3D Multiscale Unconditionally Stable Time-Domain Modeling of Nonlinear RF Thin Film Magnetic Devices

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***Abstract*— An unconditionally stable three-dimensional (3D) finite-difference time-domain (FDTD) algorithm has been proposed to solve simultaneously Maxwell's equations and the Landau-Lifshitz-Gilbert (LLG) equation with full nonlinear effects. The proposed algorithm can predict the dynamic interaction between magnetic spins and EM fields. The accuracy of the modeling has been validated by 1. Small signal simulation of a linear ferrite isolator and 2. Large signal simulation of the dispersive permeability of a continuous ferrite film. The simulations agree with the theoretical and experimental predictions, under both linear and nonlinear circumstances. Specifically, the algorithm has fully revealed that sufficiently large RF power can decrease the ferromagnetic resonance (FMR) frequency and suppress the permeability.**

***Keywords*— Electromagnetics, magnetic thin films, finite difference time domain methods, Landau-Lifshitz-Gilbert equation, multiphysics, nonlinear problems, unconditionally stable methods**

I. Introduction

Dynamic multiphysics is the general trend in the field of modern modeling, due to the upsurge of novel multiphysics devices, such as RF components based on thin-film magnetic materials. Such high-quality materials are attainable by the maturing of nanofabrication technologies. In most traditional RF systems, one dynamic physical mechanism dominates. However, novel devices usually involve multiple physical mechanisms. For example, frequency selective limiters (FSL) rely on the nonlinearity of magnetic thin film to suppress high-power jammer without sacrificing the desired signal intensity [1], and therefore both electromagnetics (EM) and magnetic spin dynamics need to be evaluated. However, the state-of-the-art design of RF magnetic devices has been hindered mainly by the lack of effective modeling tool. In order to fully understand and design the next-gen devices with desired functional behavior, this work proposes a multiphysics modeling based on a modified alternating-direction-implicit (ADI) finite-difference-time-domain (FDTD) method [2-3] for its unconditional stability in handling structures with fine details. Special techniques are introduced to model the variation of magnetization at the material interface with full consideration of boundary conditions.

II. Modeling Formulation

In RF circuitry based on magnetic materials, dynamic magnetic spins are utilized to control and manipulate the EM signals. Therefore, in order to capture the correct physical phenomenon, fully dynamic Maxwell's equations (1) and LLG equations (2) should be solved simultaneously. These two equation sets are shown as follows, respectively:

$$\nabla\times\boldsymbol{H} = \epsilon\frac{\partial \boldsymbol{E}}{\partial t} + \boldsymbol{J} + \sigma\boldsymbol{E}, \nabla\times\boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}, \tag{1}$$

$$\frac{\partial \boldsymbol{M}}{\partial t} = \mu_0\gamma(\boldsymbol{M}\times\boldsymbol{H}_{\text{eff}}) + \frac{\alpha}{|\boldsymbol{M}|}\boldsymbol{M}\times\frac{\partial \boldsymbol{M}}{\partial t}, \tag{2}$$

where the gyromagnetic ratio is $\gamma = -1.759\times10^{11} C/kg$, and the magnetic damping constant is $\alpha = \mu_0|\gamma|\Delta H/4\pi f_r$, with ΔH being the FMR linewidth and f_r the FMR frequency. As the governing rule of micromagnetics, LLG equation (1) describes the evolution of magnetization $\boldsymbol{M}$, with the total effective magnetic field $\boldsymbol{H}_{\text{eff}}$ that drives the magnetic spins. EM fields present themselves most commonly in modern magnetic systems. Therefore, Maxwell's equations (2) are included in extensive magnetic modeling, and full form of dynamic Maxwell's equations must be considered, i.e. $\partial\boldsymbol{D}/\partial t \neq 0$ [4]. There are four major challenges to model interactive magnetic spins and EM waves: 1) Nonlinear coupling between all field components; 2) Simultaneous solution of Maxwell's equations and the LLG equation within every time step; 3) Scale disparity of the multiphysics; 4) Demagnetization at the material interfaces. The first challenge is overcome by a vector calculation method through an implicit and stable iterative numerical scheme [5]. The second and third challenges are overcome by the ADI FDTD algorithm with spin dynamics modification, and the last challenge by rigorous treatment of EM boundary conditions. The advantage of utilizing the FDTD method is that the intrinsic nonlinearity of magnetic material favors time-domain representation.

III. Simulation Results

The first-step demonstration of the nonlinear algorithm is through small signal simulation, represented by ferrite isolators constructed in rectangular waveguides. As shown by Fig. 1, a waveguide structure that resembles those in [6-7] is simulated using the proposed nonlinear code and compared to theory as well as experimental data. A small signal EM wave is injected into the waveguide such that the problem reduces to the linear case. The time-step is 8 times the CFL, leading to a sampling frequency is higher than the Nyquist rate. Fig. 1 shows a passband between 9.17 GHz and 10.07 GHz, which represents EM propagation in the interval between the waveguide cutoff frequency and FMR frequency. The simulated attenuation

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spectrum (this work) more closely matches the experimental data [6] as compared to conventional analytical models [7]. The main reason for this is that this work is solving the system of micromagnetics more accurately, representing the precessional dynamics in the system as well as the losses present at resonance. This small signal simulation demonstrates the accuracy of the proposed modeling in the linear regime.

