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Nonreciprocal Magnetostatic Surface Wave in Thin Ferromagnetic Film

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NONRECIPROCAL MAGNETOSTATIC SURFACE WAVE IN THIN FERROMAGNETIC FILM

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By

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Kumar Vishal, ENTITLED Nonreciprocal magnetostatic surface wave in thin ferromagnetic film BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR DEGREE OF Master of Science in Electrical.

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ABSTRACT

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Interest in the nonreciprocal property of waves inside the magnetic material starts with its current advancement in the field of passive devices. In current technology passive devices without magnetic cores are realized on a silicon chip, usually these devices are lossy and bigger in size. Passive devices constructed with magnetic core material such as isolators, circulators, phase shifters, and gyrators; gives us the chance to minimize such losses. Nonreciprocity in magnetic material is due to the anisotropic property of permeability, it is complex in nature and represent in 3×3 matrix form. We can control the wave flow inside the nonreciprocal devices by making some changes in the matrix. This thesis work includes modeling, simulation, and investigation of ferromagnetic material to enhance nonreciprocity effect. We perform physical measurement on actual devices and then use the same parameters to design the model in comsol multiphysics software to verify the nonreciprocity. This thesis work also suggests different ways to suppress eddy current losses to increase the nonreciprocity effect. Comsol is a simulation tool for our RF passive device model containing magnetic core material. All simulation results were obtaining from comsol; it is used as to model the device and set different parameter defined for ferromagnetic devices. We successfully investigate the nonreciprocity inside the magnetic material by analyzing scattering parameters (S12 and S21). The design of any nonreciprocal device is a big challenge because propagation losses are more, even a small change in structure suppress the nonreciprocity effect. This work has shown that by using these improved configurations we can reduce loss and enhance the overall device performance. Nonreciprocal spin

wave has been observed in the ferromagnetic thin film by placing it between neighboring metallic layer.

By proper selection of line width, spacing between signal lines, position, and thickness of films, the maximum nonreciprocity up to -26.0 dB for NR-Amplitude and -180.0° phase difference for NR-Phase is reported.

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Chapter 1 Introduction

1.1 Integrated circuits in communication

As it is being said that communication is a solution for many of our problems, its principle can be applied in real life and science; communication in science can be possible by a single device like antenna or bunch of devices consist of more than one electronic components like (transceiver). If we look into our history, we found that most of the advancement in communication field took place during World War II [1]. One of the earliest and successful way of long distances communication is through smoke signals; this property is also based on electromagnetic wave theory [2]. Wireless Communication theory based on electromagnetic waves which were discovered by James Maxwell in 1873. In Later years, Marconi, Michael Faraday, and others great scientists work in this area to develop it. During the 19th century Hertz demonstrate the power of microwave communication which is also called wireless communication, this one idea changed the perspective of human on communication and interactions [3, 4].

Inspired by the discoveries of Hertz it was Marconi who gave us the first live demonstration of wireless communication after 40 years later in 1901. In the early experiment of Michael Faraday's, he demonstrated that change in a magnetic field produces electric fields which were later proved by Maxwell. In addition to this Maxwell found that inverse of Faraday law is also true. After which in the field of electromagnetic, Maxwell discovered laws of electrodynamics, theory of continuity equation, laws of electromagnetics and also proved the existence of electromagnetic waves. The famous author Richard Feynman stated in his book that "from ten thousand years from now Maxwell discoveries of electromagnetic waves are remembered as one of the greatest discoveries in the field of physics."

In early years before the 1980s, most of the microwave technology were only limited to the defense areas, and they usually work in the frequency range between 2 to 15 GHz. Thus, the 80's microwave components sizes are big and cumbersome. In later years due

to the advancement and progress made in the areas of the transistor and integrated circuit technologies for communication devices such as radio and television came into existence to common people. Later these technologies lead to the development of two-way communication devices such as phones, Computers, and wireless devices.
An integrated circuit or monolithic integrated circuit (also referred as IC, chip or microchip) is a combination of electronic circuits on a semiconductor device, normally silicon. IC can be made much smaller compared to a discrete component made from independent electronic circuits. IC's can be made very compact, and it can have billions of transistor and other electronic components [5,60]. Integrated circuits are becoming small, number of the component inside the IC's are also keep getting more and more. Regarding size, weight and cost IC's are becoming more scalable, for example, we can see advancement in our mobile phones, which can perform multi tasks and operations at the same time, due to a large number of integrated electronic components on its chip.

In recent years, due to the advancement in semiconductor devices and technology, we can integrate more and more number of elements on a single chip than before therefore we can increase the performance of the device and use it in different ways, this also helps in cost reduction and cost of production for examples fifteen years before we have to carry our camera, laptop, and phones separately but due to advancement in microchip integration our mobile phones can do all these work. Present scientists and engineers are working on integration technology, size, and cost

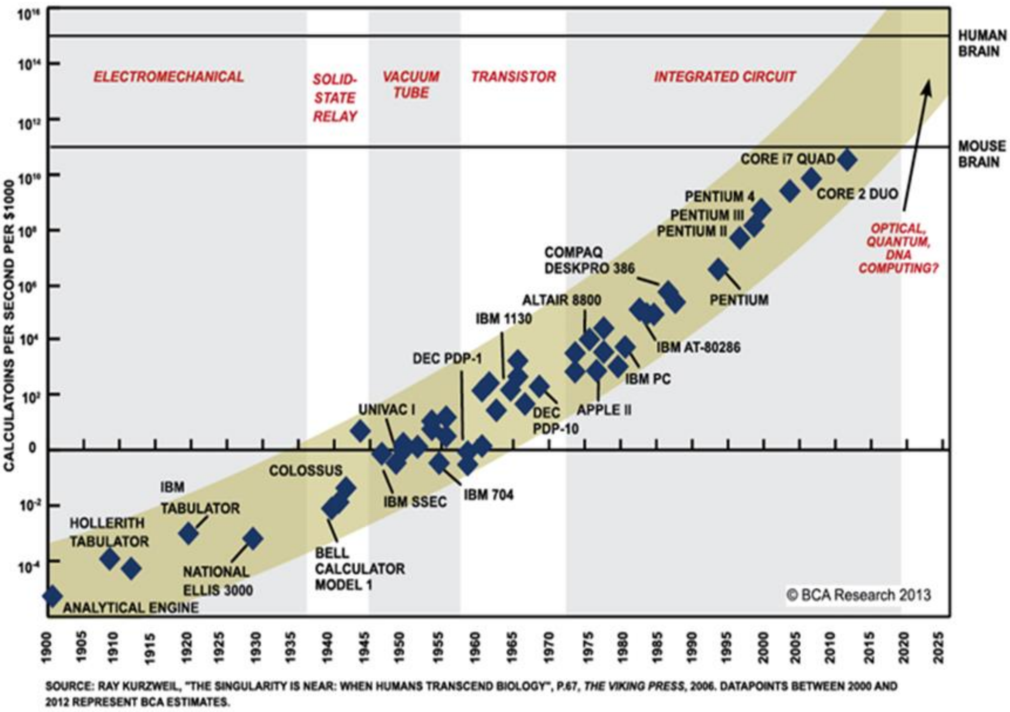


Figure 1.1: The advancement in IC's design came and how it progresses through time. (from the Viking press, 2006 to show how).

Figure 1.1 gives an idea how the advancement in IC's progress through time. We started our evolution for IC's design integration from analytical design and from now on we keep integrating more number of transistors in the single IC's. To give a number here about how much we advance, around 1980, we make IC's with thousands of transistors in it, but now this calculation changes two to three billion transistors on a single chip. We want more processing speed, less computation time, less heating, longer battery life. As we increase the number of transistors, working on variety multi-task handling capacity increases, this is one benefit other than that we also have to make sure that power consumption minimizes, size reduction, processing time reduction are an important factor in IC’s design. There are more than hundred international companies in the IC’s design. Intel ranked first since 1999. Many of these companies make IC’s for the space agency, gaming agency, windows and mac, advanced electronics products. All of these companies compete in different areas like increasing number of the electronic component on IC’s, minimize the usage of power consumption, cost reduction, quality and quantity production for the market [6,7]. IC’s industry sector is considered to be a very competitive market like any other. Just to give you knowledge about how challenging it is every year we heard about some new processor in the market and according to Moore’s law in every two years, we double our integration.

Integrated circuits are also used in communication purpose, green or blue colored board what we see inside our cell phone is called PCB (printed circuit board), it is also called as a motherboard, this is the most important part of the cell phone. All the IC’s that are designed to perform certain work are assembled on it. IC’s were consisting of both active and passive components they are designed to generate and receive signal. IC’s are composed of an antenna, RF filter, amplification (carrier), ADC (analog to digital converter), modulator/demodulator and DAC (digital to analog converter).

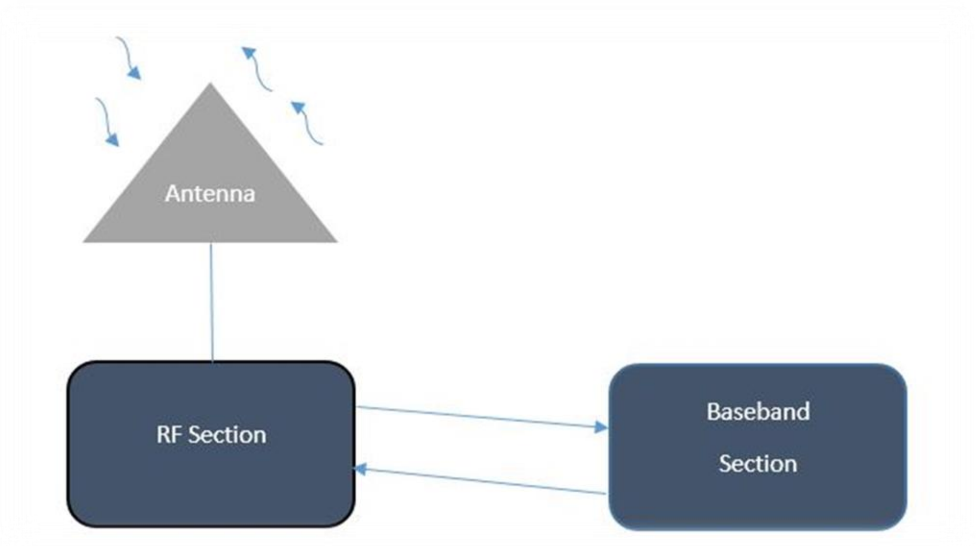


Figure 1.2: Communication system (RF transceiver system).

RF section consists of RF filter, NA (noise amplifier), Converter (Up/Down), and ADC or DAC. Baseband section includes DSP (digital signal processing), modulator/demodulator and ADC or DAC.

An IC's is a collection of various electronic devices like resistors, transistors, capacitors. Many of them are RF passive components. One of the major challenge confronted by the semiconductor industry today is the integration of RF passive components on-chip. Some RF devices, for example, inductors, transmission lines, coplanar waveguides, transformers and so on., which are the fundamental building block in RF incorporated circuit (RFIC). These components are utilized as a part of RF matching network, filter, low-noise amplifiers (LNA's), power amplifiers, etc. One of other challenge is the integration of RF components on-chip is related to using of digital CMOS technology for RF and analog circuit design, this cause tradeoff between speed and power dissipation and also cause modeling difficulties for device scaling.

Therefore, the biggest problem faced by many RF engineers today is to integrate RF components on-chip is related to operation and size of RF passive parts on-chip such as inductor and capacitors. The lumped components on IC's such as inductor and capacitor are used as to store magnetic and electric energy, this occupies the largest area of the integrated circuit. Apart from this transmission line components have a certain length, where the length has to be comparable to the electromagnetic wavelength operating at a specific frequency which is tough to scale. Therefore, the current RF passive components occupy the largest area on-chip.

In addition to the above discussion relating to difficulties faced by integration of RF components on-chip. The RF passive component is also suffering from several other drawbacks such as low inductance, poor quality factor, ohmic and substrate losses, etc. Therefore, the RF passive device not only occupies the large area on chips but it also degrades device performance due to crosstalk, substrate and conductor losses, which are caused by interfering of electromagnetic waves with the substrate.

In conclusion, RF passive device makes use of magnetic material to manufacture passive components, to scale the component size for RF circuit integration and improve the overall performance of the device.

1.2 RF Device

In spectrum regulation, RF microwave devices fall in between 1m to 1mm wavelength (frequency range 300MHz to 300GHz). Most of our communication and electronic devices are based on RF microwave technology for example; mobile phones, GPS (global positioning system), Satellite communication, RF microwave technology is critical because it provides us the freedom to transfer large data in seconds and it also covers the long range. Since the advancement of technology microwaves devices always attracts scientist and engineers because of its high integration capability and low power consumption. Microwave devices can be built tiny, one example of this is IC’s, which consist more than one microwave components and can still work very fast.

In RF circuit design, not only the electronic device performance is essential but also the quality of the passive components. In that respect, many research papers were published with different findings. Current silicon technology is based on CMOS design and fabrication; this technology is gaining speed and trying to enter in nanofabrication design technology. The biggest challenge in front of this is the realization of passive components on the chip. In the last fifteen years, many advancements were made in the field of RF passive device to make them capable with silicon technology. In general RF passive were the largest component on a chip, to make them scalable with current silicon technology, we have used magnetic material inside them [1].

RF passive devices are widely employed in different areas of science. To understand the diversity of RF devices, we must understand its classification. In a broad way this divides in two part, First, RF passive device without magnetic cores, these devices can work without magnetic cores but introduce magnetic core inside these devices certainly increases the functionality of non-magnetic core devices for examples Inductors, transmission line. Second, RF passive devices that needed magnetic cores for its functionality. Devices with non-reciprocal behavior use such kind of cores for example circulator, isolator. Figure 1.3 is given below to get the better understanding of RF device classification based on current (on-magnetic) silicon technology.

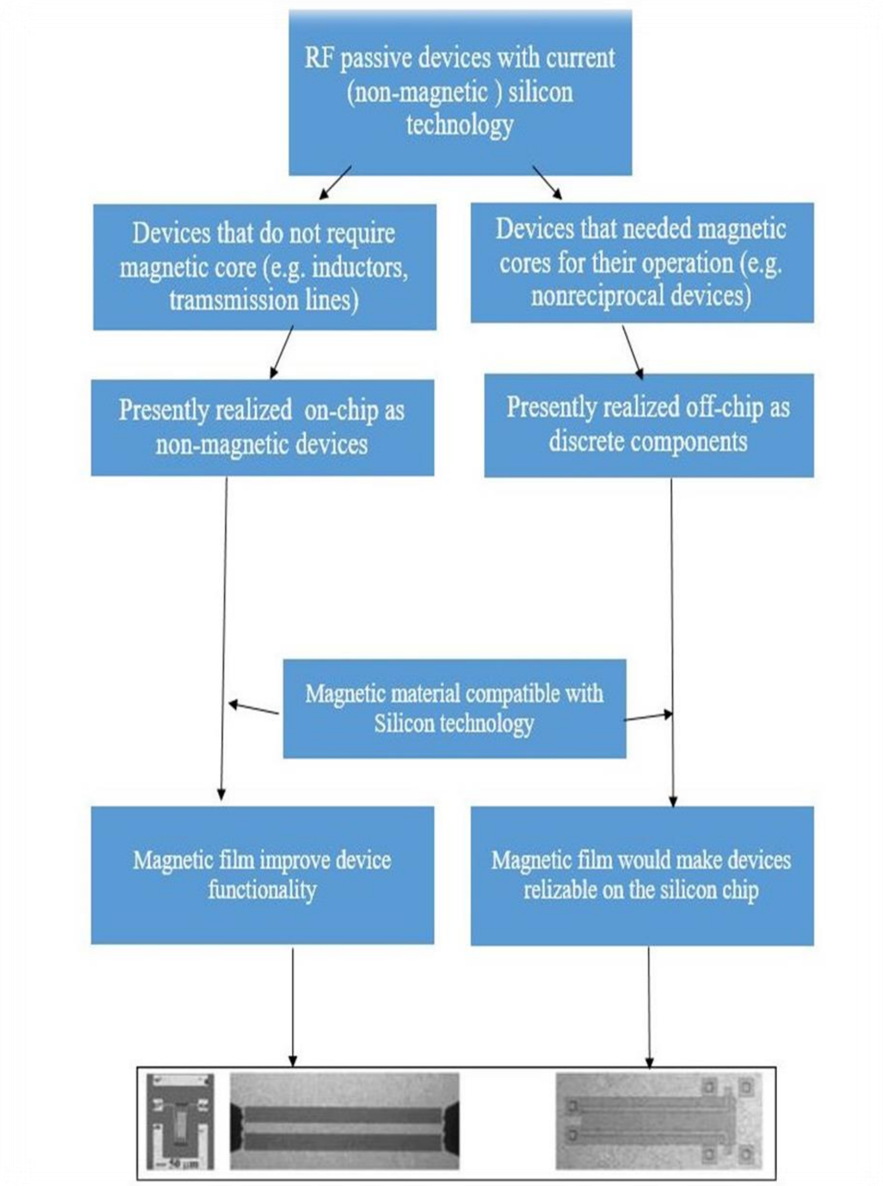


Figure 1.3: How magnetic material film can improve RF incorporated circuit technology. (Base left) Integrated solenoid inductor and microstrip transmission line

with a magnetic core. Both devices have nonmagnetic counterparts already integrated on silicon. (Base right) Integrated nonreciprocal coupled transmission line structure based on spin waves in a magnetic film [1].

The first type of RF devices like an inductor, transmission line, etc. can be manufactured without using any magnetic material, devices made without magnetic cores are much lossy and bigger in size. Practically, an inductor's magnetic center stores recoverable energy. Circuit creators determine inductors that are fit for getting and returning energy in recommended interims. Mechanically, an inductor's center gives backing to its windings. Magnetically, an inductor's center gives the medium to focus and contain magnetic flux.

Another important core parameter to consider here is permeability. Permeability is inverse to reluctance which means high reluctance will have low permeability and low magnetic flux and vice versa. Permeability is important because it related to flux multiplier in the magnetic material.

An inductor transforms electrical energy into magnetic energy. Inductor stored energy in the form of magnetic field. Energy stored inside inductor at one instant of time can be retained in the core until it is needed later. By controlling the rate at which energy is stored in the inductor and removed from the magnetic field, the designer can implement switched-mode power supplies. For example, switching power supplies can operate in the range of tens of kilohertz to a few megahertz [61]. Slower switching must store more energy per cycle than higher frequency switchers. The reason is core size is larger for lower switching frequencies and smaller for higher switching frequencies.

Inductor core material is made up of silicon steel, iron powder, and ferrite materials. All these magnetic materials have different permeability and resistivity. We cannot say that using one specific material will satisfy all our needs that is why we have to select from these options. Such as using silicon steel, having low resistivity, is suitable for fast electrical current but they are responsible for unwanted eddy current in the core material. Eddy current contribute to heat and core loss. Silicon steel core reaches

saturation quite easily and so afterward storing magnetic energy is not possible.
The soft iron core has higher resistivity than silicon steel. By special technique, the iron particle is insulated. The particle is mixed with a binder (such as epoxy or phenolic). The core is then pressed, and baking process is used to cure cores. After this, many tiny air gaps combine to provide air gap throughout this basic process. When compared to other magnetic material distributed air gap allows powder core to store high magnetic flux then ferrites.

