A Review of Microwave Relaxation in Polycrystalline Ferrites

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Abstract—The microwave losses in polycrystalline ferrites can be separated into two parts: those associated with resonance (inhomogeneous linebroadening and two magnon processes) and intrinsic losses. In recent years, both types have been studied in great detail. The near-resonance relaxation can be quantitatively explained by anisotropy and/or porosity scattering if the secondary scattering among spin-waves and spin-wave relaxation are taken into account. The off-resonance relaxation is found to be quite sensitive to the polycrystal microstructure. Several mechanisms, including transit time limited relaxation and magnetostrictive phonon scattering, appear to be important, but the understanding of the basic loss processes is far from complete.

I. INTRODUCTION

In recent years, the origin of the microwave losses in polycrystalline ferrite materials has been studied in great detail. This intensive effort has resulted in a greatly expanded understanding of the physical processes which cause these losses. The work has concentrated primarily in two areas: (1) resonance losses associated with inhomogeneous broadening or degenerate spin-wave scattering; (2) microwave losses far from resonance where such scattering should not contribute. Significant new results were discovered in both cases. Concerning the resonance losses, anisotropy and porosity scattering theories were found to explain the data only qualitatively. Additional considerations of secondary scattering between spin-waves and frequency broadening of the spin-wave spectrum were needed to render the agreement quantitative. The detailed study of losses off-resonance has led to the discovery of several new relaxation mechanisms, including transit time limited relaxation and line broadening due to magnetostrictive interactions.

II. RESONANCE LOSSES

A. Porosity and Anisotropy Broadening

The two contributions which dominate the linewidth in polycrystals are due to crystalline anisotropy and porosity [1]. First consider line-broadening due to anisotropy. In the limit of large anisotropy fields, with $H_A >> 4\pi M_s$, the dipolar coupling between crystallites is weak compared to the anisotropy fields within grains so the grains tend to resonate independently. Consequently, the observed absorption curve is simply a superposition of the individual grain resonances. Considerable work on this type of anisotropy broadening has been reported [2-7].

The interesting recent results, however, have been for the opposite extreme, $H_A << 4\pi M$, and the intermediate region, $H_A \approx 4\pi M$. In the low anisotropy limit, the dipolar coupling between crystallites is much greater than the anisotropy field and the grains tend to resonate collectively. The anisotropy field fluctuations are only a small perturbation on this response. In this limit, a collective or spin-wave approach, in which the resonance mode is coupled to degenerate spin-wave modes via the anisotropy fluctuations, is a convenient starting point for a quantitative theory. The anisotropy line broadening should be on the order of the anisotropy field H_A, but dipole narrowed by a factor $H_A/4\pi M$. Detailed spin-wave theories [8] give spherical sample linewidths of

$$\Delta H \approx (H_A{}^2/4\pi M)\ (8\pi\sqrt{3}/21) \tag{1}$$

where a weakly varying frequency dependent term close to unity has been left out. Van Hook and Euler [9] have found good agreement for polycrystalline Ca-V-In substituted garnets with anisotropy fields 50 Oe $< H_A <$ 200 Oe.

Porosity broadening for reasonably dense materials (>80%) is similar to anisotropy broadening in many respects. The crystallites are tightly coupled through dipolar forces, with a small perturbation on the response due to the pore demagnetizing fields. This situation is slightly more complicated than anisotropy broadening, however, because the fluctuations are not randomly distributed. There is a directionality specified by the magnetization direction and the symmetry of the pore demagnetizing fields and the coupling is a function of spin-wave angle θ_k between the wave vector and the internal field. Sparks [10,11] performed a rather detailed calculation of the pore scattering linewidth

$$\Delta H_{\text{porosity}} = \frac{\pi^2 \omega P M_s}{2\gamma H_0}\ \frac{(3\cos^2\theta_u - 1)^2 + 1.6}{\cos\theta_u} \tag{2}$$

where P is the porosity, ω the angular frequency, γ the gyromagnetic ratio and H_0 the internal magnetic field. This is rather close to Schlömann's early result [1], $\Delta H_{\text{porosity}} = 1.5\,(4\pi M_s)P$. Both give about 26 Oe/percent porosity for YIG at 10 GHz. This compared favorably with the observed contribution of 23 Oe/percent.

