Stripline dual-band ferrite circulators operating on weak field conditions

Vincent Olivier [*#1], Laure Huitema[#2], Bertrand Lenoir[*3], Hamza Turki[*4], Christophe Breuil[*5],
Philippe Pouliguen[^6], Thierry Monediere[#7]

[*] Inoveos company, Brive-La-Gaillarde, France
[#] XLIM research institute, University of Limoges, Limoges, France
[^] French Defense Innovation Agency, Paris, France
{[1]vincent.olivier, [2]laure.huitema, [7]thierry.monediere}@unilim.fr,
{[1]volivier, [3]blenoir, [4]hturki, [5]cbreuil}@inoveos.com, [6]philippe.pouliguen@intradef.gouv.fr

Abstract — **This paper presents a new concept of dual-band circulators using a weak field biased ferrite. Two prototypes were designed and measured, one with the same circulation direction between the first and the second band (unidirectional circulator) and the other one with an opposite circulation direction (bidirectional circulator). These new designs allow a control of the two operating frequencies and a widening of bandwidths.**

Keywords — **Y-junction circulators, ferrite, modal analysis, upper modes, dual-band, unidirectional, bidirectional.**

I. INTRODUCTION

Microwave ferrite circulators are usually used to connect a single-antenna to a Transmitter-Receiver system or for the isolation of RF sources. These components commonly operate in a single frequency band, only few articles deal with operation in multiple frequencies bands [1]–[3]. Improved performances of these devices will allow their integration into multi-band systems. Indeed, use of these devices with other multi-band components will make it possible to design RF systems combining several functions while maintaining insulation and miniaturization.

Design of circulators is based on the coupling of counter-rotating eigenmodes of a cylindrical ferrite cavity[4], [5]. Usually only pair of fundamentals counter-rotating modes are used in these cavities, in order to obtain a monoband circulation.

The first stripline dual-band circulator has been realized in [1] by coupling fundamental and upper modes simultaneously in the **strong field** zone of polarized ferrite. Its bandwidths were quite small and the ratio between F1 and F2 was undergone and not chosen. In order to solve these problems new devices working in the **weak field** zone are presented in this paper.

First section of this article presents a modal analysis on cylindrical ferrite resonator. This study will highlight that an inversion in the order of appearance of upper modes can occur when changing the shape of the central conductor. Thanks to these observations two different circulators operating on weak field conditions were designed and built. They work at 5 and 10.5GHz for the first one with unidirectional circulation and 6 and 10.8GHz for the second with bidirectional circulation. Performances will be compared with those of circulators already produced in strong field [1].

II. EIGENMODES ON FERRITE RESONATOR

A. Principle

In [1], the design of dual-band circulators is based on an eigenmodes analysis of ferrite cavities. Cavities are composed of two ferrite disks separated by a central metallic conductor (usually a disk of the same diameter as the ferrite ones) and surrounded by a dielectric ring (Fig.1a). Analytical methods can be used to obtain the resonance frequencies of these modes [4], [6]. Some of them consider ferrite/dielectric boundary as a perfect magnetic wall [4]. More complex methods take into account the dielectric surrounding ferrite [6] but are allowable only with a disk as central conductor. None of them take into account accurately the upper modes and complex central conductor shape.

Therefore, in this paper, a numerical method is used to determine resonant frequencies of eigenmodes in the cavity. It also allows to identify them. Modes under consideration are hybrid ones $HE_{\pm nm}$ where n represents the azimuthal variation and m the radial one $((n, m) \in \mathbb{N}^2)$. The numerical method consists in weakly exciting the structure Fig. 1a with magnetic probes. Simulations are made using CST Microwave Studio.

Resonant frequencies of both pairs of counter-rotating modes will inform us about the future operating frequencies of the circulator. Thus, to design a circulator with predefined operating frequencies, it is possible to modify the intrinsic parameters of the ferrite resonator and also the shape of the central conductor until the conditions are optimal for dual-band circulation. The main goal of this numerical calculation method is to find a configuration where the $HE_{\pm 11}$ modes are around F1 and the $HE_{\pm 21}$ modes are around F2 without the HE_{01} and $HE_{\pm 31}$ in order not to interfere.

Resonator parameters are material properties such as saturation magnetization, permittivity and polarization of the ferrite with the internal dc magnetic field Hi. Dimensions of the resonator are also critical factors, as well as ferrite disks radius and shape of the central conductor.

Indeed, in weak field operation, it is usual to use a WYE central conductor with stubs Fig. 1b [7]. It allows to have wider bandwidths.

