A Design Approach for Monolithically Integrated Broadband Circulators

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***Abstract*—A design approach for self-biased monolithic microwave integrated circulators using a commercial computational electromagnetic code is presented. The nano-magnetic self-biased material is included in a microwave gallium nitride (GaN) on silicon carbide (SiC) integrated circuit process allowing for the design and realization of microstrip-type circulators. Simulated design performance showing >30% bandwidth, insertion loss of approximately 2.5 dB, and isolation greater than 9.3 dB from 16 to 23 GHz is compared between two commercial computational electromagnetic (EM) solvers.**

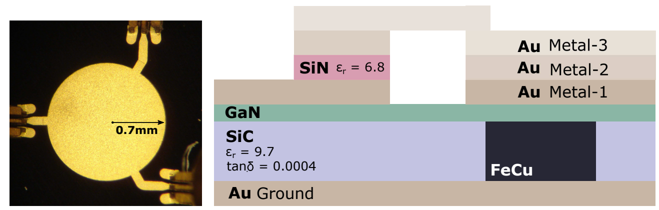
I. Introduction

Recent advancements in nano-magnetic materials have led to the possibility of self-biased circulators [1]. The materials can be deposited using several methods compatible with monolithic integration. Fig. 1 shows a photograph of a microstrip circulator fabricated on a 100-μm thick silicon carbide substrate used for gallium nitride (GaN) microwave integrated circuits (MMICs). Simulation and design challenges of integrated circulators lie in the iterative modeling with available process design kits (PDKs) used in MMIC fabrication. In many cases, it is not feasible nor time efficient to iteratively model a full MMIC design with a full-wave solver such as ANSYS HFSS.

This paper presents a design approach for monolithically integrated circulators using Qorvo's GaN-on-SiC PDK [2] and the magnetic material parameters of Argonne National Laboratory (ANL) such as the ones described in [1]. The circulator is designed starting from previous literature examples and then analyzed using an industry standard microwave circuit simulator (NI Microwave Office (MWO)) using passive matching elements from Qorvo's PDK. Scattering parameters for the circulator disk (puck) are extracted from full-wave HFSS simulations. The device performance using the combined full-wave and circuit analysis approach is then compared to a full-wave simulation of the full monolithically integrated circulator, validating the design approach.

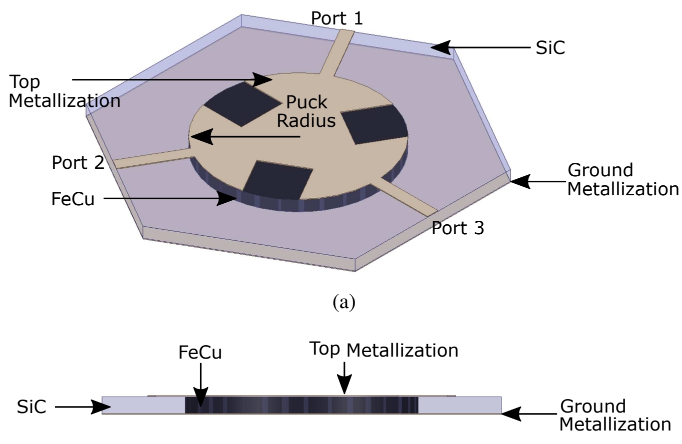
II. Circulator Geometry and Simulation Setup

The circulator geometry discussed in this paper is of a conventional shape, e.g., presented in [3] and [4]. Fig. 2 shows the geometrical model using layout and materials compatible with the MMIC process that uses a thin GaN epitaxial layer on a 100μm thick SiC substrate [2]. The passive transmission lines and lumped elements are implemented in three layers of metal interconnects with TaN resistors and various capacitor configurations with SiN dielectric. The stack-up of the process is shown in Fig.1 (b).



(a) (b)

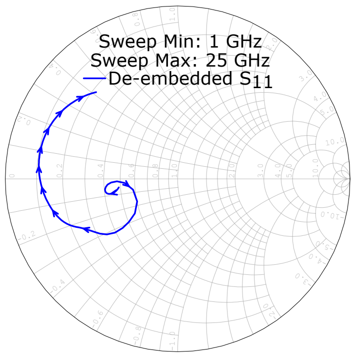
Fig. 1. (a) Photo of fabricated unmatched microstrip circulator top metalization layer, and (b) cross-section of the Qorvo GaN-on-SiC MMIC process used for the design. The nano-magnetic material from ANL will be deposited in the cavity etched in the SiC under the microstrip metalization.



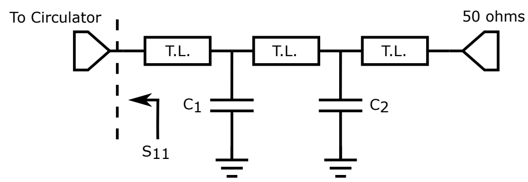
(a) (b)

Fig. 2. Circulator geometry setup based on a 0.75mm radius puck. (a) Oblique view of three-port microstrip circulator geometry. (b) Side view of microstrip circulator configuration.

