Response to Reviewers' Comments

Ref. No.: TMAG-22-01-0052
Title: Millimeter Wave Ferromagnetic Resonance of Saturated Magnetic Transmission Line
Journal: IEEE Transactions on Magnetics
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The authors take this opportunity to thank and express our sincere gratitude to the reviewers for sparing time to review the manuscript and give their thoughtful comments and suggestions. We have carefully considered the reviewers' comments and made our utmost effort to incorporate the suggestions made to improve the quality of the paper. After addressing the reviewers' comments, we believe the manuscript is now in excellent form and for this the reviewers deserve credit.

The changes made, in the manuscript, have been shown in blue colour and the manuscript has been reformatted according to the journal's formatting guidelines for revised submissions. The following remarks highlight the changes made in response to reviewers' comments.

REVIEWER #1 COMMENTS:

The authors in this article use the FDTD method to study transmission and impedance characteristics of ferrite loaded transmission lines.

While the numerical approach is sound, however the article lacks details on the application of this method, in particular the material and numerical parameters used to develop and carry out the simulations. Moreover, it is not clear how the authors observed and made comments about spin-waves when their model enforces a particular permeability spectrum (without actually computing the magnetisation) and don't consider exchange nor even evaluate magnetostatic (demagnetising fields). These questions are detailed in the comments below which need to be addressed:

Comment # 1:
It is important for authors to show how eq. (6) was derived (linearised) from the LLG equation, and what are the contributions taken for the effective field (applied, anisotropy, exchange, magnetostatics, eddy current etc.?). The authors also need to clarify what Gamma is in this equation (in the LLG equation it should be the gyromagnetic ratio, not a damping factor). The authors also need to clarify how they obtained the susceptibility tensor in (7) from (6).

RESPONSE:
We have made these corrections in Section II.
   (a) We have explained the derivation of linearized Landau Lifshitz Gilbert equation [Equation (8) in revised paper] from LLG equation [Equation (6) in revised paper]. It was assumed that magnetization has a large static term parallel to the DC bias and a small perturbation term. We have explained that only applied field contributions were considered for the effective magnetic field. Non-local effects like eddy currents,

magnetostatics, dipole-dipole, anisotropy and exchange interactions between non-neighboring dipoles were not considered.

(b) We have explained that Gamma symbol is the gyromagnetic ratio in the LLG equation [Equation (6) in revised paper]. Gamma symbol was used as a loss factor in MEEP software documentation and it caused confusion with gyromagnetic ratio, so we have replaced it with the complete form.

(c) We have explained how the susceptibility tensor was derived from the linearized Landau Lifshitz Gilbert equation [Equation (8) in revised paper] by assuming time harmonic dependence for magnetization and magnetic field intensity. The linearized Landau Lifshitz Gilbert equation [Equation (8) in revised paper] was simplified to Equation (9) in revised paper. The solution of Equation (9) in revised paper yields the magnetic susceptibility tensor.

Comment # 2:

It is not clear in Section II what material is assumed and what parameter values were used to determine the susceptibility (e.g. how did the authors work out wo - resonance frequency in (7) and Fig. 3? what was the assumed resonance mechanism and effective field contributions?). Did the authors use micromagnetic boundary conditions for the ferrite structure?

RESPONSE:

We have made these corrections in Section II:

(a) We have explained that permalloy ferromagnet sample was used for the simulation. We have also stated the following electromagnetic parameters of the ferrite: angular frequency of precession, saturation magnetization, Gilbert damping constant and relative permittivity. We assumed that the resonance frequency was 30-GHz based on product of gyromagnetic ratio $2\pi \times 23.8$ GHz/T and applied bias field strength 1000 kA/m. This is based on experimental results given in reference [9].

(b) We have explained that only applied field contributions were considered for the effective magnetic field. Non-local effects like eddy currents, long-range dipole-dipole interactions and exchange interactions between non-neighboring dipoles were not considered.

(c) We have explained that resonance occurred due to ferromagnetic resonance of the Larmor precession. Ferromagnetic resonance arises from the precessional motion of the magnetization of a ferromagnetic material in an external magnetic field. The magnetic field exerts a torque on the sample magnetization which causes the magnetic moments in the sample to precess.

