Investigation of electromagnetic feedthrough in spin wave based majority gates

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***Abstract*—This paper presents the simulation and experimental investigation of the direct electromagnetic coupling between the four U-shaped antennas of a spin wave majority gate (SWMG). A shielded and unshielded layout are investigated. The layouts are designed to be processed on yttrium iron garnet (YIG) films grown on gadolinium gallium garnet (GGG). The relative permittivity of the GGG substrate is extracted from experimental data as εr=13, with a loss tangent of 0.15 at 10 GHz. Using surface current density simulated results and S parameter measured results we show that the unshielded layout is the suggested approach for future SWMG developments.**

***Keywords*—direct coupling; GGG; permittivity; spin wave; YIG.**

1. Introduction

In the last decades the ferromagnetic resonance (FMR) and spin waves (SW) propagation have been intensely studied topics for magnonic devices such as magnonic waveguides, delay lines, spintronic computation, microwave analog systems etc. [1]-[2]. They operate without moving electrons, thus reducing dissipation and energy consumption, are less affected by radiation, and spin waves properties like interference and nonreciprocal propagation can lead to novel circuit designs and innovative solutions. Magnonic devices are well suited for building majority gates as a new approach to circuit design with improved area and power scaling efficiency [3]. A SW combiner can substitute several tens of transistors, and with three majority gates a full-adder can be configured.

In magnonic devices, FMR or SW are generated by microwave electromagnetic (EM) signals by means of inductive antennas that convert microwave currents into oscillating magnetic fields. This type of transducing principle is also used as SW detectors that inductively convert spin waves or FMR to microwave signals [4].

Beside SW propagation distance, damping, frequency dispersion and nonlinear effects, one important topic that must be investigated for a proper design of the spin wave majority gates (SWMG) is the direct electromagnetic coupling between the different ports (three inputs and one output) of the gate. Because the output power level due to SW propagation is low, the EM feedthrough between the connecting pads and lines must be minimized.

In many SW applications yttrium iron garnet (YIG) has proven to be a valuable material mainly because of its insulating properties and small Gilbert damping constant that enables spin transport on the millimeter length scale with excitation in the microwave frequency range [5]. YIG films of several hundred nanometers thick are grown on gadolinium gallium garnet (GGG) substrates with a thickness of hundreds of micrometers. Some uncertainty exists regarding GGG's permittivity due to conflicting reports between vendor specifications and published literature [6]. This leads to the need of a more careful investigation for the development of more accurate EM models.

This paper presents the results of the investigation of direct EM coupling between

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the SW antennas of a SWMG operating in the 2-12 GHz range. Two layout configurations fabricated on 500 µm thick GGG substrate are investigated. First, the dielectric parameters of the GGG substrate are extracted from measured data. Then, 3D EM models are developed in CST Microwave Studio for circuits with and without additional metallic shielding between the SW antennas. Surface current distributions are simulated. The two layouts are fabricated and the measured S-parameters are compared to simulations.

2. Extraction of GGG dielectric parameters

The material parameters of GGG (Czochralski method) given by manufacturers are a relative permittivity of 30 with a loss tangent around 0.15 (e.g. Crystal GmbH, Alineason Materials Technolgy or Princeton Scientific Corporation). This data has not been consistent with measurements performed by researchers in the GHz range, with [6] reporting a relative permittivity of 11.9 and a loss tangent of 0.052 in the 8.2 – 12.4 GHz, determined using the transmission/reflection method in a rectangular waveguide. Since these material parameters are of utmost importance when developing a simulation model, a different approach, based on coplanar waveguide transmission lines (CPW-TL) measurements was used to extract the effective permittivity in the 2 – 55 GHz range [7]. Using a 3D EM model of the CPW-TL and data fitting, the loss tangent was also estimated.

GGG is a composite material used, among others, as a seed layer for the growth of YIG. In order to extract the material parameters for high frequencies, CPW-TLs of two lengths, L_A=1 mm and L_B=2 mm, respectively were designed and fabricated.

The two CPW-TLs were fabricated on a 200 nm thick gold layer deposited on a 500 µm thick GGG substrate. The S-parameters S^A and S^B were recorded by means of on wafer measurements and the effective permittivity was extracted using (1)-(5). The result is shown in Fig. 1. Using a 3D EM model of the CPW-TL and data fitting of the extracted effective permittivity, a relative permittivity can be estimated around εr=13, for a loss tangent of 0.15 in the 2-12 GHz frequency range of interest.

