Frequency dependence of the ferromagnetic resonance linewidth and effective linewidth in maganese substituted single crystal barium ferrite

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Ferromagnetic resonance (FMR) and high field effective (HFE) linewidth measurements have been made at 10–90 GHz for low conductivity Mn substituted single crystal barium ferrite, $BaFe_{12-x}Mn_xO_{19}$, with $x=0.1$. The manganese compensates excess Fe^{2+} and reduces conductivity. Measurements were made on *c*-plane thin disks magnetized to saturation along the disk axis. A shorted waveguide technique was used to measure the FMR profiles and linewidths in the 55–90 GHz frequency range. High Q cavity techniques and an analysis procedure for the FMR high field tail response were used for the HFE linewidth determinations in the 10–60 GHz frequency range. The FMR linewidths increase linearly with frequency at 0.3 Oe/GHz and have a zero frequency intercept of 20 Oe. The HFE linewidths increase linearly with frequency at 0.4 Oe/GHz and have a zero frequency extrapolation of 4 Oe. This lower zero frequency extrapolation for the HFE linewidth supports an inhomogeneity origin for the 20 Oe FMR linewidth extrapolation. These data indicate intrinsic linewidths for barium ferrite of 0.3–0.4 Oe/GHz, a factor of 6–8 larger than intrinsic linewidths in single crystal yttrium iron garnet.

I. INTRODUCTION

Hexagonal ferrite materials hold promise for millimeter wave device applications because of their large anisotropy fields.[1] However, such uses of these materials have been limited because of large microwave magnetic losses. Especially large losses have been evident from recent ferromagnetic resonance (FMR) linewidth measurements[2] at 55–90 and 10 GHz high field effective (HFE) linewidth measurements[3] on flux grown barium M-type hexagonal ferrite single crystal materials. The FMR linewidths in relatively thin disks made from these materials increased linearly with frequency from ~25 Oe at 55 GHz to 45 Oe at 90 GHz. The HFE linewidths were found to scale with the square of the disk thickness and be related to eddy current losses.

In the present study, FMR linewidth and HFE linewidth measurements were made in the range 10–90 GHz on high resistivity flux grown single crystals of manganese substituted barium ferrite. The manganese substitution serves to compensate excess Fe^{2+} and reduce conductivity. The objective of this work was to determine the effect of the significantly reduced conductivity on these linewidth parameters at millimeter wave frequencies and establish limits on the intrinsic microwave losses for barium ferrite. Both linewidth parameters increase linearly with frequency for these substituted materials. The FMR linewidths are on the same order as the linewidths in the materials without manganese, but with some significant differences in frequency dependence. The HFE linewidths are significantly smaller than in the unsubstituted materials, no longer increase with disk thickness, and appear to be a good representation of the intrinsic losses.

II. MATERIALS, PROPERTIES, AND LINEWIDTHS

The material used in this study was high purity manganese substituted single crystal barium ferrite $BaFe_{12-x}Mn_xO_{19}$ with $x=0.1$. The single crystals were prepared at Purdue University by a flux melt growth method and characterized by x-ray diffraction, polarized light optical microscopy, scanning electron microscopy, and inductively coupled plasma emission stoichiometry.[4] For the FMR measurements, thin disks fabricated from carefully cleaved platelets of the single crystal materials were found to give clean and undistorted FMR line shapes and no significant extraneous resonances. Somewhat thicker disks were needed for the off-resonance high field effective linewidth measurements. Careful attention was paid to surface polish and edge preparation.

The disk samples for the measurements presented here are listed in Table I. Sample 1, of thickness 0.004 cm, was used for the FMR measurements over the entire range 55–90 GHz. For the present $x=0.1$ materials, thicker samples gave similar linewidths. This very thin sample was chosen for the presentation here in order to make a direct comparison with the FMR linewidths for the thin disk of the barium ferrite without manganese ($x=0$) given in Ref. 2. That sample was also 0.004 cm thick. Thicker samples of the $x=0$ materials gave larger linewidths, due to the conductivity losses discussed above.

Samples 2–5 were used for the HFE measurements at the indicated frequencies. Due to the decrease in cavity volume with increasing frequency, loading effects, and sensitivity problems, sample size was an important consideration for the effective linewidth measurements. Larger samples were needed for the lower frequencies and smaller samples were needed for the higher frequencies. The HFE linewidth determinations did not change with thickness.

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TABLE I. Mn substituted barium ferrite disks used for the FMR and HFE linewidth measurements.

Sample	Frequency (GHz)	Thickness (cm)	Diameter (cm)
1	50–90 (FMR)	0.004	0.062
2	10 (HFE)	0.030	0.250
3	20 (HFE)	0.0630	0.220
4	35 (HFE)	0.063	0.220
5	60 (HFE)	0.008	0.087

Details on the microwave techniques for both types of linewidths are given below.

