Modeling and FDTD Simulation of Dispersive, Gyromagnetic Transmission Lines

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**Abstract** –*A Finite Difference Simulation of Saturated Gyromagnetic Transmission Line is presented for studying the effects of Ferromagnetic Resonance on the Longitudinal Magnetic Admittance and Transverse Magnetic Impedance. The biased Magnetic Transmission Line was excited by a Gaussian magnetic current source in the electromagnetic Simulator MEEP. Resonance was observed when the Frequency spectrum of the input UHF signal overlapped with the Larmor Precession frequency band. The Discrete Fourier Analysis of the input and output electromagnetic fields was used to calculate intrinsic wave impedance and propagation constant. Using the Magnetic Transmission Line theory, these parameters were used to calculate the per unit length longitudinal magnetic admittance and transverse magnetic impedance. It is shown that ferromagnetic resonance leads to a drastic increase in the Transverse Magnetic Conductance which is responsible for electromagnetic losses. Also, the Transverse Magnetic Impedance dropped, indicating an increase in the Magnetic Flux Leakage.*

**Keywords:**T

# Introduction

Ferromagnetic materials are widely used in bulk power transmission and distribution transformers, elecromechanical machines, power electronic converters and radio frequency communication because their affinity for magnetic flux enables them to conduct magnetic information efficiently. They are mostly used as interfaces between isolated electric circuits which need to communicate at different voltage or current levels. This translation of electromagnetic information between the electric and magnetic domains is not perfect as it incurs energy losses due to Hysteresis, Eddy currents, Skin effect, Proximity effect, Gyromagnetism, Magnetoresistance, Magnetostriction and other residual loss mechanisms. Realistic system level models for the analysis of Ferromagnetic materials must account for this information delay, distortion and attenuation.

As evident from experimentation, Ferromagnetic materials change their channel properties under different electromagnetic stresses [13]. Many researchers have attempted to explain ferromagnetic resonance using the electromagnetic transmission line model, by including frequency dependent permittivity, permeability and conductivity [1], [13], [14]. An experimental setup for calculating frequency domain behavior of complex permeability and permittivity of a ferromagnetic transmission line was presented in [13], where the measured intrinsic impedance and propagation constant was used to determine the per unit length transmission line parameters. In [14], a closed form solution for estimating 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 power losses due to Ohmic losses were also considered in an equivalent core impedance. The propagation of UHF Gaussian pulse partial discharges in a dispersive, anisotropic, conductive ferromagnetic transformer core has been widely studied using FDTD simulations [14], [11], [1]. A closed form solution for analyzing the electromagnetic fields in a waveguide filled with an anisotropic, linear, dispersive, gyromagnetic ferrite was given in [1].

The Electromagnetic Transmission Line model has been used to accurately replicate the behavior of Ferromagnetic materials in electromagnetic simulations. The micro-magnetic FDTD simulations accurately modeled the spin transfer dynamics, and the results were comparable to analytical results [13].

Many researchers have tried to translate the Electromagnetic Transmission Line model into a system level design which can explain the flow of magnetic flux as the effective magnetic charge due to the application of Magnetomotive force [2]. The electric circuit laws are not applicable to magnetic circuits because they are not designed to conduct electric charge upon application of electromotive force. The most important magnetic circuits are the DC Reluctance model, the low frequency Permeance-Capacitance model and the high frequency Magnetic Transmission Line model.

Magnetic Reluctance circuit model is based on the G. Ohm’s Law, and it depicts magnetic core as a Magnetic reluctance which resists the flow of Magnetic Flux, which represents Magnetic Current [2]. It is not a power invariant model and the Ohm’s Law analogy is ill defined. The Reluctance model is only suitable for low frequency steady state simulations of transformers if the reluctance profile of the magnetic core is already known.

The Power Invariant Permeance-Capacitance Model based on B. Tellegen’s Gyrator Theory was proposed in [2]. The Permeance-Capacitance model uses a nonlinear permeance to model nonlinearity and hysteresis losses of magnetic materials. The Permeance-Capacitance model is only suitable for low frequency simulations of ferromagnetic materials. The model was used to predict the behavior of a ferromagnetic transformer core [2]. The circuit adopted a gyrator for the transformation between electric and magnetic domains. Nonlinear permeance elements were used to model core hysteresis losses and magnetic flux leakage. A magnetic conductance was used to represent eddy current losses. The model was improved to model hysteresis losses and frequency dependent eddy current losses in a laminated steel ferromagnetic transformer core [9]. The non-linear core permeance was designed to approximate the results obtained for a low frequency excitation. However, the model was not valid for high frequency simulations.

In [4] – [6], a Magnetic Transmission Line Model was developed based on the conventional Electric Transmission Line Model. For magnetic transmission lines, transverse impedance and the longitudinal 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.

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

# Magnetic Transmission Line Model

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 applying the magnetic laws relating Magnetomotive force to Magnetic flux rate.

Analogous to the scalar Electric Potential in Electric Transmission Lines, scalar magnetic potential can be defined as

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

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 which stores electric charges:

The per unit length Magnetic conductance dissipates energy due to Hysteresis, Eddy currents, Skin effect, Proximity effect, Magnetoresistance and other residual losses. It is closely related to the magnetic reluctance:

The Magnetic Transmission Line Equations are

The characteristic impedance is the ratio of Magnetic displacement current to the Magnetic Voltage. It is calculated as

The propagation constant is calculated by the following relation:

The Longitudinal Admittance is calculated using the following relation:

The Transverse Impedance is calculated using the following relation

# Finite Difference Time Domain 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 to the space and time partial derivatives. 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.

MEEP simulator was used to simulate anisotropic, dispersive and gyromagnetic materials.

1. Gyrotropy Model

Landau-Lifshitz-Gilbert model describes the precessional motion of saturated magnetic dipoles in a magnetic field.

describes the linear deviation of magnetization from its static equilibrium value. Precession occurs around this unit bias vector . represents oscillator strength, is the angular resonance frequency, is the oscillator damping factor.

# Simulation Results

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# Discussion

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# Conclusion

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# References

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