$$\gamma = \frac{1}{\Delta L} argch\left(\frac{S_{11}^B S_{22}^A + S_{11}^A S_{22}^B - \Delta_A - \Delta_B}{2S_{21}^B S_{12}^A}\right) \quad (1)$$

$$\Delta L = L_B - L_A \quad (2)$$

$$\Delta_{A=} S_{11}^A S_{22}^A - S_{21}^A S_{12}^A \quad (3)$$

$$\Delta_{B=} S_{11}^B S_{22}^B - S_{21}^B S_{12}^B \quad (4)$$

$$\varepsilon_{eff} = \frac{Im(\gamma)^2}{\omega^2 \mu_0 \varepsilon_0} \quad (5)$$

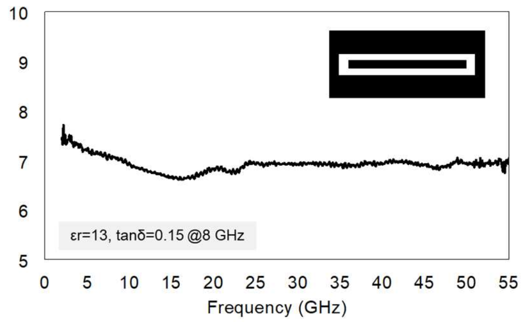

Fig. 1 Effective permittivity of GGG extracted from measured S-Parameter results (inset: CPW-TL layout)

3. 3D electromagnetic modeling

Two 3D electromagnetic models were developed in CST Microwave Studio (Fig. 2). The designs are based on U-shaped antennas with trace widths and gap equal to 2 µm. The majority gate consists of a total of four antennas, with three of them acting as inputs and the fourth as the output [8]. The vertical overlap between antennas is 40 µm and the cap of the U shape is another 3 µm. The antennas are connected by 500 µm long CPW-TLs with signal line width and gaps of 80 µm. The substrate is 500 µm thick GGG.

Fig. 2 (a) shows the 3D EM model developed for the SWMG layout without any shielding between antennas. The CPW metallization is grey, while the antennas are indicated with yellow. The placement of the YIG magnetic waveguide is also indicated. The antennas are spaced at 25 µm (antennas IN1-IN2 and IN3-OUT4) and 20 µm (antennas IN2-IN3).

In Fig. 2 (b), a shielding was added

between the antennas and extended to cover the YIG magnetic waveguide. The distance between the antenna metallization and the shielding in the waveguide area is 2 µm, and 4.5 µm for the long strip connecting the shielding to the top and bottom GND planes.

The structures were excited using rectangular waveguide multipin ports (quasi-transversal electromagnetic mode).

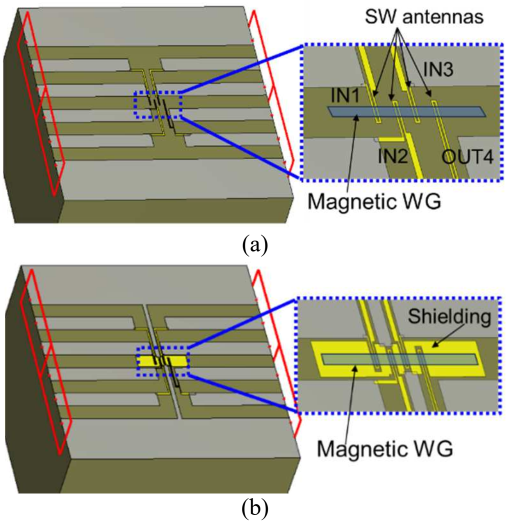

Fig. 2 3D electromagnetic models of SWMG circuits: (a) without shielding between antennas; (b) with shielding between antennas.

Although the shielding has the potential to lower the coupling between the different ports of the SWMG, particularly between IN1-IN3, and IN2-OUT4, it is important to check the currents which are induced in the additional metallization which will be placed on top of the YIG magnetic waveguide and will generate spurious spin waves which will propagate and potentially interfere with the desired signal. Fig. 3 (a) shows the simulated surface current for the shielded (top) and unshielded (bottom) devices when antenna IN1 is excited.

A comparison of the surface current amplitude along the AA' dotted line segment from Fig. 3(a) is plotted in Fig. 3 (b). The currents induced in the shielding have amplitudes about 5-10 times lower than the maximum current in the excited antenna. These levels have the potential to add significant noise to the useful spin wave signal.