These basic results have stood for many years and the question of linebroadening due to spin-wave scattering was considered to be well understood. Beginning in about 1968, workers began to examine the scattering processes in more

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detail and came up with some rather surprising results. The basic idea behind the new work was that the spin-wave scattering or two-magnon relaxation depends on the presence of modes which are degenerate with the uniform precession at the driving frequency. By modifying the density of degenerate states, the relaxation can be changed and detailed information about the scattering processes can be obtained.

Different groups varied the density of states by operating off resonance and determining the loss parameters directly from susceptibility measurements [12-17], or by operating at resonance (line-width measurement) but utilizing different frequencies, sample orientations, or different driven modes. The off-resonance technique, pursued independently by Vrehen [16] and Patton [15], has proved to be quite useful. The early data by this method revealed the drastic differences in the field dependence of the relaxation rate for anisotropy and porosity scattering, with qualitative agreement with the two-magnon scattering theories cited above.

Results [15] for anisotropy broadening for YIG materials are shown in Fig. 1. This figure shows the variation of the effective linewidth with external field for spherical samples at 10 GHz. ΔH_{eff} simply expresses the actual uniform precession relaxation rate in linewidth units. The basic confirmation of the two-magnon character of the losses comes from the abrupt increase in the effective linewidth in the field region around resonance.

The ΔH_{eff} for anisotropy scattering has essentially the same shape as the density of degenerate states curve, except for some rounding and a small bump near 3700 Oe. For porosity scattering [Fig. 3, ref. 15] an additional complication comes in because the scattering is not isotropic (the same for all θ_k), but has the angular dependence of Eq. (2). The $(3\cos^2\theta_u - 1)^2$ term goes through a minimum at $\cos^2\theta_u = 1/3$. This is precisely where the dip occurs in the ΔH_{eff} curve. Physically, this dependence comes from the fact that spin-waves are scattered differently by the dipole field around a pore, depending on the angle between k and M. Eq. (2) reflects this dependence.

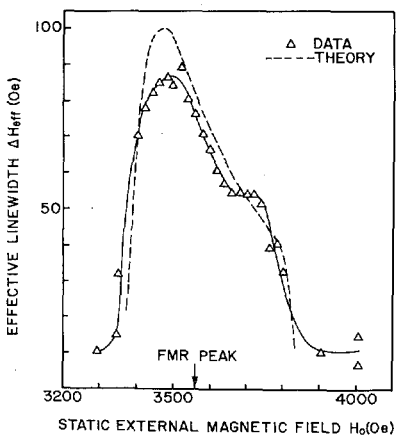

Fig. 1. Effective linewidth versus bias field for Ca-V substituted YIG at 10 GHz and room temperature [15].

B. Secondary Scattering

One disturbing feature of these near-resonance data was the nonzero value of ΔH_{eff} outside the central field region of degenerate spin waves. The residual ΔH_{eff} very far from resonance will be considered in Sec. III. Of more immediate concern in the two-magnon context, is the fact that the decrease in ΔH_{eff} as the field moves out of the degenerate region is not abrupt, but gradual. Consequently, it seems that some scattering is taking place even when there are no available spin-wave states to scatter into.

Several related ideas have been injected into the theory to resolve this contradiction. Motizuki et al. [12] and later Schlömann [18] proposed that the large ΔH_{eff} encountered outside the field interval for primary (uniform precession spin wave) scattering was due to broadening of the spin-wave frequencies themselves by secondary scattering processes with other degenerate spin waves. The dotted line in Fig. 1 was obtained from the Schlömann theory. Considering that the theory has no adjustable parameters, the agreement is quite good, even though the theoretical falloff outside the spin-wave region is still somewhat more steep than the data show. A theory by Vrehen and coworkers [19] for anisotropy broadening which includes broadening of the spin-wave energies due to anisotropy fluctuations also gives qualitative agreement with data. Motizuki [12] also included spin-wave relaxation into the porosity scattering theory. The agreement is only qualitative in this case.

Vrehen et al. have examined the effective linewidth variation near the edges of the degenerate region in great detail for the anisotropy case [20] and proposed a model which gives improved agreement. In their model, spin-wave broadening is also introduced but the broadening is attributed to anisotropy field fluctuations. In the secondary scattering theory, the spin-wave line broadening was on the order of ΔH_{eff} itself. In the Vrehen theory, it is on the order of H_A. In some cases the agreement is quite good. The correct theory probably lies somewhere in between the two limits. A modification of the same theory for moderate anisotropy materials ($H_A \simeq 4\pi M_s$) produced excellent agreement with data on Ca-V substituted YIG.

