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Monolithically Integrated Non-Reciprocal Devices Based on Magnetic Thin Films

Gregory Hartman
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Monolithically integrated non-reciprocal devices based on magnetic thin films

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering

By

GREGORY C. HARTMAN
B.S., University of Pittsburgh, 2009

2013
Wright State University
I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Gregory C. Hartman ENTITLED Monolithically integrated non-reciprocal devices based on magnetic thin films BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science in Engineering.

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ABSTRACT


For years technology developers have been reassessing current technology for ways to cut size and cost while maintaining or improving performance. One particular area that continues to grow in importance, yet remains difficult to reassess, are nonreciprocal devices. Components such as isolators and circulators are typically constructed using ferrite materials and permanent magnets; unfortunately, due to size and material properties, those materials are poor choices when attempting to scale down.

The following experiments investigate the ferromagnetic material NiFe and various patterning methods as potential solutions to the scaling and cost questions driven by modern technology requirements. NiFe is of interest since it can be fabricated using standard photolithography techniques, exploited to prevent conduction, and maintain a magnetic field without a permanent magnet. Line width, line length, spacing between lines, device placement, NiFe thickness, and patterning parameters for a coupled transmission line are manipulated through fabrication and then characterized. Results are scrutinized for nonreciprocal tendencies and ferromagnetic resonance peak locations. A shift of 1 GHz was found when NiFe thickness increased. Nonreciprocal characteristics were also enhanced when space between the coupled lines decreased, resulting in a 350MHz shift. Designs that offered promising results will assist with determining the direction of future experiments.
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I. INTRODUCTION AND BACKGROUND

Evolution of electronic devices has progressed at an extraordinary rate over the past 60 years. Devices such as cameras, GPS, phones, music & movie players that used to be separate entities are now packed into all-in-one contraptions that remarkably still have the capacity to make phone calls while fitting in a hip pants pocket. It’s because of the scaling of digital electronics that made such a wide integration possible. In turn, these amalgamations created a society with a constant need to share and acquire media over the Internet. It’s an ability that becomes more difficult each day as demand for connectivity grows.

Unfortunately, RF integrated circuit technology has significant difficulty maintaining the same pace as its digital counterpart. There are numerous considerations that go into component design and layout of RF circuits, most of which require extensive exploration and research [1]. The objective of this thesis is to test various device conditions for nonreciprocity using a coupled transmission line and patterned NiFe thin films. Hopefully this will lead into one aspect of RF circuits, particularly the nonreciprocal device: isolators and circulators, being realized on-chip. Isolators are a two-port system, typically a three port circulator with one port blocked, that transmits RF waves in one direction and absorbs in the other, Figure 1.1-(A). They are usually employed to protect a system from outside mismatched loads [2]. Circulators are three or four port devices that permit RF waves to enter from one port and then pass them to the next port through rotation; a particular application would be at an antenna used for both transmitting and receiving purposes Figure 1.1-(B) & (C). The issue with these devices, in terms of scaling, is that they have been designed around the use of ferrite cores and
permanent magnets for the past 60 years. Reviewing the history of these devices will provide a better understanding as to why it is only until recently that interest has grown to explore alternate methods of applying nonreciprocal device theory.

Ferrites of modern day were first studied towards the end of World War II by a Philips Laboratory team led by J.L. Snoek [3]. His team was interested in finding out how loss and magnetic properties of synthetic ferrite materials were influenced by their production, preparation, and composition. Snoek found magnetic loss rose as a function of frequency and that materials of a high permeability were an issue for low-loss operations in the higher frequency range. Soon after in 1947, Kittel provided an explanation for spin resonance using classical equations for motion to describe magnetic dipoles and account for the internal magnetic field.

With this information, new investigations in magnetics and ferrites began to flourish. Applications for the discoveries were used to exploit the Faraday effect for electromagnetic waves. In 1952, C. L. Hogan created a microwave gyrator based off of Faraday rotation [3]. The Faraday rotator made it possible to study rotation, loss, resonance, and nonreciprocity in waveguides; thus, providing the grounds for the development of phase shifters, one-way transmission lines, and circulators. Lax, Button, and Roth theorized a nonreciprocal phase shifter in 1954. A year later, Fox, Miller, and
Weis demonstrated the first isolator utilizing nonreciprocal attenuation in a waveguide. Around 1957, Schaug-Pettersen discussed the idea of a three-port Y-junction waveguide circulator, which was later created by Chait and Curry in 1958 [4]. It turned out to be much more compact than circulators designed using Faraday rotation and it initiated a take-off in microwave circuit design. The more innovative stripline circulator, based on a ferrite puck and permanent magnet, came to fruition in 1959.

The properties of circulator devices were soon redefined in terms of scattering matrix parameters and required conditions for operation. In the 1960’s, Fay and Comstock found that stripline circulators work as a result of resonances coupling between dielectric modes in the ferrite layer [4]. They also determined that the diagonal elements of a ferrite’s tensor permeability are the key to understanding nonreciprocal wave propagation. Armed with this information, Hershenov was able to develop the first microstrip circulator in 1966. His design, still requiring a fixed permanent magnet, lead to the integration of isolators and circulators with microelectronics in the form of “drop-in” lumped elements, thereby providing hybrid circuit components, Figure 1.2. Due to a boom in the semiconductor industry, Goodman was able to demonstrate the first latching/switching based circulator, which offered a work-around to integrate the devices on a chip level.

Drop-in lumped elements and switching devices have mostly been the standard since their inception. Unfortunately both types can’t keep up with modern technology requirements. Switching circulators and isolators tend to be slower than lumped elements, have a lower life expectancy, and produce intermodulation products if more than one frequency is present [5]. Lumped elements can meet the demands for performance;
however, they still depend on a permanent magnet to saturate the ferrite layer. This is not just an issue for scaling, but also the fabrication of integrated circuits using ferrites. As a result, this drives a question that plagues industry employing microwave technology today: ‘how do we get the performance of a lumped element circulator or isolator in a monolithic circuit without the associated size, weight, and cost that’s comes with lumped components?’

Figure 1.2 - (A) Internal overview of “drop-in” lumped circulator (B) typical package [2]

Considering that switching circulators are fairly intricate and complicated to fabricate, many have begun to reassess the materials of lumped components. Ferrite materials often entail hot/cold rolling, forging, sintering, drawing, or swaging [6]. They also require a high temperature heat treatment, in the range of 500°-900°C, to relive internal strain and achieve high permeability levels. Temperatures in this range have the capability to diffuse wafer dopants and ion implantations of integrated circuits; therefore,
such processing becomes an issue when attempting a monolithic approach for ferrite-based devices [4].

Fortunately, there are alternatives to ferrite materials that may provide an answer. Ferrites belong to a group of materials the unique property of being composed of magnetic domains, otherwise known as Weiss domains, Figure 1.3 [2]. Each domain, ranging in size from 1-100 µm, within a material is inherently magnetized due to spin motion of unpaired electrons [3]. When in the presence of an external magnetic field, the dipole moments align; thus, providing an overall magnetization for the material.

![Figure 1.3 - Randomly pointed dipoles, otherwise known as Weiss domains](image)

There exists a similar group of materials, there are a handful of element combinations that their domains tend to self-align at room temperature [3]. The magnetization strength after self-alignment greatly depends on the lattice structure. In the case of ferrites, there are two magnetic sublattices that are anti-parallel, Figure 1.4-(A) [3,7]. The lattices do not fully cancel one another out; thus, resulting in a slight level of magnetization (ferrimagnetism). Materials used in the making of ferrimagnetic devices are typically combinations of Fe₂O₃ with one of the following: Mn, Fe, Co, Ni, Cu, and Zn.