Ferrites are a crystalline magnetic material made up of iron oxide and other elements. Ferrites are made up at high temperatures and formed into the crystalline molecular structure. Unlike others, Ferrites are a ceramic material with magnetic properties. Ferrites are having high magnetic permeability and high resistivity. Using the ferrites as inductor core significantly reduce eddy current losses with their high resistivity, ferrites are ideal for use as inductors.

The second type of RF devices are non-reciprocal devices; these devices need to have a magnetic core to perform the basic operation. Devices like circulator, isolator come under this category.

Nonreciprocal RF and microwave components such as circulators, isolators, non-reciprocal phase shifters, and gyrators have been so far realized as off- cheap components using dielectric ferrite. As ferrite are not comfortable with silicon technology, the implementation of such device in RF integrated circuits require the study of nonreciprocal effects in silicon compatible magnetic films.

Circulators, a microwave 3-port circulator, is a non-reciprocal multiport device made with ferrite materials. It has the property that wave incident on port 1 routed to port 3, wave incident on port 3 does not route back to port 1 but instead moved to port 2, and so on. This particular property of circulator used as to isolate microwave components from each other, for example, when we have transmitter and receiver to a common antenna. When we connect transmitter, receiver, and antenna to different ends of this circulator, transmitted power directed to the antenna and the power received by the antenna goes to the receiver. Circulators typically rely on the use of ferrite materials, a material with high permeability and low loss magnetic material that has anisotropic nature. A 3-port circulator can we constructed by using three waveguide join at 120° and ferrite post placed at the center of the joint.

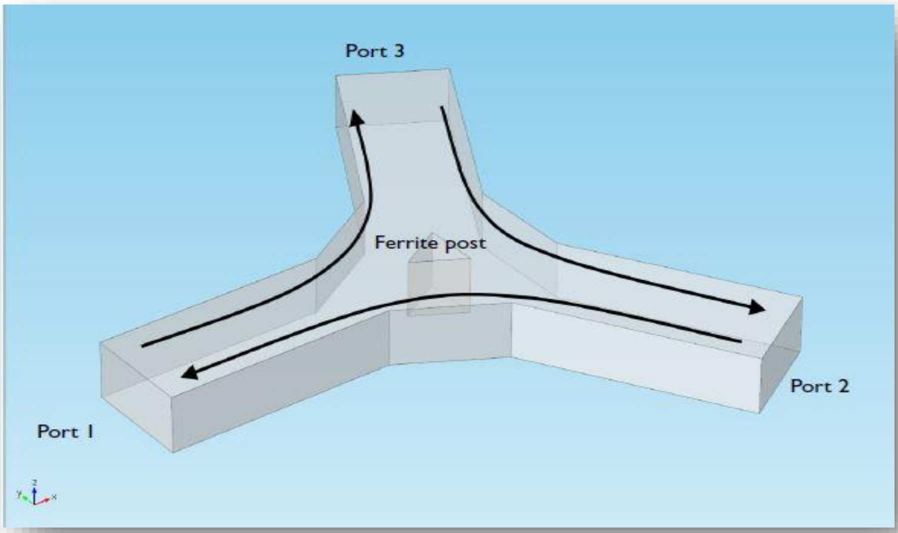


Figure 1.4: Ferrite 3-Port circulator. The port is biased with static H_0 bias field along its axis.

Isolators, in brief, if we terminate one port of circulator it will become isolator, this has the property that energy flow in one direction only, this is critical in the device for "isolating" microwave component in the chain, so that the bad VSWR do not get high ripple, or create instability (unwanted oscillations). An isolator is a non-reciprocal, passive network.

The problem in the study of nonreciprocal devices as discussed in the previous sections is mostly likely due to the high conductivity of magnetic material which overshadows the nonreciprocal effect to observe. The nonreciprocal effect is easy to see if we make certain changes in our design to do so, make sure the thickness of the magnetic films is within a certain range, this will ensure that the magnetic material has nonreciprocal effect while suppressed any active losses. The proposed device is consisting of two signal lines made of metal (Aluminum), Silicon dioxide layer, Ni-Fe core layer.

1.3 Magnetic material

When we think about the magnetic material the first thing comes into our mind is permeability [1]. This property is the main reason why we are using paramagnetic materials in our RF IC circuits. The properties of magnetic materials depend on the speed and orbital angular momentum of the electrons with the atom. The spin of electrons inside the atom determines the magnetic moment in that atom. Magnetic moments, orbital location and a total number of electrons in an atom can be explained according to Pauli, Hund, and Aufbau principles. The types of magnetic material can be determined by the rotation of electrons in the orbit. Therefore, there are three kinds of magnetic material we can find, when we try to identify the location of electrons in an atom. Usually, there are two kinds, first when all the atomic orbitals are filled, and there are no magnetic moments inside the material. In such cases, these materials do not show any magnetic effect and the net magnetic moment in such materials is zero. Therefore, these materials are classified as diamagnetic materials, and their susceptibility is negative.

On the other hand, when atomic orbitals are not filled or have unpaired electrons we classify such materials as paramagnetic materials. The magnetic moments of these electrons do not cancel each other, and thus, the magnetic materials have a positive susceptibility. The magnetic moments in the paramagnetic material are random because of their unpaired electron presence in atoms. Further, paramagnetic materials are three different types (ferromagnetic, antiferromagnetic and ferrimagnetic).

Ferromagnetic materials are those materials which are having neighboring spins parallel to each other below a certain temperature known as Curie temperature which gives us a net magnetic moment in ferromagnetic material. In this material, electron spins inside the atom align in the same direction due to which they produce some effect of the magnetic moment in any particular direction. In the case of a ferromagnetic material, spins are antiparallel to each other below the Neel temperature. When no external magnetic field is applied overall magnetic moment in ferromagnetic materials, cancel off magnetic sublet and above the critical temperature, the thermal agitation destroys the alignment of the magnetic moment which caused the transition to the paramagnetic estate. Whereas in the case of ferromagnetic materials the electron spin is aligned in antiparallel direction but odd magnetic moment into sublet base are present (shown below). Therefore, the net magnetic moment is present in the ferrimagnetic material. Examples of ferromagnetic materials are a combination of Fe_2O_3 with one of the following metals: Mn, Fe, Co, Ni, Cu, and Zn. The figures below give the idea about the type of spin in different kind of magnetic materials.

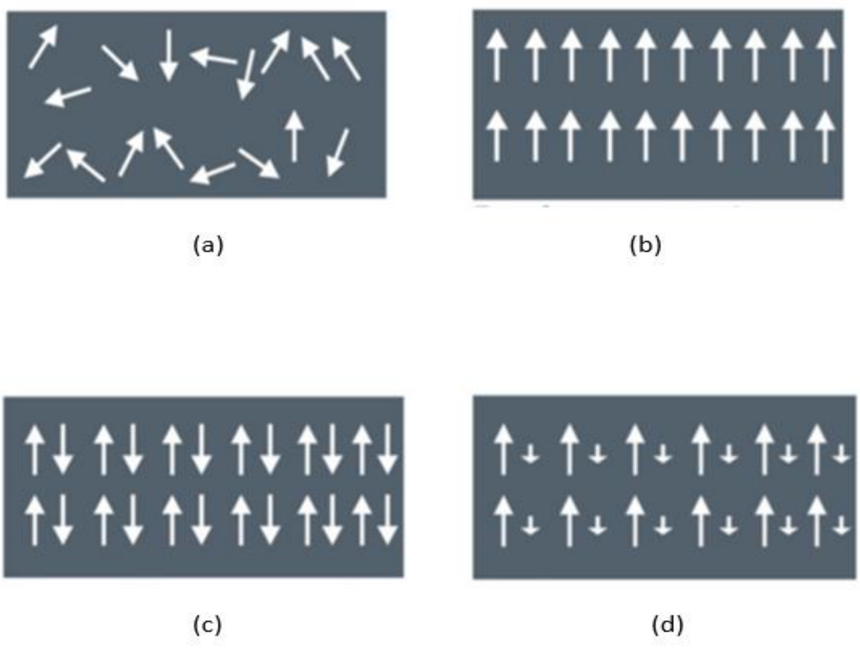


Figure 1.5: Magnetic materials moment: (a) paramagnetic, (b) ferromagnetic, (c) anti-ferromagnetic and (d) ferrimagnetic materials.

1.3.1 Ferromagnetic material

Ferromagnetic materials belong to paramagnetic materials. Ferromagnetic materials have single crystalline structure, and they have their own magnetic moments due to which these materials are easy to scalable, and they had its magnetic properties. The main advantage of ferromagnetic materials is that we can achieve high permeability and magnetic saturation without applying external magnetic field. The ferromagnetic material is fully compatible with CMOS technology and low processing temperature to integrate devices on the large-scale.

The RF integrated passive components on a chip requires the magnetic material for their operation. One of the main reason to use the magnetic materials is to make them scalable and improves the on device performance for our passive applications. Due to all these benefits, the ferromagnetic material is suitable for RF applications.
One of the amazing disadvantages of RF planar inductor is that they occupy large area on-chip and has a low-quality factor. On the other hand, for the air core inductors which are surrounded by nonmagnetic layers the energy stored is limited and increases with permeability. By incorporating high permeability magnetic materials, the quality factor of RF component can be improved. Magnetic materials can be applicable for various RF applications such as inductors, transmission lines, Coplanar Waveguides, etc. In the case of transmission line applications of using magnetic materials with high permeability reduces the propagation velocity and wavelength at a specific frequency, which reduces the transmission line component on-chip. Therefore, the ferromagnetic materials with high permeability are the most candidate for our passive applications, and this is also supervised or proposed by the international technology roadmap (ITRS).

A high permeability ferromagnetic materials are the best option to integrate and to make basic components on RF Integrated Circuits. An integrated microstrip semantic representation is shown in Figure 1.3. The easy access of the magnetic field is parallel to the signal lines, thereby ensuring that the AC field generated by the current in the hard metal is aligned with the hard axis, thus sensing a high permeability. Similar to the case of an inductor, the high permeability of magnetic film increases the inductance per unit length of transmission line, thereby also increase quality factor and characteristic impedance. Incorporation of high ferromagnetic material and solve the problem for characteristics impedance and loss, ferromagnetic core allows reduction of overall attenuation in the transmission line while maintaining constant characteristic impedance.

While the Conductive loss in magnetic film limits the overall acceptable magnetic film thickness, another limitation of this device is that permeability of magnetic film does not remain constantly high as one goes up in frequency. The frequency range of operation on microstrip is limited by so-called ferromagnetic resonance (FMR) frequency. One of the ways to increase the ferromagnetic resonance is to change the strip size to narrow.

Non-conventional or non-reciprocal devices need magnetic material core for its operation. These devices have two or more ports to transfer and detect wave. Waves are flowing like a current inside these materials; we can also control the flow of wave. There is not much discovery made in the field of realizing these devices on silicon that is why the detailed study of non-reciprocal devices are needed.

1.3.2 Ferrite material

The ferrite materials were first discovered in the World War II by J.L Snoek at the Philips Laboratory. He studied the properties of ferrite material and suggested that magnetic loss as a function of frequency and also demonstrative that materials of high permeability cannot be used for low-loss applications at high-frequency ranges. RF components that utilized ferrite materials as for improving performance off chips. The main advantage of ferrite material is their high resistivity which relates to lower losses. However, the RF component using ferrite materials need an external magnetic field aligned to align the magnetic moment inside the ferrite materials; ferrite materials have double sub-lattice crystal structures.

Therefore, it becomes tough to integrate the RF component using ferrite material. In addition to this ferrite material also needs high processing temperature range between 500°C- 900°C in order to achieve internal strain and achieve high permeability value. Thus, the high processing temperature diffuses the wafer dopants and ion implantation in the integrated circuit. Ferrite materials is a major drawback when dealing with monolithic RF surface. Thus, the ferrite material is incompatible with current semiconductor CMOS technology due to high processing temperature requirement for device fabrication in addition to this ferrite material magnetic properties depend on crystalline structures which make them even harder for device scaling. Therefore, scientists are, and researchers discovered a new type of magnetic material, which can solve this problem is a ferromagnetic material.

1.3.2 (a) Temperature and Fabrication

Ferrites are created by icy or hot squeezing powders arranged by ball processing or by precipitation from the arrangement. In the ball processing process, *NiO*, *ZnO*, and *Fe2O3* powders are blended in refined water and dried at 100°C. The blend is preferred in the air somewhere around 900° and 1,100°C and ball processed for 36 hours to a size of 0.1 to 1 um (times and temperature may fluctuate). The processed powder can then be cool squeezed and sintered, or hot squeezed in artistic kicks the bucket at 1,100° to 1,200°C. *MnZn* ferrites are framed in the comparable way aside from that the last sintering is proficient in a controlled climate of nitrogen with a little measure of oxygen, a run of the mill proportion being 0.2(O2):1.0(N2).

Elective materials, for example, *MnCO3* or *NiCO3* might be utilized as a part of powder readiness set up of *MnO* and *NiO*. The option strategy for powder arrangement, known as the "wet" or "coprecipitation from arrangement" method produces a material of higher immaculateness and a better beginning molecule size.

Different systems for acquiring high-thickness material are the vacuum sintering of *MnZn* ferrite and hot isostatic squeezing. The last system includes hot squeezing presented ferrite material that has a porosity of under 5% in an argon environment at temperatures adequate to bring about some grain development, and at a weight of 20 Mpa or more. Hot isostatic squeezing is not shape restricted and permits a huge number of blocks to be hot squeezed at the same time.

1.3.2 (b) Example and application of Ferrites

Magnetic ceramics are made of ferrites, in simple words ferrimagnetic materials are that magnetic material which is in the form of MFe_2O_4 *(where M=Mg, Mn, Cr, Co, Fe, Ni, or Fe)*. The most common ferrite is magnetite, this is naturally occurring ferrous ferrite *($Fe[Fe_2O_4]$, or Fe_3O_4)* commonly known as lodestone.

Ferrites have multiple uses in several different areas of science and physics. Hard Magnetic Ferrites can be used as permanent magnets and in refrigerator seal gasket. They are also used in microphone and speaker. Mostly permanent magnets are used in an automobile for cordless appliances.

Ferrites made of ceramic have small saturation magnetizations compare to magnetic metals; ferrites can be made much more resistive to electric currents. In soft ferrites, this can be achieved by oxidizing the grain boundaries to get high resistive layers. Greater resistive reduce eddy currents, which takes place in changing magnetic fields environment results in the loss of signal energy to heat. Due to its advantage to reduce eddy current, soft ceramic ferrites are used in telecommunication and transformers, especially at higher frequencies; ferrites were also used in memory storage devices such as tape, floppy disks, and hard drives.

Ferrites are also used in Magnetoresistive random access memory (MRAM) technology, which combines the electron spin (spintronic) devices with the standard silicon-based electronics. The advantage of MRAM over any other material is that it has unlimited read and write capacity. In general, MRAM is designed to write on high and low resistance and retain that state without any applied power. The cells inside MRAM are read by sensing the resistance and analyze it to determine the high or low. This approach is entirely different from any commercial memories such as dynamic random access memory (DRAM) and flash memory that are based on charge storage.

Chapter 2 Modelling of non-reciprocal devices

2.1 Tensor permeability (μ_r) and ferromagnetic resonance (FMR)

Magnetic material is classified based on their alignment of magnetic moments inside the magnetic material with or without the magnetic field application. Three types of magnetism can be possible.

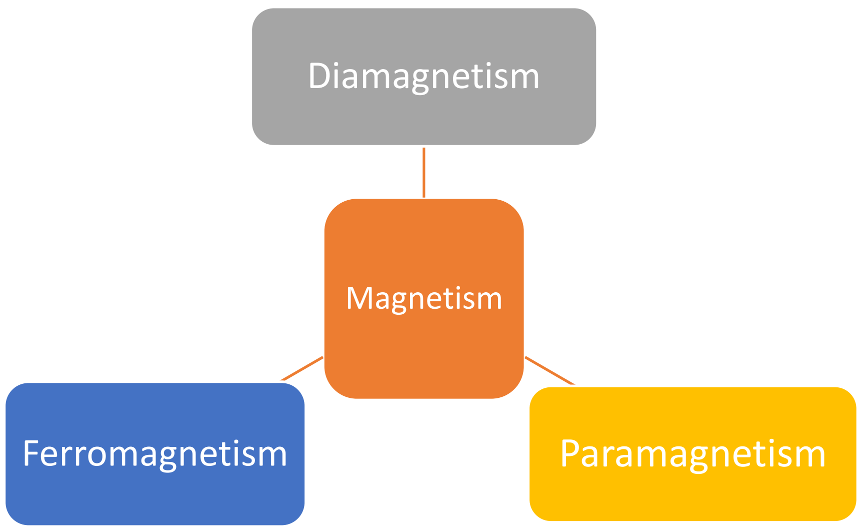


Figure 2.1: Types of magnetism.

Diamagnetism, these are a weak class of magnetism, shows some arise when external magnetic field is applied. It arises due to the orbital motion of electron changes with the magnetic field application; this does not have any magnetic moment of its own when we applied magnetic field all the dipole moment aligns in opposite direction to the field. In diamagnetic material the susceptibility is negative. Example of diamagnetic materials: Al_2O_3, Cu, Au, Si, Zn

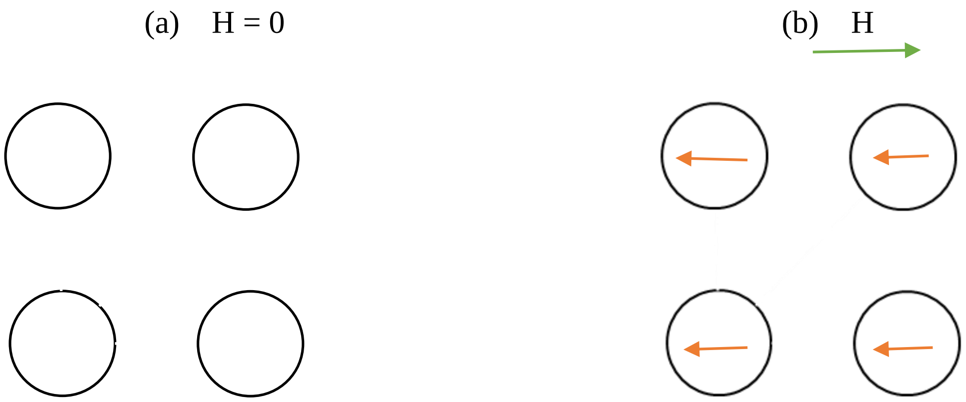


Figure 2.2: (a) Diamagnetic with no external magnetic field applied, (b) Diamagnetic with applied external magnetic field.

Paramagnetism, they have their magnetic moment because the electron pair is incomplete thus magnetic moment exist without external magnetic field. Their net magnetization is zero without any external magnetic field because random alignment of magnetic moments. When the external magnetic field is applied to this, all the dipole moments align in the direction of the field. In paramagnetic material the susceptibility is small but positive. An example of paramagnetic materials: Al, Cr, Mo, Ti, Zr.