III. LOSSES FAR FROM RESONANCE

In contrast with fairly detailed understanding of resonance losses in polycrystals, the present-day knowledge concerning the spin-wave linewidth and the effective linewidth far from resonance is very incomplete. One would expect these linewidths to be very close to the resonance linewidths for high quality single crystals, since the inhomogeneous broadening considerations do not apply. (The spin-wave linewidth reflects the relaxation rate of the renormalized spin-wave modes due to the same perturbations which give rise to two-magnon scattering. There are no low-k degenerate states far from resonance, so ΔH_{eff} should also contain no two-magnon contribution.) The experimental data, however, [16,21-23] showed that ΔH_k and ΔH_{eff} for polycrystalline YIG were much larger than single crystal linewidths, by a factor of 2 to 20 depending on the particular polycrystalline microstructure. The details of these differences and their (elusive) origin are the subject of the remainder of this paper.

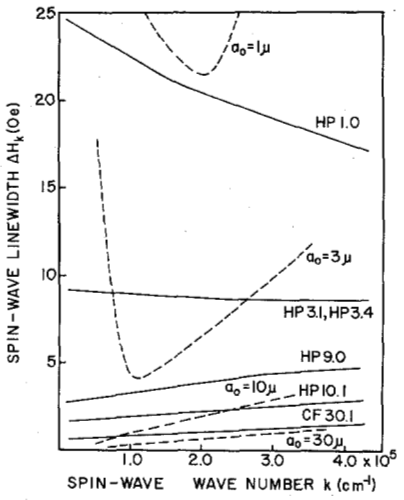

Fig. 2. Parallel pump spin-wave linewidth versus wavenumber for hot pressed YIG with various grain sizes. The dotted lines show theoretical values calculated from the transit time model [22].

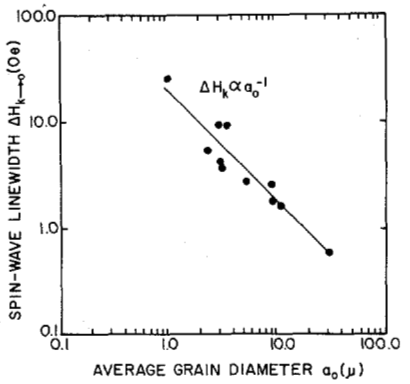

Fig. 3. Parallel pump $k = 0$ spin-wave linewidth versus average grain diameter [22].

A. Spin-Wave Linewidth and Transit-Time Relaxation

First consider the effect of grain size and porosity on the spin-wave linewidth in YIG at 9.1 GHz and 300°K. The grain size results are shown in Fig. 2 where ΔH_k versus wave-number k is shown for parallel pumping, with the average grain diameter a_0 as a parameter [22]. The data are indicated by the solid lines. CF30.1 denotes conventionally fired YIG with $a_0 = 30.1\mu$; HP10.1 denotes a hot pressed ferrite with $a_0 = 10.1\mu$, etc. The large grain (30μ) size sample shows a linear k dependence, similar to that observed in single crystals except for the somewhat larger ΔH_k. As the grain size is reduced, ΔH_k increases and for $a_0 = 1\mu$ exhibits a strong inverse k dependence. The spin-wave linewidth extrapolated to $k = 0$ is proportional to a_0^{-1}, as shown in Fig. 3. This result can be qualitatively explained by a model, proposed by Vrehen et al. [21], in which the lifetime of the excited spin-wave is limited by the transit time for the mode across an individual grain, $\tau_k = a_0/|v_g|$, where v_g is the spin-wave group velocity. The transit-time limited linewidth $\Delta H_k(t)$ is given by

$$\Delta H_k(t) = 1/\gamma\tau_k = |v_g|/\gamma a_0 . \tag{3}$$

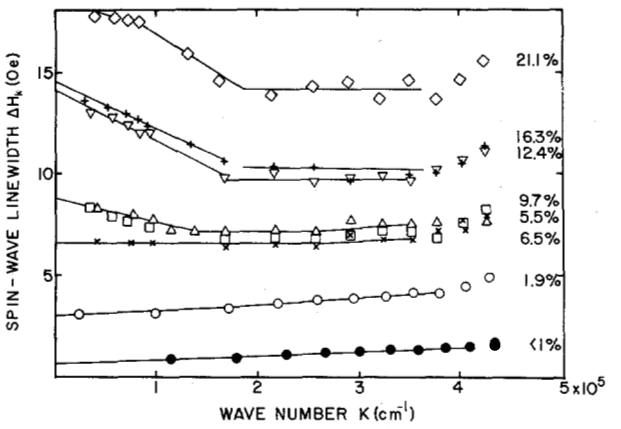

Fig. 4. Parallel pump spin-wave linewidth versus wavenumber for porous YIG [23].

