

Q-BAND PLANAR ULTRA-COMPACT MICROWAVE CIRCULATORS

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INTRODUCTION

Microwave circulators and isolators are currently used in RF front-ends to protect devices from impedance mismatches. These devices are also integrated in full-duplex systems when a single antenna is used. However, these devices are mainly fabricated by hybrid technologies (insertion of ferrite pucks in a triplate or microstrip structure) leading to high bulkiness and cost. Furthermore, bulkiness is exacerbated by the need for permanent magnets to polarize the ferrite pucks. Thus, mass production of low-cost compact circulators remains a hot topic and new ideas and technologies are needed to improve the integration of these devices.

At millimeter-wave frequencies, spinel ferrites with a high saturation magnetization lead to low losses and high levels of isolation. However, these circulators require the use of strong magnets that leads to bulky devices. As an example, a 36-38 GHz microstrip circulator from Dorado (IL < 0.9 dB, Isolation > 19 dB, RL > 19 dB) has to be associated with a 3.8-mm thick magnet whereas thickness of ferrite is only 0.2 mm. Removing the magnets appears thus to be a way to decrease circulators sizes. These circulators, called self-biased circulators, require using pre-oriented hexaferrites such as barium or strontium hexaferrites. Indeed, these materials make it possible to keep a strong magnetization without applying an external magnetic field.

Since the 90s, some studies explored the potential applications of these materials to the design and realization of self-biased circulators. These studies were mainly based on the use of strontium hexaferrites and led to the realization of circulators from Ku to Ka bands [1]-[7]. These hard materials show an anisotropy field H_A of about 18 kOe which leads to a gyromagnetic resonance between 40 and 50 GHz depending on the shape of the sample. However, in real self-biased circulators, the shape factor of the ferrite samples that are inserted in the device sets the gyromagnetic resonance frequency near 40 GHz and limits the performances of self-biased circulators in this frequency range. This fact limits the application of this technology for the future Q and V band systems.

Previously, we demonstrated that insertion losses as low as 0.4 dB at 38.9 GHz can be obtained in a rectangular waveguide circulator by using substituted strontium hexaferrite [8]. In this study, we investigated the potential of substituted strontium hexaferrites for the realization of Q-band planar ultra-compact circulators.

In a first part, we will present the properties of the materials that will be used for the design of self-biased circulators. Then, design and measurements of self-biased circulators will be presented and discussed as a function of the material properties.

MATERIALS

Strontium hexagonal ferrites with a magnetoplumbite structure exhibit a very high anisotropy field of about 18 kOe and a high remanence to saturation ratio, making it possible to realize mm-wave self-biased circulators. This ferrite was often used for such applications in the literature. It has allowed the successful realization of self-biased circulators up to Ka band. Some experimental demonstrations around 40 GHz have also been carried out. However, performances at this frequency in self-biased working mode are slightly degraded due to the proximity of the natural (without an applied magnetic field) gyromagnetic resonance frequency (FMR).

One of the solutions for realizing self-biased circulators at this frequency is to use doped strontium hexaferrite SrM with a higher anisotropy field. This way of research was investigated in this work. In a previous paper, we studied the properties of three different materials for these applications: a pure SrM and two substituted SrM [9]-[10]. These preliminary studies allow us to select a composition for Q-band applications and to demonstrate that a self-bias circulator in rectangular waveguide technology can achieve insertion losses as low as 0.4 dB at 38.9 GHz. The properties of this material are detailed in Table 1. This ferrite presents a high anisotropy field H_k , a high saturation

magnetization M_s and a high remanent-to-saturation ratio M_r/M_s . One should note that this value of $M_r/M_s = 0.88$ was measured on a small cylinder that has a shape factor of 0.23 (i.e. thickness divided by diameter). These properties are fully compatible with the realization of a self-biased circulator around 40 GHz.

Table 1. Properties of the selected hexaferrite

M_s (G)	H_k (kOe)	M_r/M_s	ΔH (Oe)	ϵ_r
4140	19.75	0.88	400	21

The transfer of this technology to planar devices is not obvious. Indeed, these materials are highly sensitive to the shape factor of the sample. Demagnetizing effects can lead to a tilt of hysteresis cycle that can strongly decrease M_r/M_s ratio. For the realization of a microstrip circulator, we selected a ferrite plate with the following dimensions: 0.1 mm x 2.5 mm x 2.5 mm. This thickness was chosen in order to avoid propagation of substrate modes in the ferrite plate at 40 GHz. These dimensions lead to a shape factor of 0.04 that increases demagnetizing field (perpendicularly to the plate) and that can induce a tilt of hysteresis cycle. Fig. 1 compares measured hysteresis cycles of a small disk (shape factor = 0.23) and the one of a plate (shape factor = 0.04). One should note a slight tilt of hysteresis cycle in the case of a flat plate of hexaferrite. However, the decrease of M_r/M_s ratio is quite low ($M_r/M_s = 0.83$ for a flat plate) and is even compatible with the realization of a self-biased circulator.

