Planar Isolator Based on Field Displacement in Ferrite Substrate

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***Abstract* — In this work, a microwave ferrite isolator is designed and realized on a planar transmission line. The design has a 50 Ω microstrip line and stubs printed on a polarized ferrite substrate. In order to create an isolation phenomenon, the isolator uses an open stub in conjunction with the field displacement on a non-reciprocal microstrip line. Ideal simulations and magnetostatic / electromagnetic co-simulations of the isolator have been carried out and demonstrated the potential for achieving good performance, with an isolation better than 20 dB around 7.5 GHz. Prototypes fabrication and measurements confirm notable isolation and matching that are in good agreement with simulations.**

***Keywords* — Ferrite device, non-reciprocal behavior, resonance absorption, field displacement, edge guided wave.**

I. Introduction

An isolator is a non-reciprocal passive device that allows an electromagnetic wave to propagate in one direction and blocks it when it propagates in the opposite direction. It serves to safeguard delicate RF components and, in some designs, uses the non-reciprocal behaviors of ferrite material polarized by a static magnetic field to attenuate signals traveling backward while permitting those traveling forward to pass.

In radar systems, microwave isolators play a crucial role in shielding power amplifiers and separating receivers from high-power signals. In transmit arrays, isolators are required to protect the power amplifier output from fluctuations in antennas impedance brought about by shifting the scanning angle or by power reflected from adjacent objects [1]. The majority of commercial isolators are based on junction circulators whose port is terminated by 50 Ω. These industrial designed isolators are constrained by size and isolation issues. In addition, they are not suitable for system integration.

The utilization of edge-guided wave features within stripline or microstrip line configurations has proved instrumental in the development of various high-performance components, including wideband isolators and phase-shifters. Indeed, based on the principles of guided wave propagation [2], particularly in planar transmission lines, this technology seamlessly integrates into various applications, notably within integrated circuits and microstrip or coplanar waveguide architectures. Ferrite isolators often use wide width transmission line loaded with absorbing materials, ferrite slab or short circuit termination [3], [4], [5]. It appears to provide a significant loss in forward propagation due to mismatch and absorber. In loaded waveguided resonance isolator [6], [7], a ferrite slab is inserted at one edge of the substrate to absorb the backward signal at gyromagnetic resonance frequency. In these cases, there is a high forward loss due the magnetic loss at the resonance frequency. Moreover, manufacturing a loaded waveguide device is a challenging task, and design performance can be greatly altered by ferrite placement, leading to increased design complexity and cost. The microstrip line resonance absorption isolators presented in [8], [9], [10] have a low isolation ratio, typically not exceeding 10 dB at maximum, which is insufficient for most microwave applications.

This paper presents an isolator that can provide a good isolation (20 dB) without the need of absorption materials or short circuits. Furthermore, the width of the through line is narrow which is sufficient to provide the edge guided mode while corresponding well to the standard input/output characteristic impedance. The isolation comes mainly from lossy ferrite while working at negative effective permeability unlike circulators, which operate in the positive effective permeability, either above or below resonance [11], [12]. To validate the viability of the concept, an isolator has been fabricated, and subjected to rigorous measurements.

II. Working Principle

A. Ferrite Properties at Microwave Frequencies

The permeability tensor is the most important parameter of ferrites. This defines their nonreciprocal behavior when subjected to a continuous (DC) magnetic field. When a dc magnetic field is strong enough to saturate a ferrite, the permeability tensor defined by (1) is known as the Polder tensor [13].

$$\mu_r(\omega) = \begin{bmatrix} \mu & -j\kappa & 0 \\ j\kappa & \mu & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1}$$

where the elements of permeability tensors are given by

$$\kappa = 1 + \frac{\omega_m \omega}{\omega_0^2 - \omega^2} = \kappa' - j\kappa''$$

$$\mu = 1 + \frac{\omega_m \omega_0}{\omega_0^2 - \omega^2} = \mu' - j\mu''. \tag{2}$$

