Self-Biased Ku-band Circulators

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***Abstract*—A self-biased *Ku*-band circulator has been designed and measured. A pre-oriented substituted strontium hexaferrite SrM with a strong anisotropy field and high remanent magnetization was used for the component design. A minimum insertion loss of 0.95 dB with more than 15 dB isolation has been measured. However, a frequency shift of 1.5 GHz has been observed between the simulation and the measurement. Retro-simulations, taking into account the metallization dimensions, led us to believe the anisotropy field and the permittivity considered to be inaccurately evaluated. Nonetheless, these experimental results demonstrate the high potential of hexaferrites for the realization of *Ku*-band circulators.**

***Keywords*—ferrite circulators, hexaferrite, self-biased component.**

I. Introduction

Circulators are often found in full-duplex systems using a single antenna. They can also be used as an isolator when a matched load terminates one of the ports in RF front ends to protect devices from impedance mismatches. However, these devices are mainly built using hybrid technologies (ferrite puck insertion in a stripline or microstrip structure), leading to high bulkiness and cost. Furthermore, the component size is substantially increased by the need for permanent magnets to polarize the ferrite inserts. Thus, mass production of low-cost compact circulators remains a topic of interest, and new ideas and technologies are still needed to improve upon the significant drawbacks of these devices.

As an example, in the case of a commercial circulator in *Ku*-band, the magnet used to polarize the ferrite takes more than 90% of the total height of the component by itself. Thus, one of the most impactful ways to reduce circulator size is to remove the magnets. To achieve that, usual soft ferrites have to be replaced by pre-oriented hexaferrites, such as barium or strontium hexaferrites. The benefit of this ferrite type is the ability to keep a strong magnetization without the need for an external magnetic field via a magnet.

Some studies, mainly employing strontium hexaferrites, explored the possibility of using these ferrites in planar self-biased components with success [1]–[9] from *Ku* to *V*-band. However, in certain cases, an external magnetic field had to be applied to the circulator to improve the measured performance, thus eliminating the main advantage of these materials. Furthermore, only one of these studies, Wang *et al.* work [6], aimed for a circulation frequency lower than 20 GHz. Their isolator achieved IL as low as 1.52 dB at 13.65 GHz and 21 dB isolation.

These materials usually have an anisotropy field H_k around 18 kOe. This leads to a gyromagnetic resonance between 40 and 50 GHz depending on the ferrite aspect ratio. In *Ka*-band, the main issue is the proximity of the desired circulation frequency and the gyromagnetic resonance. However, in *Ku*-band the main issue is the low anisotropy factor κ/μ induced by the large frequency difference between the desired working frequency and the gyromagnetic resonance.

In one of our previous works [8], we developed and measured a component which achieved state-of-the-art IL in Q-band. This paper aims to use the same substituted strontium hexaferrite SrM to develop a circulator in *Ku*-band this time. First, the used hexaferrite and its properties will be presented. Then the self-biased circulator design and measurements will be discussed. Finally, retro-simulations conducted to explain the differences between simulated and measured response will be presented.

II. Ferrite properties

Strontium M-type pre-oriented hexagonal ferrites have a strong anisotropy field, around 18 kOe, and a high remanence to saturation magnetization ratio. These characteristics have been used to make mm-wave circulators up to *V*-band.

To achieve higher circulation frequencies, it is necessary to increase the anisotropy field inside the ferrite to raise the gyromagnetic resonance frequency. That is why in *Q*-band, a substituted strontium hexaferrite SrM is used, with an increased anisotropy field. On the other hand, to obtain good performances at lower frequencies, in particular an improved bandwidth, it is necessary to maintain a good anisotropy factor κ/μ. This could be done by lowering the anisotropy field.

However, despite this consideration, the hexaferrite used to make these *Ku*-band circulators is a substituted strontium hexaferrite with a high anisotropy field which was chosen due to its good magnetostatic properties and to its low dielectric loss. Table 1 synthesises the hexaferrite properties used in simulation.

