THE MEASUREMENT OF THE LINE WIDTH OF SINGLE CRYSTAL GARNET FERRITES

by

Mark W. Niemann

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STATEMENT BY AUTHOR

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This thesis has been approved on the date shown below:

DONALD C. STINSON
Professor of Electrical Engineering
ABSTRACT

THE MEASUREMENT OF THE LINE WIDTH OF SINGLE CRYSTAL GARNET FERRITES

by

Mark W. Niemann

The line widths for yttrium iron garnet spheres were measured at various states of surface perfection using the cross-guide coupler technique. Experimental results indicated that the cross-guide coupler in conjunction with an auxiliary magnetostatic field is a sound technique for making measurements of very narrow line widths. No conclusive results were obtained on the effect of diameter on line width. However, it is thought that for the more extreme changes in diameter, there is an effect on the line width. The results definitely showed that the line width did decrease as the surface finish of the yttrium iron garnet sphere was improved.
ACKNOWLEDGMENT

The author wishes to express his appreciation to Dr. Donald C. Stinson for his many hours of patient and willing guidance without which this thesis would not have been possible.
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CHAPTER I

INTRODUCTION

1.1 General

Since their discovery some five years ago, a great deal of experimental work has gone into the determination of the basic properties of the ferrimagnetic garnet materials. One of these new materials, the yttrium iron garnet (YIG), has found considerable application in microwave device technology because of its low magnetic losses. When compared with the conventional spinel ferrites, the garnets exhibit many other desirable characteristics such as a unique valency and crystallographic position of ions. These two factors make their chemical and magnetic properties much more reproducible than the spinel ferrites.\(^1\)

The garnets, like the spinel ferrites, are ferrimagnetic oxides containing iron and rare earths. Their chemical formula is \(5\text{Fe}_2\text{O}_3 \cdot \text{X}_2\text{O}_3\) where \(X\) is a trivalent rare earth ion from samarium to lutecium, or yttrium. Of these compounds, the yttrium iron garnet (YIG) appears to have the most desirable characteristics for microwave applications.

The growth of YIG single crystals has made possible the fabrication of very narrow line width samples. Highly polished spheres of this material have exhibited line widths as narrow as 0.52 oersteds.\(^2\) This characteristic indicates an unloaded \(Q\) comparable to the \(Q\) of a simple cavity resonator. As a result, the small YIG spheres are
probably the smallest microwave gyromagnetic resonators developed to date.\(^3\)

One application of single crystal YIG resonators is as components of a narrow band-pass filter. For example, consider a conducting plate with a small hole at its center placed in a waveguide perpendicular to the direction of propagation. With a YIG single crystal sphere suspended in the hole, the combination would have a passband at the resonant frequency of the sphere and act as a short at the other frequencies. By changing the intensity of the biasing magnetostatic field, the filter can be tuned to accommodate a particular passband of frequency.\(^3\)

1.2 Statement of the Problem

A number of techniques are available to measure the line widths of ferrite materials. Of these, the one most commonly used is the resonant cavity technique. While this method is accurate throughout the line width range of ferrite materials, it has the disadvantages of being difficult to instrument and requiring considerable operator training. Another technique overcomes many of the disadvantages of the resonant cavity method by using a cross-guide coupler.\(^1\)\(^2\) The accuracy of the cross-guide coupler has been established for line width measurements in the range normally encountered with polycrystalline ferrites. However, it has not been used to measure the very narrow line widths associated with YIG single crystals. Hence, one of the objectives of this thesis is to investigate the cross-guide coupler technique as a means of measuring line widths narrower than 5 to 10
Another objective is to compare these results with data that others have obtained using the cavity technique.

From theoretical and experimental work reported in the literature, it is known that the line width of a YIG single crystal sphere can be related to its degree of surface perfection. Hence, this study will also include an analysis of the line width variation for these single crystals as a function of their surface finish.

1.3 Method of Attack

The cross-guide coupler will be used for all line width measurements. To provide an auxiliary magnetostatic field which can be varied by very small increments, the yoke of the magnet will be wound with a few turns of wire and connected to a variable dc current source.

A YIG single crystal will be ground to a spherical shape. Measurements of line width will be made as the surface finish is improved by successive polishing. The YIG sphere will then be reduced in diameter and the measurements repeated as its surface finish is improved. A comparison of the measurements made for these two diameters should give an indication of the effect of diameter on line width.

