Millimeter Wave Ferromagnetic Resonance of Saturated Magnetic Transmission Line

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**Abstract** –*Saturated Ferromagnets exhibit microwave and millimeter wave absorption because they consist of nano- magnetic harmonic oscillators. The absorption frequency and linewidth is dictated by the strength and range of interactions between the magnetic dipoles. The forced orientation of magnetic dipoles along the magnetic bias results in Zeeman splitting in the energy levels. The incoming electromagnetic wave can excite dipoles to transition between these energy levels. In order to investigate the effects of input frequency on their electromagnetic properties, a Magnetic Transmission Line circuit is presented for the saturated ferromagnet. The enhanced power loss during ferromagnetic resonance is contributed to the strong spike of Longitudinal Magnetic Admittance and Transverse Magnetic Impedance.*

**Keywords:**Magnetic Transmission Line, Longitudinal Magnetic Admittance, Transverse Magnetic Impedance

# Introduction

Gyromagnetic materials are widely used in high frequency applications like microwave devices and radar communication because of their directional and non-reciprocal properties. These materials exhibit Ferromagnetic resonance, in the micro and mm-wave region, under the influence of external magnetostatic bias fields. During ferromagnetic resonance, their affinity for magnetic flux increases greatly, enabling them to conduct magnetic information efficiently using spin waves. The heightened permeability and high resistivity makes them extremely useful for microwave devices, isolators, circulators and absorbers.

Ferromagnetic materials change their electromagnetic properties when a magnetic bias field is applied [10]. The bias field produces Zeeman splitting in energy levels, and the saturated magnetic dipoles can transition between the energy levels by absorbing microwave or millimeter wave electromagnetic fields [2]. The non-linear and anisotropic nature of magnetized ferrites can be modeled using a non-diagonal magnetic susceptibility tensor. Specialized electron spin resonance spectrometer and network analyzer are required to estimate the dispersion characteristics of the susceptibility tensor elements. The precessional magnetization dynamics can be experimentally observed using resonant cavity, stripline transducer or shorted waveguide technique. The power absorption and ferromagnetic resonance spectrum linewidth of the gyromagnetic ferrite is highly sensitive to the frequency dependence of the susceptibility tensor elements. The magnetic properties of microwave ferrites vary widely with chemical composition, crystal structure and bias field. The nano-magnetic exchange interactions and dipole-dipole interactions dictate the excitation of spin waves in the magnetized medium [6]. Realistic system level models for the analysis of ferromagnetic materials must account for the characteristic information delay, distortion and attenuation.

The electromagnetic transmission line model is commonly used to explain non-reciprocal properties of magnetized ferromagnets [1], [10], [11]. An analysis of the propagation of UHF electromagnetic fields in a waveguide filled with anisotropic, magnetized ferrite was given in [1]. Experimental results for calculating frequency dependent behavior of complex permeability and permittivity of a ferromagnetic transmission line was presented in [1] and [10], where the measured intrinsic impedance and propagation constant were used to determine the per unit length transmission line parameters. In [11], an estimate for the parasitic capacitance of a ferromagnetic core was presented, which stores electric energy in the gradient electric field developed inside the core and is responsible for the high frequency self-resonance and frequency limitation of the magnetic core. The frequency independent Ohmic losses were also considered in an equivalent core impedance.

The transcendental electrodynamic equations for propagation of fields in gyromagnetic media do not have a close form solution so they can only be solved via electromagnetic simulations [10]. The propagation of UHF signals in dispersive, anisotropic, conductive ferromagnetic transformer cores has been widely studied using FDTD simulations [11], [8], [1]. The micro-magnetic FDTD simulations in [1] accurately modeled the precessional magnetization dynamics, and the results were comparable to analytical results.

Unlike Electric Transmission Lines, these magnetic circuits are not designed to conduct electric charge upon application of electromotive force. The experimental results must be translated into an Electromagnetic Transmission Line system level design which can explain the flow of magnetic flux due to the application of Magnetomotive force. In [4], a Magnetic Transmission Line model was developed, which was based on the conventional Electric Transmission Line model. For magnetic transmission lines, transverse magnetic impedance and the longitudinal magnetic admittance determine the propagation constants for the wave modes. The Magnetic Transmission Line exhibited the behavior of a high pass filter. Simulations showed that they exhibit super-luminal phase velocity and almost zero attenuation dispersion in the microwave frequency range [5].

The Magnetic Transmission Line Model explains the flow of magnetic flux in ferromagnetic materials as the effective magnetic charge. It provides a system level circuit for relating Magnetomotive force to the applied Magnetic flux rate. Analogous to the scalar electric potential in Electric Transmission Lines, scalar magnetic potential is defined as

The Magnetic Displacement Current is defined as the rate of change of magnetic flux :

The Magnetic Transmission Line Equations can be written as

where the per unit length transverse magnetic inductance represents a magnetic Energy storage element storing magnetic flux; the per unit length longitudinal capacitance represents an Electric Energy storage element resulting from the dielectric nature of the ferromagnet; and the per unit length Magnetic conductance dissipates energy due to Hysteresis, Eddy currents, Skin effect, Proximity effect, Magnetoresistance and other residual losses.

The characteristic impedance and propagation constant are calculated by the following relations:

where is the Transverse Magnetic Impedance and is the Longitudinal Magnetic Admittance.



Figure 1: Magnetic Transmission Line Circuit Model

This research attempts to extend the Magnetic Transmission Line model for the modeling saturated ferromagnetic materials, and studying the effects of ferromagnetic resonance on the per unit length magnetic transmission line transverse impedance and longitudinal admittance.

