DEVELOPMENT AND APPLICATION OF A NOVEL NEAR-FIELD MICROWAVE PROBE FOR LOCAL BROADBAND CHARACTERIZATION OF FERROMAGNETIC RESONANCE

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By

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To my family.
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ABSTRACT

A novel near-field microwave probe is developed for the characterization of magnetic materials. The ferromagnetic resonance probe consists of a shorted micro-coax, where the current path is a Cu thin film that sits on top of a focused ion beam deposited buffer layer. The buffer layer creates a mechanically more robust probe and leads to an increase in sensitivity. This is demonstrated through measurements on a broad range of samples, from common magnetic materials such as NiFe, to advanced materials such as multiferroic nanocomposites, where the magnetization dynamics are more complex. The data from these measurements are used to extract parameters on both the static and dynamic properties of the probed sample, such as the anisotropy field and the intrinsic magnetic damping. These parameters are important in the design of magneto-electronic devices, like the components of a hard drive in the magnetic recording industry. The main attributes of this technique are that it is broadband, it is local with the potential to achieve higher spatial resolution, and it is a non-contact method, although it is possible to measure a material while in contact. Because of the probe’s metallic tip, and the ability to come in contact with the sample, it was possible to extend the measurements to both
magnetically and electrically characterize the multiferroic material, which is of interest for an advanced media concept (Electrically Assisted Magnetic Recording). Finally, the probe can also measure samples of any form factor (e.g. wafers, media disc, chips), and can therefore be used to characterize devices in their working environment, or between fabrication steps.
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Introduction

Microwave spectroscopy has proven to be a very useful method for the investigation of both the static and dynamic properties of magnetic materials. In particular, ferromagnetic resonance (FMR) experiments, where a small oscillating magnetic field ($h_{rf}$) interacts with the magnetic spins, are especially well suited for the study of the dynamic behavior of a system. This method takes advantage of the fact that if the spins are aligned with an externally applied static magnetic field ($H_{DC}$), and they are disturbed from equilibrium, they will precess back toward their initial position (along $H_{DC}$) with a given angular frequency $\omega_{FMR}$. Then, if $h_{rf}$ is applied perpendicular to $H_{DC}$ and its angular frequency matches that of $\omega_{FMR}$, there will be coupling with the precession of the spins and the system will start absorbing energy. The absorption spectra resulting from such a measurement can be used to obtain various sample parameters (e.g. anisotropy field, intrinsic damping constant). These parameters are critical to the design of magneto-electronic devices, as will be discussed in later chapters.

The first experimental observation of FMR is attributed to Griffiths in 1946 [1]. While measuring the resistivity of thin ferromagnetic films in a resonant cavity, he reported anomalous resonant frequencies that were larger than one would expect from calculating Larmor frequencies for electron paramagnetic resonance (EPR) [2]. The following year, Kittel was able to explain the observed results by taking into account the dynamic coupling due to the demagnetizing field perpendicular to the film surface [3].
Since then, FMR characterization methods have grown more sophisticated and the study of magnetic materials remains active to this day, motivated in part by the development of magnetic recording systems. These devices, driven by bigger areal densities and faster data transfer rates, are operating well into the gigahertz (GHz) regime. This higher frequency range overlaps the FMR frequency of many materials of interest used in these systems, and has prompted efforts to understand the dynamic behavior present in such materials. In addition, the design of devices with even faster switching times requires a better appreciation for all the damping mechanisms that currently impede such a process. Furthermore, the higher areal density has meant smaller storage bits, and more generally, has led to a reduction in size of magneto-electronic components down to the nanometer level. On this scale, the processes that dominate the spin excitation and its lifetime lead to different behavior than in the bulk. One therefore needs the ability to probe such structures with high spatial resolution to properly characterize the behavior, while at the same time maintaining enough sensitivity to pick up a signal over the reduced volume of material.

Figure 1 shows a diagram of the components found in a recording system. The disc contains both a media layer on which the bits are recorded (in this case, perpendicular to the plane), and a soft magnetic underlayer (SUL) that helps enhance the performance of the write pole, as discussed in chapter three. Soft magnetic materials can be demagnetized from saturation by applying a small external field. In contrast, hard magnetic materials, such as the media layer, require large external fields in order to change their magnetization orientation. The recording head also has two components
(both comprised of magnetically soft materials such as CoFe and NiFe alloys): a write pole, whose dimensions helps determine the bit sizes, and the reader which detects the orientation of the fringe fields emanating from the bits in the media layer.

Figure 1: Diagram of a magnetic recording system. The data is stored as perpendicular bits in the media layer, which sits on top of a soft underlayer. (courtesy, Tom Clinton, Phys 522 lectures, Georgetown University).

Traditional FMR characterization methods include microwave resonant cavities [4], where the magnetic field is swept while the sample is excited inside a cavity at a fixed frequency. The Q factor of the cavity is then monitored to determine when the excitation of the sample matches the resonant frequency. The drawbacks to this method are the frequency is fixed for a given cavity, the poor spatial resolution (i.e. the measured response is from the whole sample), along with the fact the cavity restricts the size and
geometry of the sample. In order to achieve greater spatial resolution, a new setup was
developed where the sample was placed underneath a hole centered on one of the cavity
walls [5]. In this case, the cavity acts as a near-field microscope, where only the section
of material underneath the hole is exposed to the microwave field. A similar technique
was developed through the replacement of the cavity by a dielectric resonator with a thin
slit aperture [6]. However, in both of the above cases, the measurement is restricted to
one frequency, that of the resonator. There are also near-field methods which are
broadband, such as non-resonant transmission striplines [7], although this offers a
relatively low sensitivity, making measurements on small samples difficult.

There are still other local FMR characterization methods, such as Brillouin Light
Scattering (BLS), which do not even use microwaves to obtain the measurement [8]. BLS
is an optical spectroscopy technique where photons from an incident laser interact with
the magnetic spin excitations, or magnons, from the sample. This interaction leads to an
energy transfer, either to or from the magnons, and results in a frequency shift of the
diffracted light. A different approach which also relies on a light source for local FMR
measurements is the magneto-optical Kerr effect (MOKE) [9, 10]. In a MOKE setup, the
sample is excited locally via a laser pulse or a pulsed DC current traveling in a stripline.
The polarization rotation of the light is then monitored after it interacts with the magnons,
with the response being measured in the time domain. In the above techniques, the spatial
resolution is limited to the focusing ability of the laser (> ~ 300 nm), and the response
can typically only be measured for the layers near the top surface (limited by the optical
penetration depth). The optics set up needed for signal detection can also be rather complex, and requires careful calibration.

Because FMR results in the absorption of energy by the system, it is possible to take advantage of thermal changes to make a local measurement. For photothermally modulated (PM-FMR) measurements, an amplitude modulated laser beam is focused on a sample to generate a local thermal wave [11]. The measured signal (usually obtained with a resonant cavity) should only come from the area where the thermal wave was generated. Conversely, it is possible to monitor the local change in temperature of a sample as it reaches resonance, using a scanning thermal microscope (SThM) [12]. SThM can achieve resolution on the order of the nanoprobe (~100 nm) used to measure the temperature change. More recently, with the advances made in atomic force microscopy (AFM) techniques, SThM has been extended to contact mode. In this case, the scanning thermoelastic microscope (SThEM) actually measures the vertical thermal expansion of the sample as it absorbs energy at resonance [13]. This allows SThEM to achieve a spatial resolution in the range of 10 nm [14]. Since they generally rely on a microwave cavity for signal generation or detection, these techniques also suffer from the disadvantage of restricting the sample’s form factor, and of only operating at one frequency. In addition, SThM and SThEM require input powers of more than 100 mW in order to generate a sufficient temperature rise for thermal detection [4].

Two other local FMR characterization techniques worth mentioning are X-ray magnetic circular dicroism (XMCD) and magnetic resonance force microscopy (MRFM). XMCD uses circularly polarized synchrotron radiation to obtain element specific
magnetic properties with a 50 nm resolution [15]. However, time resolved XMCD require ultra high vacuum, and of course, a cyclotron [16]. MRFM consists of a small magnetic tip mounted on an oscillating cantilever. By interacting with the stray fields from a sample, the tip changes the vibration frequency of the cantilever. On the other hand, MRFM is operated in a vacuum at cryogenic temperatures, and relies on a resonant cavity for sample excitation [17]. Note that although little work has been done to compare the various measurement methods, the available literature points to the fact that they tend to be equivalent [18, 19].

In this work, I will discuss the development of a local non-contact FMR characterization method. This near-field non-resonant microwave probe uses a micro-coax terminated with a short circuit to excite a sample and pick up the resulting response (e.g. the signal generation and detection are both localized). It is currently sensitive enough to locally resolve an FMR signal on a 2 nm thick sample. The probe is connected to a commercial vector network analyzer (VNA), which generates the microwave signal. Since the probe is operated in a non-resonant mode, it is intentionally broadband, as it is possible to work in a frequency spectrum that spans the whole bandwidth of the VNA (40 GHz). When combined with the ability to sweep the external magnetic field, this offers the advantage of measuring data which give a fuller picture of the dynamics present in the frequency-field space. The spatial resolution of this method is dictated by the size of the short circuit element on our probe, a current path between the inner and outer conductors of the coax. This current path is fabricated using a focused ion beam technique, so that scalability down to the sub-micron level is theoretically achievable. In
addition, since the probe sits above the sample, it places no restriction on the form factor of the material being measured. Overall, this method only needs commercially available electronic equipment, and involves a relatively simple fabrication process.

Chapter one describes the probe fabrication along with the experimental set up and method. The theoretical background for FMR, along with the sample/probe coupling and the formulas used to extract various parameters from the FMR spectra are discussed in chapter two. Chapters three and four deal with the soft magnetic under layer (material that only requires a small external field to be demagnetized from saturation) of a hard drive media disk and a series of CoCrPt samples (media storage layer), respectively. These two chapters are focused on the characterization of media components of magnetic data recording. Chapter 5 looks at a series of Holmium doped NiFe films, and its effect on the damping of magnetic excitations, an important parameter for the design of recording heads. In chapter six, a voltage source is integrated to the measurement apparatus to extend the FMR characterization to novel materials having ferromagnetic and ferroelectric properties, i.e. multiferroics. Finally, chapter seven is a summary of the results presented in this work along with suggestions for possible future work using this technique. Various computer codes used for this work are included in an appendix at the end.
References


Chapter one:
Probe fabrication and experimental set up

The initial purpose of this work is the development of a local near-field FMR probe. There are various techniques that exist for the characterization of magnetic materials, as discussed in the introductory chapter. However, they often operate in a narrow frequency range or in the time domain, require a complex set up, or put restrictions on the form factor of the sample being probed. Broadband frequency measurements are preferable to narrow band and time domain measurements, as the data obtained can be directly compared to theory, without having to perform any conversions. Furthermore, measurements that put restrictions on the geometry of the sample being probed limit the ability to understand all the factors that influence the behavior of a device (e.g. its working environment). The technique discussed below addresses all of the above limitations. More specifically, it is ideal for the monitoring of devices of any form factor in their working environment, or in between steps during their fabrication. In addition, the simplicity of the setup gives us the flexibility to extend the measurements to novel materials, as illustrated in a later chapter (see section 6.3).

1.1 Local near-field microwave microscopy

Although many magnetic material phenomena have characteristic frequencies in the microwave regime, it is not possible to probe microscopic structures made of such materials using traditional (far-field) microscopy. Indeed, the fact that the
electromagnetic waves used in this frequency range have wavelengths on the order of centimeters (cm) implies poor resolving power, as the resolution is dictated by the wavelength. However, this is no longer a limiting factor when looking at near-field interactions. In this case, it is possible to achieve much greater resolution by creating an “aperture” with subwavelength dimensions and holding it very close to the sample. The smallest dimension that could be resolved would then depend on the size of the aperture, and the sample to probe distance. Synge [1] was the first to propose this approach, while Bethe [2] provided independent theoretical backing for such an idea. And while these initial efforts were geared toward the visible spectrum, the first practical implementation of near-field microscopy was for microwaves, as the dimensional requirements for such a set up were less stringent.

This first design took the form of a microwave cavity with a small hole [3], which was sensitive to the local magnetic variations of a sample when scanned close to its surface. This was reflected in changes in the Q factor of the cavity. This was then extended to tapered hollow waveguides [4]. However, for such probes, the use of microwaves limits the resolution to the millimeter range. This is due to the fact that the incident radiation in these probes loses considerable power if it passes through an aperture smaller than ~ 1/20 of the wavelength [5]. As a result, these near-field microscopes are designed accordingly, to avoid this cut-off region. The power losses can be minimized while increasing the resolution by using a cylindrical resonant waveguide, and changing the shape of the aperture from a circle to a slit [6].
Another approach makes use of a coaxial waveguide. It has the advantage of avoiding cut off wavelengths [7], so that resolution on the micron scale is achievable. This was demonstrated for electrical characterization (e.g. dielectric permittivity) probes using open ended tapered coaxes and miniaturized micro-coaxes. Near-field magnetic microscopy was also demonstrated by Lee et al. [8] using a shorted coax. The short was made by soldering the inner and outer conductors of the coax, resulting in a probe that couples magnetically to the sample. By using a frequency following circuit to lock to one of the resonant frequencies of the coax, it is possible to monitor the frequency shift due to the sample. In other words, the coax is used as a resonator that operates at a set of distinct frequencies. Mircea and Clinton [9] extended this technique further by using a thin wire bond to short the coax. This reduced the sample to probe spacing, resulting in an improved electromagnetic coupling. This in turn allowed the use of simpler electronics for the measurements. The sensitivity was further improved by depositing and patterning a thin Cu film to form the current path between the inner and outer conductors of the coax [10].

1.2 Probe fabrication

Our current probe builds upon the design of Mircea and Clinton, scaling the dimensions down by a factor of five, while increasing the sensitivity. We have also introduced a new fabrication technique that increases the robustness of the current path, and makes it possible to safely reduce the sample to probe separation all the way to zero (i.e. contact).
1.2.1 Coax preparation

The coaxes used to make our probes are manufactured by Picoprobe [11], and are made using a semi-rigid micro coaxial cable. The coax consists of a stem that is open ended on one end and terminated by a female K-connector on the other end. This 2.92 mm connector works up to frequencies of 40 GHz. The coax is 20 millimeter (mm) as measured from the top of the connector. In figure 1.1, we see an SEM image of the micro coax before it has been pre-processed for fabrication. The inner conductor, which has a diameter of about 100 microns, is clearly protruding beyond the Teflon dielectric and the outer conductor. The outer diameter of the coax is 500 microns, while the inner to outer conductor separation is roughly 100 microns. No magnetic materials are used to make the micro coax. This is done to ensure that the probe itself will not interfere with the magnetic signal from the sample. Also, as the probe is positioned in close proximity to the sample, any applied external field will not cause changes in the sample to probe separation.
Figure 1.1: SEM image of the open end of a microcoax (80x magnification), before preparation. The coax has an outer diameter of ~500 microns and an inner diameter of ~100 microns.

The first step of the preparation is cutting off the excess coax, using a razor blade. It is important to keep the coax below a certain length. The reason for this is discussed below in section 1.4.1. This is only done the first time the coax is obtained from the manufacturer, and need not be repeated if an already cut-off coax is reused to make a new probe. Once this is done, we use ultrafine sand paper to flatten and smooth out the top surface of the coax. The sand paper used has microgrits of 16 microns. The coax is held upside down and rubbed against the sand paper using a figure eight motion. Using an optical microscope, the surface is monitored to check whether the desired flatness has
been achieved. It is also important to make sure that the top surface of the coax is not slanted. Otherwise, different sections of the current path will be at different distances from the sample during measurements, which is undesirable. During the sanding process, the coax should not be pressed too hard against the sand paper. This helps avoid accidentally bending the coax. In addition, pressing the coax too hard during sanding causes the dielectric to protrude upward, 10 microns or more, above the surface of both the inner and outer conductors. In this case, it becomes very difficult to establish a continuous current path across the dielectric.

Once the sanding step is completed, the coax’s tip is rinsed with water and dried using an air gun. We then proceed to clean off the top surface of the coax using a colloidal SiO\textsubscript{2} solution. This is accomplished by pouring a few drops of the solution on a piece of felt material, and gently rubbing the tip of the coax against it, again using a figure eight motion. With particle sizes on the order of 0.05 microns, the colloidal SiO\textsubscript{2} allows us to clean the surface from any residue that may affect subsequent material depositions. The solution also has the advantage of not damaging the dielectric, which is soft and easily deformed. The coax must be promptly rinsed off and dried once this step is completed, as the solution crystallizes relatively quickly when in contact with air.

1.2.2 Focused ion beam deposition

In previous probe designs, once the surface was processed, a 500 nm thick Cu film was deposited over the whole cross section of the coax. The deposition was done in
an e-beam evaporator. The film was then patterned into a narrow path, creating a short
to the inner and outer conductors of the coax. This removal of excess Cu was done
either by hand, using a razor blade, or with a focused ion beam (FIB). The use of a thin
film design dramatically increases the sensitivity of the probe, because it is possible to
get closer to the sample, resulting in better coupling.

For probes built on larger coaxes, the Cu adheres well enough when deposited
directly on the Teflon, even in the presence of micron scale roughness. However, as the
current path is scaled down, by using smaller coaxes and defining narrower geometries,
the adhesion and robustness become problematic. Indeed, for current path widths under
100 microns, the spotty adhesion of the sputtered Cu becomes more prominent. As a
result, the poor continuity of its surface coverage prevents us from making robust
structures.

In figure 1.2, we see a schematic representation of the top view of the coax once
the Cu has been sputtered and the current path defined. While the length of the path is
dictated by the inner to outer conductor distance, the width can be made arbitrarily
narrow, down to the nanometer scale, using the FIB. The inset of the same figure shows
an SEM image of the current path region (50 microns wide) near the inner conductor of
the coax. The spotty adhesion of the Cu is evident, along with a crack near the interface
between the dielectric and the inner conductor. This illustrates the difficulty in scaling
down the structure. We developed a new fabrication method to address these issues,
while providing a possible way to achieve further scaling of the Cu loop. This method
relies on FIB deposition [12].

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Figure 1.2: Schematic representation of top view of coax with current path (not drawn to scale). The inset is an SEM image (800x magnification) of a region near the inner conductor of the coax. The image reveals cracks in the current path (50 microns wide), and poor adhesion of the Cu.

The FIB is part of a dual beam (along with SEM) Nova NanoLab system made by FEI [13]. This instrument can perform high resolution imaging, sample preparation and analysis, along with micromachining and assembly, all on the same platform. Localized sputtering on a sample has also been demonstrated [14]. The ions from a Gallium (Ga) source can be accelerated up to 30 kV toward the grounded sample, for beam intensities of up to 21 nA. Samples are loaded in a vacuum chamber with a pressure of about $1 \times 10^{-5}$ mbar. FIB deposition is made possible due to the presence of gas injection system (GIS) needles. The needles can be inserted into the vacuum chamber, to around 100 µm above the sample surface, releasing a controlled flow of a precursor gas. The molecules from
the precursor adsorb on the sample surface, and are then “activated” by the Ga ion beam (see figure 1.3.b), as it scans a pre-set pattern. The activation is generally thought to be caused by secondary electrons produced from the sample surface by the scanning ion beam [15]. These secondary electrons break up the precursor molecules, depositing the required material on the surface in a controlled manner, while the volatile components from the process are pumped away by the vacuum system.