All measurements will be made at a single frequency.
CHAPTER 2
THEORETICAL ASPECTS

2.1 Characteristics

The yttrium iron garnet, like most ferrites, are a ceramic like material with specific resistivities over a million times greater than metals, with tensor relative permeabilities ranging up to several thousand and scalar relative dielectric constants ranging from 5 to 25. These materials are insulators, in contrast to ordinary ferromagnetic materials which are conductors. However, insofar as their general resonance behavior is concerned, they act as if they were ferromagnetic.

This class of material is a continuous magnetic medium that can be described by a magnetization vector, \( \mathbf{M}(\mathbf{r},t) \), which is the magnetic moment per unit volume of the specimen. The position vector is \( \mathbf{r} \), and \( t \) is time. With a magnetic field applied at \( \mathbf{r} \), \( \mathbf{M} \) will experience a torque. If this is a time varying field, the torque and \( \mathbf{M} \) will be time varying. The lattice spacing of the crystal is approximately \( 3 \times 10^{-8} \) cm. Hence, this is the shortest wavelength that will propagate through the sample. For wavelengths between \( 3 \times 10^{-8} \) cm and about \( 3 \times 10^{-5} \) to \( 3 \times 10^{-6} \) cm, the sample appears as an infinite medium, and the normal modes are plane waves propagating throughout the sample. However, for wavelengths considerably longer than these, the sample appears as a finite medium, and the modes can no longer be
represented by propagating waves. Under this condition propagation can be neglected and boundary conditions (shape of sample) become important.

2.2 Equation of Motion

In nonmagnetic materials, \( \vec{M} = x\vec{H} \), where \( x \) is a scalar magnetic susceptibility, and \( \vec{B} = \vec{H} + 4\pi\vec{M} = \gamma\vec{H} \) (cgs units), where \( \gamma \) is the scalar permeability. In ferrites, \( \vec{D} = \varepsilon\vec{E} \), where \( \varepsilon \) is a scalar relative dielectric constant as in nonmagnetic materials. However, the relation between \( \vec{M} \) and \( \vec{H} \) is determined by the equation of motion of \( \vec{M} \). From this it is found that \( x \) is a tensor for ferrites; therefore, the permeability is a tensor. As shown in Fig. 2.1, if a magnetic field is applied to the ferrite, \( \vec{M} \) will not be parallel to the magnetic field in general, as it will be in a nonmagnetic material. 

For our purpose, the equation of motion for the magnetization vector is

\[
\frac{d\vec{M}}{dt} = \gamma(\vec{M} \times \vec{H}_{\text{tot}}) + \text{a loss or damping term.}
\]

\( \vec{H}_{\text{tot}} \) = total magnetic field in the sample

\( \gamma = |e|/mc = -2.8 \text{ mc/sec/oersted} = \text{magnetomechanical ratio} \)

\( m = \text{mass of an electron} \)

\( c = \text{speed of light} \)

\( e = \text{charge of an electron} \)

In this equation, \( \vec{M} \times \vec{H} \) represents the torque exerted on \( \vec{M} \) by \( \vec{H} \), which causes \( \vec{M} \) to precess about the instantaneous direction of \( \vec{H} \). The damping term causes the angle between \( \vec{M} \) and the magnetic field to decrease so \( \vec{M} \) will reach an equilibrium precession around the surface of a cone.
Figure 2.1 - Equation of Motion Including Damping Effect
$H_{tot}$ is made up of three fields. The first is the applied field, $H_a$. The second is the demagnetizing field, $H_d$, which arises because the magnetization per unit volume has an associated magnetic field. For example, the magnetization at a particular point sees and is affected by the magnetic field from another magnetization at a different point in the sample. The third is the exchange field, $H_{ex}$, which is due to an extra energy between magnetic dipoles that are nearest neighbors in the crystal lattice and is over and above the energy associated with $H_d$. It is the exchange force that causes a ferromagnetic material to remain in a state of permanent magnetization in the absence of an applied field.

The relative orders of magnitude of these three fields are important and are, respectively,

$$H_a: H_d: M_0: 10^6 \cdot \frac{(2\pi/\lambda_0)^2}{a}$$

$a \approx 3 \times 10^{-8}$ cm = lattice spacing

$\lambda_0$ = wavelength of a disturbance in the sample

$M_0$ = the saturation magnetization along the z-axis.