Table 1. Properties of the selected hexaferrite

M_s (G)	H_k (kOe)	M_r/M_s	ΔH (Oe)	ε_r	tanδ
4800	20	> 0.8	200	20	$5.10e^{-4}$

III. Circulator design and measurement

A. Simulation methodology

The software used to design the circulator is Ansys HFSS™. The device substrate is a 4×4 mm^2 ferrite plate on which the metallization is a Y-junction in microstrip technology. In the case of a well-pre-oriented hexaferrite (along the z-axis), it has been proved in [10] and [11] that the Polder model, integrated into the HFSS software, can be used to predict the microwave properties of such materials by changing the model parameters as follows:

$$H_{int\ Polder} = H_k - N_z M_r \quad (1)$$

$$M_{Polder} = M_r \quad (2)$$

where $H_{int\ Polder}$ is the internal field in the ferrite, H_k the anisotropy field, N_z the demagnetization coefficient along the z-axis, and M_r the remanent magnetization. The N_z coefficient is determined using the Aharoni model which provides a good approximation for rectangular prisms [12].

Due to software limitations, it is not possible in HFSS™ to put any type of excitation, be it wave ports or lumped ports, directly on the edge of an anisotropic material such as a biased ferrite. The workaround we used is to put a buffer material on the edge of the ferrite (without adding material). This buffer material has the same permittivity as the ferrite, $\varepsilon r = 20$. The permeability is a scalar value equal to the effective permeability calculated using the Polder model. This configuration is illustrated in Fig. 1.

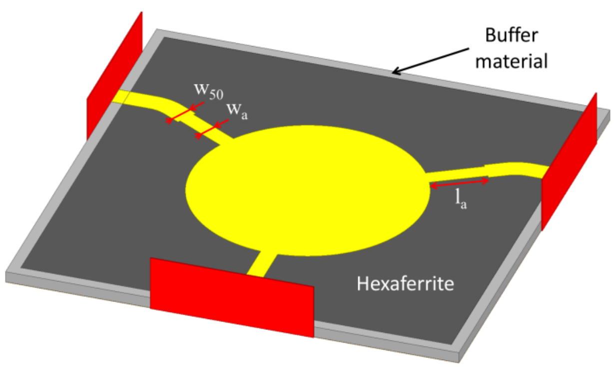

Fig. 1. Simulation structure of the self-biased circulator.

The initial design of the circulator was done using the Bosma theory [13]. This gave us the cylindrical resonator radius and the feed lines width for a working frequency of 17 GHz. Quarter-wavelength transmission lines were then added to the resonator. Finally, the circulator performances were tuned through optimizations.

Three designs based on three substrate thickness, 200 µm, 160 µm and 100 µm, have been optimized. The objective was to identify the thickest possible component able to maintain good performances. However, increasing the thickness induced a reduction in the maximum isolation achievable. This is illustrated in Fig. 2. Therefore, the selected design is the one optimized for a 0.1 mm thickness. The corresponding demagnetizing factor N_z is 0.93, implying an internal magnetic field of 16 205 Oe. The scalar permeability used to define the buffer material is equal to 1.28.

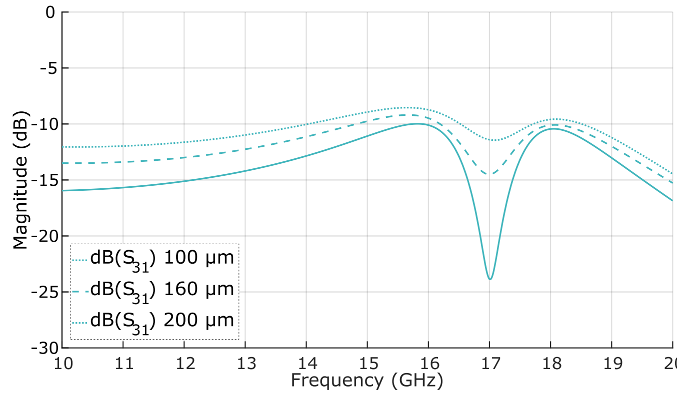

Fig. 2. Impact of the substrate thickness on the maximum of isolation achievable: 100 µm in solid line, 160 µm in dashed line and 200 µm in dotted line.