The observed a_0^{-1} dependence of $\Delta H_{k\to 0}$ indicates that the model is qualitatively correct and that for the minimum k mode which can be excited $|v_g|$ does not change appreciably with grain size. For the data in Fig. 3, $|v_g|$ is on the order of 10^4 cm/s.

Borghese [24] has made a clever test of the transit-time theory by doping fine grain materials with fast relaxers and observing the change in the ΔH_k grain size dependence with doping level. For pure YIG, the variation is as shown in Fig. 3. For Mg-Mn ferrite with 2% cobalt, ΔH_k is virtually independent of a_0, in qualitative agreement with theory. The ionic relaxation for this case is much faster than the transit-time, so that the grain size mechanism is not effective.

Since $v_g = \nabla_k \omega_k$, where ω_k is the spin-wave frequency, the transit time model can also be used to calculate the k-dependence of $\Delta H_k(t)$ through the usual dispersion relation for ω_k. When pushed this far, however, the model fails rather dismally. The group velocity is given by

$$v_g = 2\gamma D k\hat{k} + \gamma 4\pi M_s k^{-1} \sin\theta_k \cos\theta_k \hat{\theta} \tag{4}$$

where D is the exchange constant (Oe-cm^2) and $(\hat{k}, \hat{\theta})$ are unit vectors in the $(\boldsymbol{k}, \boldsymbol{k} \times (\boldsymbol{k} \times \boldsymbol{H}_0))$ directions, respectively. Calculated curves for different grain sizes are shown in Fig. 2 by the dotted lines. The sharp increase in ΔH_k at low k for $a_0 = 3\mu$ and $a_0 = 1\mu$ is due to the θ term in Eq. (4). The usual assumption of $\theta_k = \pi/2$ for parallel pumping, which would give no θ component of v_g, was modified to allow k a small parallel component on the order of $2\pi/a_0$ [22]. The theory for $a_0 = 10\mu$ and $a_0 = 30\mu$ gives the right kind of k dependence, but the increase is much more rapid than shown by the data.

One possible reason for the discrepancy is that the transit time mechanism is based on an independent grain model in which the spin waves are completely destroyed at the grain boundaries. Borghese has demonstrated the independent grain behavior for widely different crystallite sizes in the same sample [25]. But even so, it is to be expected that in dense materials some propagation across grain boundaries probably occurs. It might be expected, therefore, that the grain-size-limited transit-time-relaxation model is more applicable to porous materials in which the grains are separated to some degree. ΔH_k versus k data for porous YIG, shown in Fig. 4 sup-

port this expectation. The dense material, with less than one percent porosity, has a large (30μ) grain size. The weak linear k-dependence is comparable with that expected from theory. The more porous materials, on the other hand, generally have a much smaller grain size, on the order of a few microns. The ΔH_k for these materials show a distinct minimum in the $k = 1\text{-}2 \times 10^5 \text{cm}^{-1}$ range, and increase rapidly at lower k. This is precisely the behavior expected from the transit time theory (Fig. 2, dotted lines). From these two pieces of experimental evidence, the inverse grain size dependence and the k-dependence of ΔH_k, it appears that transit time effects play a significant role in determining the spin-wave line-width for polycrystals.

Problems still exist, however. If Eqs. (3) and (4) are applied to the $\Delta H_{k\to 0}$ data to determine the actual lower limit on k ($k_{\min}$) for the unstable modes, $k_{\min}$ is about $2 \times 10^5 \text{cm}^{-1}$, independent of grain size. This means that the portions of the data for $k < 2 \times 10^5 \text{cm}^{-1}$ are meaningless. These values of $k_{\min}$, moreover, correspond to a wavelength in the 0.5 micron range. Thus if the grain limited transit time explanation is correct, it appears that a submicron scale inhomogeneity operates to limit the wavelength of the unstable modes. It should also be noted that the instability theory which is really the basis of ΔH_k measurements was originally developed under the assumption that the dimensions of the region supporting the mode were much larger than the wavelengths of the relevant spin waves. If the modes are strictly confined to single micron size grains, this assumption is no longer satisfied.