Depending on the size of the pattern, the beam parameters are adjusted so that FIB deposition happens faster than FIB milling. The beam current determines the deposition rate and the smoothness of the resulting structure.

Figure 1.3 A.) Schematic representation of a probe with a buffer layer. B.) Illustration of FIB deposition of a SiO$_2$ buffer.
This capability is used to pattern a buffer layer that spans the whole length of the dielectric surface, along with sections of both the inner and outer conductors, as illustrated in figure 1.3.a. This microbridge structure, made with SiO$_2$, is deposited and lithographically defined using a FIB current that varies between 9 and 21 nA. A thin layer (100 nm thick) is first deposited at a low current in order to avoid milling the dielectric. The bulk of the structure is then added using a high current, in 250 nm thick segments. This is then followed by the deposition of a smooth top layer at low current. The fabrication of the microbridge using the above sequence leads to the desired smoothness, while avoiding needlessly depleting both the GIS and ion sources. Alternatively, if for some reason the last step in the buffer deposition does not yield a smooth surface, optimal smoothness can still be achieved by FIB milling. Figure 1.4 is an SEM image (6500x magnification) of a section of a 10 micron wide buffer structure. The left half of the structure is covered in bumps with submicron diameters, which resulted from poor deposition conditions. The right half of the structure has been milled away with a FIB current of 9.3 nA in 50 nm increments. Note that all the bumps are gone and the surface is now noticeably smoother.
Figure 1.4: SEM image (6500x magnification) of a buffer structure, where the right half has been milled using the FIB at 9.3 nA to get rid of the bumps, which are still present on the left half.

The use of the FIB allows for the deposition of a smooth surface on nearly a nm scale, as the FIB deposition is very forgiving to rough base surfaces. As the microbridge is scaled down to the micron level and below, surface smoothness becomes critical in ensuring the homogeneity of the structure, thereby optimizing the coupling to the sample. For most of the measurements discussed in the following chapters, the area of the buffer that sits over the dielectric is roughly 1500 square microns, with a thickness between 2 and 4 microns. The use of a buffer layer offers many additional advantages over direct deposition of Cu on the dielectric. The FIB deposited material adheres effectively to the otherwise inert Teflon. Moreover, even with the sanding and cleaning steps of section 1.2.1, there tends to be a step discontinuity at the interface between the dielectric and the
inner/outer conductors, on the order of the thin film thickness or larger. This can cause brittle spots in the current path (e.g. figure 1.2). FIB deposition has the unique characteristic of filling holes and gaps in a capillary-like fashion, so the discontinuity is effectively removed with the deposition of the buffer, creating a smooth and continuous microbridge between the inner and outer conductors. This translates into a more robust probe that shows little deterioration even after extended use.

After the deposition and patterning of the buffer, the coax is sent to the e-beam evaporator, where a 20 nm thick Tantalum (Ta) adhesion layer is deposited over the coax cross section, followed by the 500 nm Cu film. The excess Cu and Ta around the buffer are then etched away, so that the shape and dimensions of the current path are determined by the buffer. While the Cu adheres better to the SiO$_2$ surface than to the Teflon, FIB cross sections of the microbridge have revealed that there were still some gaps on the deep submicron scale (figure 1.5.a). The Ta adhesion layer solves this issue, as can be seen in figure 1.5.b. Note that in both images in figure 1.5, a Pt layer was FIB deposited on top of the Cu as part of the cross section in order to add contrast, but it is not part of the working structure. Once completed, the process results in probes with resistances of 0.8 to 1 ohm, as measured at the K-connector.
A. Figure 1.5: SEM images of FIB cross section of microbridge (200000x magnification) A.) Cu thin film evaporated directly on buffer layer where the Cu can be seen to have weak adhesion along voids. B.) Cu evaporated on 10 nm Ta adhesion layer. The Cu adheres better to the buffer layer below, as the voids are eliminated.

1.3 Experimental set up and procedure

1.3.1 Experimental set up

Our experimental set up consists of a 40 GHz bandwidth ANRITSU 37269D vector network analyzer (VNA) [16], which is connected to the probe via a 50 ohm coaxial transmission line (figure 1.6). A VNA is primarily used to analyze the transmission and reflection scattering parameters (S-parameters) in an electrical circuit. They operate at high frequencies (up to 110 GHz), and can measure the amplitude and phase characteristics of the signal. The probe is fixed between the poles of a four-pole
DC electromagnet (figure 1.6, inset). The electromagnet is connected to two MAT 100-10 Kepco power supplies [17] that can output up to 20 amps of current. Each power supply is connected to a pair of poles diagonally facing each other. When operated together, the two pair of poles can generate a DC magnetic field in any direction in the plane, up to 3400 Oe. For the purposes of our experiments, the magnet was only operated along two orthogonal directions, corresponding to its main axes. Because of the currents required to generate the larger field (>1500 Oe), the magnet was connected to a water cooling line.

A motorized stage with four axes of motion x, y, z, and θ, is used to bring the sample close to the probe, and to measure different parts of the sample. This stage is supplemented by a Klinger/micro controle manual vertical stage with 12.5 mm range and micron scale accuracy. This manual stage allows for a more stable and accurate control of the sample’s separation from the probe. The height of the probe with respect to the sample is monitored using a CCD camera, which has a maximum resolution of about 3 microns. The whole experiment is run and controlled through general purpose interface bus (GPIB) and Labview software (see appendix A) on a desktop computer. Aside from the power supplies for the magnet and the computer, the whole apparatus sits on a TMC 65 series floor isolation platform [18]. This once again emphasizes the importance of maintaining a stable probe to sample separation during the measurements.
Figure 1.6: Top: picture of the experimental set up. Inset: Close up of the probe and electromagnet. Bottom: Diagram of the set up, showing the GPIB connections.
1.3.2 Measurement parameters

The VNA is set up in reflection mode to monitor the complex $S_{11}$ parameter, which is a ratio of reflected to incident signal. This requires a calibration of the VNA, through the measurement of the reflection coefficients of three standards, an open, a short, and a matched impedance (50 Ohms). The calibration is done from the point where the coax connects to the VNA, i.e. the end of the transmission line, so that any intrinsic signal due to the VNA or the coaxial line is eliminated. Note that in order to get an accurate calibration, all the microwave components must be tightened with an 8 in-lbs torque wrench, so as not to damage them.

The signal from the VNA, as it passes through the current path of the probe, generates a small oscillating magnetic field $h_{rf}$ (see figure 1.7 below). The microbridge also acts as a pick up antenna for the reflected signal. The rf field causes the magnetic spins of the sample to precess at a given frequency $f_{\text{FMR}}$, in the presence of an external field $H_{\text{DC}}$ perpendicular to $h_{rf}$. The frequency $f_{\text{FMR}}$ can be varied by applying different $H_{\text{DC}}$ fields. When the frequency of $h_{rf}$ matches $f_{\text{FMR}}$, the coupling is maximized and the sample starts absorbing the incoming microwave energy. As the frequency of $h_{rf}$ is swept, this resonant condition is revealed as a dip in the amplitude of $S_{11}$, since less energy is being reflected back to the VNA. Because the measured signal contains both magnetic and non-magnetic components, a signal with only a non-magnetic response needs to also be measured, as explained in the next section. The magnetic response can then be extracted
through a subtraction. The sample to probe separation needs to be held constant throughout both these measurements, in order to obtain the most accurate subtraction.

Figure 1.7: Diagram illustrating the generation of $h_{rf}$ from the AC signal of the VNA. The graph on the left shows the expected $|S_{11}|$ signal as the frequency is swept through $f_{FMR}$. (courtesy Tom Clinton)

1.3.3 Experimental procedure

In a typical experiment, the sample is loaded onto the stage and brought up to the probe, within a distance that varies between 0 and 20 microns. A field $H_{DC}$ is then applied perpendicular to $h_{rf}$ ($H_{DC}^\perp$), as this leads to the largest torque on the magnetization (which drives the precession), and $S_{11}$ is measured over the bandwidth of the VNA. The VNA is operated at –2 dBm (0.63 mW), although it is possible to conduct full bandwidth measurements at powers of up to 2 dBm (1.6 mW). In order to improve
the signal quality, multiple sweeps are averaged (between 10 and 25 sweeps), where each sweep takes roughly 3 seconds. Once the FMR signal is recorded, the same measurement is repeated but with $H_{DC}$ parallel to $h_{rf}$ ($H_{DC}^\parallel$). In this configuration, no FMR response is expected since the sample is typically saturated by $H_{DC}$ along the direction of oscillation of $h_{rf}$ (i.e. $\frac{\partial M}{\partial h_{rf}} = 0$). Figure 1.8.A shows a schematic illustrating the two $H_{DC}$ field orientations with respect to $h_{rf}$. Note that the orientation of $h_{rf}$ with respect to the sample is determined by aligning the microbridge along a known direction when connecting the probe to the transmission line. Since the probe is oriented with respect to the magnet, it is possible to get an accurate alignment to within a couple of degrees, a margin of error which has no measurable effect on the sample’s response.

Figure 1.8: A.) Schematic illustrating the two different orientations of the applied $H_{DC}$ field with respect to the oscillating field $h_{rf}$. B.) Schematic of FMR resonance for magnetization and external fields similar to part (a).
Alternatively, one can obtain the no-FMR background signal by applying a very large $H_{dc}^{\perp}$ field. This pushes the FMR response outside of the frequency range of interest, so that this signal has effectively no FMR component. Another method still to obtain the appropriate background consists in measuring a similar sample, but which does not contain the magnetic material (referred henceforth as a disc-null subtraction). In theory, the perpendicular/parallel, disc-null, and large field/low field subtractions are equivalent. However, unless otherwise noted, all results discussed in subsequent chapters were obtained using a perpendicular/parallel subtraction method.

1.4 Early results

In this section we briefly discuss some early results that deal mostly with improvements in the sensitivity and signal quality of the probe.

1.4.1 Effect of coax length

Since we want our probe to be broadband instead of resonant, we try to eliminate any factor that could make the coax act as a resonator. As discussed in section 1.1, using a shorted coax as a resonator requires complex electronics for signal measurements. It also restricts the use of the probe to a set of specific frequencies. In figure 1.9, the amplitude of the reflection signal ($\log |S_{11}|$) is plotted as a function of microwave frequency, for probes with different coax lengths. The measured signal is of the probes only, with no sample present. Additionally, we note that some of the coaxes are shorted.
(short) while others are not (open). The signal that the VNA measures when no probe is attached to it is also plotted (solid red trace). The graph reveals that when the coax has a length on the order of the microwave wavelength, standing waves will form within the coax, resulting in resonant behavior. This can easily overcome a real FMR signal from the sample, especially if it overlaps with one of the resonant frequencies. We also see from the graph that the shortest coax most closely resembles the “no probe” trace, and has the least attenuation of signal.

1.4.2 Improvements in probe sensitivity due to buffer layer

The addition of a buffer layer to the design of the probe tip has led to improvements of the structural integrity of the current path (see figures 1.3 and 1.5),
along with better adhesion of the Cu. It has also led to dramatic increases in sensitivity, when compared to probes with no buffer layer [12]. In figure 1.10 (left graph), three FMR spectra of the soft underlayer (SUL, see figure 1 of introduction) of a perpendicular media disk are plotted. These were measured with probes having different tip designs. One probe has a buffer layer made of Pt (dotted line), the other has a SiO$_2$ buffer (solid line with circles), and the third has no buffer at all (solid line). All three traces were measured under the same conditions. (the slight offset in the peak frequencies is attributable to small variations in the applied field $H_{DC}$). Overall, the data shows small signal-to-noise (SNR) variations between the probes with buffers. Various measurements have shown no clear effect on the signal from the material used to make the buffer. However, SiO$_2$ is preferred due to its insulating nature, guaranteeing that the microwave current only travels through the Cu film. On the other hand, we see a two-fold increase in the signal amplitude when compared to the no-buffer design. This is attributed to the buffer structure, which makes it possible to deposit a smoother current path and to define sharper boundaries. This design makes it easier to bring the probe closer to the sample, while also generating a more unidirectional $h_{rf}$ field. In addition, we now also have a better defined pick up antenna for the reflected signal.
Figure 1.10: Left: FMR spectra for the soft underlayer of a media disk. The three different peaks were measured using a probe with a Pt buffer (dotted line), SiO$_2$ buffer (solid line with circles), and no buffer (solid line). Right: Diagram of coax cross section with buffer structure and Cu layer.

Finally, the increased sensitivity observed on a soft magnetic material is encouraging, but such systems tend to have large magnetic moments that can be relatively easily driven at resonance, and the excitations are long lived. While we observe a nice increase in signal amplitude, FMR measurements with good SNR for these samples were already possible using a probe with no buffer. However, many materials of interest have much more complex spin dynamics, where larger local fields have to be overcome, the magnetization is relatively weak, and FMR excitations decay much more rapidly. One such sample was previously measured using a no-buffer probe tip with inconclusive results, as evidenced in figure 1.11.a, where no signal is visible above the noise. This sample, which is studied in more depth in chapter 6, has nanoscale magnetic grains whose shapes dominate the spin dynamics.
Figure 1.11 FMR spectra at two different external fields for a sample with complex spin dynamics and relatively weak magnetization. A.) measurement with no buffer. B.) measurement with buffer. The traces are offset for clarity and the fits are guides to the eye.

Nonetheless, using a probe design that includes a tip with a buffer, we are able to clearly resolve the FMR signal on the same sample for two different external field (figure 1.11.b). In the graph, the traces are offset for clarity and fits can be used as guides to the eye. Our unique broadband local FMR probing technique is sensitive enough to detect previously unobservable signals, and can be used to study a wide variety of magnetic systems, as will be illustrated over the next few chapters.
References

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2. H.A. Bethe, Phys.Rev. 7, 163 (1944)


Chapter two: Theoretical background

2.1 VNA FMR measurement

In a typical experiment, the coupling between the FMR probe and a sample is monitored using the VNA, which measures the complex reflection coefficient \( S_{11} \) [1] over the frequency bandwidth of the instrument. \( S_{11} \), as its name indicates, is a measure of the ratio of reflected over incident signal, where

\[
S_{11} = \frac{V_{\text{reflected}}}{V_{\text{incident}}} = \frac{Z_{\text{load}} - Z_0}{Z_{\text{load}} + Z_0} = \left| \frac{Z_{\text{load}} - Z_0}{Z_{\text{load}} + Z_0} \right| e^{j\nu} \tag{2.1.a}
\]

\[
Z_{\text{load}} = Z_0 \frac{1 + S_{11}}{1 - S_{11}} \tag{2.1.b}
\]

with \( Z_{\text{load}} \) the total complex impedance due to the presence of the sample and \( Z_0 = 50 \ \Omega \) is the characteristic impedance of the coaxial transmission line. From eq. 2.1.a, one can see that \( S_{11} = -1 \) when \( Z_{\text{load}} = 0 \), which corresponds to a coax terminated by a perfect short circuit. The negative sign indicates that while the entire signal is reflected, it is phase shifted by \( \nu = \pi \). When the load and characteristic impedances are matched (\( Z_{\text{load}} = Z_0 \)), \( S_{11} = 0 \), so that no signal is reflected and all the power is transmitted to the load. We also have \( S_{11} = 1 \) if the coax is terminated with an open circuit (\( Z_{\text{load}} \to \infty \)). In this last case the signal is reflected with no phase shifting. We note that these three “ideal” configurations correspond to the standards used to calibrate the VNA (see section 1.3.2). From the above, it is expected that when plotting \( |S_{11}| \) as a function of frequency, \( |S_{11}| = 1 \) when no
sample is present \( (Z_{\text{load}} = 0) \). On the other hand, when measuring a sample, \( |S_{11}| \) goes to a minimum as we approach the resonant frequency, \( f_{\text{FMR}} \) (see figure 2.1.a).

![Diagram](image)

**Figure 2.1 a.)** Expected \( |S_{11}| \) response as a function of frequency for no sample (black trace) and with sample (red trace). **b.)** Schematic of circuit element used to model the probe-sample system.

In the microwave frequency regime, the wavelength of the signal (cm) is large compared to the feature size of the effective circuit (\( \mu \text{m} \)). The probe/sample system can therefore be modeled using a lumped element circuit, as shown in figure 2.1.b. [2, 3]. In this model, \( L_{0} \) is the probe’s inductance, \( L_{x} \) is the inductance of the probe’s image in the sample (\( L_{x} \rightarrow L_{0} \) for a perfect image), \( M \) is the mutual inductance between the probe and sample, and \( Z_{s} = R_{s} + iX_{s} \) is the complex surface impedance of the sample. The measured impedance \( Z_{\text{load}} \) can then be written as [2]

\[
Z_{\text{load}} = i\omega L_{0} (1 - k^{2}) + Z_{s} k^{2} \frac{L_{0}}{L_{x}}
\]

(2.2)

where \( k = \sqrt{\frac{M^{2}}{L_{0}L_{x}}} \) is a dimensionless coefficient which describes the coupling between
the probe and the sample \((0 \leq k \leq 1)\). The FMR response of interest to us is captured in the surface impedance in the second term of equation 2.2. Although some of the samples we measure are good conductors, the sample thickness (<100 nm) is generally smaller than the skin depth penetration at microwave frequencies, so that the samples are treated as thin films. In this approximation, we can express the surface impedance as \[ Z_s = i\omega t_0\mu_0\mu_r \] (2.3)

where \(t_0\) is the film thickness, \(\mu_0\) is the permeability of free space, and \(\mu_r\) is the complex magnetic permeability of the sample. In order to extract \(Z_s\), a background signal with no FMR (i.e. \(Z_{\text{noFMR load}}\)) has to be recorded. This background would still contain the first term of equation 2.2 (\(Z_{\text{noFMR load}} = i\omega L_0(1 - k^2)\)). Different techniques for measuring the background are discussed in section 1.3.3. After obtaining \(Z_{\text{load}}\) from the \(S_{11}\) measurement using equation 2.1, it can be shown, using equations 2.2 and 2.3 that

\[
Z_{\text{FMR load}} - Z_{\text{noFMR load}} = \Delta Z = \text{Re}(\Delta Z) + i\text{Im}(\Delta Z) = Z_s k^2 \frac{L_0}{L_x} = i\omega t_0\mu_0\mu_r k^2 \frac{L_0}{L_x}, \text{ so that}
\]

\[
\mu_r = \frac{L_x}{k^2 L_0 \omega t_0\mu_0} \left(\text{Im}(\Delta Z) - i\text{Re}(\Delta Z)\right)
\] (2.4)

From the above, \(\text{Re}(\mu_r) = \frac{L_x}{k^2 L_0 \omega t_0\mu_0} \text{Im}(\Delta Z)\) and \(\text{Im}(\mu_r) = \frac{L_x}{k^2 L_0 \omega t_0\mu_0} (-1)\text{Re}(\Delta Z)\).

In figure 2.2, we see the real (a) and imaginary (b) parts of \(\mu_r\), derived from the above equations, for a measurement on a CoFe-based sample. The traces are plotted as a function of frequency for different \(H_{\text{DC}}\) values ranging between 200 and 1000 Oe. The
different parameters that can be obtained from these data are discussed in the following sections.

