Tunable Non-Reciprocal Phase Shifter and Spin-Coated Ferrites for Adaptive Microwave Circuits

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***Abstract*—Tunable non-reciprocal components with ferrites that can be integrated using a foundry suitable process are key to achieving low-power adaptive microwave circuits. The current state-of-the-art still relies on electrical tuning or resistive absorbers to facilitate unidirectional propagation. Here, we demonstrate a novel process for spin-coating thick films of ferrites without the complexities of vacuum processes or high-temperature annealing. Composites of yttrium iron garnet (YIG) nanoparticles in a matrix spin-on-glass are spin-coated on silicon substrates, and magnetic properties comparable to bulk YIG are obtained in films exceeding 30 microns. We also propose a design for tunable phase shifter based on periodically serrated coplanar waveguide with a YIG cladding. A non-reciprocal phase difference of 20 – 60 degrees is obtained over a tunable band of 550 MHz between 3.85 - 4.4 GHz from a tuning magnetic field of 8 – 40 kA/m.**

Keywords— ferromagnetic resonance, tunable phase shifter, yttrium iron garnet, tunable microwave device, serrated coplanar waveguide

I. Introduction

The ability to accommodate more connected users in a modern wireless communication system relies on the ability to tune over a large band of frequencies while maintaining a small footprint and low power consumption [1], [2]. Specifically, if tunable microwave transceivers are to be realized, then non-reciprocal components that provide isolation between the transmitter and receiver should also be tunable for a full-duplex communication system [3], [4]. However, non-reciprocal components rely on bulk microwave ferrites that are typically hundreds of microns thick and their integration with microwave circuits do not conform to standard foundry processes [5]. Additionally, tuning of ferrites is possible only when they can be interfaced with other magnetoelectric or ferroelectric materials, which is also currently limited owing to the challenging process requirements.

Non-reciprocity in the context of electromagnetic (EM) waves refers to unidirectional propagation, where waves that are transmitted in the forward direction, are attenuated or phase shifted in the reverse direction. Attenuation or phase shift of EM waves can be achieved via ferromagnetic resonance (FMR), but non-reciprocal FMR is possible only when the RF magnetic fields in the forward and reverse transmissions have different polarities, that is either left-handed or right-handed circular polarization (LHCP or RHCP). The key to FMR in an integrated microwave circuit, is an integrated ferrite. Ferrites such as garnets, hexaferrites and orthoferrites require high processing temperatures and lattice-matched substrates to achieve the necessary crystallographic orientation for the desired magnetic properties [6]. Although significant improvements have been made in processing high-quality ferrite thin films, the micron-range thickness needed for microwave devices remains a challenge.

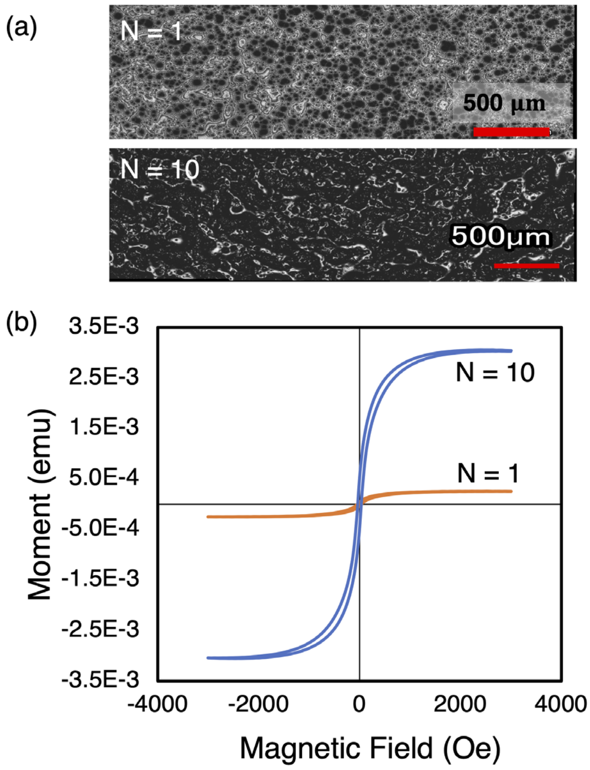

Fig. 1. Spin-Coated Ferrite Composite of YIG nanoparticles and spin-on-glass. (a) Magnetic hysteresis measurements for n = 1 and n = 10