A second category in the paramagnetic group, one that’s of interest for designing monolithic nonreciprocal devices, is ferromagnetics. These materials have a single
sublattice where all magnetic moments are pointing in the same direction, Figure 1.4-(B) [8, 7]. As a result, the domains can self align and provide a net magnetization much greater than that of a ferrite; they even have the potential to reach magnetic saturation without the assistance of an external DC field. The majority of ferromagnetic materials are alloys comprised of Fe, Co, or Ni.

![Figure 1.4 - (A) Two magnetic sublattices of a ferrimagnet [3, 7] (B) single sublattice structure of a ferromagnet [8, 7].](image)

When placed in a DC magnetic field, both ferrimagnets and ferromagnetics can achieve a strong magnetization. Ferromagnetics offer the potential to remove the need for an external magnetic field; however, the one factor keeping ferrites in use is their inherent high resistivity resulting from being an oxide [7]. This factor allows ferrite circulators and isolators to manipulate the magnetic fields of RF waves at most frequencies with minimal worry of the device promoting conduction. On the other hand, ferromagnets are normally conductive; thus, these materials have been a lesser choice for nonreciprocal device research [1, 4].
In order to keep up with the requirements of modern technology, ferromagnetic (FM) materials are being reassessed. The fabrication of ferrites for on-chip use remains an issue, but ferromagnetics can be patterned using current semiconductor fabrication equipment and procedures [9]. By neglecting conduction and solving for the general wave equation in the materials, it’s even possible to minimize conductive losses [1]. Altering film thickness, device placement (magnetization is strongest along the edges), ferromagnetic film patterns (creating multiple edge interfaces), and device dimensions provide potential to amplify wave dispersion in nonreciprocal devices for various frequencies and propagation constants [2, 10, 11]. Minimal work has been done conducted to investigate the ideal parameters required to enhance dispersion using ferromagnetic materials. Creating test devices and characterizing the effects resulting from various patterning methods is the primary goal of the study. Experiment outcomes can then be carried over into other nonreciprocal device applications such as isolators, circulators, resonators, and phase shifters. Gaining a deeper understanding of ferromagnetic materials will assist with evolving discrete nonreciprocal hybrid components into low cost on-chip devices.

II. THEORY AND PROPOSED METHOD OF INVESTIGATION

Spin Resonance

It becomes easier to gain an understanding of magnetic dipoles if the assumption is made that a spinning electron is a charged spinning mass that’s similar to a gyroscope. Also when a permanent DC magnetic field ($H_o$) is applied, it’s equivalent to gravity acting on a top [3, 12]. From the perspective of a top, precessional motion occurs around
a gravitational axis. The frequency of precession is influenced by the top’s momentum (torque) spinning around that axis. In the case when an RF magnetic field ($h_x$) is applied perpendicular to a fixed DC field, the resulting torque will give the top/spinning electron a lateral force and change the magnitude of the magnetization ($m$), Figure 2.1. The overall magnetization can be found by multiplying the gyromagnetic factor by the torque (the cross-product between magnetization $M$ and magnetic fields $H$) in the Landau-Lifshitz-Gilbert equation, which is explained later.

![Figure 2.1 - Spinning charged mass precessing about a fixed DC magnetic field/axis $H_o$ with lateral force $h_x$ and magnetization $m$](image)

There exists a multitude of magnetic dipoles in a paramagnetic material that will align to an applied magnetic field ($H_o$), thereby forcing them all to have the same natural precession frequency ($\omega_o$) [2, 3]. When an RF wave is being transmitted, the magnetic field is picked up by the dipoles. The dipoles then follow the phase of this wave, Figure 2.2 [1,3]. When multiple dipoles are tracking to the phase it permits a magnetostatic wave to propagate across the surface of a magnetic material, Figure 2.3. The natural precession frequency is one aspect that will be of great interest during experimentation; altering it can provide a better understanding of what FM patterns and device layouts suite various frequencies best and provide enhanced nonreciprocal characteristics. In order to find those frequencies, a condition known as resonance must be induced.
Resonance is when an applied RF magnetic field (\(\omega\)) matches the natural precession frequency (\(\omega_o\)) of a magnetic dipole. When such an event occurs, the energy from the applied field is absorbed by the dipole. The energy causes the precession magnitude to increase until stabilization, Figure 2.4 (B) [3]. In the case of an applied \(\omega\) that does not match \(\omega_o\), the dipole will oscillate from the resulting modulation products, Figure 2.4 (C). Energy can still be absorbed; however, it will be with a greatly reduced efficiency since the magnetization vector will be in-phase and out-of-phase, Figure 2.4-(C).
Figure 2.4 (A) Precession of a dipole moment at steady state. (B) When in a DC magnetic field, the magnetization vector grows in amplitude if an applied RF magnetic wave equals the natural precession frequency. (C) Applied RF wave does not match the natural precession frequency. Oscillating component, $\omega$, superimposed on the steady-state precessional motion over a sphere [3].

When discussing magnetization and magnetostatic waves in real world applications, it’s necessary to account for losses the dipoles contributed throughout the FM material. The primary and most comprehensive method to calculate loss in ferrites is to use the Landau-Lifshitz-Gilbert (LLG) equation (1) [1, 3]. The LLG equation calculates the magnetization while including factors for spin energy transfer ($\alpha$) and loss inherent to the internal DC magnetic field [3]. The relaxation or “Gilbert” constant ($\alpha$) represents energy loss attributed to the relaxation of spins from the uniform precessional mode. The effective magnetic field ($H_{\text{eff}}$) covers the externally affixed magnetic field, the internal magnetocrystalline anisotropy field (dipoles have a preferential alignment with respect to crystal structure), and the demagnetization resulting from boundary conditions for the patterned magnetic film ($H_{\text{eff}}$) [3].

$$\frac{\partial M}{\partial t} = -\gamma M \times H_{\text{eff}} - \frac{\alpha}{|M|} M \times \frac{\partial M}{\partial t},$$  

(1)
Demagnetization factors have a significant role in the internal DC magnetic field since the magnetic film region is finite [3]. When a FM film is exposed to a static magnetic field, aligning dipoles within the material, it becomes polarized; therefore, it results in an internal field component that opposes the static DC field, Figure 2.3. Subtracting the measured demagnetizing factor from the externally induced field results in the internal magnetic field value, which is then used as the magnetic field value in all calculations. Demagnetization is most noticeable at the edges of a patterned magnetic region, while positions more centered will receive a more uniform field. This characteristic is planned for use in later experiments by increasing the number of patterned rectangular planes.