A recent investigation [26] indicates that the basic transit-time concept is valid, but that pores or nonmagnetic inclusions are the primary source of the scattering which "destroys" the spin-waves and defines the lifetime τ_k. Scotter [27] has also calculated the mean free path for spin-waves for a cubic matrix of pores or inclusions to be

$$a = 4R/3P \tag{5}$$

where R is the pore radius and P is the porosity. By utilizing this scattering length in place of the grain size a_0 in the transit time theory, he has obtained much better agreement with data for YIG with hematite inclusions of different sizes (1.2μ and 2.5μ) and different concentrations. He also finds that the porosity data in Fig. 4 is consistent with the modified theory if pore sizes of 0.2μ are assumed. This value is a little too small for conventionally sintered YIG. The behavior should also be complicated by the variation in pore size with sintering time as densification occurs. Apart from these difficulties, the Scotter pore model is certainly a step in the right direction to extend the transit-time mechanism and include more general scattering sources.

For the sake of completeness, it is necessary to indicate one further problem in the interpretation of spin-wave linewidth data which must be eventually resolved before the origin of ΔH_k is completely clarified. This problem involves the differences in the porosity (and perhaps other) dependence for the ΔH_k for first-order processes such as parallel pumping and for second-order processes such as resonance saturation. The differences are shown in Fig. 5. The 9.1 GHz parallel pump ΔH_k extrapolated to $k = 0$ and ΔH_k from resonance saturation at

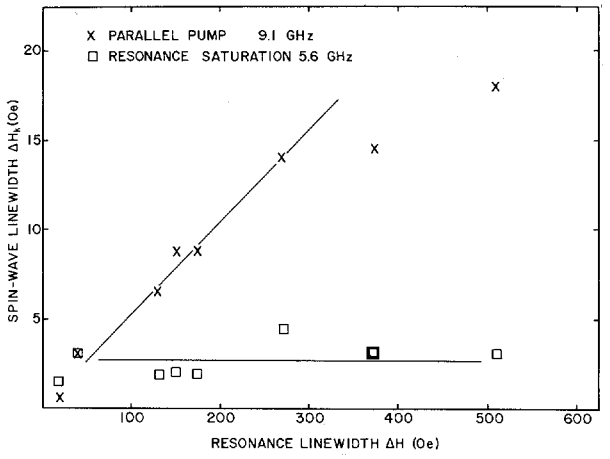

Fig. 5. Parallel pump and resonance saturation spin-wave linewidths versus resonance linewidth for YIG.

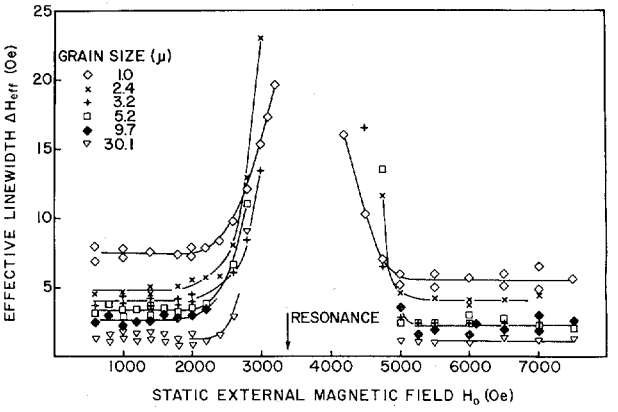

Fig. 6. Effective linewidth versus bias field for YIG samples with different grain sizes [22].

5.6 GHz are shown as a function of the resonance linewidth (used here simply as a measure of porosity). Why is the resonance saturation ΔH_k independent of porosity? Although the modes of interest are quite different, it is hard to envision a mechanism which would influence the parallel pump ΔH_k ($0 < k < 5 \times 10^5 \text{cm}^{-1}$, $\theta_k \simeq \pi/2$), but not the resonance saturation ΔH_k ($k \simeq 3 \times 10^5 \text{cm}^{-1}$, $\theta_k \simeq 0$). If there really are different mechanisms in operation, it should be possible to study different processes by using different pumping configurations. First, however, we must decide why there are differences in the first place!