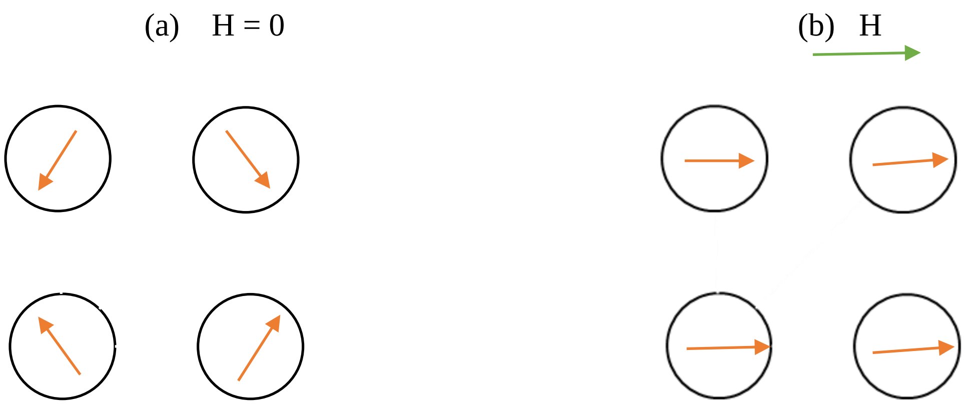


Figure 2.3: (a) Paraamagnetic with no external magnetic field applied, (b) Paraamagnetic with applied external magnetic field.

Ferromagnetism, when material shows permanent magnetic moments in the absence of magnetic field known as ferromagnetism. A permanent magnetic moment in ferromagnetism took place because of uncancelled electron spin. At this moment cause by the electron spin coupling of atoms. Ferromagnetic material has empty “d” orbital and thus unpaired electron spin.

Antiferromagnetism, in this electron spin, aligns in anti-parallel direction and cancel the net magnetic moment arise, this is known as antiferromagnetism. An example is MnO.

Ferrimagnetism, represented by MFe_2O_4, where M is metal, having permanent magnetic effect, termed ferrimagnetism, due to partial cancellation of spin moments. The basic properties of ferromagnetic material are discussed in this thesis. We have selected ferromagnetic materials for our thesis work because they do not need any external magnetic field and can attain magnetic saturation without any external magnetic field, they can also work on less temperature. The properties of ferromagnetic materials are also very similar to ferrimagnetic materials, both of these materials exhibit the same behavior within the microwave frequency range [8].

To investigate the magnetic material applications, we need to place it under the influence of external magnetic field. In general, time changing magnetization M inside a magnetic material is given by Landau-Lifshitz-Gilbert (LLG)

From quantum mechanics relationship between the magnetic spin momentum μ and angular momentum L of electron is given as

$$\mu = -\gamma L, \text{ Eqn. (2.1)}$$

Where $\gamma = 28024.95\ \mu\ Hz\ T^{-1}$ is the value for the gyromagnetic in our case, general formula to calculate γ is given by

$$\gamma = \frac{g\ |e|}{2\ m_e C}, \text{ Eqn. (2.2)}$$

Where g is Lande splitting factor, e=-1.6$\times$ 10^{-19} Kg is mass of electron, C=3$\times$ 10^{8} m/s speed of light.

By angular momentum theorem, we can say that

$$\frac{dL}{dt} = \mu \times H, \text{ Eqn. (2.3)}$$

By using Eqn. (2.1) & Eqn. (2.3)

$$\frac{du}{dt} = -\gamma\mu \times H, \text{ Eqn. (2.4)}$$

The Lamar frequency for frequency of precision is

$$f_L = \frac{\gamma H}{2\pi}, \text{ Eqn. (2.5)}$$

Eqn. (2.4) can be written for each magnetic moment with elementary volume dV_r

$$\frac{d\mu_j}{dt} = -\gamma\mu_j \times H, \text{ Eqn. (2.6)}$$

Now, by taking volume average

$$\frac{1}{dV_r}\frac{d\sum j\mu_j}{dt} = -\gamma\frac{\sum j\mu_j}{dV_r} \times H, \text{ Eqn. (2.7)}$$

Now, magnetization of vector is given by

$$M(r) = \frac{\sum_j^N \mu_j}{dVr}, \text{ Eqn. (2.8)}$$

So, the Eqn. (2.4) will transform into M, this is continuum gyromagnetic precession model

$$\frac{\partial M}{\partial t} = -\gamma M \times H, \text{ Eqn. (2.9)}$$

Where H=H_{eff},

$$H_{eff} = \frac{2}{\mu_0 M_s}\nabla.(A\nabla m) - \frac{1}{\mu_0 M_s}\frac{\partial f_{an}}{\partial m} + H_m + H_a, \text{ Eqn. (2.10)}$$

First ever dynamical model for the precessional motion of magnetization was proposed by Landau and Lifshitz in 1935, which is given by Eqn. (2.6)

The important part to investigate in Eqn. (2.6) is that if we delete the rate of change $\frac{\partial m}{\partial t}$ from this equation we left with only Brown's Equations in equilibrium condition. We can observe that Landau-Lifshitz equation is a conservative equation. Nevertheless, dissipative processes take place within dynamic magnetization processes.

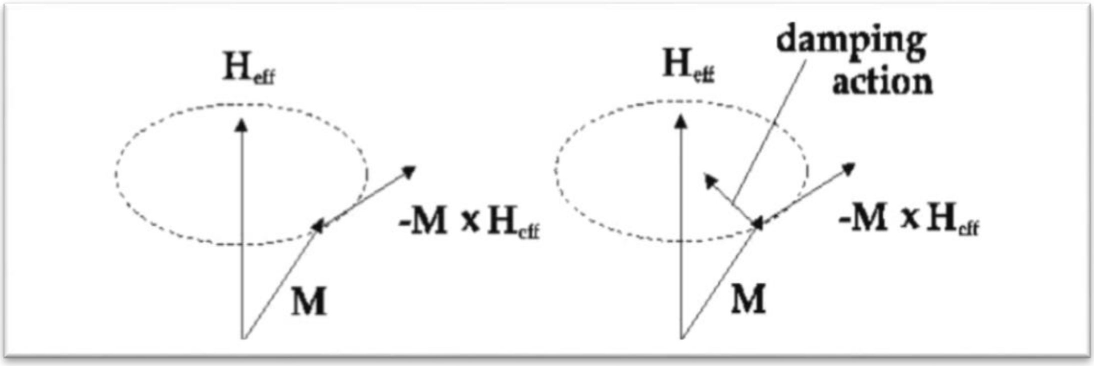


Figure 2.4: (left) Undamped gyromagnetic precession. (right) Damped gyromagnetic precession. Magnetization (M) is represented, under the influence of external magnetic field while H_{eff} is constant.

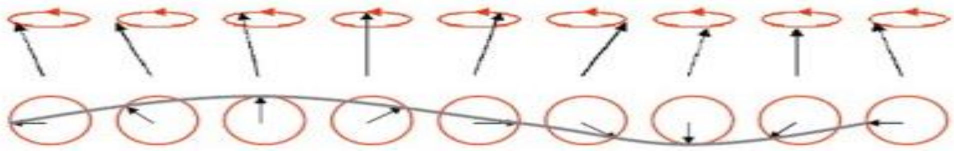


Figure 2.5: A spin wave on a spin chain. Top: the spins viewed in perspective. Bottom: the spins viewed from above, showing one wavelength. The wave is drawn through the ends of the spin vectors. For clarity, the trajectories of spin precession are shown as circles [1].

Introducing an additional torque term pushes the magnetization in the direction of the effective field. Then, Landau-Lifshitz equation becomes

$$\frac{dM}{dt} = -\gamma M \times H_{eff} - \frac{\lambda}{M_s}(M \times H_{eff}), \text{ Eqn. (2.11)}$$

Where $\lambda > 0$ is a phenomenological constant characteristic of the material. It is important to observe that magnetization magnitude is preserved according to $|M| = M_s$. This can be seen by scalar multiplying both sides of Eqn. (2.8) by M.

Gilbert proposed a new principal approach in 1995, who observed that conservative equation Eqn. (2.6) can be derived from Lagrangian formulation where the role of generalized coordinates is played by a magnetization vector M_x, M_y, M_z. Thus, the most natural way to introduce dissipation is through viscous force. He proposed the following additional torque term.

$$\frac{a}{M_s} M \times \frac{\partial M}{\partial t}, \text{ Eqn. (2.12)}$$

Which correspond to torque produced by a field $-\frac{a}{\gamma M_s} M \frac{\partial M}{\partial t}$, where $a > 0$ is the Gilbert's damping constant, depending on the material. When we analyze the fundamental properties of magnetization, we observe that Gilbert damping is connected ton the assumption of a suitable Rayleigh dissipation function. Therefore, the Eqn. (2.6), modified according to Gilbert's work and is generally referred to as Landau-Lifshitz-Gilbert equation or (LLG).

$$\frac{dM}{dt} = -\gamma M \times H_{eff} + \frac{\alpha}{|M|} M \times \frac{dM}{dt}, \text{ Eqn. (2.13)}$$

Where M is the magnetization in solids, H_{eff} is an effective field. The effective field H_{eff} is combination of external magnetic field, demagnetizing field (magnetic field due to magnetization), and some quantum mechanical effect. γ is gyromagnetic ratio and it is, given by the ratio of $\gamma/ 2\pi \simeq 28$ GHz/T. The parameter α in the above equation is Gilbert damping constant. Its value is constant but it shows, that under the influence of DC field magnetization align with the effective magnetic field acting on it.

As we discussed earlier in this chapter under ferromagnetism material, material which are having a permanent magnetic effect are classified as ferromagnetic. Based on this statement we can say that ferromagnetism can be used as to characterize the magnetic behavior of materials, the origin of this strong magnetism in ferromagnetic is because of the presence of spontaneous magnetization which is produced by a parallel alignment of spins. Instead of parallel alignment of spin if we have anti-parallel alignment of different spins, this result in ferrimagnetism. The parameter to detect ferromagnetic material is ferromagnetic resonance (FMR) method. To understand FMR we first need to understand spin waves, spin waves are eigen-excitations in ferromagnetic medium, existing in microwave frequency wave. The classical description of spin waves is given by LLG (eq.2.10).

Landau-Lifshitz-Gilbert (LLG) equation is not enough to discuss RF and microwave magnetic devices at the power level we are interested. Thus, we need to introduce the concept of time-harmonic to change this equation in susceptibility tensor $\overleftrightarrow{x}$. Then, equation will be given as [5]

The magnetic flux density B in ferromagnetic or ferromagnetic material is given by

$$\overleftrightarrow{B} = \mu_0\left(\overleftrightarrow{H} + \overleftrightarrow{M}\right), \text{ Eqn. (2.14)}$$

Where $\overleftrightarrow{B}$ is magnetic flux density, $\mu_0 = 4\pi \times 10^{-7}(H/m)$ is the permeability of free space, $\overleftrightarrow{H}$ is the applied magnetic bias field (A/m), and $\overleftrightarrow{M}$ is the magnetization (A/m). Increase in $\overleftrightarrow{H}$ to saturation and then decrease $\overleftrightarrow{H}$, the flux density $\overleftrightarrow{B}$ decreases but non rapidly as initial magnetization. When $\overleftrightarrow{H}$ reaches zero, there is residual $\overleftrightarrow{B}$ density (called the remanance). To bring back $\overleftrightarrow{B}$ to zero, we must reverse the magnetic field.

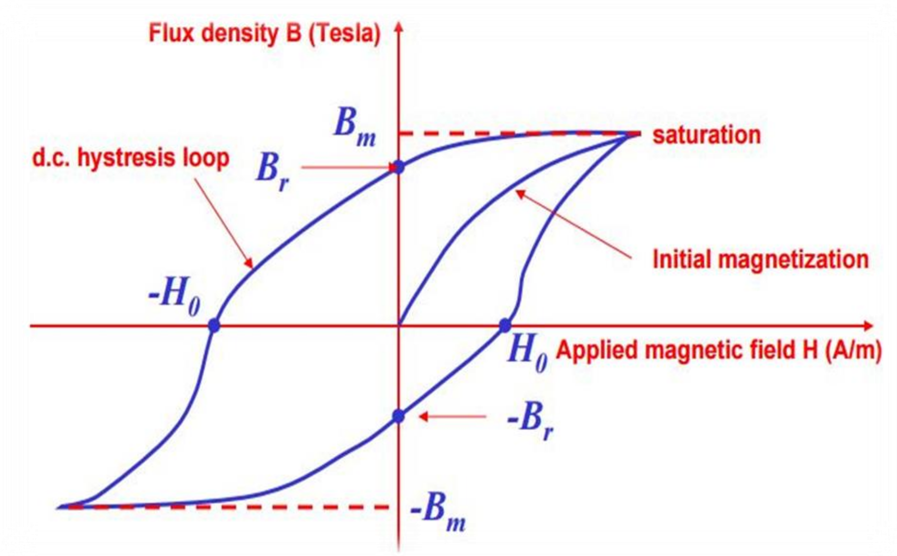


Figure 2.6: D.C hysteresis loop.

Now we see the equation when RF signal interact with ferrites, assume that RF wave is propagating through ferromagnetic material with a D.C. bias field $\hat{z}H_0$.

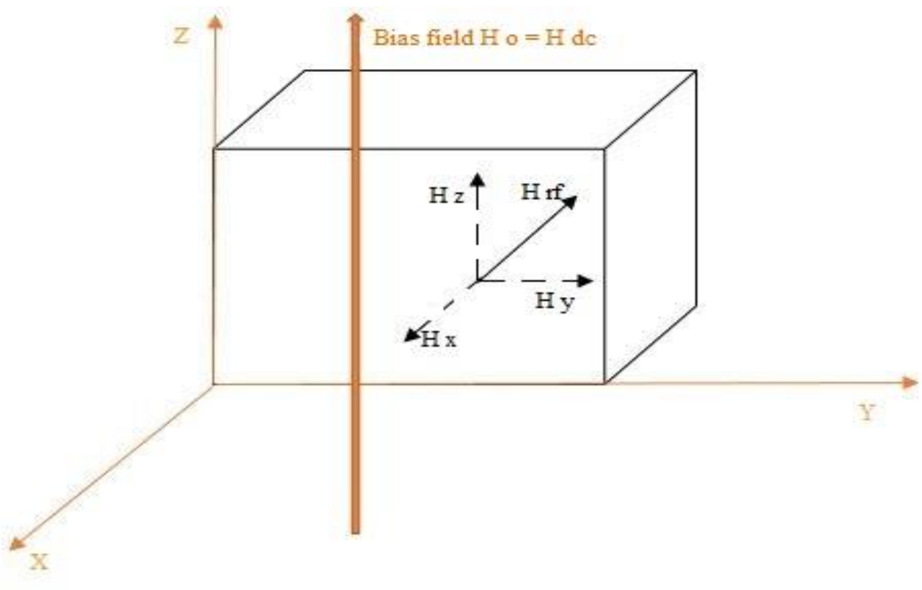


Figure 2.7: RF field on the ferromagnetic material.

The RF field acting on ferrite is given by

$$\overline{H}\,rf=\hat{x}Hx+\hat{y}Hy+\hat{z}Hz, \text{ Eqn. (2.15)}$$

The DC field is given by: $\overline{H}\,dc=\hat{z}Ho$

The total field calculation is

$$\overline{H}\,total=\overline{H}\,rf+\overline{H}\,dc, \text{ Eqn. (2.16)}$$

The field due to material magnetization is

$$\overline{M}t=\overline{M}rf+\hat{z}\overline{M}s, \text{ Eqn. (2.17)}$$

The eq. of motion is

$$\frac{d\overline{M}t}{dt}=-u_0\gamma M_t\times H_t, \text{ Eqn. 2.18}$$

$$\rightarrow \begin{cases} \frac{dMx}{dt}=-\omega_0 M_y+\omega_m H_y \\ \frac{dMy}{dt}=\omega_0 M_x-\omega_m H_x \\ \frac{dMz}{dt}=0 \end{cases}$$

For time harmonic (e^{jwt}) RF field

$$Mx=XxxHx+XxyHy+0Hz, \text{ Eqn. (2.19)}$$

$$My=XxyHx+XyyHy+0Hz, \text{ Eqn. (2.20)}$$

$$Mz = 0Hx + 0Hy + 0Hz, \text{ Eqn. (2.21)}$$

Moreover, thus we get magnetic susceptibility as:

$$Xxx = Xyy = \frac{\omega_0 \omega_m}{\omega_0^2 - \omega_m^2}, \text{ Eqn. (2.22)}$$

$$Xxy = -Xyx = \frac{-j\omega\omega_m}{\omega_0^2 - \omega^2}, \text{ Eqn. (2.23)}$$

It can also be written in matrix tensor form

$$\begin{bmatrix} Mx \\ My \\ Mz \end{bmatrix} = \begin{bmatrix} Xxx & Xxy & 0 \\ Xyx & Xyy & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} Hx \\ Hy \\ Hz \end{bmatrix} \Longrightarrow [M] = [X][\mathrm{H}], \text{ Eqn. (2.24)}$$

Where $Mx, My \; and \; Mz$ are magnetic a response. $Xxx, Xxy, Xyx, and \; Xyy$ are susceptibility tensor.$Hx, Hy, and \; Hz$ are applied RF field.

Now the magnetic flux density in the ferromagnetic material, due to RF field and D.C bias field

$$\bar{B} = \mu_0(\bar{H} + \bar{M}) = [u]\bar{H}, \text{ Eqn. (2.25)}$$

For isotropic material

$$\bar{B} = [u]\bar{H}, \text{Eqn.} \, (2.26)$$

$$\bar{B} = u[X](\bar{H}) + \mu_0 u\bar{H}, \text{ Eqn. (2.27)}$$

Where u is $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$

$$\text{So, } [u] = u_o\{[u] + [X]\} = \begin{bmatrix} u & jk & 0 \\ -jk & u & 0 \\ 0 & 0 & u_0 \end{bmatrix}, \text{ Eqn. (2.28)}$$

The following equation gives relationship between permeability tensor and susceptibility tensor:

$$u = u_0(1 + Xxx) = u_0(1 + Xyy), \text{ Eqn. (2.29)}$$

$$\left.\begin{aligned} u(\omega) &= u_0\left[1 + \frac{\omega_0\omega_m}{\omega_0^2 - \omega^2}\right] \\ k(\omega) &= -ju_0Xxy = u_0\,\frac{\omega_0\omega_m}{\omega_0^2-\omega^2} \end{aligned}\right\}$$

Depends on Ho, Ms, and frequency where ($\mu = \mu(\omega)$ and $u_a = k(\omega)$)

Note: It is assumed here that material is magnetically lossless. In this case both μ and k are real valued.

