New Concept Validation of Low-Loss Dual-Band Stripline Circulator

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***Abstract*— This paper proposes a new design methodology of dual-band stripline circulator for wireless communications applications. As far as the monoband classic circulator is based on coupling the counter-rotating fundamental modes, the operating principle of dual-band phenomenon is based on studying both fundamental and upper resonant modes within ferrite disks. Electromagnetic (EM) simulations have shown that two categories of dual-band operation could be obtained: simple (unidirectional) and left-handed /right-handed (LH–RH) circulators. The application dedicated to these two original concepts will be discussed, and simulation results will be ensured by the measurement of two prototypes in order to validate the methodology's reliability.**

***Index Terms*— Dual band, ferrite, left-handed/right-handed (LH–RH), modal analysis, radars, unidirectional, upper modes, Y-junction circulators.**

I. Introduction

MICROWAVE circulators have become widely used in wireless communications and radar applications. Their main usefulness is to separate transmit and receive functions when a single antenna is implemented.

Integrating-biased ferrimagnetic material, i.e., ferrite material has become the most popular solution to create nonreciprocity phenomenon within microwave circulators [1]. The ferrite magnetization is basically ensured by inserting permanent magnets in the structure [2], [3]. Otherwise, self-biased ferrites, such as hexaferrites [4], [5] or even ferromagnetic nanowires [6], [7], have also been developed in the last few years, to remove permanent magnets and to reduce the circulator's bulkiness. Furthermore, many circulators topologies were achieved to fulfill different specifications. Indeed, the original circulator analysis was mostly studied in the stripline form and was based on simplified boundary conditions and the Green's function to solve the junction fields [8], [9]. More recently, many papers in the literature show how to enhance stripline circulators in terms of computing accuracy and bandwidth enlargement as in [10] and [11]. Furthermore, the increasing use of MMIC technology in the few last decades induced an exponential growth of microstrip circulators, whose goal is to reduce their cost and size, and facilitate their integration. Thus, microstrip circulator were developed and enhanced in several papers as in [12]–[14]. Moreover, waveguide junction circulators have also been the subject of many papers and were dedicated especially to high-power applications [15]–[17].

Majority of works that have been presented in the literature explored only the fundamental counter-rotating modes of ferrite resonators ($e^{\pm jn\varphi}$), which gave a mono band circulator design. However, some wireless communications applications, such as radars, need to operate in two separated frequency bands [18], [19]. In [20], a dual-band waveguide circulator is proposed working either in a unidirectional way or in a left-handed/right-handed (LH–RH) configuration. Two wireless applications were demonstrated to illustrate the interest of connecting two emission/reception modules, operating at two distinct frequencies, to a single antenna. Good simulation results, issued from two different electromagnetic software solutions, were obtained, but no measurement validation is proposed. Zhang *et al.* [21] presented a dual-band microstrip circulator, which can be tuned to become a mono-band circulator, but without an experimental validation either. As for stripline circulator topologies, dual-band circulators remain a missing subject in the literature. In [22], we have shown that coupling both fundamental modes and the upper ones could involve a dual-band circulation.

This paper tends to complete our previous proposed methodology [22] for developing a dual-band stripline circulator design. As a prove of concept, our work will be based on the analytical modal analysis of ferrite resonators presented in [23]. That will lead to the determination of eigenmodes frequencies according to the dc internal magnetic field H_i. Then, based on the numerical determination of these modes, a complete electromagnetic (EM) and magnetostatic (MS) cosimulation will be developed by exploring both fundamental and upper modes for a simultaneous dual-band circulation, operating at $f_1 = 2.55$ GHz and $f_2 = 4.4$ GHz. Finally, the cosimulation results will be validated for the first time by the design and measurement of two prototypes: simple (Unidirectional) and LH–RH (Bidirectional) dual-band circulators. The main advantage of this paper is to provide a design and a reliable simulation method leading to an immediately operational device, without manual adjustment.

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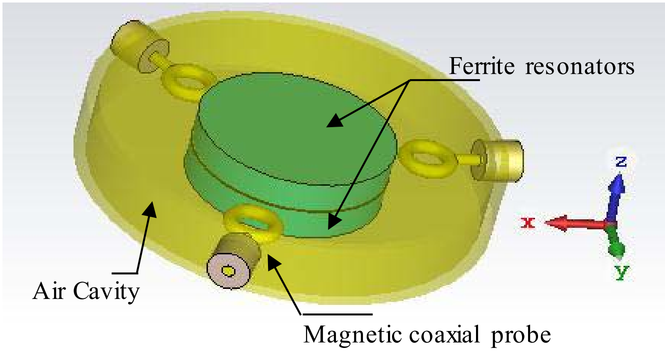

Fig. 1. Numerical model to determine resonant modes in ferrite disks.