We have made these corrections in Section III:

(a) We have explained that the tangential components and normal components of the magnetic field were continuous on the boundaries of the magnetic structure.

Comment # 3:

The authors also need to make it clear in Section II that the form of the permeability/susceptibility is enforced (preset) and not an outcome of the simulations (for example in contrast to rigorous combined simulations of micromagnetics and electromagnetics in Aziz PIER B, Vol. 15, 1–29, 2009 where the magnetisation is actually computed). In this case, the calculated impedance and transmission characteristics of the transmission line/waveguide are pre-determined since the resonance frequency and permeability are set!

RESPONSE:

We have made these corrections in Section II and III:

(a) We have explained that permeability/ susceptibility was enforced and not an outcome of the simulations. Hence, the calculated impedance and transmission characteristics of the transmission line were pre-determined since the resonance frequency and permeability were set.

Comment # 4:

In Section III, the authors need to clearly define the geometry and dimensions of the simulated structure, the ferrite material used and material parameters (e.g. magnetic and electromagnetic). The authors also need to specify the numerical parameters (grid cell size, time step, location of transmission line from PML, number of cells in PML .. etc.). The source is not clear: is it a z-directed electrical current in the transmission line or is it a z-directed plane wave? Also, what is the justification for using a 60 GHz pulse for the source (why not 10 GHz or 100 GHz)? The authors also need to specify the magnitude and direction of the bias (DC) field.

RESPONSE:

We have made these corrections in Section III:

(a) We have explained that the grid was divided into a 3-D array of cubic cells with the dimensions 10nm × 10nm × 10nm. The magnetized ferromagnetic sample had the dimensions 40nm × 40nm × 23um. The time step was chosen as $\Delta t = (1/60)$ fs. A perfectly matched boundary layer with 1600 cells was added on both ends of the transmission line. The perfectly matched boundary layer had a width of 1um.

(b) We have explained that the sample permalloy ferromagnet used for the simulation had the following parameters: gyromagnetic ratio $\gamma = 2\pi \times 23.8$ GHz/T, saturation magnetization $M_s = 790$ kA/m, Gilbert damping constant $\alpha = 10^{-5} - 10^{-2}$ and relative permittivity $\varepsilon_r = 1.5$. These values are based on experimental results given in reference [9].

(c) We have explained that a Gaussian soft magnetic current source (oscillating magnetic dipole) was placed in the magnetized ferrite. The Fourier transform of the source is plotted in Figure 5 for the frequency range 0 – 60 GHz. The oscillating magnetic dipole launched a z-directed wave which was linearly polarized in x-direction. The center-frequency of the source was 30-GHz because the precession frequency of the sample was set as 30-GHz.

(d) We have explained that the bias magnetic field was applied in z-direction and it had a magnitude of 10^6 A/m.

Comment # 5:

The authors in page 5 make the statements "The phase constant and attenuation constant were calculated for the resultant magnetic spin wave" and "The nano-magnetic exchange interactions and dipole-dipole interactions dictated the excitation of spin wave modes". There was no indication in Sections II or III in the article that the exchange contribution was taken into account (or how it was taken into account) - We assume since the material is saturated here, so how are spin-waves produced? (even if the authors refer to magnetostatic waves, then the authors don't actually calculate the magnetostatic fields as they don't compute M directly)? The authors need to clarify these statements.

RESPONSE:

We are sorry for this mistake. We have made the following corrections in Section II:

(a) We have explained that the 30-GHz ferromagnetic resonance causes the non-diagonal entries in the susceptibility matrix to become very large [see Equation (10) in revised paper]. The skew-symmetric off-diagonal entries give rise to ferromagnetic resonance when the frequency of the applied field matches the precession frequency. Hence, the magnetization executes a damped counterclockwise rotation around the bias vector. The dynamics of magnetic moments in the saturated ferrite are dictated by the linearized Landau Lifshitz Gilbert equation [Equation (8) in revised paper]. Only applied field contributions were considered for the effective magnetic field. Non-local effects like eddy currents, long-range dipole-dipole interactions and exchange interactions between non-neighboring dipoles were not considered.