![Figure 2.2 Relative permeability of CoFe sample measured at different H_{DC} fields. a) real part b) imaginary part. (proportional to |S_{11}| loss response depicted in figure 2.1.a)](image)

2.2 FMR theory

2.2.1 Derivation of uniform mode frequency for films with in-plane and out-of-plane anisotropy

When a static magnetic field H_{DC} of sufficient magnitude is applied to a ferromagnetic sample, the spins will align parallel to it. Then, if those same spins are disturbed from their alignment, they will precess back toward their equilibrium position with a precession frequency \( \omega = 2\pi f_{\text{FMR}} \). This precessional motion can be driven by a small
oscillating field, applied perpendicular to $H_{DC}$, and with a frequency matching $f_{FMR}$. This resonant frequency can be changed by varying the local field ($H_{local}$) that the spins “see”. In addition to the external field, this includes a demagnetizing field ($H_{demag}$), which arises from the fringe fields of neighboring spins. There is also a contribution from an effective anisotropy field $H_K$, which is due to the crystalline properties of the system. Because of the nature of $H_{demag}$, the value of $f_{FMR}$ will be highly dependent on the geometry of the sample.

We illustrate this last point by finding $f_{FMR}$ for an ellipsoid with principal axes along the Cartesian coordinates. The magnetization $\hat{M}$ will follow the equation of motion [5] (see figure 2.3.a)
\[
\frac{d\vec{M}}{dt} = -\gamma \vec{M} \times \vec{H}_{\text{local}}
\]  

(2.5.a)

where

\[
\frac{dM_x}{dt} = i\omega M_x = -\gamma (M_y H^y_{\text{local}} - M_z H^z_{\text{local}}) \\
\frac{dM_y}{dt} = i\omega M_y = \gamma (M_x H^x_{\text{local}} - M_z H^z_{\text{local}}) \\
\frac{dM_z}{dt} = i\omega M_z = -\gamma (M_x H^x_{\text{local}} - M_y H^y_{\text{local}}) 
\]  

(2.5.b)

In the above, \( \gamma \) is the gyromagnetic ratio, and \( \vec{M} \) varies in time as \( e^{i\omega t} \). For each coordinate direction,

\[
H^i_{\text{local}} = H^i_{\text{DC}} - (N_i + N^K_i)M_i
\]  

(2.6)

with \( i=x,y,z \), \( N_i \) a demagnetizing factor (from \( H_{\text{demag}} \)) satisfying \( N_x + N_y + N_z = 1 \), and \( N^K_i \) an effective demagnetizing factor associated with the anisotropy field (i.e. \( H^K_i = N^K_i M_i \)).

The field \( \vec{H}_K \) acts to push the magnetization back toward the anisotropic direction, and the use of effective demagnetizing factors is appropriate for planar geometries and directions of high symmetry [5]. Assuming a sample with in-plane uniaxial anisotropy (\( \vec{H}_K \) along x direction, \( N^K_x = 0 \)) and a saturating external field applied along the same direction (\( \vec{H}_{\text{DC}} = H_{\text{DC}} \hat{x} \)), we can set to first order \( \frac{dM_x}{dt} = 0 \) and \( M_x = 4\pi M_s \) (the saturation magnetization of the sample), which are valid assumptions when the angle between \( M \) and \( \vec{H}_{\text{local}} \) is small. Solving for the y and z solutions of equation 2.5 using 2.6, we get
\[
\frac{dM_y}{dt} = i \theta M_y = \gamma (M_x (H_{DC}^x - (N_z + N_y^K)M_x) - M_z (H_{DC}^z - N_x M_x)) \tag{2.7.a}
\]
\[
= \gamma M_z ((N_x - N_z - N_x^K)M_x - H_{DC}^z)
\]
\[
\frac{dM_z}{dt} = i \theta M_z = -\gamma (M_x (H_{DC}^x - (N_y + N_y^K)M_y) - M_y (H_{DC}^y - N_x M_x)) \tag{2.7.b}
\]
\[
= -\gamma M_y ((N_x - N_y - N_y^K)M_x - H_{DC}^y)
\]
\[
\omega^2 = (2\pi f_{\text{FMR}})^2 = \gamma^2 (H_{DC} + (N_z + N_z^K - N_x)M_x)(H_{DC} + (N_y + N_y^K - N_y)M_y) \tag{2.7.c}
\]

For a planar geometry (see figure 2.3.b), with the field applied in the plane, \(N_x=N_y=0\), and \(N_z=1\), so that equation 2.7.c reduces to the familiar Kittel formula
\[
f_{\text{FMR}}^2 = \left(\frac{\gamma}{2\pi}\right)^2 (H_{DC} + 4\pi M_x + H_k)(H_{DC} + H_k) \tag{2.8}
\]

where \(N_x^K M_x = N_y^K M_y = H_k [5]\).

Similarly, we can solve for \(f_{\text{FMR}}\) for the same geometry with \(\vec{H}_{DC} = H_{DC} \hat{y}\)

(i.e. \(\vec{H}_{DC} \perp \vec{H}_k\), \(\frac{dM_y}{dt} = 0\) and \(M_y=4\pi M_y\)), where, solving for the x and z solutions of 2.5, we find
\[
f^2 = \left(\frac{\gamma}{2\pi}\right)^2 (H_{DC}^x + (N_z + N_z^K - N_y - N_y^K)M_y)(H_{DC}^y + (N_x - N_y - N_y^K)M_y) \tag{2.9}
\]

In the limit \(4\pi M_x \gg H_{DC}, H_k\) equations 2.8 and 2.9 can be reduced to
\[
f_{\text{FMR}}^2 = \left(\frac{\gamma}{2\pi}\right)^2 4\pi M_x (H_{DC}^x \pm H_k) \tag{2.10}
\]
The sign in front of $H_x$ depends on the orientation of $\tilde{H}_{DC}$ with respect to $\tilde{H}_K$. When $\tilde{H}_{DC}$ is applied along the direction of $\tilde{H}_K$, the two fields add together (+). Otherwise, there is a competition between the preferential anisotropic orientation, and the external field, so that the two subtract (-).

For a more general case, where $H_{DC}$ and $M$ are oriented at angles $\theta$ and $\phi$ respectively with respect to the $z$-axis (as defined in figure 2.3.b), with $\theta$ arbitrary and $\phi$ dictated by $H_{local}$, and $H_K$ is parallel to the $z$ axis, while the sample is isotropic in plane, $f_{FMR}$ can be expressed as [6]:

$$f_{FMR} = \frac{\gamma}{2\pi} \sqrt{H_x H_y}$$

(2.11)

with

$$H_x = H_{DC} \cos(\theta - \phi) + \frac{1}{2}[2H_Ks - 4\pi M_s (3N_z - 1)] \cos^2 \phi$$

and

$$H_y = H_{DC} \cos(\theta - \phi) + \frac{1}{2}[2H_Ks - 4\pi M_s (3N_z - 1)] \cos 2\phi$$

and $H_x$ and $H_y$ are known as stiffness fields, as they capture the competing forces that prevent the magnetization from freely aligning with the applied field, $H_{DC}$.

By fitting the measured spectra using a Lorentzian profile, as in figure 2.4, and plotting the resulting $f_{FMR}$ as a function of applied field $H_{DC}$, it is possible to extract information about the sample’s anisotropy $H_K$, saturation magnetization $4\pi M_s$, ...
gyromagnetic ratio $\gamma$, demagnetizing factor $N_z$, or magnetization orientation $\phi$ using the appropriate equation (2.8 or 2.11). Examples of what values are used as fitting parameters, for different configurations, are discussed in the following chapters.

Figure 2.4: FMR spectrum for a CoFe sample measured at 1150 Oe. The fit to a Lorentzian profile (red trace) allows us to extract $f_{\text{FMR}}$ and the linewidth $\Delta f$ (~ FWHM) of the peak.

The shape of the measured loss profile, and hence of the function used to fit it, depends on the relaxation mechanisms present in the magnetic system. Two magnon scattering and intrinsic damping (discussed in sections 2.2.2 and 2.2.3 respectively) will result in a Lorentzian distribution [7]. Damping dominated by a inhomogeneous line broadening (section 2.2.4) has a more Gaussian profile [7], corresponding to the distribution of inhomogeneities in the system. As a result, a convolution of Lorentzian and Gaussian functions is the most appropriate to fit the overall loss profile.
2.2.2 Contributions to FMR linewidth

The FMR frequency derived above corresponds to the uniform mode, when all the spins of the system are parallel and precessing in phase with the same amplitude. Since all spins oriented in the same direction corresponds to the ground state, the next available state in such a system would be one where one spin is flipped with respect to all the others. But this would lead to large increase in the exchange energy, because the exchange interaction tries to keep adjacent spins pointing in the same direction. Instead, a lower energy state can be achieved when all the spins oscillate coherently in their orientation. Such an excitation has a wave-like form [8], and is known as a spin wave or, in the discrete quantum-mechanical limit, as a magnon. Along the direction of propagation of the wave, adjacent spins are out of phase by an amount proportional to the wavelength, and their magnetization along this direction is therefore reduced by a small amount. Over the whole system, the net reduction in magnetization corresponds to one flipped spin. Note that the uniform mode is a spinwave with infinite wavelength.

In most FMR experiments, such as ours, $h_{rf}$ will only excite the uniform mode precession. However, it is possible to excite higher order spinwaves if $h_{rf}$ is inhomogeneous over the probed area, or the skin depth is smaller than the sample thickness, or if the spins near the surface are pinned. Spinwaves can also be created indirectly, if they are degenerate with the uniform mode. While spinwave modes are supposed to be orthogonal, inhomogeneities or defects in the sample (e.g. pores) will break the orthogonality, leading to degenerate states [9]. This then allows a mechanism
such as two magnon scattering, where the uniform mode couples with and transfers energy to higher order magnons.

The FMR decay rate, which is measured as the full width half maximum (FWHM) of the FMR peak ($\Delta f$ in figure 2.4), is a measure of how fast the excitation energy of the uniform mode dissipates. While ultimately all the energy from the excited spinwaves is transferred to the lattice, this process happens through both intrinsic (direct) and extrinsic (indirect) phenomena. This leads to multiple contributions to the FWHM, so while a broad peak ($\Delta f$) indicates a rapid decay of the uniform mode ($\Delta f \sim 1$/time), it does not necessarily mean the magnetization has returned to equilibrium. In general, it is the intrinsic damping processes that result in the magnetization returning quickly to equilibrium, which is the ultimate goal for designing faster magnetic devices.

2.2.3 Intrinsic damping

The intrinsic mechanism can be quantified by a damping constant $\alpha_{\text{LLG}}$, and is associated with a magnon- electron scattering process that transfers the energy directly to the phonons (out of the magnetic system and to the lattice). An ideal material for a high throughput device will have a large $\alpha_{\text{LLG}}$ value, so that the magnetization will go rapidly back to equilibrium after being excited. This damping constant is introduced as an additional term in the equation of motion (2.5.a) and leads to the dynamic Landau Lifschitz Gilbert (LLG) equation:

$$\frac{d\vec{M}}{dt} = -\gamma \vec{M} \times \vec{H}_{\text{local}} - \frac{\gamma \alpha_{\text{LLG}}}{M_s} \vec{M} \times (\vec{M} \times \vec{H}_{\text{local}})$$

(2.12)
where the second term in the equation forces $\tilde{M}$ back toward the orientation of $\tilde{H}_{local}$ (equilibrium), as illustrated in figure 2.5.

![Figure 2.5: motion of the spin M as it experiences the LLG damping factor.](image)

The LLG equation is widely used in micromagnetic simulations to model the dynamic behavior of thin films and patterned structures, or to solve for their ground energy state [10, 11]. As an illustration, we used the micromagnetic package MAGPAR [12] to study the effect of $\alpha_{LLG}$ on the FMR loss profile of a thin nanodot (10nm thickness) of radius 50 nm (see figure 2.6.a). The simulation is initialized in conditions similar to those discussed during the derivation of equation 2.8 and shown in figure 1.8, i.e. magnetization M in the x-y plane at a small angle (0.5°) from the x-axis, applied field $H_{DC}$ in-plane along the x-axis, and $h_{rf}$ parallel to y-axis. The LLG equation is then solved for the magnetization that will result in the lowest total energy of the system (E), as $h_{rf}$ is swept in frequency. In order to speed up the convergence of the calculations, the only energy contributions that were considered were $E_{Zeeman}$ (due to interaction with external field), and $E_{exchange}$ (due to exchange coupling between adjacent spins). In other words, the demagnetization factors $N_i$ and anisotropy field $H_k$ were set to zero. Looking at equation
2.8, this implies that $f_{\text{FMR}}$ only depends on the external field $H_{\text{DC}}$, which corresponds to the Larmor frequency. The results of the simulation are shown in figure 2.6.b.

Figure 2.6: a.) Orientation of the nanodot geometry with respect to the Cartesian coordinates. b.) Micromagnetic simulation: Energy of the nanodot system as a function of $h_{rf}$ frequency, for different $\alpha_{\text{LLG}}$ values.

The data reveal that the LLG damping does not affect the resonant frequency, but leads to a broader energy profile (faster decay) for a larger $\alpha_{\text{LLG}}$ values, as the magnetization is "pushed" more strongly back toward equilibrium. A detailed study of the ground state of nanorings (nanodots with a hole in their center) as a function of their dimensions, using MAGPAR, is discussed in reference [13].

2.2.4 Extrinsic damping

In addition to two-magnon scattering discussed in section 2.2.2, other extrinsic damping mechanisms include inhomogeneous line broadening, which results from local
variations in the magnetic properties of the sample (e.g. distributions in the orientation of \( H_K \) or \( M \)). This leads to the superposition of multiple local FMR profiles that are spread out in frequency, and which add up to one broad peak [3, 14]. Other contributions to the linewidth, such as eddy currents [15] (proportional to film thickness), are not considered here since their effect is negligible for the thin films used in these experiments.

Because different contributions to the FWHM have different field, frequency, and angular (\( \theta \) in figure 2.3.b) dependencies [16], it is possible to isolate each contribution by plotting linewidths as a function of one of these variables. In our case, since we can sweep both the field and frequency, we look at how \( \Delta f \) varies as a function of \( H_{\text{ext}} \) and \( f \), where we have:

\[
\Delta f = \Delta H \frac{\partial f}{\partial H} \tag{2.13}
\]

where we can use equations 2.8 or 2.11 for \( f(H) \), and for an in-plane magnetized film \( \Delta H \) is defined as:

\[
\Delta H = \Delta H_0 + \Delta H_{\text{LLG}} + \Delta H_{2M} \tag{2.14}
\]

with \( \Delta H_0 \) the frequency-independent inhomogeneous line broadening contribution [14],

\[
\Delta H_{\text{LLG}} = \frac{2\alpha_{\text{LLG}}}{|\gamma/2\pi|} f \text{ the intrinsic damping [14], and}
\]

48
\[ \Delta H_{2M} = \Gamma \sin^{-1} \frac{\sqrt{f^2 + \left( f_0 / 2 \right)^2} - f_0 / 2}{\sqrt{f^2 + \left( f_0 / 2 \right)^2} + f_0 / 2} \]

the two magnon scattering term, where \( \Gamma \) is a measure of the strength of the two magnon scattering and \( f_o = \frac{\gamma}{2\pi} 4\pi M_{\text{eff}} \) (\( M_{\text{eff}} \) includes the magnetization and anisotropy terms) [17].

Finally, for a film magnetized out of plane, there is no two magnon scattering contribution to the linewidth, as the uniform mode is not degenerate with any magnon, as revealed by their dispersion relation [9].
References

1. See, for example, J.A. Kong, *Electromagnetic Wave Theory* (EMW publishing, Massachusetts, 1998), p. 116


5. Charles Kittel, Phys. Rev. 73, 155 (1948)


8. See, for example, C. Kittel, *Introduction to Solid State Physics* (8th edition, 2005), pp 300-333

9. M. Sparks, Ferromagnetic relaxation theory (McGraw-Hill)


3.1 Soft magnetic underlayer in media disk

The storage capacity of magnetic recording media has gone up dramatically with the increase in areal bit densities. This increase has led to smaller storage bits in the (granular) magnetic media layer, and to the manifestation of thermal instabilities, also known as superparamagnetism [1]. The number of grains needs to stay roughly constant to preserve the sharp spatial definition of the bit, so as bits shrink, so must grains. The thermal stability of a magnetic grain, less than a hundred of which make up a bit, is proportional to the exponential of $KV/kT$, where $K$ is an anisotropy constant (relating to how strongly the magnetization wants to stay aligned along a preferred anisotropic direction, and the anisotropy field $H_K=2K/M_s$ with $M_s$ the saturation magnetization), $V$ is the volume of the grain, $k$ is Boltzmann’s constant, and $T$ is the temperature. It is clear from this relation that as the size of the storage bits, and, thus, the media grains are shrunk to increase bit densities, the magnetic states of the grains become more thermally unstable, and, thus, more likely to randomly “flip” due to thermal noise (see figure 3.1.a). As such, the magnetization of the bit will degrade when measured over a time scale long compared to the thermal lifetime. One way to address this issue has been to transition from longitudinal to perpendicular recording technology [2]. In perpendicular recording, the magnetization of the bit is normal to the plane of the media layer, as opposed to in the plane for longitudinal recording. In addition, a magnetically soft underlayer (SUL) is
incorporated beneath the storage layer of the perpendicular media. Magnetic materials are considered soft if their coercive fields $H_c$ are small, where $H_c$ is the external field needed to bring the magnetization of a sample to zero from saturation, along the anisotropic direction. Conversely, materials with large $H_c$ values are said to be hard, and they retain their magnetization better (e.g. permanent magnets, disk media layer). The incorporation of the SUL effectively mirrors the write pole (see figure 3.1.b). In this case, the perpendicular bits experience the magnetic field within the gap between the write pole and its mirror pole, as compared to the bits experiencing the field outside the gap for longitudinal recording where the field is weaker due to spacing loss. The increased field at the media enables higher anisotropy grains to stabilize smaller bits [3, 4]. Also, the field strength is somewhat less susceptible to spacing loss, allowing the storage layer to be thicker and grains larger. Thus, for an equivalent volume, the bit can occupy a smaller surface area and areal density is increased (figure 3.1.b).
Figure 3.1: a.) Illustration of the superparamagnetic limit. As the volume of the magnetic grains (represented by colored circles) shrinks to accommodate smaller bits (represented in color by groups of magnetically oriented grains), the grains becomes more likely to switch due to thermal fluctuations. b.) Comparison of longitudinal (left) and perpendicular (right) recording systems: longitudinal writer and media; perpendicular writer and media. (courtesy, Tom Clinton, Phys 522 lectures, Georgetown University)
3.2 Experimental set up

The proper SUL design requires the consideration of different material parameters, such as the anisotropy and the saturation magnetization [3]. In our experiment, we characterize a 88nm thick FeCo SUL layer on a commercial media disk [5, 6]. Independent measurements indicate that $H_\text{k}=10$ Oe, while the saturation magnetization $4\pi M_s=1.1$ Tesla (1 Tesla=10^4 Oe). The microwave penetration allows us to measure the SUL underneath a multilayer structure with good sensitivity, when compared to the other measurement techniques such as MOKE. The probe sits at no more than 20 microns from the disk (see figure 3.2), in non-contact mode, while the external field is applied perpendicular and parallel to $h_{\text{rf}}$, as described in section 1.3.3. The field is applied from 100 to 0 Oe in 10 Oe increments, while the signal is measured over the whole bandwidth of the VNA (40 GHz), and averaged 25 times.

