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 line width are 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 and Gilbert damping constant on the electromagnetic properties, a magnetic transmission line model is presented for a 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, ferromagnetic resonance line width

# Introduction

Gyromagnetic materials are widely used in high-frequency applications such as 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 resistivity is extremely useful for microwave devices, isolators, circulators and absorbers [1].

Ferromagnetic materials change their electromagnetic properties when a magnetic bias field is applied [2]. 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 [3]. 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, strip-line transducer or shorted waveguide technique [4]. The power absorption and ferromagnetic resonance spectrum line width of a 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 [5]. 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.

Ferromagnetic resonance can be analyzed experimentally using a quasi-optical spectrometer or a vector network analyzer. In reference [3], a high frequency spectrometer was used to determine the effect of complex dielectric permittivity and magnetic permeability on the transmission and reflection coefficients during millimeter wave ferromagnetic resonance; with special emphasis on the effect of magnetic domain size and crystal structure on the ferromagnetic resonance frequency. In reference [6], a magneto-optical method was used to detect the effect of crystal structure, frequency and direct current (DC) magnetic bias on the ferromagnetic resonance spectrum peak and line width. A vector network analyzer was used to obtain multi-mode ferromagnetic spectrum for a ferrite loaded coplanar waveguide in reference [7]. The scattering parameters are directly affected by the dispersion of magnetic permeability, structural dimensions, formation of standing waves and parasitic effects [8]. A mixture of standing wave and magnetostatic modes were excited depending on the applied magnetic bias and structural dimensions, which translated into unwanted resonances in the output spectrum [9]. These methods are highly accurate for detecting spin wave resonance, but they offer very limited information about the magnetized ferrite and the individual resonance modes.

The electric transmission line model is commonly used to explain non-reciprocal properties of magnetized ferromagnets [10]. In reference [2], frequency dependent behaviour of complex permeability and permittivity of a ferromagnetic transmission line was calculated using an impedance analyzer. The measured intrinsic impedance and propagation constant were used to determine the transmission line impedance and admittance. Although the results were only applicable to the transverse electromagnetic (TEM) wave propagation; this is a very powerful technique to study electromagnetic characteristics of a magnetized ferrite. In reference [5], the magneto-impedance of saturated ferrites during ferromagnetic resonance was analyzed for different crystal structures. The resonance intensity and line width are dependent on the dominant magnetization process [5], Gilbert damping constant [11] and magnetic permeability [12]. Shorted microstrip transmission line perturbation technique was used to calculate the complex permeability during ferromagnetic resonance of a coplanar waveguide in reference [8]. Transmission line methods are suitable for the study of magnetized ferrites because individual spin wave modes can be studied and the electromagnetic properties of the transmission medium can be accurately modeled using an equivalent core impedance.

The transcendental equations for propagation of electrodynamic fields in gyromagnetic media do not have a close form solution so they must be solved via electromagnetic simulations [13]. The propagation of extremely high frequency (EHF) signals in dispersive, anisotropic, conductive ferromagnetic cores has been widely studied using finite difference simulations [4]. In reference [10], propagation of high frequency electromagnetic fields in a waveguide filled with anisotropic, magnetized ferrite was analyzed. The effect of frequency on the attenuation constant and phase constant was studied using finite difference frequency domain (FDFD) simulations and analytical results. However, the results were only applicable to two-dimensional ferrites with a fixed damping ratio and DC magnetic bias. The effect of complex permeability and permittivity on the transmission line impedance and propagation constant was studied using finite difference time domain (FDTD) simulations in reference [4]. The frequency dependent complex susceptibility tensor determines the steady state relative amplitudes, phases and ellipticities of the excited spin wave modes during millimeter wave ferromagnetic resonance [9]. Finite difference micro-magnetic simulations can accurately model the precessional magnetization dynamics, and the results are comparable to analytical results. They are very useful for studying individual resonance modes while excluding the formation of standing waves due to unwanted magnetic pinning.

Unlike electric transmission lines, these magnetic circuits are not designed to conduct electric charge upon application of electromotive force. As shown in Figure 1, the transverse electric ﬁeld lines are closed, encircling the magnetic wire; while the transverse magnetic ﬁeld lines are open, starting at the magnetic wire. 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. Such a model is presented in reference [14]. 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 behaviour of a high-pass filter; and simulations showed that they exhibit super-luminal phase velocity and almost zero attenuation dispersion in the microwave-frequency range [15].