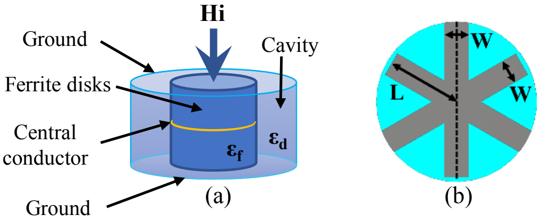

Fig. 1. Ferrite resonator model (a) and central conductor WYE with stubs and W the central conductor linewidth (b).

For the design of the weak field unidirectional dual-band circulator the operating frequencies were set at 5 GHz for F1 and 10.5 GHz for F2. Adjusting the resonator parameters and using a central conductor WYE with stubs, it was possible to set the appropriate conditions for a good circulation at F1 and F2 simultaneously.

Resonator presents the following properties: ε_r=14, $4\pi Ms$=1450G, Hi=51kA/m, $R_{ferrite}$ =6.6mm and W=1.5mm. L=6.2mm

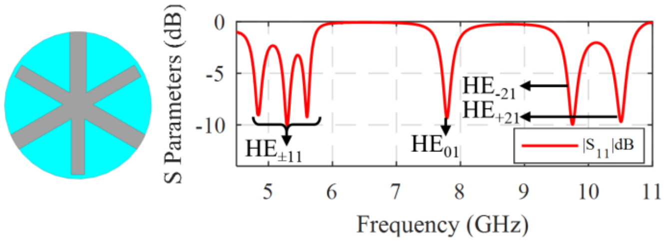

Fig. 2. Central conductor WYE with stubs width W=1.5mm and EM simulations of uncoupled ferrite resonator.

The EM simulation of the resonator Fig. 2 shows fundamental modes around 5GHz and upper modes around 10.5GHz. Because of the stubs, new modes appear around the fundamental ones. Their resonance frequencies are close to those of the fundamentals modes and they present similar fields patterns. That's why we have included them in the HE$_{\pm11}$ family.

B. *Central conductor influence*

Each parameter of the ferrite resonator affects the eigenmodes resonant frequencies. One of the most influent is the central conductor. To demonstrate this influence, a chart of the eigenmodes resonant frequencies is established using the previous resonator and only modifying the dimension W of the central conductor.

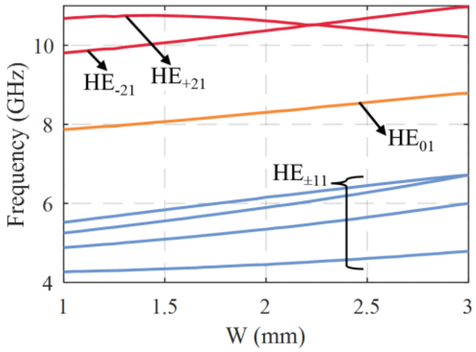

Fig. 3. Computed eigenmodes resonances frequency in a ferrite cavity as a function of line width (W) (Fig. 5b), Model parameters: ε_r=14, $4\pi Ms$=1450G, Hi=51kA/m and $R_{ferrite}$=6.6mm.

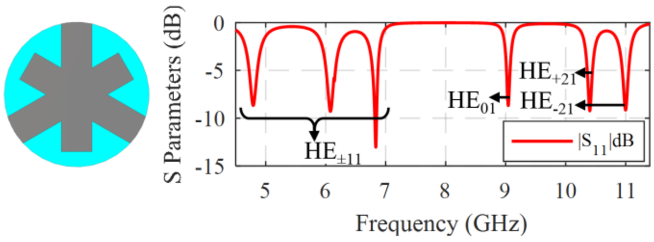

Fig. 4. Central conductor WYE with stubs width W=2.8mm and EM simulations of uncoupled ferrite resonator.

With this resonator, eigenmodes frequencies are around 6GHz for fundamental ones and around 10.8GHz for upper modes. The expected operating frequencies of the associated circulator are therefore 6GHz for F1 and 10.5GHz for F2.

The two selected resonators have led to the development of two circulators with different functions presented in the following section.

III. DUAL-BAND CIRCULATOR DESIGN

This section describes the design and measurement results of two dual-band circulators made from ferrite resonators selected in the previous modal study. The design of a circulator from a ferrite resonator involves on adding access lines and dimensioning them in order to obtain the best matching, the best isolation between ports and the lowest losses.

Analytical methods for circulators design with complex central conductors (WYE [7]) exist, but upper modes coupling is never rigorously studied. A parametric study (using CST MWS software) has therefore been used to obtain the linewidth satisfying simultaneously fundamentals and upper modes coupling.