Figure 3.2 Schematic of disk measurement using the FMR probe. Inset: Details of the probe tip and of some of the disk layers. Not drawn to scale.
Since we have the flexibility to locally probe any point on the disk, we probe the sample at two different locations, so that the FMR is measured either along the easy axis (EA) or the hard axis (HA). The easy axis of a ferromagnet corresponds to the axis parallel to the anisotropic direction (and hence, $H_k$), while HA is the direction perpendicular to it. During the EA measurement, $H_{dc}$ is applied parallel to EA to saturate the sample, and $h_{rf}$ excites the maximum FMR when it is perpendicular to $H_{dc}$. Recall that in our setup, the orientation of $h_{rf}$ is fixed, so that it is the sample that is moved and rotated in order to apply $h_{rf}$ along a specific direction. For the media disk, EA is parallel to the radial direction, and HA is along the circumference (tangential direction). Because the dimensions of the probe tip are small compared to that of the disk, we do not have to worry about the curvature of the disk, and our local measurement accurately differentiates between easy and hard directions.

3.3 Results and discussion

3.3.1 FMR spectra and anisotropy field

Figure 3.3 shows the real and imaginary part of the relative permeability of the SUL, in the left and right graphs respectively. They correspond to the dispersion ($\text{Re}[\mu]$) and FMR loss ($\text{Im}[\mu]$) profiles of the material. The traces are obtained using the subtraction method discussed in section 2.1, and are offset for clarity and shown for both EA and HA directions.
The systematic offset in frequency seen between the EA (black traces) and HA (red traces) directions is due to $H_K$. For the case of the HA measurement, the sample is saturated perpendicular to the anisotropic (radial) direction and $H_K$ subtracts from $H_{DC}$ (see equation 2.10), as the magnetic spins fight to return to their preferred orientation. For the case of EA, since $H_{DC}$ is applied parallel to $H_K$, the two fields add together. The expected frequencies, calculated using equation 2.10 with the appropriate sign in front of $H_K$, show that one indeed should see higher frequencies when measuring along EA.

In order to extract a quantitative value for $H_K$, we fit the real and imaginary parts of the permeability $\mu$, using the FMR form of the complex magnetic susceptibility $\chi$, where $\mu=\chi+1$. For a thin film magnetized in plane [7]:

$$\chi(f) \propto \frac{1}{f^2_{FMR} - f(f - i\Delta f)}$$

(3.1)
with $f_{\text{FMR}}$ and $\Delta f$ defined as in figure 2.4.

Since we are recording the complex permeability up to a proportionality constant, and to account for background subtraction effects, the susceptibility is actually expressed as $\chi = \chi_0 + \chi(f)e^{i\xi}$, where $\chi_0$ is a complex offset parameter, and $\xi$ is a phase shift adjustment that accounts for the slight asymmetry of the peaks. The fitted permeability then takes the form

$$\mu = A(1 + \chi_0 + \chi(f)e^{i\xi})$$

(3.2)

with $A$ a real proportionality constant.

In figure 3.4.a, we plot the normalized FMR peaks at three different $H_{\text{DC}}$ values, measured along the EA direction, which are also fitted using equation 3.2.

![Figure 3.4: a. three FMR peaks measured along EA of SUL, along with fits (red traces). b. In-plane MOKE B-H loop measurement of SUL along HA.](image)

The fits overlap well with the measured data, as is the case for all measurements made along both the EA and HA direction on this sample. As a comparison, figure 3.4.b
shows a representative data set measured on the same media disk using an in-plane MOKE system. The signal-to-noise ratio (SNR) of the MOKE is small due to the poor depth penetration of light. The measurement is made along HA, and represents the rotation of the polarization angle of an incident laser on the disk, as the field $H_{DC}$ is swept between -50 and 50 Oe. As a reminder, the rotation of the angle corresponds to the rotation of the magnetization as it tries to stay aligned with $H_{local}$. Since the SUL has a negligible $H_c$ value, only $H_K$ needs to be overcome in order to saturate the sample along HA. From the data of figure 3.4.b, $H_K$~10 Oe.

We now look at the FMR probe data to determine $H_K$ using the FMR theory presented in chapter 2. Because $4\pi M_s >> H_{DC}$, $H_K$ for our sample, and the SUL has a magnetization and anisotropy which are both in-plane, we use equation 2.10:

$$f_{FMR}^2 = \left( \frac{\gamma}{2\pi} \right)^2 4\pi M_s (H_{DC} \pm H_K)$$

(3.3)

From equation 3.3, the square of $f_{FMR}$ is linear with the applied field $H_{DC}$, with $4\pi M_s$ proportional to the slope and $H_K$ proportional to the x-intercept. In figure 3.5, $f_{FMR}^2$ is plotted along the EA (circles) and HA (squares) directions.
Figure 3.5: $f_{\text{FMR}}$ plotted as a function of $H_{\text{DC}}$, along the EA direction (circles) and HA direction (squares). The solid lines are fits to equation 3.3.

The results from the fits are summarized in the table below, where the appropriate form of equation 3.3 was used for each measurement direction:

<table>
<thead>
<tr>
<th>Direction</th>
<th>$4\pi M_s$ (Oe)</th>
<th>$H_K$ (Oe)</th>
<th>$\gamma$ (MHz/Oe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EA</td>
<td>10720</td>
<td>20.45</td>
<td>2.74</td>
</tr>
<tr>
<td>HA</td>
<td>10923</td>
<td>0.11</td>
<td>2.77</td>
</tr>
</tbody>
</table>

Table 3.1: Summary of parameters extracted from the fits of figure 3.5.

The fits for $4\pi M_s$ and $H_K$ were obtained while holding $\gamma$ constant at its theoretical value of 2.78 MHz/Oe. The data for the saturation magnetization agrees well with independent measurements of $4\pi M_s$ (~11000 Oe). While we expect from theory that the values of $H_K$ for both directions should be centered around 0 Oe, the x-intercepts from figure 3.5 clearly show that this is not the case, due to a systemic field offset. A close look at equation 3.3 shows that the x-intercepts should be separated by $2H_K$, so that the
offset is removed by averaging the values obtained from the fits. This yields $H_k \equiv 10$ Oe, which agrees with the MOKE measurement. The gyromagnetic ratio was calculated by keeping $4\pi M_s$ constant at its independently measured value. This did not affect the values of $H_k$, and leads to $\gamma$ values that are in good agreement with theory.

### 3.3.2 Damping parameter of SUL

We now look at the dynamic behavior of the SUL. Since the media disk was measured along two different directions, we investigate whether the orientation of the anisotropy field has any effect on the relaxation mechanisms of the FMR. We recall that for the SUL, both the magnetization and $H_k$ are in the plane of the sample.

In figure 3.6, we plot the FWHM of the peaks as a function of their resonant frequencies, using the values obtained from equation 3.2. The data are plotted for $30 \text{ Oe} < H_{DC} < 100 \text{ Oe}$, so that the sample is always magnetically saturated. We can see that the peaks are narrow at high frequencies (and high $H_{DC}$ fields), and broaden at lower frequencies. This behavior can be explained by considering the relaxation mechanisms that contribute to the linewidth. By plugging in equation 2.8 into 2.13, and neglecting the two magnon scattering contribution in 2.14, the FWHM can be expressed as:

$$\Delta f = \left( \left| \frac{\gamma}{2\pi} \right|^2 \frac{\Delta H_0}{2f} + \frac{\gamma}{2\pi} \alpha_{LLG} \right) \left( 2H_{DC} + 2H_k + 4\pi M_s \right)$$

(3.4)

Where $\Delta f = \Delta H \frac{\partial f}{\partial H}, \Delta H = \Delta H_0 + \frac{4\pi}{|\gamma|} \alpha_{LLG} f$.
\[ f = \frac{\gamma}{2\pi} \sqrt{(H_{DC} + H_K + 4\pi M_s)(H_{DC} + H_K)} \] and

\[ \frac{\partial f}{\partial H} = \frac{\gamma}{2\pi} \frac{(2H_{DC} + 2H_K + 4\pi M_s)}{2\sqrt{(H_{DC} + H_K + 4\pi M_s)(H_{DC} + H_K)}} = \left( \frac{\gamma}{2\pi} \right)^2 \frac{2H_{DC} + 2H_K + 4\pi M_s}{2f} \]

Figure 3.6: FWHM of SUL peaks as a function of \( f_{FMR} \), measured along EA (a) and HA (b). The lines are fits to equation 3.4.

It is clear from the above equation that the \( \Delta H_0 \) term, which is an inhomogeneous line broadening contribution discussed in section 2.2.2, has a \( 1/f \) dependence. Its contribution to the linewidth decreases as larger \( H_{DC} \) fields push the peak to higher frequencies. This agrees with the behavior in figure 3.6, in both EA and HA directions. The FWHM for the HA direction appear broader for similar \( H_{DC} \) fields, but that is only because they sit at lower frequencies where the \( 1/f \) contribution of the inhomogeneities is more important. The reason for the lower resonant frequencies along the HA direction was discussed in...
the previous section. Fits to the data result in an intrinsic damping $\alpha_{LLG}$ of 0.008 with $\Delta H_0 = 19.7$ Oe for the EA direction, and $\alpha_{LLG} = 0.008$ with $\Delta H_0=19$ Oe for the HA direction, where $\alpha_{LLG}$ is a dimensionless factor which quantifies how fast the uniform precession decays. Therefore, in this case, the orientation of $H_{DC}$ with respect to $H_K$ has little effect on the relaxation mechanism, and resulting values for $\alpha_{LLG}$ and $\Delta H_0$ are both reasonable for SUL materials. At the highest frequency ($f_{FMR}=3$ GHz) along EA, the contribution to the linewidth $\Delta f=512$ MHz of $\alpha_{LLG}$ is $\Delta f_{\alpha}=263$ MHz, while that of $\Delta H_0$ is $\Delta f_{\Delta H}=319$ MHz. On the other hand, at the lowest frequency ($f_{FMR}=1.6$ GHz) along EA, where $\Delta f=830$ MHz, $\Delta f_{\alpha}=260$ MHz and $\Delta f_{\Delta H}=590$ MHz. These values indicate that, while $\Delta H_0$ drives the $1/f$ behavior seen in the data of figure 3.6, the contribution to the overall linewidth of the intrinsic damping becomes significant at higher frequencies.

3.3.3 Effect of media layer on SUL behavior

Finally, we take a brief look at the effect of the media layer on the behavior of the SUL. In this section we measured a perpendicular media disk with different SUL characteristics ($4\pi M_s = 1.8$T, $H_K = 30$ Oe), for two different media layer states. Prior to the FMR measurement, the disk was placed in an out-of-plane (static, or DC) magnetic field that saturated the media layer. The field creates a uniform magnetization across the disk, essentially erasing all magnetic bits. This DC erasure causes the SUL to see an additional net field that emanates from the magnetization of the media layer. The disk was also measured after AC erasure, where, in this case, the out of plane field is swept up
and down, while decreasing its amplitude, causing the media layer to become demagnetized. Thus, the net magnetization is zero, and the SUL does not experience an extra field from the media layer.

The resulting spectra from both AC and DC erasure are plotted in figure 3.7. The measurement was made following the procedure of section 3.2, along the EA direction only. There is a clear difference in behavior between the AC erase and DC erase data. The FMR of the AC erase SUL responds more strongly to the applied $H_{DC}$ field, as evidenced by the larger frequency spread of the resulting traces (30 MHz/Oe). On the other hand, the DC erase SUL has a smaller frequency spread (27 MHz/Oe), which is to be expected as $H_{local}$ now has a contribution from the media layer, which $H_{DC}$ needs to
overcome. The influence of the media layer on the SUL illustrates one of the advantages of having the ability to do local FMR measurements on the media disk itself, as the material can be characterized in its working environment. In comparison, a method like MOKE has a hard time “seeing” the SUL because of its poor depth penetration, while vibrating sample magnetometry (VSM) does not measure the magnetization locally and, thus, cannot generate the necessary radial (easy axis) and circumferential (hard axis) fields. Indeed, the local nature of our method allows us to selectively probe the magnetization along either the EA or HA, whereas a non-local method (like VSM) would measure an average signal from both directions on this particular sample. We conclude by noting that the data of sections 3.3.1 and 3.3.2 were measured on the SUL of a disk with an AC erased media layer.
References


4.1 Media layer

Data storage relies on the ability to write a state, or bit, to a medium and to read it back reliably at a later time. Therefore, one of the essential characteristics of the media layer of a magnetic recording system is the capacity to retain its magnetic state. This requires the use of hard magnetic materials with large coercive fields $H_c$. The large $H_c$ helps ensure that a given magnetic state is thermally stable and not susceptible to being erased by fringe fields (demagnetization or demag fields) from adjacent bits, or from any remnant fields associated with the recording head of the system. As the areal densities in the media layer are increased, the superparamagnetic limit (i.e. limitations due to thermal agitation, which are discussed in chapter three) also needs to be addressed. This means using materials with large anisotropies, where a high anisotropy constant $K$ leads to greater bit stability and, consequently, longer thermal lifetimes [1]. Additionally, a material with a clear anisotropic orientation for its magnetization plays an important role in the design of the storage system (e.g. systems with longitudinal or perpendicular recording technology). The thermal instabilities inherent to the scaling down of bit sizes are addressed by using granular media with progressively larger magnetic anisotropy.
In this chapter, we look at a series of CoCrPt thin films [2], alloys of which are used as the storage layer of most commercial magnetic media. The anisotropy and saturation magnetization of this alloy can be tuned by varying the Cr and Pt concentration, to produce an effective anisotropy (discussed below) that orients the magnetization either in-plane or out of plane. When adding SiO$_2$ to CoCrPt, it is also possible to grow a layer with a fine granular structure (grain diameter $\sim$7 nm), with well defined non-magnetic grain boundaries and large out-of-plane anisotropies [3]. This makes it ideal for use in high density perpendicular recording hard drives.

4.2 Experimental set up

4.2.1 Local FMR measurement

The samples being measured are CoPtCr continuous (i.e. not granular) films, with a thickness of 17.5 nm [2]. The alloy has a uniaxial anisotropy along the c-axis (out of plane) and is isotropic in the plane. The orientation of the magnetization is dictated by the competition between the anisotropy field $H_K$, which tries to orient the spins out of plane, and the demagnetizing field ($\sim -4\pi M_s$) which tries to keep them in plane. This orientation is associated with an effective anisotropy field $H_{\text{Keff}}$ where $H_{\text{Keff}} = H_K - 4\pi M_s$. For $H_{\text{Keff}} < 0$ the magnetization is in-plane, as the demag fields exceed the anisotropy field, driving the magnetization in plane. For $H_{\text{Keff}} > 0$ the magnetization is out of plane (perpendicular orientation) as the anisotropy is large enough to overcome the demag fields and stabilize a perpendicular magnetization orientation.
The local FMR measurement was performed by applying in-plane DC fields between 600 and 1400 Oe. Because of the limited magnitude of our DC source, it was not possible to adequately saturate the samples. As a result, the data was not extracted using a perpendicular/parallel subtraction (discussed in section 1.3.3), since when \( H_{\text{DC}} \parallel h_{\text{rf}} \), we are still picking up an FMR signal i.e. \( \mu \propto \partial M/\partial H \neq 0 \). Instead, after measuring the FMR over a range of large \( H_{\text{DC}} \) fields with \( H_{\text{DC}} \perp h_{\text{rf}} \), the background is obtained by probing the sample with no external field applied (\( H_{\text{DC}} = 0 \) Oe). There is still an FMR signal present in the background, but it is well outside the frequency range of interest, as illustrated in figure 4.1.

![Figure 4.1: Im \[\mu\] vs frequency for Co\(_{90}\)Cr\(_{10}\) sample. The three peaks between 6 and 8 GHz were obtained by performing a large field/low field subtraction, where the background signal was measured at 0 Oe, which is the origin of the inverted peak at ~2.2 GHz.](image)
In the above figure, we plot the imaginary part of the relative permeability for the Co$_{90}$Cr$_{10}$ sample. The three peaks in the 6-8 Ghz region correspond to FMR signals measured at three different H$_{DC}$ fields. The background signal, measured at 0 Oe, also contains an FMR peak that appears inverted after the subtraction ($f \sim 2.2$ Ghz). We are able to properly extract the FMR signal, since this “background signal” is far enough outside the frequency range corresponding to the applied H$_{DC}$ fields.

4.2.2 Pump probe measurement

The data obtained using the local FMR probe is compared to the results of time-domain measurements on the same set of samples [2], which a Seagate Research staff member, Julius Hohlfeld, was kind enough to share with us. The experiments were carried out with a pump-probe optical technique [4]. This technique is generally used to look at events that happen in fractions of nanoseconds or faster. It consists of a pumping step that locally excites the sample from a laser source, followed by repeated probing light pulses, with probe steps that are short compared to the magnetic relaxation time ($\Delta t \sim$ picoseconds, $\tau > 100$ ps), as the system goes back to equilibrium. The technique is based on the Magneto-Optical Kerr Effect (MOKE), similar to the earlier description under static conditions, while now the dynamic, or temporal, response of the magnetization is being measured. Data is collected and then averaged as the system is pumped repeatedly at intervals much larger than the relaxation time, $\tau$, of the magnetic excitation. When measuring a magnetic sample, the pumping typically consists of a short laser pulse, which optically closes a switch and causes a current flow. This in turn
generates a magnetic field that interacts with the magnetization of the sample. Alternatively, the heat from the laser pulse can be used to demagnetize the sample, resulting in an excited state. The excitation is then probed by monitoring the rotation of the polarization of the laser beam (Kerr angle) after it reflects off the sample, which corresponds to the rotation of the magnetization.

In figure 4.2, the pump-probe measurements on four CoCrPt samples are graphed as a function of the time delay between the pump and probe signals.

Figure 4.2: Pump-probe signal for the CoCrPt series. The Kerr angle rotation (measured in µV) is graphed as a function of the time delay between the pump and probe signals. The traces are offset for clarity and are fit to a damped sinusoid function (solid traces). The resulting lifetime of the excitation $\tau$ is included for each sample.
The oscillations correspond to the Kerr angle rotation. The signal was measured with \( H_{\text{DC}} = 2315 \) Oe and \( \theta = 28^\circ \), where \( \theta \) was defined in section 2.2.1, and is the angle between \( H_{\text{DC}} \) and the normal. The traces can be fit to a damped sinusoid [5], such as the fitting function \( f_{\text{pp}}(t) \) where:

\[
f_{\text{pp}}(t) = A + B e^{-\frac{t}{\tau}} \sin(2\pi ft + \rho) + Ct
\]

(4.1)

A is an offset constant, B is a scaling factor, \( \tau \) is the lifetime of the magnetic excitation (relaxation time), \( t \) is the time, \( \rho \) is a phase shift, and C is a constant that accounts for small drifts in the background over time. For all four measurements, C is on the order of 1 \( \mu\text{V} / 1000 \) ps.

4.3 Results and discussion

Although the orientation of the field \( H_{\text{DC}} \) is different between the local FMR measurement \( (\theta = 90^\circ) \) and the pump-probe measurement \( (\theta = 28^\circ) \), we still find that the results obtained with these two methods are consistent.