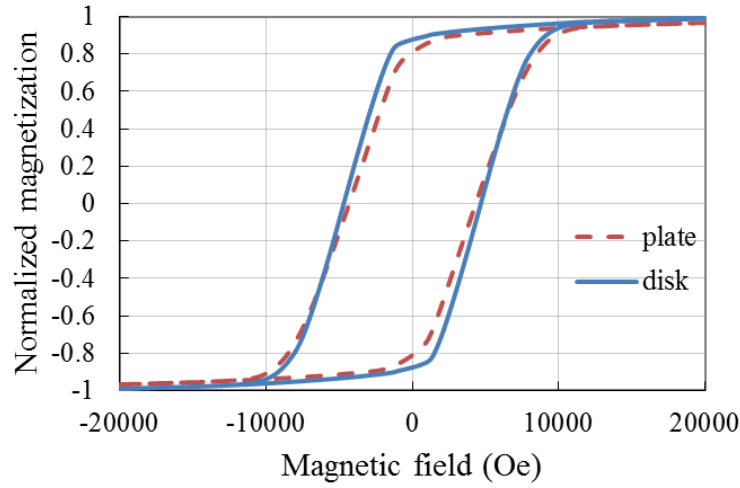


Fig. 1. Comparison of measured $M(H)$ hysteresis loops for a disk (diameter = 1.76 mm, thickness = 0.4 mm) and a plate (0.1 mm x 2.5 mm x 2.5 mm) of substituted strontium hexaferrite.

DESIGN AND CHARACTERIZATION

Design methodology

Ansys HFSS software was used to design a microstrip circulator. The device is constituted of a 0.1 mm x 2.5 mm x 2.5 mm ferrite substrate with a Y-junction in microstrip technology. In the case of a well pre-oriented hexaferrite (along z axis), it has been proved in [9]-[10] that Polder model, integrated in HFSS software, can be used to predict the microwave properties of such materials by changing the parameters of the model as follows:

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

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

where $H_{int\ Polder}$ is the internal field in the ferrite, H_k the anisotropy field, N_z the demagnetization coefficient along z axis and M_r the remanent magnetization.

At first, Bosma theory [11] was used to calculate the diameter of the cylindrical resonator and the width of feed lines for a working frequency at 38 GHz. Then, quarter wavelength lines were added in the design and optimizations were performed in order to improve overall performance of the device.

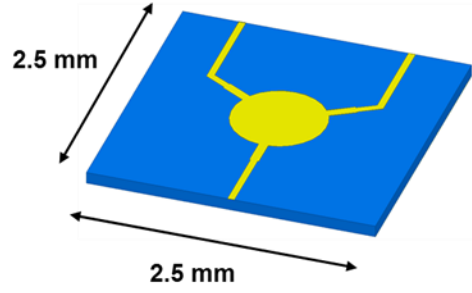


Fig. 2. Simulation model of the self-biased circulator in microstrip technology.

Simulated S-parameters are shown in Fig. 3. The circulator presents minimal insertion losses of 1.13 dB at 37.8 GHz. Isolation and return loss remain higher than 15 dB between 36.7 GHz and 39.6 GHz leading to a relative bandwidth of RBW = 7.7%.

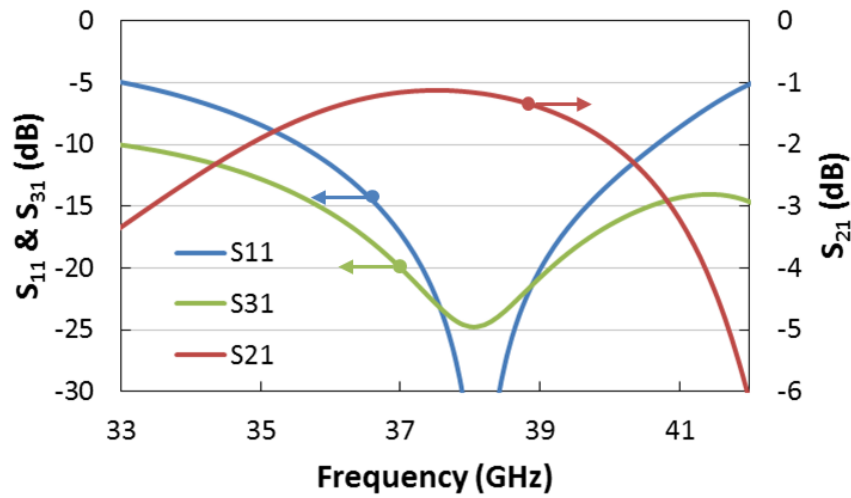


Fig. 3. S-parameters of the optimized self-biased circulator.

Realization and microwave measurement

The device presented in Fig. 2 was realized. Thin ferrite plate were manufactured and polished on both sides. Then, a standard metallization process was used to realize metallic patterns. This component was fully magnetized before the measurement. The circulator was designed to be measured with dedicated microstrip probes. Characterizations were performed with a probe station at room temperature, -15°C and $+60^{\circ}\text{C}$.

