Dual-band Microstrip Ferrite Circulator

Vincent Olivier[#1], Thierry Monédière[$2], Bertrand Lenoir[#3], Hamza Turki[#4], Laure Huitema[$5]
[#]Inoveos, France
[$]XLIM Research Institute, University of Limoges, France
[1]volivier@inoveos.com, [2]thierry.monediere@unilim.fr, [3]blenoir@inoveos.com, [4]hturki@inoveos.com, [5]laure.huitema@unilim.fr

Abstract— **Dual-band circulators are a new literature topic and so far, they have always been realized in stripline technology, therefore with bulky boxes. Changing to microstrip allows to reduce the size of the device while keeping similar performances. Furthermore it enables better integration into antenna systems. This paper presents the first design of a ferrite dual-band circulator in planar technology, operating simultaneously on two chosen frequency bands. The isolation of the device is better than 20 dB at 5 and 10 GHz.**

Keywords— **Circulator design, complex shape, dual-band, ferrite, Y-junction circulators.**

I. Introduction

Ferrite circulators are passive, non-reciprocal microwave components, usually with three ports. Their non-reciprocity property is exploited in full-duplex systems to receive and transmit simultaneously using one single antenna. Connecting one of the three ports to a matched load, they can also be used as isolator to protect devices from reflections.

In order to reduce size, a growing number of RF front-ends offer multiband operation. To maintain good isolation properties between components in these systems it is therefore necessary to use circulators which also operate on several frequency bands. The first of these circulators [1] offers an isolation better than 20 dB around two separate frequencies: 2.55 GHz and 4.4 GHz. However, the bandwidths of these devices are quite narrow and the gap between the two operating frequencies is not controlled but imposed by the structure of the resonator. The design method presented in [2] allows the control of the two frequency bands ratio, by modifying the shape and dimensions of the metallic part at the center of the ferrite stripline resonator. This method has resulted in the design of a dual-band circulator with an isolation better than 20 dB at 5 and 10 GHz. The relative bandwidths of the circulator in [2] are also wider than those in [1] with 4% for the first band and 2.9% for the second at 20 dB.

These devices [1], [2] have all been realized in stripline technology. Bulk aluminum boxes (Fig. 1(a)) are used to maintain ferrite disks and magnets at the center of the structure. In single-band operation, moving to a planar technology allows to reduce dimensions and made the integration of the device easier. Indeed, a microstrip circulator is composed of a single ferrite (or ferrite/dielectric) substrate, and generally a single magnet placed above/below (Fig. 1(b)). Thanks to the substrate's permittivity, the length of the access lines can be reduced compared to a stripline structure where lines are usually air-filled (Fig. 1(a)).

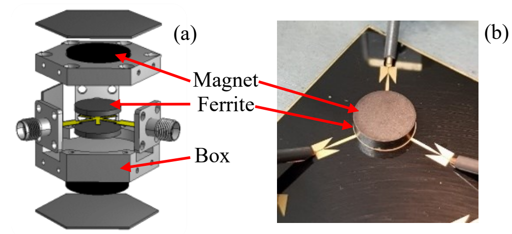

Fig. 1. Ferrite circulator stripline [2] (a) and microstrip (b).

In order to achieve better miniaturization of RF systems and components, the first dual-band ferrite circulator in microstrip technology has been developed. It operates at 5 and 10 GHz with bandwidths at 20 dB isolation of respectively 5.5% and 2.8%. The first part of the paper describes the full design methodology of the circulator, the second part presents the manufacturing of a prototype and comparison of the simulated and of the measured performances.

II. Circulator Design

The design of this circulator is based on the papers [2] and [3] method but adapted to the microstrip technology. The first step consists in dimensioning the ferrite resonator, the second in dimensioning the access lines and matching sections.

A. Ferrite resonator sizing

First, a modal study of the ferrite resonator is performed. There, unlike [1] and [2], the resonator is made of a single ferrite disk inserted in a dielectric substrate. The central conductor is modeled on the ferrite disk (Fig. 2) and a ground plane is located under the structure. To uncouple the resonant structure, microstrip lines are physically disconnected from the central conductor with a 100 µm gap (Fig. 2). This allows the excitation of eigen modes and the determination of their resonant frequencies (Fig. 3).

