EXPERIMENTS ON FREQUENCY DOUBLING IN FERRITES

by

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STATEMENT BY AUTHOR

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ABSTRACT

A frequency doubling experiment was performed using eight polycrystalline yttrium iron garnet spheres at frequencies ranging from 2.80 to 3.15 gc. The spheres varied in sample size from .084 inch to .396 inch. Increases in either sample size or frequency caused excitation of higher order modes. In large spheres the higher order modes were capable of conversion efficiencies higher than the uniform mode. For each frequency, output power varied as the sample volume raised to approximately the 1.8 power, taking maximum output without regard to mode. Maximum conversion efficiencies varied from -82 db to -39 db. The corresponding peak output powers were $2 \times 10^{-6}$ watts and $7 \times 10^{-3}$ watts, and the respective peak input powers were 234 watts and 53 watts. The doubling results confirm earlier predictions that only those higher order modes for which $m$ is zero contribute to doubling.
CHAPTER I

INTRODUCTION

1.1. General Background

In the past twenty-five years, increasing use has been made of the microwave portion of the radio frequency spectrum. As the frequency increases, new devices, materials and techniques are required to provide satisfactory performance at the shorter wavelengths. Ferrite materials have found wide use as isolators, phase shifters, and polarization rotators.

The knowledge of the characteristics and capabilities of ferrite materials is by no means complete. In general ferrites may be considered as non-metallic materials which have a crystalline structure. They have low conductivities and low hysteresis losses. In the absence of a magnetostatic field they behave essentially as a dielectric; however, when placed in a magnetostatic field they exhibit antistropic magnetic properties. One characteristic which is not completely understood is the phenomenon of ferromagnetic resonance of spin waves in large samples and magnetostatic modes in smaller samples. Progress has been
made in explaining qualitatively some of the observed phenomena, but there is presently no comprehensive theory.

The early commercial ferrites were similar in crystalline structure to the mineral spinel MgAl$_2$O$_4$. In general they could be expressed by the chemical formula XFe$_2$O$_4$, where $X$ is a bivalent metallic ion such as manganese, zinc, nickel, or cobalt. Prior to the early 1930's investigation of ferrites was limited to general exploration of electromagnetic properties of materials. When frequencies up to the megacycle range came into use, Snoek$^1$ and others began a systematic investigation of synthetic ferrites in the effort of the Philips Research Laboratories of Holland to develop materials with low hysteresis, high resistivity and high permeability.

More recently a class of ferromagnetic oxides containing iron and rare earths and having a garnet crystal structure have been developed. Particular importance is placed on the discovery by Forestier and Guiot-Guillain$^2$ of the useful properties of the rare earth-iron garnets including yttrium-iron garnet. The chemical formula for this class of ferrites is 5Fe$_2$O$_3$·$X_2$O$_3$ where $X$ denotes a trivalent rare earth ion from samarium to lutecium, or yttrium. Among the garnet structure ferrites the yttrium iron garnet (YIG) appears to have the most desirable characteristics for microwave applications. As a result YIG
ferrites are often used for experimental work; it has been said that YIG is to ferromagnetic resonance research what the fruit fly is to genetics research.

The basic phenomenon of ferromagnetic spin resonance was first developed by Landau and Lifshitz\textsuperscript{3} in their classic paper on the theory of dispersion of magnetic permeability in ferromagnetic metals. Kittel\textsuperscript{4} discussed the Landau-Lifshitz paper and suggested the possibility of observing induced ferromagnetic resonance in the presence of an externally applied static magnetic field. Later Kittel\textsuperscript{5} interpreted existing spin-resonance data by classical equations of motion for magnetic dipoles and taking the surface demagnetization into account.

The tensor properties of the permeability of ferrite media were pointed out by Polder\textsuperscript{6} in his work on the theory of ferromagnetic resonance. This was later demonstrated by Beljers.\textsuperscript{7} Bloembergen and Damon\textsuperscript{8}, and Bloembergen and Wang\textsuperscript{9} showed that the magnetic properties of ferrites at high signal power are not linearly dependent on the radio frequency field intensity. This non-linear phenomenon formed the basis of a concept which ultimately led to such devices as the harmonic generator.

The first application of the nonlinear effect came with the invention of the frequency doubler by Ayres, Vartanian and Melchor.\textsuperscript{10} A transversely magnetized ferrite
was placed at the side or in the center of a rectangular waveguide in a region of maximum (and linearly polarized) r-f magnetic field intensity. Melchor, Ayres, and Vartanian were able to acquire conversion efficiencies as large as -6db with an average output of 3 watts at 18,0 gc before the ferrite heated considerably and output decreased. Stern and Pershan\textsuperscript{11} proposed theoretically that the output power should be inversely proportional to the resonance line width of the ferrite and directly proportional to the saturation magnetization and the square of the incident microwave magnetic field intensity.

Magnetostatic modes of resonance were first observed by White and Solt\textsuperscript{12}. White, Solt and Mercereau\textsuperscript{13} and Dillon\textsuperscript{14,15} demonstrated the existence of multiple magnetostatic resonance modes. Walker\textsuperscript{16,17} developed an extensive theoretical classification of magnetostatic modes, and his work was later supplemented by Fletcher and Bell\textsuperscript{18}. Suhl\textsuperscript{19} completed the general theoretical picture with the spin wave concept and the relationship between the magnetostatic, plane wave and spin wave regions in ferrites.

1.2. \textbf{Statement of the Problem}

The generation of large amounts of power at microwave frequencies becomes more difficult as the frequency is increased. The reason for this difficulty is that
conventional microwave power sources, such as klystrons, are essentially scaled down versions of those used at lower frequencies. Thus, electronic generators of this type are severely power-limited at higher frequencies since the use of very small dimensions is prevented by voltage breakdown and inadequate cathode emission current.

