High-permittivity garnet ferrites for LTCC - compatible circulators

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INTRODUCTION

The field of telecommunications and RADAR systems is constantly evolving. Current challenges are related to the miniaturization of components operating at high frequencies, as well as to the improvement of their performance.

One of the most challenging components to integrate in terms of cost and size in a transmission/emission chain is the circulator. This passive non-reciprocal device typically consists of three ports spaced at 120° apart. Its non-reciprocity is ensured by a ferrite disk, magnetized to saturation, placed under the central conductor. The ferrite–is magnetized by applying an external magnetic field generated by a permanent magnet positioned above the circulator. This circulation mechanism enables the use of a single radiating element for both signal transmission and reception.

The fabrication of circulators is complex because it involves several processes (bonding, machining, etc.). For this reason, the possibility of manufacturing these devices using the Low Temperature Co-fired Ceramics (LTCC) process is being investigated. This process allows different components to be co-sintered at the same low temperature without additional machining which can significantly reduce manufacturing time and cost (Fig. 1.)

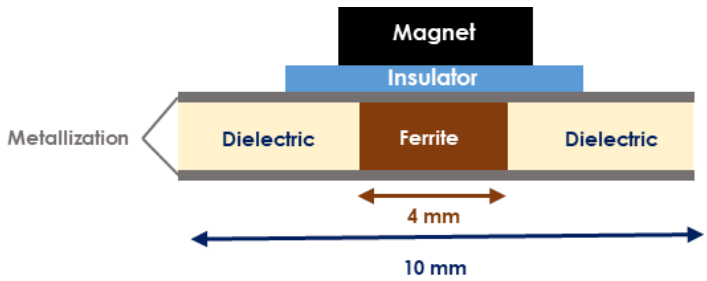


Fig. 1. Illustration of a microwave circulator

TARGETED APPLICATION AND MATERIAL DEVELOPMENT

This study targets an application in the X-band (8–12 GHz). Due to their low saturation magnetization and high permittivity, garnet ferrites are selected, specifically Yttrium Iron Garnet (YIG) with the chemical formula $Y_3Fe_5O_{12}$. YIG has a face-centered cubic structure comprising three distinct crystallographic sites: dodecahedral sites occupied by Y^{3+} ions, and tetrahedral and octahedral sites occupied by Fe^{3+} ions. [1]-[3]

The size of the ferrite resonator in a Y-junction circulator, assuming an operation under a strong magnetic field, is governed by the following equation [4]:

$$\frac{\omega}{c}\sqrt{\varepsilon_r \times \mu_{eff}} \times R = 1{,}84 \quad (1)$$

With ω, the angular frequency, c, the speed of light, ε_r, the permittivity of the ferrite, μ_{eff}, the effective permeability of the ferrite, and R, the radius of the resonator.

Two approaches can be considered to reduce the size of the component. The first approach is by increasing the magnetization of the material which can lead to an increase in the effective permeability, thereby reducing the resonator radius. However, using a ferrite with high magnetization would result in a significant increase in the size of the magnet due to the rise in the demagnetizing field, which is proportional to the material's magnetization.

In general, the impact of magnetic properties on the circulator's size is far more complex than suggested by equation (1). It depends on several factors such as the operating regime (low or high magnetic field), the frequency separation between the gyromagnetic resonance and the operating frequency, and the matching conditions. Nevertheless, achieving a high effective permeability, and consequently a considerable reduction in size, requires operation under strong magnetic field conditions.

The other option is to increase the permittivity of the ferrite. This strategy allows a reduction in the resonator radius regardless of the circulator's operating conditions. The work presented in this article has followed this latter approach.

As mentioned earlier, in order to modify the physico-chemical properties of YIG while maintaining good magnetic and dielectric performance, several ionic substitutions can be performed.