Previous efforts from other researchers have shown isolation ratios up to ~ 20 dB at frequencies > 10 GHz using serrated microstrip or coplanar waveguide structures [7], [8]. However, in most cases, the ferrite is either several hundreds

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of microns thick and flip-chip bonded to the waveguide or used as a substrate to pattern the waveguides. These methods, although effective in achieving non-reciprocity, are unsuitable for foundry integration [9]. In this paper, we describe a novel method to synthesize micron scale ferrites using nanoparticles of yttrium iron garnet (YIG) that can be directly integrated on microwave devices while circumventing the high annealing temperature and processing challenges of thick films. We also demonstrate a phase shifter using a periodically serrated coplanar waveguide that generates the required circularly polarized RF magnetic fields for selective attenuation from non-reciprocal FMR. The key novelty of the presented work is the ability to tune the center frequency of the phase shifter by the application of a magnetic field to the integrated ferrite. Such a design also allows for the variation of the ferrite's magnetic permeability tensor through magnetoelectric mechanism, paving the way for integrated tunable non-reciprocal components.

II. Results and Discussion

A. Spin Coated Ferrites with Yttrium Iron Garnet Nanoparticles

Composites of yttrium iron garnets were prepared in a vortex mixer by mixing nanopowder of YIG (< 100 nm particle size and 99.9% purity from Sigma-Aldrich) with a spin-on-glass, SOG (IC1-2000 from Futurexx Inc.) - a form of siloxane-based resin dissolved in n-butanol. The prepared mixture was ultrasonicated (at 40 KHz and 180 W) for 90 minutes in an ice bath set at 5-8 °C. The resulting mixture is static dispensed, and spin coated at 3000 rpm for 60 s on a 10 mm x 10 mm Si die. The composite was cured in two temperature steps – 60 s at 100 °C and 60 s at 200 °C, which rendered it insoluble in most common solvents. The initial mass of YIG and SOG were chosen such that the final volume percentage of YIG in SOG was about 7.5%.

The thickness and morphology of the spin-coated ferrite characterized using a Keyence laser microscope showed that the films were ~6 µm after a single coating process, with an average surface roughness of 1.22 µm as shown in Fig. 1(a). It was observed that manual mixing of the YIG and SOG during the preparation results in 40% higher area roughness compared to the long ultrasonication followed by vortex mixing. This effect is particularly exacerbated when multiple layers are spin-coated for thicker ferrites. Magnetic hysteresis measurements (from a Lakeshore 8600 series vibrating sample magnetometer) on a single layer of the ferrite revealed a saturation magnetization (M_S) of 8.4 ± 0.85 emu/cm^3. While this might appear much smaller than the theoretical M_S for YIG (143 emu/cm^3), accounting for the low YIG volume concentration of 7.6% a decreased theoretical magnetization value is expected to be around 10.8 emu/cm^3, which is comparable to the measurement results. As seen from superimposition of in-plane and out-of-plane hysteresis loops in Fig. 1(b), the spin-coated ferrite does not exhibit a preferential axis of magnetization (from anisotropy contributions) and saturates at 2000 Oe. Further, the