The obvious practical application of harmonic generation resulted in experiments whose object was primarily concerned with the maximization of output power. In order to have valid theoretical predictions compare with experiment, it is necessary to be able to describe the external and internal fields in mathematical language. With irregular samples the problem is too complex for the usual simplifying assumptions to be valid. The purpose of this thesis is to engage in a two-fold expansion of the work done by Naegele. The first is to investigate the effect of sample size of spherical samples on conversion efficiency over a narrow range of S-band frequencies immediately above those checked by Naegele. The second portion of this work is to perform a similar investigation over this S-band range plus the upper half of the range used by Naegele on several larger spherical samples, thus extending the investigation further into the region of higher order modes. Use of spherical samples enables comparison with theoretical predictions.
1.3. **Method of Attack**

In addition to the spheres on hand from previous work in this area several larger spherical samples of polycrystalline YIG were prepared. These samples were placed, one at a time, in a rectangular waveguide cavity. For a given input frequency the d-c magnetic field was varied and the values of the d-c field determined for which maxima occur in the second harmonic output power. Sample size was varied in an attempt to determine the effect of size on the number and identity of modes excited, spin wave coupling to modes, coupling between modes, and conversion efficiency. This process was repeated for a number of frequencies between and including 3.0 and 3.35 gc. Results achieved with the smaller previously prepared spheres were compared with data obtained by Naegle in an effort to confirm his work and establish an agreed upon point from which to expand.
CHAPTER II

THEORY

2.1. Geometrical Presentation of Frequency Doubling

The fundamentals of frequency doubling in ferrites is best understood by first considering a geometrical interpretation of the process. The magnetization vector $\vec{M}$, precesses about an externally applied magnetostatic field. The magnetization vector is a constant amplitude vector whose projections on the coordinate axes are represented by $m_x$, $m_y$, and $m_z$ in Figure 2.1. If no r-f fields disturb it the tip of $\vec{M}$ will precess in a circle as Figure 2.1.(a) illustrates. If a linearly polarized magnetic field at the frequency of precession and in the x-y plane is applied to the ferrite, it will drive the precession into a maximum elliptical path as shown in Figure 2.1 (b). Since $\vec{M}$ is of constant amplitude, its projection on the z axis must contain an r-f $m_z$ component. It is noted that every revolution of $\vec{M}$ causes $m_z$ to pass through two minima and two maxima, hence $m_z$ varies at twice the frequency of the driving source. If a circularly polarized r-f field had been applied there would, of course, be no r-f $m_z$ component.
Figure 2.1. Geometrical Frequency Doubling Illustration
2.2. **Mechanics of Frequency Doubling**

It has been shown by Beam, among others, that the macroscopic equation of motion of the magnetization vector, when a precessing spin system exists in a magnetic material, is stated as:

\[ \dot{M} = \gamma(\overline{M} \times \overline{H}) \]  \hspace{1cm} (2-1)

where \( \dot{M} \) is the time derivative of the magnetization vector, \( \gamma \) is the magnetomechanical ratio of the magnetic moment of the spin angular momentum of the electron, and \( \overline{H} \) is the internal field intensity. It has been demonstrated by Polder, and further demonstrated by Walker, that for a static field in the z direction and an r-f field in the x-y plane, and by neglecting all second order terms, the r-f magnetization \( \overline{m} \) and magnetic field \( \overline{h} \) are related by:

\[ \overline{m} = \left[ \chi \right] \overline{H} \]  \hspace{1cm} (2-2)

where the elements of the susceptibility tensor \( [\chi] \) are:

\[ \chi_{xx} = \chi_{yy} = \frac{\gamma^2 H^2 \pi M_0}{\gamma^2 H^2 - \omega^2} = \frac{\Omega_H}{\Omega_H^2 - \Omega^2} \]  \hspace{1cm} (2-3a)

\[ \chi_{yx} = -\chi_{xy} = \frac{J \gamma^2 \pi M_0}{\gamma^2 H^2 - \omega^2} = \frac{1}{\Omega_H} \]  \hspace{1cm} (2-3b)

In terms of the saturation magnetization, \( M_0 \), it is then possible to write the reduced angular frequency and the reduced internal field respectively as:
\[ \Omega = \frac{\omega}{\gamma 4\pi \mu_0} \]  
\[ \Omega_H = \frac{H}{4\pi \mu_0} \]  

Now if the solution for the equation of motion is represented by its cartesian components and second order terms are included, the z component of the r-f magnetization is:

\[ \dot{m}_z = \gamma (m_x h_y - m_y h_x) \]  

Admittedly this term is extremely small and is usually neglected since it contains only higher order terms. Substituting, however, for \( m_x \) and \( m_y \) in consonance with expression (2-2) demonstrates that the time rate of change of \( m_z \) is proportional to the square of the internal magnetic fields. Thus it is seen that \( m_z \) varies at twice the rate of the driving frequency. The resonance condition is met when \( \Omega = \Omega_H \).

2.3. Magnetostatic Modes

The microwave susceptibility so far discussed was evaluated in an infinite medium for simplicity. This ideal cannot be realized in practice, of course, because one must always deal with finite samples in the presence of an electromagnetic field. When demagnetization factors are taken into account, the equation of motion can be solved in terms of the external d-c and r-f fields. To evaluate the
magnetic fields inside the sample, it is necessary, in principle, to solve the electromagnetic boundary value problem. Walker used the assumption that the electromagnetic propagation does not take place or is negligible in a sufficiently small sample and that the magnetostatic condition of \( \nabla \times \mathbf{h} = 0 \) applies. This implies a scalar magnetic potential \( \psi \), where \( \mathbf{h} = \nabla \psi \). By further assuming a sinusoidal variation in both magnetization and field, the partial differential equations may be obtained for \( \psi \) inside the sphere:

\[
(1 + \chi_{xx}) \left( \frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} \right) + \frac{\partial^2 \psi}{\partial z^2} = 0 \tag{2-6}
\]

and outside the sphere:

\[
\left( \frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} + \frac{\partial^2 \psi}{\partial z^2} \right) = 0 \tag{2-7}
\]

Fletcher and Bell solved the same problem for a sphere and their results are more convenient for use. The solution for the equation both inside and outside the sphere in oblate-spheroidal coordinates involves the associated Legendre polynomial. It is important to realize that the application of boundary conditions place conditions on \( \mathcal{N} \) and \( \mathcal{H} \), which result in multiple resonances, rather than the simple solution previously shown. The resonance equations are extremely complicated algebraic expressions, which,
for simplicity, can be presented graphically as shown in Figure 2.2.

For a specimen in an applied d-c magnetic field, $H_0$, and considering demagnetizing effects, the internal field experienced may be expressed:

$$H_1 = H_0 - N(4\pi M_0) \quad (2-8)$$

where $N$, the demagnetizing factor, is a measure of the magnetic dipoles induced at the surface. For spheres the demagnetization factor is one-third. In Figure 2.2 it is seen to be convenient to plot $\omega_H + 1/3 = H_0/4\pi M_0$, the reduced external d-c field as the abcissa, and $\omega - \omega_H$, a function of the r-f frequency and internal field as the ordinate.

The resonance modes are designated by $(n,m,r)$, where $n$ and $m$ are indices of the associated Legendre polynomials of the solutions. For some values of $n$ and $m$ there can be a number of solutions since the algebraic equations are second and higher order. Walker enumerates each of these roots with integer values of $r$ where $r+1$ is the order of the root and thus introduces the three index mode scheme. Only the lower order solutions are shown in Figure 2.2.