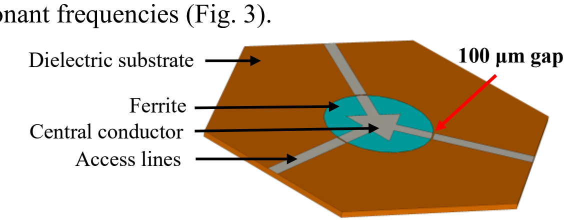

Fig. 2. Microstrip ferrite resonator weakly excited by access lines and 100 µm gap.

Resonant frequencies of the first counter-rotating mode pair $HE_{\pm 11}$ surround the first circulation frequency ([1]–[5]). The second is determined by resonance frequencies of upper modes

HE±21. In [2] a method for sizing ferrite resonators was presented to identify the parameters that influence the resonant frequencies of the different mode pairs. The most significant parameter to influence counter-rotating mode pair frequencies is the central conductor shape [2]. An iterative parametric study on the central conductor dimensions has therefore been carried out and has led to determine a resonator whose HE±11 mode pair is around 5 GHz and the HE±21 mode pair around 10 GHz. The central conductor geometry that allows these frequency conditions to be met is a side-coupled triangle (Fig. 2). The S-parameters obtained by electromagnetic (EM) simulation of this uncoupled resonator are shown in Fig. 3.

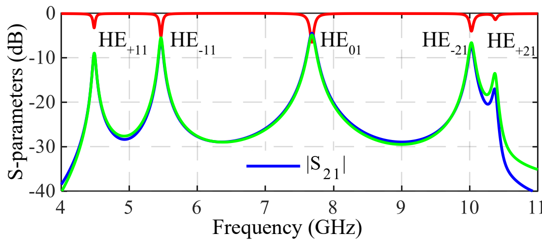

Fig. 3. Simulated S-parameters of microstrip ferrite resonator weakly excited by access lines and 100 µm gap of Fig. 2.

The iterative method of [2] allows to define all parameters of the resonator, i.e. radius of the ferrite disk, type of ferrite (magnetization (M_s), permittivity (ε_r), ...), static magnetic field inside the ferrite (H_i) as well as shape and size of the central conductor. Properties are given in Table 1.

Table 1. Circulator properties and dimensions.

Material	Parameter	Value
Ferrite Y210 [6]	Radius (mm)	5.35
	Thickness (mm)	0.6
	M_s (G)	1000
	ε_r	14.2
	H_i (kA/m)	28
Alumina substrate	Thickness (mm)	0.6
	ε_r	9.6

B. Accesses lines and matching section design

The second step of the design is the matching and coupling of the resonator. Indeed, the modal study of section II.A. only allows to define the properties of the resonator without considering the access lines. The method presented in [3] is used and modified to be also valid in microstrip technology.

It consists in computing an impedance value Z_0 to be applied to the three accesses in order to meet the circulation conditions and thus to have an optimized circulation operation. From an EM simulation with a resonator fed with 50 Ω access lines, the so-called de-embedding type calculation [3] is used to find the value of Z_0 as a function of the frequency.

Fig. 4 shows the Z_0 solution of the resonator with the triangular central conductor from Fig. 2.

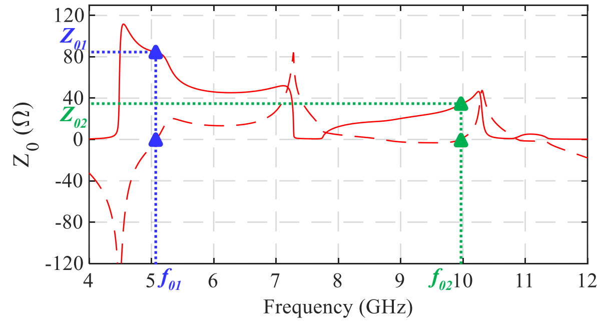

Fig. 4. Impedance Z_0 to apply to Fig. 2 resonator to fulfill circulation conditions computed following [3] method.