In lossy magnetic material, we consider $\alpha = loss\ damping\ factor$ so our $\omega_0 \rightarrow \omega_0 + j\alpha\omega$

$$\left.\begin{aligned} \chi_{xx} &= \chi'_{xx} - j\chi''_{xx} \\ \chi_{xy} &= \chi'_{xy} - j\chi''_{xy} \end{aligned}\right\}$$

Complex susceptibilities

For Z-biased lossy ferrite, susceptibilities are given by

$$\chi'_{xx} = (4\pi^2)\frac{f_0 f_m[f_0^2+f^2(1+a^2)]}{D_1}, \text{ Eqn. (2.31)}$$

$$\chi''_{xx} = (4\pi^2)\frac{f_0 f_a[f_0^2+f^2(1+a^2)]}{D_1}, \text{ Eqn. (2.32)}$$

$$\chi'_{xy} = (4\pi^2)\frac{f f_m[f_0^2+f^2(1+a^2)]}{D_1}, \text{ Eqn. (2.33)}$$

Where D_1 is given by

$$D_1 = [f_0^2 + f^2(1 + a^2)] + 4f_0^2 f^2 a^2, \text{ Eqn. (2.34)}$$

$$a = \frac{\Delta H}{2H_0^r}\ (attenuation\ factor), \text{ Eqn. (2.35)}$$

Where H_0^r is the applied field H_0.

$$\Delta H = \frac{2a\omega}{u_0\gamma}, \text{ Eqn. (2.36)}$$

To use RF and microwave devices in current IC technology, the size of ferromagnetic film is very thin. Easy axis is parallel to the signal line and perpendicular to this is the hard axis. The relative permeability, in this case, referred as effective transverse permeability. Which is given by

The effective in-plane permeability.'u_{eff}' of ferrimagnetic material is given by: [10, 11, 12, 13, 14, 15, 16]

$$u_{eff} = \mu_0 \frac{\mu_\perp t_{NiFe}+t_{Al}}{t_{NiFe}+t_{Al}}, \text{ Eqn. (2.37)}$$

Where 't_{NiFe}' and 't_{Al}' are the thickness of ferrimagnetic and Aluminum layers respectively. $\mu_\perp$ is the relative in-plane permeability of the ferromagnetic film.

The relation between permeability and frequency is plotted in the figure below.

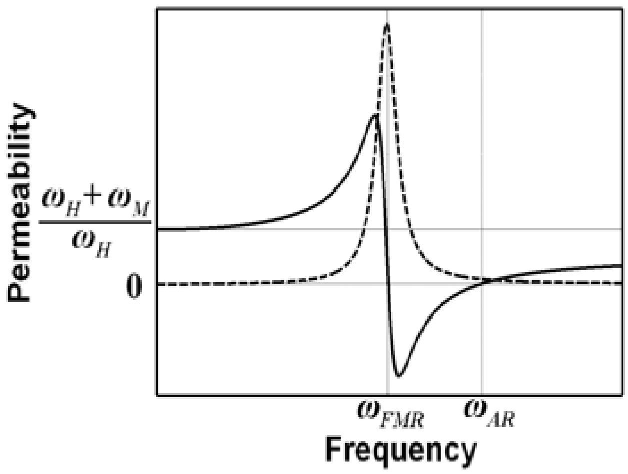


Figure 2.8: (Left) Schematic figure to show metal line. Easy and hard axes are indicated. (Right) The above figure is plotted for $\mu_\perp$, its real part is represented by solid lines and imaginary part is represented by dotted lines.

The relative in-plane permeability.'$\mu_\perp$' of ferrimagnetic film with static magnetization along the stripes is given below

$$\mu_\perp = \frac{\mu^2-\mu_a^2}{\mu} = \frac{f_{AR}^2-f^2}{f_{FMR}^2-f^2} = \frac{(\omega_H+\omega_M)^2-\omega^2}{\omega_H\,(\omega_H+\omega_M)-\omega^2}, \text{ Eqn. (2.38)}$$

In Eqn. (2.17) 'f_{FMR}' represent the ferrimagnetic resonance frequency given by Kittle [14, 15, 16]

$$\omega_{FMR} = \sqrt{\omega_H(\omega_H+\omega_M)}\text{ , Eqn. (2.39)}$$

$$f_{FMR} = \frac{\gamma}{2\pi}\sqrt{H_{H0}(H_0+M_S)}, \text{ Eqn. (2.40)}$$

The ferromagnetic resonance frequency (FMR) was taken into account in the modeling of anisotropic magnetic field by substituting result to $H_0 \rightarrow H_0 + i(\frac{2\pi f}{\gamma})a$, where '$a$' is the Gilbert damping constant.

The anti-resonance frequency is given by 'f_{AR}' is the frequency where the effective permeability goes to zero ($\mu_{eff} = 0$) Eqn. (2.16) [14, 15, 16].

$$\omega_{AR} = \omega_H + \omega_M, \text{ Eqn. (2.41)}$$

$$f_{AR} = \frac{\gamma}{2\pi} (H_0 + M_S), \text{ Eqn. (2.42)}$$

The real part of $\mu_{\perp}$ becomes negative in the frequency range $f_{FMR} < f < f_{AR}$ for small value of Gilbert constant and we call it ferromagnetic resonance (FMR), $\mu_{\perp}$ imaginary part remains positive and we call it anti-resonance frequency.

2.2 Nonreciprocal device working principle

Electromagnetic waves propagation inside the magnetic material gets affected because of its frequency depend on permeability. Landau-Lifshitz-Gilbert equation in linear form, the permeability tensor describes the interaction of magnetic moment of material with the electromagnetic waves, Maxwell equations in magnetic media are referred as 'spin waves'. These waves have small phase and group velocity (i.e., slow wave), these waves were also called as ''magnetostatic waves''.

Consider the magnetic film in Figure 2.3. Assume the conductivity of ferrimagnetic wave is close to zero, the magnetostatic equation is $\nabla \times H = 0$ and in scalar form [1]

$$H = \nabla\psi, \text{ Eqn. (2.43)}$$

Where H is the magnetic field vector, if we combine this with Maxwell's equation $\nabla . B = 0$, this will take a form of Walker's equation

$$\nabla.(\overleftrightarrow{u}\,H) = u\frac{\partial^2\psi}{\partial x^2} + u\frac{\partial^2\psi}{\partial y^2} + u\frac{\partial^2\psi}{\partial z^2}, \text{ Eqn. (2.44)}$$

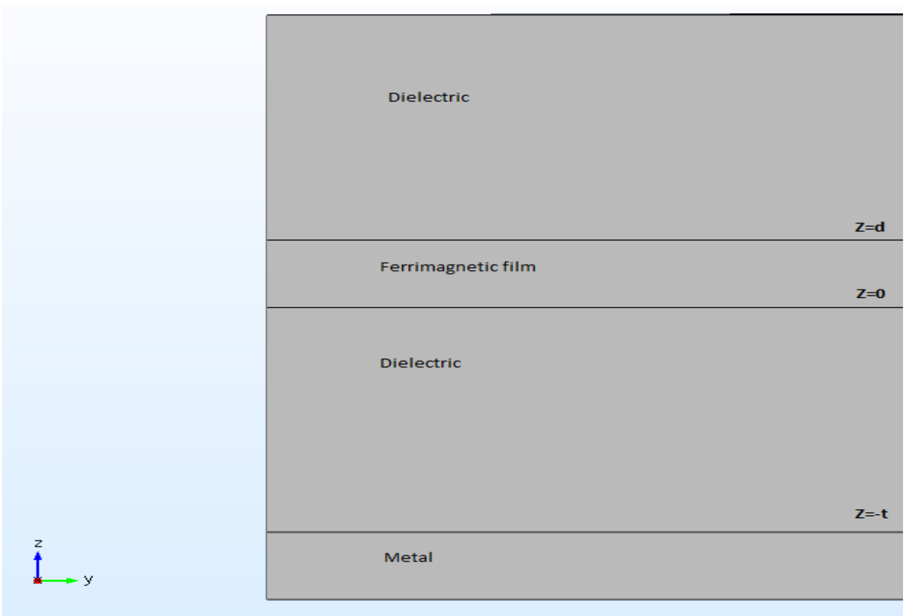


Figure 2.9: A Ferrimagnetic film with the adjacent metallic ground plane. The easy axis of magnetization is along the y-direction, and spin wave propagates in the x-z plane.

The metal layer present cause surface wave propagation to be nonreciprocal.
For magnetostatic wave propagating in the x-y plane takes the form of

$$\psi = [Aexp(\xi z) + Bexp(-\xi z)]\exp(-ik_x x - ik_y y) \quad (0 \le y \le d), \text{ Eqn. (2.45)}$$

Where

$$\xi = k\sqrt{sin^2(\theta) + \frac{1}{u}cos^2(\theta)},\ k = \sqrt{k_x^2 + k_y^2},\ \theta = tan^{-1}(\frac{k_x}{k_y}), \text{ Eqn. (2.46)}$$

$$\psi = [Cexp(ky)]\exp(-ik_x x - ik_y y) \quad (y \le 0), \text{ Eqn. (2.47)}$$

$$\psi = [Dexp(-kz)]\exp(-ik_x x - ik_y y) \quad (y \ge d), \text{ Eqn. (2.48)}$$

Imposing the correct boundary condition, we obtain the condition for wave propagating in the magnetic layer

$$\tan(\xi d) = \frac{2sgn(u)\sqrt{u[u\, sin^2(\theta)+cos^2(\theta)]}}{(u_a^2-u^2)\, sin^2(\theta)-u\, cos^2(\theta)-1}, \text{ Eqn. (2.49)}$$

The above equation results in the propagation of two waves. The first group of waves is called as ‘‘volume waves’’ which are characterized by the sinusoidal dependence of the magnetostatic potential ψ inside the film, along the out-of-plane (normal to direction).

Such solution requires ξ to be completely imaginary ($\xi = iq$) and, this is possible when

$$u[u\, sin^2(\theta) + cos^2(\theta)] \leq 0, \text{ Eqn. (2.50)}$$

The second group of waves is called as “surface waves’’ these waves are represented by the strength of magnetic field near the film surface (decrease exponentially inside the magnetic medium). In this case ξ is positive. Condition requirement for such waves:

$$u[u\, sin^2(\theta) + cos^2(\theta)] \geq 0, \text{ Eqn. (2.51)}$$

Furthermore, due to constraint 0$\leq \tanh(\xi d) < 1$, it is required.

From above equations, it can be proved that magnetostatic surface wave exists in the magnetic layer.

Nonreciprocal wave is an important case of surface wave propagation. We are interested in the flow of magnetostatic wave in a ferromagnetic film having an adjacent metal layer. For transverse propagating wave w.r.t magnetization ($\theta = \frac{\pi}{2}$), Eqn. (2.24), (2.26) and (2.27) can be written in this form

$$\psi = [Aexp(kz) + Bexp(-kz)]\exp(-ikx) \quad (0 \le y \le d), \text{ Eqn. (2.52)}$$

$$\psi = C[exp(ky) + \exp(-k(y + 2t))]\exp(-ikx) \quad (-t \le y \le 0), \text{ Eqn. (2.53)}$$

$$\psi = [Dexp(-kz)]\exp(-ikx) \quad (y \ge d), \text{ Eqn. (2.54)}$$

Now after carefully applying all the boundary condition surface wave propagating inside the ferromagnetic film is given by

$$\tan(kd) = \frac{2u}{(u_a^2 - u^2 - 1) + ((u_a - 1)^{-1} - u^2)\exp(-2kt)}, \text{ Eqn. (2.55)}$$

In reality, the main purpose for the nonreciprocity in a magnetic field is magnetostatic surface waves. These waves flow on the interface of magnetic film close to dielectric films, magnetic field dropping inside the ferromagnetic layer. The metal layer disperses the propagating direction more strongly leads to nonreciprocal effect.

2.3 Comsol Modelling

Model design and simulation is done using comsol Multiphysics software to see the non-reciprocal effect in multilayer ferromagnetic material, we have also suggested different ways to increase the non-reciprocal effect. We have used comsol Multiphysics software with RF module to construct the ferromagnetic film. These steps will guide through comsol important parameter setup, features, and modeling [17].

2.3.1 Comsol RF Module

Comsol RF module provides us a solution for those problems which consist of electromagnetic waves, such as RF and microwave applications, photonics and optics. Equations for electromagnetics are already available in physics setting window. Comsol Multiphysics is also useful in nonstandard modeling.

Physics interface of comsol consist of following types of electromagnetic field simulation and handle time-harmonic, time-dependent, and Eigenmode/Eigen frequency problems:
Comsol supports both in-plane 3D axisymmetric electromagnetics wave propagation model and 2D/3D full vector mode analysis.

Materials properties can set-up in different ways like isotropic, diagonal, symmetric, and anisotropic. Apart from post processing, we can simulate our model for S-parameters and far field patterns. We can also add plots and provide different power level and mode type; we can also add PMLs (Perfectly matched layers) to simulate electromagnetic waves that propagate into an unbound domain. For time-based simulation, we can use scattered waves or total waves. In comsol multiphysics, we can use couple simulation with heat transfer, structural mechanics, and other physics.

Using comsol multiphysics RF Module, we can solve the quasi-static and high-frequency model. There is a major difference between quasi-static and high-frequency modeling, the formulation in these types depends on electrical sizes. This dimensionless measure is the ratio between largest distances between two points in the structure divided by wavelength.

When electrical size is in the range up to 1/10, the quasi-static formulation is suitable, and we will use simulation based on quasi-static. The physical meaning of this is that wave propagation delay is small enough to be neglected. That is why phase gradients and phase shifters are caused by material and conductor arrangements being capacitive or inductive rather being caused by propagation delay.

For electrostatic, magnetostatic and quasi-static electromagnetics problem, use of AC/DC Module in comsol Multiphysics is useful for the low-frequency application.

When the model is based on high frequency, and propagation delay is a very important factor, it is important to use full Maxwell equation for electromagnetics problems. These are appropriate for electrical sizes 1/100 and larger. Thus, an overlapping reason also exists between these two types, where we can use any of these types.

Independent of the structure sizes, each module comes with nonlinear, symmetric, an isotropic or anisotropic media. It also handles material whose property vary with time and frequency –dispersive materials.

2.3.2 Modeling process flow chart for comsol Multiphysics design and simulation

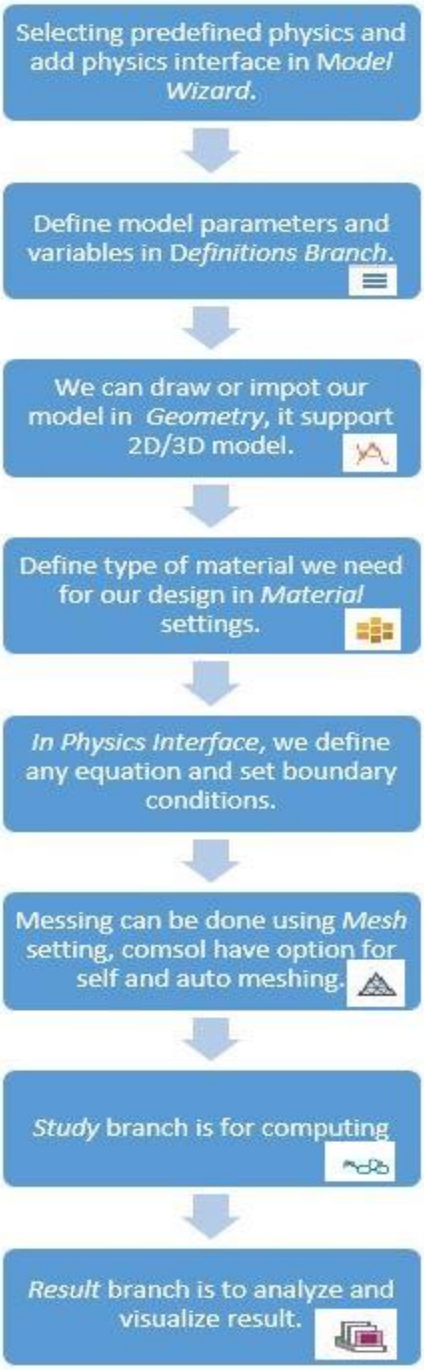


Figure 2.10: Process flow diagram for comsol design.

Even after the complete model is defined we can at any point make changes or select physics, study type, change meshing, define parameter/variable and modify the result.

2.3.3 Magnetic permeability (u_r)

Contribution of this thesis work in the nonreciprocity is that we solved the permeability tensor (u_r) equation, u_r is frequency dependent, which means we simply can't just enter its value in comsol simulation. We have calculated (u_r) value on each frequency between the range (1 GHz-12 GHz) then simulation is performed to extract the S12 and S21 scattering parameter. After, carefully extraction of results, we use software to integrate all our result and plot the real, imaginary, magnitude and phase for our nonreciprocal devices. It is important to note here that nonreciprocity is the effect, which take place close to resonance frequency but comsol does not allow us to simulate our model close to the resonance frequency, this is an open discussion here. That's why we start our simulation from 6 GHz with step size of 200 MHz but we successfully investigated the nonreciprocity in the device. In past many paper were published for nonreciprocity but none of them have suggested the ways to optimize the design. Simulation of device save our time and verified all our models. This thesis work also has suggested different ways to improve nonreciprocity in device.

Magnetic permeability (u_r) comes into effect when our magnetic material is anisotropic. This is defined under Wave Equation in RF module of comsol. Wave Equation consist of several model input options like temperature, pressure and material types. As we discussed earlier that behavior of Ni-Fe magnetic material is anisotropic nature so we have these equations to solve to get the correct relative permeability values (u_r). The above equation consists of μ and μ_a which can be calculated by these equations. μ is real part and μ_a is imaginary part here. Comsol does not allow us to solve below 6 GHz and give failed solution error because value of u_a is grater then one for frequency lesser then 6 GHz. Calculation and equations are given below.

From Eqn. [2.22-2.30]

$$\text{We assume } f_h = 1\ GHz$$

$$\text{So, } \omega_H = 2 * \pi * f_h$$

$$r = 2.8 * e^{10}$$

$$M_s = 1.1$$

$$\omega_M = r * M_s$$

From equations [Eqn. (2.28)], Where ω vary as

$$\omega = 2\omega_H\ to\ 20\omega_H$$

$$u(\omega) = u_0 \left[1 + \frac{\omega_0 \omega_m}{\omega_0^2 - \omega^2}\right]$$

$$k(\omega) = -ju_0 Xxy = u_0 \frac{\omega_0 \omega_m}{\omega_0^2 - \omega^2}$$

$$[u] = \begin{bmatrix} u & jk & 0 \\ -jk & u & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

(when we solve above equation for tensor permeability only enter numeric coefficients of k and u without u_0)

Results of theoretical calculations for (μ, μ_a):

$u(\omega)$	$k(\omega)$
-0.6340	-3.2680i
0.3873	-1.8382i
0.6732	-1.3072i
0.7958	-1.0212i
0.8599	-0.8403i
0.8979	-0.7149i

0.9222	-0.6225i
0.9387	-0.5515i
0.9505	-0.4951i
0.9592	-0.4493i
0.9657	-0.4114i
0.9708	-0.3793i
0.9749	-0.3519i
0.9781	-0.3283i
0.9808	-0.3076i
0.9830	-0.2894i
0.9848	-0.2732i
0.9864	-0.2587i
0.9877	-0.2457i

Table 2.1: Calculated values of real ($u(\omega)$) and imaginary ($k(\omega)$) part of tensor permeability.

2.4 RF Modeling and Simulation

Most of the comsol multiphysics problem are designed in 3D, model in a real environment. In most of the cases, 2D model is also sufficient to solve real problems. Addition to this, it is always good practice to know both 2D and 3D modeling because 2D model requires less time to design and finding an error in 2D is easy. Simulation and meshing were also easy in 2D modeling. Once our 2D model is free from error and it is verified, we are in a much better position to design 3D model.