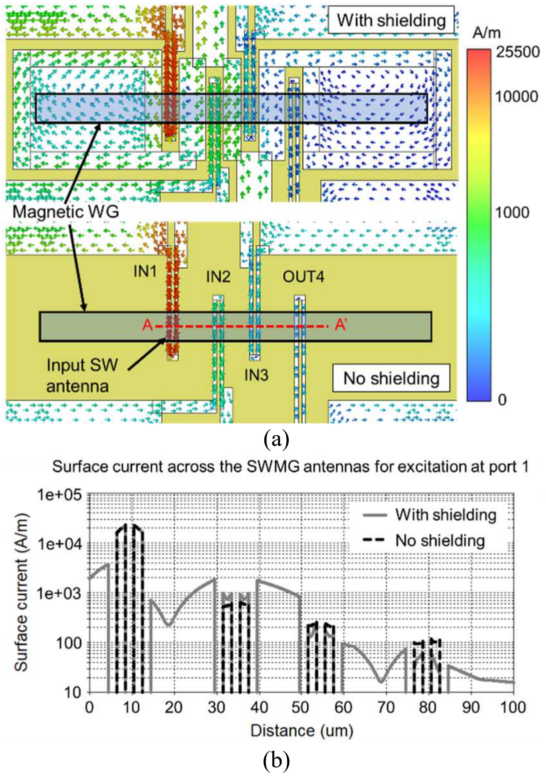

Fig. 3 Surface current distribution at 7.5 GHz when input 1 is excited for the two layouts: (a) 2D arrow plot; (b) comparison of the surface current distribution along the AA' dotted line segment from Fig. 3(a)

4. Measurement results and conclusions

Test devices were manufactured using 200 nm gold metallization on 500 µm GGG substrate, without the YIG magnetic waveguide. A photo of the manufactured shielded device is shown in Fig. 4. The input and output ports as well as the ground-signal-ground (G-S-G) contacts are indicated.

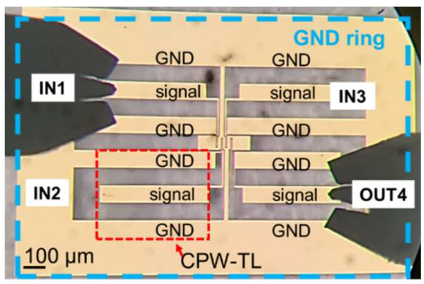

Fig. 4 Photo of the fabricated SWMG layout with shielding contacted by G-S-G measurement probes

Both devices (shielded and unshielded) were characterized on-wafer, using 150 µm pitch G-S-G probes and a 2-port VNA. A on-wafer short-open-load-thru calibration was performed using a 1 MHz frequency step and 1 kHz intermediate frequency.

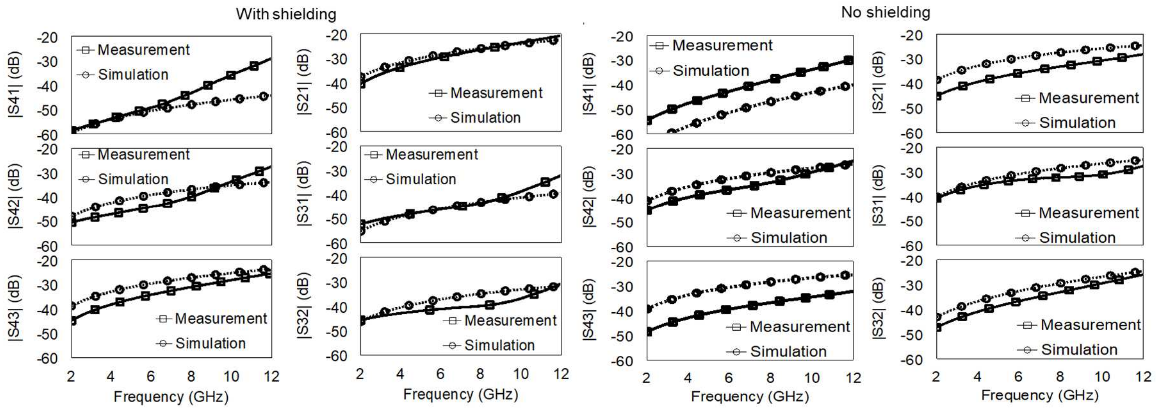

Fig. 5 Comparison of simulated and measured transmission parameters for the SWMG with shielding (left) and without shielding (right)

A comparison between the simulated and measured insertion losses (direct coupling) is shown in Fig. 5 for the two devices. The agreement is fair, especially considering the very low level of the signals. The shielding shows some reduction in the direct coupling between IN2 and OUT4 as well as between IN1 and IN3. This can be significant, particularly at lower frequencies in the 2-6 GHz range.

Measurement results for the shielded device show the highest coupling at 12 GHz of – 20 dB between ports IN1 and IN2 and – 25 dB between ports IN3 and OUT4. For the unshielded device, the highest coupling at 12 GHz is of – 25 dB between ports IN2 and OUT4 and IN2 and IN3. Nevertheless, the coupling for the unshielded device has more uniform levels for all port combinations. For example, in the center of the considered frequency range, at 7 GHz, the coupling varies between – 32…– 40 dB for the unshielded device and between – 28…– 46 dB for the shielded device.

In conclusion, there is a trade-off between EM shielding and spurious currents which need to be taken into account depending on desired operating frequency and SW signal level. The current paper gives an idea about coupling levels for SWMG based on U-shaped antennas placed at distances of few tens of microns from each other and suggests using unshielded antennas for future SWMG development.

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