And $\omega = 2\pi f$, $\omega_m = \gamma\mu_0 M_s$, and $\omega_0 = \gamma\mu_0 H_{in} + j\omega\alpha$, where the gyromagnetic ratio is a constant $\gamma = 2.8 MHz/Oe$. Another parameter is the damping factor, $\alpha = \gamma\Delta H/2f_d$, with ΔH the magnetic losses of ferrite linewidth. In addition, a significant parameter that governs the operating bandwidth and the upper and lower limiting frequencies of an edge-guided isolator is the effective permeability (3) defined by the following equation:

$$\mu_{eff} = \frac{\mu^2 - k^2}{\mu} \tag{3}$$

The operating zone of an edge-guided ferrite isolator is in the negative effective permeability. The detail of the isolation phenomenon and isolator design are presented in the following section.

B. Working Principle of an Edge-Guided Isolator

Hines in [2], was the first to study the edge mode and use the concept of non-reciprocal propagation of the ferrite substrate to build a broadband isolator and phase shifter loaded with absorptive material. Subsequent articles have deepened and developed Hines' research [3], [5], [14]. The authors thoroughly explain the electric and magnetic field components and delineate the distinct properties of forward and backward propagation. Along transmission lines made on a ferrite substrate, RF energy tends to concentrate mainly on one side of the line in the frequency band where the effective permeability is negative. Indeed, this phenomenon, known as "field displacement", appears when the ferrite is biased perpendicularly to the propagation by a static magnetic field and when its effective permeability is negative. It reverses its effect when the direction of wave propagation and magnetization change.

Table 1. Magnetic properties of spinel ferrite substrate

Description	Value
Saturation magnetization ($4\pi Ms$)	2500 G
Permittivity (ε_r)	12.45
Loss tangent ($tan\delta$)	0.00033
Resonance line width (ΔH)	484 Oe
Internal field (H_{in})	300 Oe

In addition, the operating frequency can be shifted accordingly by altering either the internal biasing or the saturation magnetization. The evolution of the Polder's tensor elements as a function of frequency is shown in Fig. 1. A ferrite (TT1-2500) from Skyworks whose properties are shown in Table 1. It is used to design an isolator.

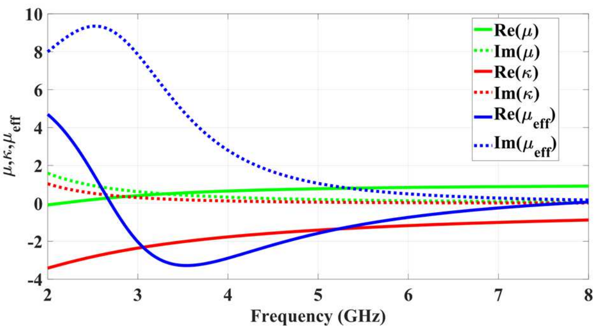


Fig. 1. Polder tensor versus frequency for TT1-2500, with H_{in} = 300 Oe.

When the "field displacement" have been introduced by the finite external biasing on the ferrite slab, the next important step is to find a way to make the isolation. As mentioned in [3], the planar isolator is still based on three port junction circulator operation, but in this case the difference is that one of the ports must terminate with a load impedance. There are many ways to attenuate the backward propagation of electromagnetic wave and implementing the full non-reciprocity function. The methods commonly employed in the literature are resistive absorption sheet, short-circuit and open circuit terminations. Each of them has advantages and limitations. The detail of different way of displacing the reverse wave is showed in Fig. 2. In conventional way, lossy absorption material is used due to its ability to absorb the backward EM wave. However, the extra-cost and deposition technology need to be considered. Another way which found to provide a high isolation ratio is the short circuit termination [7]. However, realizing a short circuit by means of a via hole is not possible for a conventional ferrite substrate. Metallization or soldering on the vertical height of the ferrite is a challenging task because the surface area is very small. Focusing on the simplification and ease of fabrication, the open circuit that mainly depends on the realization of the open stub is the most appropriate solution.