TABLE I

RESULTS COMPARISON OF RESONANT FREQUENCIES; FERRITE Y209, FERRITE DISKS RADIUS = 8 mm; FERRITE DISK THICKNESS = 2.6 mm, AIR CAVITY RADIUS = 16 mm; H_i = 180 kA/m

Modes	Analytical [23]	Measurements [23]	Numerical Method
HE_{-11}	2.39 GHz	2.4 GHz	2.47 GHz
HE_{+11}	2.61 GHz	2.7 GHz	2.69 GHz
HE_{-21}	3.85 GHz	3.9 GHz	4.04 GHz
HE_{+21}	4.4 GHz	4.55 GHz	4.54 GHz

II. FIRST STEP: MODAL ANALYSIS FOR DUAL-BAND OPERATION

A. Eigenmodes Numerical Computation

As far as Y-junction circulators have almost the properties of a low-loss transmission cavity, it is necessary to deal with the eigen resonances of the ferrite disks. Inspired from a former paper [23], and based on the boundary conditions depicted in Fig. 1, a numerical method using CST Studio Suite was developed to calculate eigenmode frequencies of the structure (Fig. 1). Indeed, commercial eigenmode solvers do not deal with gyrotropic materials. Considering the stripline topology, ferrite disks are separated by a metal cylindrical film, placed between two ground planes and inserted into an air cavity fed by coaxial magnetic probes.

By reference to modes obtained in [23], the choice was made to operate below the gyromagnetic (GM) resonance. The first step is to identify both fundamental and upper counter-rotating modes required for dual-band circulation, using the numerical method described in Fig. 1. H_i is set at 180 kA/m and the ferrite resonators were considered saturated, and modelized using Polder's Tensor [24].

The obtained numerical resonant frequencies (Fig. 2) are then compared to both analytical and experimental results presented in [23]. The latter were achieved using the measurement system described in Fig. 3. The ferrite samples are inserted into a ring cavity closed by two circular Cu ground planes, and biased with an electromagnet. To optimize the homogeneity of the dc magnetic field, high-permeability material holders are placed on both sides of the ground planes.

Table I shows a good agreement between analytical, numerical, and experimental frequencies. Let us consider that for a given HE_{np} mode in cylindrical coordinates, n denotes the azimuthal variation and p the radial one.

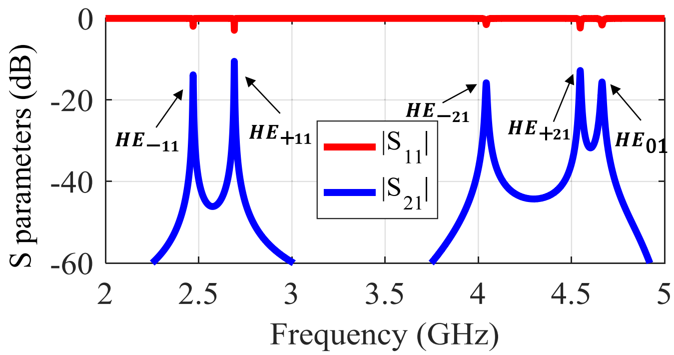

Fig. 2. Numerical result of resonant frequencies for H_i = 180 kA/m; Ferrite type: Y209, $4\pi M_s$ = 900 G; ferrite disks radius = 8 mm, ferrite disk thickness = 2.6 mm, air cavity radius = 16 mm.

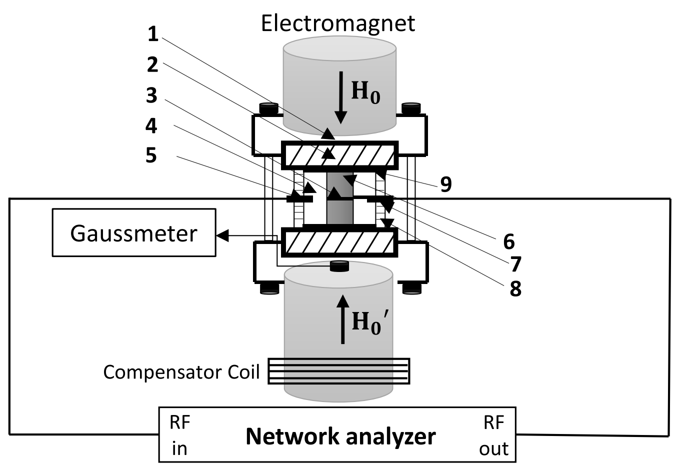

Fig. 3. Measurement system of eigenmodes frequencies. 1: Circular metallic disk, 2: high-permeability material, 3: thin disk conductor, 4: dielectric medium, 5: input probe, 6: ferrite disks, 7: output probe, 8: ring cavity, and 9: Cu sheets as ground planes.

