DETECTION OF SPINWAVE INSTABILITY THRESHOLDS IN PARTIALLY MAGNETIZED FERRITES USING DIELECTRIC RESONATORS

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Abstract

Yittrium Iron Garnet $\text{Y}_3\text{Fe}_6\text{O}_{12}$ and Lithium ferrite $\text{LiFe}_5\text{O}_8$ mono and poly crystals were investigated for their spinwave linewidth $\Delta H_k$, ferromagnetic resonance linewidth $\Delta H$ and complex magnetic losses $\mu'$ and $\mu''$ at L and S bands. Conventional methods of Spinwave linewidth typically require very high power microwave sources and associated high power components. Therefore, we developed a Dielectric Resonator (DR) based test method that allows for measurement of $\Delta H_k$ using low power, common microwave laboratory equipment, while providing additional capability to measure the other relevant magnetic material characteristics.

The samples used in this research were 0.030” diameter, abrasive milled spheres provided by Pacific Ceramics Inc, and Ferrisphere Inc. and included a variety of standard off-the-shelf material offerings. The saturation magnetization $M_s$ of the samples ranged from 75 Gauss to 3700 Gauss. The $\Delta H$ and $\Delta H_k$ of the samples were in the ranges of 0.5 to 200 Oersteds, and 0.5 to 30 Oersteds, respectively. Practical frequencies of operation for this system are 1 GHz to 20 GHz with less than 20W required RF power. Operation below 1 GHz and up to 40 GHz is possible.

Reduction of intrinsic $M_s$ in YIG in achieved by doping with Gadolinium and/or Aluminum. These additions were found to affect the microwave properties of the materials as well. Dopants like Cobalt, Manganese and Holmium do not effect the saturation magnetization but they do alter the high power microwave properties of the material similarly to Gd and Al. Several DRs were designed and modeled using Ansys HFSS electromagnetic finite element solver. We designed experiments that allow the measurement of all relevant microwave properties in one convenient test setup. This
includes simultaneous control of multiple variables including RF field, frequency and power, and DC field strength.
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Part 1 Background and Motivation

1. A Linear, non-reciprocal and non-linear

Ferrimagnetic insulator materials have many applications in RF/microwave micro-electronic devices. These include the more common linear devices like Circulators and Isolators, Phase Shifters, Filters and Oscillators as well as less common non-linear devices like frequency selective limiters, expanders and convolvers. Let us now separate the properties of the materials under discussion into 2 categories: Linear properties and Non-linear properties.

First we will discuss linear properties. When a non-magnetic material is immersed in a static magnetic field \( H \), the magnetic domains align along the applied field resulting in a magnetization moment \( M \) and magnetic field \( B \) in the material.

\[
B = \mu_0 (M + H) \tag{1}
\]

When a magnetic material is considered and the applied field alternates at high frequency, i.e. and RF signal, the magnetic field in the material takes a tensor form as

\[
B = \begin{bmatrix}
\mu & j\kappa & 0 \\
-j\kappa & \mu & 0 \\
0 & 0 & \mu_0
\end{bmatrix} H
\]

\[
\begin{align*}
\mu &= \mu_0 \left(1 + \frac{\omega_0 \omega_m}{\omega_0^2 - \omega^2}\right) \\
\kappa &= \mu_0 \frac{\omega \omega_m}{\omega_0^2 - \omega^2} \\
\omega_0 &= \gamma \mu_0 H_0 \\
\omega_m &= \gamma \mu_0 M
\end{align*}
\]
shown in equation 2. Ferrimagnetic insulators like YIG exhibit permeability $\mu$ at microwave frequencies. As can be seen in equation 2 above, the permeability tensor is non-reciprocal, and dependent on the applied field $H$. All magnetic materials exhibit ferromagnetic resonance or FMR, but insulating ferrimagnets are especially important because of their low damping parameters as well as low dielectric losses making them suitable substrates material for microwave device fabrication.

FMR refers to the tendency of magnetic spins to want to precess in the presence of an applied magnetic field. In the absence of a high frequency field contribution, the spins are heavily damped and continued precession is not possible. When an externally applied AC magnetic field is introduced, the spins are able to precess uniformly about the vector of the static applied magnetic field. This enables high frequency permeability in magnetic materials. This precession frequency depends on the applied field strength, the geometry and field vector orientation, and material properties and is described by the Kittel formula [1], which will be discussed later. When the frequency of the external AC field, or the pump, is exactly the same as the precession frequency due to the static field, strong absorption of the pump signal is experienced and the energy is dissipated in the ferrite materials crystal lattice structure. This is shown in Figure 1.1. When a high frequency EM signal with a different frequency is applied, the magnetic field component of the signal combines with the DC field to form $H_{\text{effective}}$. This now alternating
magnetization allows the spin to continue precessing. Instead of being damped to the static magnetization vector, the high frequency precession reaches an equilibrium state that is dependent on the damping in the material as well as on the amplitude of the pump. It is important to note under small signal conditions, the torque involved in precession of the magnetization is relatively small and the system is always stable. The theory of FMR was developed by Lev Landau and Evgeny Lifshitz around 1935 and amended by Gilbert about 20 years later resulting in the LLG equations. Charles Kittel developed closed form solutions to the LLG equations for various finite sample geometries and bias conditions. The LLG equations and their linearization quickly led to the invention of ferromagnetic Gyrators or circulators as they are more commonly known and can be linearized and coupled with Maxwell’s equations for use in numerical solvers and simulators.

The second group of properties is non linear. These are properties that are dependent not only on the state of the permeability tensor and the uniform precession

\[ H_{RF} < H_{\text{crit}} \]  
**Figure 1.2** Linear precession of an electron in a magnetic medium

\[ H_{RF} > H_{\text{crit}} \]  
**Figure 1.3** Non-linear precession of an electron in a magnetic medium
frequency, but also on amplitude of the electromagnetic wave propagating through the material. [2] When the amplitude of the high frequency field becomes sufficiently large the system becomes non-linear and the precession becomes non-uniform. At higher power levels, the uniform mode becomes less energetically favorable due to the large torque exerted by the product of the large DC and AC magnetizations resulting in saturation of the main FMR mode. This phenomenon gives rise to parametric oscillations known as spinwaves and their discovery and investigation is largely attributed to Harry Suhl of Bell labs circa 1950. The generation of spinwaves is a non-linear process the physical origins of which are still poorly understood and has been the focus of many researchers over the years. The generation of spinwaves at large RF power levels causes additional losses to occur which adversely affects devices like circulators. Through the parametric process of spinwave pumping, energy from the RF signal or pump is coupled into half frequency $f_0/2$ spinwaves resulting in extra losses at the carrier frequency. The critical field $H_{\text{crit}}$ is of great importance in designing micro electronic devices using ferrite materials. The spinwave linewidth $\Delta H_k$ is an experimentally derived, unitless figure of merit used to determine the critical RF field $H_{\text{crit}}$ at which spinwave emission and the associated increase in losses will start to occur under given magnetic bias, frequency and material property conditions.
1. B Dielectric resonators

A dielectric resonator differs from a conventional cavity resonator in that it does not use boundary conditions associated with metal-dielectric interfaces, but rather interfaces between two different dielectrics. A dielectric resonator can be excited with either magnetic or electric fields depending on the desired mode. A nearby microstrip transmission line, or magnetic coupling loops can provide this excitation. It is important to consider the coupling strength, as it will impact the Q of the resonator. The weaker the coupling, the higher the Q can be.