Figure 1: Transverse field lines for a magnetic transmission line.

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 line integral of magnetic field intensity vector from point a to b:

The magnetic displacement current is defined as the rate of change of magnetic flux :

where is themagnetic flux density vector.

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 [14]. The magnetic transmission line circuit is shown in Figure 2.

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

where is the transverse magnetic impedance and is the longitudinal magnetic admittance [14].



Figure 2: Magnetic transmission line circuit model.

This research attempts to present, for the first time, an extension of the novel magnetic transmission line model for modeling a saturated ferromagnet. This study discusses the effects of ferromagnetic resonance on the per unit length magnetic transmission line transverse impedance and longitudinal admittance. Using three-dimensional micro-magnetic finite difference time domain simulations, the precessional magnetization dynamics were analyzed for individual spin wave excitations. The relative amplitudes, phases and ellipticities were used to calculate the propagation constant and wave impedance for the excited spin wave modes. Unwanted resonances due to reflections at boundary walls were avoided using perfectly matched boundary layers at the ends of the magnetic transmission line. The broadband response of the magnetic transmission line was analyzed using pulse-perturbation technique. The effect of complex permeability tensor elements and Gilbert damping constant on the propagation constant, intrinsic wave impedance, longitudinal magnetic admittance and transverse magnetic impedance was studied as well.

# FDTD Electromagnetic Simulation

MIT Electromagnetic Equation Propagation (MEEP) software was used for the electromagnetic simulation of a gyromagnetic, dispersive, ferromagnetic transmission line. The finite difference time domain method discretizes Maxwell’s equations using central difference approximations for space and time partial derivatives [16]. 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:

where isthe magnetization, is the Gilbert gyromagnetic ratio, is the effective field**,** is the phenomenological damping factor and is the saturation magnetization.

wheredescribes the linear deviation of magnetization from its static equilibrium value. **m** precesses around the bias field vector . couples the magnetization to the driving field , is the angular frequency of precession, is a damping factor and is the phenomenological Gilbert damping factor [17]. Equation 6 is solved in MEEP after midpoint method discretization [16].

Assuming both andhave harmonic time dependence , the oscillating part of Equation 6 becomes

For ferromagnetic media biased in z-direction, **.** This implies that the susceptibility tensor has skew-symmetric off-diagonal entries:

where = = , = = and = .

The frequency dependent nature of the non-diagonal susceptibility element is shown in Figure 3. For a high quality crystal oscillator, the resonance has a very large peak due to the small Gilbert damping factor .



Figure 3: 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 [13]:

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 [16].

# Simulation Results

A z-directed sinusoidal soft magnetic-charge current source was placed in the magnetized ferrite. The Fourier transform of the source is plotted in Figure 4. The polarization of each frequency changed from linear polarization as it moved in the direction of propagation. The resultant polarization changed continuously as the different frequency components experienced different rates of rotation per unit distance of propagation. Hence, the magnetic field was heavily deformed as it reached the output end.



Figure 4: Fourier transform of the applied magnetic current source plotted for the frequency range 0-60 GHz.

The 30-GHz harmonic of the incident wave matched the Larmor frequency, and gave rise to gyromagnetic resonance.



Figure 5: Anticlockwise rotation of magnetic field vector **H** during resonance of Larmor precession. The spin wave magnetic field components Hx and Hy were measured at a distance of 1 mm from the source in the +z direction.

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 due to the high magnetic susceptibility and magnetic permeability during the 30-GHz gyromagnetic resonance. The 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 intrinsic wave impedance dropped when the Gilbert damping constant was increased.



Figure 4: Plot of intrinsic wave impedance calculated at 30-GHz vs. Gilbert damping constant.

The phase constant and attenuation constant were calculated for the resultant magnetic spin wave. The calculated wave attenuation constant is shown in Figure 5, which 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 30-GHz gyromagnetic resonance. A high quality crystal oscillator, with a small Gilbert damping constant, showed a strong peak of the electromagnetic absorption spectrum. When the Gilbert damping constant was increased, the attenuation constant and the electromagnetic absorption decreased.



Figure 5: Plot of attenuation constant calculated at 30-GHz vs. Gilbert damping constant.

