A Novel Design Methodology for MSSW Transmission Lines Without Iteratively Solving Maxwell-Landau-Lifshitz-Gilbert Equation

Abstract—**Magnetostatic surface wave (MSSW) has unique features of unidirectional propagation, slow group velocity, and magnetic tunability, leading to wide applications in microwave devices and components like magnetostatic surface wave transmission lines (MSSW-TLs) for analog signal processing. Due to the strong interaction between MSSW and RF signals, solving the coupled Maxwell-Landau-Lifshitz-Gilbert (Maxwell-LLG) equations is necessary in modeling MSSW devices, which is however resource-intensive and time-consuming. To avoid solving the coupled equations, in this work, a novel design methodology based on the analogy between magnetic biasing and amplification is proposed for MSSW-TLs. The performance of a biased MSSW-TL can thus be easily predicted by its unbiased performance (Maxwell's equation only) with an amplification factor, leading to a rapid optimization process that is accelerated by ~100. An yttrium iron garnet (YIG)-based MSSW-TL prototype is successfully designed using the proposed method. The experimental data proves the effectiveness of the proposed design methodology.**

Index Terms—**Electromagnetic coupling, magnetostatic surface wave (MSSW), Maxwell-LLG, termination design, yttrium iron garnet (YIG).**

I. Introduction

Over the past few decades, thin-film yttrium iron garnet (YIG) has attracted considerable attention due to its extremely low dielectric loss [1] and narrow ferromagnetic resonance (FMR) line width [2]. It facilitates the propagation of magnetostatic surface waves (MSSWs) along its surfaces, exhibiting unique features such as slow group velocity, nonreciprocity [3] [4], and magnetic tunability. These features open avenues for the development of various novel RF/microwave devices. An MSSW-based active delay line was realized in [5], offering long delay time with low decay rate. The nonreciprocal characteristic of MSSW was used to achieve an isolating bandpass filter [6]. A frequency-selective limiter utilizing MSSW propagation with low threshold power was demonstrated in [7].

One critical building block of MSSW-based devices is the MSSW transmission line (MSSW-TL), shown in Fig. 1. It consists of a YIG thin film and two microstrip lines underneath, serving as transducers from RF to MSSW, and vice versa. One end of the microstrip line (transducer) needs proper termination to facilitate impedance matching [8]. To excite MSSWs, an in-plane DC magnetic bias H_0 parallel to transducers is required.

The conventional way of designing MSSW-TL involves modelling the damped motion of magnetization using Landau-Lifshitz-Gilbert (LLG) equation as well as the EM-MSSW coupling using Maxwell's equations [9], which is resource-intensive and time-prohibitive even with commercial solvers [10]. An analytical model was developed to guide the MSSW-TL design [11]. However, the termination design, which is critical to MSSW-TL performance, was not covered.

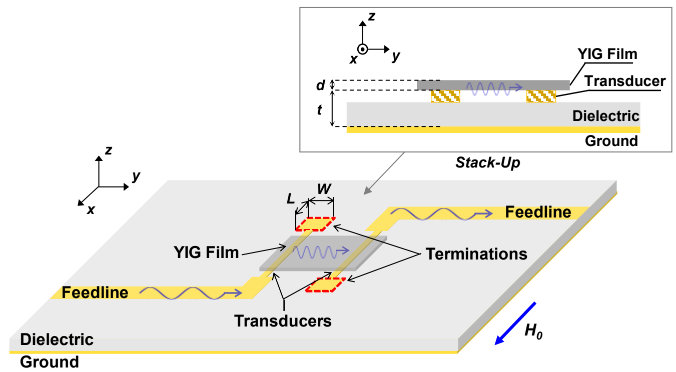

Fig. 1. MSSW-TL structure and stack-up. A magnetic bias field H_0 is applied along the x-axis.

In this paper, a novel design methodology eliminating the need for iteratively solving Maxwell-LLG equations is proposed for MSSW-TLs. First, the transition from unbiased to biased signal transmission in MSSW-TL is identified as a signal enhancement process with an amplification factor. The amplification is independent of transducer terminations. Once available, it can be used to predict the biased performance (Maxwell-LLG equations) from the unbiased one (Maxwell equations only), thus expediting the design flow. Based on the proposed design method, a MSSW-TL prototype working at 1.4 GHz is designed and measured, and the prediction is comparable to the measurement, proving the effectiveness of proposed approach.

II. Governing Equations of MSSWs

When a magnetic material is saturated under proper external magnetic field H_0, all the magnetic moments or spins within the material are aligned with the direction of H_0, allowing for the propagation of spin waves like the MSSW [3]. The excitation of MSSWs is commonly done by microwave excitation via antenna or waveguide transducers (see Fig. 1) [12], which offers precise control over the frequency and amplitude.

