# LOW-LOSS MILLIMETER-WAVE SELF-BIASED CIRCULATORS: MATERIALS, DESIGN AND CHARACTERIZATION

V. Laur(1), R. Lebourgeois(2), E. Laroche(3), J.L. Mattei(1), P. Quéffélec(1), J.P. Ganne(2) and G. Martin(3)

(1)*Lab-STICC, University of Brest, Brest, France*
*Email: Vincent.laur@univ-brest.fr*

(2)*Thales Research and Technology, Palaiseau, France*

(3)*Chelton Telecom & Microwave trading as Cobham Microwave, Villebon-sur-Yvette, France*

## INTRODUCTION

Removing magnets appears to be an exciting way to improve the integration of microwave circulators. These circulators, called self-biased circulators, require using pre-oriented hexaferrites such as barium or strontium hexaferrites.

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.

In this study, we investigated the potential of substituted strontium hexaferrites for the realization of a self-biased circulator near 40 GHz. 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. We studied the properties of three different materials for these applications: a pure SrM and two substituted SrM. Their properties are given in table 1. In both cases, substituted strontium hexaferrites present a higher anisotropy field. Moreover, ferrite SrM-S2 shows a significantly lower resonance linewidth (ΔH) than SrM-S1. One should also note that substituted SrM have a higher remanent-to-saturation magnetization ratio than pure SrM due to the higher squareness of the hysteresis cycle, illustrated on Fig.1 which compared M(H) cycles of SrM and SrM-S1.

Table 1. Properties of hexaferrites

| Name | Type | $M_S$ (G) | $H_k$ (kOe) | $M_r/M_S$ | ΔH (Oe) | $\varepsilon_r$ |
|---|---|---|---|---|---|---|
| SrM | Pure | - | 18 | 0.85 | - | - |
| SrM-S1 | Substituted | 4200 | 21 | 0.9 | 1500 | 21 |
| SrM-S2 | Substituted | 4240 | 19.75 | 0.88 | 400 | 21 |

Because of their high anisotropy fields and remanent-to-saturation ratios, these substituted SrM appear to be good candidates to make self-biased circulators up to 40 GHz.

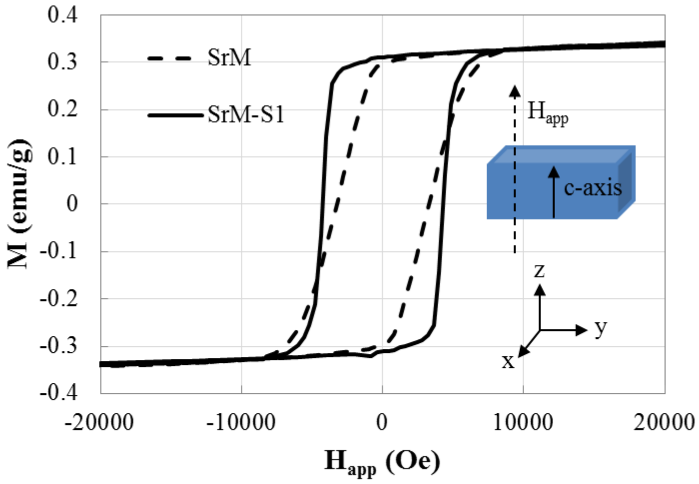


Fig. 1. M(H) hysteresis loops measured with a SQUID magnetometer on SrM and SrM-S1 materials.

## DESIGN AND CHARACTERIZATION

### 1st run: Comparison between SrM-S1 and SrM-S2 materials

Ansys HFSS software was used to design a Y-junction circulator in waveguide technology. The device is constituted of three WR-19 rectangular waveguide arms, impedance transformers and two ferrite cylinders placed at the center of the Y-junction. In the case of a well pre-oriented hexaferrite (along z axis), it has been proved in [8]-[9] that Polder model can be used to predict the microwave properties of such materials by changing the parameters of the model as follows:

$$H_{int\ Polder} = H_{app} + H_A - N_z \times M_r \tag{1}$$

$$M_{Polder} = M_r \tag{2}$$

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

The coefficient $N_z$ depend on the shape of the ferrite sample. This dependency can be modeled by using Aharoni formulae [10] and integrated in the simulation software. This integration provides the opportunity to realize an optimization of the device. Then, the variations of internal magnetic field as a function of the ferrite dimensions are automatically taken into account [11].

