Ferrite-Coupled Line Circulator Simulations For Application at X-Band Frequency

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We have designed and simulated a circulator circuit in which the magnetization aligns along the plane of an yttrium iron garnet (YIG) film. For an X-band frequency (8–12 GHz) circulator we have utilized a YIG slab (∼200 μm thick) with saturation magnetization ($4\pi M_S$) and ferrimagnetic resonance (FMR) linewidth (ΔH) of ∼139.26 kA/m and 10 Oe, respectively. Broadband circulator operation was realized for frequencies above FMR, $f = 5$ GHz. The applied FMR field was 79.58 kA/m. The Ansoft HFSS software suite was used to simulate the circulator response. The insertion loss S_{21} and the isolation S_{12} were calculated to be ∼0.9 dB and ~ -52 dB, respectively, with ∼15% bandwidth at the center frequency of 10.1 GHz. We believe that this in-plane circulator design may enable high performance with significant volume and weight reduction.

***Index Terms*—Circulators, electromagnetic propagation in nonreciprocal media, ferrimagnetic films, ferrite circulators, millimeter-wave magnetic devices.**

I. Introduction

TO date, wireless and information technology industries have been growing rapidly due to the development of compact high performance versatile communication devices. Consequently, the demand continues for microwave planar devices, such as circulators or isolators that operate at frequencies ranging from ∼4 to 12 GHz and provide high performance and small size at reduced cost.

The most common design of circulators is known as the Y-junction circulator which uses transverse magnetized ferrite materials [1]–[3]. Unlike the conventional Y-junction circulator, an alternative design was developed using longitudinal magnetized ferrite materials in a circular waveguide. This circulator had four ports and used the Faraday rotation phenomenon [4]. However, the Faraday circulator has recently seen little application because the design is not comparable to planar device geometries as is required by today's technologies. The planar design is an outgrowth of research conducted on coupled dielectric image lines through ferrite slabs [5], [6]. Several research publications [5]–[11] employed Faraday rotation to create a coupled microstrip line design and demonstrated its feasibility [6], [12], [13]. The phenomenon of nonreciprocity in two coupled lines of waveguide by a longitudinal magnetized ferrite was explained by the mode coupling theory of Marcus [12], Awai [13], Mazur [14], and Kwan [6]. The advantages of the ferrite coupled line (FCL) circulators are its planar construction, the lack of biasing magnets, ease of design and assembly, and a reduced device volume. We believe that such circulators can be improved by the choice of appropriate ferrite materials [15], [16] and eventually replace the Y-junction circulator as the choice design for most applications.

TABLE I
PARAMETERS OF YIG

$4\pi M_S$ (kA/m)	ΔH (Oe)	H_0 (kA/m)	ε YIG	ε Substrate	Loss Tangent
139.260	10	79.578	15	14	0.001

In this paper, we extend the reported designs of FCL circulators to operate at X-band frequencies. The design and simulation are based upon a simple three-port microstrip ferrite coupled line geometry and are performed using the Ansoft High Frequency Structure Simulator (HFSS[1]) software suite, which is widely used in the microwave industry. From the results of the HFSS simulations, we report isolation as high as -52 dB and an insertion loss of -0.9 dB. These performance characteristics indicate a viable opportunity for further development by the microwave industry.

II. Theory and Simulation Approaches

Here, simulations of high-frequency performance of in-plane FCL (or IP-FCL) circulators employing garnet ferrite materials are divided into two sections: A. the theory of Faraday rotation related to coupling modes of rf wave propagation, and B. HFSS simulations of IP-FCL circulators for obtaining scattering parameters for designs that include yttrium iron garnet (YIG) thick films/or slabs. YIG has been widely acknowledged as the mainstay material for microwave applications because of its low magnetic losses at microwave frequencies. Typical magnetic properties for YIG thick films/or slabs are listed in Table I. The frequency dependent permeability for YIG films is considered in the HFSS simulations.

