Methodology to Develop a Low-loss Dual-band Stripline Circulator

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***Abstract*— A design procedure of a dual-band stripline circulator has been developed by studying resonant modes within ferrite disks. Electromagnetic (EM) analyses have shown that it is possible to couple simultaneously both fundamental and upper modes in order to obtain a circulation's operation at two distinct frequency bands. Detailed EM simulations and measurement are presented and applications related to such a dual-band device are discussed.**

Keywords—ferrite; stripline circulator; resonant modes; Mono Band; Dual-Band.

I. Introduction

In the last few years, ferrite circulators have proved their great usefulness in several microwave systems. Indeed, many wireless telecommunication systems like radar duplexers, mobile telephony or satellite links need to have «emission-reception» modules while using a single carrier wave.

The three-port version of ferrite junction circulator, usually called Y-Junction circulator, is the most common nonreciprocal device in literature. Early experimenters [1][2][3][4] have explored the specific behavior of the electromagnetic wave's propagation in ferrite material to create the nonreciprocity phenomenon. Indeed, by applying a d-c magnetic field to a ferrite disk, according to its z-axis, each resonant mode is split into two counter-rotating modes (fields varying as exp(nφ)), which form a stationary pattern such that EM wave is coupled in one port and isolated in the other one. Several papers [1]-[4] have dealt with theory of Y-junction circulator operating at n=1, which gave a mono band circulator design.

Furthermore, some Telecommunications' applications need to operate in two separated frequency bands. In a recent paper [5], good simulations' results were obtained for a waveguide dual-band circulator, but no research on stripline-coaxial dual-band circulator has been presented in literature.

This paper is proposing a complete methodology based on a magnetostatic and electromagnetic co-simulation to design a low-loss and low-cost stripline dual-band circulator. In order to well understand this methodology, we will firstly explain the design of a monoband circulator working at [6-6.5] GHz, validated by the measurement of a prototype. Based on these successful results, we will present a new approach based on coupling both fundamental and upper modes within ferrite resonators leading to the conception of a Dual-Band Circulator. In this framework, two classes of Dual-Band principle are discussed: unidirectional (simple) or bidirectional (LH-RH: Left-Handed Right-Handed) circulator. Such an operation could have a great interest in Radar applications [5], to uncouple « emission-reception » modules connected to a single antenna as presented in Fig. 1.

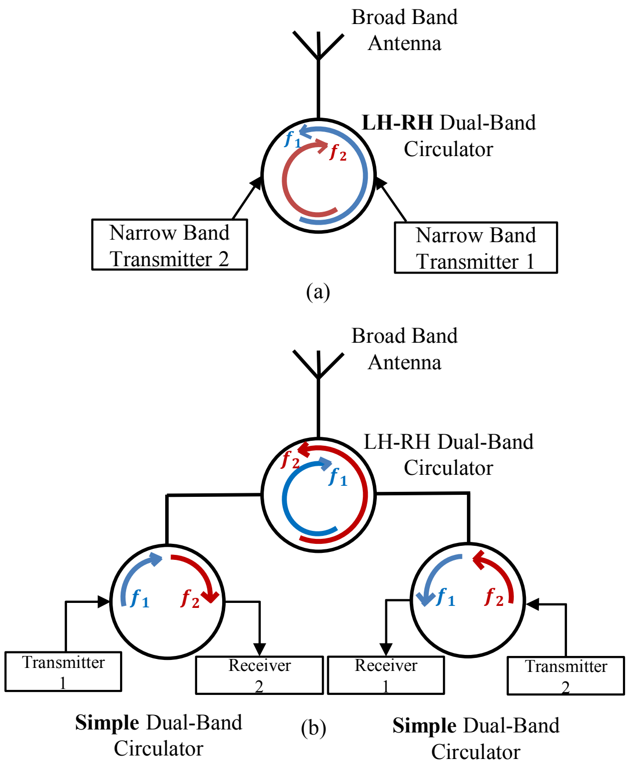


Fig. 1. Schematic diagram of two RH-LH or/and Simple Dual-Band Circulators' applications in R-F.

II. General Properties of Ferrite in High Frequency

Ferrite materials have a specific behavior in high frequency due to their magnetic features. In order to provide nonreciprocity phenomena, the ferrite shape is biased by a magnetic field H_0 along the z axis and its permeability tensor is given in high frequency by the equation (1) [6].

$$\mu = \mu_0 \overline{\overline{\mu_r}} = \mu_0 \begin{bmatrix} \mu & -jk & 0 \\ jk & \mu & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (1)$$

In the saturated case, μ and k are functions of the internal field within the ferrite material H_i, the saturation magnetization M_s and the frequency f. The evolution of real and imaginary parts of these elements according to the frequency describes the gyromagnetic (GM) resonance (Fig. 2). As far as circulators operate far from this zone, two distinct modes of operation are discussed: below-resonance et above-resonance circulators.