Fig. 2 shows the Y-junction circulator that was developed. It was realized by using WR-19 rectangular waveguides. Impedance matching is achieved through the change of sections of the WR-19 waveguide near the Y-junction. Hexaferrite disks (SrM-S1 or SrM-S2) were glued at the center of the circulator.

Circulators were measured with a Vector Network Analyzer (Rhode&Shwarz ZVA67). Thru-Reflect-Line (TRL) calibration procedure was performed in order to shift the reference plane after the coaxial-to-waveguide transitions. Self-biased circulators were measured in isolator mode (a 50 Ω load was connected to one of the ports). An external magnetic DC field, applied using an electromagnet, was also used to observe the behavior of the circulator as a function of the applied biasing field. The static magnetic field was measured with a gaussmeter during the measurement.

A comparison between measured and simulated performances of the circulator integrating SrM-S1 and SrM-S2 materials without applied field is presented in Fig. 3. From a general point of view, we observe a quite good agreement between simulated and measured S-parameters. The minimum insertion losses are 1.8 dB at 41.4 GHz and 0.9 dB at 41 GHz for SrM-S1 and SrM-S2, respectively. One should note the lower insertion losses of SrM-S2-based circulator are mainly due to the lower ΔH value of this material compared to the one of SrM-S1. At these frequencies, both circulators present isolation levels better than 15 dB. However, the circulator that integrates SrM-S2 hexaferrites suffers from a lower relative bandwidth RBW (Isolation > 15 dB) which is only 3.2% compared to a RBW of 7.2% achieved with SrM-S1 materials. One should note that the overestimation of the relative bandwidth in simulation seems to be due to the inhomogeneity of the internal field which is not taken into account in the simulation.

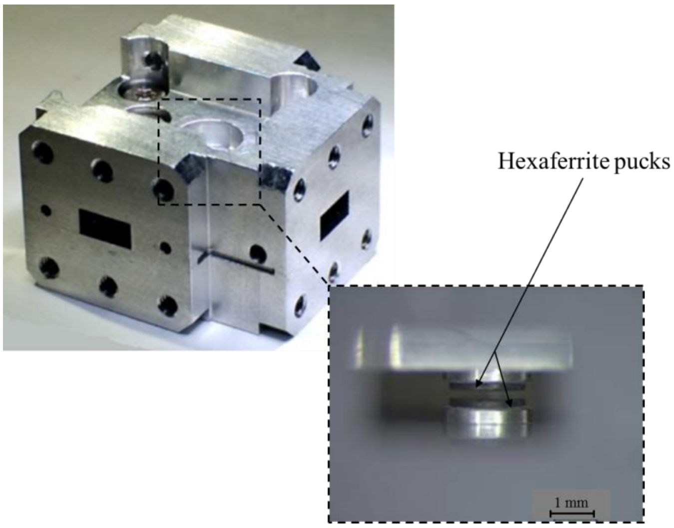
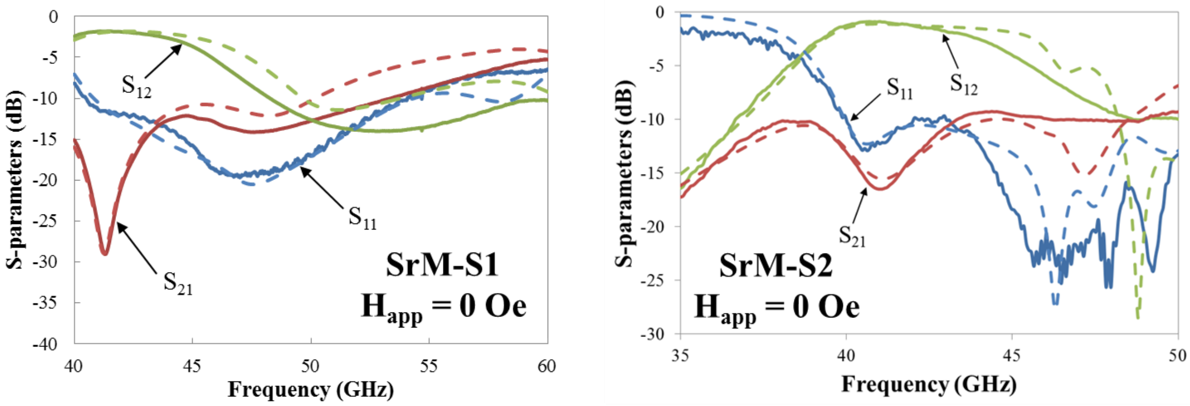