The dielectric constant of pure YIG is about 15. To increase this value, yttrium was chosen to be partially substituted by bismuth ions, because bismuth has a higher polarizability than yttrium ($\gamma_{Bi^{3+}}$ = 6.12 Å^3 > $\gamma_{Y^{3+}}$= 3.81 Å^3). However, bismuth's ionic radius is larger than that of yttrium, therefore, its incorporation increases the lattice parameter, which weakens magnetic interactions and leads to a decrease in magnetization. To compensate for this loss, introducing a non-magnetic ion such as tin in place of iron allows reaching a saturation magnetization of approximately 1900 G. The incorporation of calcium also contributes to lattice stabilization by improving structural charge balance.

Furthermore, the sintering temperature of YIG, close to 1500°C, is significantly higher than that of the dielectric material (930°C) and the silver conductive lines (960°C), making it incompatible with the LTCC process. The combined insertion of bismuth and copper overcomes this limitation reducing the sintering temperature of the ferrite from approximately 1500°C to 950°C. The optimized ferrite composition presented here is $Y_{2.297-x}Cu_{0.05}Bi_{0.67}Ca_xFe_{5-x}Sn_xO_{12}$ with a permittivity of 21.

DESIGN AND FABRICATION OF CIRCULATOR

Contribution of the high permittivity of the ferrite

To evaluate the advantage of using ferrites with high permittivity, an initial design was carried out by comparing the dimensions of a circulator incorporating a pure YIG disk (εr = 15) with those using a high permittivity substituted garnet (εr = 21). The structure under study is a Y-junction using microstrip technology (Fig. 2.). The ferrite disk of radius R is surrounded by a dielectric with permittivity of εr = 20. The circulator was initially sized using the Wu and Rosenbaum model [5] to operate around 10 GHz, and then optimized through Ansys HFSS. The simulations show that the high permittivity ferrite reduces the disk radius from 2.22 mm to 1.95 mm, corresponding to a 23% decrease in surface area.

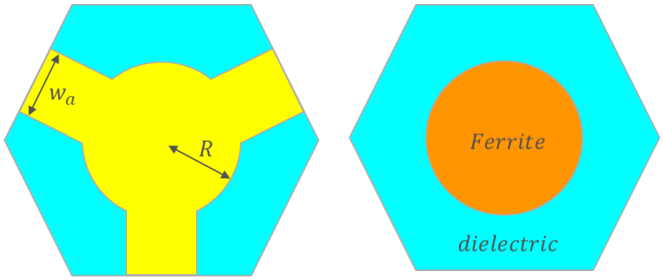


Fig. 3. Topology of the unmatched circulator

Design of a circulator with high permittivity ferrite

For practical reasons (mold availability), the ferrite radius was fixed at 2 mm. The dielectric used is a VLF220. The material properties are listed in Table 1.

	ε_r at 9.2 GHz	tanδ at 9.2 GHz	M_s (G)	ΔH_{eff}
Ferrite	21	3.10^{-3}	1900	40
Dielectric	20	1.10^{-3}	-	-

Table 1. Materials properties

The circulator was initially optimized under a uniform internal magnetic field of 40 Oe. Magnetostatic-electromagnetic co-simulations were then conducted to determine the magnet geometry required to generate a homogeneous field within the ferrite, close to the initially-targeted value. A Samarium-Cobalt magnet was selected for this purpose.

The simulation results are presented in Fig.3. The circulator has a relative bandwidth of 48.9% centered at 9.2 GHz in which isolation is greater than 15 dB and insertion losses are less than 0.6 dB with a value of 0.36 dB.