The diagonal line shown in the figure indicates a "load line" traversed for various d-c field values and a constant frequency 3.0 gc, and the direction of the parallel arrow
Figure 2.2. Some Lower Order Walker Modes. Load line is for 3.0 gc with $\gamma = 2.8$. Dashed curve is spin manifold.
indicates the direction of increasing d-c field. The intersecions with the mode curves indicate theoretical d-c magnetic field values for resonance of the various modes. The dashed curve with the same shape as the mode curve represents the top of the spin wave manifold, a subject that will be discussed later.

While the spin wave manifold will be discussed in the next section, it is possible now, knowing it limits magnetostatic mode solutions, to realize a significant result. From Figure 2.2 it will be shown that for all magnetostatic modes, \( \Omega - \Omega_H \) lies between zero and one-half, so that the complete magnetostatic spectrum lies in a frequency band between \( \gamma H_1 \) and \( \gamma(H_1 + 2\pi M_0) \).

2.4. Spin Waves

Spin waves are the appropriate natural modes of propagation in a system of coupled spins, and must be considered when the effects of the interaction between spins cannot be ignored. To illustrate the spin wave phenomenon it is possible to imagine for the moment that the r-f magnetic driving field is applied at one end of the specimen to cause some of the spins to precess with a larger precession angle than their neighbors. The exchange field, tending to align dipoles, will act to swing the neighbors into a larger precession angle, but there will be a small
delay. In this way the larger precessional disturbance can travel through the specimen in the form of a wave with both a phase and amplitude change from dipole to dipole.

Herring and Kittel\(^{22}\) treated spin waves in a semi-classical manner and showed that the equations of motion given earlier in the chapter for the uniform precessional case can be extended to include a spin wave term as follows:

\[
\dot{M} = \gamma (M \times H) + H_{\text{ex}} d^2 \frac{M \times \nabla^2 M}{|M|}
\]

where \(H_{\text{ex}}\) is the exchange field and \(d\) is the distance between neighboring spins.

A few observations will be helpful in predicting some of the effects caused by spin waves in this experimental work. The spin wave may be considered as a ripple of amplitude propagated across a sea of magnetism and Figure 2.3. gives a good physical picture of some simple spin waves. As applicable to this work several characteristics of spin waves are appropriate and are here noted:

1. Spins waves limit the precession angle by removing energy for larger precessions.

2. Spin waves can cause coupling between magnetostatic modes.

3. Spin waves can be excited in a sample by effect of surface irregularities, high r-f power, and propagation effects.
Figure 2.3. Spin Waves: (a) Constant amplitude, in phase (uniform mode); (b) Different amplitudes, in phase (higher order Walker mode); (c) Z-directed spin wave. The spin relations of (a) and (b) are also called standing spin waves.
A. Spin waves can shift the resonance peak to a higher or lower d-c field value.

A general picture of the relationship between the regions of Walker modes and the spin wave region is shown in Figure 3.4. This display is called the Suhl dispersion relation. It should be realized that there is no strict division between the regions, that is, magnetostatics modes exist in the spin wave region and spin wave effects are experienced in the magnetostatic mode region. In the center position, known as the plane wave region, propagation effects are significant but exchange effects are not. It has been pointed out by Anderson, Suhl, Clogston, and Walker\textsuperscript{23}, that for ellipsoidal samples of finite size, the frequency, $\omega_k$, of the spin wave is geometry dependent because of the effects of demagnetizing fields. When demagnetizing factors are included for the case of a d-c field applied along the axis of symmetry of an ellipsoidal specimen the spin wave frequency is given by:

$$\omega_k = \left[ (\omega_0 - i \omega + \omega m \Delta k^2 ) (\omega_0 - i \omega + \omega m \Delta k^2 + \omega m \sin^2 \theta_k) \right]^\frac{1}{2} \quad (2-10)$$

where $\omega_0$ is the uniform magnetostatic resonance frequency, $\omega_m = \gamma 4\pi M_0$, $\omega_m \Delta k^2 + \omega m \sin^2 \theta_k$ is the demagnetization factor in the $z$ direction, $k$ is the propagation constant or wave number of the spin wave and $\theta_k$ is its direction of propagation with respect to the $z$ axis.
\[ \omega_w = (H_0 + 2/3 \pi M) \]

Spherical Samples

\[ N_z = 1/3 \]

\[ 4\pi M = 1800 \quad \gamma = 2.4 \quad H_0 = 1000 \]

\[ \omega_t = \text{upper manifold frequency} \quad \theta = \pi/2 \]

\[ \omega_w = \text{upper Walker frequency} \]

\[ \omega_0 = \text{uniform mode resonance frequency} \]

\[ \omega_b = \text{bottom manifold frequency} \]

Figure 2.4. Suhl Dispersion Relation (after C.R. Buffler, Gordon McKay Laboratory of Applied Science, S. R. No. 3, Ser. 2, February, 1960)
The derivation for expression (2-10) requires the implicit assumption that the mean dimension of the sample is considerably larger than the wavelength, $\lambda_k$, of the spin wave within the sample. Larger by at least a factor of 10 is generally considered a good approximation. When the sample dimension becomes comparable to or smaller than the wavelength of the spin wave within the sample, expression (2-10) is no longer appropriate.

For this experiment the largest sample diameter is .396 inch. The highest frequency used is 3.35 gc., and the corresponding guide wavelength is 4.492 inches. The largest possible sample diameter to guide wavelength ratio is on the order of .09. It is the wavelength inside the YIG sample that is of interest here, however, and considering the commonly accepted general order values of 5 and 10 for the relative permeability and permitivity of YIG, it is noted that the internal wavelength will be approximately one-seventh of the guide wavelength. The ratio of diameter to wavelength inside the largest sample for the highest frequency will be on the order of .63.

A good rule of thumb to follow is that propagation effects become significant when the mean diameter of the sample is at least one-tenth the wavelength within the sample. It is clear, then, that propagation effects should be considered in this experiment.
2.5. **Identification of Modes**

Fletcher, Solt, and Bell\(^2^4\) compared in detail the experimentally observed resonant absorption pattern for spherical samples with the predictions of Walker's magneto-static theory, and subsequently pointed out corrections to the simple theory which must be made in order to give an accurate description of the experimental facts. It was shown that in addition to the perturbations caused by non-ideal experimental conditions, such as samples being not quite spherical, there exist mode shifts and coupling due to finite sample size and inherent propagation effects which cause serious ambiguities in mode identification unless recognized and taken into account.