Fig. 4 shows S-parameters of the compact self-biased circulator in the 25-45 GHz frequency band for different temperatures. At room temperature, measurements show a slight shift in frequency compared to simulations. However, insertion losses as low as 0.45 dB at 35.8 GHz were measured. At this frequency, isolation is 17 dB and return loss is 27 dB. Relative bandwidth is only 4.5% due to a frequency shift between maxima of return loss and isolation.

Furthermore, the circulator demonstrates reasonable temperature stability. For example, at 35.8 GHz, insertion losses only increase of 0.15 dB when the temperature increases from room temperature to $+60^{\circ}\text{C}$. Isolation and return loss remain higher than 15 dB in this temperature range.

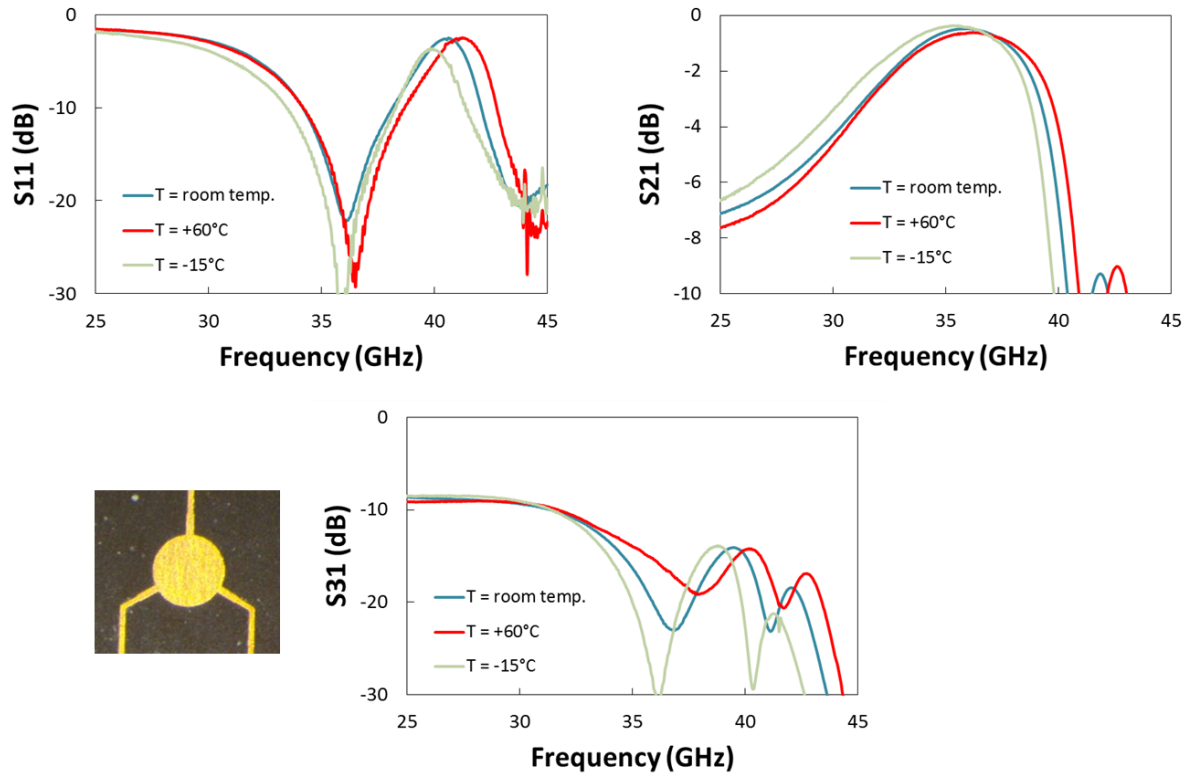


Fig. 4. Measured modulus of the S-parameters of the self-biased circulator for different temperatures.

The frequency shift between theory and experiment is still under investigation. Retro-simulations show that a center frequency of 35.8 GHz can be achieved with an anisotropy field $H_k = 18900$ Oe and a permittivity $\epsilon_r = 23$. One should note that pre-oriented strontium hexaferrites presents anisotropic dielectric properties. This higher value of permittivity can be attributed to a stronger interaction of EM wave with the in-plane permittivity (perpendicular to c -axis) of hexaferrite compared to the case of a ferrite disk inserted in a rectangular waveguide Y-junction. The lower anisotropy field can be explained by a slightly higher misalignment of magnetic moments, due to demagnetizing effects in a thin ferrite plate. This hypothesis is consistent with the decrease of coercive field observed for a thin ferrite plate compared to a disk.

CONCLUSION

We investigated the potential of substituted strontium hexaferrites for the realization of a Q-band self-biased circulator around 40 GHz. We demonstrated that insertion losses as low as 0.45 dB associated with isolation and return loss level higher than 15 dB can be achieved for a very compact microstrip circulator (2.5 mm x 2.5 mm x 0.1 mm) without using magnets. Moreover, this device demonstrates reasonable temperature stability.

This new technology paves the way to the development of a new class of circulators and isolators that can be easily integrated in millimeter wave systems such as Q-band telecommunications satellites.

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