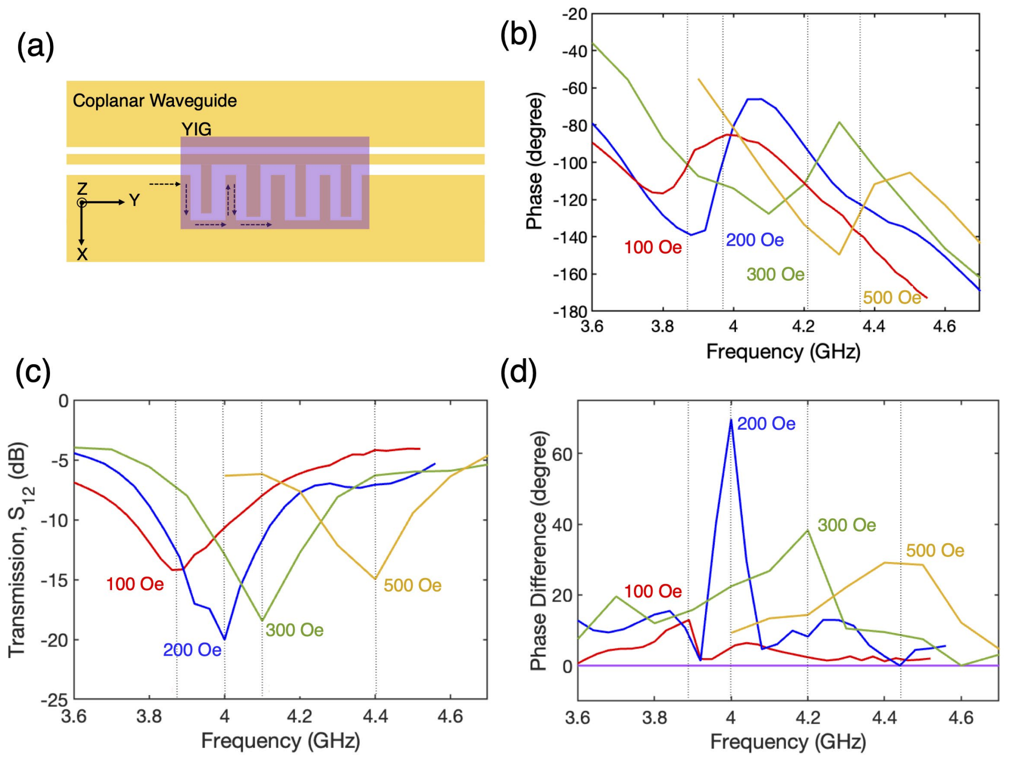

Fig. 2. Tunable non-reciprocal phase shifter. (a) Schematic illustration of coplanar waveguide with periodic serrations and YIG ferrite. The arrows indicate the serpentine path of EM propagation. (b) Phase angle for S_{12} transmission at different external magnetic fields. (c) S_{12} transmission and absorption due to FMR. (d) Phase difference between S_{12} and S_{21} for different magnetic fields

invariance of magnetization to the angle (from 0 to 90°) at which the magnetic field is applied (not shown here), suggests that these samples are magnetically isotropic.

While a single layer of the spin coated ferrite is 6 μm, thicker ferrites can be readily achieved by spin coating multiple layers with intermediary baking steps. Thickness up to 60 μm were achieved with 10 layers of ferrite (Fig. 1(a)) and the corresponding hysteresis measurements shown in Fig. 1(b) indicate that the magnetization also increases commensurately. However, the volume percent of YIG remains the same and therefore the M_S for 10 layers is 10.1 emu/cm^3. This shows that thick ferrite films with consistent magnetic properties can be achieved using the spin coating process and this technique can be used for direct device integration without the need for high-temperatures or lattice-matched substrates.

B. Phase Shifter with Serrated Coplanar Waveguide

Non-reciprocal effects that require dissimilar magnitudes of attenuation or phase shift between opposite transmission directions benefit from serrated transmission lines that can generate circularly polarized EM waves. In the coplanar waveguide shown in Fig. 2(a), the propagating EM wave along the y-axis generates RF magnetic fields (H_{rf}) in the x-z plane, represented by $H_{rf,x}$ and $H_{rf,z}$. However, if the EM wave propagates through the serrations in the x-y plane, the propagation direction alternates between +x and -x, thereby generating H_{rf} in the y-z plane with circularly polarized components $H_{rf,y}$ and $H_{rf,z}$. If the ferrite is magnetized along x-axis, the asymmetry in off-diagonal components ($\mu_{yz} \neq \mu_{zy}$) in the Polder tensor will determine the magnitude of attenuation or phase shift for the two different circularly polarized components in the waveguide.