DRs are typically a cylindrical puck made of a low loss, high permittivity material like alumina oxide, titanium oxide or some other high quality metal-ceramic oxide. DRs offer very high Q factors in the 10,000s. The microwave fields in such a resonator, driven in the TE01 mode, can be solved for using the following expressions in the cylindrical coordinate system symmetrical about the z-axis.

\[
\begin{align*}
H_z &= H_0 \cdot J_0(k_r \cdot r) \\
H_r &= -i \cdot \frac{\beta}{k_r} \cdot H_0 \cdot J_1(k_r \cdot r) \\
E_\phi &= -i \cdot \frac{\omega \mu_0}{k_r} H_0 \cdot J_1(k_r \cdot r) 
\end{align*}
\]

(3)

where \( k_r \cdot r = 2.405 \) is the first zero of the Bessel function. \( k_r \) is the radial wave number, \( r \) is the distance from the symmetry axis, \( \beta \) is the radial propagation constant and \( H_0 \) is the amplitude of the magnetic field component. The linearly polarized E field is easiest to solve. The energy can be calculated using
From which, after accounting for finite Q factor and coupling coefficient we can solve for maximum field in the center of the resonator, $H_0$

$$H_0 = 13.1 \cdot \sqrt[\frac{Q_l \cdot P_{in} \cdot (1 - r^2)}{\omega \cdot \varepsilon_0 \varepsilon_r (\omega \mu_0 D)^2 \cdot V_{DR}}]}$$

(5)

Here, $Q_l$ is the loaded Q of the resonator with ferrite, $P_{in}$ is the input power in Watts, $r$ is the reflection coefficient at the resonator input, $D$ is the diameter of the resonator and $V_{DR}$ is the volume of the resonator. Higher permittivity materials result in physically smaller resonators, which leads to higher $H_0$. The resonant frequency in GHz of a dielectric resonator with radius $r$ and height $L$ can be approximated by the following expression.

$$f_0 = \frac{34}{r \sqrt{\varepsilon_r}} \left( \frac{r}{L} + 3.45 \right)$$

(6)

where $r$ is the radius of the resonator and $L$ is its length. $\varepsilon_r$ is the relative permittivity of the dielectric material. It is desirable to keep the ratio of $L:2r$ to less than unity in order to avoid higher order modes. The hole in the center of the DR can be neglected for our application because it only affects the calculation by a few
percent. The resonator can be placed inside a metal cavity or be left in the air, a metal enclosure has to be large enough so as not to perturb the resonator itself.

Using the relative permittivity and the dimensions of the resonator, one can design DRs to provide the right level of $H_{rf}$ and the desired frequency of operation. Low loss dielectric material processing is very well developed and a wide range of dielectric constants from 1 to 100 is available. DRs for frequencies ranging from 1-40 GHz that will have sufficiently high $H_{rf}$ to saturate most ferrite materials using a conservatively power solid state or TWT power amplifier are realizable.

Several dielectric resonators were designed and simulated using Ansys HFSS. Since resonators in the low GHz range were desired, care had to be taken to ensure the

![Figure 1.5 HFSS simulation showing $H_{RF}$ amplitude at the center of a modeled dielectric resonator](image)

Figure 1.5 HFSS simulation showing $H_{RF}$ amplitude at the center of a modeled dielectric resonator
amplitude of the RF magnetic field in the center of the resonator was sufficiently high to reach critical levels in the ferrites we were testing.

<table>
<thead>
<tr>
<th></th>
<th>1.2 GHz</th>
<th>1.5 GHz</th>
<th>1.8 GHz</th>
<th>2.4 GHz</th>
<th>4.0 GHz</th>
<th>9.0 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epsilon</td>
<td>43</td>
<td>35</td>
<td>43</td>
<td>37.4</td>
<td>37.4</td>
<td>12.1</td>
</tr>
<tr>
<td>Max H field amplitude (Oe)</td>
<td>10.1</td>
<td>10.3</td>
<td>11.1</td>
<td>20.2</td>
<td>33.0</td>
<td>35.9</td>
</tr>
<tr>
<td>Diameter (mm)</td>
<td>39.78</td>
<td>37.08</td>
<td>30.48</td>
<td>19.3</td>
<td>10.5</td>
<td>8</td>
</tr>
<tr>
<td>Height (mm)</td>
<td>23.37</td>
<td>18.8</td>
<td>9.60</td>
<td>13.50</td>
<td>11.00</td>
<td>10.00</td>
</tr>
</tbody>
</table>

20W input power
Unloaded Q > 15,000
DRs can be optimized for higher $H_{RF}$ if needed

**Table 1.1** Table of attainable $H_{RF}$ levels using dielectric resonators from 1 to 10 GHz
1.C Relevant literature

Suhl’s work [2] was concentrated on deriving mathematical theory for coupling between what he called “spin wave disturbances” and the equations of motion for the magnetization vector. Due to the inclusion of several higher order terms, these equations are rather complex and large signal solutions are impractical even given the computing power available today. The power threshold levels associated with these effects are much more important for engineers than they are for researchers. In the 1960s and beyond, circulators, which are 3-port, non-reciprocal signal routing devices, became a major driver behind ferrite research. These devices required the use of ferrite materials, and along with miniaturization of high frequency microwave circuits came an increase in the RF magnetic field density found in these devices, resulting in unwanted losses through the circulator due to spinwave absorption. As such, this area of ferrite studies has gained a certain aura of “black magic”. There was a significant amount of empirical research done on high power effects in ferrites both in academia and in the industry, but a well-defined solution

![Figure 1.6 Measured typical Butterfly plot from a 1800G single crystal YIG sphere at 9.5 GHz under parallel pump. [5]]
that could be integrated into conventional simulation tools does not exist.

The derivations of the spinwave instability threshold are beyond the scope of this work, so we will focus on the threshold fields associated with instability. Suhl introduced the concept of the spinwave linewidth. The spinwave linewidth can be thought of as a damping term in the equations of the magnetization vector. Thus, materials with low spinwave linewidth will exhibit non-linear properties at lower RF magnetic field amplitudes. We used the work of Patton [5], Adam [6], Sandy and Greene [4, 7] to validate our measured results and models. These and other researchers characterized the spinwave linewidth of various ferrite materials using the methods. Their methods consisted mostly of measurement of the critical RF field \( H_{\text{crit}} \), as a function of the internal field in the ferrite. From this raw data, referred to as “butterfly curves” equations were fitted to calculate a spinwave linewidth at a given frequency. Such a plot is shown in figure 1.6.