In Comsol 2D model we have two axis X and Y, Z axis is imaginary. We first convert our 3D model in x-y coordinate assuming z is in an infinite direction (a boundary in 2D is a line). There are usually two methods to design 2D models in comsol, first, when there is no variation in solution in one particular direction and second when there is a problem when the finite extension in the third dimension can be neglected. There are different ways we can build 2D model in comsol; we can use Cartesian Coordinates, Axial symmetry (Cylindrical Coordinates). The example below gives the idea about this discussion.

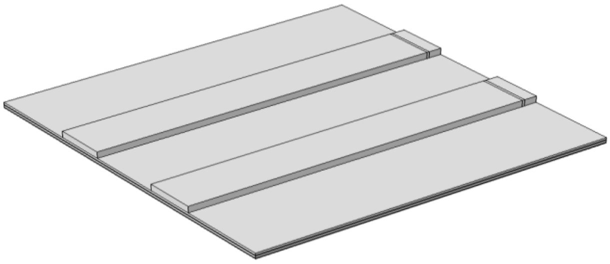
Comsol multiphysics fully supports any 3D model, but it is good practice always to look for existence for a 2D model of that because it can solve a lot of simulation time, meshing, power, and memory. The extra time spent on the simplifying model is worth spent. Below are few points which need to keep in mind before start 3D modeling in the comsol environment.
Check if the same geometry can be created in 2D, the solution is more accurate in 2D because denser meshing can be used.

There is also some condition where we know changes in one direction, and it can be used to use the analytical function. Use this to convert 3D to 2D or to convert the layer to a boundary condition.
Verify asymmetries in the geometry. Many models give the same solution for both sides of the plane.

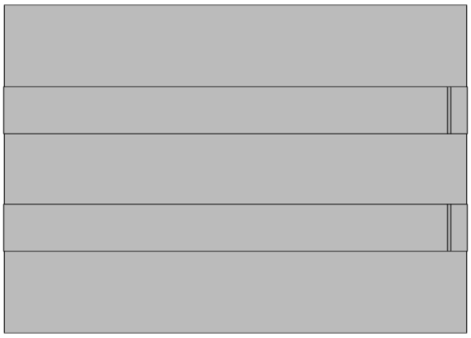
Comsol 3D Model design:

1. Default 3D view in comsol

In this default view, we can see that our model is multilayered consist of Ni-Fe and Sio2.



1. Top 3D view of model in comsol



2. Down 3D view of model in comsol

2.4.1 Using efficient boundary condition

Defining boundary with utmost accuracy can minimize size and save much time during the simulation. This can be applied to both 2D and 3D models. Firstly, it is always good practice to use PMLs (Perfectly matched layers). PMLs absorb radiated waves with little reflections. Secondly, use boundary conditions where ever you like to define layer. Comsol multiphysics has a bunch of layers to suit our need. Like if we have some high conductivity layer/material, we can replace this with perfectly electric conductor (PEC) boundary condition.

2.4.2 Meshing and Solving

The mesh can be very crucial part in comsol; it can be finer or coarse type. We can do meshing by two types First; we can easily mesh by automatic meshing function inside comsol this is called physics controlled mesh this can be found in types of physics interface. Secondly, when we mesh our model manually there are few important steps in meshing manually which we should always keep in our mind while meshing:

1. Firstly, if we choose to do our modeling mesh using automatic meshing then at the places of finer geometrical details mesh will be much finer. Finer mesh is ok, but sometimes when it is not needed it cause solution delay and increase the size so we should always check our geometry if we do not need finer mesh and it does not affect our solution, then we should change it accordingly.

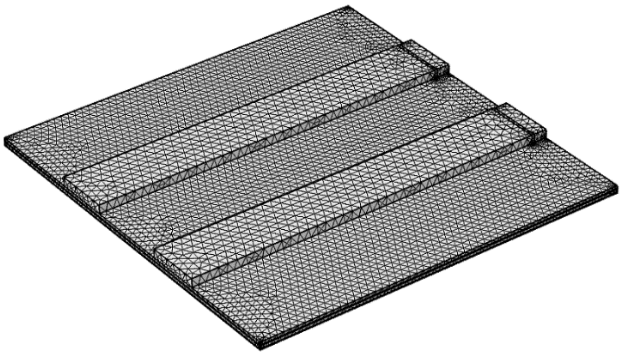
2. Secondly, it is important to solve skin effect or variation field losses; it can be solve using skin depth with boundary conditions.

3. The third and last point are to keep in mind the wavelength; wavelength depends on the material. To solve the problem, it is necessary to use 10 liner element per wavelength.

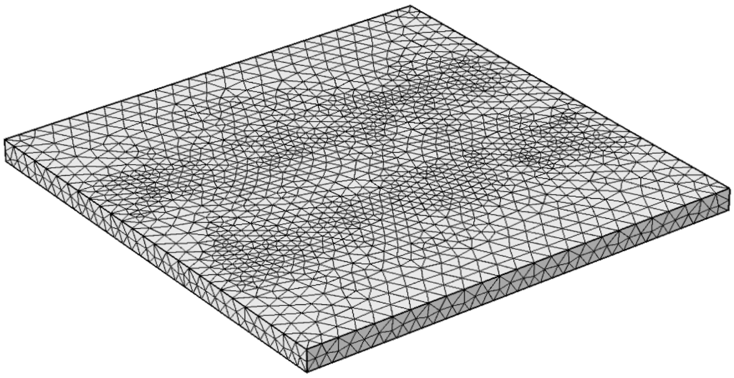
Comsol has its automatic solver generation for each problem. We can use the same solver, or we can modify based on our requirement and geometry. In 3D model, this is important because usually, they are larger in size and sometimes need a 64-bit platform.

Comsol 3D model meshing

1. Meshing of 3D model



2. Meshing of 3D model with boundary



2.5 S-Parameters and Ports

2.5.1 Electric field and S-parameters

Scattering parameters (or S-parameters) are complex quantity, S-parameters are frequency dependent matrices. These are defining for transmission and reflection of electromagnetic waves at different ports. S-parameters can be calculated for following electromagnetics devices like transmission lines, antennas, waveguide, and filters. S-parameter concept came from transmission line theory and defined in the terms of transmission and reflected voltage waves. All ports are connected to matched loads; there is no direct reflection at ports.
S-parameters for a device with n ports are

$$S = \begin{bmatrix} S_{11} & S_{12} & . & . & S_{1n} \\ S_{21} & S_{22} & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ S_{n1} & . & . & . & S_{nn} \end{bmatrix}, \text{ Eqn. (2.56)}$$

Where S_{11} and S_{21} is given by

$$S_{11} = \frac{V_{1,\ out}}{V_{1,\ in}} \ (S_{11}\ is\ voltage\ reflection\ coefficiient\ at\ port\ 1), \text{ Eqn. (2.57)}$$

$$S_{21} = \frac{V_{2,\ out}}{V_{1,\ in}} \ (S_{21}\ is\ voltage\ transmission\ coefficient\ from\ port\ 1\ to\ port\ 2), \text{ Eqn. (2.58)}$$

We know that the voltage and current are not well defined for high-frequency electromagnetics, and so s-parameters are defining regarding the electric field.
Defining s-parameters ports in comsol are easy. There is two type of ports available in comsol one is simple port and the other one is lumped port, lumped port is useful when

our port width dimension is much smaller than the wavelength.

RF module automatically generates a variable for S-parameters. Suppose if we define port 1 and port 2 then S_{11} is the reflected wave and S_{21} is the transmitted wave. If we like to change both of this port in dB, then it can be done by this equation.

$$S_{11_{dB}} = 20log10(|S_{11}|), \text{ Eqn. (2.59)}$$

Port Sweep setting inside the Electromagnetic wave provides us with Touchstone file.

2.5.2 Lumped ports

When the mode is difficult to calculate, or voltage is applied to the port, then it is better to use lumped port. Lumped ports are also useful when we use electrical circuits. Lumped ports are not very precise as normal ports regarding getting S-parameter, it is very easier to use. For example, lumped ports can be applied directly to any transmission feed lines or printed circuit board or any internal port. Lumped port must be applied between two conductive surface and distance between these surfaces must be smaller than the wavelength.

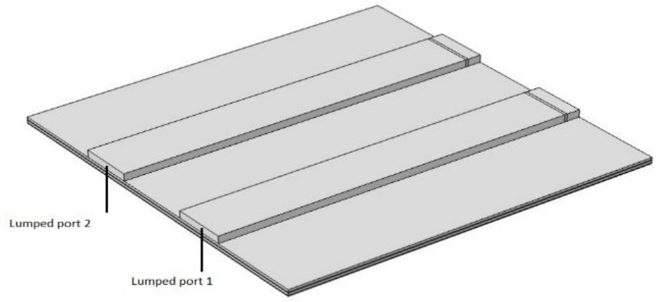
A lumped port as input port calculates Z_{port}, andS_{11}, S - parameter for that port.

The parameters are given by:

$$Z_{port} = \frac{V_{port}}{I_{port}}, \text{ Eqn. (2.60)}$$

$$S_{11} = \frac{V_{port} - V_{in}}{V_{in}}, \text{ Eqn. (2.61)}$$

Where V_{port} is extracted voltage and I_{port} is the average current.



In transmission line theory voltage and current does not exit, electric field and magnetic field work, so we need to be lumped ports to provide an interface between these two.

2.6 The Electromagnetic Waves, Frequency Domain Interface

This physics interface helps us to solve the problem in time-harmonic electromagnetic field distribution. In this physics interface, the mesh in any electromagnetics model relate with their wavelength but for our case, the mesh must resolve local wavelength. Ferrite material has lossy domains, and their skin depth is also too high. We have used thumb rule according to which maximum element size that is one fifth of the local wavelength or less.

In any electromagnetics model, the maximum meshes element size determined by the fraction of a wavelength. The domain simulation must be scale with memory on the computer and the available wavelength. The physics interface supports in Frequency domain study, Eigen frequency, Mode Analysis, and Boundary Mode Analysis. The Frequency domain study can be used to simulate for a single frequency or the range of frequency. Eigenfrequency study is used to find resonance frequencies and Eigenmodes study. This physics interface solves the time-dependent electric field equations.

With this physics interface, we get wave equation, Electric, Perfect Electric Conductor, and Initial Values. Then if we like to add additional physics setting we can do by just right click on physics interface and select the types of boundary or ports we need for example lumped port, wave equation, perfect electric conductor, etc.

Domain selection in comsol is easy, if we know names of the domain then we can directly enter them in paste box or we can select the domain in graphics window by just click on it. All physics interfaces are inbuilt with SI unit's standards.

2.7 Boundary Conditions

Use of scattering boundary condition for outer covered layer makes a boundary transparent for scattered wave. The boundary condition is also transparent for an incoming plane, scattered cylindrical wave, and spherical scattered wave.

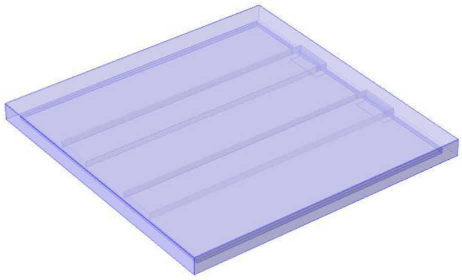
$$E = E_{sc}e^{-jk(n.r)} + E_0 e^{-jk(k.r)} \quad \text{Plane scattered wave, Eqn. (2.62)}$$

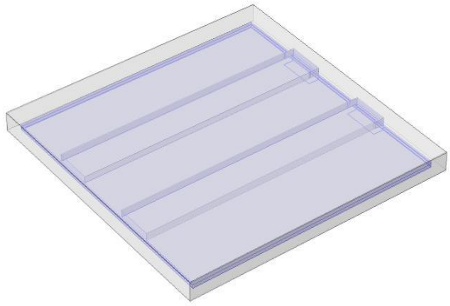
$$E = E_{sc}\frac{e^{-jk(n.r)}}{\sqrt{r}} + E_0 e^{-jk(k.r)} \quad \text{Cylindrical scattered wave, Eqn. (2.63)}$$

$$E = E_{sc}\frac{e^{-jk(n.r)}}{r_s} + E_0 e^{-jk(k.r)} \quad \text{Spherical scattered wave, Eqn. (2.64)}$$

The E_0 is the incident plane wave travel in k direction. Scattering boundary conditions are transparent for any incoming plane waves with any angle of incidence.

1. Boundary over model 2. Transparent view





The boundary is only perfectly transparent for scattered waves.

2.8 Comsol Simulation Results:

In regular propagation media, wave obeys basic property, reciprocity. Reciprocity means wave travel symmetrically between two points in space; reciprocity guarantees that wave propagation always occurs in a symmetrical fashion. If a wave can travel from source from the observer, the opposite path, from observer to source, is equally possible, and the transmission is symmetric [62]. Reciprocity is very naturally occurring concept. When we hear neighbor through a common wall, we also know that they can hear us [59]. In reciprocal network power losses is same between any two port regardless of propagation direction (scattering parameter$S_{12} = S_{21}, S_{13} = S_{31}, etc.$) a network is known as reciprocal if it is passive and contain only isotropic material. Example of reciprocal networks include cables, attenuators, and all passive power splitters and couplers.

The anisotropic material has different electrical properties (such as dielectric constant and concept of complex permeability tensor is introduced) depending on which direction propagation took place. One example of the anisotropic material is the ferrite materials from which circulators and isolators are made. A Classical example of the non-reciprocal device is RF power amplifier and isolators. In both cases S_{12} is different fromS_{21}.

A microwave ferromagnetic multilayered non-reciprocal device is an electromagnetics based model. It has the property that when a wave incident on lumped port 1 gets coupled to port 2 and vice versa. This property of the device is the reason for generating a non-reciprocal effect in the ferromagnetic film. A typical example to understand these waves flow is that when port 1 is excited with incident electromagnetics wave, wave started here is spin wave gets picked up by port 2 and thus wave starts flow on the magnetic film perpendicular to the direction of magnetization, spin wave propagates on lower and upper surface of magnetic film, depending on the direction of propagation. Therefore, the ground connection has to be made at one end of ports; this cause wave dispersion depends on propagation direction. Waves traveling in a different direction have different frequency spectra and thus results in non-reciprocal coupling of microstrip lines.

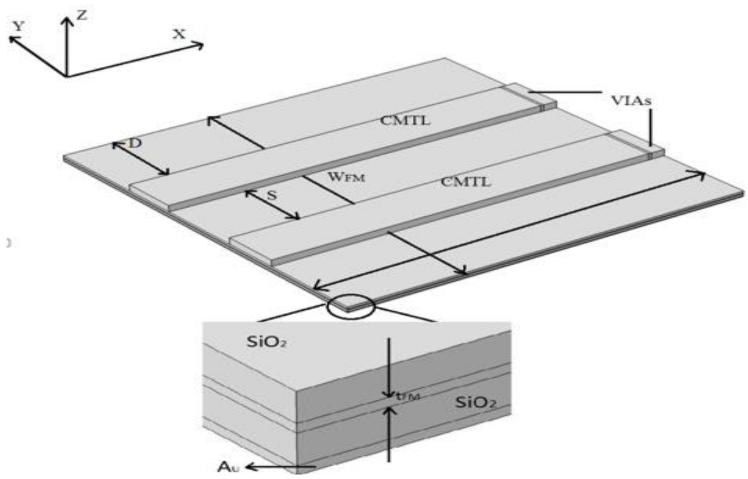


Figure 2.11: The model above is given without the scattering boundary; we can clearly see that the two port ferromagnetic model is placed multilayered. The ferromagnetic magnetic layer is placed between two SiO2 layers. Signal lines are via to ground on one end. Signal line and Bottom layer are being made up of Al, and they are shorted at one end of the signal line.

An important part in designing any microwave based model is to match its input impedance for a given operating frequency. We do impedance matching to minimize the reflections at the inports. The RF module automatically computes s-parameters once the model is designed and all the conditions are fulfilled. The above ferromagnetic-based model is studied between 6 GHz-15 GHz. Comsol does not allow to simulate model below 6 GHz because value of $\overleftrightarrow{\mu_a}$ is greater than one. The model runs fine between 6 GHz-15 GHz, we have made very detailed study on non-reciprocal effect while changing different settings like distance between signal lines, thickness of ferromagnetic layer and etc. The thickness for ferromagnetic film for our research purpose is about 5um-8um, because we also try to change thickness of ferromagnetic film and study non-reciprocal effects.

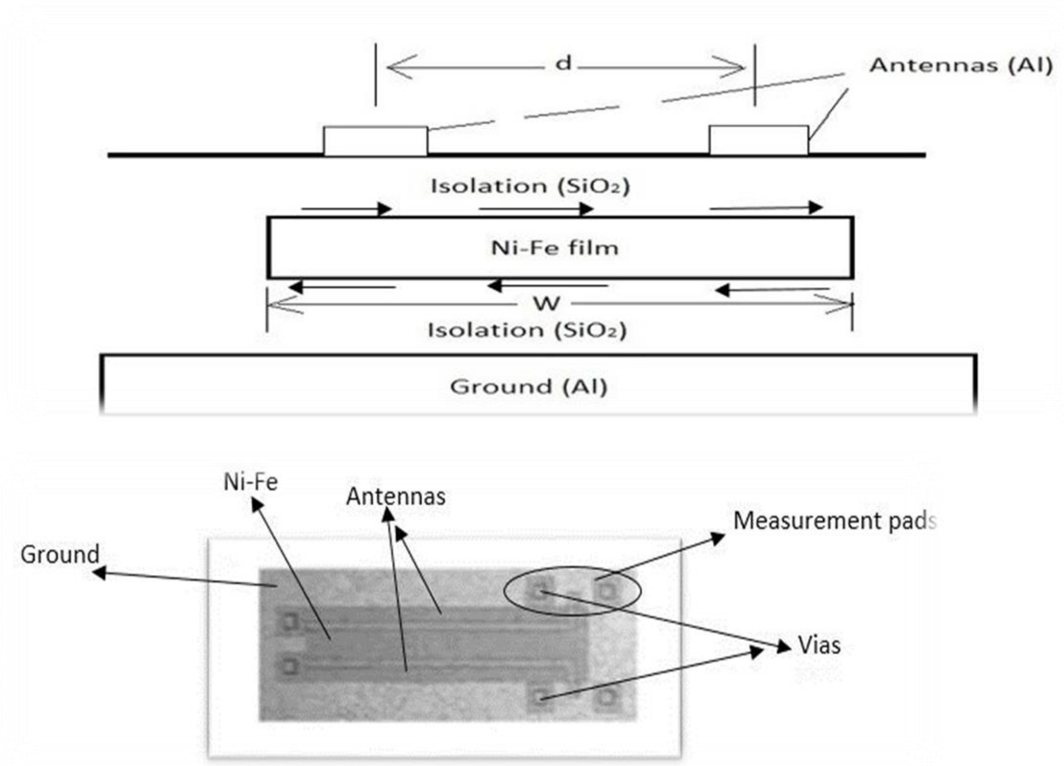


Figure 2.12: (Top) Schematic cross section of the coupled microstrip structure; two aluminum lines are coupled via surface waves propagating on a Ni–Fe layer. The nonreciprocity is enhanced by reducing the 1 um ground-to-ferromagnet separation. (Bottom) Top view microphotograph of a sample device, where the aluminum ground, rectangular patterned Ni–Fe core, microstrip acting as antennas, measurement pads, and via connections to the ground can be seen [63].

