

New Concept of Dual-Band Microstrip Ferrite Circulator Based On Wideband Configuration

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Abstract — This paper presents a new concept of dual-band ferrite circulator offering a significant bandwidth improvement. Dual-band circulators described in the literature have previously been based on the first two pairs of resonant modes in ferrite cavities to achieve circulation at two distinct frequencies. Here, this new concept proposes using only the first pair of modes of a wideband single-band circulator resonator. The dual-band function is achieved by optimizing the matching around the two desired frequencies. This method is applied to the design of a dual-band circulator operating at 5 and 7.5 GHz. Prototype measurements show a significant bandwidth improvement compared to the literature. The measured bandwidths of the prototype are 12.6% and 17.9%, respectively.

Keywords — Circulator, dual-band, ferrite, Y-junction circulators, wideband.

I. INTRODUCTION

This article presents a new dual-band circulator concept. Dual-band circulators are a recent topic in the literature. A first concept using stripline technology [1] was presented in 2018 with weak circulation bandwidths and an unselected gap between the two operating frequencies. In 2020, a method allowing the selection of two circulation frequencies was developed, enabling the design of a circulator operating with isolation greater than 20 dB around 5 and 10 GHz [2]. To achieve miniaturization, a microstrip version [3] was proposed in 2023. Nevertheless, performance in terms of bandwidth for these circulators is still limited. Indeed, bandwidths with 20 dB isolation are 5.5% around 5 GHz and 2.8% around 10 GHz in [2]. These bandwidths are narrower than those of commercial single-band circulators, which are around 10-20% [4] for narrow-band models and up to 100% [4] for wide-band models, generally reducing isolation levels.

To achieve a circulation, passive circulators generally use ferrite materials. Ferrites are ceramics with high permittivity. Their main characteristic, when biased by a static magnetic field, is their anisotropy. This anisotropy leads to counter-rotating mode pairs in ferrite cavities. It is the pair of modes coupling that enables the circulation function.

Dual-band circulators described in the literature ([1]-[3]) use the principle of upper mode coupling to obtain a second circulation band. Indeed, in the circulators in [1]-[3], the pair of fundamental modes is used to obtain a first circulation band. To obtain a second circulation band, upper modes are used.

The new dual-band circulator concept presented in this article consists of using a wide-band circulator configuration

([5]-[7]) and optimizing the matching around the two desired frequencies. This method allows sub-bands that are much wider than those obtained using upper modes. This paper presents this new method and its application to the design of a dual-band circulator with sub-bands centered at 7.5 GHz.

The design method is described, first with the design of the ferrite resonator. A description of the matching circuit is also provided. A simulation of the entire circulator completes the design. A prototype was built and measured. The measurements are compared to simulations and to dual-band circulators described in literature. These new results present sub-bands of 17.9% for the first and 12.6% for the second, which are significantly better than the results of previous dual-band studies [1]-[3].

II. CIRCULATOR DESIGN

A circulator consists of several parts. Fig. 1 shows an overview of these parts for a microstrip configuration [3]. The central part, the resonator, consists of a ferrite disk and a central conductor. The circulator's operating frequencies are determined by this part. Indeed, resonant modes in this cavity are responsible for the circulation phenomenon. The second part of the device includes the substrate surrounding the ferrite and the access lines connected to the resonator. In this design, the substrate chosen is a 0.6 mm-thick alumina. Microstrip lines provide coupling between counter-rotating modes of the resonator and ensure impedance matching to the 50 Ω ports. Permanent magnets are another key component of this circulator. Indeed, to obtain its anisotropic properties, the ferrite must be biased by a static magnetic field.