When $\lambda_0$ is $10^{-5}$ to $10^{-6}$ cm, the exchange field is comparable to $H_a$ and $H_d$. For $\lambda_0$ between $3 \times 10^{-8}$ and $3 \times 10^{-5}$ cm, the exchange field is larger than $H_a$ and $H_d$, and they may be neglected. The frequencies of the spin waves, which will be explained in the next section, are determined by the exchange field, and to a lesser extent, by the demagnetizing field which also causes an anisotropy. As a result, the dispersion relation for spin waves differs depending on the
direction of propagation through the sample relative to $H_a$.

2.3 Spin Wave Analysis

A spin wave is considered to be a sinusoidal variation in a given direction of the precession angle of the electron spins about their own axis, with each succeeding spin the same number of degrees out of phase with the one preceding it. The spin wave wavelength is the distance between two in-phase spins. This type of disturbance propagates through the spin system with a direction and wavelength indicated by the vector $\mathbf{k} = (2\pi/\lambda)\mathbf{S}$ where $\mathbf{S}$ is a unit vector in the direction of propagation, and $\lambda$ is the spin wave wavelength. An infinite number of spins, all precessing uniformly with a zero phase angle between them, constitutes a spin wave with infinite wavelength. This is the $k = 0$ condition or uniform precessional mode. The Kittel relation for the resonant frequency of this mode reduces to

$$\omega_0 = \gamma H_0$$

for a sphere, where $H_0$ is the applied magnetostatic field.

Spin wave analysis is valid only for $k$ values corresponding to wavelengths much smaller than the sample size. With this as a criteria, the spin wave manifold is defined as that region of Suhl's dispersion relation where spin wave analysis is valid. This is usually taken as the region for $k > 2\pi/0.1d$, where $d$ is the sample diameter. For wavelengths larger than this, the $\mathbf{e}$ and $\mathbf{H}$ of the sample make it appear as a finite body. Acting as a resonant cavity, the longer wavelengths excite various magnetostatic modes which are independent of the impressed rf frequency. Wave solutions for these values of $k$
are the magnetostatic or Walker modes,\textsuperscript{9} and are shown by the dotted line in Fig. 2.2. Walker has shown that for samples that are spheroids, the magnetostatic mode spectrum is limited to the frequency range

$$\left| \mathbf{H}_0 - N_z M_0 \right| \leq \omega \leq \left( H_0 + 2\pi M_0 \right)$$

where $N_z$ is the demagnetization factor in the Z direction and can take on values of from 0 to $\frac{1}{4}\pi$ depending on the sample shape. The uniform mode ($k = 0$) is also a Walker mode and both the spin waves and the Walker modes are solutions of the Suhl dispersion relation.

The spin wave manifold can be divided into two parts as shown in Fig. 2.2. The first, for medium $k$ values, is a very flat region where the exchange effect can essentially be neglected. The second, for high $k$ values, is a curved region where exchange must be taken into account. The transition between these two regions occurs when $H_{ex} = a^2 k^2 \approx 1/10(H_0 - N_z M_0)$. There are an infinite number of spin waves that can exist within the manifold.

One of the major contributors to the ferromagnetic relaxation process is the scattering of the uniform precession or $k = 0$ spin waves into higher $k$ states where they are degenerate. The scattering can take on several different forms depending on the scattering mechanism and the portion of the spin wave manifold involved. For example, Geschwind and Schloemann have proposed that the major portion of line width in polycrystalline materials stems from scattering into the medium $k$ region of the manifold by the disordered properties of the magnetic sample at the grain boundaries. Such
Figure 2.2 - A Graphic Representation of Suhl's Dispersion Relation
scattering would have wavelengths corresponding to the size of the disorder or an average of from one to ten microns for spinels and garnets.\(^8\)

Cogston, et al., have indicated that a possible major contributor to the intrinsic line width of most ferrites is the energy loss to the very high \(k\) or exchange region of the manifold caused by local fluctuations of the anisotropy fields of the randomly distributed magnetic dipoles. These fluctuations have mean separations on the order of several lattice constants causing scattering to states with \(k\) values corresponding to these dimensions.\(^8\)

Another factor contributing to single crystal line widths is the surface finish of the sample. Measurements by Spencer, et al.,\(^10\) have shown that the line width of YIG single crystals decreases directly with the grit size used for polishing and approaches the intrinsic line width of a fraction of an oersted for grit sizes around 0.25 microns. Early explanations of this effect considered that the rough surface produced an inhomogeneous internal magnetic field, thus causing different spins to see different fields and producing a broadened line width. From this point of view a line width proportional to the surface irregularities and independent of frequency should result.