The main design dimensions are given in Table 2 as simulated. Those are the resonator radius R_f, the access lines width w_{50}, the quarter-wavelength lines' width w_a and length l_a.

Table 2. Simulated and measured circulator dimensions

	R_f (µm)	w_{50} (µm)	w_a (µm)	l_a (µm)
Simulated	1 025	48	45	500
Measured	1 047	Unknown	52	Unknown

The simulated S-parameters are presented in Fig. 3. The minimal simulated IL is 0.68 dB at 17.05 GHz. Isolation and RL both remain above 15 dB for a 580 MHz bandwidth (3.4%). The maximum IL on this bandwidth is 0.96 dB. A slight frequency shift can be observed between the central frequency and the desired 17 GHz. This is due to a reduction in the surface of the component to manufacture a higher number per substrate plate. The reduced size of 3.5×3×0.1 mm implied a lower demagnetizing factor of 0.918, thus increasing the internal magnetic field and the circulation frequency.

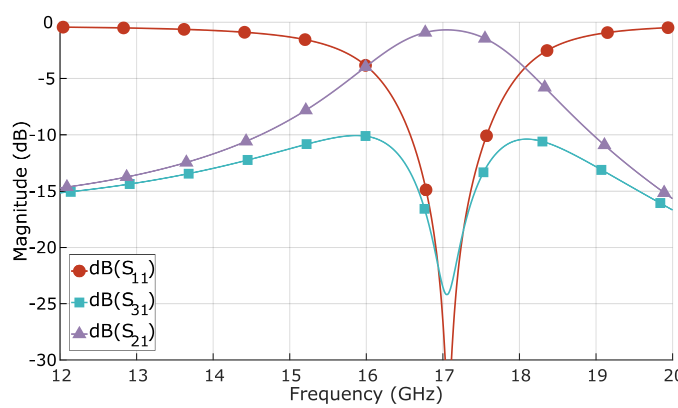

Fig. 3. Simulated S-parameters of the self-biased circulator: IL in purple/triangle markers, Isolation in blue/square markers, RL in red/circle markers.

B. Circulator measurements

The simulated circulator has been manufactured. A thin plate is cut from a bulk of hexaferrite. This plate is then polished on both sides to obtain the desired thickness of 100 µm. The circulator has been properly magnetically saturated before being measured. The measurement has been done using coplanar probes on microstrip-coplanar transitions. These transitions are each connected to the circulator using two bond wires. The measurement configuration is presented in Fig. 4. The 3-port measurement was performed at room temperature. The transition insertion losses have been experimentally estimated to be between 0.2 and 0.3 dB over the frequency band of measurement. This range is in good agreement with the simulated insertion loss difference between the simulation of the circulator by itself and the simulation of the measurement configuration with its transitions.

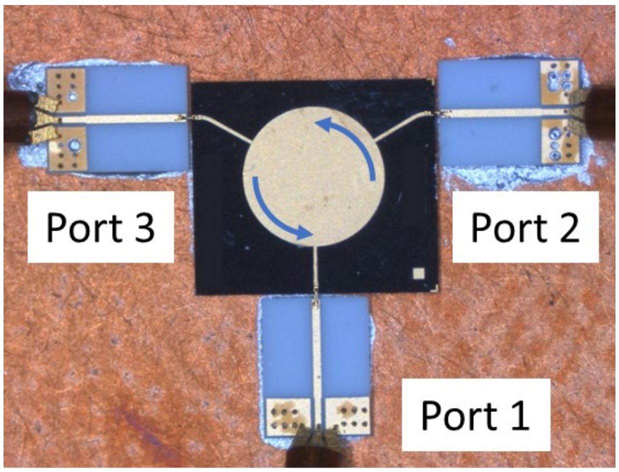

Fig. 4. Measurement configuration.

