Design-Oriented Modelling of Microstrip Ferrite Circulators

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***Abstract*— A modeling approach for the design of microstrip ferrite circulators is presented and validated on several examples using the same commercially-available ferrite disk. A baseline narrowband 4.25-GHz microstrip circulator is first demonstrated with a commercial 4.97-mm radius ferrite disk operated in saturation and below the ferromagnetic resonance. The non-uniform DC magnetic field distributions of a cylindrical permanent magnet is taken into account by spatial discretization of the ferrite properties in full-wave simulations. Several design parameters are shown to affect the frequency response; the ferrite thickness relative the microstrip substrate thickness shifts the operating frequency, while external matching networks can increase the fractional bandwidth from 10% up 40%. Another degree of freedom is the applied DC magnetic field, which can be reduced to set the ferrite operation below the ferromagnetic resonance with significant miniaturization of the overall device, as demonstrated with a 1.6-GHz circulator designed with the same 4.97-mm radius ferrite disk, resulting in an almost factor of 3 reduction in linear electrical size.**

***Keywords*— circulators, ferrites, non-uniform magnetic fields.**

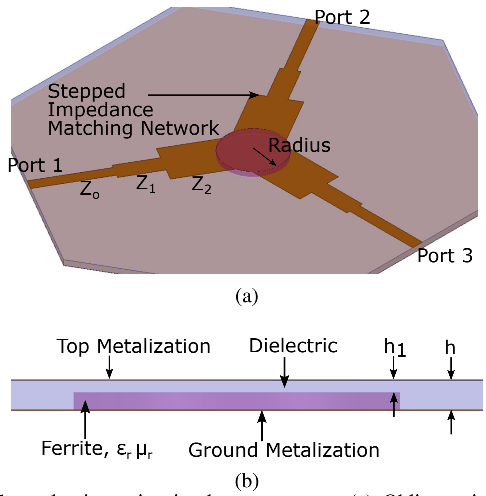


Fig. 1. General microstrip circulator geometry. (a) Oblique view showing matching network and patterned metalization. (b) Side view showing non-homogeneous circulator cavity with indicated dielectric and ferrite layers.

I. Introduction

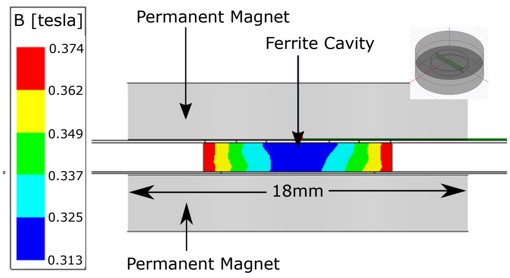
Circulators have been in use for a long time in microwave systems as non-reciprocal devices to, e.g. isolate a receiver from a transmitter, and remain essential components for transmit/receive front-ends [1]. Advances in magnetic material technology [2] continue towards achieving integrated circulators [3], though a concise comprehensive trade-off study of the many design variables is not commonly found in the literature. Standard design approaches for circulators with saturated magnetic materials are described in [4]. Externally biased ferrite circulators were first examined in the 50's, e.g. [5]. The theoretical framework for circulator design has been extensively discussed since the 1960's [6] [7], but few publications present the modeling and design of ferrite circulators through the use of commercially available full-wave solvers. Although many publications address waveguide devices, planar microstrip and stripline circulators have been explored to a limited degree [6], [8].

This paper presents modeling techniques that can be effectively used to predict the effect of various parameters on circulator performance. Three parameters that affect the operating frequency of the circulator are investigated here: DC magnetic bias field; ferrite-dielectric filling factor in the circulator cavity; and microstrip matching network. The magnetic design of the biasing structure is discussed in [4], but does not address field non-uniformity within the ferrite material. The filling factor of an inhomogeneous stripline circulator has been investigated in [9] [10] and shown to be consistent with the classical stripline circulator design equations in [6] [7], but has not been investigated in the context of microstrip circulators. Finally, external matching has been shown in [8] to increase bandwidth significantly over that of a constant transmission impedance feed for a circulator with the ferrite operated in saturation above the ferromagnetic resonance (FMR). In this paper, we present simulations and experimental validation related to variations in the three design parameters, using a Skywork's Trans-Tech ferrite material and both quasi-static and full-wave finite element simulations.