B. Study of the Upper Mode Behavior

1) Influence of to the Internal Field H_i: A set of values of H_i, from 135 to 175 kA/m, were considered to investigate the influence of the dc magnetic internal field on the eigen frequencies of Fig. 2. This paper has shown that the mode HE_{01} (invariant according to ϕ) tends to have a frequency shift greater than the HE_{+21} mode when H_i varies. Indeed, HE_{01} mode is interposed between $HE_{\pm 21}$ modes when H_i decreases, instead of remaining at higher frequencies (Fig. 4). We will see in Section III the influence of this behavior on the circulation direction.

2) Influence of a Dielectric Medium Around Disks: A complementary investigation on resonant frequencies variation led to the determination of another solution to invert the HE_{01} and HE_{+21} modes order. Indeed, if we have a dielectric ring around the ferrite disk (with a close permittivity)

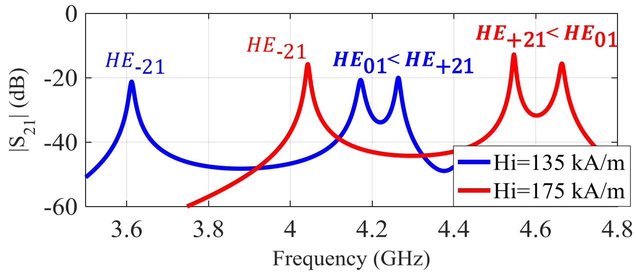

Fig. 4. HE_{01} position according to HE_{+21} as a function of H_i.

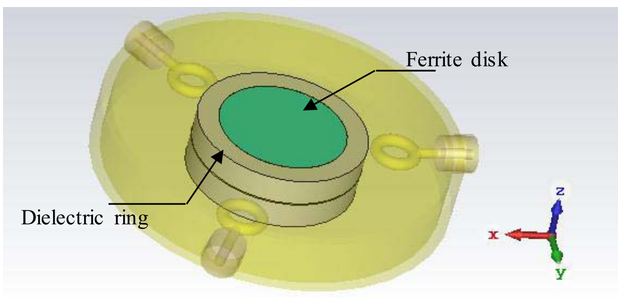

Fig. 5. Numerical model for the modal analysis of ferrite disks surrounded by dielectric rings.

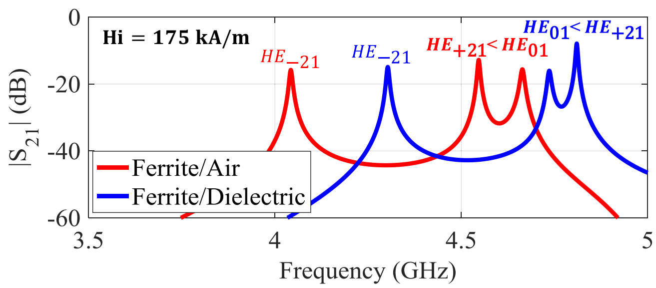

Fig. 6. HE_{+21} position according to HE_{01} as a function of the dielectric medium surrounding the ferrite disks. Ferrite type Y209, $4\pi M_s = 900$ G; ferrite disks radius = 6 mm, dielectric ring external radius = 8 mm, air cavity radius = 16 mm, $\varepsilon_d = 0.85.\varepsilon_f$.

(Fig. 5), we can observe the same phenomenon described in the previous paragraph with a constant value of H_i. The HE_{01} mode is then interposed between $HE_{\pm 21}$ modes. This is due to the greater increase of the resonant frequencies of $HE_{\pm 21}$, whose field patterns are more disturbed than that of HE_{01} (Fig. 6).

III. Second Step: Mode Coupling For Dual-Band Operation

The cavity system depicted in Fig. 1 is now replaced by symmetrical Y-striplines to ensure the impedance matching between ferrite junction and feedlines, necessary to get the circulation phenomenon. The operating distinct frequency bands will be obtained through both fundamental ($HE_{\pm 11}$) and upper $HE_{\pm 21}$ modes determined in Table I.

