical tube furnace using the technique developed by AuCoin, Savage, and Tauber [8]. The sample was characterized by means of X-ray powder diffraction, TEM imaging, and magnetic susceptibility measurements. The saturation induction $4\pi M$ was 2.34 kG and the planar anisotropy field H_A was 8.48 kOe, as measured with a vector vibrating sample magnetometer. The measured half-power FMR linewidth was 88 G at 35 GHz. Effective linewidth measurements were performed with the applied field in the plane of the platelet. The linearly polarized millimeter wave excitation was out-of-plane. FMR for this sample resides at the lower edge of the spin-wave manifold at 8.2 kOe, as shown. The spin-wave manifold region for this sample is from 8.2 to 9.0 kOe, as indicated in the figure.



outside this region provide a clear indication of the relation between the intrinsic losses and the losses around FMR. The FMR losses are large, corresponding to effective linewidths on the order of 100 Oe, about the same magnitude as the actual FMR linewidth. The off-resonance losses, on the other hand, are much smaller. At fields between 3 to 6 kOe the effective linewidth of this material is about 30 Oe. This value is consistent with expected values of the intrinsic losses in Zn_2-Y materials.

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