Fig. 2. Photograph of the circulator in rectangular waveguide technology (Insert: internal view of hexaferrite pucks integrated into the circulator).



(a) (b)

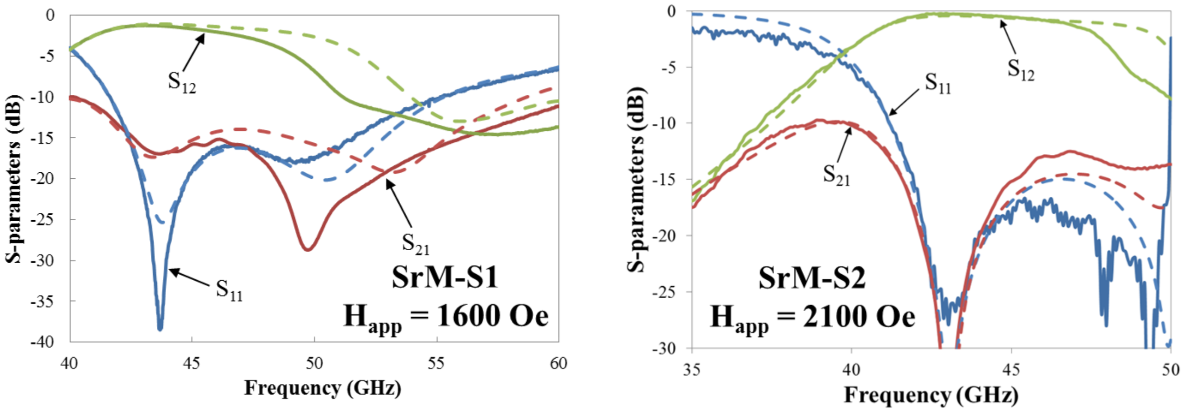
Fig. 3. Comparison between measured and simulated S-parameters of the circulator integrating (a) SrM-S1 and (b) SrM-S2 hexaferrites without applied field.

We then applied an external magnetic field on these circulators. Fig. 4 presents the S-parameters of both circulators for bias field amplitudes of 2100 Oe (SrM-S1) and 1600 Oe (SrM-S2). We observe a noticeable improvement of insertion losses for SrM-S1- and SrM-S2-based circulators.

Indeed, insertion losses of SrM-S1-based circulator decrease down to 1.25 dB at 43.2 GHz when an external field of amplitude 1600 Oe is applied.

When a 2100-Oe magnetic field is applied on the SrM-S2-based circulator, insertion losses are only 0.2 dB at 41.3 GHz. Moreover, isolation level remains lower than -15 dB between 41.5 and 45.1 GHz leading to a relative bandwidth of 9.7%. One should note that insertion losses are kept quite low in this bandwidth, with a maximum value of 0.8 dB.