We first look at the FMR data for all four samples. Figure 4.3.a shows the FMR peaks for all four samples measured with \( H_{\text{DC}} = 1000 \) Oe in-plane. It can be seen from the graph that the variations in composition lead to different resonant frequencies and peak linewidths \( \Delta f \) (FWHM) for the same applied magnetic field, \( H_{\text{DC}} \).
The resonant frequency $f_{\text{FMR}}$ is plotted as a function of applied field $H_{\text{DC}}$ (see figure 4.3.b). Since we are measuring a thin film that is isotropic in plane and with $H_K$ out of plane, we can use equation 2.11, $f_{\text{FMR}} = \frac{|y|}{2\pi} \sqrt{H_x H_y}$, to fit the data, where $\theta = 90^\circ$ for an in-plane field and $N_z = 1$ for a thin-film geometry, so we have:

$$H_x = H_{DC} \sin \phi + [H_K - 4\pi M_S] \cos^2 \phi$$

and

$$H_y = H_{DC} \sin \phi + [H_K - 4\pi M_S] \cos 2\phi$$

(4.2)
While we have analyzed the data of figure 4.3.b using an arbitrary orientation of the magnetization $\phi$, we find the best fit is for an in-plane magnetization with $\phi = 90^\circ$, in which case equation 2.11 reduces to:

$$f_{\text{FMR}} = \frac{\gamma}{2\pi} H_{DC} \sqrt{1 - \frac{H_{\text{Keff}}}{H_{DC}}}$$  \hspace{1cm} (4.3)

where, again, $H_{\text{Keff}} = H_K - 4\pi M_s$.

The extracted values of $H_{\text{Keff}}$ for all four samples are summarized in column IV of table 4.1. They are compared to $H_{\text{Keff}}$ values obtained from vibrating sample magnetometry (VSM) measurements (column III) on the same samples. The VSM measurement technique will be discussed in greater detail in chapter five. We see that increasing the concentration of Cr decreases the magnitude of $H_{\text{Keff}}$, while substituting Pt for Cr leads to a larger $H_{\text{Keff}}$. The negative $H_{\text{Keff}}$ values are consistent with an in-plane magnetization, and there is reasonable agreement between the VSM and FMR data. Some of the discrepancy can be explained by the limited field strength of our electromagnet, which does not permit a proper saturation of the sample being probed.

<table>
<thead>
<tr>
<th></th>
<th>$H_K$ (Oe)</th>
<th>$4\pi M_s$ (G)</th>
<th>$H_{\text{Keff}}$ (Oe)</th>
<th>FMR: $H_{\text{Keff}}$ (Oe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co$<em>{90}$Cr$</em>{10}$</td>
<td>6700</td>
<td>12,553</td>
<td>-5853</td>
<td>-5735</td>
</tr>
<tr>
<td>Co$<em>{98}$Cr$</em>{15}$</td>
<td>8110</td>
<td>11,110</td>
<td>-3000</td>
<td>-3447</td>
</tr>
<tr>
<td>Co$_{82}$Pt$_8$</td>
<td>6700</td>
<td>15,683</td>
<td>-8983</td>
<td>-7316</td>
</tr>
<tr>
<td>Co$_{87}$Cr$_5$Pt$_8$</td>
<td>12,200</td>
<td>14,125</td>
<td>-1925</td>
<td>-4676</td>
</tr>
</tbody>
</table>

Table 4.1: columns I-III are VSM measurements on the CoCrPt sample. $H_{\text{Keff}}$ values of column IV were extracted from the fits to the FMR probe data (figure 4.3.b).
We also look at the linewidth $\Delta f$ behavior, as a function of frequency, which we plot in figure 4.4 for all four samples (solid symbols). The graph also includes equivalent linewidths from the pump-probe measurements (open symbols). The relaxation time, $\tau$, (from the pump-probe measurements) is converted to $\Delta f$ using the Fourier relation $\Delta f = 1/\pi \tau$.

![Figure 4.4: Linewidth $\Delta f$ as a function of the corresponding $f_{\text{FMR}}$ (solid symbols). The open symbols are converted linewidths from the pump-probe measurements. The traces are reproductions of fits performed by Kalarickal et al., [6] based on results from Krivosik et al.[7]](image)

The data reveal clear trends in the behavior of $\Delta f$. The linewidths are broad (>1 GHz), which corresponds to a large damping (that includes both intrinsic and extrinsic contributions). This rapid relaxation is confirmed by the time-domain measurements, where $200 < \tau < 400$ ps. For the samples without Pt, Co$_{85}$Cr$_{15}$ and Co$_{90}$Cr$_{10}$, an increase in Cr concentration leads to a broader linewidth (larger damping),
and a correspondingly shorter relaxation time. On the other hand, samples which do contain Pt, Co$_{92}$Pt$_8$ and Co$_{87}$Cr$_5$Pt$_8$ display the broadest linewidths, $\Delta f$. This indicates the addition of Pt effectively increases the overall damping (i.e. decreasing the lifetime of the magnetic excitations). Kalarickal et al. [6] were able to nicely fit our data based on a two-magnon scattering (TMS) model developed by Krivosik et al.[7] (solid traces in figure 4.4). In this case, the relaxation process corresponds to uniform (FMR) modes decaying into spinwaves i.e. magnon to magnon. The spatial variations in the magnetization of the sample, due to local inhomogeneities, are explicitly included in the equation of motion (equation 2.5). Using the Hamiltonian formalism, solutions to the equation lead to coupling terms that account for TMS. The fits to the data include TMS, and a small intrinsic damping ($\alpha_{LLG}=0.004$) term. Therefore, for these samples, the magnetic excitations decay rapidly, but the energy remains inside the magnetic system. Note that the pump-probe data (open symbols) were not measured in-plane, and thus cannot be fit to the theory. This is because TMS has an angular dependence, and contributes less to the total linewidth at $\theta=28^\circ$ (pump-probe measurement) than it does at $\theta=90^\circ$ (FMR measurement) [8]. Hence the narrower linewidths measured on each sample with the pump-probe technique. Finally, except for the Co$_{87}$Cr$_5$Pt$_8$, we see a general trend of $\Delta f$ decreasing with increasing frequency. This is consistent with extrinsic mechanisms contributing more to the linewidth, as discussed in the previous chapter, and in other works [8].
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Chapter Five: Effect of Holmium doping on the static and dynamic properties of Ni$_{80}$Fe$_{20}$

5.1 Intrinsic damping and rare earth doping

In this chapter, we turn our attention to the effects of doping on the magnetic properties of soft materials, and more specifically Ni$_{80}$Fe$_{20}$. In chapter three, we studied a soft underlayer material that was used to increase the performance of the recording media layer, and in chapter four we demonstrated the ability to measure fast excitation decay rates (under 1 ns). We now take a closer look at magnetic relaxation mechanisms, which control the switching speeds and data rates in magneto-electronic devices. As discussed in section 2.2.2, the FMR decay rate (linewidth of FMR peak) is governed by contributions from both intrinsic ($\alpha_{\text{LLG}}$) and extrinsic damping phenomena. The design of faster devices requires the ability to tune $\alpha_{\text{LLG}}$ to make it larger, thereby ensuring a faster return to equilibrium as the excess energy leaves the magnetic system. In addition, a large $\alpha_{\text{LLG}}$ can help minimize spin-torque effects in current-perpendicular to plane (CPP) read sensors [1]. A large intrinsic damping can also lead to write heads reaching their maximum output fields faster, as it would reach a stable after switching in less time. However, the magnetization of a material or device with a large extrinsic damping contribution would, in this case, continue to oscillate after switching (i.e. the energy would still be in the magnetic system). Conversely, if a sensor relies on small magnetic
oscillations for detection, a large $\alpha_{\text{LLG}}$ would lead to a suppressed signal. For such a device it is therefore desirable to minimize $\alpha_{\text{LLG}}$.

The ability to tune the resonant frequency and linewidth of ferromagnetic thin films, was demonstrated in recent experiments, through the use of transition metals or rare earth impurities [2-4]. The following sections will discuss the characterization of Holmium (Ho) doped permalloy ($\text{Ni}_{80}\text{Fe}_{20}$) thin films [5]. Ho is a rare earth from the lanthanide family, and is therefore an f-block element. In other words, it has valence electrons in 4f orbitals, and this partially filled 4f shell is where its magnetic moment originates. The Ho orbital moment couples indirectly to the 3d spins of permalloy via intra-atomic coupling of the Ho outer-shell 5d spins and NiFe 3d moments, and inter-atomic (RKKY) coupling of the Ho 5d spins and 4f orbital moments [6]. Some of the motivation for doping with Ho, in particular, is that it has the largest orbital moment of the rare earths ($L = 6$), and, thus, a large spin-orbit coupling was anticipated. Although this plays a role in the damping, it is not necessarily the overriding factor, as other rare earths have been shown to be even more effective dopants, which will be discussed further below [7]. As it turns out, this coupling provides a channel for the relaxation of the uniform mode directly to the lattice, and hence out of the magnetic system.

The 15 nm thick Ho doped samples have uniaxial in-plane anisotropy, and were co-sputtered on SiO$_2$ coated Si substrates. The Ho concentration was varied from 0% to 10%, and was adjusted by changing the deposition power for the sputter gun used on the Ho target. A 2 nm tantalum buffer and capping layer were used to prevent film oxidation [5].
5.2 Static properties of Ho-doped permalloy

5.2.1 Vibrating sample magnetometer

Vibrating sample magnetometry (VSM) is a technique used to study the magnetic behavior of samples, which relies on Faraday’s law of induction. This law states that a changing magnetic field will induce an electric field. A sample to be studied is magnetized by being placed in an external magnetic field. The sample is then vibrated (at around 90 Hz) between a set of pick-up coils, where the oscillating magnetic moments of the sample will induce a current in the coils. The measured current is proportional to the moment of the whole sample. The VSM signal measured on the 2% Ho doped sample is shown in figure 5.1.a (blue dotted trace), where the external magnetic field is applied perpendicular to the film plane. This signal contains a background contribution due mostly to diamagnetism from the sample’s substrate [8]. Diamagnetism is a weak effect present in most materials, where the system will create a field to oppose an externally applied field. Note that the diamagnetic effect is orders of magnitude smaller than effects due to ferromagnetism. The background is eliminated by fitting the linear portion of the trace with a negative slope to a line, and subtracting that fit from the data. Once the data is corrected, extending the linear portion of the trace up to the saturation value (as illustrated in figure 5.1.a) will yield the saturation magnetization ($4\pi M_s$) of the sample.
Figure 5.1: a.) VSM signal (blue dotted trace) measured on 2% Ho doped sample. The solid red trace is the corrected signal once the diamagnetic background is subtracted. Lines are fitted to the linear parts of the trace in order to extract $4\pi M_s$. b.) $4\pi M_s$ as a function of Ho concentration. The linear decrease results from ferrimagnetic coupling of the NiFe and Ho moments, due to an effective antiferromagnetic 4f-3d exchange coupling.

In figure 5.1.b, the saturation magnetization obtained from the VSM measurements is plotted as a function of Ho concentration. The data is fit to a slope which indicates that the saturation magnetization decreases by 635 Oe for every percent increase in Ho. The behavior can be explained by the presence of the rare earth, which couples ferrimagnetically to the permalloy magnetic moments due to an effective antiferromagnetic 4f-3d exchange coupling [7]. Unlike ferromagnetic systems where the coupling interaction aligns all the spins parallel, in ferrimagnetic samples, the coupling will align the moments from two different sublattices (in this case NiFe and Ho) anti-
parallel to each other. This results in a net decrease in the overall saturation magnetization.

5.2.2 In-plane MOKE measurement

The samples were also measured using an in-plane MOKE system in order to obtain hysteresis loops that reveal additional magnetic properties (for a description of the MOKE measurement see section 3.3). The magnitude of the magnetization of the sample along the direction of the applied external field was monitored, as the field was swept between -100 Oe and 100 Oe. The coercive (H_c) and anisotropy (H_K) fields were extracted by performing measurement along both the easy axis (parallel to anisotropy direction) and hard axis (perpendicular to anisotropy direction), as illustrated in figure 5.2.

![In-plane MOKE hysteresis loop measurement on 2% (black trace) and 4% (red trace) Ho doped samples. Loops are measured along easy axis (a) and hard axis (b).](image)

Figure 5.2: In-plane MOKE hysteresis loop measurement on 2% (black trace) and 4% (red trace) Ho doped samples. Loops are measured along easy axis (a) and hard axis (b).
The difference in the shape of the loops of figures 5.2.a and 5.2.b reveals the effect of $H_K$ on the direction of the magnetization in the presence of an external field. In the easy axis measurement, the spins are aligned along their preferred orientation. In this case, once the sample has been saturated, it retains its magnetization even as the external field is brought to zero. The spins will then abruptly flip by $180^\circ$ once a field large enough to demagnetize the sample is applied. This is the coercive field, $H_c$, which corresponds to the x-intercept of the hysteresis loop. Beyond this field the sample is again saturated but in the opposite direction. This behavior corresponds to the square open loops seen in figure 5.2.a. For the case of the hard axis measurement, the spins are constantly trying to return toward the anisotropic orientation. As the external field is swept from saturation to zero, the magnitude of the magnetization along the measured direction also goes to zero, since at zero field the spins reorient themselves along their easy axis (perpendicular to the measurement direction). For these flattened loops the field required to saturate the sample corresponds to $H_K$, which needs to be overcome to keep the spins oriented along this direction.

The magnetic properties measured so far for the samples with different Ho concentrations are summarized in figure 5.3. The most prominent feature is the more than threefold increase in anisotropy, as the Ho concentration is increased from 2% to 4%. This is also evident in the hysteresis loops of figure 5.2.b, where there is a clear change in the slope of the loops between the 2% and 4% Ho doped samples. Further increases in Ho concentration do not lead to any more changes in $H_K$. The reason for this step increase is
not clear, but is not thought to be due to a phase change in the material, especially at such low Ho concentration. This behavior is also not observed in $H_c$, which shows almost no change with the introduction of Ho, or the saturation magnetization, which follows a linear decrease due to ferrimagnetic coupling, as explained in the previous section.

![Plot of $H_K$ and $H_C$ vs. Ho concentration](image)

Figure 5.3: Plot of $H_K$ (black squares) and $H_C$ (red circles) as a function of Ho concentration, as measured by MOKE. Inset: $4\pi M_s$ (red diamonds, left axis) versus Ho along with the linear fit to the data. As a comparison $f_{FMR}^2$ (black triangles, right axis) is also plotted as a function of Ho.

### 5.3 Dynamic properties of Ho-doped permalloy

In order to determine the effect of rare earth doping on the dynamic behavior of Ni$_{80}$Fe$_{20}$, the sample was measured along the easy axis at $H_{DC}$ fields between 200 and 1200 Oe. Two of the measured FMR spectra (for $H_{DC} = 300$ Oe), obtained using a perpendicular/parallel subtraction, are shown in figure 5.4. The peaks are plotted on two different scales for clarity and correspond to permalloy with 0% Ho doping (red trace, right axis) and 4% Ho doping (black trace, left axis). The data are fit to a Lorentzian loss
profile using equation 3.2, which is appropriate for thin films with in plane magnetization and uniaxial anisotropy. One such fit is shown overlapping the 4% peak.

The peaks in figure 5.4 already reveal some of the effects of Ho doping on the dynamic behavior of permalloy. We can observe a downward shift in $f_{\text{FMR}}$ with increasing Ho concentration, from 5.7 GHz, to 5 GHz. This can partly be attributed to the decrease in $4\pi M_s$. The data also shows an order of magnitude broadening of the linewidth $\Delta f$ between the pure NiFe, $\Delta f(0\%) = 0.252$ GHz, and the doped NiFe, $\Delta f(4\%) = 2.65$ GHz. The origin of this broadening is discussed further below.

Figure 5.4: $\text{Im}[\mu]$ as a function of frequency for NiFe with Ho doping of 0% (red trace, right axis) and 4% (black trace, left axis), for $H_{\text{DC}} = 300$ Oe in plane field. The solid trace overlapping the 4% data is a fit to a Lorentzian loss profile.

In figure 5.5, the extracted resonant frequencies $f_{\text{FMR}}$ are plotted as a function of the external field $H_{\text{DC}}$ for Ho concentration ranging between 0% and 6%. The dependence of $f_{\text{FMR}}$ on the applied field, for a thin film saturated along the in-plane uniaxial anisotropy direction, follows the Kittel formula (equation 2.8):
\[ f_{\text{FMR}} = \frac{\gamma}{2\pi} \sqrt{(4\pi M_s + H_{\text{DC}} + H_K)(H_{\text{DC}} + H_K)} \]  

(5.1)

where \( \gamma \) is the gyromagnetic ratio. The solid lines in figure 5.5 are fits to the data using equation 5.1, where we use the \( H_K \) and \( 4\pi M_s \) values obtained from the MOKE and VSM measurements, and \( \gamma \) is a fitting parameter. We find that \( \gamma/2\pi = 3.1 \text{ MHz/Oe} \), except for the sample with 4\% Ho doping, where \( \gamma/2\pi = 3.2 \text{ MHz/Oe} \) (the difference is larger than the margin of error of the fit), where the free-electron value for \( \gamma/2\pi \) is 2.78 MHz/Oe.

These values are consistent with other published results on NiFe [2,9].

Figure 5.5: Resonance frequency \( f_{\text{FMR}} \) as a function of applied field \( H_{\text{DC}} \) for 0\% (diamonds), 2\% (triangles), 4\% (squares) and 6\% (circles) Ho doping. The solid lines are fits to the Kittel formula, Eq. 5.1.

Earlier, the observed downward shift in resonant frequency with increasing Ho concentration was partly attributed to the decrease in \( 4\pi M_s \). However, this decrease alone does not fully explain the behavior of \( f_{\text{FMR}} \). As an illustration, we compare the linear decrease of \( 4\pi M_s \) with increasing Ho, to the behavior of \( f_{\text{FMR}}^2 \), measured at 900 Oe, also
as a function of Ho (see figure 5.3 inset). From equation 5.1, $f_{\text{FMR}}^2 \sim 4\pi M_s$, but we clearly see that for 4% Ho, there are other contributions to $f_{\text{FMR}}$, beside the saturation magnetization. This is also evident in figure 5.5, where the 4% Ho (squares) nearly overlaps the 2% Ho data (triangles) over the whole $H_{\text{DC}}$ range. Both the measured jump in $H_K$ and the larger $\gamma$ value do not fully account for this upward shift in frequency. Still, this is consistent with independent measurements, where the coupling mechanism between the rare earth and the NiFe leads to an additional effective field contribution [7].

The linewidth broadening observed in the FMR response is large, but we still need to determine its origin. We recall there can be both intrinsic and extrinsic contributions to the linewidth, and that we are interested in controlling the intrinsic damping parameter $\alpha_{\text{LLG}}$. In other words we want to control the mechanism which dissipates the magnetic excitation energy directly into the lattice. On the other hand, increasing the contribution of extrinsic effects (distribution in $H_K$, sample inhomogeneities, eddy currents…etc.) would be undesirable as the magnetic system could stay in an excited state for too long. Eddy current contributions ($\propto$ sample thickness) are negligible and can already be discarded due to the relatively thin sample thickness (15 nm).

The linewidth contributions from the other effects are quantified by plotting the linewidths as a function of their respective $f_{\text{FMR}}$ for the Ho doped series up to concentrations of 6% (see figure 5.6).
The data can then be fit to the appropriate expression for the linewidth of a soft magnetic material, measured along its easy axis (e.g. equation 3.4), where $\Delta f$ is expressed as:

$$
\Delta f = \left( \frac{|v|}{2\pi} \right)^2 \frac{\Delta H_0}{2f} + \left( \frac{|v|}{2\pi} \alpha_{\text{LLG}} \right) \left( 2H_{DC} + 2H_K + 4\pi M_S \right) \tag{5.2}
$$

where $\Delta H_0$ is an empirical expression for peak broadening due to inhomogeneities (extrinsic contribution) [10]. From equation 5.2 it is clear that a large $\Delta H_0$ will dominate the linewidth at low frequencies, while its effect will become smaller as the signal is pushed to higher frequencies by the applied $H_{DC}$. The intrinsic $\alpha_{\text{LLG}}$ on the other hand does not have a $1/f$ dependence. We can therefore differentiate between the intrinsic and extrinsic mechanisms by sweeping $H_{DC}$, and obtaining $f_{\text{FMR}}$ over a wide frequency range.
Using equation 5.2, we have determined that the observed broadening with increasing Ho concentration is mostly the result of an increase in $\alpha_{\text{LLG}}$. The measured $H_K$ and $4\pi M_s$ values, along with the $\gamma$ values derived from equation 5.1 were used for the fits.