Buffler and others\(^10,11\) have subsequently shown that the line width of YIG single crystal spheroids are not frequency independent except for very highly polished spheroids which are nearly frequency independent. The frequency dependence is caused by the surface pits or irregularities which can be considered as scattering centers.
exactly as the grains and pores are in the polycrystalline materials. Hence, the uniform precession will lose energy predominately to the degenerate spin wave states that have k values corresponding to the dimensions of the surface irregularities.

During the process of forming and polishing the small YIG spheres, abrasives of various grit sizes are used. Those that produce surface irregularities greater than approximately 1/10 the sample diameter cause a frequency independent excitation of the modes in the low k region of the manifold on which the frequency dependent portion is superposed. This frequency independent contribution is analogous to the classical inhomogeneity line broadening mentioned earlier. As the sample is polished with grit sizes less than 1/10 the sample diameter, scattering takes place predominantly to the medium k region of the manifold. As the grit size is further reduced, a point is reached where the scattering is only to the high k region of the manifold. This means that as the surface irregularities are reduced in size, scattering due to surface effects can take place only at wavelengths corresponding to these and the smaller surface irregularities. In the final polishing with very small grits, the resulting small surface irregularities produce a measured line width which approaches the intrinsic value associated with that material.

2.4 Effects of Crystallographic Orientation

Direct measurements have established that the line widths of single crystals are different along various crystallographic directions. Unfortunately, no satisfactory explanation has been given to
date for this effect. For the frequency (approximately 9.3 km/s) at
which data were taken for this thesis, the easy (111) axis should
produce the broadest line width, the hard (100) axis the narrowest
line and the (110) axis an intermediate value. For an unpolished
single crystal sphere, there is a considerable variation in the mag-
nitude of line width measurements as a function of crystal orientation.
However, as the surface reaches a high polish, this effect is much less
noticeable. 11
CHAPTER 3
EXPERIMENTAL ASPECTS

3.1 The Test Section

As stated in Chapter 1, the cross-guide coupler technique was chosen primarily to investigate its suitability for making measurements of very narrow line widths. In addition, this method is easier to operate and both simpler and cheaper to instrument than the cavity technique. While a complete treatise covering the theory of the cross-guide coupler appears elsewhere, the method will be briefed to provide continuity for the reader.

A schematic of cross-guide couplers for various operating frequency bands is shown in Fig. 3.1. Essentially, the system consists of a source of microwave power which feeds into a test section. The test section is made from waveguide stock appropriate to the frequency band at which measurements will be made. For X-band, which was used for this thesis, the coupler is constructed from two pieces of waveguide stock, joined at right angles to their broad faces. At their joined surfaces, each waveguide is machined down such that their combined thickness is less than that of ordinary waveguide stock. A small coupling hole is drilled through the common wall, and the sample is suspended therein with ducco cement. The primary arm is terminated with a tunable short. One end of the secondary is terminated with a matched load and the other with a sensitive, calibrated detector.
Primary waveguide

Secondary waveguide

H_{dc}

<table>
<thead>
<tr>
<th>Coax</th>
<th>Common Wall Thickness</th>
<th>Coupling Hole Diameter</th>
<th>Outside Diameter</th>
<th>Inside Diameter</th>
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<tr>
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<td>0.200 in.</td>
<td>0.311 in.</td>
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Primary Waveguide