Fortunately for the experimenter, the power levels required to investigate nonreciprocity effects of integrated FM materials are low enough that it allows the LLG equation to be linearized [1]. When under the assumption of a time-varying input and performing small-signal analysis, it becomes easier to directly describe magnetization as susceptibility and permeability tensors. Analyzing the magnetic region as a collection of magnetic moments, it’s now possible to calculate a FM material’s magnetization (M) over an entire region [3]. Equation (2) then provides a method to relate the time-varying external magnetic field (h_{ext}) and magnetization vectors (m) to the susceptibility tensor “χ.” In turn, the general permeability tensor “µ” for a magnetic material can be found using “χ” and equation (3), where I is a unit tensor and µ_{0} is the permeability along the easy axis or axis of alignment. Showing frequency dependence for a magnetostatic wave is done with equation (4), which gives µ with respect to the saturation magnetization.
frequency ($\omega_M$) and the frequency ($\omega_H$) resulting from the combination of the external DC field, applied time-varying magnetic field, and dampening factor ($\alpha$). Magnetostatic waves will be propagating perpendicular to the lines of transmission; therefore, the transverse permeability is given in equation (5) and the ferromagnetic resonance condition in equation (6). These equations are critical to solving for propagation constant “k,” thereby allowing for later derivation of the necessary Z-parameters for use in software simulations.

\[
\hat{\mu} = \frac{\omega}{\chi} \hat{h}_{ext} \tag{2}
\]

\[
\hat{\mu} = \mu_a (\hat{I} + \hat{\chi}) = \mu_0 \begin{bmatrix} \mu & i\mu_a & 0 \\ i\mu_a & \mu & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}
\]

\[
\mu = \frac{\omega H (\omega H + \omega_M) - \omega^2}{\omega H^2 - \omega^2} \tag{4}
\]

\[
\mu_a = \frac{\omega \omega_M}{\omega H^2 - \omega^2} \tag{5}
\]

\[
\omega_{FM} = \sqrt{\omega_H (\omega_H + \omega_M)} \tag{6}
\]

\[
\omega_M = \gamma M_0, \quad \omega_H = \gamma H_a + i\alpha \omega \tag{7}
\]

Device Principles and Operation

The intent of this experiment is to gain a better understanding of nonreciprocal behavior in integrated ferromagnetic thin films. A device that produces the desired nonreciprocal effect is a set of coupled microstrip transmission lines acting as antennae, placed in a two port configuration over a thin layer of ferromagnetic (FM) material, Figure 2.5 [3, 9]. A DC magnetic field is parallel to the major axis of the FM material, thereby resulting in the creation of an easy axis (parallel to the antenna) and a hard axis (perpendicular to the antenna). One line is used to transmit magnetostatic waves and the other antenna receives propagating waves. Waves will propagate in opposing directions.
perpendicular to the strip lines across the top and bottom of FM film surfaces, Figure 2.3 [9].

Figure 2.5 - Coupled transmission line proposed to investigate nonreciprocal behavior [9]

Nonreciprocity is induced when a metallic ground plane is introduced below the antennae to short circuit the devices, causing a break up in the field distribution symmetry of propagating surface waves, Figure 2.6 [1]. Dispersion will result from the lack of symmetry, thus giving the signals different propagation constants (k). Designing a device to work at resonance with a particular “k” value will lead to absorption of signals having the associated propagation constants. Unabsorbed waves will then be received by nearby antennae.
Since a ferromagnetic material will be used as the magnetic layer, it’s also important to understand how conduction and loss can be avoided. The key is to neglect conduction (8) when solving for the relative permeability and a propagating wave in the x and x directions through the materials as shown in Figure 2.6 (A) [1]. Neglecting conduction permits the integration of the magnetic field to equal zero, which then allows for the definition of a magnetic scalar potential \( \Psi \) in (9). In equation (9), \( A \) and \( B \) are constants, \( k_x \) and \( k_z \) are wave vector values. Deriving the general equation describing a propagating wave through a magnetic substance (10), where \( (\theta) \) is the angle of propagation with respect to the easy axis, it then becomes possible to predict loss for varying wave conditions. Considering a magnetostatic wave can be a complex quantity (9), each component is considered and tested using (10). In the case of a (volume) wave propagating in x, y, and z direction, the frequency range \( \omega \) is revealed in equations (11).

If the (surface) wave propagates only in the x and z direction then (12) is the resulting frequency range. Figure 2.7 better represents the ranges found for each component tested. Operating below ferromagnetic resonance will occur if the wave propagates through the volume of the magnetic material, resulting in conductive losses. Solving (10) for no propagation through the material volume, surface waves only, provides a frequency range that offers operation without conductive loss. Employing an above resonant frequency permits waves to propagate across a material and avoid signal attenuation.

\[
\nabla \times \vec{H} = 0, \quad \vec{H} = \nabla \Psi
\]

\[
\Psi = (Ae^{i\gamma y} + Be^{-i\gamma y})e^{-jk_x x - jk_z z}
\]

\[
\tan \xi d = \frac{2 \sin(\mu)\sqrt{\mu^2 \sin^2 \theta + \cos^2 \theta}}{(\mu^2 - \mu^2) \sin^2 \theta - \mu \cos^2 \theta - 1}
\]
III. PLANNED EXPERIMENT AND EXECUTION

Previous experiments have been performed using 20μm wide antennas with a spacing of 100μm between edges, NiFe film thicknesses ranging from 50nm- 500nm, and a SiO₂ insulation layer of 1μm [9]. The results concluded a 200μm NiFe film provided the most noticeable nonreciprocal response. Lower thicknesses showed weaker responses, while thicknesses at the higher end were claimed to almost have nonreciprocity vanish. Reducing the separation between the ground plane and FM layer was suggested to enhance nonreciprocity.

Intending to conduct a more rounded out investigation, the proposed experiment will include tests for device placement, line widths, line lengths, transmission line spacing, strips of NiFe with varied spacing, and varied NiFe thicknesses. Table 3.1 contains proposed values for these factors. Figure 3.1 contains a CAD screenshot of

\[
\begin{align*}
\omega_H & \leq \omega \leq \sqrt{\omega_H (\omega_H + \omega_M)} \\
\sqrt{\omega_H (\omega_H + \omega_M)} & \leq \omega \leq \sqrt{\frac{2\omega_H^2 + \omega_M^2 \sin^2 \theta + \omega_H \omega_M (H \sin^2 \theta) }{2}}
\end{align*}
\]
various planned devices on a ground plane. Devices are arranged in six rows with up to ten devices in each row.

<table>
<thead>
<tr>
<th>NiFe Thickness: 0.2/0.3/0.4 (µm) -- Line Length 1000/2000(µm)</th>
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<td><strong>Row/Dev</strong></td>
<td><strong>Line width (µm)</strong></td>
</tr>
<tr>
<td>x_0/y_0 &amp; x_1/y_1</td>
<td>20/50</td>
</tr>
</tbody>
</table>

Table 3.1 - Proposed device configurations for testing

Figure 3.1. Layout for devices (ordered from left to right) 1/2, 1/6, 1/7, 1/8, and 1/9. Ground plane has been moved to provide a clearer image.

Upon completion of device fabrication portion, devices are then characterized at Wright State University in the Microwave laboratory. In order to improve characterization and analysis, a permanent magnet with field strength of about 300 Oersted is used to distribute the magnetization more evenly across the ferromagnetic (NiFe) plane. This will increase magnetostatic surface wave propagation, thereby easing the identification of peaks of coupling. Two-port measurements are collected in the form of S-parameters. Collected data can then be later used for comparison against software simulations and direct future experiment designs.
Fabrication Procedures

Equipment and procedures are outlined in the following pages. Fabrication of the nonreciprocal devices proved to be a unique learning experience in both patience and technique. The procedures involved typically require weeks to months to fully develop in order to yield large quantities and high quality devices. Much of the processing entailed wet etching materials using rough guidelines for time, which resulted in fair results. Fortunately, a number of functioning devices were created that provided sufficient data for discussion.