(b) We have explained that magnetization is assumed as a sum of a large static term parallel to the applied bias field, and a small perturbation term. The solution [Equation (10) in revised paper] of linearized Landau Lifshitz Gilbert equation [Equation (8) in revised paper] was obtained by assuming time harmonic dependence for the magnetization and magnetic field intensity. The magnetization was calculated by discretizing Equation (8) in revised paper using midpoint rule.

We have made the following corrections in Section III:

(a) We have replaced the term "spin wave" with "electromagnetic wave" in the statement "The phase constant and attenuation constant were calculated for the resultant magnetic spin wave".

We have made the following corrections in Section IV:

(a) We have removed the statement "The nano-magnetic exchange interactions and dipole-dipole interactions dictated the excitation of spin wave modes".

(b) We have replaced the term "spin wave" with "electromagnetic wave" where ever it was used.

Comment # 6:

The authors need to indicate (in the figure captions) the frequencies at which the quantities in Figures 4, 5, 6 and 7 were calculated.

RESPONSE:

We have edited the captions for the respective Figures plotting intrinsic wave impedance, attenuation constant, longitudinal admittance and transverse impedance. The quantities were calculated at the ferromagnetic resonance frequency of 30 GHz.

Comment # 7:

The authors also need to comment on or indicate the purpose of the equivalent circuit model they introduced in Section I with the FDTD simulations.

RESPONSE:

We have made the following corrections in Section IV:

(a) We have explained the purpose of equivalent magnetic circuit model introduced in Section I. From the results of micromagnetic finite difference time domain simulations, the longitudinal magnetic admittance and transverse magnetic impedance were calculated using Equation (4) and Equation (5) in revised paper. In Figure 2, 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; and the per unit length magnetic conductance dissipates energy.

(b) We have explained that as seen in Figure 8, the longitudinal magnetic admittance was small during ferromagnetic resonance hence it provided a low reluctance path for magnetic flux. From Figure 9, it was derived that the magnetic flux leakage was reduced during ferromagnetic resonance because the transverse magnetic impedance was large. Hence the results of micromagnetic simulation were verified by using the equivalent magnetic circuit model given in Section I.

(c) We have explained that when the Gilbert damping constant was increased, the magnetic reluctance increased and the absorption of magnetic flux dropped. The damping of Larmor precession increased because the off-diagonal entries in the magnetic susceptibility tensor became smaller. This caused the effective magnetic susceptibility to decrease. As seen in Figure 8, this resulted in an increase in the longitudinal magnetic admittance. Meanwhile, the magnetic flux leakage increased which resulted in the decrease of transverse magnetic impedance in Figure 9. Hence the results of micromagnetic simulation were verified by using the equivalent magnetic circuit model given in Section I.

Comment # 8:
Minor typing errors:
- Abbreviations must be defined in the text (e.g. EHF, TEM, .. etc.).
- Page 2, paragraph 2, "FDTD simulations .. "

RESPONSE:
We have defined the abbreviations EHF, TEM, FDTD, FDFD, MEEP at the point they are first used.

REVIEWER # 2 COMMENTS:

The authors describe a transmission-line model based on magnetic fields and magnetic currents instead of the electric field/electric current model normally found in standard electromagnetic text books. At first glance, the idea of developing a magnetic transmission line framework seems redundant since the transmission of power and energy must be invariant to whatever conjugate basis one uses. However, in the context of new approaches established by the field of magnonics, it makes sense to address such measurements in terms of a magnetic basis for which the contribution does provide an original perspective on the problem.

The article is well written and the comments below, albeit mandatory from a clarity standpoint, does not change the contents and conclusions of the manuscript.

Comment # 1:
The acronyms EHF, FDFD, FDTD, MEEP are used without prior description and must be defined at the point they are first used.

RESPONSE:

We have defined the abbreviations EHF, TEM, FDTD, FDFD, MEEP at the point they are first used.

Comment # 2:

The use of adjectives such as the word "huge" in the second paragraph of the Simulation Results section must be removed.

RESPONSE:

We have removed the adjective "huge" in the second paragraph of the Simulation Results section.