Complete Methodology of Low-loss Ultra-wideband Junction Circulator

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***Abstract*—An ultra-high-bandwidth Y-junction circulator is demonstrated using the "continuous tracking" operation. The analysis is developed starting from Bosma's circulation conditions and based on several previous works that have been investigated in order to complete the methodology and enhance the circulator's performances. Indeed, the broadband junction impedance matching is illustrated and the real inhomogeneous internal field H_i is considered in the electromagnetic (EM) analysis. A complete EM and magnetostatic (MS) co-simulation is presented and validated by experimental results of a prototype operating on the [4.5 GHz-10.5 GHz], i.e. on an 80% of bandwidth. The performances are also compared to the previous works presented in literature in terms of bandwidth and insertion losses.**

***Index Terms*—Tracking circulator, stripline, wideband, EM-MS co-simulations.**

I. INTRODUCTION

Wideband microwave circulators have known a great usefulness in communication systems, since the broadband emission-reception signals needed to be highly isolated. Basically, the broadband circulator design is based on the "continuous tracking" principle discovered by Wu and Rosenbaum [1] and developed and enhanced in several papers as in [2]-[5]. This technique employs the two circulation conditions of Bosma [6], which should be simultaneously solved for ideal circulation, and requires the intrinsic and external junction impedance matching to the largest possible frequency range.

Many attempts have been made to improve electrical performances of wideband circulators but following notions are generally not achieved in literature:

- Insertion losses are approximately around 1-3 dB and considered relatively high for some circulator's applications. Low insertion losses are then required.
- The analysis description is often limited at the determination of only internal junction parameters. The 3-section impedance transformers should be clearly depicted for circulator's designers.
- Experimental curves are always plotted without theoretical results comparison, even though it is necessary to validate the methodology's reliability.
- H_i included in the ferrite tensor's high frequency (HF) modelization is generally admitted as a constant. By assuming thin ferrite disks, it is calculated such that:

$$H_i = H_a - 4\pi M_s \tag{1}$$

where H_a is the applied DC magnetic field and $4\pi M_s$ is the saturation magnetization of ferrite material. This could make the synthesis not perfectly rigorous and could influence the real circulator response.

This paper proposes a detailed design of a wideband stripline circulator, by optimizing the analytical computations' description of the "continuous tracking" technique, leading to a complete EM-MS co-simulation. Finally, the prototype manufacturing process will be detailed and its performances will be compared to numerical results.

II. ANALYTICAL ANALYSIS OF CIRCULATION CONDITIONS

The theoretical scattering matrix of a three-port Y-junction circulator was widely presented, as in [1]-[6].

$$\overline{\overline{S}} = \begin{bmatrix} \alpha & \gamma & \beta \\ \beta & \alpha & \gamma \\ \gamma & \beta & \alpha \end{bmatrix} \tag{2}$$

where α the return loss

β the isolation coefficient

γ the transmission coefficient

An ideal circulation phenomenon involves a perfect isolation at the junction's third access ($\beta = 0$). This condition led to a system of two equations that should be solved simultaneously [1][2]:

$$P = \frac{M(M^2 - 3N^2)}{M^2 + N^2} \tag{3}$$

$$Q = \frac{N(3M^2 - N^2)}{M^2 + N^2} \tag{4}$$

where

$$P = \frac{\psi B_0}{2A_0} + \sum_{n=1}^{\infty} \frac{\sin^2 n\psi}{n^2\psi} \frac{A_n B_n}{A_n{}^2 - (n(\kappa/\mu)x)^2 B_n{}^2} \tag{5.a}$$

$$M = \frac{\psi B_0}{2A_0} + \sum_{n=1}^{\infty} \frac{\sin^2 n\psi}{n^2\psi} \frac{A_n B_n \cos(2n\pi/3)}{A_n{}^2 - (n(\kappa/\mu)x)^2 B_n{}^2} \tag{5.b}$$

$$N = \sum_{n=1}^{\infty} \frac{\sin^2 n\psi}{n^2\psi} \frac{(n(\kappa/\mu)x) B_n{}^2 \sin(2n\pi/3)}{A_n{}^2 - (n(\kappa/\mu)x)^2 B_n{}^2} \tag{5.c}$$

$$Q = \frac{\pi Z_d}{2Z_{eff}} \qquad (5.d)$$

$$A_n = J_n'(kR)$$

$$B_n = J_n(kR)$$

$x = kR\,;\, k = (\omega/c)\sqrt{\mu_{eff}\varepsilon_f}$ the wave propagation constant