II. Baseline Microstrip Circulator Design

As a starting point for comparison, a baseline circulator is designed to operate at 4.25 GHz. A Rogers 4350B 1.524 mm thick substrate with relative permittivity of $\epsilon_r = 3.66$ and $\tan\delta = 0.0037$ is used for the microstrip circuit. The cavity is milled for a Skywork's TT1-105 magnetic ferrite disk with a radius of 4.97 mm, thickness of 1.524 mm and properties listed in Table 1 [11].

Given the standard design equation for a saturated ferrite of cylindrical shape, $R = 1.84/[\omega_0\sqrt{\epsilon_r\mu_{r,eff}}]$, the radius of the disk corresponds to operation around 4 GHz. Excitation of a DC magnetic field within the ferrite using a disk-shaped permanent magnet will result in a non-uniform distribution



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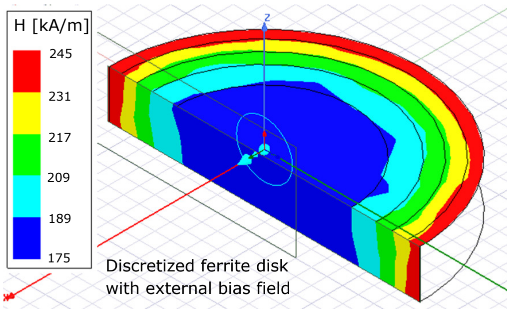
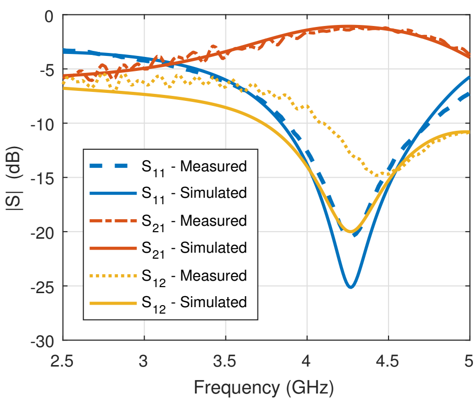


(b)

Fig. 2. (a) Magnetic flux density distribution of a cylindrical permanent magnet on top of a circular ferrite cavity, with values taken from manufacturer specifications. (b) Internal magnetic field distribution in a circular ferrite.



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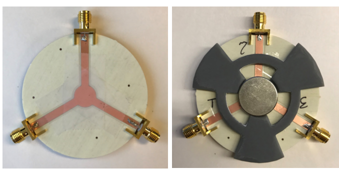


(b)

Fig. 3. (a) Baseline circulator simulated and measured performance of S_{11}, S_{21}, and S_{12}. (b) Photograph of fabricated microstrip circulator, showing the position of the permanent magnet.

along the ferrite cylinder radius, which will affect the frequency response. To quantify this behavior, quasi-static magnetic field simulations are first performed with Ansys Maxwell, Fig. 2. Two rare-earth permanent magnets, 18 mm in diameter and 3 mm thick, are placed on the two sides of the ferrite disk, resulting in a magnetic flux density distribution as shown in Fig.2(a), where the nonuniformity along the radius

Table 1. TT1-105 Material Properties

Parameter	Value	Units
$4\pi M_s$	1750	G
ΔH	< 270	Oe
μ_r	55	-
ϵ_r	12.2	-
$\tan\delta$	< 0.00025	-

of the ferrite disc cavity ranges from 0.3129 T to 0.3737 T. This nonuniform distribution is used to calculate the value of the applied field, H_o and thus the gyromagnetic (f_0) frequency for each domain. The magnetization saturation frequency (f_m) is calculated from $M_s = 0.175$ T. The effective relative permeability of the ferrite along its radius is next determined using [4],

$$\mu_{r,eff} = \frac{\mu_r^2 - \kappa_r^2}{\mu_r} \tag{1}$$

$$\mu_r = 1 + \frac{f_0 f_m}{f_0^2 - f^2}, \quad \kappa_r = \frac{f f_m}{f_0^2 - f^2} \tag{2}$$