The perpendicular pump threshold, referring to the direction of the RF magnetization with respect to the DC magnetization is given by Patton [5] as

\[
H_{\text{crit}} = \frac{\omega_p}{\omega_M} \frac{\Delta H_k}{|W(\theta_k, \phi_k)|}
\]

where \( \omega_M \) is a term related to the RF frequency and \( \omega_p \) is the FMR precession frequency. \( \Delta H_k \) is the spinwave linewidth, \( \theta_k \) and \( \phi_k \) refer to the propagation angle and wavenumber of the given spinwave. The above equation is referenced from Patton’s work done on spheres. Different authors have performed experiments on other geometries and have arrived at slightly different expression of this equation.

For parallel pump, \( H_{\text{crit}} \) is defined as
It should be noted that for the parallel pump case, there exists no uniform precession mode, which means no FMR. Non-linear absorption occurs in both parallel and perpendicular pump cases, but many microwave devices that operate due to the FMR principle would experience non-linear losses due to perpendicular pump, since that is the orientation that supports FMR. Additionally, it is very difficult and uncommon to make a planar microwave circuit that allows for true parallel pumping due to the nature of magnetic field geometries and electrical conductors.

Using these equations above we were able to validate that our measurement results using the dielectric resonator test method were in good agreement with the findings of previous researchers. In both cases the terms associated with the spinwave angle and wavenumber are minimized under certain operating conditions, yielding a first order approximation that is \( k \)-independent. This condition typically implies full saturation of the ferrite such that \( \frac{\omega_p}{\omega_M} \) approximately equal to 1, i.e. operation relatively close to FMR in frequency. Under these conditions \( H_{crit} \) approaches \( \Delta H_k \).

Although it is quite convenient to minimize the \( k \)-dependency of spinwave absorption to allow for simple calculations, it doesn't provide a practical analysis in terms of predicting device behavior under various magnetic bias conditions. Rather these assumptions yield the minimum \( H_{crit} \), but under specific operating conditions the \( H_{crit} \) may be significantly different. Thus, the main purpose of this research was to develop a
practical, modern method of characterizing these properties as well as to study them under low magnetic bias field and at low frequency (<2 GHz).

Part 2 Technical Approach

2. A High-power testing method

Traditionally, FMR spectroscopy and related measurements have been performed using waveguide technology. This is due to several factors, including what was available and convenient at the time, as well as for accommodating samples under the needed RF and DC magnetic field configurations. Till this day, most instruments used for FMR measurements are electron paramagnetic resonance (EPR) spectroscopes. Because of low demand, dedicated FMR characterization instrumentation is somewhat commercially rare. EPR signals are much weaker than FMR signals because the samples are paramagnetic and do not possess long-range magnetic order. High Q-factors afforded by waveguide microwave cavities are beneficial for extracting the weak paramagnetic signal. In ferro- and ferrimagnetic materials, the magnetic signal is very strong relative to paramagnetic materials because of the highly ordered structure. As such, lower Q-factor test fixtures can effectively be employed.

At lower microwave frequencies (L an S band), waveguides get quite large, about 2” x 4” cross section at 2000 MHz, and in order to generate high enough RF magnetic
field amplitude, kilowatt RF sources are needed. Instead of a traditional waveguide system, a DR was used to generate high $H_{rf}$ fields using power levels of less than 50W.

The dielectric resonator driven in the $TE_{01}$ mode creates high levels of $H_{rf}$ and minimal levels of electric field in the center of the resonator. The level of RF $H$-field is on the same order of magnitude as what one would find in a microstrip or other microelectronic device. This allows us to subject a sample of ferrite material (a sphere or disk) to similar $H_{rf}$ field intensities as in the relevant form factor without going through the expensive and labor-intensive process of fabricating a device. Additionally, high uniformity of RF and internal DC magnetic field can be attained over the volume of the sphere, which allows the intrinsic response of the material to be determined with better accuracy. The field amplitude in the center of the dielectric resonator can be easily calculated without the use of finite element solvers, but has been validated using these tools.

Figure 2.1 A) dielectric resonator cavity in electromagnet with RF connections. B) Teflon holder mounted in cavity lid. Small black dot on end of white rod is the ferrite sample. C) Open resonator cavity in electromagnet showing the dielectric resonator
The dielectric resonator is placed in a simple cylindrical aluminum cavity with RF connectors. The center conductor of the RF connector is fed through the wall of the cavity and a short loop is formed from the tip of the center conductor to the wall of the aluminum cavity. This couples the microwaves from the coaxial line to the aluminum cavity and the dielectric resonator via the respective RF magnetic fields. An electromagnet is used to provide the DC bias in a direction that is perpendicular or parallel to the RF magnetic field vector.

This method of testing non-linear effects in ferrites was first used by Ulrich Hoeppe. [12] The concept of using resonators, dielectric or otherwise to excite non-linear behavior in ferrite materials is quite old [13]. The method has multiple benefits over the waveguide method, including lower cost, smaller size, and greater frequency flexibility. The downside to the dielectric resonator (DR) method that we have discovered so far includes the time constant of the DR, which due to being a highly resonant structure has a significant rise and fall time on the order of microseconds. The rise time of the non-linear

Figure 2.2 High power dielectric resonator test setup block diagram
The spinwave effect is on the order of 100ns to 1 microsecond. [6] The fact that the spinwaves could appear faster than the resonator would reach a steady state is of some concern for transient or time-resolved spinwave excitation measurements, but didn’t appear to affect the current scope of measurements negatively. Additionally, this method required a more rigorous calibration procedure than the waveguide method. As the DC magnetic field is varied during the measurement, the Q and resonant frequency shift slightly. The source has to be adjusted for the correct frequency, and the change in Q has to reflect in the calculation of the RF magnetic field incident on the sample.

The goal of this measurement is to find the critical RF power level that causes the material to go non-linear under a range of DC bias fields. This is achieved by increasing the RF power of a single frequency signal incident upon the resonator in a stepwise manner while monitoring the shape and peak amplitude of the output pulse. Due to the weak coupling of the resonator needed to achieve a high Q factor, a variable attenuator and preamplifier is used to keep the power level of the output pulse well below the

![Flowchart for spinwave linewidth test](image)

Fig 2.3. Flowchart for spinwave linewidth test
The incident power of the pulse is not measured directly during the experiment, because it has been determined that the output power of the solid-state amplifier is very predictable over multiple retests of the entire power range. Instead, at the start of each testing session, the output power of the amplifier is verified with a power meter and the deviation from a calibration table is noted. This deviation is typically on the order of 0.25 dB.