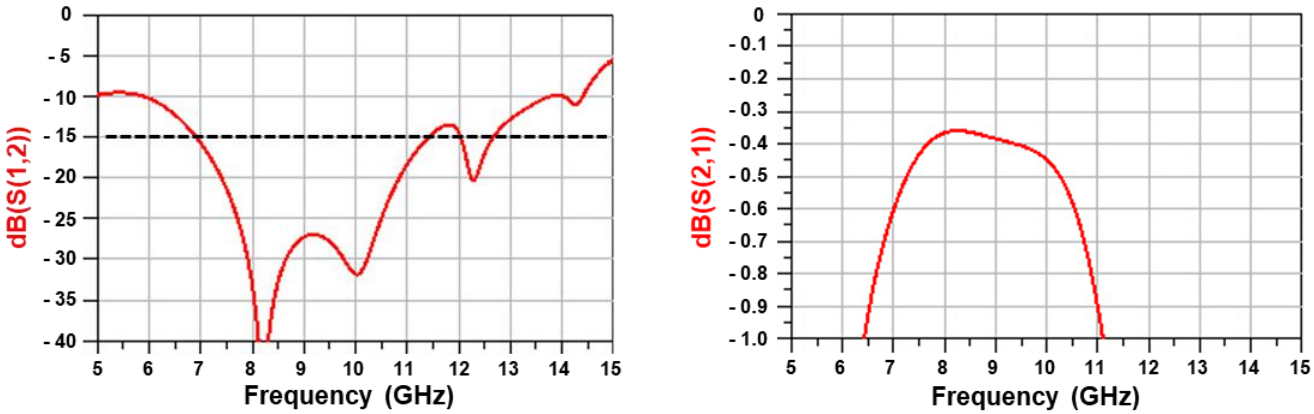


Fig. 2. Simulations of the S-parameters of the co-fired circulator

SYNTHESIS AND CHARACTERIZATION OF FERRITES

Ferrite synthesis by conventional ceramic process

The ferrite used in this study was synthesized using the conventional ceramic process, which is divided into three main stages: powder preparation, shaping, and heat treatment.

First, oxide powders are selected and weighed according to the stoichiometric composition. They are then ground/mixed in an aqueous medium using attrition milling. Once the mixture is ground, the slurry, separated from the grinding beads, is dried in an oven and then sieved to break up any remaining aggregates.

The powder undergoes an initial heat treatment called 'calcination,' which thermally activates the reaction and forms the garnet phase. The calcined powder with agglomerates, is subjected to a second attrition milling.

An organic binder (polyvinyl alcohol) is finally added to ensure the mechanical strength of the green body. The powder is subsequently placed in a steel mold and shaped by uniaxial pressing. The resulting compact is then ready for sintering.

Co-firing ferrite/dielectric/conductive lines

Initially, a ferrite pellet is inserted into a bulk piece of the dielectric. Then, silver conductor lines and a ground plane are deposited on both faces of the substrate by screen printing. The entire assembly is co-fired at 930°C, resulting in the final component as shown in Fig. 4. The obtained circulators were then characterized and the S parameters results are presented on Fig. 6.

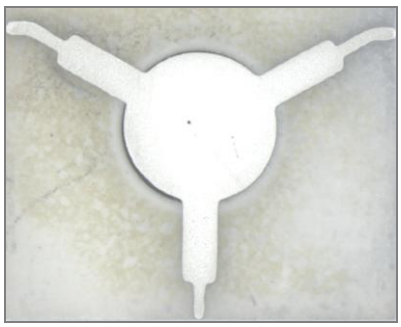


Fig. 4. View of the co-fired ferrite/dielectric assembly with silver metallization

CIRCULATOR CHARACTERIZATION

The circulator was measured in a dedicated cell for this component (Fig. 5.). The measurements confirm the strong non-reciprocity of the component but show a slight difference with the simulations (Fig. 3). The center frequency is shifted to 9.7 GHz and the losses within the bandwidth are slightly degraded, with a minimum value of 0.6 dB. However, the impact of the connectors was not accounted for in the measurements, which largely explains the discrepancy between simulation and experiment. It should also be noted that the measured relative bandwidth is close to the expected value, reaching 41.6%. These promising results confirm the potential of the developed materials for the design of compact circulator with high performance and moderate cost.