This non-uniform distribution is then discretized resulting in 5 concentric disks with radii of 2.9, 3.6, 4.1, 4.5 and 4.97 mm, as shown in Fig. 2(b) to find an approximation to the magnetic field amplitude that can then be imported into a full-wave simulator. This DC value of the H-field ranges from 175 to 245 kA/m and is specified within Ansys HFSS as 5 concentric disks, using the ferrite properties given in Table 1. The full-wave simulation setup in HFSS for the geometry in Fig.1 specifies top and bottom copper metalization of thickness = 35 μm. 50-Ω microstrip lines are excited with waveports, normalized to 50-Ω, and the S-parameters are plotted in Fig.3(a). The baseline design is then fabricated, as shown in Fig.3(b), with no additional microstrip matching. Two permanent magnets are placed directly above and below the ferrite disk. The measured and simulated performance is presented in Fig.3(a), and the good agreement validates the non-uniform field modeling approach.

III. Effects of Dielectric Fill Factor

The ferrite thickness, relative to the substrate thickness, offers an additional parameter for tuning the operating frequency of the circulator, Fig. 1(b). This nonunifirmity can be analyzed by calculating an effective permittivity and permeability [9].

If the ferrite is thinner than the substrate, a dielectric layer (Fig.1) affects the operating frequency and bandwidth. Three ferrite thicknesses of 1.25, 0.762 and 0.305 mm are inserted into the baseline design, with the same dielectric filling as that of the microstrip substrate. Fig.4 shows measured results for the three cases. We observe a frequency shift of up to 20% and a bandwidth variation with increased insertion loss. The frequency shift brings the operation closer to the FMR frequency, resulting in higher loss. The three cases of different

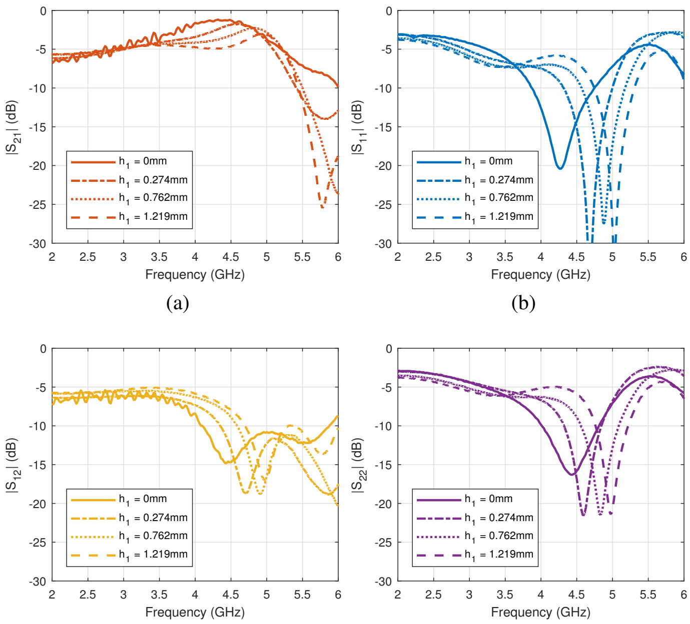


Fig. 4. (a)-(d) Measured performance of the narrowband circulator with filling of $h_1 = 0$, 0.274, 0.762, and 1.219 mm.

ferrite thicknesses were measured with 50-Ω microstrip line ports in Fig.4 with no additional matching circuits. The results in the next sections show examples of performance achieved with different matching networks.

