

Adapted Modelling of a Microstrip Wideband Circulator (5–7,5 GHz) Design on an All-Ferrite Substrate

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Abstract — This article presents the methodology developed for the design and modelling of a broadband microstrip circulator implemented on a ferrite substrate containing regions that are fully magnetized, partially magnetized, or non-magnetized. The device operates in the ferrite’s low-field region over a frequency range from 5.1 GHz to 7.75 GHz. The design approach starts with a modal analysis of an ideally magnetized ferrite resonator. It then takes into account the inhomogeneous distribution of the static magnetic field within the ferrite when it is biased by permanent magnets. Under these conditions, different regions of the material can be saturated, partially magnetized, or demagnetized. Therefore, to achieve accurate electromagnetic modelling of the substrate, distinct permeability models corresponding to each magnetization state are employed.

Keywords — Circulator, complex shape, ferrite, wideband, Y-junction circulators.

I. INTRODUCTION

Ferrite circulators are nonreciprocal three-port devices that exploit the properties of biased ferrite materials to achieve circulation. They are commonly connected to antennas in applications such as communication and radar systems. Numerous studies in the literature focus on improving their performance, including bandwidth, isolation, insertion losses, and multiband operation, across various configurations such as microstrip, waveguide, and stripline designs [1]–[5]. Furthermore, the rapid growth of wireless communication systems has introduced additional requirements, particularly compactness. In this context, printed devices have become especially attractive. The solution investigated here involves the use of an “all-ferrite” substrate in order to enable a more cost-effective and easier manufacturing process. Moreover, to achieve accurate device modelling which is the goal of this study, the magnetization behaviour and intrinsic properties of ferrite materials must be thoroughly characterized.

The primary objective of this work is to design a broadband circulator by employing carefully selected permeability models that accurately describe the ferrite substrate behaviour under different magnetization states. Unlike previous designs based on a fully saturated biased ferrite disk, the ferrite substrate considered here is not entirely saturated. Consequently, it is divided into distinct regions corresponding to non-biased, partially biased, and fully biased ferrite.

Section II presents three permeability models for ferrite materials and discusses their relevance for modelling the

different magnetization regions. In previous studies, the biased ferrite disk was generally assumed to be fully saturated. In contrast, in the present work, the ferrite substrate is not uniformly saturated. As a result, it is partitioned into distinct regions representing non-biased, partially biased, and fully biased magnetization states. Section III describes the design methodology and experimental validation of the proposed wideband circulator. The various design steps and investigations are detailed. The fabricated device operates from 5.1 GHz to 7.75 GHz, achieving better than –18 dB for both return loss and isolation, with insertion losses close to –0.6 dB.

II. PERMEABILITY OF FERRITE SUBSTRATES

Ferrite-based materials are widely used in the design of circulators. When subjected to a static magnetic field, they become anisotropic and their permeability can be expressed as a tensor. When the material is magnetized using a permanent magnet the internal magnetic field is generally non-uniform. It can be in various states of magnetization (depending on the regions): saturated magnetized (it is then modelled by the Polder tensor), partially magnetized (the Green and Sandy tensor is then used), or demagnetized, in which case the Schloemann permeability model is used.

A. Schloemann: Demagnetized Ferrite Model

When ferrite material is not subjected to an external magnetic field, its permeability (μ_{demag}) is described by the model proposed by Schloemann in [6], which only depends on the frequency and the saturation magnetization.

$$\mu_{demag} = \frac{1}{3} \left\{ 1 + 2 \sqrt{1 - \left(\frac{\omega_m}{\omega} \right)^2} \right\} \quad (1)$$

where $\omega_m = 2\pi\gamma M_s$, M_s is the saturation magnetization, et $\gamma = 2.8$ MHz/Oe is the gyromagnetic ratio.