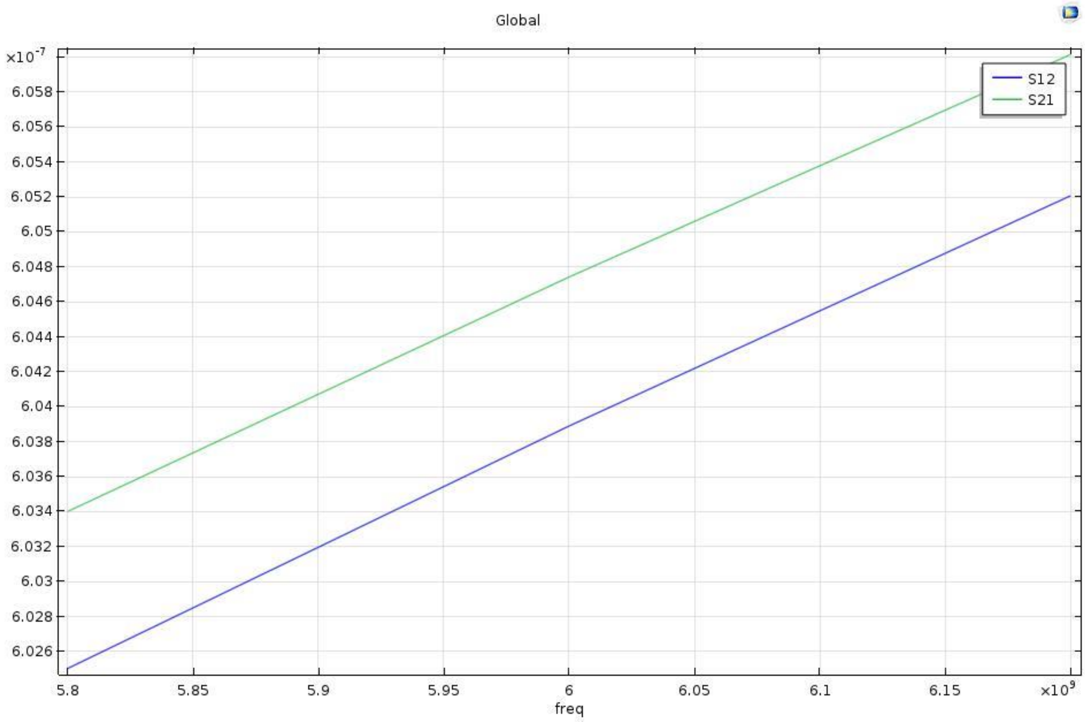
One of the rectangular port is excited by TE_{10} mode, at the ports the boundary is transparent to TE_{10}. The following equation work inside the film

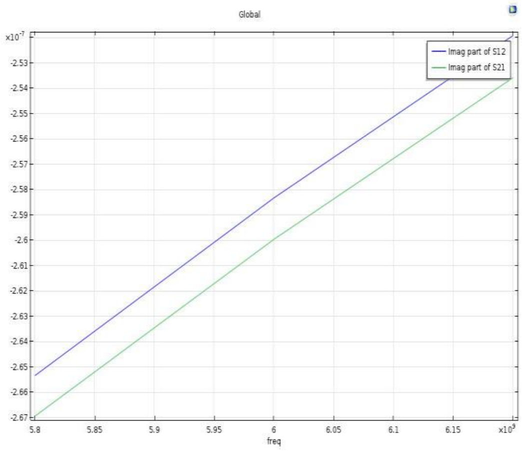
$$\nabla \times (\mu_r^{-1} \nabla \times E) - k_0^2 \left(\varepsilon_r - \frac{j\sigma}{\omega \varepsilon_0}\right) E = 0, \text{ Eqn. (2.65)}$$

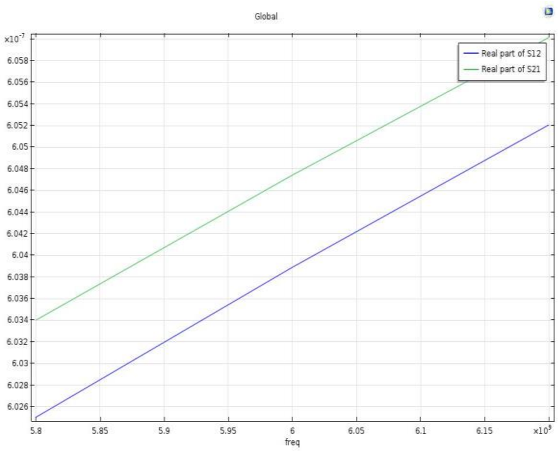
Where μ_r represent the relative permeability tensor, ω is the angular frequency, σ represent conductive tensor, ε_0 is the permittivity of vacuum, ε_r is the relative permittivity tensor, and k_0 is the free space wave number. The conductivity is zero everywhere else. Losses in ferromagnetic are in the complex value of permittivity and permeability tensors. The magnetic permeability μ_r is of great importance here because anisotropic behavior of this leads to nonreciprocal effect in the multilayer ferromagnetic film. The complicated form of permeability is already defined in introduction of ferromagnetic material.

Case 1 study:

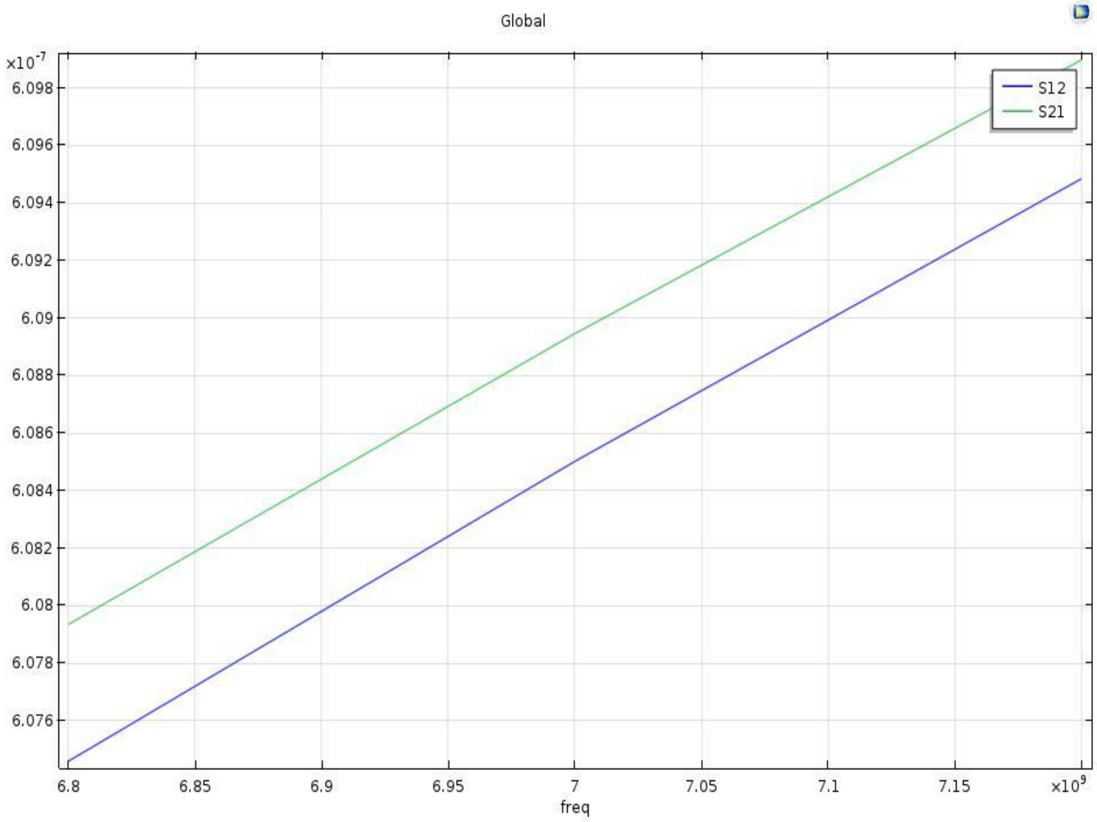
Result 1: Comsol simulation result plot of S12 and S21 parameter for 6 GHz

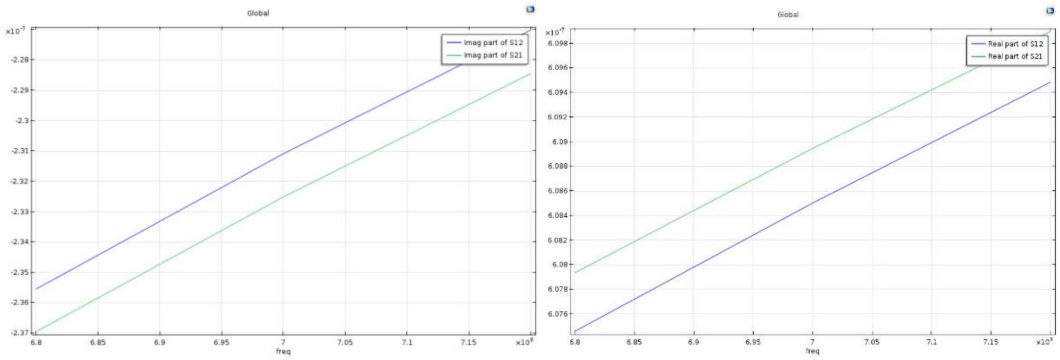




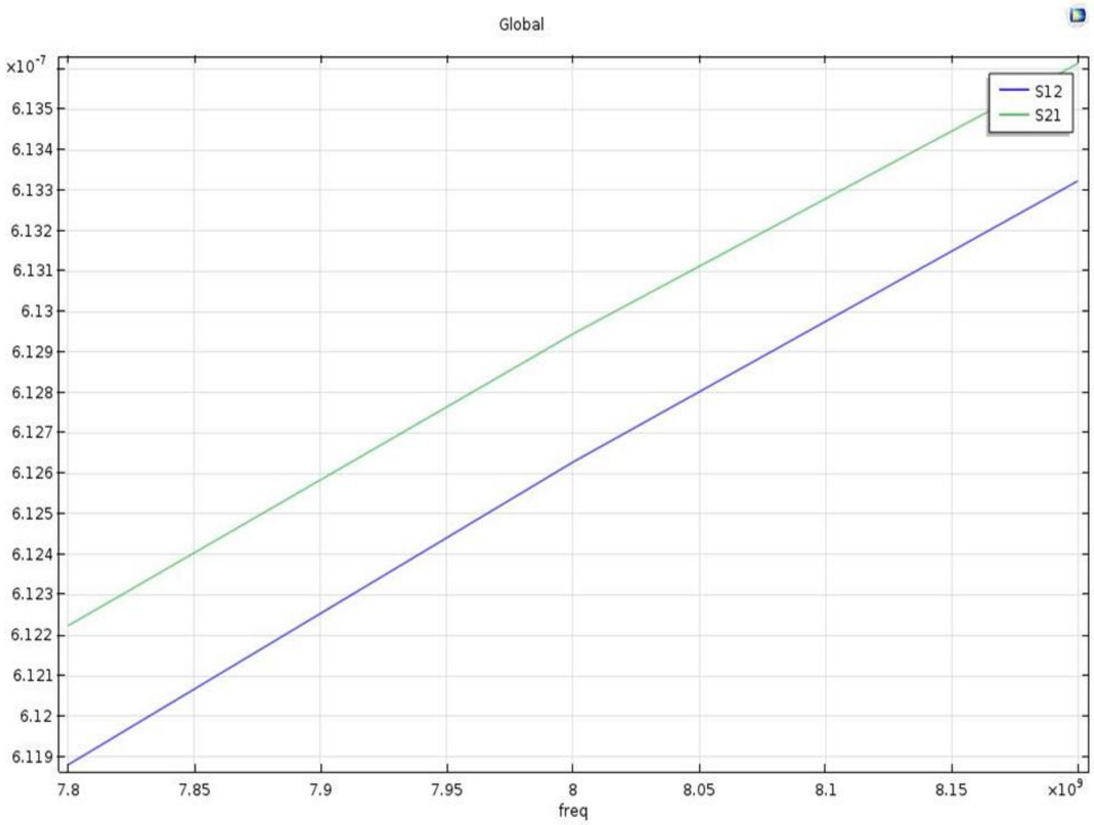


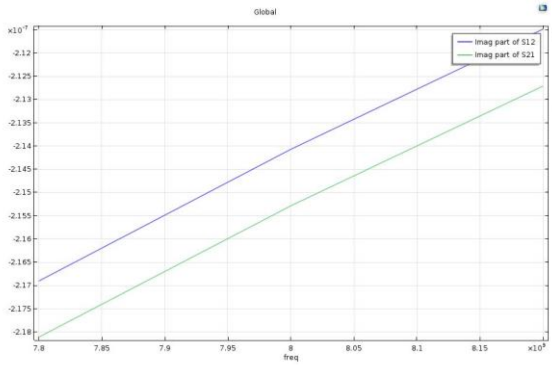
Result 2: Comsol simulation result plot of S12 and S21 parameter for 7 GHz

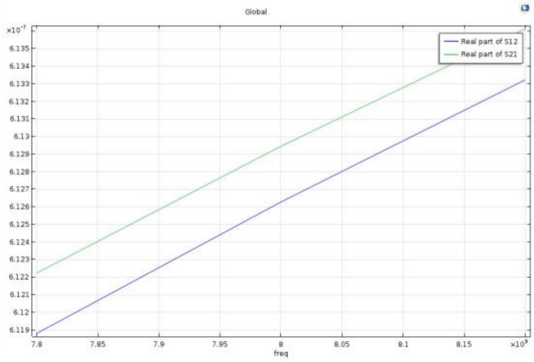




Result 3: Comsol simulation result plot of S12 and S21 parameter for 8 GHz



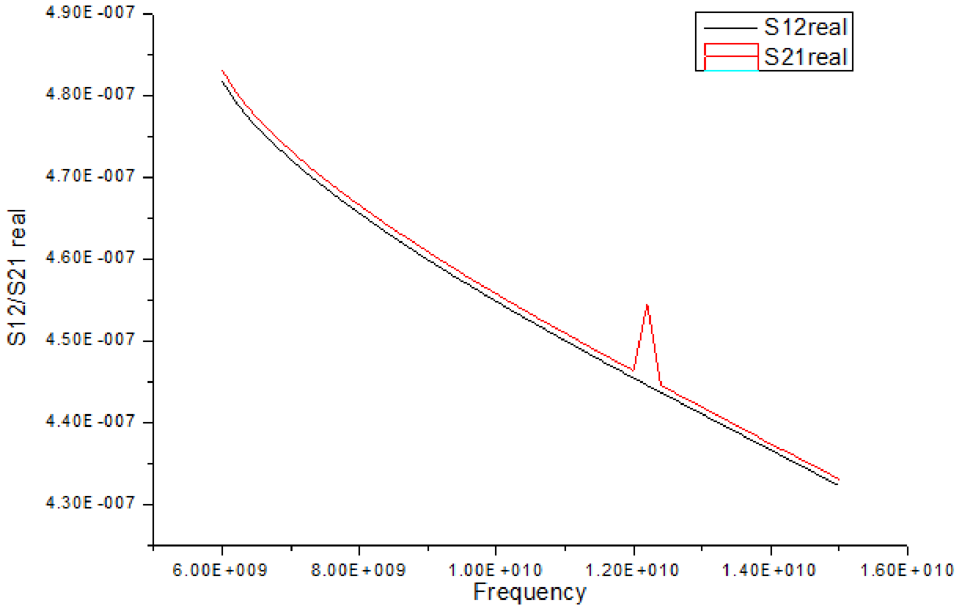


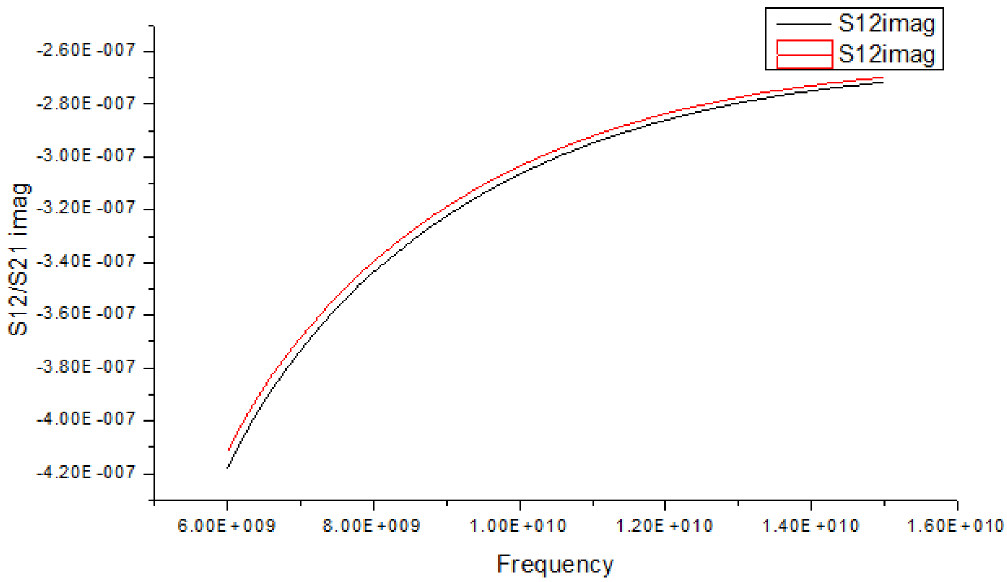


We can easily verify that all these simulation results represent nonreciprocity in the model. Comsol simulation software can simulate single model for one particular frequency because μ_r is frequency dependent parameter. After making more than thousand simulations we note down the values of S12 and S21 parameter for particular frequency and used origin software to combine all the result we get from simulation.