In figure 5.7, we plot the extracted intrinsic damping on a log scale, as a function of Ho concentration (percent Ho, %). We see that the doping results in a nearly two orders of magnitude increase in $\alpha_{\text{LLG}}$ over the range of Ho concentration used. The $\Delta H_0$ contribution on the other hand remains small (~7% or less of total linewidth) and shows no clear dependence on the doping.

![Figure 5.7: $\alpha_{\text{LLG}}$ versus Ho concentration. $\alpha_{\text{LLG}}$ increases by two orders of magnitude over the measured concentrations. The error bars for the 0% and 2% data points are on the order of the square markers.](image)

Because our experiment is limited to in-plane external field $H_{\text{DC}}$ at room temperature, we cannot adequately explore the mechanism responsible for the increased damping. However, there are several theoretical and experimental works that correlate rare earth orbital moments and magnetic damping. In particular, Woltersdorf et al.[7] have made temperature dependent measurements on samples doped with different rare earths, and have shown that their results agree well with a longitudinal slow-relaxing
impurity model. In this model, the 4f orbitals of the rare earth element provide a direct channel for the relaxation of the oscillating magnetization energy into the lattice [7, 11]. This mechanism also explains the effective field discussed above to account for the upward shift in $f_{\text{FMR}}$.

Finally, we conclude by observing that our data suggests that Ho concentrations as small as 2% can lead to nearly order of magnitude increases in $\alpha_{\text{LLG}}$, while causing minimal changes in all other practical magnetic parameters. This shows Ho can, indeed, be used to effectively tune and optimize the magnetization dynamics in a recording system through the materials engineering of NiFe and other transition-metal ferromagnets (such as CoFe alloys), typical of recording heads and media soft underlayers (SUL).
References


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Chapter Six: Electrical control of magnetization dynamics in multiferroic nanocomposites

6.1 Multiferroic materials

The development of new materials is an integral part of the improvement in the performance of magneto-electronic devices. In section 4.1, the use of granular CoCrPt alloys with large out of plane anisotropies was discussed in the context of its use for higher density perpendicular recording hard drives [1]. The appeal of the CoCrPt rested in the ability to control critical magnetic parameters (i.e. grain coupling, $H_K$, $M_s$). Perpendicular magnetic recording cannot sustain the advance of areal densities indefinitely, as the magnetic anisotropies of the storage layer are ever increasing to stabilize smaller bits. To this extent, the media anisotropy fields ($H_K$) will soon exceed the field a write head can generate i.e. $H_{\text{writer}} < H_K$, at which point a bit cannot be written. This necessitates research and development of more advanced magnetic recording methods. One approach to overcoming this barrier is to incorporate additional methods for switching the magnetization of the media, i.e. something to assist the writer and effectively generate a larger magnetic field at the media. For example, Heat Assisted Magnetic Recording (HAMR) uses an optical transducer integrated with the head to locally heat the media, reducing the temperature-dependent media anisotropy enough to write a bit [2]. Another assist technology of interest is known as Electrically Assisted
Magnetic Recording (EAMR) [3], where a voltage source is integrated with the writer to apply a voltage to a storage layer having both magnetic and electrical sensitivity. Thus, a class of materials that has been attracting a lot of interest recently is multiferroics [4], but their applications extend beyond EAMR, as will be discussed below. By definition, these are materials that display simultaneously two of the following three ferroic properties [4]:

- **Ferroelectricity**: The ability to retain a stable electric polarization that can be reversed by an applied electric field and which displays hysteretic behavior (piezo-electricity originates in the ferroelectric properties of a material, which is of particular interest here).

- **Ferromagnetism**: The ability to retain a stable magnetization that can be reversed hysteretically by an applied magnetic field (This also includes antiferromagnetism, where adjacent spins are anti-parallel instead of parallel, resulting in a null net magnetization, and ferrimagnetism, where a net magnetization is retained after anti-parallel alignment). An additional common property of ferromagnets, magnetostriction, where strain induces a change in magnetic properties, is of particular interest here.

- **Ferroelasticity**: The ability of a crystal structure to switch between stable orientations by the application of mechanical stress, i.e. the material can be physically deformed and retains its new shape.

In general however, the term multiferroic usually refers to a material displaying the first two properties. The co-existence and coupling between these two order parameters offers
the possibility of electrical control of magnetic properties (and vice versa), which presents an enticing prospect for various technological applications. In particular, simpler designs that are more robust and efficient can be implemented for voltage control, while generating less cross talk and other noise arising from magnetic interference. This can lead to improvements in a large array of devices, such as high-sensitivity field sensors [5], voltage modulated rf filters [6] and transducers [7], and data storage systems [3, 8]. In the latter case, the use of multiferroics has been proposed for both high density media layer, where $H_K$ can be tuned during writing [3], and for a read head, where reduced power consumption and better thermal performance are possible [8,9].

Since single phase materials that displayed strong ferroelectric and ferromagnetic signals at room temperature were elusive [10], earlier studies on multiferroic were conducted at low temperatures [11,12]. On the other hand, room temperature studies were performed on multilayered structures consisting of independent ferromagnetic and piezoelectric layers. In this case, each phase of the composite contains one of the ferroic properties, and the magneto-electric (ME) coupling manifests itself on macroscopic scales [13]. More recently, Chu et al. [14] demonstrated local ME coupling on heterostructures made of multiferroic BiFeO$_3$ (BFO, ferroelectric and antiferromagnetic) and CoFe (ferromagnetic), using electrodes embedded in the BFO layer. Another approach still, that shows a clearer path to scaling, is nanocomposite ME system. These display good phase separation on the nanoscale, while retaining both ferromagnetic and ferroelectric properties at room temperature [15, 16].
6.2 BiFeO$_3$-NiFe$_2$O$_4$ magneto-electric nanocomposites

In this chapter, we study the effects of an applied electric field on the magnetic properties of a BiFeO$_3$-NiFe$_2$O$_4$ (BFO-NFO) ME nanocomposite [17]. The BFO-NFO composites, ranging in thickness from 100 to 1200 nm, consist of epitaxial ferrimagnetic NFO nanopillars, with average lateral dimensions between 40 and 180 nm, which are embedded in a multiferroic BFO matrix (see figure 6.1). This two phase system is sandwiched between 50 nm thick SrRuO$_3$ (SRO) electrodes, except for the 1200 nm thick sample where only a bottom La$_{0.5}$Sr$_{0.5}$CoO$_3$ (LSCO) electrode is present. All samples were grown at an oxygen pressure of 100 mTorr and a temperature of 700$^\circ$ C, via pulsed laser deposition on a (LaAlO$_3$)$_{0.3}$(Sr$_2$AlTaO$_6$)$_{0.7}$ (LSAT) substrate [15]. The samples were obtained from Steven Crane at the department of materials science and engineering, UC Berkeley.
The intimate contact between the magnetostrictive NFO and the piezo-electric BFO leads to a strain-mediated ME coupling which alters the local anisotropy field $H_K$ [4, 16]. Since the FMR frequency depends on the local field that the magnetization experiences, to which $H_K$ contributes, we can anticipate a shift in the resonant frequency with an applied electric field.

6.3 BFO-NFO characterization

6.3.1 Experimental set up

Figure 6.2 shows a schematic of the experimental set up used for the characterization of this particular set of samples. The apparatus is modified through the addition of a Keithley 2400 Digital SourceMeter, which allows us to generate the electric
field necessary to probe the ME coupling. The voltage source is connected to the bottom
electrode of the sample on one end, and to the probe via an integrated bias tee in the VNA
(not shown in the schematic) on the other end. The presence of a bias tee ensures that
there is no mixing between the AC signal of the VNA and the DC signal of the voltage
source. All the measurements discussed below were performed with the probe in contact
with the sample. The fabrication of a robust microbridge at the probe tip, using a buffer
layer (top inset of figure 6.2) is essential. The buffer layer not only improves SNR, as
discussed in chapter 1, but it also increases the mechanical strength of the micro-bridge,
making the probe highly reliable even for contact measurements, as well as elevating the
Cu bridge far enough off the coax surface to make the bridge the electrical contact point
with the sample. These measurements would not be possible with just a thin film Cu
current path. The measurement sequence was conducted in the usual manner, with a null
electric field, and while applying a voltage across the sample’s thickness. In the latter
case, this was achieved by biasing the sample at the bottom electrode, and grounding it at
the top electrode through the probe. For the case of the 1200 nm thick sample (no top
electrode), it was still possible to bias the sample by coming in direct contact with the top
surface of the sample. Note that on these nanocomposites, contact is not necessary for
FMR measurements with no applied electric field, as the probe couples effectively to the
sample even in non-contact mode.
In the ME coupling measurements, it is not possible to extract a clean FMR signal using a large-field/low-field subtraction. For ME samples, the measured background depends on both the applied magnetic and electric fields, as opposed to ferromagnetic samples where the background signal (with no FMR) is independent of the applied magnetic field. Therefore the $S_{11}^{\text{FMR}}$ and the background signal must both be recorded at the same magnetic and electric field.

6.3.2 Magnetic characterization

The magnetic characteristics of the sample are first tested without applying any
electric field. Figure 6.3.a shows the FMR signal measured on the 1200 nm thick BFO-NFO over $H_{DC}$ fields ranging between 0 and 3400 Oe. The resonant frequency increases with increasing magnetic field, as is shown more explicitly in the inset of the same graph. The data are fit using a generalized model derived by Hurben and Patton (equation 4.2), which is appropriate for the magnetic configuration of the experiment (i.e. in-plane $H_{DC}$, $h_{rf} \perp H_{DC}$):

$$f_{FMR} = \frac{\gamma}{2\pi} \sqrt{H_x H_y}$$

$$H_x = H_{DC} \sin \phi + [H_K - 2\pi M_s (3N_z - 1)] \cos^2 \phi$$

$$H_y = H_{DC} \sin \phi + [H_K - 2\pi M_s (3N_z - 1)] \cos 2\phi$$

(6.1)

In the above, we use a gyromagnetic ratio value $\gamma/2\pi = 3.22$ MHz/Oe appropriate for NFO, and a saturation magnetization $4\pi M_s = 3500$ Oe, which was obtained from independently measured M-H loops [15]. Phi, $\phi$, is the angle between M and the z axis, $H_K$ is the anisotropy field, and $N_z$ is the out of plane demagnetization factor ($N_x+N_y+N_z=1$ and $N_k = N_y \equiv N_{xy}$ where the system is assumed to have symmetry about the z-axis), all of which are used as fitting parameters. The field-dependence of the angle $\phi$ can be calculated by setting the torque on M to zero (under static-equilibrium conditions) [18].
Figure 6.3: a.) Imaginary part of the magnetic permeability of a 1200 nm thick sample for different in-plane $H_{DC}$ fields (traces offset for clarity). Inset: $f_{FMR}$ as a function of applied field (squares). The solid line is a fit of the data. b.) In-plane and out-of-plane M-H loops.

The fit yields a perpendicular anisotropy $H_K = 900$ Oe, and $N_z = 0.1$ ($N_{xy} = 0.45$). The small $N_z$ value is consistent with the demagnetization constant associated with a pillar geometry magnetized in the plane [19]. The values of $H_K$ and $N_{xy}$ also show good agreement with the M-H loop of figure 6.3.b, where the in-plane saturation magnetization $H_{sat} \sim 2500$ Oe = $H_K + 4\pi M_s N_{xy}$. However, a limitation of the fit is the value we obtain for the angle $\phi$, where convergence is achieved for $\phi = 24^\circ$. This is smaller than the angle one would expect from the M-H loop, where as $H_{DC}$ approaches the saturation field $H_{sat}$, $M$ should be mostly in-plane ($\phi \rightarrow 90^\circ$). In addition, the assumption of symmetry about the z-
axis is not necessarily true for such composites. This highlights the difficulty of modeling all the dynamics present in such a complex system.

The magnetization of the NFO pillars is dictated in large part by their geometry and dimensions. Figure 6.4 is a plot of $f_{\text{FMR}}$ as a function of film thickness. The data are plotted for four different in-plane fields of 1800 Oe (circles), 2400 Oe (diamonds), 3000 Oe (triangles), and 3400 Oe (squares). For all field values, we see a drop in resonant frequency beyond 400 nm, followed by a gradual increase above 600 nm, albeit at a slower rate than the increase between 100-400 nm. This behavior is consistent with a change in the magnetic anisotropy, from predominantly in-plane to out of plane as the film thickness and shape anisotropy increase [15].

![Figure 6.4: $f_{\text{FMR}}$ as a function of sample thickness for fields $H_{\text{DC}} = 1800$ Oe (circles), 2400 Oe (diamonds), 3000 Oe (triangles), and 3400 Oe (squares). There is a visible transition near 400 nm](image)

In figure 6.5, the imaginary part of the permeability for the 1200 nm sample is plotted as a function of frequency, for measurements made at $H_{\text{DC}} = 2400$ Oe, along four
different in-plane orientations. The directions are defined from one of the sample’s edges, and the corresponding data indicate the presence of a bi-axial anisotropy in the plane of the sample, along the diagonal direction (+/- 45°). This results in a nearly 1 GHz upward shift in $f_{\text{FMR}}$, when compared to the resonant frequencies along the hard axes directions ($0^\circ$ and $90^\circ$). This preferential orientation can be explained by the shape anisotropy of the pillars, which tend to be elongated along the diagonal direction (see figure 6.6.a). All of our measurements were made along the in-plane easy direction ($45^\circ$ orientation).

![Graph](image)

Figure 6.5 Im[$\mu$] versus frequency measured along four different directions, where the orientations are defined with respect to the sample edge.

The distribution of anisotropy fields, both in-plane and out of plane, along with the inherent grain boundaries imposed by the nanocomposite film morphology, can explain the broad linewidths seen for the peaks shown in figure 6.3.a [20, 21].

6.3.3 Electrical characterization

We now demonstrate the ferroelectric properties of the BFO matrix in the
presence of embedded NFO pillars. Figure 6.6.a shows a perpendicular piezo-force microscopy (PFM) image of a 3µm x 3µm area of the BFO-NFO composite [16], taken by Florin Zavaliche at Seagate Research. The whole area shown in the picture was scanned with an electrically conductive probe at +167 kV/cm (+20 V). The darker area in the center (1.5µm x 1.5µm) was then scanned at -167 kV/cm (-20 V). The contrast between the two regions corresponds to the piezoresponse of the BFO, which either expands (light) or contracts (dark) depending on its polarization. This indicates that the electric polarization can be switched between to stable orientations perpendicular to the plane.

While one might expect the polarity orientations to be equivalent, the polarization curves (P vs E) on these samples reveal that the BFO is not isotropic, but has instead a preferred polarization orientation out of plane, as shown in figure 6.6.b
Figure 6.6: a.) PFM image of the sample, where the larger (light) square was poled at +167 kV/cm (+20 V) and the center (dark) square was poled at -167 kV/cm (-20V). b.) Polarization curve, P vs E, demonstrating an offset in E (solid trace is a fit to an arctangent function.)

The P vs E curve is measured along two directions, positive (+) and negative (-), where the sign corresponds to the sign of the field applied to first saturate the sample. This data was also provided by Steven Crane. The solid trace is a fit to an arctangent function, a typical form for a field-driven polarization curve, which is discussed in the following section. In addition to the expected hysteretic behavior, the loop reveals a large positive polarization for a null E field. It is also clear that a much larger field is needed to switch from positive to negative polarization than vice versa (x-intercepts). In other words, an offset field needs to be overcome to fully switch the polarization with a negative field. Note the P vs E measurement was not made on the 1200 nm sample.
because it was not fabricated with a top electrode, however the data is representative of the behavior of the BFO matrix.

6.4 Magneto-electric coupling

Having established the ferroelectric and ferromagnetic character of the BFO-NFO composite, we now evaluate the coupling between these two order parameters, and its effect on the magnetization dynamics of the sample. To accomplish this, the local FMR measurement is made while applying a voltage through the microprobe and across the sample thickness. While applying $H_{\text{DC}}$, the sample is biased with a negative voltage. Once the data collection is complete, the polarity of the voltage is switched, and the measurement is repeated. This sequence is continued while varying the voltage from large to zero bias. Note that before the start of each measurement, the resistance of the sample at the point of contact with the probe was measured across the thickness, to ensure that no short circuit path was present.

The results made from measurements at different $H_{\text{DC}}$ fields are summarized in figure 6.7, where the observed $f_{\text{FMR}}$ shift is plotted as a function of applied E field for the 1200 nm thick sample. The shift is calculated as the difference between $f_{\text{FMR}}(+E)$ and $f_{\text{FMR}}(-E)$, and is shown for three different $H_{\text{DC}}$ values of 1800 Oe (open squares), 2400 Oe (open circles) and 3000 Oe (open triangles). The solid curves are fits to the same arctangent function used in figure 6.6.b. The fitting function has the form:
\[ g(E) = a_0 + \frac{2}{\pi} \beta \arctan \left( \frac{E - (E_0 + E_{\text{offset}})}{C} \right) \] (6.2)

Where \( a_0 \) is an offset factor along the y-axis, \( \beta \) is a scaling factor, \( E_0 \) is the onset of the curvature of the trace, \( E_{\text{offset}} \) is an offset factor along the x-axis, and \( C \) is a measure of how fast the curve reaches saturation. The fact that the data of figures 6.6.b and 6.7 can be fit to the same function, suggests that the shift in the resonant frequency is, indeed, coupled to the electric polarization.

Figure 6.7: Measured shift in \( f_{\text{FMR}} \) as a function of applied electric field for the 1200 nm thick BFO-NFO sample. Solid lines are fits with arctangent functions. The shift is the difference between \( f_{\text{FMR}} \) at a positive bias (+E) and a corresponding negative bias (-E).

The largest observed frequency shift was nearly 0.3 GHz, for an in-plane \( H_{\text{DC}} \) field...
of 1800 Oe \( f_{\text{FMR}}(0V) = 7.5 \text{ GHz} \), and for an applied E field of magnitude \(|E|=250 \text{ kV/cm} \) (30 V), or in other words, the shift between a sample biased 30V and -30 V. This corresponds to a few percents of \( f_{\text{FMR}} \) and about 10% of the linewidth at zero bias (V=0). The effect is diminished at higher magnetic fields, which is revealed by the data at 2400 \( f_{\text{FMR}}(0V) = 8.4 \text{ GHz} \) and 3000 Oe \( f_{\text{FMR}}(0V) = 9.1 \text{ GHz} \). This trend of a smaller resonant frequency shift at higher magnetic fields is to be expected, as the anisotropy \( H_K \) makes an ever smaller contribution to the local field, i.e \( f_{\text{FMR}}[H(E)] \approx f_{\text{FMR}}(H_{\text{DC}}) \) for \( H_{\text{DC}} \gg H_K(E) \). Since the ME coupling causes changes in \( H_K \), the electric field will have less of an influence on the overall resonant frequency. For \( H_{\text{DC}} \) fields smaller than 1800 Oe, electric field driven shifts in \( f_{\text{FMR}} \) are also difficult to measure, as the magnetization is far from saturation, which could be obscuring the effect.