As noted, previously, changes of the DC magnetic field while a ferrite sample is in the DR result in a change of the DR resonant frequency. This is due to a changing permeability in the ferrite as it becomes saturated and goes through FMR, which in turn influences the effective permeability of the entire resonator. This phenomenon requires the frequency of the DR input signal to be corrected for these changes in order to ensure a maximum and predictable $H_{\text{rf}}$ at the sample location, as well as to avoid detuning of the resonator, which distorts the output pulse making detection of the non-linearity threshold impossible.

The following steps describe the process of the $H_{\text{crit}}$ detection.

1) Load sample into DR cavity and load cavity into electromagnet with appropriate orientation (parallel or perpendicular pump)
2) Apply the desired initial DC bias
3) Set the source power low and turn on the HPA. Turn RF on.
4) Adjust the frequency for a maximum power output from the resonator. Program the pulse profile as needed. (Figure 5.A)
5) Observe the low power pulse on the oscilloscope. Make sure there are no-linearities. If the low power pulse is distorted, go back to step #4
6) Increase the input power in steps of 1dB and monitor Oscilloscope (Figure 5.B and Figure 5.C)
7) If a threshold is reached, the output pulse will be distorted. (Figure 5.D and 5.E)

--- Instructions continue on next page ---
8) Note the field and input power level at which non-linearity occurred and reduce the power to an initial low level.
9) Adjust the bias field to the next value. Note that the low power output pulse may have become distorted. (Figure 7.A)
10) Adjust the frequency for maximum output from the resonator. Typically this means going up in frequency if the bias field has been incremented up.
11) Repeat steps 4 through 10 to complete the measurement.

Figure 2.5. Output power vs Input power of the resonator measurement from Figure 5. The non-linearity threshold is clearly seen at -37dBm input power.

--- Instructions continue on next page ---
Figure 2.6. A) cavity detuning after the bias field has been changed. B) cavity frequency adjusted for maximum output power. C) input power increased. D) Input power increased and non-linearity threshold exceeded.
Figure 2.7. Output power vs Input power of the resonator measurement from Figure 7. The non-linearity threshold is clearly seen at -43dBm input power.
2.B Detection of onset of non-linear response and critical RF magnetic field $H_{\text{crit}}$

Figure 2.8 shows the three basic states of the ferrite material as it is subjected to increasing power levels [18]: linear ($H_{\text{rf}} < H_{\text{crit}}$), at threshold ($H_{\text{rf}} \approx H_{\text{crit}}$), and non-linear ($H_{\text{rf}} > H_{\text{crit}}$). The threshold for perpendicular pump test scenario is defined as the input power level that causes the shape of the output pulse to deteriorate, or two consecutive steps where output power compresses by 0.2dB or more per 1dB of gain. In the case of the former, it is clear when the threshold is reached because it is easily discernable on the oscilloscope and it is always coincident with the latter. However, some materials exhibit a more pronounced absorption above threshold than others and in some cases a visual cue is not easily seen on the oscilloscope. In these cases, consecutive steps of output power compression of 0.2dB or more per 1 dB of input Gain are used to detect the non-linearity threshold.

It can be clearly seen from the testing procedure that it is critical to separate the effects of the ferrite on the DR from the measurement for a couple of reasons. 1) The detuning of the resonator results in a detector output that is visually similar to that created by spinwave non-linearity. 2) The detuning of the resonator influences the $H_{\text{RF}}$ incident on the sample, so even if spinwave effects are truly detected, the calculated threshold may be wrong.
We recall equations 3 and 4 from part one and note that only $\varepsilon_r$ is included in the denominator of both. This is because DRs are typically made of dielectric materials with $\mu_r = 1$ so it is omitted from the equations. When a ferrite sphere is placed in the middle of the DR, it loads the resonator, lowering its Q and changing its resonant frequency. Figure 2.9 shows the effect of the permeability resonance typically observed in magnetic materials on the resonant frequency of a resonator [15]. This dispersion of the resonant frequency is why the resonant frequency of the resonator must be carefully monitored. As will be discussed in later section, much useful information can also be extracted from the dispersion of the resonant frequency with applied field.

As discussed earlier, the resonant rise time of the DR is on the order of microseconds, which can be slower than the rise time of spinwaves. We believe this is the reason the non-linearity can be detected by a simple peak power measurement, without observing an initial spike followed by absorption. Once the power is above threshold, the spinwaves start to build up before the resonator reaches full power during each 10-20 microsecond pulse cycle.

\[
f_0 = \frac{34 \pi}{r \sqrt{\varepsilon_r}} \left( \frac{r}{L} + 3.45 \right) \quad (5)
\]

\[
H_0 = 13.1 \sqrt{\frac{Q_{IP} \omega_P (1-r^2)}{\omega P_{in} (\omega \mu_0 D)^2 \gamma_{DR}}} \quad (6)
\]
This means that output pulse of the DR is always affected by spinwave absorption in the ferrite. This implies that the output power from the resonator is initially higher, as evident from the initial spike. The duration of this spinwave build up period is in 10s of nanoseconds after which the output power is reduced to its steady state value. Due to the slow rise time of the resonator it wasn’t always possible to observe the initial leakage spike.

Once a critical RF power level is determined, the $H_{\text{crit}}$ maximum inside the DR is calculated based on the material properties of the DR, the resonator components and the geometry, as well as the input pulse power. This gives us the value $H_{\text{crit}}$, which refers to the critical RF magnetic field that induces non-linearity in the material.

2.C Low-power swept DC magnetic field testing

Figure 2.10 shows the FMR spectrum as a function of internal magnetic field and power. The high power measurements described in previous section are performed at a fixed frequency and measure the response of the material to increasing levels of $H_{\text{RF}}$. The goal of these measurements is to measure the low-field or below-resonance losses in the material. These losses are called “low field” in reference to the inter relation between the operating frequency and the FMR resonance frequency which is determined by the internal field in the material. The field used is considered low as compared to the field required for FMR at the desired operating frequency. If we were to flip figure 2.10 along the Loss, or Y-axis, we would look at the FMR spectrum in frequency domain, then the losses would appear above the FMR frequency.
Figure 2.10 Notional FMR spectrum in the field (top) and frequency (bottom) domains with various input powers levels
In this configuration, the RF power was kept constant instead of the frequency, as in the previous section. A vector network analyzer (VNA) was used to sweep a signal through the resonator and measure the response while applying a DC magnetic field. Power is kept well below the threshold power level to simulate small-signal conditions. A preamplifier at the output of the resonator was necessary in some cases to keep the signal within the dynamic range of the VNA. The DC magnetic field was changed incrementally and the S-parameters were recorded. The resultant raw data was processed in Matlab to extract the critical parameters, such as resonant frequency, the 3-dB bandwidth, and the absolute insertion loss.