Thus, a phase shifter can be designed by placing the ferrite on top of the serrations that is magnetized along negative x-axis. In the forward (reverse) propagation, the serpentine path of the EM wave induces an RHCP (LHCP) H_{rf} in the ferrite, which results in the two waves experiencing non-reciprocal phase shifts in their respective transmission directions. Here, simulations of a serrated coplanar waveguide with a YIG ferrite are performed using Ansys HFSS. The simulation parameters and the physical dimensions of the structure are – waveguide width = 573 μm, gap = 365 μm, thickness of Cu = 35 μm, thickness of substrate (Rogers 4003C) = 0.203 mm, length of the stub = 15 mm, and inter-stub spacing = 1.3 mm. The ferrite had the dimensions of 2 cm × 7 mm x 50 μm, centered with respect to the CPW and spanning equally on either side of the waveguide. The Rogers 4003C substrate was assigned a relative permittivity of 3.38 and the YIG was assigned a relative permittivity of 11.8 and saturation magnetization of 1750 G. While the presence of right-angled bends and discontinuities are known to be sources of odd mode (or slotline mode) generation in CPW, this work does not consider the effects of odd modes in the operation of the phase shifter. Future studies will consider engineering odd mode excitation in enhancing the phase shift of the device.

The simulation results in Fig. 2(b) show that the center frequency at which a sharp phase change is observed, shifts as a function of external magnetic field. This enhanced phase shift is observed only for the S_{12} propagation as the applied bias in the negative x-axis induces a magnetization precession that matches the LHCP polarity expected for the reverse direction. Therefore, the EM wave is strongly attenuated along with a sharp phase change in the reverse direction due to the FMR effect. Furthermore, for magnetic fields ranging from 8 kA/m to 40 kA/m, the center frequency shifts from 3.85 GHz to 4.4 GHz, spanning a tunable range of 550 MHz. It is worth noting that the FMR frequencies in YIG at these applied fields are below 1 GHz, and the phase shift observed here is a consequence of the serrations and the interaction of circularly polarized components with the ferrite. Fig. 2(c) shows the preferential absorption of the S_{12} transmission at the different frequencies due to non-reciprocal FMR from the applied bias. Outside the FMR absorption band, the signal can be transmitted with an insertion loss less than 5 dB. This suggests that phase-shifters designed at a center frequency that lies between two channel frequencies (in a full duplex radio system) will induce a large phase shift between the two channels signals. Such a scheme facilitates seamless separation of transmitted and received components from the two channels for further signal processing. The tunable phase difference between the forward and reverse transmission (S_{12} and S_{21}), shown in Fig. 2(d) indicate that phase shifts as large as 65° are possible with a magnetic bias of 16 kA/m when YIG is used as the microwave ferrite. In the absence of a ferrite or an external magnetic field, the phase difference is zero for all frequencies, confirming that the observed non-reciprocal effect is a consequence of the magnetized ferrite.

III. SUMMARY

In summary, this work shows the development of foundry-suitable processes for thick ferrite synthesis and a tunable non-reciprocal phase shifter on coplanar waveguide. A combination of YIG nanoparticles and spin-on-glass are shown to form ferrite composites that can be readily spin-coated on microwave devices. The saturation magnetization of the synthesized ferrites is comparable to the bulk film, and thickness > 50 μm are achieved with multiple layers of spin-coating. On the other hand, a tunable non-reciprocal phase shifter is demonstrated on a novel coplanar waveguide platform with periodic serrations and a YIG ferrite. Simulation results show that the phase shift can be tuned over a band of 550 MHz in an external magnetic field range of 8 – 40 kA/m. The observed non-reciprocal phase difference as large as 65° and insertion loss lower than 5 dB pave the way for fully integrated tunable phase shifters for adaptive microwave transceivers.

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