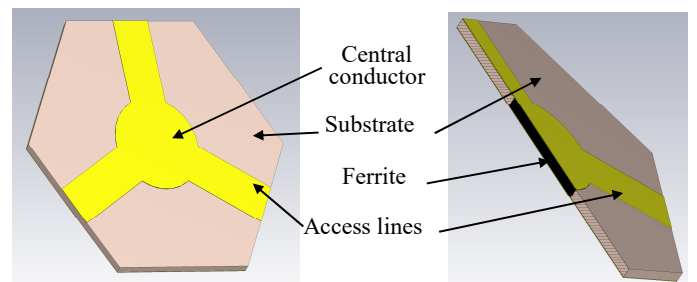


Fig. 1. Schematic view of a microstrip ferrite circulator

The new dual-band circulator concept is based on the topology shown in Fig. 1. The design details for each part are provided in the following sections.

A. Ferrite resonator definition

Design process begins with the ferrite resonator. In paper from the literature on dual-band circulators ([2], [3]), the method used to adjust the two operating frequencies consisted of modifying the shape of the central conductor. In this work, only the pair of fundamental modes is used to achieve dual-band operation. Therefore, the configuration must maximize the frequency gap between these two modes.

Work based on an ultra-wideband circulator using J. Helszajn's "semitracking" method [8] allows achieving this configuration. Paper [8] shows the design of a circulator with 100% bandwidth, the following conditions are required:

$$H_i = 0 \quad (1)$$

$$|\kappa/\mu| = 0,75 \text{ à } f = f_c = (f_{min} + f_{max})/2 \quad (2)$$

$$f_{max} = 3 \times f_{min} \quad (3)$$

H_i is the internal static magnetic field in ferrite, κ/μ the anisotropy factor, and f_c the operating frequency. Here, main goal is to design a dual-band circulator, the center operating frequency thus corresponds to the average frequency between the two operating frequencies : 5 and 7.5 GHz. Thus, the central frequency is 6.25 GHz and, according to (1-3), the corresponding frequencies f_{min} and f_{max} are 3.125 GHz and 9.375 GHz.

The ferrite configuration closest to the criterion in [8] using commercially available ferrites is as follows: Saturation magnetization $M_s = 1600$ G, permittivity $\epsilon_r = 14.8$, internal field in ferrite $H_i = 50$ Oe.

This configuration provides an anisotropy factor value of 0.75 at 6.1 GHz, which is close to the center frequency goal of 6.25 GHz. Fig. 2 shows the curves of effective permeability and anisotropy factor as a function of frequency, using Polder's permeability tensor [9].

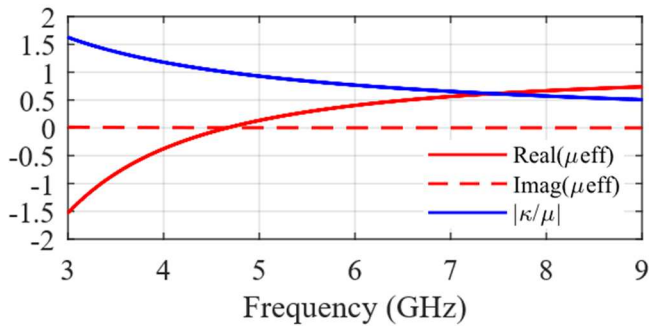


Fig. 2. Effective permeability and anisotropy factor as a function of frequency

Similar to a wideband circulator, the central conductor is a disk with the same diameter as the ferrite disk ([6], [7]). To determine the radius of the ferrite disk, a modal study is carried out. This step is performed using a numerical method and electromagnetic simulations. Three access lines are positioned facing the resonator, with a gap of 100 μm between them [3]. This configuration allows weak excitation of the counter-rotating modes of the ferrite resonator ([2], [3]). A ferrite radius is selected such that the first fundamental pair of modes lies between f_{min} and f_{max} . This ferrite disk radius is 3.5 mm, and the corresponding simulated S-parameters are shown in Fig. 3.