Equipment:

MA6 - Mask Aligner – Exposed photoresist covered wafers

Spinner – Used to deposit liquid coatings; photoresist

Plasma Asher – used to remove photoresist and solvents present on wafers

Sputtering system – Sputtered NiFe and Al layers

Evaporator – Evaporated Au and Ti layers

PECVD- deposited thermal SiO₂ layer

Curve tracer w/ probe station – used to verify device connectivity

Hotplate

Mask – glass plate with positive or negative image of desired patterns

Chemicals:

Etchants:

BOE:DI - Buffer Oxide Etch; used to etch SiO₂ and Ti in 1:1 mixture

KI- Potassium Iodide – used to etch Au

HCL:HNO₃:H₂O₂ – used to etch NiFe in 1:1:1 mixture
HPO₄:H₂O₂:DI - used to etch Al in 8:1:1 mixture

3012 PR - Photoresist

Acetone – used to strip photoresist

Isopropyl – used after acetone to remove remaining solvent

351 Developer – used to develop resist post-exposure

DI H₂O – De-ionized water

Materials:

Si substrate – 3” p-type wafers

Al

Au

NiFe

Teflon beakers/container/wafer baskets

Equipment & Photoresist Concepts

**Spinner:**

The user affixes a wafer to the vacuum chuck and spins the wafer at a prescribed RPM level. A spin time of 30s was used for the application of 3012 resist in the processing described. Spin rates are used to determine photoresist thickness.

**Mask Aligner:**

The mask aligner provides the means to expose a photoresist. A mask is loaded into the mask holder and then placed underneath a microscope. The wafer is set onto a vacuum chuck and inserted into the machine below the mask. The chuck is raised a few micron short of contact with the mask. Micrometers are used to align the wafer in-line
with markers present on the mask. Once aligned, the wafer is brought into contact with
the mask by vacuum. A UV light source is then used to expose the photoresist. In the
case of positive photoresist, light photons bombard the resist through the open areas in
the mask and leave the resist chemically resistant. Once exposed, the wafer can be
unloaded, baked, and developed to reveal the transferred pattern. The MA6 aligner used
provides a 10mW/cm² power density.

*Photoresist:*

Photoresist coatings are photosensitive chemicals that provide a method of
transfer for patterns from a mask to the wafer. Resists are either negative or positive,
thereby allowing the negative or positive image of a mask to be transferred. The type
chosen depends on the available processing equipment. Resists often include a datasheet
from the manufacturer that tabulates thickness against spin rate, bake and post-bake
times/temperatures, and developing time.

**Procedures & Processing Concepts**

*Photolithography (3012 positive photoresist (PR) process):*

The photolithography process works much like film processing. In place of film
and photopaper, a glass mask and a PR coated wafer are used. A UV light source is used
to pass through an image carrier, the mask, and transferred onto a wafer coated with
photoresist.

To begin the process, photoresist is spin coated on the wafer at 4000RPM for 30s,
Figure 3.2 (A). The wafer is then removed and checked for resist that ran on to the wafer
backside. Runs are removed using acetone and a swab. Next, the coated wafer is placed
on a hotplate set to 90°C. After one minute, the wafer is removed and let to cool for an additional minute.

The sample can now be transferred into a mask aligner loaded with the desired mask pattern. Alignments are made and exposure settings are programmed, 4s and low-vacuum/contact, Figure 3.2 (B). A post-exposure bake is performed at 90°C for one minute. Upon completion, the wafer is ready for developing.

The wafer is loaded onto a vacuum chuck in a spinner used for developing. Developer 351 is puddled, completely covered and left to sit, onto the wafer for 20s. More developer is sprayed for an additional 20s. The spinner is activated at 500RPM after a total of 40s. Deionized water is used to rinse the developer from the wafer for 30s followed by N₂ gas dispensed from a gun to dry the sample. PR thickness and clearing of the wafer can be verified using a light microscope and surface profilometer. The developed wafer is now ready for etching or deposition, Figure 3.2 (C).

*Wet Etching (general process)*:

Removing materials through chemical means is referred to as wet etching. This process often requires time, patience, good recipes, and a touch of voodoo magic to develop procedures that can yield great results. Over-etching can undercut photoresist and remove too much material, leaving less than stellar devices that don’t represent intended lengths or widths.

Processing begins by donning the proper safety gear, apron/face shield/goggles/heavy rubber gloves, calcium gluconate availability, ensuring a second person is in the laboratory, and triple rinsing the appropriate Teflon containers or beakers. Acids are poured to the desired amount and mixed in a labeled and dated Teflon
container. The wafer is placed in a basket and then submersed in the etchant solution to etch for the required amount of time. Figure 3.2 (D) shows expected results after etching SiO₂. Upon material clearing, the sample is immediately submerged in a basin with running water. Drying is done using N₂ gas after placing the wafer on a cleanroom wipe.

Figure 3.2 – The photolithography process [13]

Metal deposition:

Two common methods of metal deposition are evaporation and sputtering. Evaporation entails the heating up of a source material using a beam of focused electrons while under vacuum, Figure 3.3. The material reaches a temperature that causes it to vaporize and deposit on surfaces facing the material. It’s not preferred for use when the sidewalls, such as a “VIA,” require material adhesion. Au was evaporated on to wafers as the “bottom metal.”
Sputtering requires a source material and substrate to be placed on opposing surfaces under vacuum, the source becomes the cathode and the substrate is the anode as in Figure 3.4 [13]. Argon flooding the chamber is ionized using a DC current, creating a plasma. The Ar⁺ ions bombard the source material causing source atoms to be emitted. This material is then pulled toward the anode, thus being deposited on the wafer surface. Deposition in this manner can reach locations on the wafer that are not in plain view of the source. Sidewalls typically receive material adhesion. For the devices studied, the “NiFe-ferromagnetic layer” and Al-“top metal” mask patterns were sputtered onto the samples.

Figure 3.3 – Metal evaporator [13]

Figure 3.4 - Sputtering system [13]
**PECVD (SiO₂ deposition):**

Plasma-enhanced chemical vapor deposition involves a reaction of one or multiple gases to form a thin film on a substrate surface. Plasma is used to transmit energy to the reaction gases in order to increase the number of reactions. Although the quality may not be nearly as high, this process allows thin film deposition to take place under much lower temperatures than required for a furnace based oxidation system.

The SiO₂ deposition performed in the process flow was done using a mixture of SiH₄ and N₂O₂ at a deposition rate of 500Å/min.

**Process Flow**

![Process Flow Diagram](image_url)

Figure 3.5 - Process Flow
Figure 3.5 (A) - .5µm of Au was evaporated onto a wafer previously coated with SiO₂.

There were no issues etching the gold using a ready-to-use KI solution. Etching time averaged about 1.5 minutes for Au to clear. An over etch of 10-15s is included. Caution was needed. Depending on device size, over etching could undercut the resist and etch away the device completely.

Figure 3.5 (B) - NiFe layers are what varied between each wafer. Thickness of the material is one factor to be studied in the experiment. Wafers were coated with .2µm, .3µm, and .4µm of NiFe. Etching this material required a fresh batch of etchant mixed each time. The solution would froth up and increase in temperature once combined. It’s believed that temperature affected etch rates. After etching the wafer, it was noticed that submersion of an immediate second substrate into a semi-warm solution would etch poorly. Rather than taking ~5s like the first wafer, the second sample took over 4 minutes and did not fully clear. Further investigation into temperatures and etch rates were not performed.

Figure 3.5 (C) - Etching the VIAs proved to be difficult. About 1µm of SiO₂ needed to be removed. The combination of feature size (10-40µm), photoresist, and etchant formula caused difficulty when attempting to reach the bottom metal layer. A straight BOE etch was attempted; however, it resulted in an overly aggressive removal of SiO₂. It over-
etched the VIAs, undercutting the resist and opening the ground plane to the main transmission line; thus, shorting out the device. A 1:1 mix of BOE:DI provided cleaner results.