Static magnetic properties of the samples were measured by vibrating sample magnetometry. The saturation induction $4\pi M_{\text{sat}}$ was determined to be 4.6 ± 0.1 kOe. The $x=0$ materials in Ref. 2 had $4\pi M_{\text{sat}}=4.7$ kG. The anisotropy field, defined by $H_A=2K_u/M_{\text{sat}}$, where K_u is the usual first order uniaxial anisotropy energy density parameter, was determined from measurements of the static saturation field H_{sat} for in-plane, hard direction static fields and disks of various thicknesses. Domain demagnetization effects were taken into account by measuring H_{sat} as a function of the approximate in-plane disk demagnetizing factor $N_{\|}$ and extrapolating this saturation field to $N_{\|}=0$. The anisotropy field H_A was determined to be 16.3 ± 0.2 kOe, essentially the same as for the $x=0$ materials in Ref. 2.

The FMR linewidths were determined from standard resonance absorption curves measured on the disks from 55 to 90 GHz in 5 GHz steps using the same shorted waveguide technique as in Ref. 2. The samples were placed in the center of a TE_{10} waveguide short, parallel to the side wall and one-half wavelength from the short. The microwave field was in the disk plane. The external static magnetic field was applied perpendicular to the disk plane. The incident power level was held constant at 1.5 mW for all measurements. This power level was sufficiently low to avoid the well-known FMR line broadening in hexagonal ferrites due to heating effects and nonlinear processes.[5–7]

Figure 1 shows a typical FMR absorption curve of microwave loss versus static magnetic field. This particular profile is for 90 GHz. The profile is clean and symmetric, with a half-power linewidth ΔH_{FMR} of 46 ± 1 Oe. Similar profiles were obtained over the entire frequency range from 50 to 90 GHz. If present at all, higher order modes were always weak and well separated from the main FMR peak. The resonance field increased linearly with frequency as expected from uniform mode theory and yielded a Landé g factor of 2.02. The FMR half-power linewidths were in the 35–45 Oe range and increased linearly with frequency. These linewidths for Mn substituted Ba ferrite were roughly on the same order as for the $x=0$ materials discussed in Ref. 2, but with important differences in the rate of increase in linewidth with frequency and the zero frequency linewidth intercepts. These differences are directly related to the effect of the manganese on the FMR losses. Detailed results and discussion of these FMR results will be given in Sec. III. The FMR linewidths will be denoted by ΔH_{FMR} to distinguish them from the high field effective linewidth ΔH_{HFE} introduced below.

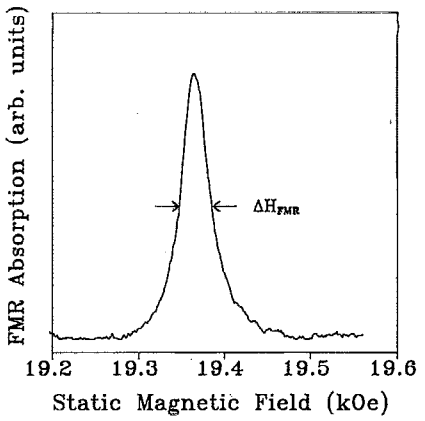

FIG. 1. FMR absorption vs. the static external magnetic field at 90 GHz for a 0.062 cm diam, 0.004 cm thick c-plane disk of single crystal manganese substituted barium ferrite $BaFe_{12-x}Mn_xO_{19}$ with $x=0.1$. The static external magnetic field was applied parallel to the c axis and perpendicular to the disk plane. The FMR linewidth, ΔH_{FMR}, given by the width of the resonance curve at half-power and indicated by the arrows, is 46 ± 1 Oe.

While FMR has been the traditional technique for the determination of microwave losses in ferrite materials, HFE linewidth values extracted from the high field tail part of the absorption curve can often provide a better measure of the intrinsic losses.[8] This effective linewidth is not usually affected by many of the inhomogeneity related relaxation processes which increase the FMR linewidth from intrinsic values. Additionally, for barium ferrite with c-axis static fields, it is possible to determine effective linewidths from the high field FMR tails at frequencies *below* the cutoff for FMR peak and linewidth measurements. The results in Ref. 3, for example, are for 10 GHz. The cut-off frequency for easy-axis field FMR in saturated barium ferrite thin disks is on the order of 43 GHz.

As indicated above and discussed in Ref. 3, HFE linewidth data have revealed a large conductivity contributions to the linewidth in unsubstituted barium ferrite. The observed increases in both the FMR and HFE linewidths with thickness reported in Refs. 2 and 3 for the $x=0$ materials were quantitatively explained in terms of eddy current loss. In this work, these HFE effective linewidth measurements have been extended to the $x=0.1$ low conductivity Mn substituted barium ferrite materials described above over a wide range of frequencies from 10 to 60 GHz.