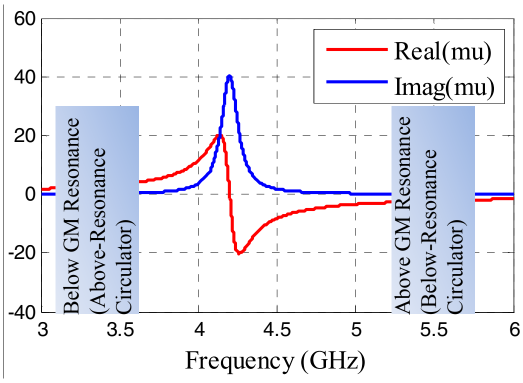


Fig. 2. Real and Imaginary parts evolution of μ versus frequency

III. Resonant Modes within Ferrite Material

The analysis of resonant modes is based on the stripline structure shown in Fig. 3. The ferrite disks, placed between two ground planes and separated by a thin circular center conductor are axially magnetized. The theoretical aspects of analytical modal analysis related to such a structure have been investigated in several papers [1]-[3].

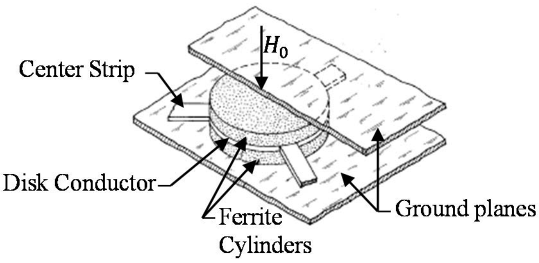


Fig. 3. General topology of stripline circulator

Bosma's theory [1] is using simplified boundary conditions and is giving a good approach of Transverse Magnetic (TM) modes, independent of the z axis. Otherwise, a more rigorous analytical method was studied in [7] by computing fields in both ferrite disk and dielectric ring surrounding it, with taking into account the boundary conditions at the ferrite-dielectric interface as depicted in Fig. 4. TM but also Hybrid modes (HE) were obtained, for both fundamental and upper orders, and good agreement with measurements was ensured both below and above resonance as presented in Fig. 5 (a) and Fig. 5 (b) respectively.

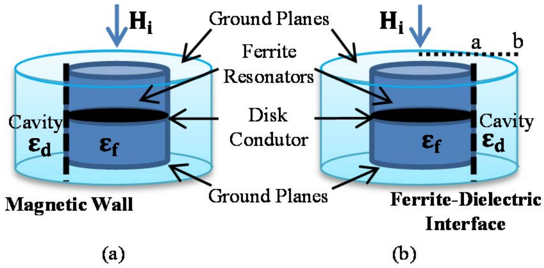


Fig. 4. Boundary conditions for computing EM fields in Ferrite Resonators: (a): Bosma's Assumption [1]; (b): Rigorous Method [7]

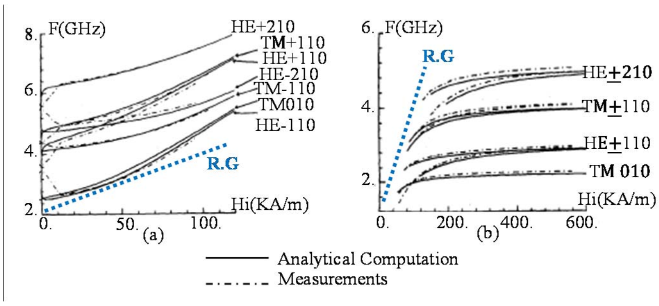


Fig. 5. Below (a) and Above (b) resonance modes frequencies versus Hi: Analytical Rigorous Study vs Measurements; Ferrite **Y209** ; a=8mm, b=16mm, $\varepsilon_d = \varepsilon_0$ [7]

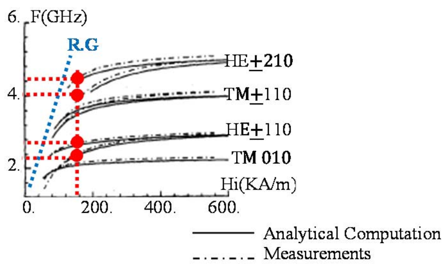
A. Below-resonance modes

In this case, the applied magnetic d-c field could be weak enough to imply that ferrite disks are unsaturated. Computations are then made by using an unsaturated tenor's model [8] and the resonant frequencies dependence of H_i is plotted in Fig. 5 (a).