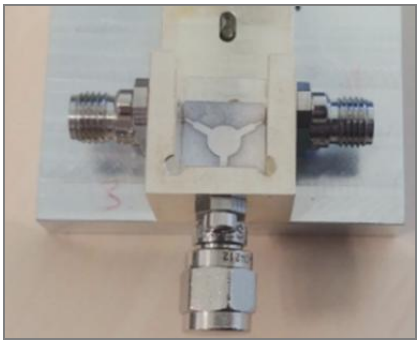


Fig. 5. Measurement cell with the circulator under test

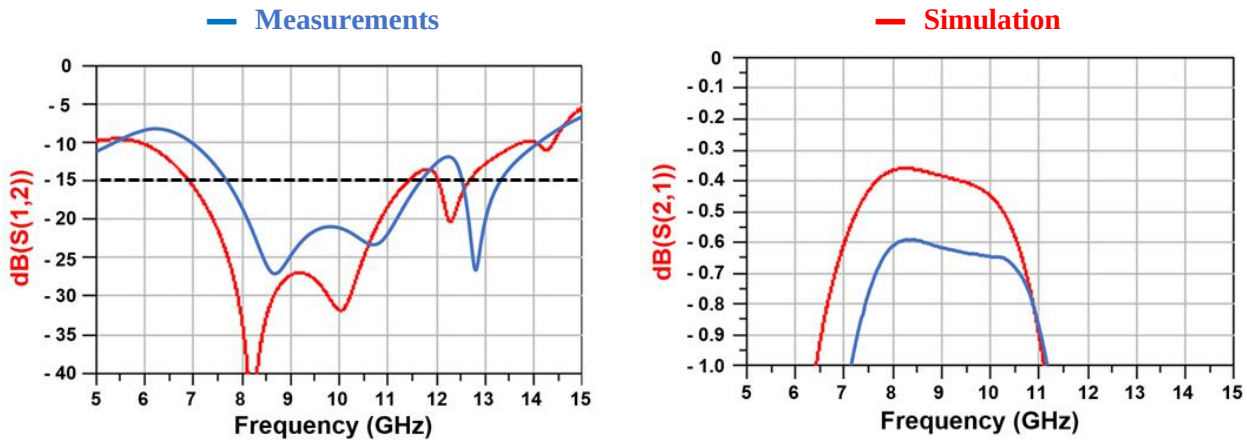


Fig. 6. Comparison between the simulated and measured S-parameters of the co-fired circulator

CONCLUSION

LTCC-compatible ferrites have been developed in this paper. Yttrium-iron garnets substituted with bismuth, copper, and tin exhibit magnetic properties suitable for the design of a circulator operating in the X-band. This material was successfully co-fired at 950°C with the VLF220 dielectric and silver-based metallization, enabling the fabrication of a demonstrator. The S-parameters of the manufactured circulator show good overall performance.

These new LTCC-compatible ferrites pave the way for the development of low-cost, compact, and efficient non-reciprocal devices operating at high frequencies Ongoing studies aim to further increase the ferrite permittivity enabling additional size reduction of future components.

REFERENCES

[1] T. Jensen, V. Krozer, and C. Kjærgaard, "Realisation of microstrip junction circulator using LTCC technology," *Electron. Lett.*, vol. 47, no. 2, p. 111, 2011, doi: 10.1049/el.2010.2419.

[2] R. van Dijk, G. van der Bent, M. Ashari, and M. McKay, "Circulator integrated in low temperature co-fired ceramics technology," in *2014 44th European Microwave Conference*, Rome, Oct. 2014, pp. 1544–1547. doi: 10.1109/EuMC.2014.6986744.

[3] L. Qassym, V. Laur, R. Lebourgcois, and P. Queffelec, "Ferrimagnetic garnets for Low Temperature Co-fired Ceramics microwave circulators," in *2018 IEEE/MTT-S International Microwave Symposium - IMS*, Philadelphia, PA, Jun. 2018, pp. 750–752. doi: 10.1109/MWSYM.2018.8439250.

[4] H. Bosma, "On Stripline Y-Circulation at UHF," *IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES*, p. 12.

[5] Y. S. Wu et F. J. Rosenbaum, "Wide-Band Operation of Microstrip Circulators," IEEE Transactions on Microwave Theory and Techniques, vol. 22, no 10, p. 849-856, oct. 1974.