As a protective mask for the VIAs, the photoresist arose to be the largest problem. It would often fail to fully clear from the regions to be etched. A slight amount of resist remaining in the well of the VIA greatly hindered or prevented an etch from occurring. Increasing UV exposure time from 4 to 10 seconds on the mask aligner relieved most of the issue. Multiple etches were performed in increments of 2-3 minutes followed by an inspection with a light microscope and verification through the curve tracer. Eventually the resist began to fail around 6 minutes of combined wafer submersion time, leading to splotches of etching occurring over the entire substrate surface. Resist was reapplied and the sample was etched for an additional 6 minutes. An average time of 12 minutes was used to reach the bottom metal layer. This method also left a number of devices with over-etched VIAs, shorting out transmission lines and NiFe layers, thereby yielding non-functioning devices.

Although it was not investigated, it is recommended to bake the protective mask at 110°C for 5 minutes in future processing. This will remove more of the solvent from the resist, hopefully allowing it to tolerate the BOE:DI formula for extended periods of time.

Figure 3.5 (D) - An aluminum etch was performed using a standard recipe. Phosphoric acid mixed with hydrogen peroxide and heated to 40°C yielded great results. On average, 1µm of Al was removed in about 4 minutes.
Devices were characterized using an Agilent network analyzer with a GSG – ground-signal-ground probe. A frequency sweep of 500MHz to 20GHz was performed on each device. Devices were evaluated in an environment with a DC magnetic field, field strength of about 300 Oersted.

IV. DISCUSSION OF EXPERIMENT RESULTS

Fabrication went quite well for wafer 5, NiFe thickness of .3µm, yielding 39 working devices. Wafer 4a, a NiFe thickness of .4µm, yielded eight devices. Images of patterned devices on wafer 5, all 1000µm in length are contained in Tables 4.1, 4.2, and 4.3. Observing the images, it is easy to see that some had overetched VIAs, nearly compromising the signal lines, while others had issues with adhesion of the top metal layer. Fortunately, out of the 23 pictured, 16 were functioning and resulted in a great collection of S-parameters. The following discussion will only utilize a handful of these devices to compare differences between NiFe pattering, NiFe thickness, line width, line spacing, line length, and location over the NiFe film. Tables of consolidated frequency characteristics are tabulated using the real component for the devices being compared. The complex values from the data were plotted for working devices on all wafers and can be found in Appendix A.

Patterns were characterized using scattering parameters measured by a network analyzer. Discussions and tabulated results will include ferromagnetic resonance peak location (FMR – frequency maxima), the absolute value of the frequency shift (nonreciprocity) between ports S12 and S21 at the FMR location, and the above resonance location (frequency minima). When comparing devices, it’s important to recall
the intentions of the experiment. The goal is to find a device that may lead to a future of integrated nonreciprocal devices that can function without a fixed DC magnetic field. Therefore, devices that continue to show enhanced nonreciprocity and increased resonant frequencies are of great interest for later study and experiments.
## Fabricated Device Images & Physical Traits

<table>
<thead>
<tr>
<th>Row/Dev</th>
<th>Line width (µm)</th>
<th>Line spacing (µm)</th>
<th>Position</th>
<th>NiFe Pattern (µm)</th>
<th>Device Image</th>
</tr>
</thead>
<tbody>
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<td>50</td>
<td>Center</td>
<td>Solid</td>
<td><img src="image1" alt="Image" /></td>
</tr>
<tr>
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<td>50</td>
<td>20</td>
<td>Center</td>
<td>Solid</td>
<td><img src="image2" alt="Image" /></td>
</tr>
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<td>20</td>
<td>50</td>
<td>Center</td>
<td>3</td>
<td><img src="image3" alt="Image" /></td>
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<tr>
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<td>20</td>
<td>50</td>
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<td><img src="image5" alt="Image" /></td>
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<td><img src="image6" alt="Image" /></td>
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<td>Solid</td>
<td><img src="image7" alt="Image" /></td>
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<td>1/9</td>
<td>20</td>
<td>50</td>
<td>Edge2</td>
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<td><img src="image8" alt="Image" /></td>
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<td>20</td>
<td>50</td>
<td>Edge1</td>
<td>Solid</td>
<td><img src="image9" alt="Image" /></td>
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Table 4.1. Row 1 device parameter list for .3 µm thick NiFe film & 1000 µm length
<table>
<thead>
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<th>Row/Dev</th>
<th>Line width (µm)</th>
<th>Line spacing (µm)</th>
<th>Position</th>
<th>NiFe Pattern (µm)</th>
<th>Device Image</th>
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<tbody>
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<td>5</td>
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<td>2/3</td>
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<td>10</td>
<td></td>
</tr>
<tr>
<td>2/4</td>
<td>50</td>
<td>20</td>
<td>Center</td>
<td>Solid</td>
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<tr>
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<td>100</td>
<td>Center</td>
<td>Solid</td>
<td></td>
</tr>
<tr>
<td>2/6</td>
<td>50</td>
<td>50</td>
<td>Edge2</td>
<td>Solid</td>
<td></td>
</tr>
<tr>
<td>2/7</td>
<td>50</td>
<td>50</td>
<td>Edge1</td>
<td>Solid</td>
<td></td>
</tr>
<tr>
<td>2/8</td>
<td>10</td>
<td>50</td>
<td>Center</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>2/9</td>
<td>20</td>
<td>50</td>
<td>Center</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2. Row 2 device parameter list for .3 µm thick NiFe film & 1000 µm length
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<th>Row/Dev</th>
<th>Line width (µm)</th>
<th>Line spacing (µm)</th>
<th>Position</th>
<th>NiFe Pattern (µm)</th>
<th>Device Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/10</td>
<td>20</td>
<td>50</td>
<td>Center</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>3/1</td>
<td>20</td>
<td>100</td>
<td>Center</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>3/2</td>
<td>20</td>
<td>50</td>
<td>Edge1</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>3/3</td>
<td>20</td>
<td>50</td>
<td>Edge1</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3 Device 2/10 and row 3 device parameter list for .3 µm thick NiFe film & 1000 µm length

Initial Observations

Figure 4.1 - Results seen in [9] having oscillations and a 500 MHz shift. A DC field of ~80 Oersted was used.
It was noticed that a majority of the characterized results have a ferromagnetic resonance greater than those done in [9]. Comparing the graphs in Figure 4.1 and Figure 4.2, they also tend to only have one oscillation. Figure 4.3 is one device that contradicted the majority of the other results. After further comparison, it was found that the magnet used to apply the DC field supplied nearly 300 Oe. The experiment conducted in [9] utilized an 80 Oe source. Application of a stronger DC field is the likely culprit behind
the greater ferromagnetic resonance frequency; equations (5) & (6) in chapter 2 support this reasoning. As for the observation of only one oscillation, it’s possible that the edges of the patterned NiFe are not perfectly square. A protective mask was used to preserve the NiFe layer during the etching process; although, there is a chance that the solution undercut the resist and left the rectangular patterns with varying degrees of roughness on all sides. An imperfect edge may reflect magnetostatic waves in directions other than the orthogonal. Perfectly reflected waves would contribute to stronger nonreciprocity and additional oscillations beyond what is received from the transmitting antenna.

**NiFe Thickness**

As mentioned, the bulk of the characterized devices lack the oscillations. A key-contributing factor could be that wafer 5 and wafer 4a have a variation in NiFe thickness. Wafer 5 received .3 µm of NiFe, Figure 4.2, while wafer 4a had .4 µm, Figure 4.3. As per Table 4.4, the FMR frequency for the .4µm deposition was about 750MHz higher than the .3µm NiFe wafer. The second maximum was used to measure shift since it’s a better indicator for nonreciprocity over using the minimums. The measured 970 MHz shift for the thicker film, a jump of 580 MHz over the .3µm film that could possibly be due to a combination of spacing and film thickness, was the largest of all devices measured in the overall experiment. These results follow those seen in prior experiments conducted by [9]. It’s quite possible that a thinner NiFe film may hinder surface waves propagating in opposing directions. There could exist an optimal film thickness that prevents interference between waves. There’s also a chance that the stronger DC magnetic field
lowers magnetic permeability; thus, weakening skin effects. As a result, the reduction in loss yields better oscillations and greater nonreciprocal effects.