A. Bidirectional Dual-Band Circulator

A first configuration was made of Y209 Ferrite and has been developed by keeping ferrite disks surrounded by air.

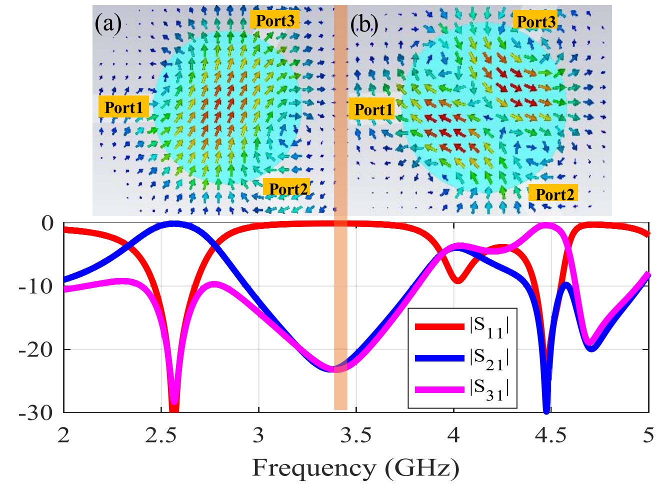

Fig. 7. EM simulation results of bidirectional dual-band circulation. (a) Stationary pattern issued from HE ± 11 modes: H-field is transmitted from port 1 to port 2 and isolated from port 1 to port 3. (b) Stationary pattern issued from HE ± 21 and HE01 modes: circulation's direction is inverted.

H_i was set at 175 kA/m, so that HE_{01} mode is generated above HE_{+21}, as illustrated in Fig. 4. In order to match the two distinct frequency bands, it was necessary to find the appropriate impedance matching network for an ideal coupling of the counter-rotating modes. Considering that we operate below the GM resonance, the central conductor's shape was kept as a filled circular conductor, as mentioned classically in the works of Bosma [8], and the stripline width was optimized numerically. For a stripline width $w = 3.1$ mm, it appeared that not only fundamental modes (HE_{-11} and HE_{+11}), but also HE_{+21} and HE_{01} modes can be easily coupled, simultaneously. Besides, their stationary pattern was inverted comparing to that issued from coupling the fundamental $HE_{\pm 11}$, which provided a bidirectional circulation operation as depicted in Fig. 7. Indeed, from port 1 to port 2, the signal is transmitted at $f_1 = 2.55$ GHz and isolated at $f_2 = 4.45$ GHz.

B. Unidirectional Dual-Band Circulator

To conserve the circulation's direction, EM simulations have also shown that the HE_{01} mode should be generated below HE_{+21}, so that their coupling would make azimuthal modes turning in the same direction as the fundamentals. As mentioned previously, two solutions could be considered: on one hand, the internal field can be decreased until reaching the desired condition, as illustrated by the blue curve of Fig. 4. Otherwise, by inserting ferrite disk into dielectric ring while conserving the same external radius, the two modes were inverted, and the same result was obtained without modifying H_i such that the frequency bands were conserved. EM simulations have led to unidirectional circulation phenomenon at $f_1 = 2.55$ GHz and $f_2 = 4.4$ GHz as well (Fig. 8).

IV. Third Step: Magnetostatic-Electromagnetic Cosimulation

It has already been mentioned that one of the main goals of this paper is to provide a reliable methodology for an immediately operational design without manual adjustment.

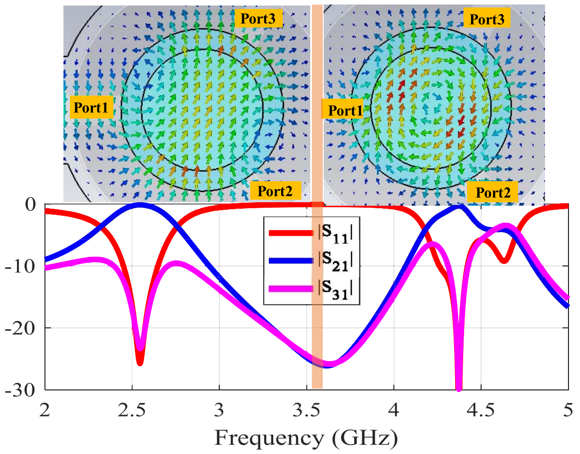

Fig. 8. EM simulation results of unidirectional dual-band circulation. (top) Stationary pattern issued from HE ± 11 modes: H-field is transmitted from port 1 to port 2 and isolated from port 1 to port 3. (bottom) Stationary pattern issued from HE ± 21 and HE01 modes: circulation's direction is conserved.