R the ferrite radius

$Z_d = 120\pi/(\varepsilon_d)^{1/2}\Omega$; the wave impedance of surrounding medium; ε_d the relative permittivity of dielectric

$Z_{eff} = (\mu_0\mu_{eff}/\varepsilon_0\varepsilon_f)^{1/2}$; the intrinsic wave impedance of ferrite; μ_{eff} effective permeability and ε_f relative permittivity

μ, κ Polder tensor's terms; κ/μ the anisotropy factor of ferrite

ψ the angular stripline width

P, M and N are infinite series, where n denotes the nth eigenmode's order of ferrite resonator. Wu and Rosenbaum [1] showed that retaining terms up to the third order is sufficient for accurate computations of perfect circulations conditions. Solving (3) means to determine the set of solutions' pairs $[x;\kappa/\mu]$, for a given ψ. Indeed, for each value of x, κ/μ is sought from 0 through 1 until (3) is reached (Fig. (1(a)). Then, for each roots' pair $[x;\kappa/\mu]$, (5.d) is explicitly solved to determine the normalized junction impedance ratio Z_{eff}/Z_d (Fig. 1(b)).

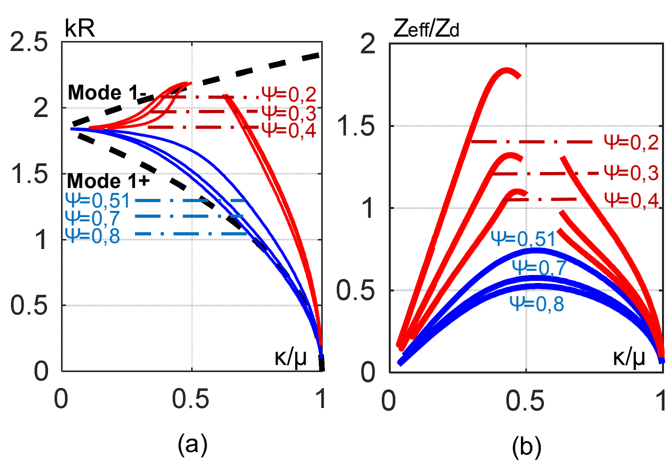

Fig. 1. Roots of the first (a) and second (b) conditions for different values of coupling angle ψ .

In "Fig. 1", the black dashed curves correspond to the roots of the resonance equation [6] for n=1.

$$[J_n'(x) - (n/x)|\kappa/\mu|J_n(x)] \\ .[J_n'(x) + (n/x)|\kappa/\mu|J_n(x)] = 0 \qquad (6)$$

Conditions depicted in "Fig. 1" represent a fundamental graphic tool to design a wideband Y-junction circulator, as far as the first one gives the ferrite resonator's radius according to the frequency, and the second gives the appropriate dielectric permittivity of the surrounding medium according to the ferrite intrinsic impedance. This will be discussed in the next sections.

III. Continuous Tracking Operation Description

The junction impedance ratio can also be determined as a function of κ/μ by computing directly the wave impedances in both ferrite and dielectric mediums, such that:

$$Z_d/Z_{eff} = (\varepsilon_d/\varepsilon f)^{1/2}/(1-(\kappa/\mu)^2)^{1/2} \qquad (7)$$

where $(1-(\kappa/\mu)^2)$ is the approximation of μ_{eff} in the weakly magnetized ferrite case.

The main operation of the tracking circulator is to find the appropriate compromise between ferrite-dielectric permittivity and the stripline coupling angle ψ in order to superpose the two conditions (5.d) and (7).