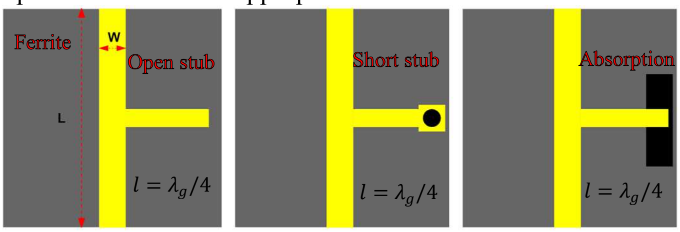


Fig. 2. Non-reciprocal realization on field displacement isolator.

In this paper, the open stub is used to attenuate the backward RF signal and thus make an isolation using losses of the ferrite under external biasing. The transmission line is placed on the ferrite substrate. The main line width has a characteristic impedance of 50 Ω ($W_m = 0.892\ mm$), and has a length L_m = 3.65 mm.The transition between the microstrip line to Ground-Signal-Ground (GSG) probe has been designed and integrated into the isolator for device characterization (Fig. 3).

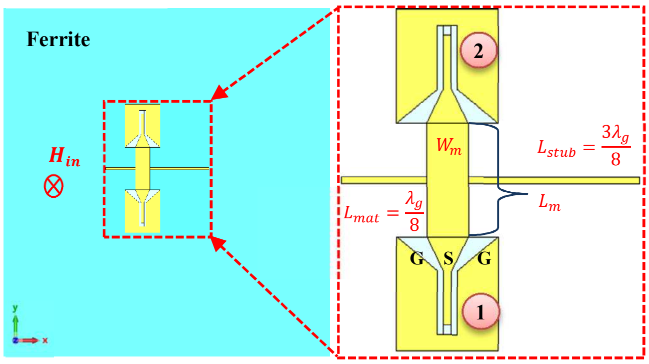


Fig. 3. Completed designed of microstrip isolator.

The stub is placed on the right-hand side of input signal (port 1) in order to attenuate the reversed signal that enters from output port (port 2) and vice versa if the opposite manner of a propagation is used. A stub matching with an electrical length (L_{mat}) is also inserted to get |S11| and |S22| greater than 20 dB for our specification requirement. In [9], the authors showed that isolator performances are better if the width of side stubs is narrow with lengths of approximately $\lambda_g/8$ and $3\lambda_g/8$ for matching and main stub, respectively. However, it can be optimized but the electrical length of main stub must be at least a quarter of the guided wavelength. The design of the isolator is shown in Fig. 3.

III. Co-Simulation and Validation

The isolator can operate as an edge-guided isolator over the frequency band where the effective permeability of the material is negative. With the ferrite presented in section II and applying a DC magnetic field to obtain an internal field of 300 Oe, we choose an operating frequency of around 7.5 GHz. Considering the design procedure described in section II, the dimensions of the isolator are presented in Table 2.

Table 2. Optimized dimension of isolator parameter

Parameter	Value (mm)
Main line width (W_m)	0.892
Main line length (L_m)	2.203
Side stub length (L_{stub})	3.656
Matching stub length (L_{mat})	1.828

The size of the isolator, including the microstrip to coplanar transition, is 6.37 mm wide by 6.66 mm long corresponding to $\lambda_0/6.3$ x $\lambda_0/6$ at 7.5 GHz. The substrate used has a total size of 40mm x 40mm x 1mm, enabling us to produce several isolators on the same plate and thus check performance reproducibility and any interactions between devices.