The high field effective linewidth was measured at 10, 20, 35, and 60 GHz using the high Q cavity technique described in Refs. 3 and 9. The samples were oriented with the external static field applied perpendicular to the disk plane and the linearly polarized microwave field in the disk plane. The technique involves the measurement of the cavity quality factor Q and the cavity resonance frequency as a function of the applied magnetic field. Then, in conjunction with cavity perturbation theory and an analysis of the dynamic magnetic response of the material, these data are

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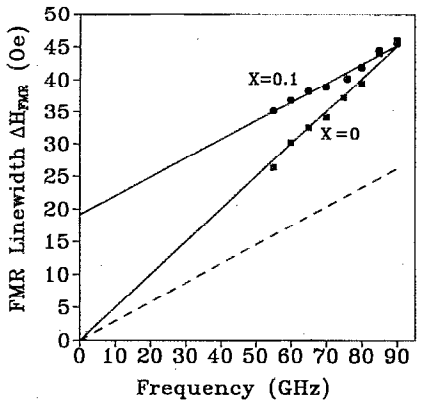

FIG. 2. FMR linewidth vs frequency for two 0.004 cm thick barium ferrite $BaFe_{12-x}Mn_xO_{19}$ c-plane thin disks with the static magnetic field perpendicular to the disk plane. The circles show data for the Mn substituted material with $x=0.1$. The squares show data for barium ferrite with no manganese ($x=0$) from Ref. 3. The solid lines show linear best fits to the data. The dashed line is the same as the fitted line for the $x=0.1$ data but shifted down to go through the origin.

used to obtain the real and the negative imaginary parts of the high frequency susceptibility on the high field tail of the FMR profile. The imaginary part of the susceptibility scales with high field effective linewidth, ΔH_{HFE}. This ΔH_{HFE} linewidth parameter can be extracted from the high field tail FMR response by a simple analysis procedure.[3]

It is to be emphasized that the applicable static field regime for ΔH_{HFE} is typically several kOe to tens of kOe *above* the FMR peak position. In this field regime, many of the inhomogeneity and two-magnon scattering based line broadening mechanisms which affect the FMR linewidth do not apply because the spin wave band is well above the operating frequency point. Under these conditions, ΔH_{HFE} may be taken as a representation of the more-or-less intrinsic losses in the absence of two-magnon or inhomogeneous linebroadening contributions.

III. FMR LINEWIDTH AND HIGH FIELD EFFECTIVE LINEWIDTH RESULTS

The measurements of the FMR half-power linewidth versus frequency for 0.004 cm thick sample 1 in Table I are shown in Fig. 2. For comparison, data for the 0.004 cm thick disk of the $x=0$ material from Ref. 2 are also shown. The $x=0.1$ data are shown by circles and the $x=0$ data from Ref. 2 are shown by squares. The solid lines show the results of straight line fits to the two sets of data. The dashed line is the same as the upper solid line fit for the present data, but shifted down to have a zero frequency intercept. Both the present $x=0.1$, FMR linewidths and the previous $x=0$, FMR linewidths increase linearly with frequency. However, both the slopes and the zero frequency intercepts are different. The slope is greater for the $x=0$ data than for the $x=0.1$ data. The zero frequency extrapolated FMR linewidth, in contrast, is relatively high for the $x=0.1$ data and near zero for the $x=0$ data. The apparent match in linewidths ~90 GHz for the $x=0$ and the $x=0.1$ samples is fortuitous and a direct result of the differences in intercepts and rise rates. The origins of these linewidths are clearly different.

Consider first the slopes for rates of increase in linewidth with frequency for the two sets of data in Fig. 2. From the dashed line, the rate of increase for the Mn substituted $x=0.1$ thin disk is 0.3 Oe/GHz. The $x=0$ sample with no Mn has a rate of increase of 0.5 Oe/GHz. The *low conductivity* Mn substituted material with $x=0.1$ has a *smaller* rate of increase than the *high conductivity* material with $x=0$ by ~0.2 Oe/GHz. This decrease is consistent with the 10 GHz eddy current effective linewidth results in Ref. 3. Those results indicate an eddy current linewidth in unsubstituted barium ferrite ($x=0$) of ~0.15 Oe/GHz for a 0.004 cm thick disk, about the same as the decrease seen here. The 0.05 Oe/GHz discrepancy is related to the frequency dependent conductivity. It is possible, therefore, to explain the decrease in the FMR linewidth frequency response for the Mn substituted barium ferrite disks in terms of an elimination of the eddy current contribution to the losses. The $x=0.1$ material, moreover, shows *no* increase in FMR linewidth with thickness. This result supports the conclusion that eddy current losses are negligible for the Mn substituted materials.