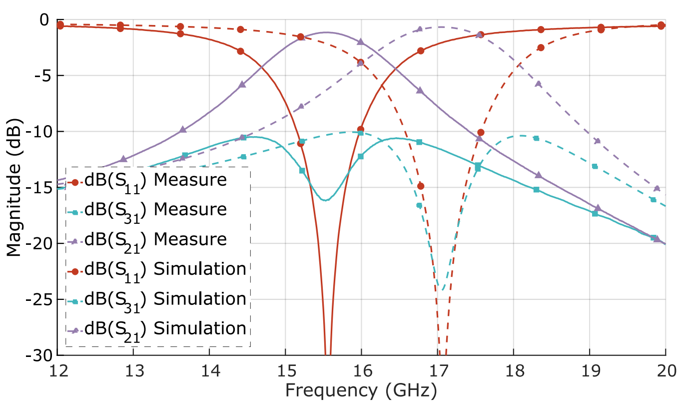

Fig. 5. Measured S-parameters of the self-biased circulator (solid lines) against the simulated S-parameters (dashed lines): IL in purple/triangle markers, Isolation in blue/square markers, RL in red/circle markers.

The measured S-parameters are available in Fig. 5, as solid lines, alongside the simulated performances as dashed lines. The minimal IL is 1.15 dB at 15.55 GHz, taking into account the transitions. Isolation and RL are above 15 dB for a 360 MHz bandwidth (2.3%) where the max IL is 1.34 dB. If we consider the microstrip-coplanar transitions losses equal to 0.2 dB, the minimal IL is further reduced to 0.95 dB. The maximum of isolation is reduced compared to the simulation. These good performances are however tarnished by an important frequency shift of 1.52 GHz (8.9%) between the simulation and the measured response.

IV. Retro-simulations

The degradation in the maximum of isolations may be explained by a variation of the substrate thickness. As shown in Fig. 2, the thicker the substrate, the worse the isolation becomes. However, verifying this theory is complicated. The circulators have been fixed on a copper plate using conductive glue. It is thus impossible to measure the device thickness accurately enough. This will however be considered as a critical point for further device fabrication.

The observed frequency shift has been investigated through multiple retro-simulations. The impact of the microstrip-coplanar transition on the circulator response was evaluated in simulation. This impact was negligible thus, retro-simulation were done on the circulator only.

Firstly, a software parameter in HFSS™ has been modified. The initial mesh, by default, was not curvilinear around the central resonator. A comparison between the two meshes is shown in Fig. 6. This meant the effective size of the conductor was underestimated and led to a higher central frequency in simulation. This led to a reduction of 160 MHz (10.5% of the discrepancy) of the central frequency.