The observed shifts in frequency appear to reach saturation near \(|E|=250 \text{ kV/cm} \) (30 V). This is consistent with the voltage needed to pole the sample out of plane (as shown in figure 6.6.a.) It was not possible to apply larger voltage without risking damaging the sample, due to excessive leakage currents, as the contact area of the probe, that is the area of the Cu microbridge (width \( \times \) length), is relatively large \( \sim 15\mu\text{m} \times 100 \mu\text{m} \). Although there were leakage currents present during the measurement, they were not found to have any influence on the ME coupling. Still, a smaller probe tip would result in an accordingly smaller contact area, thereby alleviating leakage issues. Shifts in FMR frequencies induced by applied E fields were also observed on thinner sample. However, due to a weaker FMR signal from smaller sampling volumes (\( \propto \) thickness), the data
contained considerably more scatter. There may also be less induced strain in thinner samples.

We also consider the effect of ME coupling on the linewidth of the measured FMR loss profiles. Figure 6.8 shows a plot of the FMR linewidth as a function of applied electric field on the 1200 nm thick sample, for $H_{\text{DC}}$ fields of 1800 Oe (squares), 2400 Oe (triangles), and 3000 Oe (circles). The data reveal a broadening of the peaks as the E field is increased. The measurements are made over the same E field range as in figure 6.7.

![Graph showing FMR linewidth vs applied electric field for different $H_{\text{DC}}$ fields.](image)

Figure 6.8: FMR linewidths vs applied electric field for a range of $H_{\text{DC}}$. The solid lines are guides to the eye. Inset: FMR linewidth (LW) versus $f_{\text{FMR}}$ for E = 0. The data were fit to a $1/f$ function (solid trace).
The observed electric-field induced broadening can be quite large, reaching at higher electric fields as much as a 50% increase, when compared to the equivalent linewidth at zero bias. Contrary to the trend for \( f_{\text{FMR}} \) shifts, the broadening is more pronounced at higher \( H_{\text{DC}} \) fields. Since linewidths are, in a sense, a measure of non-uniformities in the magnetic system, the uniform applied field, \( H_{\text{DC}} \), does not directly broaden LW in an analogous fashion to its effect on the resonant frequency, \( f_{\text{FMR}} \). This makes sense if we consider the source of the line broadening. Whereas \( H_{\text{DC}} \) plays a more important role in driving \( f_{\text{FMR}} \) as it is increased, larger \( H_{\text{DC}} \) values lead to narrower BFO-NFO linewidths. This is illustrated in the inset of figure 6.8, where the linewidth at zero bias is plotted as function of resonant frequency (triangles). The data follow a \( 1/f \) form (solid trace), which points to a system where the line broadening is dominated by contributions from inhomogeneities (i.e. distribution in anisotropy field \( H_K \)) and grain boundary scattering. Thus, it is likely that the broadening is driven by an E-field induced increase in sample inhomogeneities, both in the crystal and magnetic lattices. This effect will contribute more to the linewidth of peaks at higher \( H_{\text{DC}} \) fields (and frequencies), since these are narrower in zero bias.

Overall, the behavior of the linewidths show the same asymmetry as the polarization curve of figure 6.6.b, which was explained above as a result of the existence of a preferred polarization orientation in the BFO matrix. In both cases the observed effects are more easily driven with a positive E field, i.e. the BFO is more easily saturated, and FMR linewidths display more broadening. This further illustrates the
coupling of the electric polarization and the FMR line broadening.

Finally, we conclude by noting that the characterization of the BFO-NFO nanocomposite has revealed complex magnetic dynamics, which are dominated by the shape anisotropy of the magnetic pillars. We also established the presence of ME coupling through strain-induced changes in the magnetic anisotropy, leading to shifts in $f_{\text{FMR}}$ and linewidth broadening. The latter effect, in particular, shows a strong correlation with the asymmetric nature of the electric polarization in the BFO matrix. This suggests the possibility of designing rf filters with electrically tunable frequencies and bandwidth for example, and, more generally, that ME nanocomposites are viable for high frequency applications, although an adequate modeling of the magnetization dynamics is a challenge that needs to be addressed.
References


14. Ying-Hao Chu, Lane W. Martin, Mikel B. Holcomb, Martin Gajek, Shu-Jen Han, Qing He, Nina Balke, Chan-Ho Yang, Donkoun Lee, Wei Hu, Qian Zhan, Pei-Ling Yang, Arantxa Fraile-Rodríguez, Andreas Scholl, Shan X. Wang and R. Ramesh, Nature Mat. 7, 678 (2008)

In summary, a local near-field microwave probe for ferromagnetic resonance characterization was developed, and its high utility and sensitivity were demonstrated through measurements on a broad range of materials, from common magnetic materials such as NiFe, to advanced materials such as multiferroic nanocomposites. The main attributes of this measurement technique are that it is broadband, it can measure samples of any form factor (e.g. wafers, media discs, chips…etc), and is local with the potential to achieve high spatial resolution. It is also a non-contact method, although it is possible to measure a sample while in contact. In addition, since the technique operates in a broad frequency range, it offers an additional phase space in which to study the magnetization of a sample, and it relies on simpler commercially available electronics (i.e. vector network analyzer). Many other local FMR techniques only drive the resonance at a single frequency. Furthermore, since it is a non-destructive measurement and there are no restrictions placed on the sample geometry, materials and devices can be studied in a laboratory or in a production line during their fabrication process.

The probe consists of a shorted micro-coax, where the current path (microbridge) is a Cu thin film sitting on top of a FIB deposited buffer layer. The use of a buffer layer creates a mechanically more robust probe tip, and leads to an increase in sensitivity. The microbridge creates an even, continuous path across the coax dielectric, especially at the
interfaces between the dielectric and the inner and outer conductors. At the same time, FIB deposition results in a structure with surface smoothness on the nanometer scale. Both of these are important factors for further scaling of the probe tip.

The sensitivity gains have allowed the measurement of a variety of materials. Magnetically soft materials, with relatively long lived magnetic excitations (low-damped CoFe), were studied on a multilayer structure in a hard drive media disc. Because the probe is local, the curvature of the disc did not affect measurements along different orientations, which revealed the influence of the anisotropy field on the magnetic response of the CoFe. The capability to probe the deeper layers in a multilayer structure can be used to investigate the magnetic coupling between layers. For example, layers that are coupled will display a dynamic response different from that of uncoupled layers [1-3], such as with the CoFe and the media layer, where the response changed depending on whether the media layer was magnetized or not. The quality of the deposition can as well be monitored in this way, where interface roughness results in orange peel coupling [4].

We also characterized another soft material, Ho-doped NiFe, where the damping of magnetic excitations was engineered in the material by varying composition, the effects of which were manifested in the FMR linewidths. In particular, these materials had their dynamic response modified through the addition of the rare earth dopant (Ho). We were able to determine that the Ho leads to an increase in intrinsic damping. Establishing whether the excitation energy leaves the magnetic system (intrinsic), or is redistributed within that system (extrinsic), is important for the design of devices with faster switching times (write heads) or higher sensitivity (field sensors).
Hard materials used for the recording media layer (CoCrPt) are another class of materials that was studied. The results revealed how the concentration of alloy components could be varied to change the orientation of the magnetization in the layer. As our probe has a metallic tip (the Cu microbridge), it was possible to extend the measurements to both magnetically and electrically probe a material of interest for an advanced media concept (Electrically Assisted Magnetic Recording, EAMR), the multiferroic nanocomposites, BFO-NFO. In this case the probe was in contact with the sample. The sample displayed complex dynamics in the magnetic phase (NFO) along with clear magneto-electric coupling with the ferroelectric phase (BFO), thus establishing the viability of this novel material, more generally, for high frequency applications.

While the FIB deposition process allows us to pattern structures on the nanometer scale, the dimensions of the overall active area of the probe, the microbridge, is still limited by the inner to outer conductor separation (~100 µm). Therefore, further scaling efforts should focus on ways to reduce the sample area being probed. This can be done either by using coaxes with smaller inner to outer conductor separations [5] or by implementing the buffer geometry shown in figure 7.1
Figure 7.1: Proposed fabrication method for achieving smaller probe tips. The SiO$_2$ buffer tapers off towards the top, making the current path parallel to the sample smaller.

This three dimensional fabrication approach would allow us to make probe tips on a nano-scale. The buffer structure would taper as it grows higher (like a pyramid), allowing accurate control of the dimension of the current path on the flat top, which couples to the sample. Keeping in mind that as we scale down the microbridge, we will see a smaller signal from the shrinking magnetic volume being probed, additional modifications must be made to the apparatus in order to retain adequate sensitivity. Because the data extraction relies on a background subtraction method, better control of the sample to probe distance will become critical, especially as the sample will need to be brought closer to the probe (sensitivity $\sim$ distance $<$ probe dimension). This could be addressed through the use of a feedback loop that monitors the capacitance between the probe and sample, or the $S_{11}$ signal outside the frequency range where an FMR response
is expected. A further improvement would be the integration of a lock-in amplifier into the apparatus, with the modulation of the signal coming from an AC component added to the applied DC field [6]. Moreover, we need the ability to sweep the external field at arbitrary angles from the normal to the plane of the sample (all measurements have been for an in-plane field, due to the limitation of the external magnetic field source). While we have been able to separate out the different contributions to the damping through their frequency dependence, the extrinsic contributions show a strong angular dependence [7], so that a more thorough analysis of the dynamics would be possible in that case. Overall, we have been able to use our probe to study a wide variety of magnetic materials, in particular as they relate to the magnetic recording industry. The results agree well with other measurement methods, and have helped us gain insight into high frequency response of different systems on a local scale.
References

5. For example, GGB industries inc. (http://www.ggb.com/) offer micro-coaxes with inner to outer conductor separation as small as 50 microns, while there is a patent for micro-coaxes with separations of 15 microns (U.S. patent 6953888 B2)
Appendix

This appendix contains computer codes which I wrote as part of my dissertation work. These codes were written to streamline the running of the local FMR experiment and the analysis of the recorded data. Section A.1 deals with code written for the LabVIEW program [1] that controlled the various instruments that were used, i.e. the VNA, the power supplies of the electromagnet, and the Keithley 2400. The code was run on a single computer to which all the instruments were connected via GPIB cables. Section A.2 is a procedure file written for the Igor Pro program [2], a technical graphing and data analysis software.

A.1 LabVIEW code

LabVIEW is a widely used graphical programming environment made by National Instruments. It integrates various scientific instruments into a centralized interface, and allows the set up of sophisticated routines for data collection. The program is intuitive in that it relies on a series of graphical icon and wires that resemble a flowchart (block diagrams). The collection of commands written in this way can be saved as a virtual instrument (VI), which may itself contains subVI’s. For more information, visit [http://www.ni.com/labview](http://www.ni.com/labview).

Since LabVIEW is not based on written code, it will be displayed below as images showing the various block diagrams of the main VI and its subVI’s, along with
brief descriptions. The main VI of the FMR experiment can be broken up into three parts, the input, the measurement, and the shutdown.

A.1.1 Input of main VI

The input portion of the main VI (Figure A.1) initializes all the instruments controlled by the VI through the desktop computer. A signal is sent to all the instruments instructing them to switch to remote operation, so that they can start to communicate with the computer. In addition, in this portion of the VI all the necessary parameters for the measurement are specified by the user via a graphical interface on the computer. This part also contains three subVI’s, associated with the VNA (VNA INIT), the KEPCO power supplies of the electromagnet (KEPCO INIT), and the Keithley multimeter (VOLT INIT). These subVI’s are discussed below.
In VNA INIT (figure A.2), the frequency range of the measurement is specified by fSTART and fEND, with the values given in MHz. The GPIB address of the VNA (VNA GPIB) is also specified at this point. This corresponds to a dedicated two-way communication channel between the instrument and the desktop computer. All the values that are input in VNA INIT are passed on to the main FOR loop discussed in A.1.2.
The KEPCO INIT subVI is not shown as it contains a device specific command structure that I did not write. It sends a command to the power supplies turning them on and setting them to current mode. The Kepco GPIB address is set here and passed to the main FOR loop.

The “Hdc list” subVI shown in figure A.3 takes an input string list of Hdc field given in Oe, and outputs the same list in array form, along with a numeric corresponding to the number of Hdc values in the list. This numeric sets the number of iterations for the main FOR loop (see figure A.1)
The VOLT INIT subVI (figure A.4) takes a list of voltage values in string format and converts them to array, while also outputting the size of the array. This is done in “V list”, which is the same as Hdc list.vi (figure A.3). The size of the array determines the number of iteration in the FOR loop of the “create voltage folder.vi”, and the “applied voltage loop” in the main FOR loop of section A.1.2. The GPIB address of the Keithley multimeter is also defined here.

![Figure A.4: VOLT INIT](image)

Additionally, VOLT INIT initializes the Keithley multimeter to apply a voltage while measuring current, while also setting the compliance current in units of mA (Init_Source_Volt_Compliance_Curr.vi, figure A.5). If the measured leakage current
during the measurement is at least equal to the compliance, the voltage source is turned off.

Figure A.5: Init_Source_Volt_Compliance_Curr.vi

One other parameter that is input through VOLT INIT is the path of the folder where the data is stored (Create voltage folder.vi, figures A.6 and A.7). After the user specifies a folder directory, or path, the subVI goes through the list of voltages and checks to see if a folder with the name of the voltage value already exists. If it does not (true for case structure in figure A.7), a folder with that name is created. Otherwise nothing happens (false in case structure of figure A.7).
Figure A.6: Create voltage folder.vi. Pick out voltage value from array.

Figure A.7 Create voltage folder.vi. Check if folder exist. If not create folder, if it does, do nothing.
Other parameters which are directly input into the main For loop of the measurement portion of the main loop, without going through a subVI, are:

Angle for DC field: sets the in-plane angle of the applied magnetic field. In our experiment it is held at a constant of -45°.

Power [dB]: the power setting of the VNA, in dB units.

Calibration setting: Set to true if the calibration is done in the VNA, or false if the data is collected raw and calibrated at a later time.

Avg: Set the number of times the VNA averages the frequency sweeps.

A.1.2 Measurement of main VI

The measurement part of the main VI comprises a main FOR loop for the DC field, where the number of iterations corresponds to the number of DC field values that were input (figure A.8). This FOR loop contains a two-step sequential loop (sequence for direction of applied field), where each step corresponds to an in-plane Hdc field orientation, with the two orientations being perpendicular to each other. The sequential loop itself contains another FOR loop (Applied voltage loop), where the voltage is applied and the VNA measures the data, with each iteration of the loop corresponding to a voltage value.
Figure A.8: Main FOR loop. Top: Sequence along first Hdc angle. Bottom: second sequence at angle perpendicular to first sequence angle.

For each iteration of the main FOR loop, the steps of the experiment happen in the following order:
I. The magnet is swept up to saturation (~3500 Oe), then saturated in the opposite direction, then once more in the original direction (up-down-sweep_angle-45.vi, figure A.9), this done to remove any remanent field in the magnet poles from previous measurements.

II. The desired field is set and the system is given a five seconds delay in order to stabilize (up_down_sweep&set_field_angle-45_voltage.vi, figure A.10)
III. We then enter the “Applied voltage loop”, where the voltage value is set (Source_on&set_volts.vi, figure A.11). This subVI checks the list of voltages. If there is only one value in the list AND this value is zero (true in case structure of figure A.11), then no voltage is applied and the multimeter is turned off.

Figure A.11: Source_on&set_volts.vi. No voltage applied

Otherwise, the voltage is set to zero (figure A.12 top) and then to the desired voltage value (Figure A.12 bottom).
Figure A.12: Source_on&set_volts.vi. Top: set voltage to zero. Bottom: set voltage to desired value.

IV. Once the magnetic field and the voltage are set, the VNA starts measuring and outputs the recorded data (VNA_big_voltage.vi, VNA_small_voltage.vi, figure A.13) in the folder specified by “Path for output files” that was created by “Create voltage folder.vi, figure A.7). Note that “VNA_big_voltage.vi” and “VNA_small_voltage.vi” are the same subVI, except that they output files with different extenstions (*.big, *.small) in order to differentiate the Hdc direction along which the measurement was made.
Figure A.13: VNA_small_voltage.vi.

The actual commands sent to the VNA are shown in figure A.14 (VNA_CONTROLcal_uncal2.vi).
The “applied voltage loop” FOR loop is repeated for all voltage values, for both field directions of “Sequence for direction of applied field” sequential loop, and for all the number of Hdc values of the “For loop for the DC field” FOR loop (the main FOR loop).

A.1.3 Shutdown of main VI

Once the measurements have been completed for all voltage values and for all Hdc fields along both directions, the main FOR loop is exited and the shutdown sequence stops the Kepco power supplies, the voltage source, and returns the VNA to local control (figure A.15).
A.2 Igor Pro code

Igor Pro is a powerful graphing and analysis software made by wavemetrics (http://www.wavemetrics.com/). The data in the graphs or the data browser of the program can be manipulated both through the graphical interface and through a command line window. I wrote a procedure file for this program. The file is a collection of routines that streamline the conversion of the recorded data into graphs of the relevant parameters, which are then suitable for data analysis. It is in part based on a similar MATLAB code written by Dragos Mircea. For more details and help with the code syntax, see the Igor Pro help files. Although there are no known bugs in the file, any person using this code does so at his/her own risk.

```plaintext
#pragma rtGlobals=1  // Use modern global access method.

//Lines preceded by two forward slashes “//” are comments.

///This function colors the first 8 traces in a graph different colors
```
function color(type, tracename, count)

    string tracename, type
    variable count
    string tuy = type

    if (count == 0)
        ModifyGraph/W = $tuy rgb($tracename) = (0, 0, 0) // black
    elseif (count == 1)
        ModifyGraph/W = $tuy rgb($tracename) = (39168, 39168, 39168) // grey
    elseif (count == 2)
        ModifyGraph/W = $tuy rgb($tracename) = (26112, 8704, 0) // brown
    elseif (count == 3)
        ModifyGraph/W = $tuy rgb($tracename) = (0, 65280, 0) // green
    elseif (count == 4)
        ModifyGraph/W = $tuy rgb($tracename) = (16384, 16384, 65280) // blue
    elseif (count == 5)
        ModifyGraph/W = $tuy rgb($tracename) = (65280, 16384, 55552) // magenta
    elseif (count == 6)
        ModifyGraph/W = $tuy rgb($tracename) = (65280, 43520, 0) // orange
    elseif (count == 7)
        ModifyGraph/W = $tuy rgb($tracename) = (57856, 49408, 1792) // dark yellow
    elseif (count == 8)
        ModifyGraph/W = $tuy rgb($tracename) = (65280, 16384, 16384) // red
    endif
end
// This function generates a graph or appends data to that graph if it already exists.