B. Green and Sandy: Partially Magnetized Ferrite Model

When partially magnetized the material permeability is described by a tensor (2). From experimental measurement performed for different magnetization states, J.J. Green and F. Sandy [7] obtained a tensor model by fitting experimental results with the tensor parameters.

$$[\mu] = [\mu_0 \overline{\mu_r}] = \mu_0 \begin{bmatrix} \mu' & -j\kappa' & 0 \\ j\kappa' & \mu' & 0 \\ 0 & 0 & \mu_z' \end{bmatrix} \quad (2)$$

$$\mu' = \mu_{demag} + (1 + \mu_{demag}) \left(\frac{M}{M_s} \right)^{3/2},$$

$$\text{With: } \mu_z' = (1 + \mu_{demag}) \left(\frac{M}{M_s} \right)^{5/2},$$

$$\kappa' = \frac{\gamma(4\pi M)}{\omega},$$

C. Polder: Saturated Ferrite Model

In a saturated biased ferrite, this permeability is defined by the Polder tensor [8] such that:

$$[\mu] = [\mu_0 \overline{\mu_r}] = \mu_0 \begin{bmatrix} \mu & -j\kappa & 0 \\ j\kappa & \mu & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$$\text{where: } \mu = 1 + \frac{\omega_m(\omega_r + j\omega\alpha)}{(\omega_r + j\omega\alpha)^2 - \omega^2}, \quad \kappa = \frac{\omega_m\omega}{(\omega_r + j\omega\alpha)^2 - \omega^2}$$

$$|\omega_r = 2\pi\gamma H_i, |\omega_m = 2\pi\gamma M_s.$$

μ and κ , depend on the internal field H_i , the saturation magnetization M_s , the frequency by $\omega = f/2\pi$, and the damping factor α reflecting magnetic losses.

The frequency dependence of the real and imaginary parts of the permeability tensor reveals two distinct regions, referred to as the strong-field and weak-field regimes. These regions are separated by the gyromagnetic resonance (GMR), where magnetic losses become significant at the Larmor frequency ω_r as reported in [8].

III. WIDEBAND CIRCULATOR DESIGN

As mentioned in the first section, this part discusses the design of the wideband circulator proposed in this paper. A well-known methodology for wideband circulator design is the “Continuous tracking Circulator” developed by J. B. Davies and P. Cohen [9], and validated by Y. S. Wu and F. J. Rosenbaum in [10]. This theoretical design works with different types of ferrite and allows the theoretical radius of the ferrite disk and width of the feed lines to be obtained. However, as presented by J. Helszajn in [11], [12], this methodology often requires a quarter-wave line to return to an input impedance of 50 ohms. Fig.1 presents the classical geometry of a microstrips circulator, designed with a ground plane and three access lines separated from each other by 120° connected to a central conductor. In order to miniaturize our device and achieve an impedance of 50 ohms, the central conductor will be modified allowing us to eliminate the matching lines in our design.

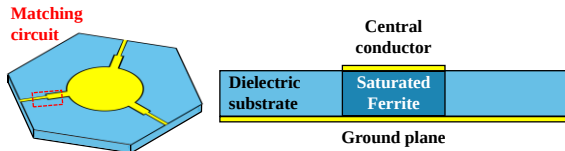


Fig. 1. Microstrips circulator illustration.

A. Electromagnetic simulation and optimization

First, the resonant modes of a Y215 ferrite disk ($M_s = 1450$ G; $\epsilon = 14.7$) with a radius of 5.2 mm, subjected to an internal field $H_i = 250$ Oe, are determined. The ferrite disk is modelled

using Polder’s tensor, while the region outside the disk is treated as a dielectric.

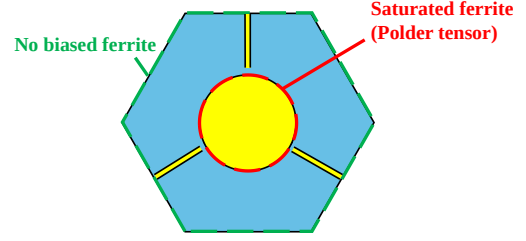


Fig. 2. Simulation of the resonator for a modal study.