B. Off-Resonance Effective Linewidth

The origin of the "larger than single crystal" effective linewidth ΔH_{eff} is the least understood of the off-resonance loss parameters. The basic problem can be seen with reference to Fig. 6. The effective linewidth for YIG at 10 GHz and 300°K is shown as a function of external field with average grain diameter as a parameter [22]. These data show the drastic increase in the relaxation in the 3000-4000 Oe region around resonance which is attributable to two-magnon scattering. Even though the off-resonance ΔH_{eff} are much smaller than ΔH_{eff} near resonance, and independent of field as well for

$H_0 < 2000$ Oe and $H_0 > 5000$ Oe, the off-resonance values are larger than for single crystals and clearly depend on microstructure. The off-resonance ΔH_{eff} also increases with porosity [23], at a rate of about 0.6 Oe/percent for YIG.

Why should the off-resonance effective linewidth increase with porosity and decreasing grain size? Two-magnon scattering to degenerate low-k modes is not possible (no degenerate modes exist). The grain size dependence for ΔH_{eff} is $a_0^{-1/2}$, and $|v_g|$ should be very small for the excited near-uniform precision mode. Both of these factors should exclude the transit time explanation. This is probably the most important remaining problem in the study of polycrystalline relaxation. It is far from resolved. Recent work has provided a few clues which may be helpful in resolving the origin of ΔH_{eff}.

Probably the most important clue is the fact that, for most of the ferrite materials examined, ΔH_{eff} (off-resonance) and ΔH_k are linearly related. For YIG, there is about 1.7 Oe of ΔH_k per Oe of ΔH_{eff}. This correlation strongly suggests that ΔH_{eff} and ΔH_k have a common origin. Borghese [24] has found similar results for small grain and rare earth doped YIG. The fine grain YIG had a ΔH_k which increased with ΔH_{eff} with about 4 Oe of ΔH_k per Oe of ΔH_{eff}. The variation for rare earth doped YIG was much weaker, with about 0.5 Oe of ΔH_k per Oe ΔH_{eff}. This particular variation (rare earth YIG) is in exact agreement with ionic relaxation theory, which gives a linewidth (ΔH_{eff} or ΔH_k) which varies linearly with frequency. ΔH_k is for parametrically excited spin-waves at $\omega/2$, while ΔH_{eff} is for the near-uniform mode at the driving frequency ω. Hence, ΔH_k should be half ΔH_{eff}.

One problem in the way of assigning a common origin to ΔH_{eff} and ΔH_k is the difficulty in rationalizing the applicability of the transit-time model to effective linewidth. For a near-uniform mode in typical 1-2 mm diam samples, the mode wavenumber is on the order of $10^3 cm^{-1}$, so that the transit time theory yields ΔH_{eff} values one hundred times smaller than the corresponding ΔH_k, even for the same scattering lengths. The applicability of transit-time arguments to uniform precession relaxation must be resolved if this common-origin view is to be accepted.

The common-origin view is weakened somewhat, however, by the clear differences in the ΔH_{eff} and ΔH_k variation with grain size. ΔH_{eff} increases as $a_0^{-1/2}$, while ΔH_k varies as a_0^{-1}. This indicates that something different must be happening. One very likely source of this difference is induced magnon-phonon magnetostriction scattering [28]. Physically, this loss channel may arise because different crystallites oriented at random will tend to deform differently during uniform mode precession. This may be viewed as the excitation of elastic vibrations (phonons) by the uniform mode, and will produce linebroadening. For the strain free case, the resultant linewidth is calculated to be

$$\Delta H_{eff}^{m-p} = 2 \frac{(\lambda_{100} - \lambda_{111})^2}{M_s} C_{44} F(\omega a_0/c_t) \qquad (6)$$

where λ_{100}, λ_{111} are magnetostriction constants, C_{44} is the shear modulus, and c_t is the shear wave velocity. $F(\omega a_0/c_t)$ depends on the shape of the inhomogeneity spectrum with a maximum value of unity at $\omega a_0/c_t = 1$. The predicted magnitude of ΔH_{eff}^{m-p}, however, is much too small to account for the data. For YIG at room temperature, $\Delta H_{eff}^{m-p} \simeq 0.03$ Oe.