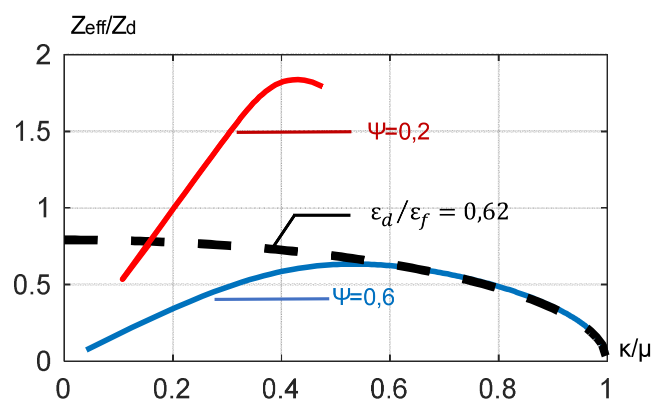

Fig. 2. Example of the tracking technique by superposing the junction impedance ratio issued from both (5.d) and (7), for chosen ε_f , ε_d and Ψ .

"Fig. 2" shows that two assumptions should be considered: On one hand, tightly coupled resonators (Ψ<0.5) cannot satisfy the tracking solution, because of the missing roots for $0.5 < \kappa/\mu < 0.6$ (Fig. 1). On the other hand, this technique is achieved only for weakly magnetized ferrite case (modes above the gyromagnetic resonance), where the ferrite anisotropy is high ($\kappa/\mu > 0.5$) and both impedance ratio curves have a negative slope. Since these two conditions are considered, a broadband impedance matching can be reached, as far as κ/μ is a frequency-dependent quantity. Indeed, in the weakly magnetized ferrite case, $|\kappa/\mu|$ is approximated by f_m/f, where f_m is the gyrotropic frequency defined as $f_m(\text{MHz}) = 2{,}8.4\pi M_s(\text{G})$. This means that a bandwidth of $[f_m; 2f_m]$ can be achieved where the tracking technique is ensured for $0.5 < \kappa/\mu < 1$.

IV. Wideband Circulator Design

By means of the previous graphical tools, the design of a wideband stripline circulator becomes an easy task. Indeed, the first step is to choose the ferrite material such that the center circulator frequency $f_0 \approx 3/2.f_m$. Then, ψ and ε_d are sought, according to ε_f until the curves overlap is reached for the largest possible κ/μ range, as depicted in "Fig. 2". The next step is to locate the abscissa relative to the first intersection point of κ/μ. Once the operating point is specified, the ferrite disk radius can be then determined by using plots of condition (3) (Fig. 1(a)). The final step is to match the input impedance junction, imposed by the chosen ψ and ε_d, to 50Ω by means of a 3-sections quarter wavelength transformers [7].

Considering the previous theoretical study, a stripline circulator was designed to be operating on the [4.5 GHz-10.5 GHz] frequency band (80% of bandwidth), with the EM numerical tool CST Microwave Studio [8]. The complete design is presented in "Fig. 3" and its parameters are detailed in Table I.

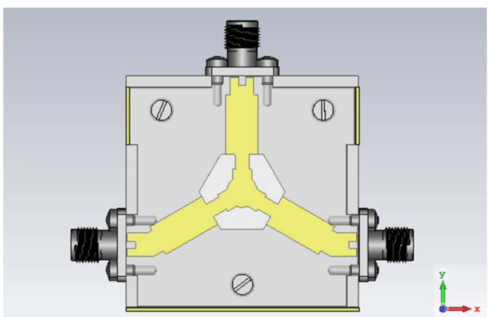

Fig. 3. Top view of the final wideband circulator design.

TABLE I
Wideband Circulator Design's Parameters

Parameters	Values
$4\pi M_s$ (G)	1820
ε_f	15
ε_d	9.4
R(mm)	2.7
ψ (rad)	0.63
$Z_1(\Omega)$	18.89
$Z_2(\Omega)$	23.09
$Z_3(\Omega)$	40.07
$Z_L(\Omega)$	50
H_i (Oe)	150

Furthermore, a rigorous MS study is developed by the MS solver of [7], to obtain the real distribution of the inhomogeneous internal field H_i. Thus, magnet's selection and sizing are done iteratively until a good agreement with this initial value of H_i is obtained (Fig. 4). After parametric magnetostatic study, the device was biased with two 9-mm-diameter magnets generating around 1500 Oe of applied magnetic d-c field.