The Matlab script written allows batch processing of many sets of S-parameters quickly. Especially when measuring materials with relatively low losses, it is necessary to have small field increments and the amount of data becomes cumbersome.
Part 3 - Analysis of Measurement Results

3.4 Effects of 4πMs

The reduction of the intrinsic $4\pi M_s$ value of pure YIG of about 1780 Gauss is achieved by doping the garnet crystal structure with non-magnetic cations, such as gadolinium (Gd) and aluminum (Al) that replace the magnetic iron cation in the unit cell and thus reduce the total magnetic moment per unit cell. Materials with the prefix “39” are doped with both elements, while “64” grade materials are doped only with Gd. One of the effects of adding these dopants is increased magnetic loss. [7] This is due in-part to structural defects introduced in the unit cell by the doping process. The added loss manifests itself in a broader FMR linewidth as well as higher spinwave linewidth value.
The two additives, Gd and Al will be considered as primary dopants in this analysis. It is important to remember that the simultaneous lowering of the $4\pi M_s$ and the increasing of the spinwave linewidth occur as a result of adding the elements Gd and Al. The secondary additives that we have studied such as Holmium, Cobalt and Manganese do not have the effect of lowering the $4\pi M_s$ of the material, but can still influence the spinwave linewidth.

It was our expectation that materials with the highest $4\pi M_s$ would have the lowest $H_{\text{crit}}$ values because they would be structurally closest to pure YIG. However, the lowest measured value of 0.23 Oe was actually for the 0.020” diameter 1000 G single crystal sphere purchased from Ferrisphere Inc. We don’t have a lot of information about the composition of this sphere, but know it is free of any dopants to increase spinwave linewidth. Single crystal YIG has typically has a spinwave linewidth nearly one order of magnitude lower than that of polycrystalline YIG.
magnitude lower than polycrystalline YIG. We measured an $H_{\text{crit}}$ of 1.1 Oe in a Gadolinium and Aluminum substituted 1000 G sphere, which is consistent with our expectations.

For reference, in figures 3.1 through 3.3 vertical dashed lines pointing to applied DC values on the X axes. The lower line corresponds to the approximate field required for saturation of the spherical sample. The upper line corresponds to field required for FMR at the test frequency of 1.85 GHz under the assumption of a saturated sample. It is shown that for materials with 4piMs of 1780, the field required for FMR is almost the same as the field required for saturation, which means that a partially saturated state in the material is likely. Samples with lower 4piMs should be fully saturated at the field required for FMR, which is indicated by the larger spacing between the dashed lines in the figures.

These facts lead to broadening of the FMR linewidth, which we observed in low power experiments, the results of which will be described in the subsequent sections. In the 1780 materials, only 91.5% saturation is actually achieved at an applied field of 600 Oe based on measured results using a Vibrating Sample Magnetometer. Materials with lower 4piMs have over 98% saturation at this field. This means that our calculation for the FMR frequency, which will be explained in greater detail in the next section, is probably not valid for the high 4piM case at 1.850 GHz.

The high power measurements indicate fairly low $H_{\text{crit}}$ values for 1780 G materials above the field required for FMR in a YIG sphere. Conversely, materials with lower 4piM have very high $H_{\text{crit}}$ values at the FMR field and above. This observation leads us to conclusion that the high power absorption in the high 4piMs materials is not
entirely due to spinwave excitation in the below resonance region and is likely a combination of the broad main FMR mode and a spinwave mode known in previous literature as coincidence limiting absorption. [20] In this process low $H_{\text{crit}}$ values are possible very close to the main FMR mode and the subsidiary absorption mode can even overlap with the fundamental mode. Typically, the main FMR mode requires higher power to saturate. [2] In the lower 4πMs materials, we see that low $H_{\text{crit}}$ values are only possible below the FMR field, as is expected, with very high threshold power levels at FMR. In fact, no spinwave can propagate in the above resonance regime.

Table 2 summarizes the general trends and effects of dopants on the magnetic properties of the materials. The data for Cobalt doping is inconclusive because we do not

![Figure 3.3 Butterfly curves for 1780 4πMs materials.](image)
believe the 1780 4πMs materials that were doped with Cobalt could be accurately measured at 1.9 GHz. Higher frequency measurements are recommended for this material.

<table>
<thead>
<tr>
<th>Atomic Number</th>
<th>Dopant</th>
<th>4πMs</th>
<th>Low field loss</th>
<th>ΔH</th>
<th>ΔHk K → 0</th>
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<td>Gadolinium</td>
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<td>−</td>
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<tr>
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<td>−</td>
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<td>−</td>
<td>?</td>
<td>−</td>
<td>−</td>
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<tr>
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<td>67</td>
<td>Holmium</td>
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<td>−</td>
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</table>

Table 3.1 Table defining effects of dopants based on low power and high power testing.

3.B Low power swept field results
3.B.i FMR

These tests were used to measure the FMR linewidth of the materials, as well as to characterize their below resonance losses as a function of applied DC field. The shift of the resonant frequency that is experienced as the DC field is varied is related to the change in permeability of the ferrite. When the resonance condition is satisfied with the correct DC field, the real part of the permeability first reaches a maximum, then collapses and becomes negative and as the field is increased further, returns to a value of about 1. This change is reflected in the resonant frequency of the resonator. The amount of frequency shift is determined by the size of the sample and the filling factor of the DR. The difference in DC field required to move from the maximum resonant frequency (maximum permeability) to the minimum resonant frequency (minimum permeability) is representative of the peak-to-peak FMR linewidth \(\Delta H\) [15], to be differentiated from 3 dB FMR linewidth, typically reported on material datasheets. In the case of a 3dB representation, that is referring to field values that cause the amount of absorbed power to fall by 3dB. This is typically done by measurement of the imaginary part of the
permeability. In the peak to peak representation, this is referring to the maximum and minimum of the real part of the permeability. The peak to peak case represents the method of measured we used to characterize the linewidth. It is better to use the real part of the permeability to measure the linewidth, because in the imaginary case, the detuning of the cavity frequency due to the real part introduces error into the measurement. This is less important in the case of conventional waveguide and air cavity type measurements, but could still have an impact with very low loss samples.

Typically FMR spectrometers perform a derivative operation on the voltage combing back from the cavity, which results in a curve that has two inflection points, representing FWHM of the absorption due to FMR. This is shown in 3.4 along with a raw data plot of the dielectric resonator when a similar FMR measurement is performed. The dual inflection point in the case of the right hand side of the figure is due to the maximum and minimum inflections of the permeability at FMR.