A. Theory Faraday Rotation and Coupling Modes of rf Wave Propagation in FCL Circulator

Faraday rotation per unit length is a critical parameter in the design of IP-FCL circulators because the amount of phase angle

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TABLE II
IN-FCL CIRCULATOR DESIGN PARAMETERS

W_{YIG} (cm)	L (cm)	t_{YIG} (μm)	w (μm)	G (μm)	a (cm)	b (cm)
0.139	1.60	249.1	300	200	0.200	1.605

A w is width of coupled microstrip lines and G is a gap between two coupled lines. A dimension of dielectric substrate is $a \times b = 0.2 \times 1.605$ cm^2.

rotation is always related to the length of the magnetic material used in the design. Hence, the length of the YIG slab will determine the length of the microstrip coupled line and will be the key parameter influencing the device size. The basic idea of the Faraday rotation per unit length has been widely used in the Faraday rotation four-port circulator [4]. Since the system has an in-plane magnetization that is colinear with the wave propagation direction, the Faraday rotation can be analyzed using perturbation theory whereby the ferrite volume is small compared to the guided structure. Solving Maxwell's equations using perturbation theory we obtain the complex propagation constant [18]

$$\beta - \beta_0^* = \frac{\omega \int_S \mu_0(\vec{\chi}_m \cdot \vec{h}) \cdot \vec{h}_0^* + \varepsilon_0(\vec{\chi}_e \cdot \vec{e})\vec{e}_0^* dS}{\int_S \hat{z} \cdot (\vec{e} \times \vec{h}_0^* + \vec{e}_0^* \times \vec{h}) dS} \tag{1}$$

where $\vec{\chi}_m = [\mu] - \mu_0$ and $\vec{\chi}_e = [\varepsilon] - \varepsilon_0$ is the magnetic and electric susceptibilities, respectively. Since the given complex propagation constant is $k = \beta - j\alpha$ and $k_0^* = \beta_0^*$, α is neglected. Assuming transverse electric (TE) modes of circular polarization, the above equation can be approximated leading to the Faraday rotation per unit length as [4], [17]

$$\theta / L = \frac{\beta_- - \beta_+}{2} = -j\beta_0 \chi_{\mathrm{xy}}^{\mathrm{eff}} \frac{\Delta S}{S} \tag{2}$$

where the ratio $\Delta S / S$ is the loading factor of YIG in the circulator design, and β_-^+ are propagation constants. The circulator length is approximately $L\Delta\beta_0 \propto (\pi/4) + 2n\pi$. An analytical expression for L is found in [7]–[10], [12]

$$L = \frac{\pi}{4C} \tag{3}$$

where C is called the coupling constant defined as [9], [14]

$$C = \frac{1}{2} k_0 \eta_0 \mu_{\mathrm{zx}} \int_S \left(h_x^{e^*} h_z^0 - h_z^{e^*} h_x^e \right) dS. \tag{4}$$

B. HFSS Simulations

Ansoft HFSS software was used for the design and simulation of IP-FCL circulators. The HFSS software is a full wave electromagnetic (EM) field simulator for arbitrary 3-D volumetric passive device models. HFSS software employs the finite-element method (FEM), adaptive meshing, and graphics to provide simulation of 3-D EM problems of given input to the IP-FCL circulator. The wave equation solved by HFSS software is derived from the differential form of Maxwell's equations. Therefore, it is assumed that the field vectors are single-valued, bounded, and have continuous distribution along with their derivatives. Boundary conditions for EM wave propagation, however, are unique to magnetic media, which depend upon the magnetic structure, see Fig. 1. Present HFSS software only allows for simulating the case of an isotropic magnetic material such as slab of YIG, since the permeability tensor is assumed to contain diagonal terms which are equal. No magnetic anisotropy is included in the permeability tensors.

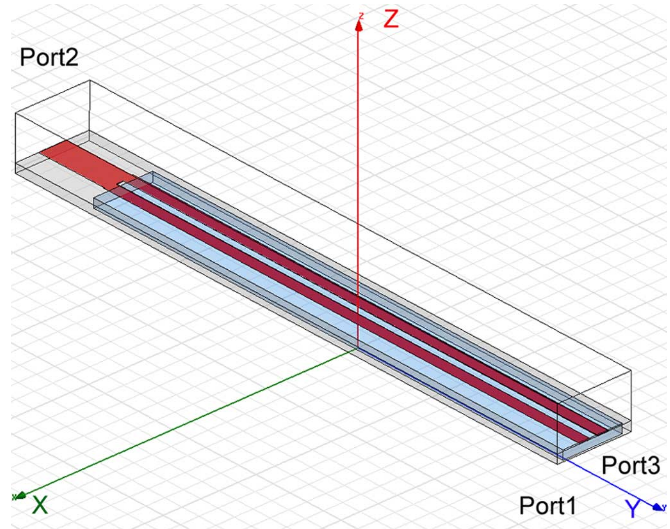

Fig. 1. Schematics of IP-FCL circulator created by HFSS 3-D modeler simulator. Direction of applied external magnetic field is opposite to y axis.