From Fig. 4 results, two solutions are considered. Indeed the method [3] specifies that the circulation is ideal when the imaginary part of Z_0 is null. Thus, the two solutions considered are $Z_{01} = 83$ Ω at $f_{01} = 5.1$ GHz and $Z_{02} = 37$ Ω at $f_{02} = 9.95$ GHz.

Then, to connect the circulator to 50 Ω ports and fulfill impedance conditions, it is necessary to design a dual band matching circuit 83 Ω to 50 Ω at 5 GHz and 37 Ω to 50 Ω at 10 GHz respectively. The matching circuit shown in Fig. 5 is obtained through circuit optimization. The properties of the circuit are as follows: $Zc_1 = 61$ Ω, $L_1 = 3.4$ mm, $Zc_2 = 77$ Ω, $L_2 = 2.3$mm.

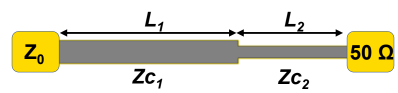

Fig. 5. Dual band matching circuit schematic.

A matching circuit is added to each of the three resonator ports and then terminated with a 50 Ω section. The complete model is shown in Fig. 6 and the EM simulation results in Fig. 7. The S-parameters in Fig. 7 thus show a circulation phenomenon around 5 and 10 GHz with more than 20 dB of isolation and matching.

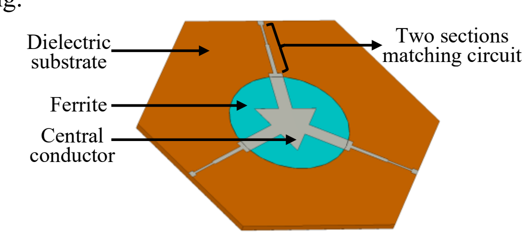

Fig. 6. Microstrip dual band ferrite circulator model for EM simulations.

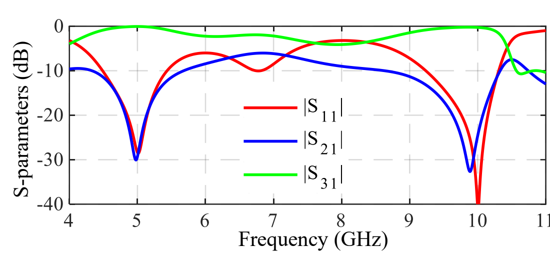

Fig. 7. Simulated S-parameters of the Fig. 6 circulator model.

To enable measurements using ground-signal-ground (GSG) probes, microstrip to coplanar transitions are added [7]. The S-parameters and 3D model of these transitions are shown in Fig. 8. Transitions losses are less than 0.2 dB at the operating frequencies.

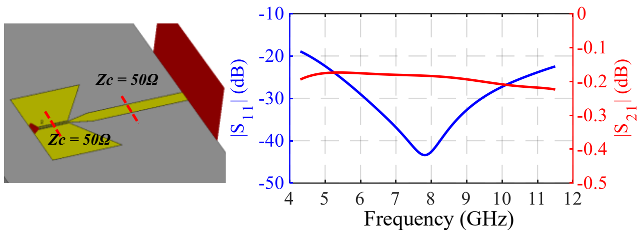

Fig. 8. Model and simulation of microstrip to coplanar transitions.

C. Magnetostatic study

So far, the EM simulations of the device are based on a static magnetic field of 28 kA/m inside ferrite, which is not reliable as the real magnetic field inside ferrite is inhomogeneous. A magnetostatic study of the device is then performed to design the appropriate permanent magnet leading to a magnetic field distribution as close as possible to 28 kA/m. The magnetostatic simulation is carried out using CST Studio Suite.

In order not to short-circuit the triangular shape of the central conductor, the magnet is placed under the structure (Fig. 9).