Figure 3.4 Typical measurement of FMR absorption, and first derivative (left) measurement of dielectric resonator frequency due to FMR (right)
The dashed lines in figures 3.1 through 3.3 represent the DC field required for saturation of a sample with a particular $4\pi M_s$ value as determined by VSM measurements, and the field at which FMR occurs as determined experimentally, as well as from the FMR condition equations for a sphere. As can be seen in figure 3.3, for a 1780 $4\pi M_s$, the field required for FMR at the measurement frequency nearly overlap with the field required for saturation, while the lower $4\pi M_s$ samples hit saturation well before reaching the FMR field. This results in a broadening of the FMR linewidth because the losses from partial saturation of the sample merge with the onset of FMR losses. The same sphere was remeasured with the same DR, but operating in a higher order HEM$_{12\delta}$ mode. Although this field configuration would not be appropriate for high power testing, it is still valid for small signal testing because of orientation of the DC and RF fields remains correct, simply for the HEM mode there exists no large concentration of $H_{rf}$ at the sample location. When measured at a frequency of 3.165 GHz as opposed to 1.850 GHz, the 1780 materials yielded much narrower linewidths, which were consistent with those reported in datasheets. This suggests that there exists a low frequency cutoff that is related to the $4\pi M_s$ of the material, the degree of saturation and the operating frequency. For the 1780 G material, the 1.850 GHz frequency is too low to assume the FMR linewidth is the same as the measured, intrinsic value at 3.165 GHz and 9 GHz.

The 1000 and 1200 G materials did not show this broadening effect.
There are several approaches towards deriving the ferrimagnetic resonance condition. Here we follow the approach outlined in C. Vittoria’s book entitled “Magnetics, Dielectrics, and Wave Propagation with MATLAB® Codes,” (CRC Press 2010). The free energy of a magnetic system includes terms associated with all fields, both external and internal, acting upon the system. For materials we study here, mostly polycrystalline compacts of spheroid shapes, the significant energy terms to consider include magnetizing energy and demagnetizing energy. For an infinite medium, the free energy is written as follows:

![Figure 3.5 FMR measured data for various $4\pi M_s$ materials](image)

For the infinite medium, the free energy is written as follows:
\[ F = -\vec{M} \cdot \vec{H} \sin \theta \cos \phi, \]  

(9)

where \( M \) is the magnetization vector and \( H \) the externally applied magnetic field vector, both expressed in directional cosines from spherical coordinates to Cartesian ones. The FMR condition is found by calculating the equilibrium condition of the magnetization from the equation

\[ \omega = \left[ F_{\theta \theta} F_{\phi \phi} - (F_{\theta \phi})^2 \right] \frac{1}{M_0^2 \sin^2 \theta_0}, \]  

(10)

where \( \omega \) is the radial frequency of the magnetic moment precession, \( \gamma \) is the gyromagnetic constant, \( F_{\theta \theta}, F_{\phi \phi} \) and \( F_{\theta \phi} \) are partial derivatives of the free energy with respect to spherical coordinate variables, \( M_0 \) is the magnitude of the magnetization vector and \( \theta_0 \) its direction. Solving this equation for FMR frequency \( f_0 \) we get

\[ f_0 = \gamma' H, \]  

(11)

where \( \gamma' \) is the familiar \( \gamma / 2\pi \) approximately equal to 2.8 GHz/kG.

If we take a finite magnetic volume, such as a sphere for example, we have to add a demagnetizing term to the free energy equation as follows

\[ F = -MH \sin \theta \cos \phi + \frac{1}{2} \left( \frac{4\pi}{3} \right) M^2 \left( \sin^2 \theta \cos^2 \phi + \sin^2 \theta \sin^2 \phi + \cos^2 \theta \right), \]  

(12)
where $4\pi/3$ is the demagnetizing factor $N_x = N_y = N_z$. The equation can be simplified to

$$F = -MH \sin \theta \cos \phi + \frac{2\pi}{3} M^2,$$

(13)

which is basically the infinite medium case in (9) with an added term associated with the demagnetizing energy. Solving for the equilibrium condition according to (10) we find

$$\omega/\gamma = H, \quad H \geq H_D,$$

(14)

where $H_D$ is the demagnetizing field equal to $4\pi M_s/3$. Therefore, FMR can only be observed in isotropic sphere samples once they are magnetically saturated using an external field strong enough to overcome the maximum demagnetizing field. The FMR frequency, however, is not dependent upon the saturation magnetization through the demagnetizing fields because these terms cancel for RF magnetic fields out due to the symmetry of the sample.

As another example we will consider a thin film sample with external field applied normal to the film plane. The free energy in this case, consisting of both magnetizing and demagnetizing terms, can be expressed as

$$F = -MH \sin \theta \cos(\phi - \alpha) + 2\pi M^2 \sin^2 \theta \sin^2 \phi$$

(15)
where the new variable $\alpha$ is the angle at which the magnetization vector lies relative to the film plane. Taking the case where the magnetization is aligned perpendicular to the film plane ($\alpha = \pi/2$), we get

$$\omega_f \gamma = H - 4\pi M$$  \hspace{1cm} (16)

which again is only valid for $H > H_D$, $H_D$ in this case being equal to $4\pi M_S$. For reference, a commonly used, closed form for expression for FMR frequency is given as,

$$f_0 = \sqrt{\gamma' \frac{(H + (N_x - N_y)M_S)(H + (N_x - N_y)M_S)}{(H + (N_y - N_z)M_S)}}$$  \hspace{1cm} (17)

under the conditions that the sample is an ellipsoid magnetically saturated in the direction normal to the surface, and the RF magnetic field lies transverse to this direction, in the plane of the sample.
3.B.ii Low field loss

Low field losses were characterized by measuring the insertion loss of the cavity, as well as the Q factor, as a function of DC applied field. Both methods yielded similar results, but the insertion loss data is shown here because the Q calculation yielded noisier data.

As was illustrated in figure 2.10, there exist several regions in the FMR spectrum for a given frequency. In the below resonance region we expect a certain range of $H_{dc}$, typically associated with saturation of the ferrite, to yield low loss. Lower DC bias than this minimal $H_{dc}$ value is expected to result in low field losses due to the partially magnetized state of the material, while higher DC bias will approach the FMR condition. This “sweet spot” of low loss DC field range is crucial to circulator designers because it allows for low loss operation and the bounds of this region limit the circulator bandwidth. Figure 3.6 shows the loss spectra of materials with various $4\pi M_s$. In order to highlight the effect of the saturation magnetization on the low field loss region we have plotted the loss spectra for materials with 472, 803 and 1000 $4\pi M_s$ in...
The absolute loss values have been offset to highlight the trend along the x-axis. The fixed frequency of operation puts a hard limit on the maximum DC field one can apply in a below resonance condition, because if the field were to be increased beyond 700 Oe the operation regime would switch to above resonance after a region with prohibitively high losses. On the other hand, the lowest DC field one can apply is governed by the $4\pi M_s$ of the material, as can be seen Figure 3.7. The low loss region cutoff field is related to the $4\pi M_s$ of the material. This suggests that the lower the operating frequency is for a given $4\pi M_s$ material, the narrower the range of available low loss biasing conditions. Further, a lower $4\pi M_s$ value potentially allows for increased bandwidth on the low frequency end of the spectrum due to the reduced frequency of onset of low field loss. As such, there is an inherent dichotomy that drives the designer for higher $4\pi M_s$ material to increase the bandwidth on the high frequency end of the spectrum while increasing the bandwidth on the low end requires reduced $4\pi M_s$. 
The condition for the onset of low loss can be approximated for a given frequency by the following relation

\[ 4\pi M_S \cdot N < H_{\text{low loss}} < \frac{F}{\gamma} - \Delta H \]  

(18)

where \( F \) is the operating frequency in MHz, \( \gamma \) is the gyromagnetic constant of 2.8 MHz/Oe and \( \Delta H \) is the FMR linewidth. This can be clearly seen in figure 3.7.
From this relation it is clear that if the frequency is fixed, increasing the $4\pi M_s$ will reduce the range of available $H$ fields that will allow for low loss below resonance operation.