// The graph automatically generates a legend and a title that includes the date and the folder “Probe” from which the data was retrieved

function graph(tracename,count,title,type)
    string tracename ,title , type
    variable count
    wave freq0
    string tuy=type
    SVAR probe
    if (count>0)
        appendtograph/W=$tuy $tracename vs freq0
    else
        Display/N=$tuy $tracename vs freq0 as title
        legend/W=$tuy
        textbox/N=$tuy/F=0/A=mt/X=0/Y=0 title+"r "+ probe+" r "+ date()
    endif
end

// function to calculate calibration coefficients and display

// phase and log magnitude of probe after calibration

function calibrate(state)
    variable state //0 for calibrated data, 1 for raw data
    string power="5", average="35"  // These should be the actual values used during the measurement
    string/G probe="pprIII13" // This is the name of the folder which contains all the voltage data folders
    NewPath Data1 "c:Document and Settings:nopassword:Desktop:work:FMR:"+probe+":uncalibrated:"
Settings:nopassword:Desktop:work:FMR:"+probe+":uncalibrated:"
if (state==1)
    LoadWave/A=sht/J/D/Q/K=0/P=data1
"standards&probe:"+power+"dBm_"+average+"averages.short";
    LoadWave/A=opn/J/D/Q/K=0/P=data1
"standards&probe:"+power+"dBm_"+average+"averages.open";
    LoadWave/A=load/J/D/Q/K=0/P=data1
"standards&probe:"+power+"dBm_"+average+"averages.load";
    LoadWave/A=freq/J/D/Q/K=0/P=data1
"standards&probe:"+power+"dBm_"+average+"averages.probew";
WAVE/C Ed, Es, Er
        wavestats/Q freq0
        WAVE load1, load2, opn1, opn2, sht1, sht2
        killwaves load0, opn0, sht0
        Make/C/N=(V_npnts) Ed=cmplx(load1, load2)
        Make/C/N=(V_npnts) Es=(cmplx(opn1, opn2)+cmplx(sht1, sht2)-2*Ed)/(cmplx(opn1, opn2)-cmplx(sht1, sht2))
        Make/C/N=(V_npnts) Er=(1+Es)*(Ed-cmplx(sht1, sht2))
    else
    LoadWave/A=freq/J/D/Q/K=0/P=data
"standards&probe:"+power+"dBm_"+average+"averages.probe1";
        wavestats/Q freq0
        Make/C/N=(V_npnts) Ed=cmplx(0,0)
        Make/C/N=(V_npnts) Es=cmplx(0,0)
        Make/C/N=(V_npnts) Er=cmplx(1,0)
// execute if condition is FALSE
endif

WAVE freq1, freq2, freq0
WAVE/C Ed, Es, Er
Make/C/N=(V_npts) Reflection=(cmplx(freq1,freq2)-Ed)/(Er+Es*(cmplx(freq1,freq2)-Ed))
Make/C/N=(V_npts) angle1=Reflection
Make/C/N=(V_npts) angle
Make/C/N=(V_npts) mag1=Reflection
Wavetransform/O phase, angle1
Unwrap 2*pi, angle1
CurveFit/Q line, angle1 /X=freq0;
WAVE W_coef
angle=Reflection*exp(cmplx(0,-W_coef[1]*freq0))
duplicate/O angle, angle5, angle6
Wavetransform/O phase angle
Wavetransform/O magnitude mag1
Make/N=(V_npts) probe_S11=20*log(mag1)
Display/N=phase angle vs freq0 as "phase S11"
Label left, "phase angle (radians)"
Label bottom, "frequency (Hz)"
Display/N=magnitude probe_S11 vs freq0 as "log |S11|"
Label left, "amplitude (dB)"
Label bottom, "frequency (Hz)"
movewindow/M/W=magnitude 15,0,29,7.5
End
function S11(volts,average,field, folder1, size1, folder2, size2, state)

string volts, field, folder1, size1, folder2, size2, average

variable state

string power="5"", average="10"

variable V_npnts

WAVE/C Ed, Es, Er

if (state==1)
    LoadWave/J/D/Q/K=0/P=data1/A=trace1
    folder1+":"+volts+":"+power+"dBm"+average+"averages"+field+"Oe."+size1
else
    LoadWave/A=trace1/J/D/Q/K=0/P=data
    folder1+":"+volts+":"+power+"dBm"+average+"averages"+field+"Oe."+size1
endif

WAVE W_coef, trace11, trace12, freq0, mag01

wavestats/Q freq0;

if(waveexists(trace11)==0)
    abort
endif

Make/C/N=(V_npnts) Reflection1= (cmplx(trace11,trace12)-Ed)/(Er+Es*(cmplx(trace11,trace12)-Ed))*exp(cmplx(0,-W_coef[1]*freq0))

wavetransform magnitude, Reflection1

string size11, size21

if (stringmatch(size1,"small")==1)
size11="x"

else

size11="y"

endif

if (stringmatch(size2,"small")==1)

size21="x"

else

size21="y"

endif

Duplicate/O W_Magnitude, mag01; KillWaves W_Magnitude

string name_trace11=volts+"_"+folder1+"_"+field+"Oe_"+size11+"11"

string name_trace12=volts+"_"+folder1+"_"+field+"Oe_"+size11+"12"

string name_1S=volts+"_"+folder1+"_"+field+"Oe_"+size11+"S11"

string name_1S11=volts+"_"+folder1+"_"+field+"Oe_"+size11+"logS11"

Make/O/N=(V_npnts) LogReflection1=20*log(mag01)

if(waveexists(Sname_trace11)==1)

abort "wave already graphed"

endif

rename trace11, Sname_trace11

rename trace12, Sname_trace12

rename Reflection1, Sname_1S

rename LogReflection1, Sname_1S11

//graph1

string poo=tracenamelist("magnitude5",";",1)

variable count=itemsinlist(poo,";")

if (count>8)
count=count-8
endif

graph(name_1S11,count,size1+" log|S11|","magnitude5")
color("magnitude5",name_1S11,count)
if(count==0)
appendtograph/W=magnitude5 probe_S11 vs freq0
endif

killwaves trace10
if(strlen(folder2)!=0)
  if (state==1)
    LoadWave/A=trace2/J/D/Q/K=0/P=data1
    folder2+":"+volts+":"+power+"dBm_"+average+"averages_"+field+"_Oe."+size2
  else
    LoadWave/A=trace2/J/D/Q/K=0/P=data
    folder2+":"+volts+":"+power+"dBm_"+average+"averages_"+field+"_Oe."+size2
  endif
WAVE trace21, trace22, mag02
Make/C/N=(V_npnts) Reflection2= (cmplx(trace21,trace22) -Ed)/(Er+Es*(cmplx(trace21,trace22)-Ed))*exp(cmplx(0,-W_coef[1]*freq0))
wavetransform magnitude, Reflection2
Duplicate/O W_Magnitude, mag02; KillWaves W_Magnitude

string name_trace21=volts+"_"+folder2+"_"+field+"_Oe."+size21+"11"
string name_trace22=volts+"_"+folder2+"_"+field+"_Oe."+size21+"12"
string name_2S=volts+"_"+folder2+"_"+field+"_Oe."+size21+"S11"
string name_2S11=volts+"_"+folder2+"_"+field+"_Oe."+size21+"logS11"
Make/O/N=(V_npnts) LogReflection2=20*log(mag02)
rename trace21, $name_trace21
rename trace22, $name_trace22
rename Reflection2, $name_2S
rename LogReflection2, $name_2S11
//graph2
poo=tracenamelist("magnitude2",";",1)
count=itemsinlist(poo,";")
if (count>8)
count=count-8
endif
graph(name_2S11,count,size2+" log|S11|","magnitude2")
color("magnitude2",name_2S11,count)
movewindow/M/W=magnitude2 15,0,29,7.5
killwaves trace20
if(count==0)
appendtograph/W=magnitude2 probe_S11 vs freq0
endif
endif
end
//
//displays real part of impedence Z
//
function ReZ(volts,field,folder1,size1, folder2, size2,state)
variable state
string volts, folder1, field, size1, folder2, size2
string size11, size21

if (stringmatch(size1,"small")==1)
    size11="x"
else
    size11="y"
endif

if (stringmatch(size2,"small")==1)
    size21="x"
else
    size21="y"
endif

variable V_npnts

string name_1S=volts+"_"+folder1+"_"+field+"Oe_"+size11+"S11"

string name_1Z=volts+"_"+folder1+"_"+field+"Oe_"+size11+"ReZ"

wave freq0, '$name_1S', angle5

if(waveexists($name_1S)==0)
    abort name_1S" does not exist. Check parameters or try running S11(field,folder,state) for corresponding field."
endif

if(waveexists($name_1Z)==1)
    abort "wave already graphed"
endif

wavestats/Q freq0;

duplicate/O $name_1S, bigS

make/N=(V_npnts) Z1=real(50*(1+bigS)/(1-bigS))

rename Z1, $name_1Z
//big graph

string poo=tracename(list("ReZ1",";",1)

variable count=itemsinlist(poo,";")

if (count>8)
    count=count-8
endif

graph(name_1Z,count,size1+" Re[Z]","ReZ1")
color("ReZ1",name_1Z,count)

if(count==0)
    make/N=(V_npnts) probe_ReZ=real(50*(1+angle5)/(1-angle5))
    appendtograph/W=ReZ1 probe_ReZ vs freq0
endif

if(strlen(folder2)!=0)
    string name_2S=volts+_folder2+_field"Oe_"+size2"S11"
    string name_2Z=volts+_folder2+_field"Oe_"+size2"ReZ"
    wave '$name_2S'
    if(waveexists($name_2S)==0)
        abort name_2S+" does not exist. Check parameters or try running S11(field,folder,state) for corresponding field."
    endif
    if(waveexists($name_2Z)==1)
        abort "wave already graphed"
    endif
    duplicate/O $name_2S, smallS
    make/N=(V_npnts) Z2=real(50*(1+smallS)/(1-smallS))
    rename Z2, $name_2Z
//small graph
poo=tracenamelist("ReZ2",";",1)
count=itemsinlist(poo,";")
if (count>8)
count=count-8
endif

graph(name_2Z,count,size2+" Re\[Z\]","ReZ2")
color("ReZ2",name_2Z,count)
movewindow/M/W=ReZ2 15,0,29,7.5
if(count==0)
appendtograph/W=ReZ2 probe_ReZ vs freq0
endif
endif
end

//
//displays imaginary part of impedance Z
//
function ImZ(volts,field,folder1,size1, folder2, size2,state)
variable state
string volts, folder1, field, size1, folder2, size2
string size11, size21
if (stringmatch(size1,"small")==1)
size11="x"
else
size11="y"
endif

if (stringmatch(size2,"small")==1)
size21="x"
else
size21="y"
endif

variable V_npnts
string name_1S=volts+"_"+folder1+"_"+field+"Oe_"+size11+"S11"
string name_1Z=volts+"_"+folder1+"_"+field+"Oe_"+size11+"ImZ"
wave freq0, '$name_1S', angle5
if(waveexists($name_1S)==0)
abort name_1S+" does not exist. Check parameters or try running S11(field,folder,state) for corresponding field."
endif
if(waveexists($name_1Z)==1)
abort "wave already graphed"
endif
wavestats/Q freq0;
duplicate/O $name_1S, bigS
make/O/N=(V_npnts) Z1=imag(50*(1+bigS)/(1-bigS))
rename Z1, $name_1Z
//big graph
string poo=tracenamelist("ImZ1", ";", 1)
variable count=itemsinlist(poo,";")
if (count>8)
count=count-8
endif

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graph(name_1Z,count,size1+" Im[Z]","ImZ1")

color("ImZ1",name_1Z,count)

if(count==0)
    make/O/N=(V_npnts) probe_ImZ=imag(50*(1+angle5)/(1-angle5))
    appendtograph/W=ImZ1 probe_ImZ vs freq0
endif

if(strlen(folder2)!=0)
    string name_2S=volts+"_"+folder2+"_"+field+"Oe_"+size21+"S11"
    string name_2Z=volts+"_"+folder2+"_"+field+"Oe_"+size21+"ImZ"
    wave '$name_2S'
    if(waveexists($name_2S)==0)
        abort name_2S+" does not exist. Check parameters or try running S11(field,folder,state) for corresponding field."
    endif
    if(waveexists($name_2Z)==1)
        abort "wave already graphed"
    endif

    duplicate/O $name_2S, smallS
    make/O/N=(V_npnts) Z2=imag(50*(1+smallS)/(1-smallS))
    rename Z2, $name_2Z

    //small graph

    poo=tracenamelist("ImZ2",","1)
    count=itemsinlist(poo,"","")
    if (count>8)
        count=count-8
    endif
graph(name_2Z,count,size2+" Im[Z]","ImZ2")

color("ImZ2",name_2Z,count)

movewindow/M/W=ImZ2 15,0,29,7.5

if(count==0)
    appendtograph/W=ImZ2 probe_ImZ vs freq0
endif
endif
end

//
//displays real part of relative permittivity mu
//
function ReMu(volts,average,field,folder1,size1, folder2, size2,state)
    variable state
    string volts, folder1, field, size1, folder2, size2,average

    variable V_npnts

    string size11, size21

    if (stringmatch(size1,"small")==1)
        size11="x"
    else
        size11="y"
    endif

    if (stringmatch(size2,"small")==1)
        size21="x"
    else
        size21="y"
    endif
end
string name_1S=volts+"_"+folder1+"_"+field+"Oe_"+size11+"S11"
string name_1Z=volts+"_"+folder1+"_"+field+"Oe_"+size11+"measZ"
string name_2S=volts+"_"+folder2+"_"+field+"Oe_"+size21+"S11"
string name_2Z=volts+"_"+folder2+"_"+field+"Oe_"+size21+"baseZ"
string name_ReMu=volts+"_"+folder1+size11+folder2+size21+"_"+field+"Oe_Remu"
//string name_2S=volts+"_"+folder2+"_"+field+"Oe_"+size21+"S11"
//string name_2Z="0"+"_"+folder2+"_"+field+"Oe_"+size21+"baseZ"
//string name_ReMu=volts+"_"+folder1+size11+folder2+size21+"_"+field+"Oe_Remu"
wave freq0, '$name_1S', angle5,'$name_2S', base, signal
if(waveexists($name_1S)==0)
  abort name_1S+" does not exist. Check parameters or try running S11("+field+","+folder1+","+size1+"",state) for corresponding field."
endif
if(waveexists($name_2S)==0)
  abort name_2S+" does not exist. Check parameters or try running S11("+field+","+folder2+","+size2+"",state) for corresponding field."
endif
wavestats/Q freq0;
wave '$name_1Z', '$name_2Z', bigS, smallS
if (waveexists($name_1Z)==0)
duplicate/O $name_1S, bigS
make/C/O/N=(V_npnts) Z1=50*(1+bigS)/(1-bigS)
rename Z1, $name_1Z
endif
if (waveexists($name_2Z)==0)
duplicate/O $name_2S, smallS
endif
149
make/O/N=(V_npnts) Z2=50*(1+smallS)/(1-smallS)

rename Z2, $name_2Z

endif
duplicate/O $name_1Z, signal
duplicate/O $name_2Z, base

variable mu0=4*pi*10^(-7)

make/O/N=(V_npnts) MuReal=real((signal-base)/cmplx(0,2*pi*100*10^-9*freq0*mu0))

if(waveexists($name_ReMu)==1)
abort "wave already graphed"
endif

rename MuReal, $name_ReMu

//graph
string poo=tracenamelist("RealMu",";",1)
variable count=itemsinlist(poo,";")
if (count>8)
count=count-8
endif

graph(name_ReMu,count," Re[Mu]","RealMu")
color("RealMU",name_ReMu,count)
movewindow/M/W=RealMu 7.5,5,21.5,12.5
end

//
//displays imaginary part of relative permittivity mu

function ImMu(volts,average,field,folder1,size1, folder2, size2,state)

variable state

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string volts, folder1, field, size1, folder2, size2, average

variable V_npnts

string size11, size21
if (stringmatch(size1,"small")==1)
size11="x"
else
size11="y"
endif
if (stringmatch(size2,"small")==1)
size21="x"
else
size21="y"
endif

string name_1S=volts+"_"+folder1+"_"+field+"Oe_"+size11+"S11"
string name_1Z=volts+"_"+folder1+"_"+field+"Oe_"+size11+"measZ"
string name_2S=volts+"_"+folder2+"_"+field+"Oe_"+size21+"S11"
string name_2Z=volts+"_"+folder2+"_"+field+"Oe_"+size21+"baseZ"
string name_ImMu=volts+"_"+folder1+size1+folder2+size2+"_"+field+"Oe_Immu"

//string name_2S=volts+"_"+folder2+"_"+field+"Oe_"+size21+"S11"
//string name_2Z="0"+"_"+field+"Oe_"+size21+"baseZ"
//string name_ImMu=volts+"_"+folder1+size1+folder2+size2+"_"+field+"Oe_ImM"

wave freq0, '$name_1S', angle5,'$name_2S', base, signal
if(waveexists($name_1S)==0)
abort name_1S+" does not exist. Check parameters or try running
S11("_"+field+"_"+folder1+"_"+size1+"_",state) for corresponding field."
endif

if (waveexists($name_2S)==0)
    abort name_2S+" does not exist. Check parameters or try running S11("+field+","+folder2+","+size2+",,,state) for corresponding field."
endif

wavestats/Q freq0;
wave 'Sname_1Z', 'Sname_2Z', bigS, smallS
if (waveexists($name_1Z)==0)
duplicate/O $name_1S, bigS
make/C/O/N=(V_npnts) Z1=50*(1+bigS)/(1-bigS)
rename Z1, $name_1Z
endif
if (waveexists($name_2Z)==0)
duplicate/O $name_2S, smallS
make/C/O/N=(V_npnts) Z2=50*(1+smallS)/(1-smallS)
rename Z2, $name_2Z
endif
duplicate/O $name_1Z, signal
duplicate/O $name_2Z, base
variable mu0=4*pi*10^-7
make/O/N=(V_npnts) MuImaginary=-imag((signal-base)/cmplx(0,2*pi*100*10^-9*freq0*mu0))
if(waveexists($name_ImMu)==1)
abort "wave already graphed"
endif
rename MuImaginary, $name_ImMu

//graph
string poo=tracenameList("ImagMu",";",1)

variable count=itemsinlist(poo,";")

if (count>8)
    count=count-8
endif

graph(name_ImMu,count,"Im[Mu]","ImagMu")
color("ImagMu",name_ImMu,count)
movewindow/M/W=ImagMu 15,5,29,12.5
end

/// function that displays the difference between the log|S11| traces specified by folder1-size1 and
/// folder2-size2
function deltaS(volts, field, folder1, size1, folder2, size2, state)
string volts, field, folder1, folder2, size1, size2
variable state
string size11, size21

if (stringmatch(size1,"small")==1)
    size11="x"
else
    size11="y"
endif

if (stringmatch(size2,"small")==1)
    size21="x"
else
    size21="y"
endif

string name_1S11=volts+"_"+folder1+"_"+field+"Oe_"+size11+"logS11"
string name_2S11=volts+"_"+folder2+"_"+field+"Oe_"+size21+"logS11"

// string name_2S11=volts+"_"+folder2+"_0Oe_"+size21+"logS11"

string delta_1S2S=volts+"_"+"Delta"+folder1+size11+folder2+size21+field+"Oe1"

if(waveexists($delta_1S2S)==1)
    abort 'wave already graphed'
endif

wave freq0
wavestats/Q freq0;

wave '$name_1S11', '$name_2S11', wave1, wave2

if(waveexists($name_1S11)==0)
    abort name_1S11+" does not exist. Check parameters or try running S11("+field+","+folder1+","+size1+",",,state) for corresponding field."
endif

if(waveexists($name_2S11)==0)
    abort name_2S11+" does not exist. Check parameters or try running S11("+field+","+folder2+","+size2+",",,state) for corresponding field."
endif

duplicate/O $name_1S11, wave1
duplicate/O $name_2S11, wave2

make/O/N=(V_npnts) delta=wave1-wave2
rename delta, $delta_1S2S

string poo=tracename(list("deltaS11",";",1)
variable count=itemsinlist(poo,";")

if (count>8)
    count=count-8
endif
References