Experimental results of investigation of the first propagation effects is shown for several modes in a YIG sample in Table 2.1. The shift of all resonant absorption peaks is toward the high field side and is shown tabulated in the form of a propagation slope. The propagation slope indicates the slope of the straight line \(\omega/\gamma\) versus \(4\pi M_0\) obtained by Fletcher, Solt and Bell as they varied saturation magnetization by varying sample temperature. As an example, for the shift in the 110 mode in YIG which has a saturation magnetization given as 1690 gauss, the shift would be \(2.06 \times 0.01 \times 1690 = 34.8\) oersteds. Since the associated sample size and frequency used by Fletcher, Solt,
Table 2.1. Propagation slopes, \( \Delta (\omega / \gamma) / \Delta (4\pi M_0) \), for 0.050" diameter YIG sphere at 9.688 gc. (After Fletcher, Solt and Bell, "Identification of the Magnetostatic Modes of Ferrimagnetic Resonant Spheres," Phys. Rev., Vol. 114, No. 3, p. 343, May 1959)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Slope ( \times 10^2 )</th>
<th>Mode</th>
<th>Slope ( \times 10^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>2.06</td>
<td>320</td>
<td>0.74</td>
</tr>
<tr>
<td>200</td>
<td>1.25</td>
<td>400</td>
<td>1.01</td>
</tr>
<tr>
<td>210</td>
<td>1.15</td>
<td>410</td>
<td>0.83</td>
</tr>
<tr>
<td>220</td>
<td>1.15</td>
<td>411</td>
<td>0.65</td>
</tr>
<tr>
<td>300</td>
<td>0.89</td>
<td>500</td>
<td>0.69</td>
</tr>
<tr>
<td>310</td>
<td>1.05</td>
<td>510</td>
<td>0.45</td>
</tr>
<tr>
<td>311</td>
<td>1.00</td>
<td>540</td>
<td>0.59</td>
</tr>
</tbody>
</table>
and Bell are considerably different from those utilized in this experiment, calculated shifts using Table 2.1. will not be accurate. They do, however, give an order of magnitude of expected shifts.

The second effect that propagation has on the resonant field may occur when the resonant fields approach degeneracy. When this occurs each mode apparently repels each other and this effect is called mode coupling. A r-f field formerly driving one mode alone may now drive both.

2.6. High Power Effects

In comparing the results of this experiment with the simple Walker theory it is also necessary to consider effects of a high intensity r-f level. The scattering of uniform precession into higher order modes, spin wave modes, can be inhibited or even suppressed at low power levels, either by removing sample imperfections or by shifting the frequency of the main resonance away from the central portion of the spin wave manifold. As the driving field intensity is increased, however, nonlinear phenomena arise even in a crystal containing no imperfections. This nonlinearity can provide a mechanism for coupling the uniform precession to spin wave modes at a power level much less than that which would ordinarily be required for r-f saturation of the precession.
The first experimental observations of the broadening of the main resonance line due to nonlinear effects were made by Bloembergen and Damon\textsuperscript{8}. These observations have finally been explained by the onset of an instability in the motion of the magnetization vector which couples energy exponentially to the spin wave of the appropriate precessional frequency. This flow of energy out of the uniform motion prevents the precession angle from increasing and brings about the early onset of the decline of permeability at resonance.

Buffler\textsuperscript{25} demonstrated that the linewidth for YIG as a function of r-f frequency reached a minimum near $f_{m}/2$ and a maximum near $2f_{m}/3$. This result showed good correlation with his theory of excitation of degenerate spin waves in the region of maximum linewidth. Additionally, experiments have shown a subsidiary absorption which occurs at a d-c field less than that required for the resonance. It was shown by Suhl\textsuperscript{26} that the subsidiary peak can arise for a spontaneous transfer of energy from the uniform precession to spin waves of half the resonance frequency. The critical field intensity required to experience these effects is not a well defined parameter in polycrystalline specimens such as the one used in this experiment.

High r-f power may also cause heating of the sample which, in turn, would cause a decrease in saturation.
magnetization. In this experiment it was attempted to minimize heating effects by choosing a low pulse repetition rate.

2.7. **Higher Order Magnetostatic Modes**

Richards\(^2^6\) has examined the magnetostatic modes theoretically to include their contribution to doubling. He arrived at the conclusion that the only higher order modes which can contribute to doubling are those for which \(m = 0\) and \(n\) is greater than or equal to 2. He specifically excludes from consideration the case of two degenerate modes combining to produce a non-zero space average of second harmonic magnetization in the \(z\) direction. Thus he concludes that the modes which can produce doubling are the uniform or 110 mode, the 200 mode, the 300 mode, and so forth. Since the \(r\) only indicates the order of the root for a solution and has no physical significance, \(r\) could have any possible value in modes with \(m = 0\).

2.8 **Effects of Frequency and Sample Size and Shape**

The sample size and frequency will have a very significant effect on the doubling modes excited. As the sample size is increased, or as the frequency is raised, a greater portion of the wavelength will exist within the YIG specimen. Hence, the internal field will be less uniform and it can be expected that higher order modes will result. There should
be a difference in the modes excited in different size samples, if the size difference is sufficient to allow an appreciable difference in the internal field distribution. Likewise, for any one sphere, an increase in frequency may also cause a variation in the modes excited by altering the internal field distribution. Additionally it has been discussed that a shift in the resonance field to a value higher than that predicted by the Walker theory can be expected.

With regard to high power it should be recalled that a subsidiary absorption may exist. Also the excitation of spin waves may remove energy from the uniform mode, and limit the amount of second harmonic power which can be produced from that mode. The sample symmetry and finish can be critical.

It is seen from equations (2-3) and (2-5) stated earlier that the output power can be expected to be proportional to the square of the absorbed power. Since the absorbed power is proportional to the volume of the sample, the output power should be proportional to the square of the volume of the sample. Results for this experiment are limited to the uniform mode and the higher order modes for which \( m = 0 \) since examination of doubled output restricts direct view to those modes contributing.
CHAPTER III

EXPERIMENT WORK

3.1. Equipment and Arrangement

The basic equipment arrangement and techniques used in this experiment are similar to those used and described by Richards. Additional work along these lines has been performed by MacDougall and Naegle, and this experiment is primarily designed to be an extension of Naegle's work. The equipment used for the experimental work is shown schematically in Figures 3.1. and 3.2.

