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Ku-Band Microstrip Junction Circulators Manufactured using Low Temperature Co-fired Ceramics Technology

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Abstract — The high cost and size of circulators have always been the main drawbacks of these components. Low temperature co-fired ceramics technology (LTCC) could reduce the cost by simplifying the manufacturing process. Two new ferrites with low sintering temperature were developed and evaluated: a garnet-based ferrite with a high permittivity and a spinel-based ferrite with a high saturation magnetization. Two circulators based on these ferrites have been designed using coupled magnetostatic and electromagnetic simulations and fabricated. Their insertion losses and sizes are very close. The high magnetization of the spinel ferrite allows a bandwidth twice as high as the garnet-based circulator. Both circulators showed good performance and demonstrate that low temperature co-fired ceramics technology can be used for the collective realization of low cost circulators.

Index Terms—Ferrite devices, Circulators, Ceramics, LTCC.

I. INTRODUCTION

Ferrite based devices such as circulators or isolators are known for their bulkiness and high cost. However, despite these drawbacks, they are commonly used for RADAR applications and in particular for Active Electronically Scanned Arrays (AESA). In this case, each transmit/receive module is independent and individually controlled, meaning each module needs a circulator to achieve full duplex operation.

The Low Temperature Co-fired Ceramics (LTCC) technology could allow a simplification of the usual circulator fabrication process and thus reduce the cost of these components. Complicated procedures requiring tooling or glue become redundant as they are unnecessary in the usual LTCC workflow. However, the development of new ferrimagnetic materials, generating the non-reciprocal response of the circulators, compatible with this fabrication process is essential to improve the existing LTCC circulator performance [1]–[5].

Two new types of ferrimagnetic materials, garnets derived from Yttrium Iron Garnets (YIG) and spinels derived from nickel-zinc ferrites, have been developed. The garnet ferrite offers a lower saturation magnetization M_s coupled with a high permittivity whereas the spinel ferrite has a higher saturation magnetization coupled with a more moderate permittivity (Table 1). The dielectric used is the commercially available

VLF220. By designing and measuring Y-junction circulators on both of our ferrimagnetic materials, we will try to identify their respective strengths and weaknesses.

Table 1. Materials properties

Material	ϵ_r	$\tan\delta$	$4\pi M_s$ (G)	ΔH (Oe)
Garnet1900	21	$3 \cdot 10^{-3}$	1900	100
Spinel3800	13	$1 \cdot 10^{-3}$	3800	100
VLF220	21	$3 \cdot 10^{-3}$	-	-
Teflon™	2.1	$1 \cdot 10^{-3}$	-	-

II. FERRITES SYNTHESIS AND CHARACTERIZATION

Both of the ferrites used in this work have been synthesized using dry process grinding. The main steps of this procedure are detailed below:

- Weighing and grinding of the raw materials
- Calcination: thermal treatment during which the crystalline phase will form
- Second grinding: increases the powders reactivity
- Formatting (axial or isostatic pressing, tape casting...)

A. Garnets

The base formulation of our study is $Y_3Fe_5O_{12}$. Adapting the characteristics of this garnet is possible by means of substitutions made in the specific sites of its crystallographic structure (occupied by Fe^{3+} ions - tetrahedral Δ and octahedral \square sites and Y^{3+} ions – dodecahedral sites). In our case, for a Ku-Band circulator, these substitutions will allow us to adapt the saturation magnetization, the permittivity and the sintering temperature.

In order to increase the saturation magnetization, the magnetic moment in octahedral sites must be lowered. By substituting the iron by a non-magnetic ion, such as zirconium, whose preferred spot is an octahedral site, the saturation magnetization can be controlled. A saturation magnetization of around 1900G can then be achieved by a judicious picking of the iron by zirconium substitution ratio.

The initial sintering temperature of the YIG is around 1450°C. In [5], it has been established that substitutions of the yttrium ion by bismuth and copper ions allows a notable decrease of the sintering temperature, from 1450°C to 950°C. Furthermore, the utilization of bismuth ions, which has a strong polarizability, enables a substantial increase of the permittivity, jumping from 15 for a basic YIG to 21 for our garnet.

B. Spinels

The spinel developed is a Nickel-Zinc (NiZnFeO) ferrite. Copper is added as substitute in octahedral sites for purposes of adjusting the sintering temperature. Coupled with the use of bismuth oxide with a low melting point (added between the calcination and sintering stage), the sintering temperature can be lowered to 950°C.

The adjustment of the saturation magnetization is possible through the variation of the Ni/Zn ratio as shown in Fig. 1.

For each value of saturation magnetization between 3000 and 5000G, two different ferrite compositions are available. In our case, the intended saturation magnetization is 3800 G. Two compositions have thus been selected. As the electromagnetics properties of both of these ferrite compositions are similar, they will both be named Spinel3800 in the rest of the paper. The choice regarding which composition will be used to manufacture the components will be made following the sintering tests with our dielectric material.

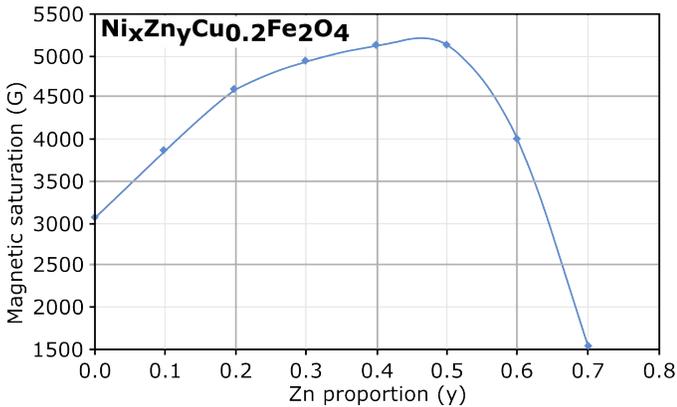


Fig. 1. Saturation magnetization variation depending on the zinc rate ($x + y + 0.2 = 1$).