The simulated results (Fig. 3), obtain from CST studio suite, show HE modes appearing at very close frequencies, which will not allow the design of a broadband circulator around 6.5GHz.

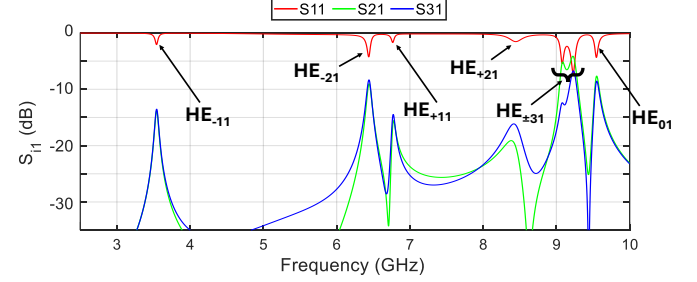


Fig. 3. Results of the modal study for the first simulation design.

As demonstrated in the work of V. Olivier *et al.* [13], the addition of a stub to the central conductor allows the resonant modes to be shifted. This approach makes it possible to position these modes within the targeted frequency band of 5–7.5 GHz.

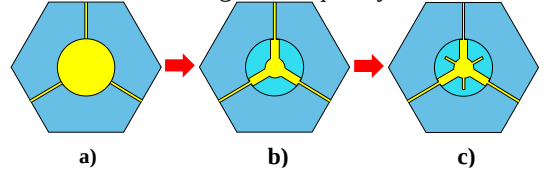


Fig. 4. Modification steps of the central conductor: a) disk central conductor; b) Y junction central conductor; c) central conductor with stubs.

We can observe the influence of the stub in Fig. 5.

After optimization of the length and radius parameters, a broadband circulator with a homogeneous field distribution is obtained. The theoretical radius of the polarized ferrite region is 5.2 mm. The central metallic disk has a radius of 1.7 mm, with 1.5 mm-wide lines and stubs that are 2.4 mm long.

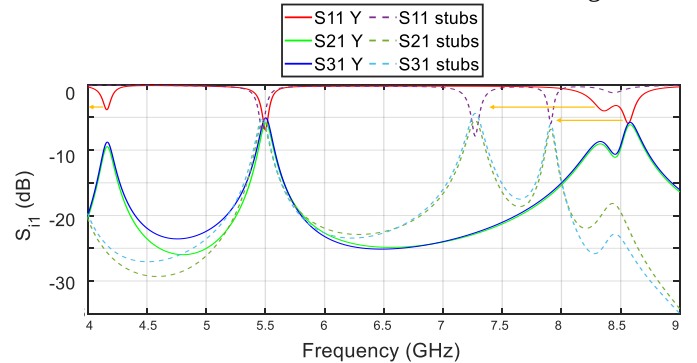


Fig. 5. Results comparison of the Y central conductor shape with and without stubs.

B. Magnetostatic studies and co-simulation

In a practical implementation, only the central part of the ferrite (see Fig. 6) is magnetically biased by permanent magnets. The resulting static magnetic field is relatively uniform at the center and progressively decreases toward the edge of the ferrite, where it becomes negligible.

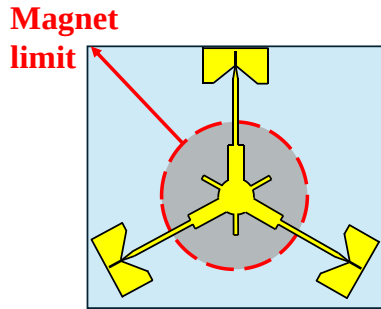


Fig. 6. View from above of the circulator with the magnet.

The final device (Fig. 7) consists of a Y215 ferrite substrate with overall dimensions of 30 x 27 x 0.8 mm³. The central part of the device is polarized by two magnets located at equal distances from the substrate, with a steel disk above, which allows for a more homogeneous internal field. The magnets are 8c ceramic cylindrical magnets ($B_r = 4.3$ kG, $bH_c = 2.5$ kOe) with a diameter of 14 mm and a thickness of 3.1 mm.