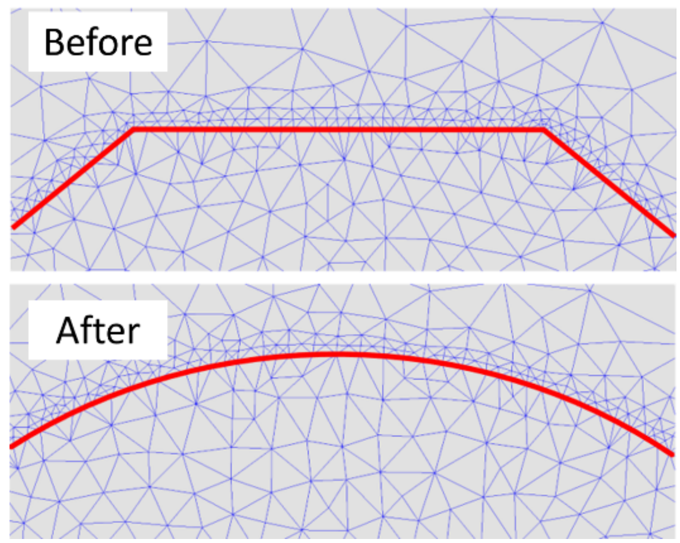

Fig. 6. Comparison between the two initial mesh settings

The second parameter evaluated was the impact of the metallization. Their consistency has been shown to have an important impact on the circulation frequency [8]. This has been the case here as well. The integration of the measured metallization values, given in Table 2 as measured, induced a reduction of the frequency shift of 600 MHz (39.5% of the discrepancy), mainly due to the oversized resonator size. Due to a minimal width difference between the access lines and the quarter-wavelength lines, only one quarter-wavelength width has been measured. The relative width variation has then been applied uniformly to the two other lines. The access line width has not been measured. No quarter-wavelength line length has been measured. Their lengths are considered equal to the nominal value.

Thirdly, new characterizations of the used strontium hexaferrite have been done using a direct measurement of the resonance frequency of a hexaferrite sample on top of a microstrip line. The extracted effective anisotropy field H_k was determined to be around 18.5 kOe. This value is lower than the one used in the original design of 20 kOe. Once implemented in simulation, this decrease in anisotropy diminished the central frequency of our component by 300 MHz (19.7% of the discrepancy).

Lastly, newer characterization of our material led us to consider a relative permittivity ε_r closer to 21 instead of 20 used until now. This higher permittivity is coherent with measured values [14] in mm-wave. A permittivity of 21.3 has been used to finally have a good frequency agreement between the retro-simulation and the measured response.

The result from the final retro-simulation, taking into account all the modified parameters, is plotted in Fig. 7 as dotted lines with the measured S-parameters as solid lines and the original design simulation as dashed lines. One should note that this new set of parameters allows a better agreement between simulation and measurement of other circulators previously designed, fabricated and measured in Ka and Q bands using the same material.

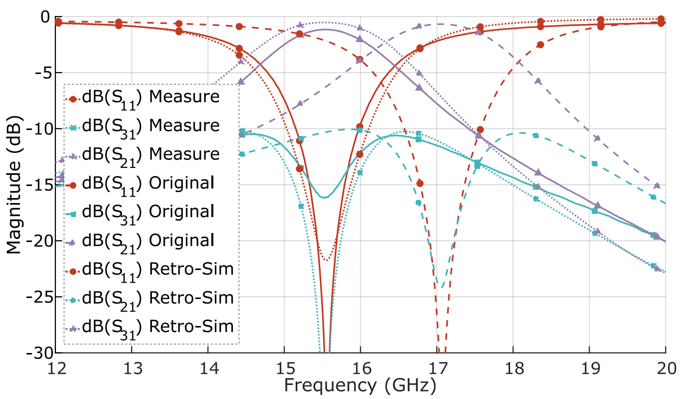

Fig. 7. Comparison between the measured S-parameters (solid lines), the original design (dashed lines) and the last retro-simulation (dotted lines): IL in purple/triangle markers, Isolation in blue/square markers, RL in red/circle markers.

V. Conclusion

The possibility of using a pre-oriented substituted strontium hexaferrite to realize a *Ku*-band compact planar circulator has been explored. State of the art IL, as low as 0.95 dB at 15.55 GHz, have been achieved in *Ku*-Band. A 360 MHz bandwidth where both isolation and RL were maintained above 15 dB. The maximum IL in this bandwidth were 1.14 dB. Both IL values are given without taking the microstrip-coplanar transitions into account. The component is only 0.1-mm thick and its mass is less than 6 mg. The frequency shift is explained by our retro-simulation parameters. However, this new set of material characteristics will have to be validated through new circulator designs and experimental validations in various frequency bands.

These performances, albeit slightly worse than those of the commercial circulator mentioned in the introduction, were obtained on a 0.1 mm thick component. This leads to a volume 99.3% lower than the volume of a conventional 6×6×4 mm^3 circulator using a magnet coupled with a soft ferrite. The total mass is less than 6 mg and has to be compared with the 300 mg of a conventional circulator of this size.

We believe this type of self-biased circulator performance can be further improved by the use of a better suited hexaferrite, with a lower anisotropy field to increase the anisotropy factor κ/μ in the material.

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