It is important to note that the FMR condition for a sphere sample is not influenced by $4\pi M_s$, see Equation 14. In contrast, all other parameters we studied, like spinwave linewidth and low field loss, do appear to be influenced by the $4\pi M_s$ value of the material. In a puck sample, as one would have in a circulator, FMR condition would also become a function of $4\pi M_s$ due to the presence of demagnetizing fields. In other words $N_x \approx N_y \approx 0$, and $N_z \approx 4\pi$, as would be the case for a relatively large diameter thin puck magnetized through the thickness, Equation 17 reduces to the familiar

![Insertion Loss Graph](image)

Fig 3.7 Low field loss measured data for 472, 803 and 1000 G materials
\[ f_0 = \gamma'(H-4\pi M_s) \]

(19)

The effects of Cobalt and Holmium doping appeared difficult to characterize, especially for the 1780 material measured at 1.850 GHz. The tests yielded no clear trends as to the effects of those additives.

Fig 3.8 Low field loss measurements for 1200 G material with increasing levels of holmium doping
Limitations on measurement repeatability and accuracy

At the start of every high power test, the same sample was re-measured to make sure the setup was producing consistent results. Typically this was done using either the 1000 G polycrystalline sphere or one of the 39-1000-554 spheres. Steps of 1dB were used to vary to input power to the resonator which is the resolution of the $H_{\text{crit}}$ test. This results in an $H_{\text{crit}}$ resolution of about 12%, e.g. at 10 Oe the resolution would be 1.2 Oe. Ideally, the power sweep would have much smaller resolution on the order of 1%. The automation of measurements would make calibration much easier and thus more accurate measurements could be achieved by collecting series of data and performing statistical analysis to determine the exact error margins of the measurement.

Further, determining the $H_{\text{rf}}$ in the DR requires an accurate input for the Q factor and the Reflection Coefficient. In our calculations, these were assumed to be fixed at 10,000 and 0.9, respectively. As was found in low power testing, the Q factor is dependent on the DC bias field and sample size, and its effect is varies for samples with different $4\pi M_s$. For example, 1000 $4\pi M_s$ sample have a maximum Q around $H_{dc} = 4\pi M_s/3$, while the 1780 materials have very low Q at $H_{dc} = 4\pi M_s/3$. For the single test frequency of 1.850GHz, this results in a very wide range of error margin that is dependent on the samples $4\pi M_s$. Based on sensitivity analysis, we estimate that error margin to be between 10-50%, with the high error being for the 1780 $4\pi M_s$ materials.

In our calculations of $H_{\text{crit}}$, a constant value of Q factor was used in the calculation of the $H_{\text{rf}}$ at the instability threshold. As was found in the low power experiments, the Q
factor is dependent on the size of the same. We measured a 0.020” and a 0.030” sphere and found a factor of 2 difference in the Q factors, which if unaccounted for would result in a 50% error margin in the $H_{\text{crit}}$ calculation. Patton [14] reported on the effects of sphere size, both in terms of intrinsic $H_{\text{crit}}$ value as well in terms of cavity effects and resultant errors. He concluded that the apparent effects of sphere size on $H_{\text{crit}}$ are due to non-uniformity of $H_{\text{RF}}$ magnetic field in larger samples, as well as due to cavity loading which leads to lower Q and lower $H_{\text{RF}}$ levels. Patton used a waveguide measurement system where sample position is of utmost importance since the RF magnetic field is non-uniform in the waveguide. Consequently, a larger sample will result in parts of the material being exposed to different amplitudes or even orientations of $H_{\text{RF}}$. The DR has relatively large and uniform $H_{\text{RF}}$ “sweet spot” when compared to the size of the sample, however the downside is that the Q, and thus the $H_{\text{RF}}$ can be significantly reduced by larger, lossy samples. Variations in apparent $H_{\text{crit}}$ were observed during high power testing but they were discarded for 2 reasons: Firstly, the variations could be quantitatively accounted for by adverse cavity detuning effects and secondly, the purpose of these experiments was to compare the intrinsic power handling capability of various materials, not explore the effects of sample geometry.

Figure 3.9 shows 3 measurements of the same single crystal sphere, on different days without changes to the setup except for re-mounting of the sample. There is a significant variation in the X-axis position of the butterfly curve, which is the magnitude of the DC bias to reach $H_{\text{crit}}$ minimum. This is possibly due to the crystalline anisotropy in the single crystal sphere. For a single crystal sample, the crystalline anisotropy is not
averaged out over all the grains, as in the case with a polycrystalline material. This means that there is an additional internal field of cubic symmetry present in the sample. Since the orientation of the sphere was not controlled during the measurement, the effect of the sphere’s crystalline anisotropy would be different every time. This effect will likely be significant due to the relatively low bias field. This shifting of the minimum $H_{\text{crit}}$ position on the butterfly curve was also observed on the polycrystalline sample, but to a much lesser extent. Here is might be attributable to shape anisotropy for less-than-perfectly spherical samples, microstructural texturing of the sample, and finally discrepancies in sample placement.

Another inconsistency in the measurements was the response of some different

![Fig 3.9 Hcrit plot for 3 different measurements of the same 1000 4piMs single crystal sphere](image-url)
spheres, within the sample material batch, at low DC bias conditions where

\[ H_{DC} < \frac{1}{3} 4\pi M_s \]

Figure 3.10 shows \( H_{crit} \) plots for 3 similar materials with increasing Cobalt content. All three samples were measured at field values down to 200 Oe. The low field side of the plot shows a discontinuity for some of the samples. There appears to be a large, abrupt increase in \( H_{crit} \) at low field values, something also reported in prior publications [6,16]. Although the data in Figure 3.10 shows different materials, this effect was also observed in some samples of the same material. These variations could be produced by several factors, such as differences in size or surface finish. Additionally, microstructural texturing could be inducing residual crystalline anisotropy in polycrystalline samples and may be dependent on the dopants used. The effects seem to be too large to be considered measurement error related.
In short, further refinement of the measurement method, as well as a more rigorous study with a larger sample set are needed to isolate why certain spheres have different behavior in partially magnetized conditions. This is very important because those conditions are very close to the ones employed in broadband circulators. It should also be noted that these variations may well be intrinsic to the manufacturing process used in creation of the ferrites. Since spinwave linewidth is not a material parameter that most ferrite manufacturers control on a lot by lot basis, there is no guarantee of consistency in the materials’ high power properties.