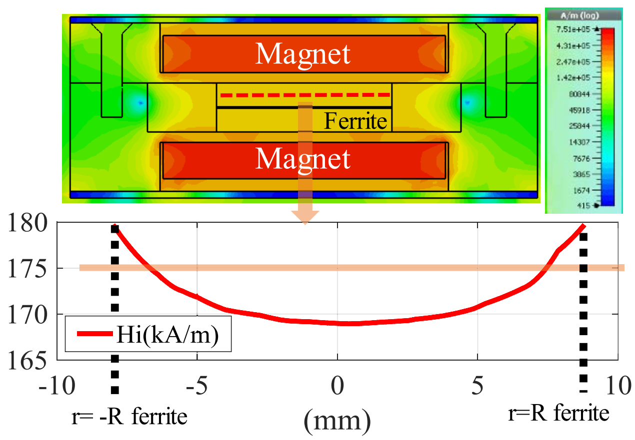

Fig. 9. Numerical determination of required H_i for circulation (as near as possible to 175 kA/m), with an MS study on CST MS solver.

So, before the prototype's manufacturing, we must choose the magnets correctly to obtain an internal field H_i around 170 kA/m in the ferrite disks, while considering the demagnetizing effect. Therefore, among the challenges that should be reached, H_i should be rigorously predicted, owing to the influence that it could have on the HE_{+21} and HE_{01} modes. Thus, a MS study is ensured to determine efficiently the strength and the size of permanent magnets. Indeed, these two parameters should be processed iteratively until the initial value of internal field H_i, required in EM study, is reached as homogenous as possible. After this parametric study, the structure was biased by two Samarium-Cobalt magnets with 0.88 T of residual field. Their diameter is fixed at 27 mm and their thickness was chosen at 3 mm, such that they generate around 240 kA/m of dc magnetic field.

Based on this MS study, the previous EM results are now coupled to the real internal field H_i (Fig. 9) while inserting the permanent magnets and considering the complete mechanical design of the stripline structure (Fig. 10).

TABLE II

SPECIFICATIONS OF THE DUAL-BAND CIRCULATORS' PROTOTYPES

S-parameters		f_1 =2.55 GHz	f_2 =4.4 GHz
$\|S_{11}\|_{dB}$		-20	
$\|S_{21}\|_{dB}$	Simple	-0.2	-0.2
	LH-RH	-0.2	-20
$\|S_{31}\|_{dB}$	Simple	-20	-20
	LH-RH	-20	-0.2

TABLE III

OPTIMIZED PARAMETERS OF THE PROTOTYPES' DESIGN

Parameters	Simple (unidirectional)	LH-RH(bidirectional)
Ferrite radius (mm)	6	8
External dielectric ring radius (mm)	8	/
ε_f	15	
ε_d	12.85	/
H_i (Oe)	MS-EM co-simulation (Fig. 9)	
$4\pi M_s$ (Gauss)	900	
Stripline width (mm)	3.1	

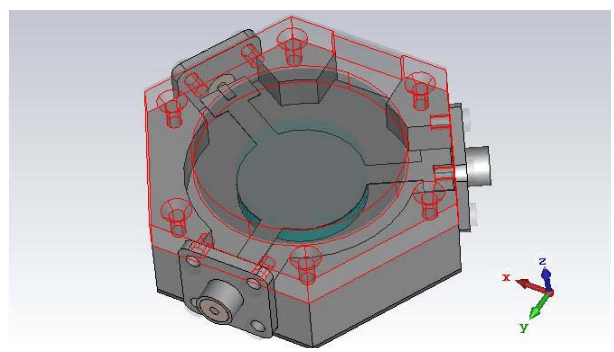

Fig. 10. Complete numerical model after MS-EM cosimulation.

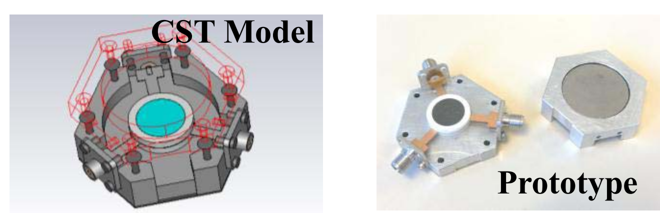

Fig. 11. Prototype manufacturing of the unidirectional dual-band circulator design.