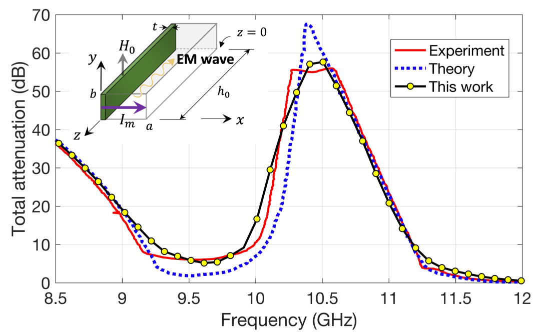
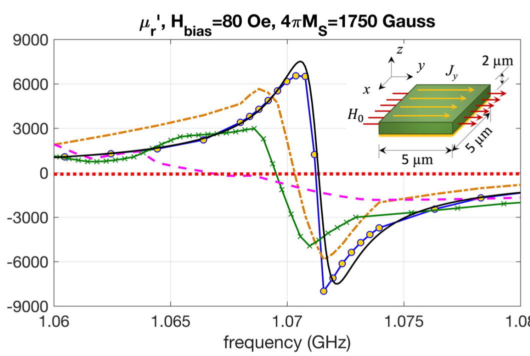
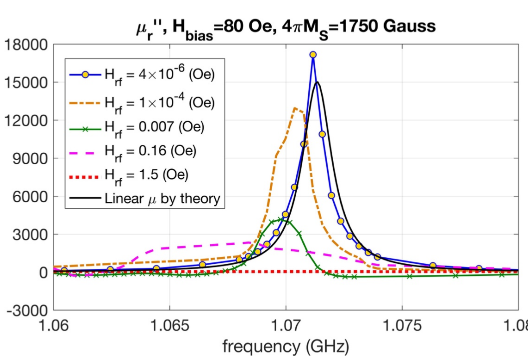


Fig. 1. Small signal verification of the nonlinear modeling by the simulated attenuation. The length of the waveguide is h_0 = 49 mm. The waveguide has a thin YIG ferrite slab against one sidewall. a = 14.95 mm, b = 11.43 mm, h = 140 mm, t = 0.45 mm, ϵ_r = 13, $4\pi M_S$ = 1750 Gauss, H_0 = 2890 Oersted, ΔH = 35 Oersted, Δx = 0.04 mm, Δy = 3.387 mm, Δz = 2 mm. The magnetic current line source is located at y=b/2 and z=h_0, where a PEC boundary condition is assumed. The four sidewalls are PEC and the other end of the waveguide is terminated by first-order Engquist-Majda one-way ABC. The simulated magnetic field inside the ferrite slab is 1.25×10^{-3} Oersted.



(a)



(b)

Fig. 2. Nonlinear dispersive permeability simulated with the structure in the inset of the Fig. 2(a). (a) real part μ', (b) imaginary part μ''. A YIG thin film is backed by PEC, and is covered by a uniform electric current sheet J_y. The film is 2 μm-thick and is magnetized by H_0. The four sides of the structure are enclosed by periodic boundaries, leading to an infinite planar dimension. The simulation space is 5 μm × 5 μm × 60 μm with 1 μm × 1 μm × 0.4 μm spatial resolution. The top surface of the simulation space is covered by ABC. The simulation space is filled with vacuum.

The second step is to apply the proposed modeling to large-signal nonlinear problem. The nonlinear behavior of permeability in ferromagnetic materials manifests itself as lower FMR frequencies and smaller peak permeability. In this section, we demonstrate this phenomenon by varying the RF signal intensity in a thin film of YIG backed by a PEC ground. A continuous current sheet of varying magnitudes is placed on top of the thin film shown by Fig. 2. The time-step is 5000 times the CFL ($\Delta t_{CFL} = 7.6980\times10^{-16}$ s). The thin film is magnetized by an in-plane DC magnetic bias ($H_0 = 80$ Oersted) parallel to the electric current. The magnetic spin is initialized in the y direction. As can be seen in Fig. 2, when the excited RF magnetic field is low, the simulated permeability matches with the small signal perturbation theory. This agreement again validates the proposed method in the linear region. When the RF field increases to be larger than 1×10^{-4} Oersted, the FMR frequency down-shifts due to lower longitudinal magnetization in the bias direction. In addition, the dispersive permeability suffers peak value suppression and linewidth broadening as the RF field further increases. This phenomenon has been experimentally discovered by the magnetics society, however, is first reported numerically by this work in the 3D form. The simulated nonlinear permeability can demonstrate the potential of the proposed modeling for design of nonlinear devices such as FSL. The authors are working toward the experimental validation of the large signal case.

IV. Conclusion

This work represents the first 3D multiscale unconditionally stable time-domain modeling of nonlinear RF thin film magnetic devices. Both small-signal and large-signal validations have been shown. This work is suited to be the workforce model code for miniature device design involving multiphysics.

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