Fig 3.10 $H_{crit}$ plots for 1780 YIG with increasing Co content
The accuracy of the FMR measurement for samples having $4\pi M_s$ of 1200 or less is in very good agreement with measured data provided by the manufacturer as is shown in figure 3.11. The measured FMR linewidth is generally lower because the vendor data was collected at 9.5 GHz, a standard frequency for FMR testing, as such our measurements are expected to be somewhat lower since FMR linewidth is proportional to frequency.

Determining the accuracy of the high power testing is difficult because there is no published data that details spinwave linewidth measurement at below 2 GHz frequencies and because the data provided from the vendor is notional and is not generated through measurement of produced materials. Our measured results and how they differ from the vendor’s data are shown in figure 3.11. Using the vendor’s spinwave linewidth data is not optimal because that data is typically an approximation based on previous results and extrapolations. Additionally it depends on the equation used to calculate $\Delta H_k$. Since the vendor does not measure the spinwave linewidth of every material batch, its hard to say

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<th>Doping</th>
<th>Material</th>
<th>$4\pi M_s$</th>
<th>Happlied</th>
<th>Hcrit</th>
<th>$\delta H$</th>
<th>Catalog spinwave linewidth</th>
<th>Spinwave linewidth error</th>
<th>Measured FMR linewidth</th>
<th>Catalog FMR linewidth</th>
<th>FMR linewidth error</th>
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Fig 3.11 Deviation from vendor specified FMR and spinwave linewidth as a function of $4\pi M_s$
where our results fall as far as measurement error, because we don't have an accurate specification. There exists no such “standard” sample that will always yield the same $H_{\text{crit}}$ value.
Part 4 Future work

Measurements as a function of temperature

The DR setup could be fairly easily integrated with a temperature control apparatus. By flowing inert gas into the aluminum cavity and over the sample $H_{\text{crit}}$, FMR linewidth and low field loss measurements could be carried out as a function of temperature in the military or space range. A similar approach is presently used in the VSM to perform temperature measurements. This information would be useful in further understanding both the small and large signal behavior of partially magnetized ferrites at low GHz frequencies.

High-power main ferrimagnetic resonance linewidth measurement

It is of interest to perform the low power swept field test as a function of power. Along with increased losses in the subsidiary absorption region, a broadening of the main FMR linewidth is observed when the $H_{\text{rf}}$ is high and was depicted in figure 2.10. This test could be conveniently performed with this setup if the high power amplifier was used to amplify the swept VNA signal. Proper modifications would need to be made to the VNA to protect the input couplers from high power.

Data collection and analysis automation
Due to the limited scope and funding of this program, all the parameter controls during the experiments were tuned manually, greatly increasing the time to complete the tests as well as the skill and experience required from the tester. For the low power swept field measurements, the process of incrementally increasing the field and collect s-parameters could be easily automated with a programmable DC power supply to drive the electromagnet and Labview code to control the VNA. The $H_{crit}$ measurement process could also be automated but care would have to be taken to correctly address cavity detuning effects. One way around this is to perform the low power swept field measurement first and use this data to program a high power test routine. The same high power test procedure as that shown in figure 2.2 can then be used to test for spinwave linewidth but instead of searching for the resonant frequency of the DR iteratively, the low power swept field data can be used to predict the resonant frequency of the resonator allowing for automation of the power sweep. Detection of non-linearity by visual deterioration of the output pulse shape alone is not the optimal method of performing these tests. Deterioration can be a subjective term and as mentioned earlier this visual cue is often not seen for some materials and at very high power levels. Traditionally FMR linewidth measurement is done using a lock-in amplifier to extract the relatively small FMR signal. Although lock-in amplification is probably not needed for spinwave linewidth tests, there is another element we can be borrow from traditional FMR measurements where the derivative of the absorbed power with respect to the DC field is used to detect FMR. Instead, we could use the derivative of the absorbed power with respect to the input power to detect the non-linear response, while stepping the field in increments rather than sweeping it.
Part 5 Summary and Conclusions

The method of using Dielectric Resonators to test the linear and non-linear properties of microwave ferrites was found to yield results in good agreement with previous studies and published data. Unlike conventional methods, the DR enables the measurement of high power associated effects without the needed for high power during testing. The critical threshold was found to be inversely proportional to the saturation magnetization obtained through the use of Gadolinium and Aluminum crystal lattice substitution. Additionally, Holmium, Manganese and Cobalt were studied as dopants for manipulation of the spinwave linewidth without affecting the saturation magnetization. An analysis of the effects of various substitutions and dopants was provided. Additionally, effects of partial saturation were studied and analyzed but in terms of non-linear dynamics and effects on small signal losses and FMR linewidth.

Our experiments found that the models established for determining the spinwave linewidth and associated critical field levels are mostly valid under partially magnetized conditions at the relatively low frequency of 1.85 GHz. Previous studies have concentrated on measurements at ~9.5 GHz, with some ranging going as low as 3 GHz. In the extreme case of the 1780 material, partial saturation effects seem fairly significant,
distorting the small and large signal spectra, causing significant broadening of the FMR linewidth and lower than expected spinwave linewidth.

**Part 6 Acknowledgements**

I would like to thank James Carr and Raj Rajendran of Raytheon Co. for funding this work at Northeastern University. The guidance and input of Professor Vincent Harris and Dr. Anton Geiler has been invaluable throughout this program. I would also like to thank all my colleagues at the Center for Microwave, Magnetic Materials and Integrated Circuits (CM3IC) as well as at Metamagnetics Inc. for their help, support and contributions of knowledge and expertise that has helped me numerous times during my studies. I would also like to thank Faith Crisley, the student coordinator in the ECE department at northeastern university for her help and support throughout my graduate studies. Last but not least, I thank Elwood Hokanson from Pacific Ceramics Company for sharing his knowledge of ferrite materials and test methods, and John Deriso of Skyworks Inc. for providing the dielectric resonators used in the experiments.
References

17. Pacific Ceramics Inc. product catalog, 2014.
## Advanced Microwave Ceramic Materials

### Garnet Materials

#### Yttrium Iron Garnets

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<th>Product</th>
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**Garnet Materials**

**Yttrium Iron Garnets**

**High Power RF Applications**

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**Dysprosium Doped, Aluminum Substituted Garnets**

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**Type 3, Lithium Ferrites, Narrow Linewidth**

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