# FDTD Electromagnetic Simulation

MEEP software was used for the electromagnetic simulation of the Gyrotropic, Dispersive, Ferromagnetic Transmission Lines using the Finite Difference Time Domain method which discretizes Maxwell’s Equations using central difference approximations for space and time partial derivatives [7]. The different field components at a grid location are stored in the edges and faces of a cubic element called Yee’s Cell. The electromagnetic fields are evolved in discrete time steps using leap frog method.

Landau-Lifshitz-Gilbert model describes the precessional motion of saturated magnetic dipoles in a magnetic field [3]:

wheredescribes the linear deviation of magnetization from its static equilibrium value. **M** precesses around the effective Magnetic Field Intensity . represents gyromagnetic ratio, and is the phenomenological Gilbert damping factor.

For ferromagnetic media biased in the z-direction, a non-diagonal susceptibility tensor is used to relate Magnetization and Field intensity **M**= **H**.

where = = , = = and =

The frequency dependent nature of the non-diagonal susceptibility element is shown in Figure 2. For a high quality crystal oscillator, the resonance has a very small bandwidth due to the small damping factor .



Figure 2: 30 GHz Ferromagnetic Resonance of Susceptibility Tensor Element

The Hx and Hy fields are coupled due to the off-diagonal terms in the susceptibility tensor. The resulting equations for the evolution of magnetic field components are:

Equations (8) – (10) can be solved by taking the inverse Fourier Transform and discretizing the resulting equations [9]:

Finite Difference Time Domain simulator MEEP solves these equations by the modified Yee’s Algorithm. The continuous integrals in (11) - (13) are implemented using discrete sums [7].

# Simulation Results

A Magnetic Gaussian Current Pulse with a bandwidth of 60 GHz was applied at the input side of the magnetized ferrite. The Fourier Transform of the pulse is shown in Fig. 3.



Figure 3: Fourier Transform of Input Gaussian Magnetic Current Pulse

Different frequencies faced different degrees of rotation per unit of propagation distance. The resultant polarization changes continuously as the different frequency components experience different rates of rotation per unit distance of propagation. The polarization of each frequency changed from linear polarization as it moved in the direction of propagation. Hence, the Gaussian pulse was heavily deformed as it reached the output end. The resultant polarization was a combination of all the polarizations of the different frequencies.

The 30 GHz harmonic of the incident Gaussian wave matched the Larmor frequency, and gave rise to Gyromagnetic resonance. The wave impedance shown in Figure 4 was calculated using the Fourier Transform of a small window of input and output signals, during steady state of gyromagnetic resonance. The intrinsic wave impedance spikes during gyromagnetic resonance; due to the huge spike in magnetic susceptibility and magnetic permeability during the 30 GHz gyromagnetic resonance. The huge value of intrinsic wave impedance increases the electromagnetic power losses across the saturated ferrite. It absorbs a lot of electromagnetic energy from the Transverse Field, and starts to heat up. The strength and linewidth of the spike is dictated by the complex magnetic permeability of the magnetic sample.



Figure 4: Plot of Intrinsic Wave Impedance vs. Frequency

The phase constant and attenuation constant was calculated for the resultant magnetic spin wave and the calculated wave attenuation constant is shown in Figure 5. The attenuation constant was calculated by comparing the magnetic field strength at input and output sides. The output signal was heavily attenuated compared to the input signal hence the attenuation constant was very high during the 30GHz gyromagnetic resonance. The quality of the crystal oscillator is dictated by the linewidth of the absorption spectrum.



Figure 5: Plot of Attenuation Constant vs. Frequency

During Gyromagnetic Resonance, the per unit length Longitudinal Admittance drops as shown in Figure . This leads to a severe increase in the power dissipation in the Ferrite sample; which makes the saturated ferrite sample highly conductive to electromagnetic flux. The saturated ferrite sample absorbs a lot of electromagnetic energy and starts to heat up. The complex permittivity and magnetic permeability dictate the dielectric and magnetic losses of the resonating sample.



Figure 6: Plot of Longitudinal Admittance vs. Frequency

During Gyromagnetic Resonance, the per unit length Transverse Impedance spikes as shown in Figure 7. The 30GHz gyromagnetic resonance leads to a severe increase in the power dissipation in the Ferrite sample. The magnetic flux leakage drops heavily and this makes the saturated ferrite sample highly conductive to electromagnetic flux. Ultimately, the saturated ferrite sample absorbs a lot of electromagnetic energy. The strength of the spike is dependent on the oscillator damping factor, size of nano-magnetic domains and crystal structure.



Figure 7: Plot of Transverse Impedance vs. Frequency

# Conclusion

The Finite Difference Time Domain simulation of saturated ferromagnet was used to study the effects of gyromagnetic resonance on its longitudinal magnetic admittance and transverse magnetic impedance. The gyromagnetic precession of saturated magnetic dipoles was modeled using linearized Landau-Lifshitz-Gilbert model in MEEP simulator to show that the gyromagnetic resonance can be observed when the frequency spectrum of the input electromagnetic signal overlaps sufficiently with the Larmor precession frequency band. It was shown that gyromagnetic resonance leads to a drastic increase in the Transverse Magnetic Impedance and the electromagnetic energy losses of Longitudinal Magnetic Conductance. The quality of the crystal oscillator is dictated by the complex permittivity and permeability profile. These results are useful for modern high frequency applications like spintronic devices, space navigation, wireless communication, maritime and geophysical prospecting instruments.

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