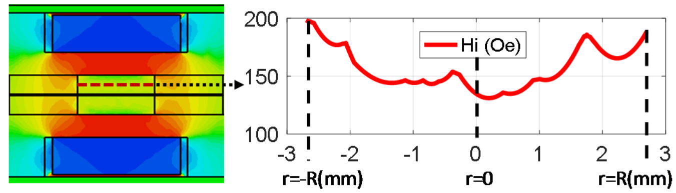

Fig. 4. Magnetostatic study to determine the appropriate internal field fixed in Table I, as homogeneous as possible.

Finally, the complete structure is designed while considering all mechanical constraints and its performances are obtained thanks to a magnetostatic and electromagnetic co-simulation. To validate this design procedure, a prototype is realized and its performances are compared to the simulations (Fig. 5).

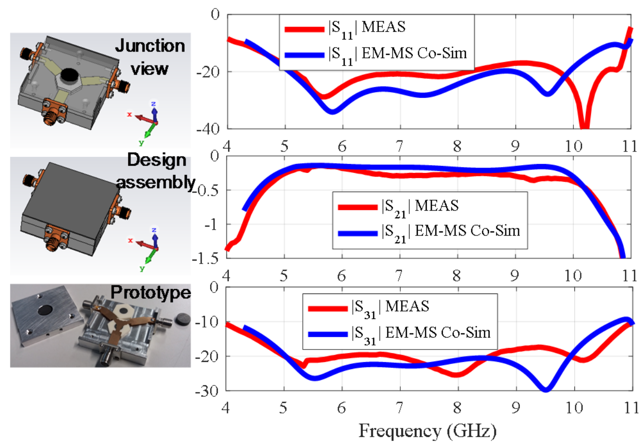

Fig. 5. Results of the wideband circulator prototype: EM-MS Co-Simulations vs Measurements

Measurements results plotted in "Fig. 5" show a good agreement with the co-simulation presented in this section. These experimental results were immediately obtained, without any manual adjustment, which can prove the methodology's reliability. 0.37 dB insertion losses were obtained all over the frequency bandwidth, which remains relatively low comparing to previous works presented in literature [1]. 18 dB return losses and isolation were reached as well.

V. Conclusion

This paper proposes a complementary description of the "continuous tracking" circulators, by analyzing the circulation conditions of Bosma [6] and processing the broadband impedance matching proposed by Wu and Rosenbaum [1]. A complete EM-MS co-simulation is then presented for a wideband stripline circulator having 80% of bandwidth and 0.37 dB low insertion losses. Comparison of theoretical and experimental results have showed a good agreement, and proved then the method's accuracy.

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REFERENCES

[1] Y. S. Wu, F; J. Rosenbaum, «Wide band operation of microstrip circulators», IEEE Transactions on Microwave Thoery and Techniques., vol. WIT-22, pp. 849-856 ct. 1974.

[2] S. Ayter, Y. Ayasli, «The frequency behavior of stripline circulator junctions», IEEE IEEE Transactions on Microwave Thoery and Techniques, Vol.26, NO. 3, March 1978.

[3] J. Helszajn, «Operation of tracking circulators», IEEE Transactions on Microwave Thoery and Techniques, Vol.29, NO. 7, July 1981.

[4] J. Helszajn, «Synthesis of octave-band quarter-wave coupled semi-tracking stripline junction circulators», IEEE Transactions on Microwave Thoery and Techniques, vol. 43, 3, March 1995.

[5] P.Krivic, G.Radosavljevic, S.Birgermajer, N.Cselyuszka, H.Arthaber, «Design and fabrication of the Bosma stripline circulator in LTCC technology», 2015 IEEE International Conference on Microwaves, Communications, Antennas and Electronic Systems (COMCAS), Tel Aviv, Dec.2015.

[6] H. Bosma, «On Stripline Y-circulation et UHF», IEEE Transactions on Microwave Thoery and Techniques, Vol.12, pp.61-72, Jan 1964.

[7] R. E. Collin, «Foundation for Microwave Engineering», second edition, The IEEE Press Series on Electromagnetic Wave Theory, Donald G. Dudley, Series Editor.

[8] CST Microwave Studio, www.cst.com