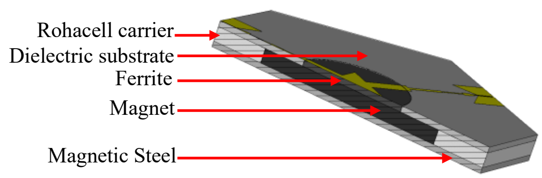

Fig. 9. Microstrip dual-band circulator model for magnetostatic study.

An iterative optimization has allowed to choose a NdFeB magnet of 19.1 mm radius and 1.45 mm thickness. The static magnetic field inside the ferrite obtained by simulation is plotted in Fig. 10 along a line at mid-height of the ferrite.

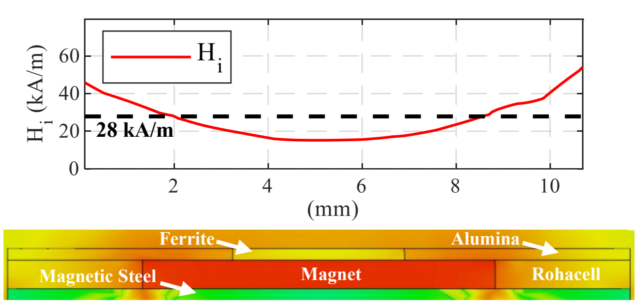

Fig. 10. Static magnetic field along a line at the center of the ferrite Fig. 9 and H field distribution in a cut plane of the structure .

The average field is close to the 28 kA/m target. It is however higher than 48 kA/m at the ferrite boundaries. Indeed this is a planar structure, the field is less homogeneous than for stripline designs. Magnet's properties are given in Table 2.

Table 2. Magnet properties and dimensions.

Material	Parameter	Value
NdFeB magnet	Radius (mm)	19.1
	Thickness (mm)	1.45
	B_r (G)	11600

D. Magnetostatic-electromagnetic co-simulation

A magnetostatic-electromagnetic (MS-EM) co-simulation taking into account the static magnetic field of the magnet in the ferrite biasing has been performed. The complete model is shown in Fig. 11 and the results of co-simulation performed with CST Studio Suite are shown in Fig. 12.

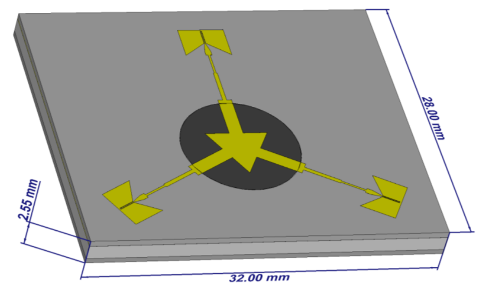

Fig. 11. Final circulator model.

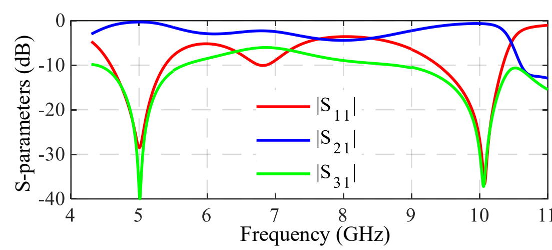

Fig. 12. MS-EM co-simulation of the final microstrip dual band circulator Fig. 9.

The co-simulation results in Fig. 12 clearly show a circulation phenomenon at 5 and 10 GHz. The matching and isolation levels are better than 20 dB at both of these frequencies.

III. PROTOTYPING AND MEASUREMENTS

In order to validate the performances of the circulator, a prototype is manufactured. The substrate is a drilled Alumina plate in which a ferrite disk is inserted. The sample is fully metallized on both sides with 4 µm of gold. The top side design was then laser etched with LPKF ProtoLaser U4 [8]. All the properties of the substrate, ferrite and magnet as well as a picture of the prototype are given in Table 1,Table 2 and in Fig. 13.

Finally the prototype was measured using GSG probes. A comparison of the measured and simulated S-parameters is shown in Fig. 14. Measurement results are very close to simulations. Considering an isolation better than 20 dB, circulator bandwidths are 5.5% at 4.9 GHz and 2.8% at 10.1 GHz. Losses of the prototype have a maximum of 0.65 dB for the first band and 1.3 dB for the second.