Secondary Waveguide

H_{dc}

<table>
<thead>
<tr>
<th>Band</th>
<th>Common Wall Thickness</th>
<th>Coupling Hole Diameter</th>
<th>Access. Hole Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>S Band</td>
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<td>0.393 in.</td>
<td>1.0 in.</td>
</tr>
<tr>
<td>X Band</td>
<td>0.020 in.</td>
<td>0.125 in.</td>
<td>0.75 in.</td>
</tr>
<tr>
<td>K_u Band</td>
<td>0.015 in.</td>
<td>0.085 in.</td>
<td>0.50 in.</td>
</tr>
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Figure 3.1 - Cross-Guide Test Couplers
With no external magnetostatic field applied, only the electric field component of the dominant mode can couple power from the primary into the secondary arm. To prevent this, the primary tunable short is adjusted to a multiple of half guide wavelength from the coupling hole, causing a null of electric field at that point. With a magnetostatic field applied normal to the broad face of the coupler and adjusted for ferromagnetic resonance, the transverse component of the rf magnetic field in the primary excites the uniform mode in the sample. The precession of spins in the sample induces an rf microwave field in a plane which is orthogonal to both the exciting rf field and the magnetostatic field. This induced field will be longitudinal in the primary arm and transverse in the secondary. However, in the primary arm, the TE_{10} mode is the only permitted one; hence, the induced component will not propagate in the primary, but will propagate in the secondary. The coupled power can be expressed in terms of the non-diagonal component of the magnetic susceptibility of the ferrite where

\[
\begin{align*}
C' &= C_0 + 20 \log |X_{xy}| \\
C_0' &= 20 \log \left[ \frac{2\pi d^3}{(3ab\lambda g)^{-1} F_H} \right] \\
X_{xy} &= \text{non-diagonal magnetic susceptibility} \\
d &= \text{diameter of the coupling hole} \\
a \text{ and } b &= \text{width and depth of the waveguide, respectively} \\
\lambda g &= \text{guide wavelength} \\
F_H &= \text{quantity measuring attenuation due to coupling hole thickness}
\end{align*}
\]
As shown in Fig. 3.2, the line width ($\Delta H$) is defined as the incremental field between the points where the real part of $X_{xy}$ (absorptive component) is one half the peak resonance. However, this difference in field is the same as that measured at the 3 db points on the coupled power curve. Therefore, the line width can be determined by simply noting the two values of the magnetostatic field where the coupled power is down 3 db from its peak value.

3.2 Measurement Procedure

All measurements were made with the klystron set at 9.289 kmc and modulated with a 1000 cps square wave. A block diagram of the instrumentation is shown in Fig. 3.3. Not shown is the six inch Varian magnet which provided the magnetostatic field and the Numer Model M-2 precision gaussmeter which was used to determine the magnitude of the magnetostatic field.

Detailed procedure entailed placing the sample in the test section and making the appropriate adjustments. A standing wave indicator (VSWR) was connected to the detector on the secondary arm to indicate a measure of the coupled power. With the rf field applied, the intensity of the magnetostatic field was adjusted to ferromagnetic resonance and left in this condition until the VSWR showed that steady state conditions had been reached in the sample.

For measurements of line widths greater than 2 oersteds, only the magnetostatic field of the Varian magnet was required. The VSWR was adjusted to 0 db at ferromagnetic resonance by proper adjustment of a variable attenuator in the primary arm. The magnetostatic field
Magnetic susceptibility ($\chi$) and absorbed power ($P$) as a function of field $H_{dc}$

Figure 3.2
Figure 3.3 - Block Diagram of Measurement System
was reduced to 0 and subsequently increased until the VSWR indicated 3 dB. \( H_1 \) was determined by use of the gaussmeter, a Collins R-288/URR communications receiver as an external means of measuring the frequency of the gaussmeter oscillator, and suitable conversion tables. The static field was further increased until the VSWR again registered 3 dB, or \( H_2 \). The line width was determined by \( H_2 = H_1 \).

For measurements of line widths less than 2 cemisteds, the field of the Varian magnet was used to establish and make large changes in the magnetostatic field. To provide an auxiliary static field which could be varied by small increments, the yoke of the Varian magnet was wound with 10 turns of wire and connected in series with a dc source and a carbon pile rheostat. By use of the gaussmeter and the Collins receiver, a plot was made of the value of the current in the yoke windings versus the magnetostatic field established by this current. The rest of the procedure was generally the same as before except that the Varian magnet was used to establish the field to the first 10 dB point. The auxiliary field was then increased and the value of the dc current was noted at each of the 3 dB points. The values of field at each of these points was found by entering the dc current vs field curve.