A. *Unidirectional circulator*

To couple the resonator in Fig. 2, three access lines separated by 120° are added. These simulations give a first overview of the dual-band circulation obtained using the first designed resonator (W=1.5mm). The design is completed by sizing the permanents magnets which enable to obtain a Hi field in the ferrite as close as possible to the value of 51kA/m. Finally, an magnetostatic/electromagnetic co-simulation (MS-EM) is performed considering the complete model (Fig. 5), including: magnets, connectors…

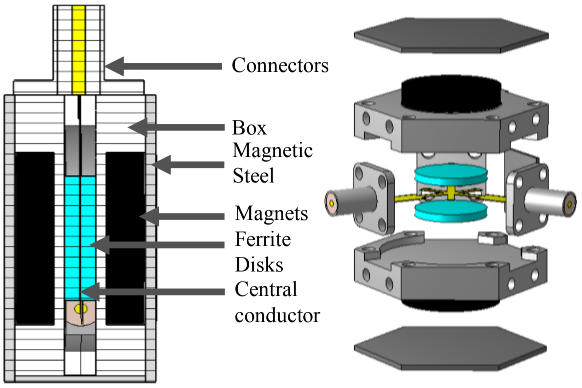

Fig. 5. Complete model of unidirectional dual-band circulator

This circulator has been realized and measured, Fig. 6 shows the realized prototype and Fig. 7 shows a comparison of MS-EM co-simulation and measurements. A dual-band circulation clearly appears around 5GHz and 10.5GHz with a very good agreement between simulations and measurement. It validates the design method.

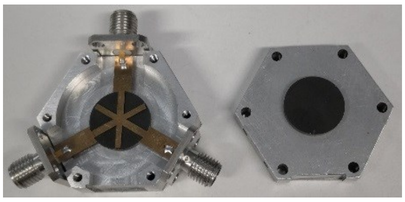

Fig. 6. Prototype of the unidirectional circulator

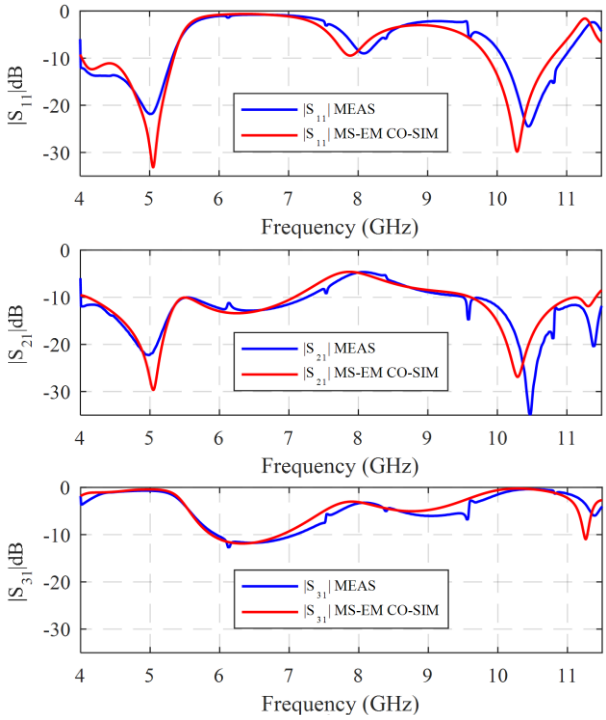

Fig. 7. Unidirectional dual-band ferrite circulator with weak bias field: MS-EM co-simulation and measurement.

Measurements are close to simulations with an isolation and a matching better than 20dB in bands [4.9GHz - 5.1GHz] and [10.3GHz - 10.6GHz]. Assuming these requirements, insertion losses are respectively better than 0.78dB and 0.45dB.

After retro-simulations, it appeared that observed spurious peaks were caused by a slight misalignment of the two ferrite disks.

B. *Bidirectional circulator*

The first circulator was realized using a ferrite resonator and a central conductor for which the higher mode HE_{-21} appeared at a lower frequency that of the HE_{+21}. It exhibited a unidirectional behavior.

To demonstrate that the eigenmodes appearance order is decisive in the circulation direction, a second circulator was conceived. It was designed with the resonator presented Fig. 4, so with a HE_{+21} mode which appears first. For the second resonator, the only changes are dimensions W of lines and stubs of the central conductor. The same process is used to switch from the resonator to the associated circulator. Adding and sizing the access lines will allow the best coupling compromise. For this resonator the linewidth which allows an optimal coupling is 7.2mm, its characteristic impedance is 32**Ω**.