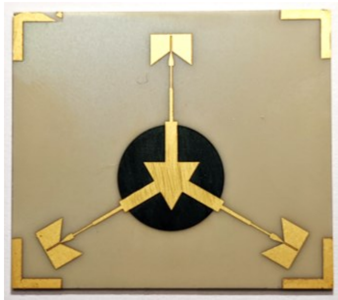

Fig. 13. Prototype of dual band microstrip circulator.

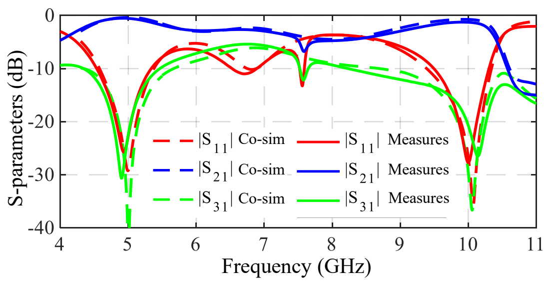

Fig. 14. MS-EM co-simulation and measurements.

IV. Conclusion

In this paper the first dual band circulator in microstrip technology is presented. Made of a ferrite/dielectric composite substrate, it has been designed by adapting literature methods [2] and [3] from stripline topology to a microstrip structure. The two operating frequencies have been chosen and well controlled. A good agreement between simulations and measurements was obtained. The circulator shows a good isolation (better than 20 dB) at 4.9 and 10.1 GHz. The performances are similar to those of the state of the art in stripline [2].

Finally, with a substrate size of 32×28 mm and a height of 2.55 mm including the magnet, this first planar dual-band circulator has much smaller dimensions than previous stripline designs ([2], [3]).

Acknowledgment

This work has been done in the framework of the joint laboratory Inogyro (http://inogyro.xlim.fr) involving the Xlim Research Institute and Inoveos SME. The authors also thank the French Defence Innovation Agency for subsidizing a part of this work.

References

[1] H. Turki, L. Huitema, T. Monediere, B. Lenoir, and C. Breuil, “New Concept Validation of Low-Loss Dual-Band Stripline Circulator,” *IEEE Trans. Microwave Theory Techn.*, vol. 67, no. 3, Art. no. 3, Mar. 2019, doi: 10.1109/TMTT.2018.2890632.

[2] V. Olivier *et al.*, “Dual-Band Ferrite Circulators Operating on Weak Field Conditions: Design Methodology and Bandwidths’ Improvement,” *IEEE Trans. Microwave Theory Techn.*, vol. 68, no. 7, Art. no. 7, Jul. 2020, doi: 10.1109/TMTT.2020.2988003.

[3] V. Olivier *et al.*, “General Coupling Method for Stripline Ferrite Circulators: Application on Dual-Band Devices With Complex Central Conductor Shape,” *IEEE Trans. Microwave Theory Techn.*, vol. 70, no. 7, pp. 3486–3497, Jul. 2022, doi: 10.1109/TMTT.2022.3175168.

[4] H. Bosma, “On the principle of stripline circulation,” *IEE-Part B: Electronic and Communication Engineering*, vol. 109, no. 21S, Art. no. 21S, 1962.

[5] M. Latrach, T. Monediere, and F. Jecko, “A new design of cylindrical closed triplate ferrite resonators compared with magnetic wall approximation,” *IEEE Trans. Magn.*, vol. 26, no. 5, Art. no. 5, Sep. 1990, doi: 10.1109/20.104897.

[6] “https://exxelia.com/fr/produits/liste/materiaux-et-hyperfrequence/ferrites.”

[7] Guizhen Zheng, J. Papapolymerou, and M. M. Tentzeris, “Wideband coplanar waveguide RF probe pad to microstrip transitions without via holes,” *IEEE Microw. Wireless Compon. Lett.*, vol. 13, no. 12, Art. no. 12, Dec. 2003, doi: 10.1109/LMWC.2003.820638.

[8] “https://www.lpkf.com/en/industries-technologies/research-in-house-pcb-prototyping/produkte/lpkf-protolaser-u4.”