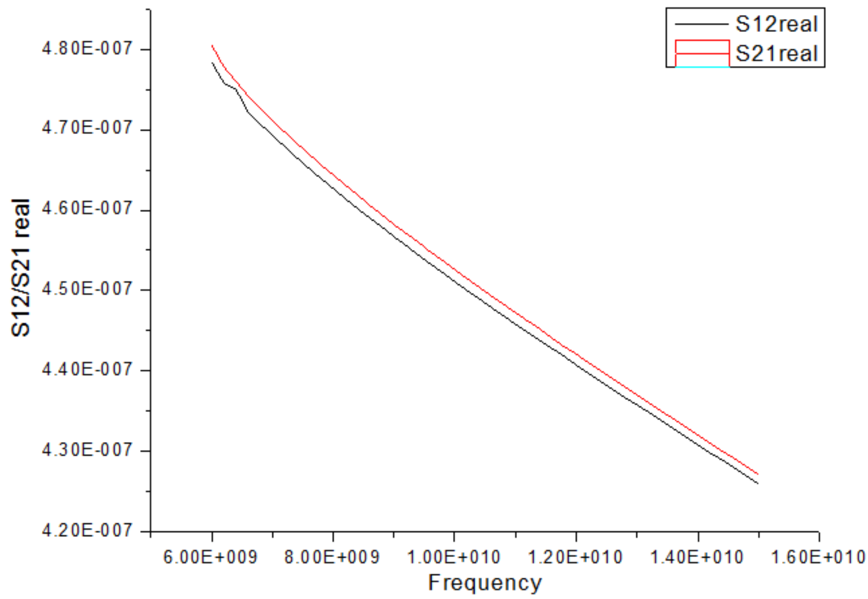
Case 2 Study: Origin software used as to integrate all the results we obtain from simulation

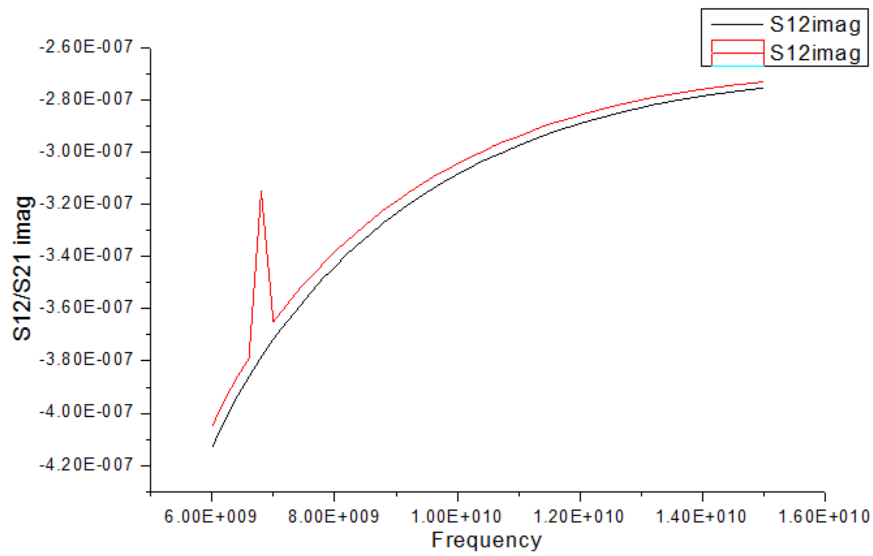
Result 1: When NiFe is 0.3 um and sio2 0.5 um and the distance between signal line is 20 um.





Result 2: When NiFe is 0.4 um and sio2 0.5 um and the distance between signal line is 20 um.


S12real
S21real
4.80E-007
4.70E-007
4.60E-007
4.50E-007
4.40E-007
4.30E-007
4.20E-007
S12/S21 real
6.00E+009
8.00E+009
1.00E+010
1.20E+010
1.40E+010
1.60E+010
Frequency


S12imag
S12imag
-2.60E-007
-2.80E-007
-3.00E-007
-3.20E-007
-3.40E-007
-3.60E-007
-3.80E-007
-4.00E-007
-4.20E-007
S12/S21 imag
6.00E+009
8.00E+009
1.00E+010
1.20E+010
1.40E+010
1.60E+010
Frequency

Chapter 3 Integrated nonreciprocal device at microwave frequency

3.1 Introduction

Devices that are having non-reciprocal characteristics arise a lot of excitement for developing RF based nonreciprocal devices. There are several new methods like magnetic recording and spintronics devices, but spin wave concept is currently the best approach for analyzing and create nonreciprocal devices at RF frequencies [18, 19, 20, 21]. Spin waves are characterized based on its propagation direction relative to the magnetization of the magnetic field; this is usually two types: 1) Volume waves; and 2) Surface waves. These waves are widely discussed in chapter 2. For more in-depth knowledge about the flow of spin waves in these two types of single and multilayer magnetic layer were examined in these papers [22, 23, 24, 25, 26, 27, 28, 29, 30]. Volume Waves and Surface waves propagate along the magnetic thin film, as discussed in chapter 2 these waves are having a property of exponential decay in nature, this mainly depends on the level of the film with the adjacent materials. One of the best example of ferrite material and widely use as making a magnetic film is yttrium iron garnet (YIG), because YIG is having fewer losses at RF microwave frequencies [31, 32, 33, 34, 35, 36]. Ferrite processed material are not entirely compatible with current integrated circuit industry.

We have found theoretically and experimentally that surface wave present in between ferromagnetic material and dielectric [37, 38, 39, 40, 41]. Paper [41] have many principles for spin waves flow, the propagation spin wave spectroscopy (PSWS) was first discussed in [41] to analyze magnetic thin films and then later it was discussed in spectrum domain [42], [43] and time domain [44], [45]. Spin wave is also used in to create logic operations [46], [47] and a special case of the spin wave, which is nonreciprocal spin wave propagation [48, 49, 50]. The spin wave flow in magnetic material and ferrite is the conductive loss; this also limits the use of ferrite. In the single film magnetic layer structure, the magnetic permeability complex value is high below the resonant frequency, which limits the flow magnetostatic volume waves, while above the resonant frequency the complex part of magnetic permeability having a small value; which excites magnetostatic surface waves. In the metallic ferromagnetic film, volume waves have more eddy current loss due to high permeability than magnetostatic surface waves.

Many studies have been conducted to investigate the nonreciprocal spin wave effect under continuous and patterned metallic ferromagnetic film [48, 49, 50]. The majority of nonreciprocal study are done on ferrite YIG material [31, 32, 33, 34, 35, 36]. There are very few works, who suggested some ways to enhance the nonreciprocity effect in ferromagnetic thin films [41].

This chapter includes very systematic study of nonreciprocal spin waves on metallic ferromagnetic thin film. We have analyzed the nonreciprocal effect on magnetic thin film by changing its physical structure.

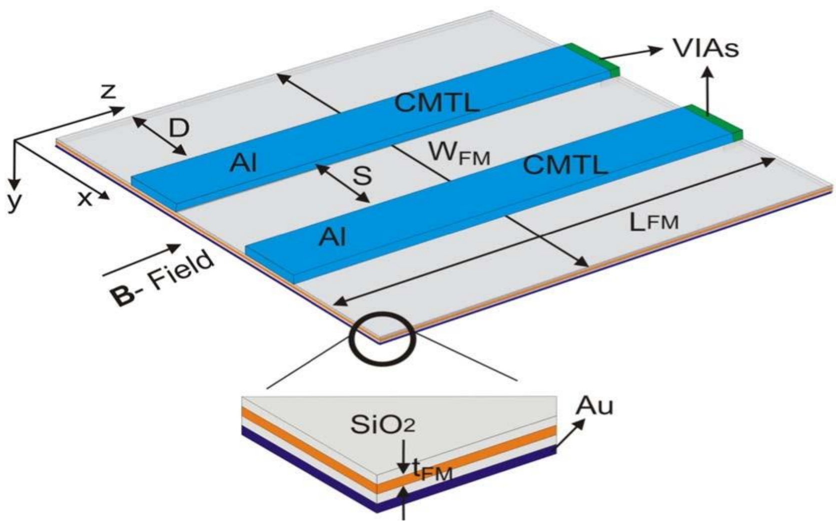


Figure 3.1: Sketch of CMTLs over a thin permalloy ($Ni_{80}Fe_{20}$) layer. The structural parameters are listed in Table I. During the measurements, external magnetic field (***B***-field) was applied along the *z*-axis. MSSWs are excited along the *x*-axis.

Device No.	t_{FM}	W_{FM}	L_{FM}	W	S	D
#1	0.3	300.0	1000.0	20.0	50.0	105.0
#2	0.3	300.0	1000.0	20.0	20.0	120.0
#3	0.3	300.0	1000.0	50.0	20.0	90.0
#4	0.4	300.0	1000.0	50.0	20.0	90.0
#5	0.3	300.0	1000.0	20.0	50.0	75.0

Table 3.1: Structural parameters of the nonreciprocal devices: $t_{FM}, W_{FM}, and\ L_{FM}$ are the thickness, width, and length of the FM film, respectively, W is the width of the metallic line, S is the spacing between transmitting and receiving lines, and D is the distance of the transmitting line from the left edge of the FM film.

We have observed that physical structure of metallic ferromagnetic film impacts the nonreciprocal wave very effectively. In our study, it is found that distance between signal lines, the thickness of the ferromagnetic film, the height of ferromagnetic film from a metallic layer, and device dimension are capable of increasing wave dispersion in nonreciprocal devices.

3.2 Experiments

The nonreciprocal spin waves were excited by coupled microstrip transmission lines (CMTLs). These coupled lines are present on thin film of ($Ni_{80}Fe_{20}$).

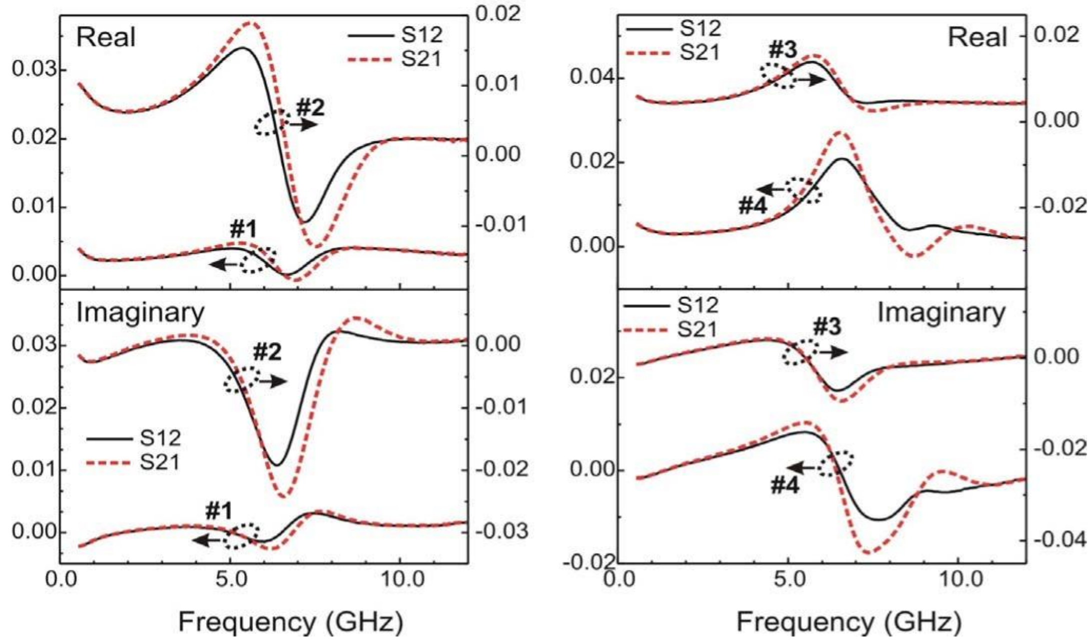


Figure 3.2: Measured real and imaginary parts of $S12$ and $S21$ versus frequencies of devices #1–#4. The frequency shifts between the $S12$ and $S21$ are the results of nonreciprocal MSSW propagation.

Device fabrication steps are given in chapter 1 of this thesis work (1.3.2 (a) Temperature and Fabrication). Each device was made with the given instructions in Table 1. The device was measured using a Keysight network analyzer (Keysight-PNA-L), frequency sweep performs range 500 MHz to 20 GHz. A static magnetic field of ~300 Oe is applied across z-axis.

3.3 Results and Discussion

MSSW fed to the CMTL signal line, will excite along x-axis perpendicular to signal lines. Waves are fed to one signal line at a time such that the first one with signal act as an antenna and the other one serve as a receiver for MSSW. Waves flow upper and bottom surface of magnetic film ($Ni_{80}Fe_{20}$). As bottom surface of device is Au ground layer, the MSSW flow on the surface and below the surface are different in nature due to Au ground; which will leads to nonreciprocal effect. The measurement for nonreciprocal behavior is done by phase and amplitude measurement between two different MSSW [46], [55].

$$\text{NR – Amplitude} = 20\ log_{10} \frac{|S_{12}|}{|S_{21}|}, \text{ Eqn. (3.1)}$$

$$\text{NR – Phase} = \theta(S_{12}) - \theta(S_{21}), \text{ Eqn. (3.2)}$$

Where S_{12} and S_{21} are the scattering parameters and θ is the phase of scattering parameter.

The measurement results are shown in Fig. 2. For device #1 and device #2 we can say that split in frequency waveform between scattering parameters confirms the nonreciprocal behavior and device #2 also shown more nonreciprocity effect then device #1 due to decrease in line spacing between signal lines. Nonreciprocal wave is very sensitive and can be easily lost because of the ferromagnetic conductivity and eddy current losses.

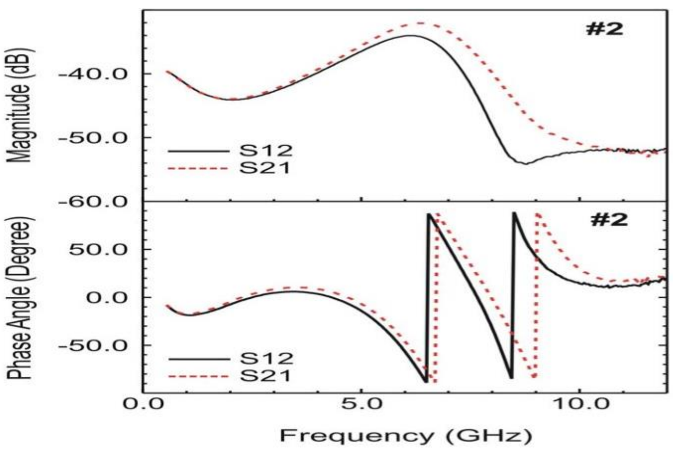


Figure 3.3: Measured magnitude and phase angle of $S12$ and $S21$ versus frequencies of device #2.

It is important to note that during propagation of MSSW, we did not observe any oscillations at the ferromagnetic resonant [31], [32]. MSSW propagate only along the NiFe film surfaces, due to certain roughness along the edges of the film cause multiple reflections on the edges. The phase shift generated by multiple reflections integrate the phase generated along the z-axis and cause harm to the oscillations. Phase angle and Magnitude of device #2 is shown in Figure 3.3; we can conclude that S_{12} and S_{21} are depend on the direction of propagation of MSSW.

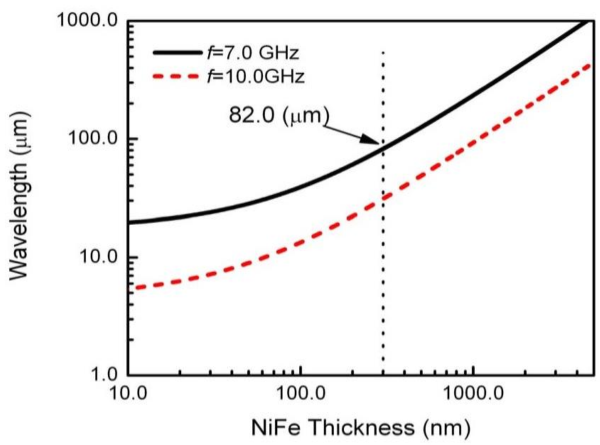


Figure 3.4: Computed propagation wavelength of the MSSWs versus the thickness of the NiFe film at 7.0 and 10.0 GHz. The saturation magnetization of the NiFe film in the calculation is 1.0 T. The external magnetic field is 300 Oe. In the model, the thickness of SiO2 is 0.5 um.

We try to change the thickness of NiFe film to observe the MSSW effect. In device #3 and device #4, we kept everything same except the thickness of the magnetic film, device #3 with a film thickness of (0.3 um) and device #4 with a film thickness of (0.4). Device #4 is having many clear oscillations then device #3. For the better understanding of this result, we have performed the numerical simulation. Our simulation model consists of 0.5 um thickness SiO_2 bottom layer, NiFe film with different thickness, and top layer of SiO_2 of 0.5 um thickness. We have assumed everything in our model to be isotropic for electrical permittivity and magnetic permeability except the NiFe film. . The NiFe film parameters are set for anisotropic behavior, it can be done by calculating the permeability tensor (μ_r) value using the Landau-Lifshitz (LL) equation. In simulation model CMTL signal lines are made up of aluminum and ground layer is made up of gold but we set them as perfect electric conductor for infinite conductivity. Conductive material are having very negligible permeability compare to NiFe film. The propagation wavelength of MSSW for different thickness of NiFe film can be calculated by solving [56], [57].

$$\tanh\left(\frac{2\pi}{\lambda}.t_{FM}\right) = \frac{2u}{(u_a^2-u^2-1)+[(u_{a-1})^2-u^2]e^{-\frac{4\pi}{\lambda}.t_{sio_2}}}, \text{ Eqn. (3.3)}$$

$$\overleftrightarrow{\mu} = \mu_0 \begin{bmatrix} \mu & j\mu_a & 0 \\ -j\mu_a & \mu & 0 \\ 0 & 0 & 1 \end{bmatrix}, \text{ Eqn. (3.4)}$$

Where $\overleftrightarrow{\mu}$ is the permeability tensor, μ_0 is the permeability of vacuum, t_{FM} is the thickness of ferromagnetic film and t_{sio_2} is the thickness of SiO_2 insulation layer. If we increase the thickness of ferromagnetic film we will have longer propagation wavelength, which makes phase shift effect weak because of MSSW are reflected by edges. If we have no magnetic field applied, then we cannot differentiate between the S12 and S21 as shown in Fig. 5.

To intensify the nonreciprocity, the ratio of S12 and S21 for device #4 are observed in the sense of phase and amplitude (Fig.6). The maximum amplitude of -16.3 dB with the phase of 72^o.

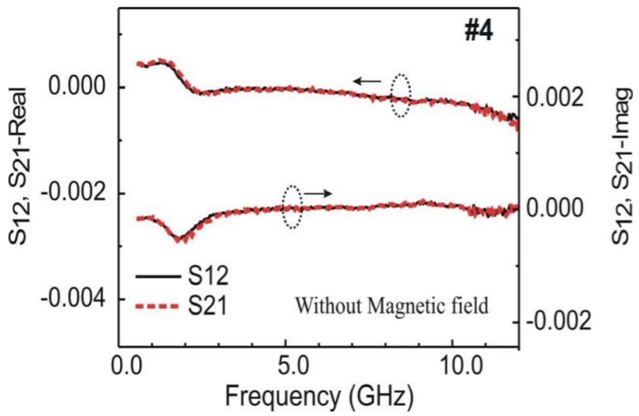


Figure 3.5: Measured real and imaginary parts of S_{12} and S_{21} for devices #4 in absent of external magnetic field.

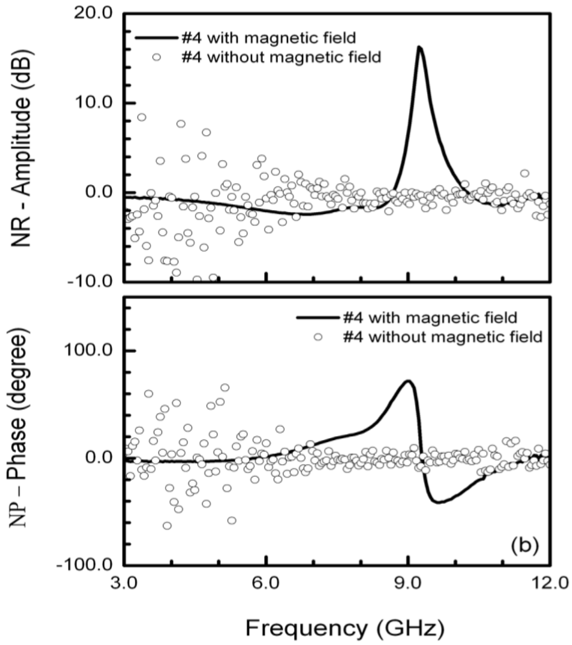


Figure 3.6: Measured nonreciprocal factors NR-Amplitude and NR-Phase versus frequencies for device #4 in the presence and absence of magnetic field.