A matching step has been added in order to connect the circulator to SMA 50Ω connectors. It consists of two $\lambda/4$ sections with F=(F1+F2)/2. Characteristic impedances of these two sections were calculated using the method explained in [8]. Circulator is therefore matched for two frequencies F1=6GHz and F2=10.5GHz. As with the first circulator, a MS-EM co-simulation was done to take into account the complete model of the device and to choose the good magnets. The circulator is presented Fig. 8.

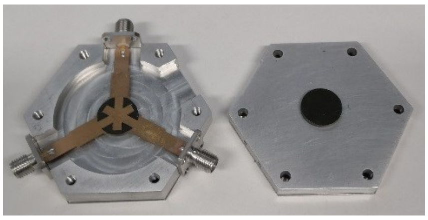

Fig. 8. Prototype of the bidirectional circulator

As expected, measured and simulated results are in good agreement and exhibit a bidirectional circulation direction. Indeed, for this second circulator, the circulation direction is different between F1 and F2.

As for the first circulator, return losses and isolation are better than 20dB for frequencies: [5.5GHz – 6.3GHz] for F1 and [10.6GHz – 10.8GHz] for F2 with insertion losses lower than 0.65dB and 0.75dB, respectively.

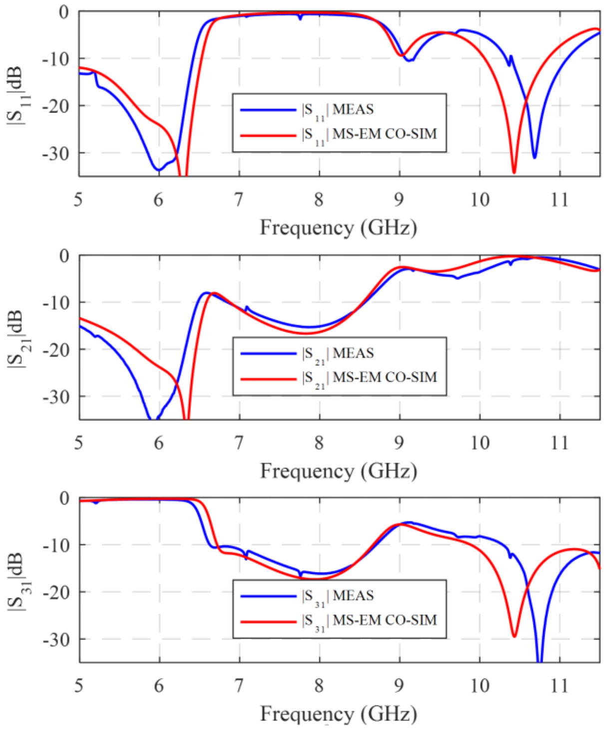

Fig. 9. Bidirectional dual-band ferrite circulator with weak bias field: MS-EM co-simulation and measurement.

C. Performances comparison

Table 1 summarizes the obtained performances for these two new weak field circulators and compares them to those of previously published devices working in the strong field zone [1]. It shows frequency bandwidths twice as wide than in [1].

Table 1. Measurement results comparison of dual-band circulators with weak and strong biasing fields [1].

Circulator	**Unidirectional circulators**			
	Weak field		**Strong field**[1]	
Central frequency	5.0GHz	10.5GHz	2.55GHz	4.4GHz
BW(%) (|S_{11}|>15dB)	13.5	5.9	5.0	1.5
BW(%) (|S_{11}|>20dB)	4.0	2.9	2.2	0.7
Circulator	**Bidirectional circulators**			
	Weak field		**Strong field**[1]	
Central frequency	5.9GHz	10.7GHz	2.55GHz	4.4GHz
BW(%) (|S_{11}|>15dB)	19.2	3.4	5.0	1.5
BW(%) (|S_{11}|>20dB)	13.6	1.9	2.2	0.7

IV. CONCLUSION

This paper presents the firsts two dual-band circulators working in the weak field zone of the biased ferrite. The operating frequencies of these circulators **are chosen** through a modal study of ferrite resonators. They are perfectly mastered and not undergone as it was the case in [1]. The modal study showed the correlation between the order of appearance of the eigenmodes and the circulation direction. Indeed, by modifying the central conductor, upper modes order has been reversed and so a different circulation direction appeared for the second band. Finally, a comparison of the measurements results with strong-field circulators showed a great improvement of bandwidths.

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