It is quite conceivable that internal strains are present in polycrystals which increase the magnetostriction contribution to ΔH_{eff}. The variation with grain size and frequency should follow Eq. 6. For typical experimental conditions, $\omega a_0/c_t$ is about 10-20 so that $F(\omega a_0/c_t)$ is an inverse function of the ωa_0 product. Such a dependence has, in fact, been reported [28] but the scatter is much too great to make any definite conclusions at this time. More data over a wide frequency range for ferrites prepared under similar conditions but with a wide variation in grain size are needed.

At this point, then, the only viable contenders as explanations for ΔH_{eff} off-resonance are the transit-time model and magnetostriction induced magnon-phonon scattering. Different data lend support, to varying degrees, to each process. Much work clearly remains before the origin of ΔH_{eff} will be resolved.

IV. ULTRA-LOW-LOSS POLYCRYSTALS

Perhaps the strongest motivation for the detailed study of relaxation processes in polycrystals summarized in the last two sections lies in the expectation that better understanding will lead to better materials. Indeed, the detailed investigation of anisotropy linebroadening has led to a progressive reduction in the anisotropy linewidth. Polycrystalline garnets with resonance linewidths in the 2.0-2.5 Oe range may now be prepared routinely.

The question arises: Can these losses be reduced even further? To answer this question, it is necessary to first identify the participating mechanisms and then eliminate or minimize their contribution. From the previous sections, it is clear that the first step should be nontrivial. The basic mechanisms are not completely understood even for conventional materials. Surprisingly, however, it turns out that the losses in the new ultra-low-loss materials can be explained completely in terms of known processes. This final section will summarize the study of these materials and use the results to specify realistic lower limits on attainable loss properties for polycrystalline ferrites.

The linewidth reduction which led to the ultra-low-loss was accomplished by reducing the crystalline anisotropy field to very low values with Ca, V, In, and related substitutions [6, 7, 9, 29]. The residual linewidths were attributed to the remaining anisotropy. Effective linewidth data, however, indicate that the off-resonance ΔH_{eff} is about the same order as these FMR linewidths [22, 23]. This indicates that the resonance linebroadening cannot be dominated by anisotropy. A complete analysis of the ultra-low-linewidth origin, based on room-temperature ΔH_{eff} data and linewidth measurements versus temperature [30], indicates that anisotropy accounts for only about 0.1-0.2 Oe of the linewidth, with an ultimate polycrystalline linewidth limitation of 0.5 Oe. The presence of residual porosity ($\simeq 0.05\%$) pushes the practical limit up to about 1.2 Oe.

TABLE I
LINEWIDTH BREAKDOWN FOR SEVERAL ULTRA-LOW-LOSS SUBSTITUTED GARNETS

Sample	$\Delta H_{impurity}$ (Oe)	$\Delta H_{anisotropy}$ (Oe)	$\Delta H_{residual}$ (Oe)	$\Delta H_{effective}$ (Oe)	$\Delta H_{porosity}$ (Oe)	$\Delta H_{intrinsic}$ (Oe)
YCIVF45	0.88 ± .06	2.37 ± .11	1.15 ± .06	1.3 ± .3	0.73 ± .42	0.42 ± .36
YCIVF40	0.58 ± .16	0.22 ± .11	1.40 ± .06	1.0 ± .3	0.98 ± .52	0.42 ± .46
YCIGeF	0.35 ± .16	0.05 ± .04	1.60 ± .12	1.1 ± .3	0.85 ± .58	0.75 ± .46

This breakdown was obtained by fitting linewidth temperature data to a working equation,

$$\Delta H_{observed}(T) = \Delta H_{impurity}(300/T)^2 + \Delta H_{anisotropy}[H_A^2/4\pi M]_T/[H_A^2/4\pi M]_{300°K} + \Delta H_{residual}, \quad (7)$$

where $\Delta H_{impurity}$, $\Delta H_{anisotropy}$, and $\Delta H_{residual}$ refer to the respective linewidth contributions at 300°K. For purposes of analysis, contributions other than impurity and anisotropy broadening were lumped into a temperature independent $\Delta H_{residual}$. Equation (7) was applied to data at 300°K, 77°K, and various intermediate temperatures to get the three room temperature linewidth contributions.