<table>
<thead>
<tr>
<th>Row/Dev – Graph Fig 4.x</th>
<th>NiFe thickness</th>
<th>FMR location (GHz)</th>
<th>FMR Shift:</th>
<th>Above resonance Freq location (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/4 – Fig 4.2</td>
<td>.3 µm</td>
<td>S21:(5.77, .015)</td>
<td>(.39, .0018)</td>
<td>S21:(7.67, .0044) S12:(7.28, .0026)</td>
</tr>
<tr>
<td>2/4 – Fig 4.3</td>
<td>.4 µm</td>
<td>S21:(6.54, .027)</td>
<td>(.97, .003)</td>
<td>S21:(10.25, .0049) S12:(9.28, .0051)</td>
</tr>
</tbody>
</table>

Observations:
- Frequency maxima & minima increased
- Nonreciprocal characteristics greatly enhanced

Table 4.4 – Wafer 5 with a .3µm NiFe thickness and wafer 4a with a .4µm thickness (real values)

NiFe Patterning

Figure 4.4 - Device 1/2; Spacing:50µm/L:1mm/W:20µm/Pos:Center/Pattern:Solid
Figure 4.5 - Device 1/4; Spacing: 50µm/L: 1mm/W: 20µm/Pos: Center/Pattern: 3µm

Figure 4.6 - Device 1/5; Spacing: 50µm/L: 1mm/W: 20µm/Pos: Center/Pattern: 5µm

Figure 4.7 - Device 1/6; Spacing: 50µm/L: 1mm/W: 20µm/Pos: Center/Pattern: 10µm
Figures 4.4 through 4.7 represent measured S-parameters for devices having a varied NiFe film. The film was solid, spaced 3 µm, 5 µm or 10 µm. Tabulated measurements of the real portion for these transmission lines are located in Table 4.5. Although the solid NiFe film for device 1/2 held the lowest FMR and above resonance frequencies, it did have the greatest overall shift. In comparison, devices 1/4, 1/5, and 1/6 had a much lower overall shift since the magnetic film depended on a coupling effect between NiFe strips to transfer the time-varying wave. Amplitudes between all devices remained nearly constant.

<table>
<thead>
<tr>
<th>Row/Dev – Graph Fig 4.x</th>
<th>NiFe Pattern spacing</th>
<th>FMR location (GHz)</th>
<th>FMR Shift:</th>
<th>Above resonance Freq location (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2 – Fig 4.4</td>
<td>Solid</td>
<td>S21:(5.38, .0048)</td>
<td>S12:(4.99, .0040)</td>
<td>(.30, .0008)</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>1/4 – Fig 4.5</td>
<td>3 µm</td>
<td>S21:(5.57, .0048)</td>
<td>S12:(5.47, .0042)</td>
<td>(.15,.0007)</td>
</tr>
<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td>1/5 – Fig 4.6</td>
<td>5 µm</td>
<td>S21:(5.62, .0050)</td>
<td>S12:(5.57, .0053)</td>
<td>(.15,.0007)</td>
</tr>
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</tr>
<tr>
<td>1/6 – Fig 4.7</td>
<td>10 µm</td>
<td>S21:(5.57, .0053)</td>
<td>S12:(5.47, .0046)</td>
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</tr>
</tbody>
</table>

Table 4.5 -Wafer 5 devices having a varied NiFe film pattern (real values)

Frequency characteristics had a negligible increase for the patterned films. A device with 3µm spacing between NiFe strips resulted in a FMR increase of .190 GHz for S21 and .480 GHz for S12 when compared to device 1/2. The 5 µm patterned device increased yet again, this time by .240 GHz for S21 and .580 GHz over device 1/2. At a 10
µm spacing between magnetic strips, the FMR went back to that of the 3 µm device (1/4). In a similar fashion, the above resonance frequency followed the same pattern. Regarding the shift for devices 1/4, 1/5, and 1/6, it remained constant. Breaking up the NiFe pattern has minimal effect on nonreciprocity.

Transmission Line Location

![Figure 4.8](image1)

**Figure 4.8 - Device 1/2; Spacing:50µm/L:1mm/W:20µm/Pos:Center/Pattern:Solid**

![Figure 4.9](image2)

**Figure 4.9 - Device 1/9; Spacing:50µm/L:1mm/W:20µm/Pos:Edge2/Pattern:Solid**

The collected S-parameters for couple transmission lines placed in the center and 20µm to the edge are plotted in Figures 4.8 and 4.9. Frequency characteristics are
organized in Table 4.6. When comparing devices 1/2 and 1/9, it’s seen that both have similar FMRs, above resonant frequencies, and total shift between minimums. Moving the transmission line closer to the edge did result in a slightly larger bandwidth, a trivial 40 MHz increase, but not stronger nonreciprocal characteristics. This could be a result of the strong DC field influencing the device.

<table>
<thead>
<tr>
<th>Row/Dev – Graph Fig 4.x</th>
<th>T-Line Location</th>
<th>FMR location (GHz)</th>
<th>FMR Shift:</th>
<th>Above resonance Freq location (GHz)</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>S21:</td>
<td></td>
<td>S21:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S12:</td>
<td></td>
<td>S12:</td>
</tr>
<tr>
<td>1/2 – Fig 4.8</td>
<td>Center</td>
<td>(5.38, .0048)</td>
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<td></td>
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<td>(4.99, .0040)</td>
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<td>(6.64, .00015)</td>
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<td>1/9 – Fig 4.9</td>
<td>Edge</td>
<td>(5.42, .0026)</td>
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<td>(6.93, -.0017)</td>
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<tr>
<td></td>
<td></td>
<td>(4.99, .0019)</td>
<td></td>
<td>(6.64, -.0011)</td>
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</table>

Observations:
- Frequency maxima & minima increased
- No noticeable change in nonreciprocal characteristics

Table 4.6 - Wafer 5 device centered and shifted 20 µm from edge of NiFe film (real values)

**Line Width**

Figure 4.10 - Device 1/5; Spacing:50 µm/L:1 mm/W:20 µm/Pos:Center/Pattern:5 µm
Figure 4.11 - Device 2/2; Spacing: 50µm/L: 1mm/W: 50µm/Pos: Center/Pattern: 5µm

Since it was concluded that pattern variation had almost no contribution to nonreciprocity, comparisons can be made between devices 1/5 and 2/2 on wafer 5. Device 2/2 had an increased FMR, a slight decrease in the minimum frequency, and a shift of 60 MHz less than device 1/5. In contrast to devices with 20 µm wide line, most utilizing a 50 µm wide line did not show much, if any, beneficial enhancement of nonreciprocal tendencies.