The micromagnetic in a magnetic material under the influence of external magnetic fields and the internal magnetic properties of the material can be described by LLG equation [9]:

$$\frac{\partial \boldsymbol{M}}{\partial t} = -\gamma \boldsymbol{M} \times \boldsymbol{H}_{\mathrm{eff}} + \frac{\alpha}{M_s} \boldsymbol{M} \times \frac{\partial \boldsymbol{M}}{\partial t} \tag{1}$$

where $\boldsymbol{M}$ is the magnetization; M_s represents the saturation magnetization; α is the damping factor; γ is the gyromagnetic ratio and $\boldsymbol{H}_{\text{eff}}$ is the effective magnetic field considering the contributions of external bias field H_0, demagnetization and anisotropy fields.

Once $\boldsymbol{H}_{\text{eff}}$ is fixed, the dispersive permeability μ_r of a magnetic material can be determined by solving LLG equation. For a lossless material, a Polder tensor can be obtained

$$\mu_r = \begin{bmatrix} \mu_1 & i\mu_2 & 0 \\ -i\mu_2 & \mu_1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

where μ_1 and μ_2 are expressed by

$$\mu_1 = 1 + \frac{\omega_0 \omega_{\text{m}}}{\omega_0^2 - \omega^2}, \quad \mu_2 = \frac{\omega \omega_{\text{m}}}{\omega_0^2 - \omega^2}, \tag{3}$$

where $\omega = 2\pi f_{\text{RF}}$, $\omega_0 = 2\pi\gamma H_{\text{eff}}$, $\omega_m = 2\pi\gamma(4\pi M_s)$.

By plugging (2) into the Maxwell's equation under magnetostatic approximation, the dispersion equation of MSSW can be obtained [13],

$$e^{2|k|d} = \left(\frac{\mu_1 - \mu_2 s - 1}{\mu_1 + \mu_2 s + 1}\right)\left(\frac{\mu_1 + \mu_2 s + \tanh(-|k|t)}{\mu_1 - \mu_2 s - \tanh(-|k|t)}\right) \tag{4}$$

where $s = k/|k|$. It relates the propagation characteristics of a MSSW to frequency.

III. Design Methodology

In the design of MSSW-TLs, the most critical step is the optimization of the transducer terminations (see Fig. 1), while the rest TLs like feeding lines and transducers can be easily determined. The transducer termination is crucial to the power conversion efficiency from RF to MSSW,

$$\eta_{\text{RF-to-MSSW}} = \frac{P_{\text{MSSW}}}{P_{\text{RF}}} = \frac{4Z_0 R_{\text{i}}}{(Z_0 + R_{\text{i}})^2 + X_{\text{i}}^2} \tag{5}$$

where Z_0 is the characteristic impedance of the feeding TLs, $Z_{\text{i}} = R_{\text{i}} + \text{j}X_{\text{i}}$ is the input impedance looking into the terminated transducers [8]. Therefore, it is desirable to optimize the termination of a transducer for the maximum $\eta_{\text{RF-to-MSSW}}$.

Two ways are often used in modeling MSSW-TLs: a) solving the coupled Maxwell-LLG equations and b) solving Maxwell's equations with material dispersion and anisotropy from LLG solution or measurement (commercial EM solvers like HFSS) [14]. Both of them are resource-intensive and time-consuming.

In this work, inspired by the analogy that a biased MSSW-TL works like an amplifier, enhancing the transmittance between the two transducers under no magnetic bias, an amplification factor F is introduced to represent the enhancement (see Fig. 2). Consequently, the transmission performance of a biased MSSW-TL can be easily predicted by

$$S_{21,\text{biased}} = F(f, H_0) \cdot S_{21,\text{unbiased}} \tag{6}$$

Such an analogy is reasonable because when biased to saturation, a magnetic material becomes less lossy, thus facilitate MSSW propagation [3]. One important feature of F is that when in the linear region of MSSW-TLs, it is almost independent of P_{RF} and thus the transducer termination. Hence, in a termination-oriented optimization, F can be re-used. Not only will the optimization process be expedited, but also no Maxwell-LLG equations or the simplified version will need to be solved iteratively.

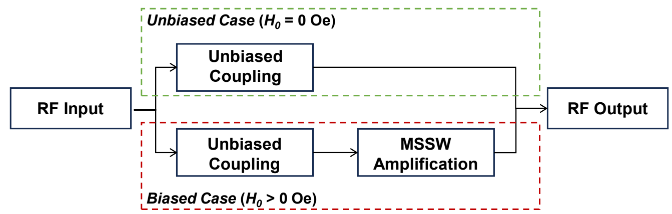

Fig. 2. Diagram of MSSW-TL operating mechanism in biased and unbiased cases.