3.3 Sample Preparation

Many attempts were made to form YIG crystals into usable samples; however, only three formed into usable spheres. One of these samples was obtained from Melabs and the other two from The Microwave Chemical Co. During the grinding of the Melabs sample on 600 paper, two small inclusion holes appeared, so it was decided to reject this sample in favor of the two from Microwave Chemicals. Of these two,
one displayed an erratic power absorption curve for which no explanation could be given. We were later informed by the manufacturer that such odd characteristics did occur occasionally during his preparation of spheres and that these samples were rejected. Therefore, measurements of line width should be made early in the sample preparation so that any erratic samples can be rejected. The other Microwave Chemical sample displayed a normal power absorption curve and was used for most of the experimental work.

Two methods were used to form the rough YIG single crystals into small spheres. The first was the conventional method in which the crystal is whirled in a closed abrasive raceway by compressed air introduced tangential to the circular portion of the device. Although this method has proven sound in forming spheres of polycrystalline materials, it displayed a number of disadvantages when used for YIG single crystals. First, the hardness of the YIG crystal appears to vary in different crystalline directions, causing the material to form into shapes other than spherical. Second, the crystals have a tendency to cleave along a preferential direction due to the impact caused by the stream of compressed air. Third, the rotation of the sample during the tumbling process takes place around the centroid of mass, hence, grinding tends to include preferentially any inclusion holes.

The second method of grinding and polishing did produce more spherical samples. This method consisted of a circular, 8 inch diameter, horizontally rotating disk mounted on the shaft of an 1800 rpm
electric motor. The wheel was surrounded by an open can which extended above the wheel and acted as a catcher for flying debris. The entire device was mounted on a suitable frame. A band cut to the same diameter as the wheel secured the abrasive disks to the flat surface of the wheel. The sample was retained on the rotating abrasive by means of a vertically supported aluminum tube which was lined with a soft plastic material to reduce the pitting effect of the crystal impacting against the interior of the aluminum tube. In order to retain the sample within the tube, it was necessary to have a very close, non-contacting fit, between the bottom of the plastic lined tube and the top of the wheel. Variations in grinding severity can be obtained by appropriate positioning of the tube with respect to the wheel radius. This method worked satisfactorily for this thesis down through the metallurgical polishing papers, and for sample diameters as small as 0.035 inches.

Final polishing of the spheres was accomplished by use of a ball mill. The sphere was placed in a small, square, plastic box, together with a quantity of aluminum oxide powder. The small box was taped closed and rotated in the ball mill for three days. After removal, an inspection showed that the surface finish of the sample had improved considerably, and that the aluminum oxide had adhered to the walls of the plastic box causing it to act as a hard polishing surface.

During all phases of grinding and polishing, a 20 power microscope was used to inspect the surface finish of the spheres.
3.4 Experimental Errors

Two quantities were measured and should be investigated for error. These were the operating frequency of the klystron and the magnetostatic field intensity.

Since one of the objectives of this thesis was to study the line width of the single crystal YIG as a function of surface finish, the experimentation was conducted at a single klystron frequency. As a result, the operating frequency of the klystron oscillator was not critical so long as it remained constant. This frequency was measured with an H P X 530A cavity frequency meter which has an accuracy of ±0.10 percent.

Characteristically, the line width of a small, polished YIG single crystal is very narrow. Hence, measurement of the magnetostatic field at each of the 3 db points of the coupled power curve is critical. These points were indicated by an H P 415B standing wave indicator (VSIR) whose accuracy within a given range setting is ± 0.1 db assuming a square law crystal characteristic. An error of ± 0.1 db out of 3 db corresponds to an error of ± 3%. Therefore, while the absolute value of the line width may be in error by 3%, the variation of line width between different settings would be more on the order of 1.0%. Since X-ray equipment was not available to determine the crystallographic axes, two separate readings were made for each of three random orientations of the YIG crystal. In all cases, the line widths for one orientation were within 20% of another. For each orientation the two readings were almost always the same,
indicating excellent resatability of the equipment.

The magnitude of the magnetostatic field was measured with a Numar Model M-2 precision gaussmeter. This device has an oscillator whose frequency is proportional to the intensity of the field to an accuracy of ± 0.001%. The gaussmeter frequency was detected externally by a Collins R 288/URR communications receiver which is accurate to ± 500 cps. The field intensity was approximately 3300 oersteds. Therefore, the accuracy of measurement at this value of field is on the order of ± 0.003%.