<table>
<thead>
<tr>
<th>Row/Dev – Graph Fig 4.x</th>
<th>Line Width</th>
<th>FMR location (GHz)</th>
<th>FMR Shift:</th>
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<td></td>
<td></td>
<td>[S21-S12]</td>
<td></td>
</tr>
<tr>
<td>1/5 – Fig 4.10</td>
<td>20µm</td>
<td>S21:(5.62, .0050)</td>
<td>(.15, .0007)</td>
<td>S21:(7.67, -.0033) S12:(7.52, -.0026)</td>
</tr>
<tr>
<td>2/2 – Fig 4.11</td>
<td>50µm</td>
<td>S21:(6.01, .0015)</td>
<td>(.09, .0001)</td>
<td>S21:(8.89, -.0004) S12:(8.98, -.0003)</td>
</tr>
</tbody>
</table>

Observations:
- Frequency maxima & minima increased
- Nonreciprocal characteristics were reduced

Table 4.7 - Wafer 5 devices having a varied line width of 20 µm and 50 µm (real values)
Increasing line length also provided little benefit to nonreciprocity. The shorter line had higher maximum and minimum frequencies. Extending the transmission line, device 4/5 lengthened to 2mm, delivered similar performance but at a lower frequency. As expected, varying the length of the transmission line can tune the device to particular frequencies; however, it does not influence the nonreciprocal characteristics.
NiFe Thickness: .3 (µm)--Line Location: Center--Insulating layer: .5 µm SiO2
NiFe pattern: Solid--Line Width: 20µm--Line spacing: 50µm

<table>
<thead>
<tr>
<th>Row/Dev – Graph Fig 4.x</th>
<th>T-Line Length</th>
<th>FMR location (GHz)</th>
<th>FMR Shift:</th>
<th>Above resonance Freq location (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>[S21-S12] (GHz)</td>
<td></td>
</tr>
<tr>
<td>1/5 – Fig 4.12</td>
<td>1000 µm</td>
<td>S21:(5.62, .0050)</td>
<td>(.15, .0007)</td>
<td>S21:(7.67, -.0033) S12:(7.52, -.0026)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S12:(5.57, .0053)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4/5 – Fig 4.13</td>
<td>2000 µm</td>
<td>S21:(4.01, .0043)</td>
<td>(.15, .0003)</td>
<td>S21:(6.11, -.0050) S12:(5.96, -.0047)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S12:(3.96, .0039)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Observations:**
- Frequency maxima & minima decreased with respect to λ
- No change in nonreciprocal characteristics

Table 4.8 - Wafer 5 devices having a varied line length of 1mm and 2mm (real values)

**Line Spacing**

Figure 4.14 - Device 1/7; Spacing: 20µm/L: 1mm/W: 20µm/Pos: Center/Pattern: Solid
Line spacing was varied to test for nonreciprocal enhancement. When space between the coupled lines was decreased to 20\(\mu\)m, shift increased to 350 MHz. The FMR remained went up slightly, but it was relatively in the same range as device 1/2.

Increasing the separation to 100\(\mu\)m provided no value. The FMR decreased and there was no observable shift. Decreasing the space between coupled lines does have the potential to improve nonreciprocal performance.

<table>
<thead>
<tr>
<th>Row/Dev – Graph Fig 4.x</th>
<th>T-Line spacing</th>
<th>FMR location (GHz)</th>
<th>FMR Shift: ([S21-S12]) (GHz)</th>
<th>Above resonance Freq location (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/7 – Fig 4.14</td>
<td>20(\mu)m</td>
<td>S21:(5.57, 0.019)</td>
<td>S21:(5.47, 0.019)</td>
<td>S21:(5.47, -0.014)</td>
</tr>
<tr>
<td>1/8 – Fig 4.15</td>
<td>100(\mu)m</td>
<td>S21:(2.69, .00016)</td>
<td>S21:(2.69, .00016)</td>
<td>S21:(5.47, -0.0014)</td>
</tr>
</tbody>
</table>

Observations:
- Frequency maxima & minima decreased for line separation increase
- Nonreciprocity was enhanced by decreasing space

Table 4.9 - Wafer 5 devices having a varied line space of 20\(\mu\)m and 100\(\mu\)m (real values)
V. CONCLUSION AND REMARKS

The overall experiment was considered a success. It can be concluded that line spacing and NiFe thickness influenced nonreciprocity. These factors will require additional characterization to better understand them. One such step will be to re-measure devices using a weaker DC magnetic field. This will allow for a better comparison against results in previous work. It will also confirm whether a stronger DC magnetic field does reduce losses in thicker materials or if it hinders performance by preventing further oscillations in thinner NiFe material.

Future Work

NiFe film thickness and coupled line separation do offer a direction to pursue for further investigation. It’s likely that thresholds exist for each parameter and finding these could lead to improved performance beyond what was discussed. Such findings can also be tested in device areas beyond that of a simple isolator. The techniques and associated trends can carry over when designing other types of nonreciprocal devices. Possible interests for exploration may include resonators, transmission lines, and phase shifters. However, before delving into further patter design, it’s necessary to perform software simulations to strengthen current findings. Proper software analysis would facilitate modeling of designs and promote efficient use of time and resources. It’s hopeful that analysis resulting from these devices will lead to the development of a catalog containing associated wave numbers and design techniques. Amassing such a library can enable industry with the information needed to better integrate nonreciprocal devices and achieve a low cost scalable solution to meet today’s technology needs.
REFERENCES


APPENDIX A

By neglecting conduction through the material shown in Figure A.1, it’s possible to find the optimal conditions that prevent conductive losses. Assuming zero conduction, the curl of the magnetic field becomes zero, (A.1); thus, leaving the integration of the magnetic field vector to also be zero. As a result, the magnetic field can be defined in scalar terms as \( \Psi \). Solving for the divergence of the magnetic flux \( \mathbf{B} \) then provides Walker’s equation (A.6).

\[
\nabla \times \mathbf{H} = 0, \quad \mathbf{H} = \nabla \Psi \quad (A.1)
\]
\[
\nabla \cdot \mathbf{B} = 0 \quad (A.2)
\]
\[
\mathbf{B} = \mu \mathbf{H} \quad (A.3)
\]
\[
\nabla \cdot \mu \mathbf{H} = 0 \quad (A.4)
\]
\[
\mu = \mu_0 \left( \mathbf{1} + \chi \right) = \mu_0 \begin{bmatrix} \mu & i\mu_a & 0 \\ i\mu_a & \mu & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (A.5)
\]
\[
\nabla \cdot (\mu \mathbf{H}) = \mu \frac{d^2 \Psi}{dx^2} + \mu \frac{d^2 \Psi}{dy^2} + \mu \frac{d^2 \Psi}{dz^2} = 0 \quad (A.6)
\]
When magnetostatic wave with wave vector values \( k_x \) and \( k_z \) propagates in the x and z plane, where \( d \) is the material thickness and \( \theta \) is the angle between the propagating wave and easy axis, it becomes possible to solve for magnetic potential \( \Psi \) inside the magnetic thin film (A.7). Using the boundary conditions \( y=0 \) and \( y=d \), the general wave equation describing the propagating wave is provided in (A.10).

\[
\Psi = [A e^{\xi y} + B e^{-\xi y}] e^{(-i k_x x - ik_z z)} \quad 0 \leq y \leq d
\]  
(A.7)

\[
\xi = k \sqrt{\sin^2 \theta + \frac{1}{\mu} \cos^2 \theta}, \quad k = \sqrt{k_x^2 + k_z^2}
\]  
(A.8)

\[
\tan \theta = \frac{k_3}{k_z}
\]  
(A.9)

\[
\tan \xi d = \frac{2 \sin(\mu) \sqrt{\mu \sin^2 \theta + \cos^2 \theta}}{(\mu^2 - \mu^2) \sin^2 \theta - \mu \cos^2 \theta - 1}
\]  
(A.10)

The equation given in A.10 describes two types of magnetostatic waves. The first being volume waves which represent propagating waves internal to the material and have a varying y component. For this case to occur, \( \xi \) needs to be imaginary which is considered loss and defined by A.11. The second case, surface waves, \( \xi \) is entirely real (A.12) and infers that the concentration of propagation takes place on the surface of the magnetic material. When using the conditions given in A.11 or A.12 in combination with A.13 and A.14, it then becomes possible to find a frequency range for the two propagating wave conditions. For volume waves, they’re found to be most abundant below FMR (A.13). On the contrary, surface waves have a greater presence when above FMR (A.14). Figure A.1 display a more graphical representation of the operating conditions.