IV. Effects of Matching Network

Further improvements in circulator performance can be accomplished by matching the ferrite cavity impedance to 50-Ω. From the baseline saturated circulator (Fig.3), the complex impedance over frequency at the cavity reference planes can be de-embedded to reference planes at the edge of the ferrite cavity using Ansys HFSS simulations, with $36.7 + j28.5\,\Omega$ obtained at 3.5 GHz. A stepped-impedance matching network topology is designed using the TT1-105 magnetic ferrite disk with a radius of 4.97 mm and substrate thickness of 1.524 mm. Fig. 5 shows measured and simulated performance with a smaller permanent magnet (6 mm in radius). A smaller magnet us used in this case so as to not modify the characteristic impedance of the non-uniform matching circuit lines. A dramatic increase in bandwidth from 10% to 40% is observed, with degraded isolation, as expected. This example in which simulations match the measurement, serves as a validation of the design-oriented modeling approach, rather than an optimized broadband circulator.

V. Circulator with Non-Saturated Ferrite

An additional parameter that is investigated here is a reduction in the applied DC field, which has a direct effect on frequency, bandwidth and size [4], [12]. Fig.6(a) shows the DC magnetic flux density magnitude across the cross-section of the ferrite disk for cases above and below saturation. For the saturated case, magnets are placed 0.1 mm above and below the

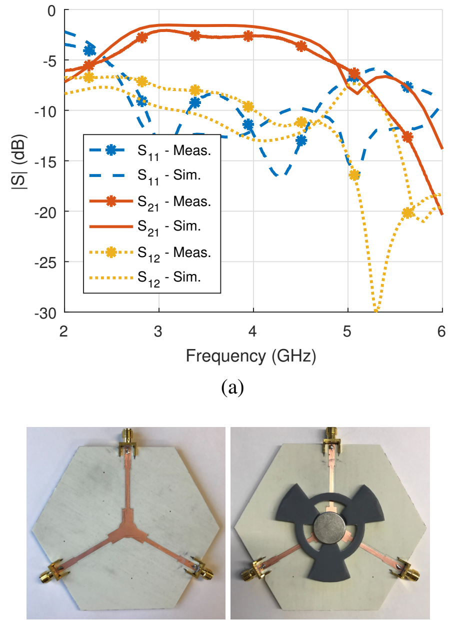


Fig. 5. (a) Simulated and measured matched circulator performance using a stepped-impedance microstrip matching network. (b) Fabricated circuit.

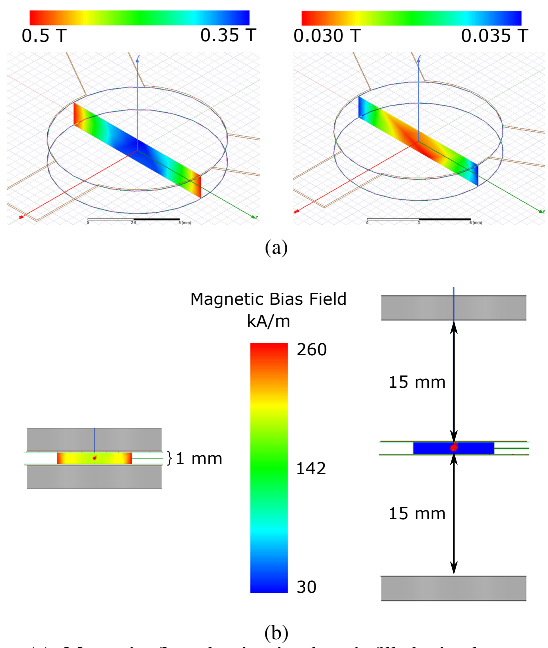


Fig. 6. (a) Magnetic flux density in the air-filled circulator cavity for permanent magnets spaced 1 mm on each side of substrate (left) and 15 mm apart (right). (b) Magnetic field in the TT1-105 ferrite. The maximum fields are 260 kA/m and 30 kA/m for saturated and unsaturated cases, respectively.

substrate. For the below-saturation case, the same permanent magnets are placed 15 mm above and below the surface of the substrate. Quasi-static solutions for the magnetic flux density magnitude within an air-filled puck cavity (in Ansys Maxwell) are used to find material properties and operating frequency. The magnetic bias field is then calculated and applied as the magnetic bias boundary condition for the ferrite within the full-wave FEM simulations (Ansys HFSS).