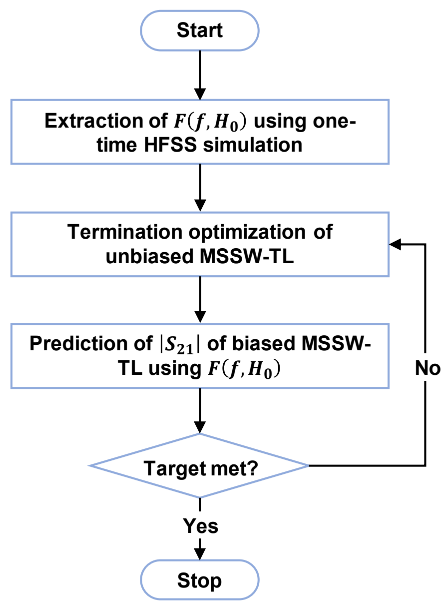

Fig. 3. Flowchart of the proposed MSSW-TL design methodology.

Fig. 3 shows the flow of the proposed design methodology based on F. A one-time HFSS simulation is first conducted to find F at different bias H_0 and frequency f. The subsequent optimization for transducer terminations requires only EM simulations for unbiased MSSW-TL which do not involve highly dispersive and anisotropy magnetic materials. The whole process will be greatly simplified and accelerated.

IV. Method Implementation and Experiment

To validate the proposed design methodology, it was implemented to designing a MSSW-TL prototype at 1.4 GHz (see Fig. 4). The key design parameters are (d, t, W, L) = (4.6 um, 0.64 mm, 1 mm, 1 mm) according to Fig. 1, and the lateral dimensions of the YIG film are 1 cm^2.

Fig. 5 (a) shows the extracted amplification factors of MSSW-TL under various magnetic biases. H_0 of 100 Oe can be used to excite MSSW at around 1.4 GHz. The terminations are optimized in HFSS to achieve impedance matching at the desired frequency. Fig. 5 (b) shows good agreement between predicted and measured transmission results of the prototype.

It is worth highlighting that the HFSS simulation times of the biased and unbiased MSSW-TL using HFSS are ~30 hours and ~20 minutes, respectively. A design time of ~1/100 is achieved by using the proposed method, indicating significant efficiency improvements.

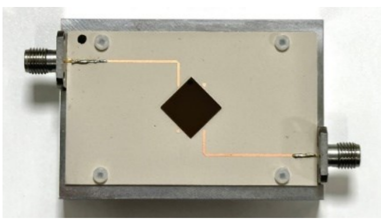

Fig. 4. Prototype of MSSW-TL.

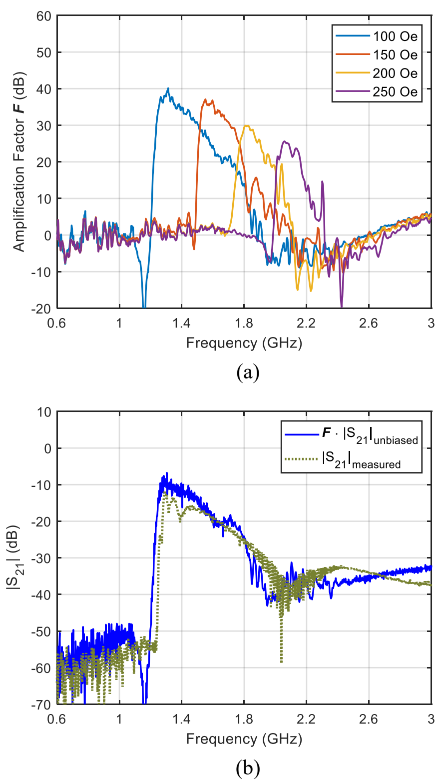

Fig. 5. (a) Amplification factor F of MSSW-TL with open-circuited terminations under various H_0. (b) Comparison between predicted and measured results with a termination dimensions of 1 mm^2.

V. Conclusion

A design methodology eliminating the need of iteratively solving Maxwell-LLG equations is developed for YIG-based MSSW-TLs. The amplification factor for MSSW-TL modelling is proposed based on the analogy that a biased MSSW-TL works as an unbiased MSSW-TL plus an amplifier where the amplification is independent of transducer termination. Hence, in optimizing the termination of a MSSW-TL, only the simulation of the MSSW-TL under no bias is needed, eliminating the need of solving the coupled Maxwell-LLG equations iteratively. A YIG-based MSSW-TL prototype is successfully designed using the proposed method with each optimization cycle significantly accelerated. Good agreement is observed between the prediction and measurement, proving the effectiveness of the proposed design methodology.

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