Unlike reciprocal materials, magnetic biasing is essential when working with ferrimagnetic materials, such as ferrite. In ideal simulations, the internal field is assumed to be uniform (homogeneous) when calculating the S-parameters. However, these preliminary simulations, based on homogeneous internal field assumptions, are not totally accurate. In order to characterize the internal magnetic field behavior into the ferrite substrate, we proceed to a magnetostatic study (MS) for the isolator structure (Fig. 4a). The ferrite is magnetized using a magnet placed under the ferrite. In the MS simulation, the type of magnet and its dimensions are chosen to obtain an internal field (H_{in}) as closed as possible to the ideal case: H_{in} = 300 Oe This study is carried out iteratively until we get the closed performances as ideal case. Fig. 4b shows the internal magnetic field distribution within ferrite while using a commercial permanent magnet (Sm2Co17-26MGOe) from Cermag. The magnet is placed under the ground plane. The steel plate of 1 mm thickness is added between the ferrite and magnet to improve homogenous distribution.

Fig. 4b also shows that an average internal magnetic field of 280 Oe is obtained under the isolator, i.e., close to ideal simulations. Then, a co-simulation is performed in CST Microwave Studio. The process involves linking magnetostatic (MS) and electromagnetic (EM) simulations by integrating the real internal field within the ferrite substrate.

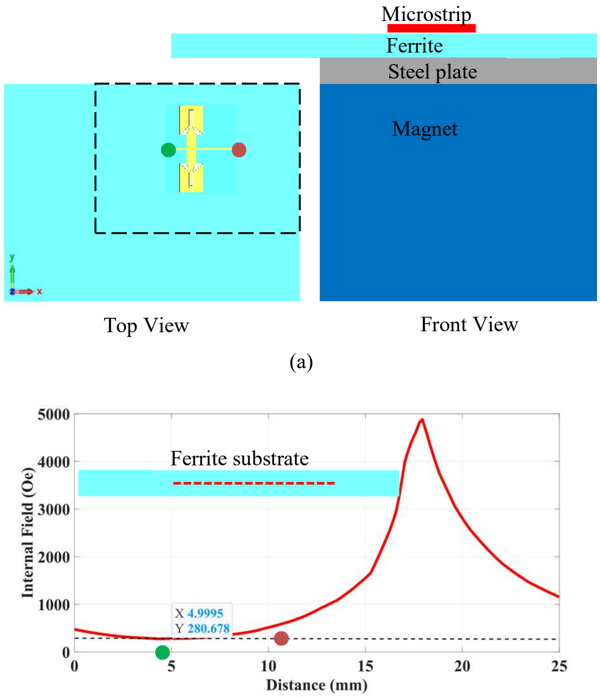


Fig. 4:(a) View of the co-simulation of isolator; (b) Inhomogeneous field in the middle of ferrite substrate.

Fig. 5 compares S-parameters performances between the ideal case (H_{in} = 300 Oe) and the co-simulation integrating the bottom magnet. The isolator exhibits a very good reflection and isolation, i.e. at center frequency of 7.5 GHz, the simulated insertion loss, reflection and isolation are 4.25 dB, 21 dB, and 25 dB, respectively. The comparison between ideal case and co-simulation gives a good agreement indicating that the co-simulation of the asymmetrically magnet provides exactly the magnetic field required for the isolator to operate at the predicted center frequency of 7.5 GHz with both isolation and matching greater than 20 dB.

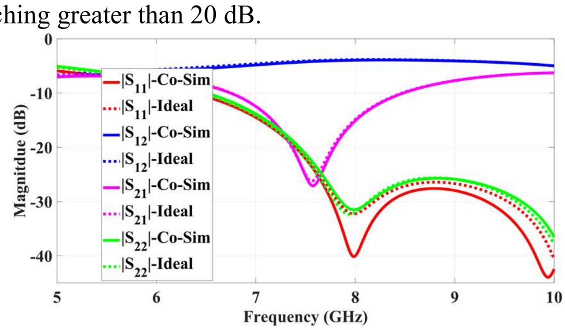
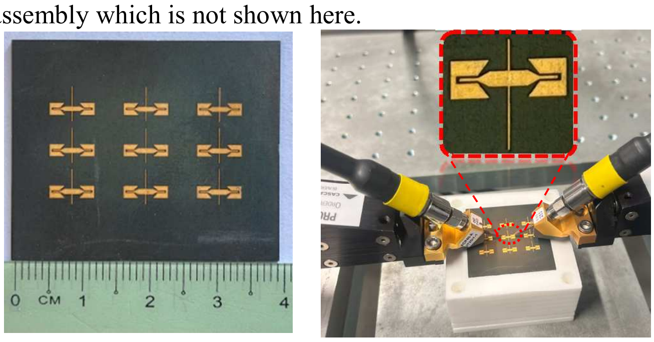