The combination of results from the above analysis and effective linewidth data allow an unambiguous determination of the porosity linewidth and the intrinsic linewidth as well, based on the equations

$$\Delta H_{residual} = \Delta H_{porosity} + \Delta H_{intrinsic} \quad (8a)$$

$$\Delta H_{eff} = \Delta H_{impurity} + \Delta H_{intrinsic}. \quad (8b)$$

The results of the analysis [30] for three substituted garnets are summarized in Table I. The rare-earth impurity contribution to the linewidth decreases from 0.88 Oe for YCIVF45 down to 0.35 Oe for YCIGeF. Based on a purity of 99.99% for the Y_2O_3 starting material, an impurity linewidth of 0.5 Oe is expected for the YCIVF40. The 0.58 Oe value from the data analysis is close to this value. The anisotropy linewidth for YCIVF45 is almost exactly the same as expected from anisotropy measurements on single crystals of the same nominal composition. For YCIVF40, single crystal data are not available. A crude extrapolation form materials with half the indium content gives H_A = 23 Oe, which is much too large to fit the data. Although the errors are relatively large for the YCIGeF materials, the anisotropy contribution to the linewidth is clearly very small, less than 0.1 Oe.

The porosity linewidths are less than 1.0 Oe in all cases, corresponding to effective porosities for YCIVF45, YCIVF40, and YCIGeF of 0.04, 0.06, and 0.05%, respectively. Such low porosities are typical of values attainable by careful material preparation using standard sintering techniques. Of course, these effective porosities include second phase content as well as air pores. The residual porosity broadening, therefore, represents a major part of the linewidth in these ultra-low-loss materials. It is unlikely, moreover, that significantly higher densities can be attained with known ceramic procedures. Consequently, it appears that no major reductions in this linewidth contribution can be accomplished, except possibly by reducing the saturation magnetization.

The remaining linewidth is tabulated in the last column of Table I, under the label $\Delta H_{intrinsic}$ for lack of any better designation. This is the remaining loss after contributions due to anisotropy, impurities, and porosity have been subtracted. The linewidth values, 0.42, 0.42, and 0.75 Oe for YCIVF45, YCIVF40, and YCIGeF, respectively, are still somewhat larger than the room temperature 0.22 Oe linewidth reported for ultra-pure single crystal YIG. This intrinsic YIG linewidth, however, was reported to vary inversely with $4\pi M$. If the smaller $4\pi M$ for the present low-loss materials ($4\pi M \simeq 1750$ G for YIG) is taken into account, the expected intrinsic linewidths are about 0.35 Oe. This value is quite close to the $\Delta H_{intrinsic}$ values in Table I for YCIVF45 and YCIVF40 and within the experimental error for the YCIGeF.

In summary, it appears that the linewidth in state-of-the-art ultra-low-loss substituted YIG is completely resolvable in terms of well established relaxation processes. A detailed analysis of the linewidth variation with temperature, combined with effective linewidth data, indicates that the 2 Oe linewidth breaks down to 0.5 Oe of impurity relaxation, a few tenths of Oe from anisotropy broadening, about 0.9 Oe due to a residual 0.05 percent porosity, and approximately 0.4 Oe due to intrinsic processes of the sort used to explain single crystal YIG relaxation. The impurity contribution could be removed, in concept, simply by using higher purity Y_2O_3 starting material. The anisotropy contribution could also be eliminated by proper substitution levels. The residual porosity of 0.05% is probably a factor which must be lived with, barring the advent of radically improved ceramic processing techniques. As a result, the lowest attainable polycrystalline linewidth should be on the order of 1.2 Oe, depending on the magnetization. This represents a further 40% reduction from the present state-of-the-art linewidths.

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Temperature and Stress Sensitivities of Microwave Ferrites

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Abstract—The effect of changes in remanent magnetization on the performance of microwave ferrites employed in latching phase shifter applications has been a serious problem for many years. Reductions in the remanence ratio R are caused both by increases in temperature and by stresses which arise from thermal or mechanical origins. Recently, the molecular field theory developed by Néel has been modified to account for the effects of possible sublattice canting on the magnetization-temperature curves of substituted microwave garnets. The results of this work have made it possible to compute magnetization-temperature characteristics for a wide range of substituted iron garnets. The problem of the stress sensitivity of R has also been examined theoretically, and it has been concluded that the ratio of the magnetostriction constant to the first-order anisotropy constant is the important variable. The magnetostriction constant involved depends on the relationship of the stress direction to the applied magnetic field. In comparison with experimental results for $Y_3Mn_xFe_{5-x}O_{12}$ in both single crystal and polycrystalline forms, the theory was shown to give at least qualitative agreement. This paper will serve as an up-to-date review of this work.

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