Fig. 7. Magnetostatic simulation configuration.

The magnetostatic analysis illustrates the evolution of the magnetic field inside the ferrite (Fig. 8). The field magnitude varies from a few Oersteds to about 250 Oe beneath the central conductor of the device, revealing the inhomogeneous polarization of the ferrite along the x and y directions.

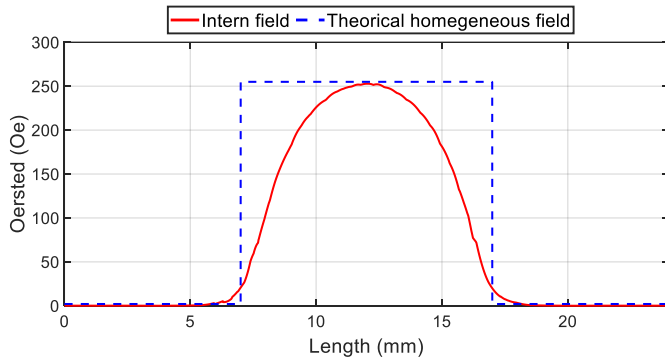


Fig. 8. Intern field from a magnetostatic simulation.

To partition the substrate in the most representative configuration, the region corresponding to the magnet diameter is assumed to exhibit a significant internal magnetic field. The remaining areas are therefore considered to be either partially magnetized or non-magnetized. On this basis, three simulation

approaches combining electromagnetic and magnetostatic analyses are carried out and their results are compared (Fig. 12):

- Model 1 : Polder under the magnet et dielectric elsewhere

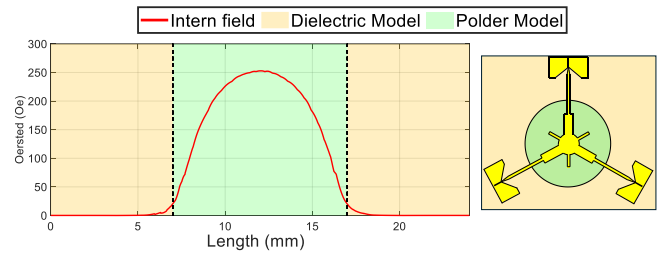


Fig. 9. Intern field H_i associated with the first model.

- Model 2 : Polder under the magnet et Shloemann elsewhere

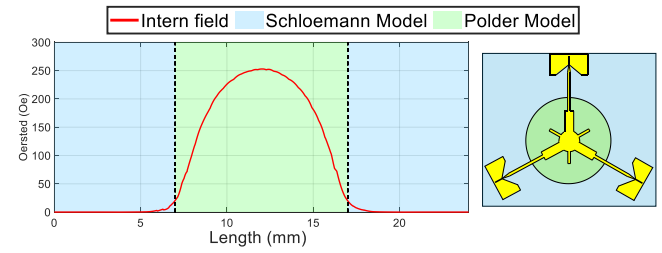


Fig. 10. Intern field H_i associated with the second model.

- Model 3 : Polder under the magnet, Green and Sandy close to the border of the magnet et Shloemann elsewhere.

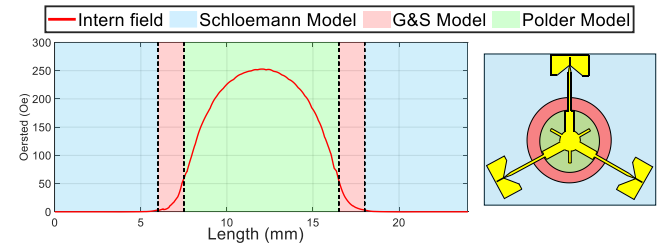


Fig. 11. Intern field H_i associated with the third model.

The simulated results of the S-parameters for each case are compared in the figure below. From these results, we can highlight that Schloemann permeability modifies the S parameters in the low-frequency band compared to the dielectric model simulation.