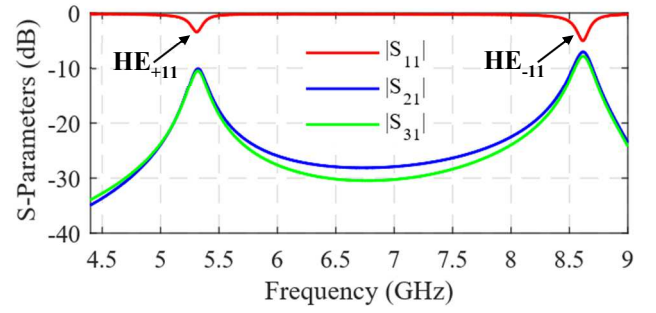


Fig. 3. Simulated S parameters from Fig. 3 model

B. Matching circuit definition

As in [2] and [10] and papers, the second step in the design process is to size the access lines and a matching circuit. This allows a coupling between counter-rotating eigenmodes and impedance matching to 50 Ω . The same method as described in [10] is used. Therefore, impedance Z_0 is calculated as a function of frequency. Z_0 refers to the impedance value that should be applied to the three access of the resonator to achieve an ideal circulation phenomenon [10]

Using a de-embedding method described in [10], the value of Z_0 is calculated as a function of frequency (Fig. 5).

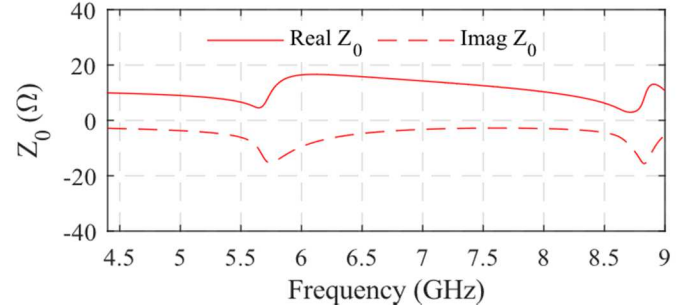


Fig. 4. Impedance Z_0 to be applied to the resonator for ideal matching

In order to obtain a circulation function around 5 and 7.5 GHz, it is necessary to apply the impedance Z_0 corresponding to these two frequencies to the three access points of the resonator. A matching circuit from Z_0 to 50 Ω was therefore designed. This matching circuit was dimensioned by numerical optimization using simulation software. The circuit, consisting of three line sections shown in Fig. 5.

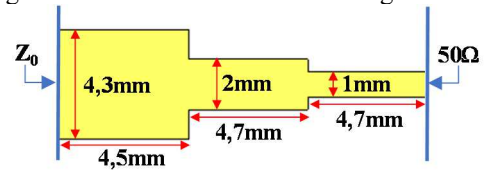


Fig. 5. Matching circuit from Z_0 to 50 Ω at 5 and 7.5 GHz.

These matching sections are added to the three resonator ports. Fig. 6 shows the model of the 50 Ω matched circulator on an alumina substrate.

The structure shown in Fig. 6 was simulated. The S-parameters are presented in Fig. 7. They show broadband transmission and high isolation around 5 and 7.5 GHz, with levels greater than 20 dB.

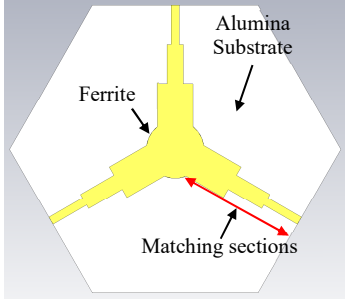


Fig. 6. 50 Ω matched circulator on alumina substrate.