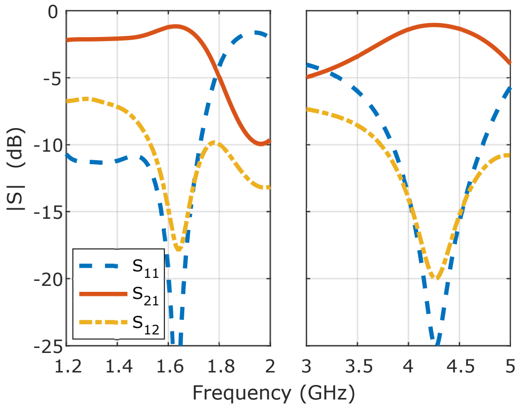
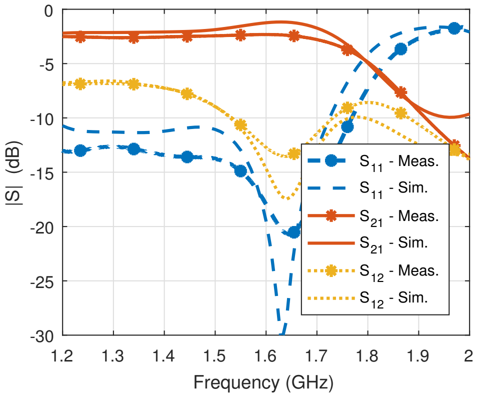
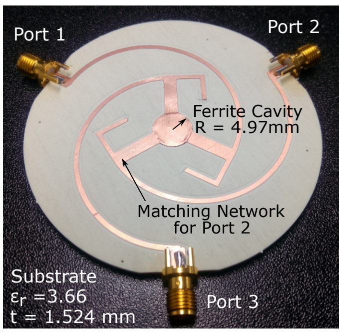


Fig. 7. Simulated circulator response for non-saturated (left) and saturated (right) ferrite, showing operating frequencies of 1.6 and 4.25 GHz, respectively.



(a)



(b)

Fig. 8. (a) Measured and simulated performance of a circulator operating below-saturation with matching network for bandwidth improvement. (b) Photograph of miniaturized microstrip circulator including matching network.

Due to the radial uniformity in the lower-field case, a single value of the bias field may be used instead of the concentric bias fields solution for the saturated case (Fig.2(a)). The simulation results in Fig.7 compare the saturated and non-saturated cases and show a large shift in frequency from 4.25 to 1.6 GHz, using the same ferrite size. This implies that the use ferrites below saturation offers the flexibility of frequency tuning and miniaturization.

The impedance at the cavity ports of the unsaturated circulator cavity can be found using the same method as in the saturated case. For the DC applied field in Fig.6, the complex impedance de-embedded to the cavity reference planes at 1.6 GHz is found to be $35+j25\,\Omega$. A single stepped-impedance with tuning stub is designed for the matching network. Fig.8(a) shows good agreement between measured and simulated results of a circulator operating below saturation.

VI. Conclusion

This paper demonstrates a design-oriented modeling approach for microstrip ferrite circulators, validated by several experimental prototypes. The main conclusions are: (1) the DC magnetic bias field non-uniformity needs to be taken into account for accurate modeling of circulators through co-simulation of the DC and high-frequency performance; (2) the external field also controls the size and bandwidth of the device; (3) the ferrite-dielectric volume ratio (fill factor) impacts the frequency of operation; (4) frequency tuning and miniturization can be accomplished with unsaturated ferrites. In particular, we show an almost factor of 3 reduction in linear electrical size and a factor of 8 reduction in area, with similar electrical parameters, when applying a weaker magnetic field and with appropriately designed matching circuits.

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