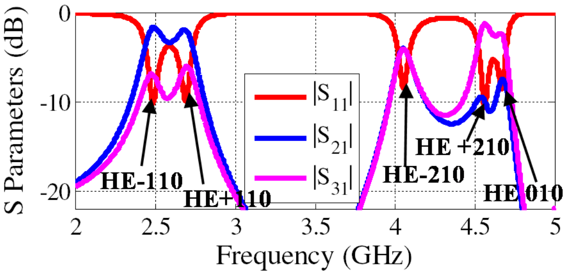
B. Above-resonance modes

Considering that ferrite disks are biased with a high magnetic field, they are supposed to be magnetized to saturation. Thus, resonant frequencies are calculated using Polder's tensor [9]. Theoretical curves versus H_i, compared to experimental results, are presented in Fig. 5 (b).

Based on these analytical results, we used electromagnetic simulations (CST Microwave Studio [10]) for a given internal field H_i to retrieve and identify resonant modes. Let's consider the above-resonance case (Fig. 6) with H_i equal to 180 KA/m (≈2260 Oe) and the geometric parameters given in Fig. 5.



(a)



(b)

Fig. 6. (a): Theoritical resonant modes frequencies for Hi=2260 Oe (b): Numerical resonant peaks for Hi=2260 Oe on CST Microwave

Fig. 6 shows that resonance peaks are in good agreement with theoretical HE modes for $H_i = 2260\ Oe$. It appears that only these modes are generated. Indeed, TM modes determined by Bosma's theory are based on the magnetic wall assumption at the ferrite-air interface, which is not the case in reality. Magnetic r-f fields were plotted at each frequency to identify the modes (Fig. 7). Let us consider that for a given H_{np} in cylindrical coordinates, n denotes the azimuthal variation and p the radial one.

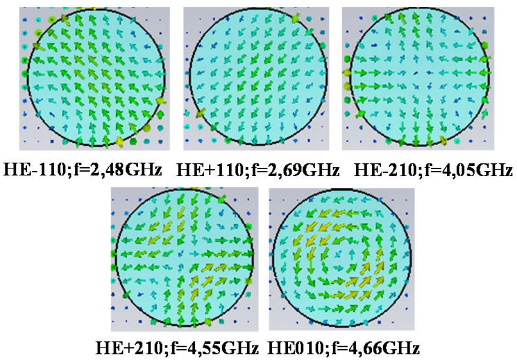


Fig. 7. H Field plots for each mode frequency: Identification of HE Modes

Whatever the resonance position, having a circulation phenomenon on only one frequency band is mostly obtained by coupling both HE_{+110} and HE_{-110} fundamental modes. This will be the topic of the next part while the part V will present the coupling of higher modes to have a Dual-Band Circulator.

IV. Mono Band Circulation's Operation

In previous sections, we have shown that the circulation's phenomenon is based on the analysis of eigen modes within ferrite material. For the moment, let us consider that only fundamental modes are coupled to give a mono band circulation, which was the subject of several investigations [1][2][3]. These researches have used analytical approaches allowing to obtain Ferrite disks and feed striplines' dimensions. A new home-made conception procedure was developed to explore the eigen modes by EM simulations and led to a complete design of monoband circulator without any manual adjustment. For a given frequency range, ferrite material should be selected and dimensioned, and the value of the internal field H_i is fixed according to the gyromagnetic resonance's position.

The identification of HE_{+110} and HE_{-110} fundamental modes is then investigated (Fig. 8).

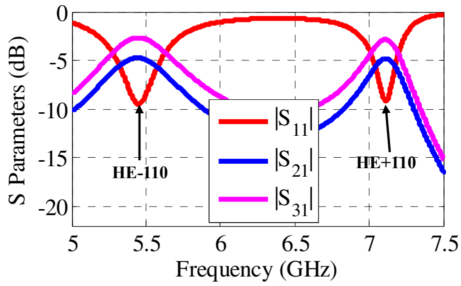


Fig. 8. Fundamental modes of a stripline circulator based on ferrite disks. Ferrite material: **Y39** ; R_Ferrite=4.7 mm ; H_Ferrite=1.5mm.

The interest of fundamental modes' identification is to check that no upper mode is intercalated between them, so that they could be easily coupled. The next step is to satisfy impedance conditions to couple ferrite disks with transmission striplines. Once r-f simulations are done, the initial value of internal field H_i fixed previously should be determined by a rigorous magnetostatic study. Thus, magnet's selection and sizing are done iteratively until a good agreement with this initial value of H_i is obtained. Finally, the complete structure is designed while taking into account all mechanical constraints. To validate this design procedure, a prototype has been realized in the [6-6.5] GHz band. The circulator prototype and its performances are presented in Fig. 9.