Referring to the diagram of the S-band generation setup, Figure 3.1., the center of this system is the signal source, a triode cavity oscillator. One of two triode oscillators shown were utilized depending on the frequency desired. Either oscillator produces a one microsecond pulse with a peak power of approximately one kilowatt. The pulse generator shown is used to drive the high voltage pulser which in turn powers the selected triode cavity oscillator. The internally controlled repetition rate of the pulse generator is not known to be accurately calibrated, and therefore it is necessary to employ a square wave generator as an external triggering device. Accurate control of the pulse
Figure 3.1. Block Diagram of S-Band Generation and Monitoring System.
Figure 3.2. Block Diagram of Frequency Doubling and Receiving System to include Calibration Set Up.
repetition frequency is essential in order to convert average power measurements to peak power values. It is known that:

\[ P_{\text{peak}} = \frac{P_{\text{average}}}{T \beta} \]  

(3-1)

where \( T \) is the duration and \( \beta \) is the repetition rate. Using the one microsecond pulse repeated 500 times per second yields an input average power to peak power ratio of -33 db.

The pulse produced by the triode cavity oscillator was fed through a ferrite isolator and three sections of lowpass filter. The filter sections were necessary to attenuate the second harmonic of the oscillator frequency which would otherwise contribute to the double frequency output. The dual bi-directional coupler was utilized next in line to permit simultaneous measurement of the incident and reflected power. The bi-directional coupler also provided a convenient terminal, by disconnecting one of the power meters, to monitor oscillator frequency.

The oscillator pulse was then fed into the S-band waveguide through an S-band adaptor which is designed to excite the TE\(_{10}\) mode. The S-band slide screw tuner is used to match the load presented by the test section.

The test section consisted of a section of S-band waveguide attached to a section of J-band waveguide rotated 90°. This equipment was made by MacDougall\(^27\) and the
specifications are given in Figure 3.3(a). The guide junction was essentially a short to the $TE_{10}$ mode of the input signal so proper adjustment of the S-band tuner caused the S-band section to act as a $TE_{105}$ or $TE_{106}$ cavity.

The YIG sample was located at a point one half wavelength from the junction so that the most nearly uniform r-f magnetic field possible was experienced. The r-f electric field here was nearly zero. The sample was mounted in a polyfoam block approximately the size of the waveguide transverse dimensions. The polyfoam block had two strings attached, one running out the S-band tuner and the other out the J-band tuner. Manipulation of the strings permitted adjustment of the ferrite position after the equipment was assembled.

The test section was then placed in a d-c magnetic field so that this d-c field was perpendicular to the r-f magnetic driving field of the S-band $TE_{10}$ mode. A precision gaussmeter was used to measure the d-c field values. A signal generator was required to beat with the low output of the gaussmeter in order to trigger an electronic counter. Frequency readings were then converted to d-c field strengths by using a conversion table.

In the waveguide, when a d-c magnetic field which satisfied the conditions for resonance was applied, the ferrite sphere radiated a double frequency signal in both directions.
Figure 3.3. Fabricated Equipment: (a) Test Section fabricated from standard S-band and J-band copper guide stock and couplings; (b) Selective absorber.
The magnetic field of the generated double frequency signal was perpendicular to the input signal magnetic field, that is, parallel to the short dimension of the S-band guide. Hence the $TE_{01}$ mode propagated in the S-band guide. Energy traveling back toward the source was attenuated by a selective absorber made of resistance card. The selective absorber was located in the waveguide at the source end and was held in position with polyfoam blocks. The selective absorber was also fabricated by MacDougall and its dimensions are given in Figure 3.3(b).

A slide screw tuner at the output end of the test section was used to match the J-band portion of the waveguide. Hence a double frequency $TE_{10}$ mode propagated in the J-band section and a J-band adaptor was used to couple the double frequency out of the waveguide. At this point it was necessary to use known value precision coaxial attenuators to reduce the signal power to a level sufficiently low to insure that the mixer preamplifier was not saturated. Keeping below a maximum power level of -55 dbm into the mixer preamplifier was found to be sufficient to prevent saturation, as will be discussed in the next section.

Approximately one milliwatt of cw local oscillator power at twice the input frequency plus or minus 30 mc was supplied to the mixer. One of the three reflex klystrons shown in Figure 3.2. was used for the local oscillator.
depending on the required frequency. From the mixer-
preamplifier the 30 mc signal was fed to the laboratory receiver. The receiver had variable internal input attenuation up to 101 db selectable in steps of 1 db. The gain of the receiver is variable to a maximum value of 65 db. The video output of the receiver was then displayed on an oscilloscope.

3.2. Measurement Procedure

The following sequence was followed in taking experimental data for this thesis:

1. The triode cavity oscillator was tuned to the desired frequency using the frequency meter.

2. The triode output coupling was adjusted for maximum output power.

3. Using the reflected power reading, the S-band slide screw tuner was adjusted for minimum reflection from the test section.

4. The local oscillator was then tuned with the frequency meter to twice the triode frequency plus or minus 30 mc.

5. The d-c magnetic field was turned on and adjusted until a double output signal was seen on the oscilloscope screen. Altering magnetic field strength revealed one or more maxima.
6. The local oscillator klystron and J-band tuner were adjusted for maximum output power and best pulse shape on the oscilloscope.

7. The S-band tuner was then readjusted for maximum output signal.

8. The d-c magnetic field was then tuned until the particular maxima under investigation was located.

9. Precision attenuators were inserted in front of the mixer preamplifier until an added value produced a reduction in pulse height on the oscilloscope equal to the increase in height obtained by removal of amplifier input attenuation. This procedure insures that the mixer preamplifier is not saturated.

10. With the receiver gain set at a fixed value, the receiver input attenuation was inserted so as to produce a four centimeter pulse height on the oscilloscope screen for a sensitivity setting of one volt per centimeter.

11. Then the receiver attenuation setting and mixer preamplifier input attenuation was noted along with the approximate magnet setting for each observable output maxima.

12. The precise field value was located for each resonance from the lower field side, with the field reduced to zero between each reading to minimize hysteresis effects.

13. For each field value at resonance producing a maximum on the oscilloscope the following data was recorded:
a. The precise field value using the precision gaussmeter and electronic counter.
b. The receiver input attenuation.
c. The mixer preamplifier input precision attenuation.
d. The amplifier gain setting.
e. The source input signal incident and reflected power levels.

Prior to the actual evaluation of the experimental data it was necessary to calibrate the mixer preamplifier receiver combination, which was accomplished using the equipment schematically shown in Figure 3.2. As in the principle experiment the source is used to produce a one microsecond pulse at 500 pulses per second and the local oscillator provides a one milliwatt cw signal to the mixer. For a fixed receiver gain setting, known precision attenuators are inserted before the mixer and the receiver input attenuation setting is adjusted to produce a four centimeter pulse on the oscilloscope at a sensitivity setting of one volt per centimeter. Calibration curves were obtained in this manner for two amplifier gain settings and are shown in Figure 3.4. Naegle\textsuperscript{20} showed previously in his calibration that there is little variation with a change in signal frequency, therefore, calibration was conducted
Figure 3.4. Mixer-Preamplifier and Receiver Calibration. One Microsecond Pulse at 500 Pulses per Second and 6.4 gc.
only at a source frequency of 6.4 gc., a frequency approximately midway in the series of frequencies investigated.