Turn now to the zero frequency FMR linewidth extrapolations for the two sets of data in Fig. 2. The $x=0$ material has a zero frequency extrapolated FMR linewidth close to zero. The substituted material has a zero frequency extrapolated FMR linewidth of almost 20 Oe. The Mn substitutions, in addition to the effect of lowering the conductivity and the related eddy current linewidth discussed above, also appear to introduce some sort of impurity related residual FMR linewidth contribution. As will be discussed shortly, this residual linewidth does not show up to the same extent for the high field effective linewidth, ΔH_{HFE}. Further work is needed to determine the origin of this FMR linewidth contribution. In any event, the effect of $x=0.1$ Mn substitution on the zero frequency FMR linewidth in these materials is substantial.

The high field effective linewidth results for the Mn substituted HFE samples in Table I are shown in Fig. 3. The squares show the ΔH_{HFE} linewidth determinations versus frequency for these samples. For comparison purposes, the circles in Fig. 3 show the same FMR linewidth data (ΔH_{FMR}) as in Fig. 2. The solid lines represent straight line fits to the data. As with the FMR linewidth results discussed above, the two key features of interest are the linewidth intercept at zero frequency and the rate of linewidth increase with frequency. The zero frequency intercept for ΔH_{HFE}, as already noted, is less than 5 Oe. This intercept is significantly smaller than the 20 Oe value for ΔH_{FMR}. The implication here is that the origin of the large ΔH_{FMR} intercept is inhomogeneity related. If the increase in linewidth due to the Mn was intrinsic, it would show up as a 20 Oe intercept for ΔH_{HFE} as well as for ΔH_{FMR}.

Turn now to the rate of increase in ΔH_{HFE} with frequency. The ΔH_{HFE} data in Fig. 3 show an increase of ~0.4 Oe/GHz. Recall that the rate of increase for ΔH_{FMR} is 0.3 Oe/GHz. Even though the agreement here is not

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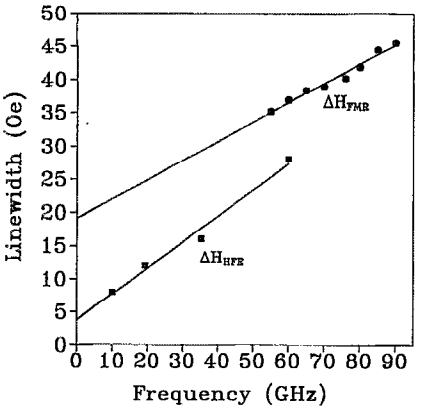

FIG. 3. HFE and FMR linewidths vs frequency for the Mn substituted single crystal barium ferrite $BaFe_{12-x}Mn_xO_{19}$ c-plane thin disks with $x=0.1$, as listed in Table I. The static magnetic field was applied perpendicular to the disk plane. The squares show data from the high field effective linewidth measurements on samples 2–5. The circles show the FMR linewidth data for sample 1 from Fig. 2.

perfect, the collective data do indicate an intrinsic linewidth in barium ferrite of 0.3–0.4 Oe/GHz. As a point of comparison, the intrinsic linewidth in single crystal yttrium iron garnet (YIG) at room temperature is ~0.05 Oe/GHz, a factor of 6–8 smaller than for barium ferrite.

IV. SUMMARY AND CONCLUSION

Measurements of the ferromagnetic resonance and high field effective linewidths for low conductivity Mn substituted barium ferrite, $BaFe_{12-x}Mn_xO_{19}$, with $x=0.1$ have been made over the frequency range 10–90 GHz. The FMR linewidth (ΔH_{FMR}) has a zero frequency intercept of 20 Oe and a rate of increase with frequency of 0.3 Oe/GHz. Previous FMR data for barium ferrite with no manganese (Ref. 3) give an intercept of zero and a 0.5 Oe/GHz rate of increase. The larger zero frequency extrapolated linewidth is attributed to inhomogeneous linebroadening due to the random Mn substitutions. The reduced rate of increase with frequency is attributed to the elimination of significant eddy current linebroadening due to the effect of the manganese in reducing the conductivity. The high field effective linewidth (ΔH_{HFE}) has a lower zero frequency intercept of ~4 Oe and a rate of increase with frequency of ~0.4 Oe/GHz. The lower zero frequency extrapolation for ΔH_{HFE} supports the conclusion that the zero frequency ΔH_{FMR} extrapolation is inhomogeneity related. The similar rates of increase for ΔH_{HFE} and ΔH_{FMR} with frequency suggest an intrinsic linewidth for barium ferrite in the 0.3–0.4 Oe range, ~6–8 times larger than for single crystal yttrium iron garnet. The fundamental origin of this larger intrinsic linewidth is unresolved. Further work on effective linewidth in the near FMR field regime and high power spin-wave linewidth for barium ferrite is needed to determine the physical origins of these losses.

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