The full-wave simulation setup in HFSS for the geometry in Fig. 2 specifies the top trace and bottom ground as gold (thickness = 7 μm). The 100-μm thick SiC dielectric substrate has a relative permittivity of $\epsilon_r = 9.7$ and $\tan\delta = 0.0004$. It was found that the thin GaN epitaxial layer does not affect the results, while it substantially adds to the simulation time, so it is not included in the presented data. Wave ports are used on all three ports to excite the proper microstrip mode, with a radiation boundary condition. The magnetic material parameters assumed in the simulations are [1]: saturation magnetization $M_s = 0.5\,\mathrm{T}$; ratio of remnant to saturation



(a)



(b)

Fig. 3. (a) Circulator impedance de-embedded to the port of the circular circulator cavity. (b) Matching network topology used to match the circulator to 50-ohm impedance.

magnetization, $M_r/M_s = 0.5$; $\Delta H = 500\,\text{Oe}$; $\mu_r = 2$; $\epsilon_r = 10$ and $\tan\delta = 0.002$. A uniform magnetic field excitation boundary condition is used for simulation of an internal, self-biased field of the magnetic material.

III. Circulator Design Approach

The initial circulator with only the magnetic puck is simulated in HFSS. All three ports are de-embedded to the plane of the puck and the scattering parameters normalized to $50\,\Omega$ are extracted and used for the design of the matching network with MWO and Qorvo's PDK. Fig. 3 (a) shows the de-embedded circulator impedance from 1 to 25 GHz. A low-Q matching network, Fig. 3 (b), provides increased bandwidth [5], and is implemented with capacitors and microstrip lines available in the process. EM simulations of the matching network using MWO's method of moment (MoM) solver are performed for the layout.

Finally, a full-wave simulation of the circulator together with its matching network is performed using HFSS. The model and simulation results of the bandwidth-optimized circulator are presented in Fig. 4 and Fig. 5, respectively. A comparison in Fig. 5 shows agreement between the design approach using only the magentic puck scattering parameters in conjunction with the planar MoM solver for the matching network and full-wave FEM simulations.

IV. Conclusion

In summary, this paper presents a simulation-based design approach for a miniature self-biased circulators using state-of-the-art MMIC integration. Predicted performance based on nano-magnetic material parameters result in a bandwidth of >30% with insertion loss and isolation of approximately 2.5 dB and >9.3 dB, respectively, from 16 to 23 GHz. Simulation results of the design approach show good agreement with the full-wave HFSS model.

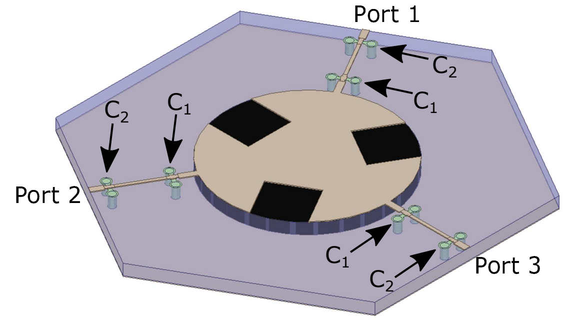


Fig. 4. Circulator geometry including matching network. The matching network including transmission lines and shunt capacitors are full-wave simulated together with the magnetic puck in HFSS.

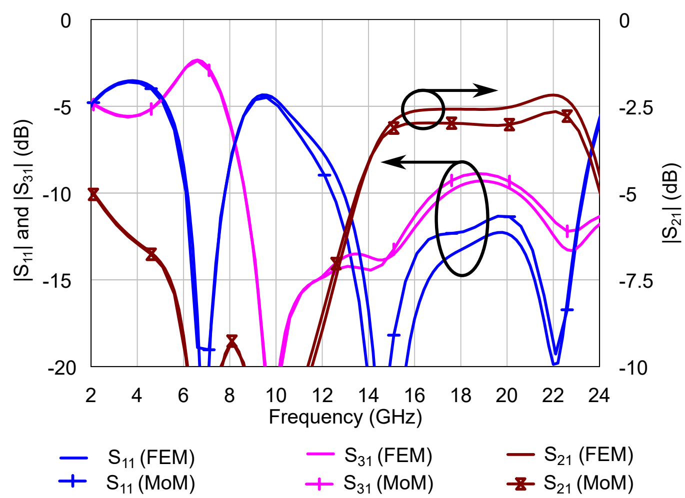


Fig. 5. Simulated performance of matched circulator. Insertion loss of approximately 2.5dB from 16-23GHz with isolation performance of greater than 9.3dB.

Acknowledgment

This work was funded by the DARPA M3IC program under a sub-contract to Qorvo. The authors would like to thank Qorvo and Argonne National Laboratory for the collaboration.

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