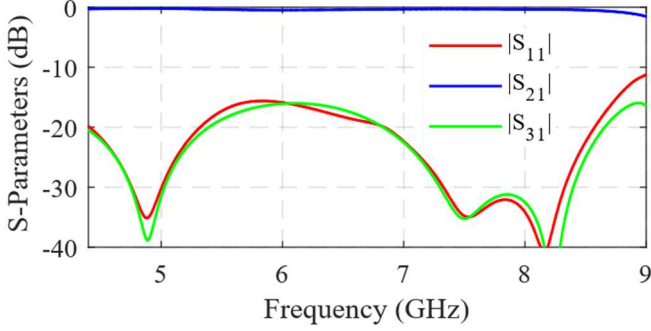


Fig. 7. Simulated S-parameters from Fig. 6 circulator

C. Final design and co-simulation

The simulations Fig. 7 were performed assuming a uniform static magnetic field inside the ferrite and with a value of 50 Oe. In practice, the ferrite are biased by permanent magnets. The static magnetic field inside the ferrite is therefore not uniform and is affected by edge effects. To design the magnets and take these edge effects into account, a magnetostatic study of the structure was carried out ([2], [3]). Two identical magnets are positioned on both side of the structure (Fig. 8). A magnet configuration providing the most uniform 50 Oe field possible in the ferrite is found using magnetostatic simulation. The corresponding magnets have a remanence field B_r of 4300 G, a radius of 4.4 mm, and a height of 5 mm.

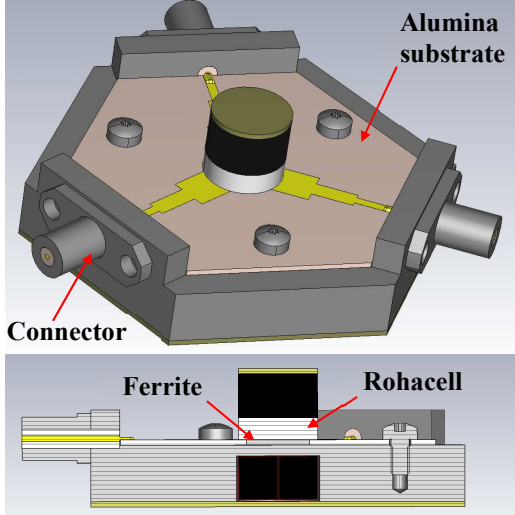


Fig. 8. Comprehensive model of a connectorized microstrip ferrite dual-band circulator

The 3D model of the entire structure is shown in Fig. 8. This model includes a base plate and connectors. The structure shown in Fig. 8 was co-simulated with magnetostatic-electromagnetic (MS-EM) simulation. This co-simulation takes into account the non-uniformity of the internal static magnetic field and therefore of the ferrite's permeability in the electromagnetic simulation. The S-parameters of this simulation are presented in Fig. 10.

The co-simulated S-parameters from Fig. 10 clearly show a dual-band operation. The isolation is greater than 20 dB from 4.6 to 5.4 GHz and from 7 to 8.7 GHz. Furthermore, for broadband operation and assuming minimum isolation and matching of 15 dB, the bandwidth is nearly 70%, which is ultra-wideband.

III. PROTOTYPING, MEASUREMENTS, AND PERFORMANCES COMPARISON

A prototype of the circulator shown in Fig. 8 has been produced, the substrate consists of a ferrite-alumina assembly. Both sides are fully metallized with a thin layer of gold (4 μm thick). The pattern on the top side is etched using laser ablation using an LPKF laser prototyping machine, the LPKF ProtoLaser U4. Fig 9 shows the fabricated prototype. The circulator was measured in a connectorized setup using a 4-port vector network analyzer.