The theory of the Faraday rotation circulator can be explained by perturbation theory, which is a useful theory for approximating the solution for the case of a ferrite loaded microstrip lines. The theory was modeled after a longitudinally magnetized ferrite rod at the center of a square waveguide [17]. In the simulation, we assumed a design in which a YIG slab is loaded in a coupled microstrip lines guided structure. This configuration is similar to Faraday rotator circulators [4], but here two coupled microstrip lines were considered as the waveguide system. Hence, we expect results from perturbation theory to be in reasonable agreement with the predictions of the HFSS software, since the geometrical configurations are very similar between the two approaches.

III. RESULTS AND DISCUSSIONS

All the magnetic properties of the YIG film and design parameters of the IP-FCL circulator are listed in Table I and are used as input to the HFSS simulation. The ferromagnetic resonance (FMR) frequency was estimated to be $f_r \sim 4.6$ GHz for $H_0 = 79.578$ A/m, which agrees with the FMR frequency as calculated by HFSS. Since the real part of the permeability curve approaches 1 at about 5 GHz, the IP-FCL circulator was modeled for X-band frequencies, $8 < f < 12$ GHz.

Fig. 1 shows a schematic of a three-port IP-FCL circulator based upon a typical microstrip line design [11]. The design contains a YIG slab, dielectric substrates surrounding the YIG,

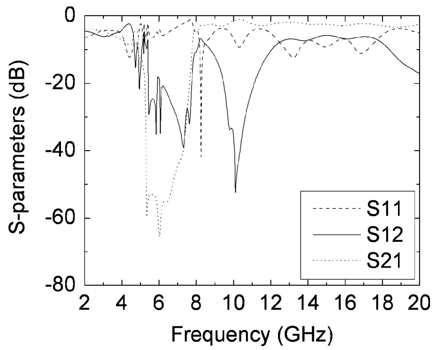

Fig. 2. S-parameter plots from HFSS for IP-FCL circulator design shown in Fig. 1.

and a copper coupled microstrip lines with a ground plane located at the bottom of the YIG and the dielectric. The approximate length of the YIG and coupled microstrip lines was estimated from (2)–(4) and the coupling coefficient was assumed to be equal to one for maximum coupling. The length of the YIG slab was $L \sim 1.39$ cm. The thickness and width of the YIG slab was designed to be 241 μm and 1.60 cm, respectively. As is well known, the width of the microstrip line is strongly affected by the impedance match between the media and the propagating microwave signal and the gap between the two coupled microstrip lines [18]. Here, our design incorporates matching to 50-Ω lines such that $w \sim 300$ μm. There are a number of design parameters that need to be varied in order to match impedance between device and feeder lines and they are: width of the strips, gap between strips, substrate thickness, and dielectric versus ferrite loading. Our attempt is a best effort in achieving this match.

Fig. 2 shows HFSS simulation results for scattering parameters versus frequency for the Fig. 1 design. Circulation behavior is observed to occur at $f_c \sim 10.1$ GHz. The S^{12} curve indicates a maximum isolation in the three-port IP-FCL to be ~ -52 dB at the f_c. The bandwidth corresponding to -20 dB of isolation was measured to be $\sim$1.6 GHz or 15 % of the f_c. The S_{21} curve shown in Fig. 2 indicates an insertion loss to be $\sim$ 0.9 dB at the f_c. An ideal insertion loss value is determined using the expression $20\log_{10}|S_{21}| \cong 8.68\alpha L$ [18] which yields a value of 0.3 dB. The difference between insertion loss derived from HFSS and the numerical estimate is believed to be from impedance mismatch. A second circulation occurs near and above 20 GHz and exhibits relatively low isolation and large insertion loss compared with the primary circulation at $f_c \sim 10.1$ GHz.

IV. Conclusion

IP-FCL circulators have been simulated using the Ansoft HFSS simulation suite and optimized for X-band operation. Circulation is calculated to occur at 10.1 GHz with a maximum circulation of -52 dB and a corresponding insertion loss of 0.9 dB. If an insertion loss of 0.5 dB is the desired threshold value, a calculated value of 0.9 dB is encouraging since not all design parameters have been optimized. The theoretical limit is 0.3 dB according to our estimate. The optimum device design is 0.2×1.605 cm^2 in the device plane. The thickness of the dielectric substrate and the YIG film was 0.0249 cm. We believe that IP-FCL circulators are viable devices for at X-band frequency applications.

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