For the highly polished spheres, the relative fields were determined with the auxiliary magnetostatic field. The current in the yoke windings at each point of measurement was determined with a Weston ammeter whose accuracy is ± 0.5% at a full scale reading. Using these currents, a human inaccuracy, estimated at ± 2.0%, was experienced in reading relative values of \( H_1 \) and \( H_2 \) from the curve. However, averaging the values obtained for each of the three crystal orientations for a given state of polish should cause this error to decrease. Additionally, this thesis was not directed toward obtaining the absolute minimum line width for YIG single crystals, but rather toward studying the effect of surface finish as it relates to line width. As a result, relative orders of magnitude of line width for each state of surface polish were of more importance than absolute values.

3.5 Results

A. Measurement technique: In Fig. 3.4, it can be seen that
Polishing Materials

<table>
<thead>
<tr>
<th>Grit Designation</th>
<th>Measured Particle Size - Microns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alum. Oxide</td>
<td>?</td>
</tr>
<tr>
<td>4/0</td>
<td>5</td>
</tr>
<tr>
<td>3/0</td>
<td>15</td>
</tr>
<tr>
<td>0</td>
<td>25-30</td>
</tr>
<tr>
<td>600</td>
<td>40</td>
</tr>
<tr>
<td>320</td>
<td>70</td>
</tr>
</tbody>
</table>

Figure 3.4 - A Comparison of Line Width vs. Grit Size for a YIG Single Crystal at a Frequency of 9.289 kmc.

Data obtained by Spencer, et al.

Experimental for this thesis.
for single crystal YIG spheres, the line width decreases as the surface finish is improved. In addition, the experimental data obtained with the cross-guide coupler shows a favorable comparison with the data obtained by Spencer, et al., who used a cavity resonator. Part of the apparent difference between the two methods no doubt arises from the difficulty in estimating the grit sizes of the various grinding and polishing papers with a 100 power microscope. The experimental point plotted at one micron is a pure estimate of grit size for the aluminum oxide powder as the particles were too small to measure under the microscope.

At certain states of surface finish which produced line widths of less than 2 cersteds, extra measurements were made to study the effects of varying the position of the sample in the test section. The line width was measured with the sample in three different positions along the axis of the center of the coupling hole. In the first position, it protruded into the primary arm; in the second, it was equidistant between the primary and secondary arms; and in the third, it protruded into the secondary. Other measurements were made with the sample equidistant between the two arms, but at different positions around the periphery of the hole. In all positions, no effect on the line width was noted. However, each separate positioning did produce a different value for the magnitude of power coupled into the secondary arm.

The use of the Varian magnet to establish and make changes in the magnetostatic field near ferromagnetic resonance worked quite well
for line widths of 2 oersteds or greater. For lines less than this, a threshold error was apparent in that conversion of the gaussmeter frequencies to values of magnetostatic field could be interpolated no closer than 0.23 oersteds. In addition, it was quite difficult to effect small changes in the magnetostatic field using the Varian magnet alone. As a result, use of the auxiliary field in conjunction with the Varian magnet proved best in this range of line width measurements.

B. Effect of diameter on line width: Nothing conclusive can be presented on this effect. The Microwave Chemical sample on which the majority of measurements were made, was reduced in diameter 10 mils from where the original line width was measured for 600 paper polish. The line width at the reduced diameter was 0.57 ± 0.1 oersteds less than that for the larger size. However, during early grinding a hard plastic tube was used to hold the sample on the grinding wheel. This tube was discarded when it was noted that pitting was occurring even when polishing with 4/0 metallurgical paper. As a result, the sample was repolished successfully using the three metallurgical papers and the soft plastic lined tube. To study the diameter effect, the polished sample was reduced in size with 600 paper which should have yielded a sphere with pits no larger than this grit size. No doubt, when the line width was measured for the larger diameter, surface pits larger than 600 grit size were present. This should account in part for the differences in line width at the two diameters. Unfortunately, the Microwave Chemical sample was shattered with the micrometer at the
conclusion of 3/0 polishing so that no further comparison of the diameter effect could be made. The remaining measurements were made on the Melabs crystal which was out of round by 3 to 4 mils. By regrinding this sample on the coarse 180 paper, it again assumed a spherical shape. As grit sizes were reduced, the line width increased. The cause for this became apparent during the 3/0 polishing when a relatively large cone of inclusion dropped out of the sample.