SrM-S2 materials lead to better performances near 40 GHz than SrM-S1 hexaferrites. A low external magnetic field makes it possible to significantly improve insertion losses and isolation of the circulator. As a consequence, it appears that a modification of the geometry of the circulator could lead to an improvement of the performances of such circulator without applied field. Thus, a new geometry was defined on the basis of the measurement of these preliminary results in order to improve the behaviour of SrM-S2-based circulator without applied field.



(a) (b)

Fig. 4. Comparison between measured and simulated S-parameters of the circulators integrating (a) SrM-S1with an applied magnetic field of 1600 Oe and (b) SrM-S2 hexaferrites with an applied magnetic field of 2100 Oe.

## 2nd run: Optimization of SrM-S2-based circulator

A new version of SrM-S2-based circulator was designed. The automatic procedure of optimization that takes into account the evolution of the internal field as a function of the shape factor of SrM-S2 disks was employed. Impedance transformers were especially modified in order to improve the behaviour of the circulator without applied field.

Fig. 5 presents the measured S-parameters of the new version of the circulator without applied field. Minimum insertion losses of 0.4 dB were measured at 39 GHz. At this frequency, isolation level is higher than 25 dB. This circulator presents a relative bandwidth of more than 4 GHz (10.7%) in which ripple of insertion losses does not exceed 0.28 dB.

One should note that these performances constitute a strong improvement compared to the measured performances of 1st run circulators which were already at state-of-the-art of millimetre-wave self-biased circulators.

Moreover, measurements of the device as a function of the temperature were performed [11]. A quite good stability was observed up to 115°C. Indeed, an increase of 0.25 dB of insertion losses was measured while keeping an isolation level higher than 15 dB at 40 GHz.

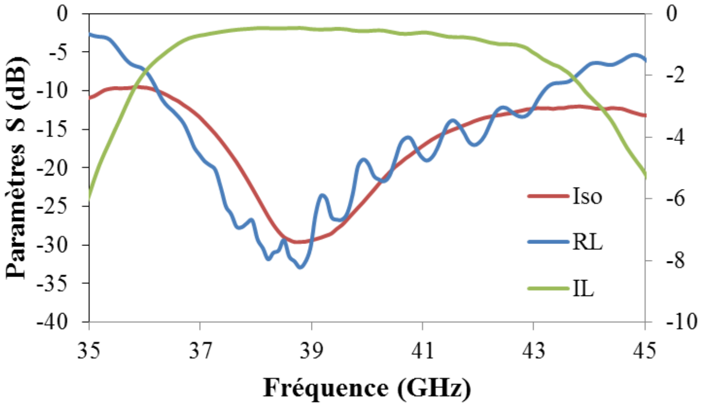


Fig. 5. Measured S-parameters of the optimized SrM-S2-based circulator without applied field.

## CONCLUSION

We investigated the potential of substituted strontium hexaferrites for the realization of a self-biased circulator around 40 GHz. Substituted strontium hexaferrites present higher anisotropy field than pure strontium hexaferrites and very high remanent-to-saturation magnetization ratios that makes it possible to design a self-biased circulator up to 40 GHz. A first run allows us to compare two different substituted SrM hexaferrites. SrM-S2 appears to be the best candidate for these applications mainly because of its low magnetic losses (ΔH). The performances of the self-biased circulator were then improved by modifying the geometry of the device. Very low insertion losses of 0.4 dB and high isolation level of more than 25 dB at 39 GHz were measured without applied field. These results constitute, to our knowledge, the state-of-the-art of millimetre-wave self-biased circulators.

## ACKNOWLEDGEMENTS

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## AUTHORS

**Vincent Laur** received his Ph.D. degree in electronics from the University of Brest, France, in 2007.
In 2008, he was a post-doctoral fellow at XLIM laboratory, Limoges, France. He is currently Assistant Professor at the Lab-STICC laboratory, Brest, France. His research interests are focused on the characterization, modeling and integration of functional materials (ferroelectrics, ferromagnetics, ferrites …) for microwave applications.
He authored and co-authored more than 60 international journal and conference papers. He co-supervised 6 PhD, 2 post-doctoral research fellows and 6 Master research students graduated.