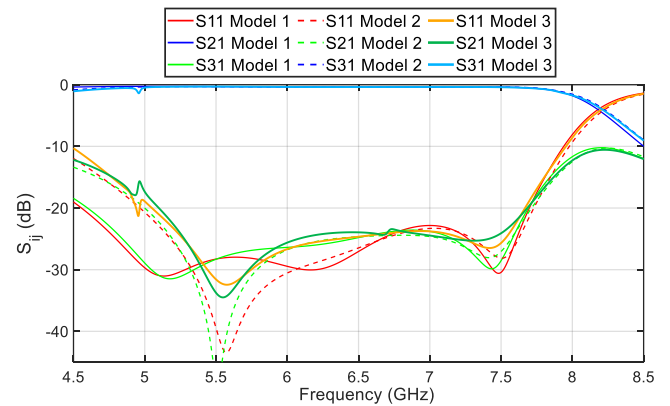


Fig. 12. S-parameters comparison for each ferrite permeability model.

The third model (Polder + Green and Sandy + Schloemann) exhibits behaviour similar to that of the second model (Polder + Schloemann), with some differences, such as the appearance of parasitic resonances within the operating band. Moreover, regardless of the model considered, the wideband performance remains very good, with return loss and isolation better than 20 dB and low insertion losses.

C. Prototype and measurement

A prototype has been realized (Fig. 13), as well as a measurement support made with Rohacell to contain the device with the two magnet and the steel cylinder.

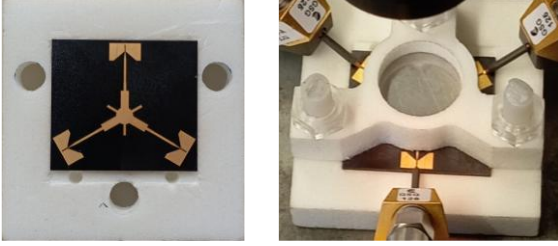


Fig. 13. Photography of the prototype circulator before and during the measurement.

The measurement results were compared with the different models presented above, and the third model showed the best agreement with the experimental data. Figure 14 shows very good agreement between simulations and measurements, with only a slight frequency shift in the S-parameters and minor variations in the shapes of the isolation and matching curves. This can be attributed to a slightly stronger internal magnetic field in the ferrite than simulated, as well as possible inaccuracies in the fabrication of the metallic components. These results validate the accuracy of the ferrite modelling, the proposed circulator exhibits broadband performance (41%) with low insertion losses (<0.6 dB) and measured matching and isolation exceeding 18dB. The device is compact and implemented on a fully ferrite substrate, which simplifies manufacturing and lowers production costs.

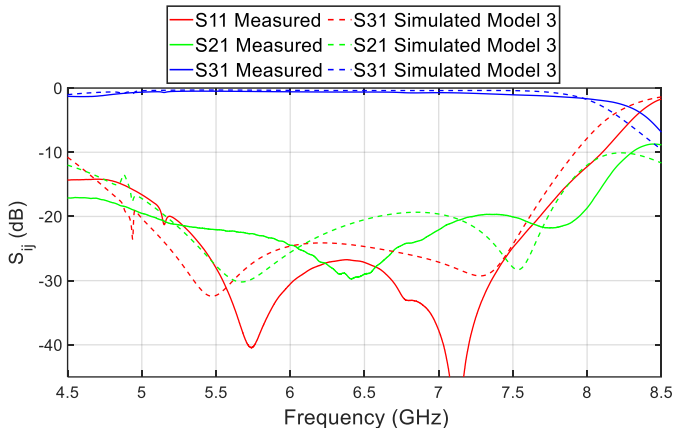


Fig. 14. Comparison between the co-simulation using the third model and the measurement of the parameters S_{ij} .

IV. CONCLUSION

This work proposes a rigorous methodology for the modelling a broadband circulator implemented on an “all-ferrite” substrate. A comprehensive device model, integrating several permeability formulations, was developed. By combining modal analysis with a well-modelled representation of varying magnetization states within the substrate, a broadband circulator was successfully realized. The excellent agreement between simulation and experimental results confirms the validity of the methodology.

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