C. Relative power absorption curves: Curves are plotted of power absorption in the sample as a function of the magnetostatic field for both the Microwave Chemical and Melabs samples. Data for these curves was taken at 9,289 kmc throughout the range of sample response. They are shown in Figs. 3.5 and 3.6, respectively. As can be noted, on the figures, each of the two samples had a different diameter and surface finish. In spite of these small differences, both curves are similar in shape except for the sharpness of peaks for the well polished, large diameter Microwave Chemical sample. As noted earlier, the reproducibility of the characteristics of the garnets is one of their advantages over the spinel ferrites. It is believed that the uniform precessional mode is represented by the four sharp peaks, and that the magnetostatic modes are represented by the peaks at the outer edge of the curve. The Walker (magnetostatic) modes were explained in Chapter 2.

The sharp peaks of the uniform precessional or Kittel mode are related to the sample size, frequency and temperature. Each peak has the properties of the uniform mode. Soli, et al., have observed
Figure 3.5 - Relative Power Absorption Curve for Microwave Chemical YIG Single Crystal Sphere. Diameter, 0.048"; rf Frequency, 9,289 kHz; and Surface Finish, Varigated Aluminum Oxide Powder.
Figure 3.6 - Relative Power Absorption Curve for Melabs Single Crystal YIG Sphere. Diameter, 0.0355", rf Frequency, 9.289 km; and Surface Finish No. 3/0 Metallurgical Polishing, but with a Small Conical Pit.
4 such lines for a single crystal MnZn ferrite sphere in the temperature range of 0°C to 200°C, and in the frequency range of 8 to 12 kmc. They found that with decreasing temperature or frequency, the amplitude increases for the lower field line and decreases for the higher field line. Increasing the temperature and frequency has the reverse effect. They point out that in measuring the line width, one must be certain to observe the same line throughout. Furthermore, they state that the line widths of these peaks are functions of the sphere diameter, and as the diameter decreases, the line widths increase. As yet, there is no substantial evidence in favor of either the small sphere or large sphere values of line width. In addition, the separation of these lines decreases with decreasing sphere size. It is thought that this is caused by the spins precessing together in some normal mode which looks externally like a dipole and higher multipoles. Hence, an externally observed phase shift is not produced by a change in wavelength within the material but by a change of phase, or retardation, of the reradiated wave relative to the incident wave. This change appears greatest near resonance.

The foregoing points appear to be borne out in Figs. 3.5, 3.6, and 3.7. Figure 3.7 is a relative power absorption curve for the Melabs sample with the same orientation as in Fig. 3.6, but with the frequency raised to 11.3 kmc. As can be seen, a magnetostatic mode appears at the right of the curve. The uniform precessional mode is a smooth curve in which all other peaks have disappeared. As noted before, this effect could be expected for an increased frequency.
Figure 3.7 - Relative Power Absorption Curve for Melabs Single Crystal YIG Sphere. Diameter, 0.0355" ± 0.0015"; rf Frequency, 11.3 kc; and Surface Finish, No. 3/0 Metallurgical Polishing, but with a Small Conical Pit.
CHAPTER 4

CONCLUSIONS

4.1 Conclusions

An analysis of the results of this thesis forms a basis for the following observations and conclusions:

Measurement Technique: Use of the cross-guide coupler as a test section in conjunction with an auxiliary field appears to be a sound technique for making measurements of very narrow line widths. In the test section, the location of the sample in the coupler hole does not appear to have any appreciable effect on the magnitude of line width.

The Effect of Diameter on Line Width: No conclusive results were obtained for this effect because of an early shattering of the sample. However, it is thought that for the more extreme changes in diameter, there is an effect on the measured line width.

The Effect of Surface Finish on Line Width: It can be concluded that the line width for a YIG single crystal does decrease as the surface finish of the sample is improved.

4.2 Suggestions for Further Study

Using the cross-guide coupler, a further experimental study should be made of the YIG single crystal line width as a function of frequency. To be complete, this effect should be studied at each state of surface polish down to the point where the line width is
made to approach the intrinsic value associated with the material.

In addition, a more definitive study is needed on the effect of diameter as it affects the line width for YIG single crystals.
REFERENCES