**Richard Lebourgeois** received the Engineering degree of the "Ecole Nationale Supérieure d'Ingénieur Electricien de Grenoble" (Polytechnic Institute of Grenoble) in 1986 and a Ph.D in Material Science at the Polytechnic Institute of Grenoble in 1989. He joined the Central Research Laboratory of THOMSON-CSF (now THALES Research & Technology) in October 1989. He made many works and published many papers on Ferrites and magnetic materials for power electronics (more than 15 patents and 40 papers including 5 invited papers).
He is now in charge of the studies related to Magnetic Materials, Ferrites and Dielectrics for high frequency applications at THALES Research & Technology.

**Eric Laroche** received the Engineering degree of the "Ecole Nationale Supérieure d'Ingénieur Electricien de Grenoble" (Polytechnic Institute of Grenoble) in 1980. He joined the ferrite devices activity of Thomson-CSF in 1983 as microwave designer. He studied various ferrite devices on all kinds of applications from UHF up to W-band and became an expert in high power waveguide circulators and isolators in THOMSON CSF, and then in TEKELEC group. He is now Technical Director of the Cobham business unit involved in microwave circulators and isolators.

**Jean-Luc Mattei** was born in 1961. He received the Ph.D. degree in Solid State Physics from the University Joseph Fourier, Grenoble, France, in 1990. He received the French accreditation to supervise research in 2000. He is currently Associate Professor at the Electronic Department, University of Brest, and a member of the Lab-STICC (UMR CNRS 6285). His main research activities deal with nanoferrites (soft and hard): processing and applications in the microwave range.

**Patrick Quéffélec** (M'99-SM'07) received his PhD degree in Electronics from the Université de Bretagne Occidentale, Brest, France, in 1994 and his Habilitation à diriger des recherches [accreditation to supervise research] in 2002.

He is now a professor at the Laboratory of Sciences and Techniques of Information, Communication and Knowledge (Lab-STICC), a research unit associated with the Centre National de la Recherche Scientifique (UMR CNRS n°6285). In Lab-STICC, he is the Head of the Microwave, Optoelectronics, Material Research Department. His research activities concern electromagnetic wave propagation in heterogeneous and anisotropic media. He works on developing new approaches in materials and measurements for microwave ferrites and devices. Motivated by the applications of new magnetic materials in non-reciprocal or tuneable devices, in antennas, he is investigating the fundamental properties of magnetoelectric nanocomposites at microwave frequencies.

**Jean-Pierre Ganne** received his Master in Engineering degree from the Ecole des Mines de Paris, and his "Docteur-ès-Sciences" (PhD) degree from the University of Paris VI in 1980. He joined TRT in 1981. From 1984 to 2004 as the manager of the Electroceramics Laboratory he initiated new subjects in the field of materials and technologies for microwave and optical applications. He transferred to industrial production several materials and was involved in many European Projects and served the EC as an expert for selection or reviewing of projects. In the position of senior scientist, he managed the transverse Programmes of TRT "Imaging Components & Applications" and "Functional Materials" for several years.

**Gilles Martin** is graduated engineer from Ecole Spéciale de Mécanique et d'Electricité, Paris in 1976.

He joined Thomson-CSF in 1977 as microwave engineer on ground based radars, in departments dedicated to Tx/Rx components, PLL sources, amplifiers and RF head assemblies. Then he joined the Ferrite Activity as Ferrite Devices Department Manager. In 1986 the activity has bought by Tekelec-Temex and he was Business Development Manager of ferrite devices and of filters, duplexers and then of waveguide components. He was also Marketing Manager at Temex. He is currently Marketing and Strategy Director and Project Leader of IMICIMO, LOCCIMIM programs for LTCC ferrite devices.