\[
\mu [\mu \sin^2 \theta + \cos^2 \theta] \leq 0
\]  
(A.11)
\[ \mu [\mu \sin^2 \theta + \cos^2 \theta] \geq \mathcal{C} \]  
(A.12)

\[ \omega_{FMR} = \sqrt{\omega_H (\omega_H + \omega_M)} \]  
(A.13)

\[ \mu = \frac{\omega_H (\omega_H + \omega_M) - \omega^2}{\omega_H^2 - \omega^2} \]  
(A.14)

\[ \omega_H \leq \omega \leq \sqrt{\omega_H (\omega_H + \omega_M)} \]  
(A.13)

\[ \sqrt{\omega_H (\omega_H + \omega_M)} \leq \omega \leq \sqrt{\frac{2\omega_H^2 + \omega_M^2 \sin^2 \theta + \omega_H \omega_H (H \sin^2 \theta)}{2}} \]  
(A.14)

Figure A.1 – Above (lossless) and below (lossy) resonant operation regions [2]
APPENDIX B

WAFER 5: SIDE 2 - PLOTTED DATA

NiFe Thickness .3 (µm) -- Insulating layer .5 µm SiO₂

Figure B.1 - Device 1/2; Spacing:50µm/L:1mm/W:20µm/Pos:Center/Pattern:Solid

Figure B.2 - Device 1/3; Spacing:50µm/L:1mm/W:50µm/Pos:Center/Pattern:Solid
Figure B.3 - Device 1/4; Spacing:50µm/L:1mm/W:20µm/Pos:Center/Pattern:3µm

Figure B.4 - Device 1/5; Spacing:50µm/L:1mm/W:20µm/Pos:Center/Pattern:5µm

Figure B.5 - Device 1/6; Spacing:50µm/L:1mm/W:20µm/Pos:Center/Pattern:10µm
Figure B.6 - Device 1/7; Spacing:20µm/L:1mm/W:20µm/Pos:Center/Pattern:Solid

Figure B.7 - Device 1/9; Spacing:50µm/L:1mm/W:20µm/Pos:Edge2/Pattern:Solid

Figure B.8 - Device 2/2; Spacing:50µm/L:1mm/W:50µm/Pos:Center/Pattern:5µm
Figure B.9 - Device 2/3; Spacing: 50µm/L: 1mm/W: 50µm/Pos: Center/Pattern: 10µm

Figure B.10 - Device 2/4; Spacing: 20µm/L: 1mm/W: 50µm/Pos: Center/Pattern: Solid

Figure B.11 - Device 2/6; Spacing: 50µm/L: 1mm/W: 50µm/Pos: Edge2/Pattern: Solid
Figure B.12 - Device 2/7; Spacing: 50µm/L:1mm/W:50µm/Pos:Edge1/Pattern:Solid

Figure B.13 - Device 2/8; Spacing: 50µm/L:1mm/W:10µm/Pos:Center/Pattern:3µm

Figure B.14 - Device 2/9; Spacing: 50µm/L:1mm/W:50µm/Pos:Center/Pattern:3µm
Figure B.15 - Device 2/10; Spacing: 20µm/L: 1mm/W: 20µm/Pos: Center/Pattern: 3µm

Figure B.16 - Device 3/6; Spacing: 50µm/L: 1mm/W: 20µm/Pos: Center/Pattern: 3µm

Figure B.17 - Device 4/3; Spacing: 50µm/L: 2mm/W: 50µm/Pos: Center/Pattern: Solid
Figure B.18 - Device 4/5; Spacing: 50µm/L: 2mm/W: 20µm/Pos: Center/Pattern: 5µm

Figure B.19 - Device 4/8; Spacing: 100µm/L: 2mm/W: 20µm/Pos: Center/Pattern: Solid

Figure B.20 - Device 4/9; Spacing: 50µm/L: 2mm/W: 20µm/Pos: Edge/Pattern: Solid
Figure B.21 - Device 5/2; Spacing: 50µm/L: 2mm/W: 50µm/Pos: Center/Pattern: 5µm

Figure B.22 - Device 5/3; Spacing: 50µm/L: 2mm/W: 50µm/Pos: Center/Pattern: 10µm

Figure B.23 - Device 5/6; Spacing: 50µm/L: 2mm/W: 50µm/Pos: Edge/Pattern: Solid
Figure B.24 - Device 5/8; Spacing: 50µm/L:2mm/W:10µm/Pos:Center/Pattern:3µm

Figure B.25 - Device 5/9; Spacing: 50µm/L:2mm/W:50µm/Pos:Center/Pattern:3µm

Figure B.26 - Device 5/10; Spacing: 20µm/L:2mm/W:20µm/Pos:Center/Pattern:3µm
Figure B.27 - Device 6/1; Spacing: 100µm/L: 2mm/W: 20µm/Pos: Center/Pattern: 3µm
APPENDIX C

WAFTER 5: SIDE 1 - PLOTTED DATA

| NiFe Thickness .3 (µm) -- Insulating layer .5 µm SiO₂ |

Figure C.1 - Device 1/5; Spacing:50µm/L:1mm/W:20µm/Pos:Center/Pattern:5µm

Figure C.2 - Device 1/6; Spacing:50µm/L:1mm/W:20µm/Pos:Center/Pattern:10µm
Figure C.3 - Device 1/7; Spacing:20µm/L:1mm/W:20µm/Pos:Center/Pattern:Solid

Figure C.4 - Device 1/8; Spacing:100µm/L:1mm/W:20µm/Pos:Center/Pattern:Solid

Figure C.5 - Device 1/9; Spacing:50µm/L:1mm/W:20µm/Pos:Edge/Pattern:Solid
Figure C.6 - Device 2/7; Spacing: 50 µm/L: 1 mm/W: 50 µm/Pos: Edge2/PATTERN: Solid

Figure C.7 - Device 2/9; Spacing: 50 µm/L: 1 mm/W: 50 µm/Pos: Center/PATTERN: 3 µm

Figure C.8 - Device 3/5; Spacing: 50 µm/L: 1 mm/W: 20 µm/Pos: Edge2/PATTERN: 3 µm
Figure C.9 - Device 5/10; Spacing:20µm/L:2mm/W:20µm/Pos:Center/Pattern:3µm
APPENDIX D

WAFER 4a: SIDE 1 - PLOTTED DATA

NiFe Thickness .4 (µm) -- Insulating layer  .5 µm SiO₂

Figure D.1 - Device 2/2; Spacing:50µm/L:1mm/W:50µm/Pos:Center/Pattern:5µm

Figure D.2 - Device 2/4; Spacing:20µm/L:1mm/W:50µm/Pos:Center/Pattern:Solid
Figure D.3 - Device 2/5; Spacing:100µm/L:1mm/W:50µm/Pos:Center/Pattern:Solid

Figure D.4 - Device 2/7; Spacing:50µm/L:1mm/W:50µm/Pos:Edge1/Pattern:Solid

Figure D.5 - Device 2/8; Spacing:50µm/L:1mm/W:10µm/Pos:Center/Pattern:3µm
Figure D.6 - Device 3/4; Spacing: 100µm/L: 1mm/W: 20µm/Pos: Center/Pattern: 3µm

Figure D.7 - Device 3/5; Spacing: 50µm/L: 1mm/W: 20µm/Pos: Edge1/Pattern: 3µm