V. EXPERIMENTAL VALIDATION

MS and EM complete cosimulation results have then been validated by producing the design of two prototypes (Fig. 11): unidirectional (simple) and bidirectional (LH–RH) stripline-coaxial circulators, whose specifications are presented in Table II and optimized parameters are summarized in Table III.

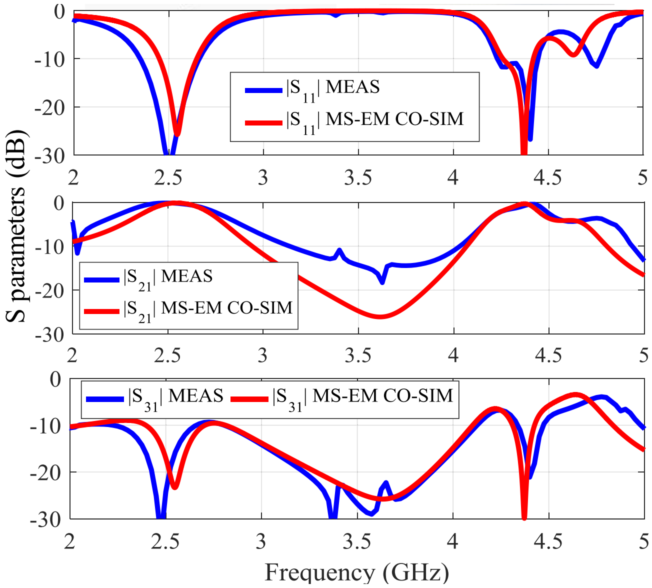

Fig. 12. Experimental validation of dual-band unidirectional circulator prototype.

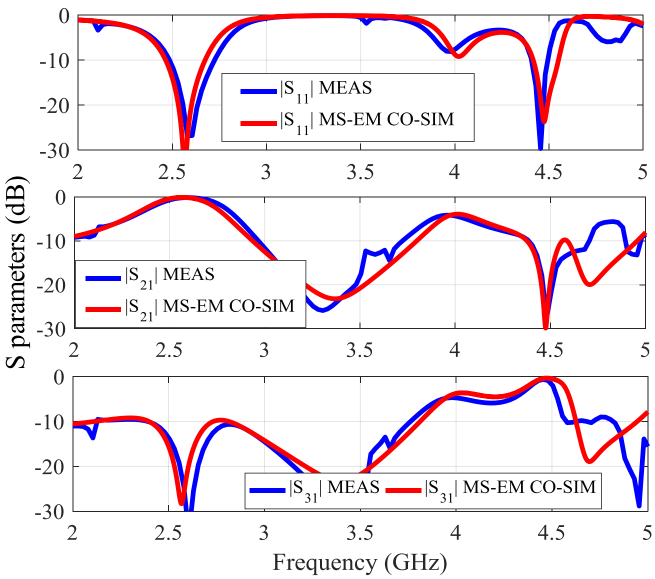

Fig. 13. Experimental validation of dual-band bidirectional circulator prototype.

Fig. 12 shows a very good agreement between our cosimulation and experimental results for the unidirectional dual-band prototype, with an error rate of 3% and insertion losses lower than 0.2 dB.

A good agreement between simulations and measurements is reached for LH–RH dual-band prototype as well (Fig. 13), despite the sensitivity of the upper modes order according to H_i, as seen in the previous simulations results. Low insertion losses of 0.2 dB were obtained, and 20 dB of return losses and isolation were reached as well for both designs, which is near the state of the art. The proposed methodology offers reliable results, without any manual tuning, which represents a great added value for circulators manufacturing, where the optimization of such a device need a lot of expertise and human intervention.

VI. Conclusion

This paper proposed a solution of dual-band stripline circulator by studying both fundamental and upper resonant modes within ferrite disks. First, ferrite resonators' eigen-modes are studied and compared to analytical and measurement results. Second, a complete MS-EM cosimulation is detailed and validated by the measurement of two prototypes, whose performances were obtained without manual tuning. A first experimental validation is then demonstrated in the literature for dual-band circulators, with 0.2 dB of insertion losses and 20 dB of isolation and return losses. This new concept could be a great solution for wireless applications, when two emission-reception systems, operating at two distinct frequencies, are connected to a single broadband antenna.

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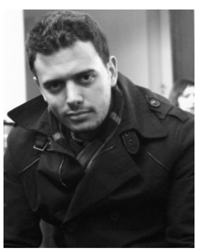

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C. Breuil, photograph and biography not available at the time of publication.