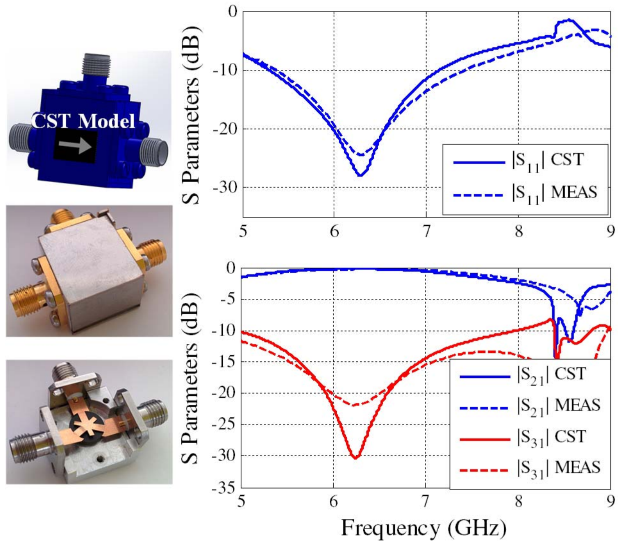


Fig. 9. Results of Mono Band Circulator: Simulations Vs Measurements

Measurements' results plotted in Fig. 9 show a good agreement with EM Simulations without any manual adjustment, which presents a great added value for ferrite circulator's industry.

For the moment, only fundamental modes are supposed to be coupled, providing then a single-band circulation phenomenon. In this section, we will prove that in a specific configuration, it is possible to couple simultaneously both fundamental and upper modes, which allows a dual-band circulation's function.

V. Dual-Band Circulation's Operation

To avoid intersection between fundamental and upper modes as shown in Fig. 5, the choice of the dual-band circulator's development was made for above-resonance case, in which the fundamental modes are adjacent and well separated from upper ones (Fig. 5 (b)). Such a configuration is obtained due to the low anisotropy factor related to the high applied d-c magnetic field. A parametric study of the internal field H_i has shown that the HE_{01} mode (invariant according to φ) tends to be intercalated between the $HE_{\mp 210}$ modes for values of $H_i < 2100\,Oe$. By ensuring a good impedance matching condition between ferrite disks and feeding lines, having the HE_{01} mode between the two $HE_{\mp 210}$ modes involves a simultaneous circulation function at $f_1 = 2.4\,GHz$ and $f_1 = 4.4\,GHz$.

A. Bidirectional dual-band circulator

A first configuration was made of YIG Ferrite and has been developed by keeping ferrite disks surrounded by air. The internal field H_i was set at 2000 Oe. When coupling upper modes, they showed an inverted azimuthal polarization comparing to the first ones, which provided a bidirectional circulation function, as shown in Fig. 10. This could be useful in the case where two transmitters having two distinct carrier frequencies are connected to a single antenna for radar « LH-RH » applications [5] (Fig. 1).

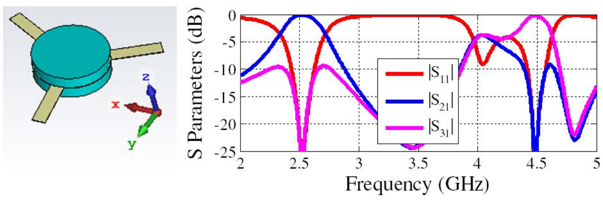


Fig. 10. Simulation Results of bidirectional dual-band stripline circulator, $\varepsilon_d = \varepsilon_0$

B. Unidirectional dual-band circulator

It is also possible to conserve the direction of circulation by making azimuthal modes turning in the same way for both fundamental and upper modes. This configuration was obtained by inserting dielectric medium around ferrite disks and the same approach was followed. A unidirectional circulation phenomenon was then achieved at $f_1 = 2.4\,GHz$ and $f_1 = 4.4\,GHz$ (Fig. 11).

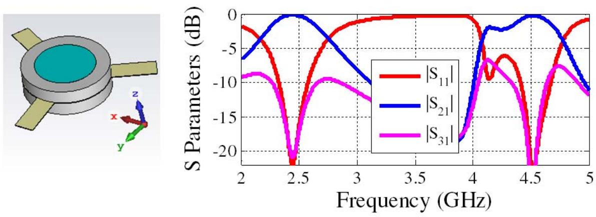


Fig. 11. Simulation Results of uniidirectional dual-band stripline circulator, $\varepsilon_d = 14.\varepsilon_0$

VI. Conclusion

This paper proposed a solution of dual-band Stripline Circulator by studying resonant modes within ferrite disks. Firstly, ferrite resonators' eigen modes have been studied and compared to analytical and measurement results. Then, a complete design of a mono band circulator is summarized and validated by a prototype's realization. Moreover, EM analysis have shown that for the above-resonance case, fundamental modes are adjacent due to the high anisotropy factor of ferrites, and well separated from upper ones. Thus, two separated narrow bands were obtained.

These results are being investigated by realizing a complete prototype of Dual-Band Circulator in order to validate simulations performances.

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