The important point to mention here is that without the adjacent metal layer, the nonreciprocity of MSSW can be constructive or destructive interference between in and out plane components. When we used the metal layer underneath NiFe on our device, magnitude and phase changed. This approach can be used to designed nonreciprocal phase based device. The nonreciprocal effect will be maximum when NR-Amplitude or NR-Phase attain their peak values, after this point nonreciprocal device behave more like reciprocal devices as shown in Figure 3.2. For higher frequency values for $S12$ and $S21$ seems to be overlapping.

It is worth mentioning that without placing a neighbor metallic layer, the origin of the nonreciprocity of the MSSW stems from either the constructive or destructive interference between the in- and out-plane components of the RF signals. In this case, the magnitude of the counterpropagating MSSWs is different, while the phase is preserved [55]. This is different from our results: by placing a metallic layer underneath the NiFe film, both the magnitude and the phase are changed. This pro- vides an alternative approach to manufacturing a phase-based nonreciprocal device. A frequency shift of about 0.25 GHz exists between the maximum values of NR-Amplitude and NR-Phase. The nonreciprocity occurs mainly in the vicinity of the frequency where either NR-Amplitude or NR-Phase reaches their maximum. Beyond this local frequency range, the device exhibits more reciprocal behavior, as observed in the results in Fig. 2. At higher frequencies, the S_{12} and S_{21} overlap. In the absence of magnetic field, the $S12$, and $S21$

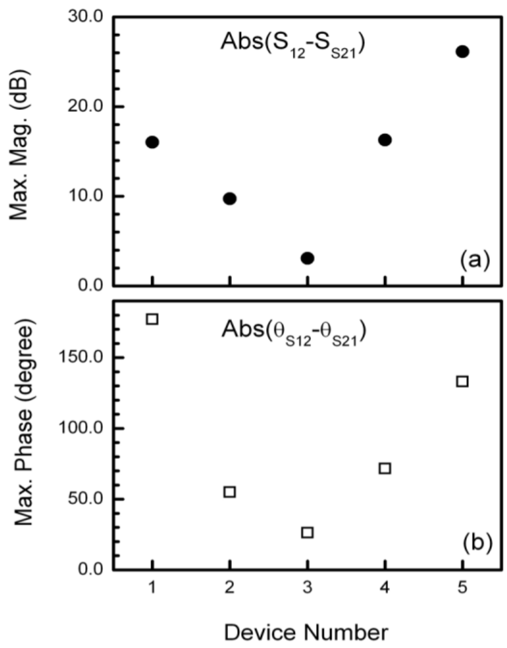


Figure 3.7: Comparison of the nonreciprocal effect of the five devices with different layout configurations. (a) Maximum values of NR-Amplitude. (b) Maximum values of NR-Phase. ABS represents the absolute value, and θ is the phase angle of the scattering parameters.

Our model verifies that nonreciprocity largely depends on the structure of the device. It very much depends on CMTL. Signal lines width, spacing, and distance from ferromagnetic film and thickness of the ferromagnetic film. To advance our design such that it will have a more nonreciprocal effect, the nonreciprocity of all the five devices are shown in Figure 3.7, maximum phase and maximum magnitude are plotted on device number.

Comparing device #1 and device #2 in our model, we conclude that as the spacing decrease from 50 um to 20 um, the value for NR-Amplitude and NR-Phase decreases. Figure 3.2, shows us that device #2, S_{12} and S_{21} real and imaginary parts are four times in magnitude of device #1, which indicate that if we like to go for #2 in compare for device #1 we will have more nonreciprocity, but the propagation losses are more, more spacing between signal line results in that.

In device #2 and #3, we have varied the width of the signal line; it is increased from 20 um for device #2 to 50 um for device #3. In both of these cases, NR-Amplitude and NR-Phase decreases thus proving the less nonreciprocal effect. By comparing S_{12} and S_{21} for device #2 and #3, we also conclude that with the wider signal line we reduce the intensity. In conclusion, if we want more nonreciprocal effect our signal width should be smaller.

In device #4 we try to increase the ferromagnetic film thickness to 0.4 um, this result in the higher value of NR-amplitude and NR-Phase. Device #4 also certainly has more nonreciprocity. It is being shown in previous work [48] that thinner film increase device characteristic as conductive magnetic losses are comparably small for thin film. There could also be a possibility that static magnetic effect decreases the material permeability [51], this result in weaker skin effect and greater nonreciprocity.

In Device #5 we have changed the distance of transmitting line to 75 um. In device #1 it is 1.0 um. With this change in device #1 NR-Amplitude increases and NR-Phase goes down, in this case, as the distance is shorter, so films are considered to be uniformly magnetized, symmetrical field scattering in NiFe is present [54].

Chapter 4 Summary and Future work

Summary

Designing of nonreciprocal coupled microstrip transmission lines (CMTLs) is a big challenge because of propagation losses present in the magnetic film. This thesis work has shown that improved CMTLs design can reduce loss and increase overall device performance. CMTL with narrower line width increase magnetostatic surface wave propagation (MSSW) and large line spacing provide strength to nonreciprocity effect. Placing of CMTLs away from the center of magnetic film lying underneath will increase the nonreciprocal effect.

Nonreciprocal waves are observed in ferromagnetic thin magnetic film placed with neighboring metallic nonmagnetic layer. Effects of CMTLs on nonreciprocal propagation are discussed with the intensity and nonreciprocity in MSSW. By selecting proper thickness of magnetic film, line width, spacing, and position the maximum nonreciprocity of -26.0 dB for NR-Amplitude and -180^0 phase difference for NR-Phase has been obtained.

Future work

1. We can make multilayer structure; more than one magnetic film can be used to observe the nonreciprocal effect.
2. We try to solve the problem with software so our design can easily run close to resonance frequency.
3. We can use this thesis work to improve passive device cores.
4. We can use above discussed ways to improve circulator, nonreciprocal based memory devices.

Reference

[1] P. Khalili Amiri, ”Magnetic Materials and Devices for Integrated Radio-Frequency Electronics", Ph.D. Thesis Delft University of Technology, 2008.

[2] R.P. Feynman, R.B. Leighton, M.L. Sands, “The Feynman Lectures on Physics", Vol. 2, Addison-Wesley, Reading, Massachusetts, 1964.

[3] S. B. Cohn and R. Levy. “History of microwave passive components with particular attention to directional couplers", IEEE Transactions on Microwave Theory and Techniques, Vol. 32, No. 9, pp. 1046-1054. 1984.

[4] G.E. Moore,``Cramming more components onto integrated circuits," Electronics, Vol. 38, No. 8, pp. 114-117, 1965.

[5] Sheena Hussaini,“Integrated Magnetic Components for RF Applications”, Ph.D. Thesis, 2015.

[6] G.E. Moore,``Cramming more components onto integrated circuits," Electronics, Vol. 38, No. 8, pp. 114-117, 1965.

[7] J. R. Long. SiGe radio frequency ICs for low-power portable communication. IEEE Proceedings, vol. 93, no. 9, pp. 1598-1623. 2005.

[8] Lecture 14, Ferrite Materials, A. Nassiri – ANL

[9] T. Nakamura, T. Tsutaoka b, K. Hatakeyama,” Frequency dispersion of permeability in ferrite composite materials”, Journal of Magnetism and Magnetic Materials 138 (1994)

[10] B. Rejaei and M. Vroubel,’’Suppression of skin effect in metal/ferromagnet superlattice conductors’’, J. Appl. Phys., Vol. 96, No. 11, pp. 6863-6868. 2004.

[11] Behzad Rejaei. ``Impedance of a planar solenoid with a thin magnetic core", Journal of Applied Physics, 2007.

[12] P. K. Amiri and B. Rejaei, ``Magnetostatic waves in layered materials and devices,"

J. Appl. Phys., Vol. 100, No. 10, pp. 103909, 2006.

[13] A.G. Gurevich, G.A. Melkov, ``Magnetization oscillations and waves", CRC

Press, New York, 1996. 134
[14] I. Iramnaaz, T. Sandoval, Y. Zhuang, H. Schellevis, B. Rejaei,``High quality factor RF inductors using low loss conductor featured with skin e_ect suppression for standard CMOS/BiCMOS." IEEE 61st, Electronic Components and Technology Conference (ECTC), pp. 163-168, 2011.
[15] I. Iramnaaz, H. Schellevis, B. Rejaei, R. Fitch, Y. Zhuang, ``High-Quality Integrated Inductors Based on Multilayered Meta-Conductors," IEEE Microwave and Wireless Components Letters., Vol. 22, Issue 7, pp. 345-347, 2012.
[16] I. Iramnaaz, H. Schellevis, B. Rejaei, R. Fitch, Y. Zhuang,``Self-Biased Low Loss Conductor Featured with Skin E_ect Suppression for High Quality RF Passives," IEEE Transactions on Magnetics, Vol. 48, Issue 11, pp. 4139-4142, 2012.
[17] https://www.comsol.com/rf-module (Comsol pdf for RF Module)
[18] J.-P. Lazzari and I. Melnick, “Integrated magnetic recording heads,” *IEEE Trans. Magn.*, vol. MAG-7, no. 1, pp. 146–150, Mar. 1971.
[19] G. A. Prinz, “Magnetoelectronics applications,” *J. Magn. Magn. Mater.*, vol. 200, pp. 57–68, Oct. 1999.
[20] J. Fabian, A. Matos-Abiague, C. Ertler, P. Stano, and I. Žutic´, “Semi-conductor spintronics,” *Acta Phys. Slovaca,* vol. 57, pp. 565–907, 2007.
[21] J. H. Kwon, S. S. Mukherjee, P. Deorani, M. Hayashi, and H. Yang, “Characterization of magnetostatic surface spin waves in magnetic thin films: Evaluation for microelectronic applications,” Appl. Phys. A, vol. 111, no. 2, pp. 369–378, 2013.
[22] A. S. Andreev et al., “Propagation of magnetostatic waves in yttrium iron garnet films of submicron thickness,” Sov. Phys.—JETP, vol. 59, no. 3, pp. 586–591, 1984.
[23] W. S. Ishak, “Magnetostatic wave technology: A review,” Proc. IEEE, vol. 76, no. 2, pp. 171–187, Feb. 1988.
[24] S. L. Vysotskii, G. T. Kazakov, Y. A. Filimonov, and A. V. Maryakhin, “Magnetostatic volume waves in exchange-coupled ferrite films,” Tech. Phys., vol. 43,

no. 7, pp. 834–845, 1998.
[25] M. J. Hurben and C. E. Patton, “Theory of magnetostatic waves for in- plane magnetized anisotropic films,” J. Magn. Magn. Mater., vol. 163, pp. 39–69, Oct. 1996.
[26] V. Vlaminck and M. Bailleul, “Spin-wave transduction at the sub- micrometer scale: Experiment and modeling,” Phys. Rev. B, vol. 81, p. 014425, Jan. 2010.
[27] P. K. Amiri and B. Rejaei, “Magnetostatic waves in layered materials and devices,” J. Appl. Phys., vol. 100, no. 10, p. 103909, 2006.
[28] A. K. Ganguly and D. C. Webb, “Microstrip excitation of magnetostatic surface waves: Theory and experiment,” IEEE Trans. Microw. Theory Techn., vol. MTT-23, no. 12, pp. 998–1006, Dec. 1975.
[29] M. Mruczkiewicz and M. Krawczyk, “Nonreciprocal dispersion of spin waves in ferromagnetic thin films covered with a finite-conductivity metal,” J. Appl. Phys., vol. 115, no. 11, p. 113909, 2014.
[30] F. Ma and Y. Zhou, “Interfacial Dzialoshinskii–Moriya interaction induced nonreciprocity of spin waves in magnonic waveguides,” RSC Adv., vol. 4, no. 87, pp. 46454–46459, Sep. 2014.
[31] T. Schneider, A. A. Serga, B. Leven, B. Hillebrands, R. L. Stamps, and M. P. Kostylev, “Realization of spin-wave logic gates,” Appl. Phys. Lett., vol. 92, no. 2, p. 022505, 2008.
[32] T. Schneider, A. A. Serga, T. Neumann, B. Hillebrands, and M. P. Kostylev, “Phase reciprocity of spin-wave excitation by a microstrip antenna,” Phys. Rev. B, vol. 77, p. 214411, Jun. 2008.
[33] H. Yu et al., “Magnetic thin-film insulator with ultra-low spin wave damping for coherent nanomagnonics,” Sci. Rep., vol. 4, Oct. 2014, Art. no. 6848.
[34] Y. V. Khivintsev, Y. A. Filimonov, and S. A. Nikitov, “Spin wave excitation in yttrium iron garnet films with micron-sized antennas,” Appl. Phys. Lett., vol. 106, no. 5, p. 052407, 2015.
[35] M. Mruczkiewicz, E. S. Pavlov, S. L. Vysotsky, M. Krawczyk, Y. A. Filimonov, and S. A. Nikitov, “Observation of magnonic band gaps in magnonic

crystals with nonreciprocal dispersion relation," Phys. Rev. B, vol. 90, p. 174416, Nov. 2014.
[36] N. Kanazawa, T. Goto, J. W. Hoong, A. Buyandalai, H. Takagi, and M. Inoue, "Metal thickness dependence on spin wave propagation in magnonic crystal using yttrium iron garnet," J. Appl. Phys., vol. 117, no. 17, p. 17E510, 2015.
[37] P. Kabos, W. D. Wilber, C. E. Patton, and P. Grünberg, "Brillouin light scattering study of magnon branch crossover in thin iron films," Phys. Rev. B., vol. 29, pp. 6396–6398, Jun. 1984.
[38] R. E. Camley, "Nonreciprocal surface waves," Surf. Sci. Rep., vol. 7, pp. 103–187, Jul. 1987.
[39] K. L. Wong et al., "Unidirectional propagation of magnetostatic surface spin waves at a magnetic film surface," Appl. Phys. Lett., vol. 105, no. 23, p. 232403, 2014.
[40] M. Kostylev, "Non-reciprocity of dipole-exchange spin waves in thin ferromagnetic films," J. Appl. Phys., vol. 113, no. 5, p. 053907, 2013.
[41] M. Bailleul, D. Olligs, C. Fermon, and S. O. Demokritov, "Spin waves propagation and confinement in conducting films at the micrometer scale," Europhys. Lett., vol. 56, no. 5, pp. 741–747, 2001.
[42] M. Bailleul, D. Olligs, and C. Fermon, "Propagating spin wave spec- troscopy in a permalloy film: A quantitative analysis," Appl. Phys. Lett., vol. 83, no. 5, pp. 972–974, 2003.
[43] K. Yamanoi, S. Yakata, T. Kimura, and T. Manago, "Spin wave excita- tion and propagation properties in a permalloy film," Jpn. J. Appl. Phys., vol. 52, no. 8R, p. 083001, 2013.
[44] M. Covington, T. M. Crawford, and G. J. Parker, "Time-resolved measurement of propagating spin waves in ferromagnetic thin films," Phys. Rev. Lett., vol. 89, no. 23, p. 237202, 2002.
[45] K. Sekiguchi et al., "Nonreciprocal emission of spin-wave packet in FeNi film," Appl. Phys. Lett., vol. 97, no. 2, p. 022508, 2010.
[46] N. Sato, K. Sekiguchi, and Y. Nozaki, "Electrical demonstration of spin- wave

logic operation," Appl. Phys. Exp., vol. 6, no. 6, p. 063001, 2013.
[47] M. Jamali, J. H. Kwon, S.-M. Seo, K.-J. Lee, and H. Yang, "Spin wave nonreciprocity for logic device applications," Sci. Rep., vol. 3, Nov. 2013, Art. no. 3160.
[48] P. K. Amiri, B. Rejaei, M. Vroubel, and Y. Zhuang, "Nonreciprocal spin wave spectroscopy of thin Ni-Fe stripes," Appl. Phys. Lett., vol. 91, no. 6, p. 062502, 2007.
[49] P. K. Amiri, B. Rejaei, Y. Zhuang, M. Vroubel, D. W. Lee, and S. X. Wang, "Nonreciprocal spin waves in Co-Ta-Zr films and multilay- ers," IEEE Trans. Magn., vol. 45, no. 10, pp. 4215–4218, Oct. 2009.
[50] G. C. Hartman, R. Fitch, and Y. Zhuang, "Nonreciprocal magnetostatic wave propagation in micro-patterned NiFe thin films," IEEE Microw. Wireless Compon. Lett., vol. 24, no. 7, pp. 484–486, Jul. 2014.
[51] Y. Zhuang, M. Vroubel, B. Rejaei, and J. N. Burghartz, "Integrated RF inductors with micro-patterned NiFe core," Solid-State Electron., vol. 51, pp. 405–413, Mar. 2007.
[52] M. Nakayama, K. Yamanoi, S. Kasai, S. Mitani, and T. Manago, "Thickness dependence of spin wave nonreciprocity in permalloy film," Jpn. J. Appl. Phys., vol. 54, no. 8, p. 083002, 2015.
[53] J. C. Slonczewski, B. Petek, and B. E. Argyle, "Micromagnetics of laminated permalloy films," IEEE Trans. Magn., vol. 24, no. 3, pp. 2045–2054, May 1988.
[54] P. K. Amiri, B. Rejaei, M. Vroubel, Y. Zhuang, and J. N. Burghartz, "Experimental determination of the nonuniform shape-induced anisotropy field in thin Ni-Fe films," IEEE Trans. Magn., vol. 43, no. 5, pp. 1880–1883, May 2007.
[55] P. Deorani, J. H. Kwon, and H. Yang, "Nonreciprocity engineering in magnetostatic spin waves," Current Appl. Phys., vol. 14, pp. S129–S135, Mar. 2014.
[56] P. K. Amiri, "Magnetic materials and devices for integrated radio- frequency electronics," Ph.D. dissertation, Dept. Microelectron., Delft Univ. Technol., Delft, The Netherlands, 2008.
[57] A. G. Gurevich and G. A. Melkov, Magnetization Oscillations and Waves. New

York, NY, USA: CRC Press, 1996.

[58] P. Gruszecki et al., “Influence of magnetic surface anisotropy on spin wave reflection from the edge of ferromagnetic film,” Phys. Rev. B, vol. 92, p. 054427, Aug. 2015.

[59] Fleury, R., Sounas, D., & Alù, A. (2015). An invisible acoustic sensor based on parity-time symmetry.Nature Communications, 6, 5905. doi:10.1038/ncomms6905.

[60] "IC - An integrated circuit or monolithic integrated ...".N.p.,n.d. Web. 09 Aug. 2016 <https://www.coursehero.com/file/12586996/IC/>.

[61] "Inductor Core Material: The Heart of an Inductor.
<http://powerelectronics.com/content/inductor-core-material-heart-inductor>.

[62] Scattering Boundary Condition - Montana Tech High ... (n.d.). Retrieved from http://hpc.mtech.edu/comsol/html/woptics/woptics_ug_optics.4.50.html.

[63] “Nonreciprocal spin wave spectroscopy of thin Ni–Fe stripes”
Pedram Amiri - Behzad Rejaei - Marina Vroubel - Yan Zhuang - Appl. Phys. Lett. Applied Physics Letters - 2007