The calculated per unit length longitudinal admittance during gyromagnetic resonance is shown in Figure 6. Ferromagnetic resonance leads to a severe increase in 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. When the Gilbert damping constant was increased, the longitudinal magnetic admittance increased as well.



Figure 6: Plot of longitudinal magnetic admittance calculated at 30-GHz vs. Gilbert damping constant.

The calculated per unit length transverse magnetic impedance during gyromagnetic resonance is shown in Figure 7. The 30-GHz gyromagnetic resonance leads to a severe increase in 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. When the Gilbert damping constant was increased, the transverse magnetic impedance dropped. This indicated an increase in the magnetic flux leakage across the magnetized ferrite.



Figure 7: Plot of transverse magnetic impedance calculated at 30-GHz vs. Gilbert damping constant.

# Discussion

The non-linear and anisotropic nature of magnetized ferrites was modeled using a non-diagonal magnetic susceptibility tensor. The nano-magnetic exchange interactions and dipole-dipole interactions dictated the excitation of spin wave modes. The bias field produced Zeeman splitting in energy levels and the saturated magnetic dipoles transitioned between the energy levels by absorbing millimeter wave electromagnetic fields [9].

Magnetic transmission line method was suitable for the study of individual spin wave modes. The electromagnetic properties of the transmission medium were accurately modeled using an equivalent transverse magnetic impedance and the longitudinal magnetic admittance.

Finite difference micro-magnetic simulations accurately modeled the precessional magnetization dynamics. The frequency dependent complex dynamic susceptibility tensor determined the steady state relative amplitudes, phases and ellipticities of the excited spin wave modes during millimeter wave ferromagnetic resonance. Unwanted resonances due to reflections at boundary walls were avoided using perfectly matched boundary layers at the ends of the magnetic transmission line [9]. The broadband response of the magnetic transmission line was analyzed using pulse-perturbation technique.

During ferromagnetic resonance, the longitudinal magnetic admittance of the saturated ferrite dropped hence it provided a low reluctance path for magnetic flux. The magnetic flux leakage was small because the transverse magnetic impedance dropped. The nano-magnets exhibited a strong absorption of millimeter wave which resulted in a high attenuation constant.

The Gilbert damping constant was varied to simulate the effect of magnetic hardness on the ferromagnetic resonance. Gilbert damping constant depends on the crystal structure, chemical composition, ferrite grain size, structural dimensions and annealing temperature [5]. A high quality crystal oscillator must have a very low Gilbert damping constant, so that it can absorb millimeter waves and excite spin waves efficiently [11].

The intrinsic wave impedance and attenuation constant were a strong function of effective magnetic susceptibility [7]. They explain the high electromagnetic power losses across the saturated ferrite when it absorbs electromagnetic energy from the input signal. When the Gilbert damping constant was increased from to , the damping for precessional motion was increased, and the excitation of spin wave modes was restrained. The low magnetic susceptibility caused the intrinsic wave impedance and attenuation constant to drop. Hence, the electromagnetic absorption of millimeter waves by nano-magnets reduced significantly. When the effective magnetic susceptibility decreased, the magnetic reluctance increased and the absorption of magnetic flux dropped. This resulted in a huge increase in the longitudinal magnetic admittance. Meanwhile, the magnetic flux leakage increased which resulted in the drop of transverse magnetic impedance. The results were affirmed by calculating the longitudinal magnetic admittance and transverse magnetic impedance for each case. These observations are consistent with the experimental results [5].

# Conclusion

A magnetic transmission model was presented for a saturated ferrite exhibiting ferromagnetic resonance. Finite difference time domain simulation 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 accurately modeled using linearized Landau-Lifshitz-Gilbert model in MEEP simulator. It was shown that ferromagnetic resonance leads to a drastic increase in the transverse magnetic impedance; and the electromagnetic energy losses of longitudinal magnetic admittance. The quality of the crystal oscillator is dictated by Gilbert damping constant. When the precessional damping was increased, the electromagnetic absorption of millimeter waves was reduced due to the high longitudinal magnetic admittance and low transverse magnetic impedance. These results are useful for modern high frequency applications of gyromagnetic materials like spintronic devices, space navigation, wireless communication, maritime and geophysical prospecting instruments.

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