3.3. Measurement Problems

A very serious initial problem encountered was the presence of a double frequency output signal without any d-c magnetic field. Some double frequency signal was even detected with the source disconnected from the test section. The causes were discovered to be insufficient input filtering and stray radiation from the source. The addition of three low pass filters was successful in reducing the direct harmonic signal. Benefiting from the lessons learned by Naegele it was found that radiation can be significantly reduced by completely enclosing the high voltage pulser, triode cavity oscillator, isolator, and filters in an aluminum foil covered box. Extreme care in completely sealing all openings was essential. Unfortunately this created an additional problem and it became necessary to periodically open the foil box to allow cooling of the enclosed voltage pulser. The high voltage pulser was unstable when allowed to get too hot.

An additional reduction in second harmonic radiation was achieved by similarly enclosing the mixer pre-amplifier in a foil container. Flexible coaxial cable lengths with a solid copper outer conductor were fabricated
and used for all inter component connections resulting in a further reduction of radiation. As a combined result of all these precautions the spurious signal was reduced to a few db above the noise level.

Naegele encountered a problem due to a variation of input power of approximately 3 db over the triode tuning range. A similar variation in power was also found with the second triode cavity oscillator used in these experiments. In general it was desired to use a high power to increase the probability of observing predicted effects, however, it was often necessary to reduce power to gain triode stability.

In order to eliminate the necessity of excessive calibration of the laboratory receiver, only two gain settings were utilized. One of these was always found suitable for the observed signal level.

A problem already mentioned is mixer preamplifier saturation. Steps to avoid this and thus obtain misleading data have already been discussed.

The encountering of multiple modes primarily in the larger spheres at the higher frequencies caused serious detection and identification problems. While identification of detected modes was accomplished basically in the method described by Fletcher, Solt and Bell \(^{24}\), it was found that frequently detection of one mode was hindered by the proximity of another mode. The position of the sample was
found to be extremely critical, and subsequently it was discovered that the best results were achieved by positioning the YIG specimen to maximize the uniform mode output. It was also found of invaluable assistance to trace a difficult mode through various size samples at a given frequency. Knowing approximately where to look in this way aided in detecting modes.

As the sample size increased it became increasingly difficult to detect a pip on the gaussmeter, and it was assumed that the large sphere disturbed the d-c field to an extent so as to hinder measurement by the gaussmeter probe. This problem was partially overcome by continuously referring to previous values for similar magnet settings.

3.4. Sample Configuration and Mounting

A spherical sample shape was used due to the need for a predictable demagnetizing factor. A .4 inch diameter cylindrical single bulk polycrystalline YIG specimen was available for this experiment. Desired lengths were cut from the bulk YIG cylinder with a diamond saw. The resulting sections were formed into rough spheres by hand grinding. The spherical samples were completed by the tumbling technique on 180c, 300, and 600 grit size papers successively.

The polyfoam sliding block previously described was utilized to mount the sample in the test section. Naegele\textsuperscript{20}
discovered that the use of Duco model glue in mounting caused dielectric loading. Use of polyfoam to eliminate dielectric loading inhomogeneities had been used by Dillon. The largest sample used was .396 inch in diameter with two additional samples ground down in approximately .05 inch increments. One additional sample was later ground to .282 inch, a size approximately midway between the previous smallest sample and Naegle's largest sample of .252 inch. This was done to investigate what appeared to be a significant change in the number of modes in this size range.

The YIG specimen used for preparing the additional spheres described above was not obtained from the same source as the YIG used by Naegle. As a precaution, line width measurements were made in the interval from 1.6 to 8.6 gc. The cross guide coupler measurement technique described by Stinson was used and the results are shown in Figure 3.5. The line width characteristics of the new specimen compared with those of Naegle's material to a reasonable degree and it was therefore decided that the new YIG material was suitable for these additional experiments.

3.5. Results

A continuous check of the measurement technique and procedure employed was performed during this experiment. This was achieved by duplicating some of the data for the smaller samples used by Naegle. Once an acceptable
Figure 3.5. Line Width Characteristics of YIG Sample as a Function of Frequency.
agreement was achieved, or a difference rechecked and confirmed, new information was sought. In this way data was combined to show mode generation trends as the frequency and sample size were increased.

There was some disagreement with Naegele on the number of modes detected for small sphere readings, specifically the .084 inch sphere. It is felt that the maximizing technique of adjusting sample position by running strings out the tuners as previously described aided in detecting weak modes. There was some additional disagreement in distinguishing between the 200 and 300 mode for the .252 inch sphere and this is also influenced by precise specimen positioning. This will be discussed later in view of presented data.

The value of $\gamma$, the gyromagnetic ratio, and the saturation magnetization are assumed to be the same for the two specimen bulk materials used in this experiment. The values were unknown, however, and it was necessary to evaluate these constants so that an accurate identification of modes could be made. $\gamma_{\text{eff}}$ is defined as $\frac{\omega}{H_0}$ for the uniform mode and includes propagation effects but neglects any variation of these effects due to mode, sample size and frequency. The effective value of $\gamma$ used in this experiment was determined by Naegele using a .200 inch sample at a frequency of 3.0 gc. A $\gamma_{\text{eff}}$ value of 2.84 mc/oe was
determined and was subsequently used for all samples and frequencies for the remainder of this experiment.

Lacking an independent means of determining the saturation magnetization, a value of 1690 gauss was assumed. This is the generally accepted value of YIG and the consistency of the experimental results with theory show this value to be very close to the actual value.

In all, eight different samples were investigated. An additional sphere, the smallest available at .045 inch diameter, had been previously examined by Naegle and was checked at the two highest frequencies used in this work. There was no significant change in the data, therefore investigation of this sphere was discontinued and it will be discussed no further.

Identification of the modes which produce doubling was achieved by plotting the observed resonances on a Walker mode graph. The data for the four smallest samples is shown in Figure 3.6. For reference purposes the 90° spin wave frequency $\omega$, and the magnetostatic modes for which $m$ is zero have also been plotted. Also plotted are the 512 and 531 modes, for which theoretically coupling with the uniform mode is possible, and the 311 mode, which Fletcher and Solt found to have the strongest interaction with the uniform mode due to surface irregularities.
Figure 3.6: Comparison of Observed Resonances with the Walker Modes for the four smallest spheres.
The 521 mode has been plotted as one which could theoretically couple with the 200 or 501 mode. Likewise, these could couple with each other. Similarly, the 511 mode has been plotted in the vicinity of the 300 mode. In Figure 3.6 the data displayed for the three lowest frequencies was taken from Maegle to illustrate the difference in mode identification for the .252 inch sample.