Fig. 5. Ideal versus co-simulation (MS-EM).

IV. Realization and Measurements of the Device

A gold metallization of 10 μm thick was deposited on both sides of a ferrite substrate of 40mm x 40mm x 1mm using the different clean room microfabrication techniques of the Xlim laboratory. An array of 3 x 3 devices was laser-etched on the top side as shown in Fig. 6a. The purpose of having 9 isolators on the same substrate is to avoid any defects during the metallization or etching process, to check performance reproducibility and to investigate any interactions between isolators. The measurements show that all the isolators are well connected and metallized while providing very similar performance, and the interactions between them are negligible. The magnet, ferrite, and steel plate are assembled by compressing them into a single Rohacell block ($\varepsilon_r = 1$) using plastic screws (Fig. 6b). Each isolator has its own biasing assembly which is not shown here.



(a) (b)

Fig. 6 : (a) Top view of the etched ferrite substrate; (b) Experimental setup and measurement.

The comparison between experimental and co-simulated results is presented in Fig. 7. There is a good agreement between simulation and measurement with a frequency shift of around 4 %. The isolation is greater than 20 dB at 7.64 GHz. The same graph shows that the reflection parameter is shifted with a magnitude of more than 20 dB from 8.5 GHz (considering both $|S_{11}|$ and $|S_{22}|$). The shifted of reflection upward is caused from the tolerances of main and side stub dimensions after etching (smallest line). The decreases of line dimensions lead to migrate the resonance frequency of the device slightly above the simulated one. And the overall small variations in S-parameters are due to the tolerance of ferrite permittivity which could be lower than the nominal value defined in the datasheet. Retro-simulations are conducted after measurement and show that by taking a value of permittivity $\varepsilon_r = 11.8$, the minimums of both $|S_{11}|$ and $|S_{22}|$ parameters are shifted towards higher frequencies without affecting the isolation parameter.

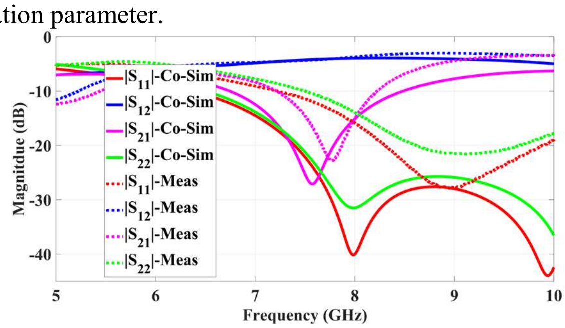


Fig. 7. Comparison of co-simulated and measured isolator's performances

V. Conclusion

This paper presents an isolator implemented using a low-cost microstrip deposited on a ferrite substrate. Emphasizing simplicity, a single stub is utilized with a lossy ferrite to attenuate the backward EM wave. This solution is less complex than a short circuit termination or the use of a loaded absorption material, while providing adequate isolation. This approach has not been demonstrated in the literatures yet as per our reviewing within the same context. Additionally, a coupled EM-MS simulation is performed, demonstrating good performance while mitigating the edge effects of external biasing by placing a permanent magnet asymmetrically. Experimental results show good agreement with the simulation. Other studies on improving the isolator's insertion loss and bandwidth of operation are the subject of our ongoing project.

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