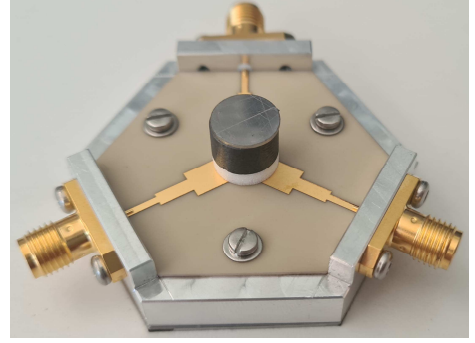


Fig. 9. Microstrip dual-band circulator prototype

Fig.10 shows the of the co-simulation and measured results. The circulation function was clearly identifiable, with high isolation levels around two frequencies (5 and 7.9 GHz) and a wide band with isolation greater than 15 dB. The results define three distinct bands. The first two sub-bands, designated as B1 and B2, represent dual-band operation of the circulator. With isolation and matching greater than 20 dB in these bands, they are centered at 5 and 7.9 GHz respectively, with measured bandwidths of 17.9% and 12.6%. Losses in these bands are less than 0.4 dB for B1 and 0.73 dB for B2. A third band can be identified, designated as B3. For this band, the matching and isolation are greater than 15 dB over 72.1% of the bandwidth centered at 6.5 GHz. In addition to its dual-band behavior, the circulator also demonstrates good performance for ultra-wideband applications.

Comparison shows good correlation between measurements and simulations. However, the width of the second band appears to be reduced in the measured results.

Table 1 compares the measured performance of this circulator with dual-band circulator from literature. Bandwidths are significantly wider while maintaining low losses. Applying this new concept of dual-band circulator with a wideband resonator has enabled the design of a circulator operating at 5 and 7.5 GHz. The 20-dB isolation bandwidths are 17.9% and 12.6%, respectively, more than three times wider than the values reported in the literature.

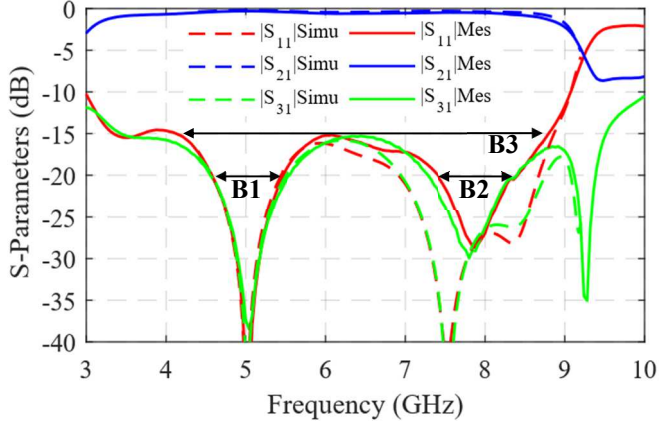


Fig. 10. Comparison of S parameters from co-simulation and measurements

Table 1. Performances comparison

Circulator	Stripline Dual-Band [2]		Microstrip Dual-Band [3]	
Frequency (GHz)	5.08	10.10	4.9	10.1
S21 dB	0.55	0.35	0.65	1.3
BW (%)				
Iso(dB)>20	4.0	2.9	5.5	2.8
S11 dB>20				
Circulator	This work			
BW ID	B1	B2	B3	
Frequency (GHz)	5.0	7.9	6.5	
S21 dB	0.40	0.73	1.28	
BW (%)			BW (%)	
Iso(dB)>20	17.9	12.6	Iso(dB)>15	
S11 dB>20			S11 dB>15	
			72.1	

IV. CONCLUSION

This paper introduces the design of a dual-band ferrite circulator using microstrip technology. The development of this circulator is based on a new dual-band operating concept. Instead of dual-band circulators in the literature, only fundamental modes are used. To create two separate circulation bands, a resonator from an ultra-wideband circulator is used. A matching circuit was then designed to optimize isolation and matching around two specified frequencies. This concept was been applied to a circulator operating at 5 and 7.5 GHz. The complete design is described in the paper. Measurement results obtained from a prototype show bandwidths of 17.9% and

12.6% with losses of less than 0.8 dB across these bands, for isolation greater than 20 dB.

These results represent a significant improvement for ferrite dual-band circulators, with an increase of more than three times in bandwidth. These sub-band performance results are therefore equivalent to those of commercially available single-band circulators.

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