A similar data display is shown for the four larger spheres in Figure 3.7. As was expected, the introduction of larger spheres resulted in the excitation of more non-uniform higher order modes. Also there was more apparent scatter. This is attributed mainly to more coupling with other modes, not all of which are capable of producing a double frequency output.

In general the scatter of the points in both figures can be attributed to several possible causes. In many cases the observed resonances were very broad. While this in itself caused considerable difficulty in making a precise measurement, quite often the output observed on the oscilloscope was so broad as to critically affect the neighboring resonance maximum. This interference was particularly noted among the larger spheres; the effect being so severe that often a peak of relative small amplitude would appear only as a slight pause in the otherwise essentially uniform
Figure 3.7. Comparison of Observed Resonance with the Walker Modes for the Four Largest Spheres.
decay of a neighboring peak as the d-c magnetic field was varied. While the broadness in itself may easily have caused an error in reading of up to 20 oersteds in either direction, the influence of neighboring overlapping maximum undoubtedly increased this error. Most likely this type of error also rendered some lower power peak undetectable.

The value of $\gamma_{\text{eff}}$ used was that value determined for the .200 inch sample at 3.00 gc. Propagation effects should be different for all sample sizes, frequencies, and modes, therefore a systematic deviation of unknown amount will also add to the scatter.

There was no method of controlling the sample temperature in this experiment. It was assumed that if a sample were held in a resonance condition for a period of time it would achieve an equilibrium temperature, but it is probable that each sample could have a different equilibrium temperature for each of its resonances. It was noted that the larger spheres felt warm when they were removed from the test section immediately after making resonance readings.

Since it was not known if the equilibrium temperature was sufficiently high to cause a decrease in the saturation magnetization, it was necessary to determine if the average output power remained a linear function of the average input power. To do this the peak input power and pulse width were held constant as the average input power was
increased by varying the pulse repetition rate from 50 to 500 pulses per second. The result is shown in Figure 3.8, and it is observed that the relation remains linear for this material through the 500 pulse per second repetition rate used for this experiment. The conversion efficiency remained nearly constant throughout the range of average input power. Hence it was assumed that the order of error caused by variation of the saturation magnetization due to temperature for this material is not critical.

The already mentioned coupling interaction could undoubtedly account for much of the apparent scatter. As observable in Figures 3.6 and 3.7 several of the modes are near degeneracy with other modes over the frequency range under consideration. This interaction could cause a shift of the observed doubling mode to either a lower or higher resonance field value depending on the relative mode positions.

In several cases the data plotted on the Walker graph left doubt as to whether the 110 mode of the 401 mode was excited, and likewise, whether the 200 mode or the 501 mode was excited. In such cases the modes were identified as the simpler of the two, 200 and 300 mode respectively. Since the sample was located at the r-f magnetic field maximum the simpler excitation seemed more likely.
Figure 3.8. Frequency Doubling Average Output Power as a Function of Average Input Power for the 200 mode with the .301 inch sphere at 3.25 g. Average Input Power was adjusted by varying the Pulse Repetition Rate.
In addition to those resonances plotted on the Walker graph, some unknown low and high field resonances were noted. Similar unknown resonances had been observed by Naegele. Generally the power output at these field settings was quite low and they were therefore not considered serious contributors to frequency doubling. Their appearance was erratic and it was suspected that they possibly could be the results of surface irregularities, lack of sphericity, or a direct coupling of the second harmonic output of the triode cavity oscillator. These unknown modes were affected, and in cases could even be totally eliminated, by sphere rotation within the test section. This gave testimony to the importance of sphericity and the position of the specimen.

Figures 3.9., 3.10., 3.11., and 3.12. show the double frequency conversion efficiency ($10 \log \frac{P_2}{P_1}$) plotted as a function of frequency for the eight spheres utilized, sequenced in size by twos, .084 and .138, .201 and .252, .282 and .301, and .349 and .396 inch respectively. The uniform mode predominates in the smallest sphere, with a higher order mode, identified as the 200 mode, observed at a lower conversion efficiency. The uniform mode output increases for the .138 inch sphere, and in this size sample it is seen that the 200 mode has approximately the same conversion efficiency as the uniform mode.
Figure 3.9. Conversion Efficiency versus Frequency for Two Samples with Diameters of (a) .084", and (b) .138".
Figure 3.10. Conversion efficiency versus frequency for two samples with diameters of (a) .200", and (b) .252".
Figure 3.11. Conversion Efficiency versus Frequency for two samples with diameters of (a) .282" and (b) .301".
Figure 5.12. Conversion Efficiency versus Frequency for two samples with diameters of (a) .349" and (b) .396".
Throughout the remainder of the larger spheres a higher order mode was always predominant. The 200 mode predominants in the .200, .252 and .282 inch spheres and Figures 3.10(a), 3.10(b) and 3.11(a) show that the conversion efficiency of the 110 mode also increased with increasing sample size but remained weaker than the 200 mode by approximately the same amount. In Figure 3.11(a) it is also noted that the 300 mode was detected at the highest frequency, but that it was weaker than the 200 mode.

The situation for the .301 inch sphere is shown next in Figure 3.11(b). Here it is seen that the 300 mode has increased in conversion efficiency to a value slightly greater than the 200 mode. Also in this sphere the 500 mode was detected as is seen in the figure. This mode was at a relatively low power level; approximately that of the uniform mode.

It is interesting to note that the 500, and not the 400 mode, was excited after the 300 mode. The exact reason for this is uncertain, however Gaustad showed that the 400 and 500 modes have extremely complicated distributions with respect to the lower order modes. The 500 mode is similar to the 300 mode in that it requires a significant field variation in the direction of the applied d-c field for strong excitation. It is therefore considered reasonable that the 500 mode would be excited were a strong 300 mode detected.
The largest two spheres, with .349 and .396 inch diameters, are shown respectively in Figures 3.12(a) and 3.12(b). The 300 mode continues to predominant and increase in conversion efficiency as the sphere size is increased. The 500 mode increases, however it does not approach the 300 mode even for the largest sample size. The 200 mode is now weaker than the predominant 300 mode by what appears to be a generally constant value, however, it would take more data from experiments with larger spheres to confirm this.

As mentioned before sample position became extremely critical for accurate mode detection, particularly for the larger spheres. A good example of this is given in Table 3.1. For a frequency of 3.0 gc, the data has been presented for the .301 inch sphere. Extreme care was taken to position the sample for maximum uniform mode output. Then the sample position was intentionally disturbed to cause an approximate 1 db decrease by moving the sphere a very small distance, approximately one eighth of an inch. The detectable higher order modes suffered conversion efficiency changes of as much as four db and resonance field shifts of as much as 12 oersteds. Much more important was the fact that the 300 mode was not detectable in the adjusted position.

Also important was the orientation of the sphere within the test section. Some of the samples used in this experiment were out of round by as much as .008 inch. Quite
Table 3.1. Example of Mode Detection and Identification Errors introduced when .301 inch sample was intentionally offset from maximum position so as to cause a 1 db loss in the conversion efficiency of the uniform mode. Taken at 3.00 gc.

<table>
<thead>
<tr>
<th></th>
<th>At uniform maximum position</th>
<th>At offset position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonance Field, (mode identification), and conversion efficiency.</td>
<td>1057 (110) -64.5</td>
<td>1056 (110) -63.7</td>
</tr>
<tr>
<td></td>
<td>1169 (200) -54.5</td>
<td>1168 (200) -58.0</td>
</tr>
<tr>
<td></td>
<td>1215 (300) -59.7</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>1496 (500) -69.5</td>
<td>1508 (500) -73.7</td>
</tr>
</tbody>
</table>
conceivably, this lack of sphericity could cause an alteration in resonance field values, conversion efficiencies, and even the modes detected.

Readings were taken with the .301 inch sphere, which is .008 inch out of round, at 3.25 gc. The sphere was removed from the test section, then rotated approximately $90^\circ$ in the plane perpendicular to the applied d-c field, and finally placed back into the test section. A third and final set of readings were taken after the sphere had been similarly rotated approximately $90^\circ$ in a plane parallel to the applied d-c field. The tabulated results are shown in Table 3.2. Sample rotation caused a change in resonant d-c field values by as much as 40 oersteds and a change in conversion efficiency as much as 8 db.

Figure 3.13 shows the variation of conversion efficiency plotted versus the logarithm of the sample volume at a frequency of 3.25 gc. This frequency value was chosen for this display from Figures 3.9., 3.10., 3.11. and 3.12. The conversion efficiency appears to have a mean value at 3.25 gc, and there are no sharp deviations in conversion efficiency suggesting a possible error in reading.

It is noted that if the power absorbed by the sample is directly proportional to the sample volume, then the output power is proportional to the input power raised approximately to the 1.8 power. This result compares very well
Table 3.2. Example of variation of Resonance Field and Conversion Efficiency when .301 inch sphere sample .008 inch out of round was rotated 90° in plane perpendicular to d-c magnetic field and then 90° in plane parallel to the d-c field. Taken at 3.25 ge.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Original Orientation</th>
<th>1st 90° Rotation (perpendicular to d-c field)</th>
<th>2nd 90° Rotation (parallel to d-c field)</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>1137</td>
<td>-81.7</td>
<td>1140</td>
</tr>
<tr>
<td>200</td>
<td>1241</td>
<td>-73.5</td>
<td>1241</td>
</tr>
<tr>
<td>300</td>
<td>1305</td>
<td>-77.2</td>
<td>1312</td>
</tr>
<tr>
<td>500</td>
<td>1437</td>
<td>-81.8</td>
<td>1432</td>
</tr>
</tbody>
</table>
Figure 3.13. Variation of Conversion Efficiency as a function of the logarithm of the sample volume at 3.25 gc.
with the value of 1.8 obtained by Melchor, Ayres, and Vartanian for output power as a function of input power, and with the value of 1.74 obtained by Naegele.

The exact slope of the line, of course, depends on how one connects the various points. In this case judgment is important and dashed lines have been drawn in Figure 3.13 showing what were considered reasonable limits for connecting the points. From this it is seen one might say that output power is proportional to the input power raised to a power of from anywhere from 1.5 to 1.9.
CHAPTER IV

CONCLUSIONS

4.1. Conclusions

The many theory considerations presented in Chapter II as well as the variation of effects of increasing sample size in Chapter III somewhat obscure the conclusions which may be drawn from this experiment. Those which are made here appear to be confirmed by an agreement between theory and experiment and should be capable of being further confirmed and extended by additional experiments.

The double frequency output power varies as the sample volume raised to approximately the 1.8 power. First the uniform mode, and then the higher order modes, will predominate in conversion efficiency as the sample volume is increased. Once a mode had been replaced as the predominant mode it will continue to increase in conversion efficiency at a rate similar to the predominant mode after it has fallen to what appears to be a set amount behind the predominant mode.

The sample size and frequency both have an obvious effect on the modes which can be excited. Since an increase of either frequency or sample size increases the portion of a
wavelength within the sample, such increases will cause excitation of higher order modes. The surface irregularities will have increasing effect as the sample size increases, as will the effect caused by the sphere being slightly out of round. Since the higher order modes eventually surpassed the uniform mode in conversion efficiency, it can be postulated that with external techniques for distortion of the field, such as dielectric loading, higher order modes could produce greater conversion efficiencies than the uniform mode.

The observed maximum conversion efficiencies varied from -98 db to -51 db for sample sizes from .084 to .396 inch at 3.25 gc. The variation for the other frequencies was similar.

The results of this experiment also seem to confirm that only those higher order modes for which m is zero can contribute to doubling. The scatter of the resonant field values indicate that spin waves enter the picture in a manner not fully explained by current theory, however, the theory that the greatest spin wave activity occurs in the region of increased line width seems to be confirmed. The uniform mode conversion efficiency greatly decreases in Figures 3.9., 3.10., 3.11. and 3.12. at the higher frequencies. Figure 3.6. shows that this frequency level is the threshold of an acute increase in linewidth for the
uniform mode. There is also a decrease in conversion efficiency at the low frequency end for some of the spheres. The reason for this behavior is not known.

4.2. Recommendations for Future Study

It would be beneficial to conduct an accurate cavity power absorption experiment in conjunction with this work. In this way some idea of the modes excited in addition to those which cause frequency doubling could be gained. This in turn would aid in evaluating coupling effects. An attempt was made to monitor the reflected power level for this reason; however, it was not successful since it was necessary to adjust the S-band tuner to match the load presented by the test section with the resonating sample, and this was only possible with the doubling modes since only they produced a signal on the oscilloscope.

Table 3.1, illustrates that conversion efficiency and mode excitation as a function of position within the test section cavity would be an interesting experiment. This would be similar to introducing dielectric symmetry.

An exploration of the effect of rotating a sphere out of round has just been touched. Unfortunately, in this experiment, the sphere had to be removed from the test section in order to be rotated. Hence it is very doubtful if the replaced sphere was put in exactly the original
position. An experiment with spheres, perhaps intentionally more out of round than .008 inch, with the ability to rotate within the test section, would be extremely interesting.
REFERENCES