III. CO-FIRING EXPERIMENTS

Some trial runs have been done using the usual LTCC workflow. The different steps of the fabrication are illustrated in Fig. 2.

The used lamination parameters are a 10 MPa pressure for 20 minutes at 75 °C. The 10 MPa pressure is lower and the duration is longer than those commonly used in the LTCC process (21 MPa for 10 minutes at 70 °C). However, these parameters allowed a correct association of the two materials. The sintering consisted of a progressive increase in temperature until 950 °C. This temperature is maintained for 2 hours.

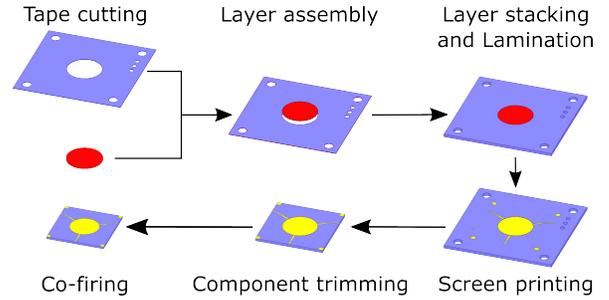


Fig. 2. Materials assembly steps: ferrite in red; dielectric in blue

One obtained sample for the Garnet1900-VLF220 association is shown in Fig. 3. The ferrite cylinder is centered and no delamination could be noted. The interface between the materials is net and no gap has been observed. However, achieving a good co-firing of Spinel3800-VLF220 association has been more challenging than anticipated. While the work on this association continues, the VLF220 dielectric has been replaced by a substitution of the Spinel3800 allowing it to have a null magnetization so that this material can acts as a dielectric surrounding the ferrite resonator.

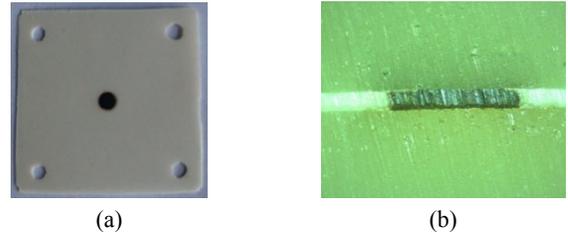


Fig. 3. VLF220-Garnet1900 assembly: (a) Top view; (b) Split view

To speed up the fabrication of the circulators while the conventional LTCC process is improving, a mould was used to assemble the two different materials before sintering. This allows the fabrication of a bigger substrate assembly in which a slice will be cut and polished to achieve the desired substrate thickness.

IV. CIRCULATORS DESIGN AND MEASUREMENTS

The dielectric and magnetic properties of the materials which will be used in our designs are given in Table 1. These properties have been used to design two Y-junction circulators in the Ku-Band. Bosma theory [6] was applied to model both ferrites. Quarter wavelength impedance transformers were used to broaden the bandwidth of both designs. The designs were computed and optimized using the Ansys Electronic Desktop suite via a coupled magnetostatic (Maxwell3D) and electromagnetic (HFSS) computation. The magnetostatic solver determined the mapping of the magnetic field inside our ferrite. This mapping was then imported as magnetic bias in the electromagnetic solver for our ferrite. The biasing field is thus not homogeneous and is more in phase with the reality. The permanent magnet used for these designs is a Magsy YXG-28 magnet with a diameter of 3 mm and a height of 2 mm.

As stated earlier, the measured substrates were built using a mould. The screen printing has thus been realized on an already sintered substrate. Furthermore, in order to use a single mould and thus reduce the overall cost, both resonators will have the same diameter of 2.2 mm. However, the size of both Y-junctions with their impedance matching transmission lines are similar.



Fig. 4. Manufactured circulators: (a) Garnet1900-based; (b) Spinel3800-based

A. Garnet1900 based circulator

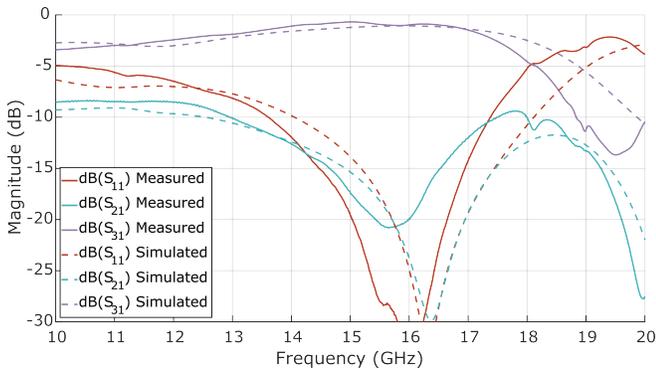


Fig. 5. Comparison between the measured and simulated S-Parameters for the Garnet1900 based circulator. Adaptation in red, Isolation in cyan and Transmission in purple.

The comparison between simulated and measured S-parameters of the Garnet1900-based circulator is presented in Fig. 4. A slight frequency shift can be observed but overall, the measured response is in good agreement with the simulated one. A 1.87 GHz bandwidth at -15 dB has been achieved with insertion losses lower than 1.05 dB. The minimal insertion loss was of 0.68 dB at 15.04 GHz.

B. Spinel3800 based circulator

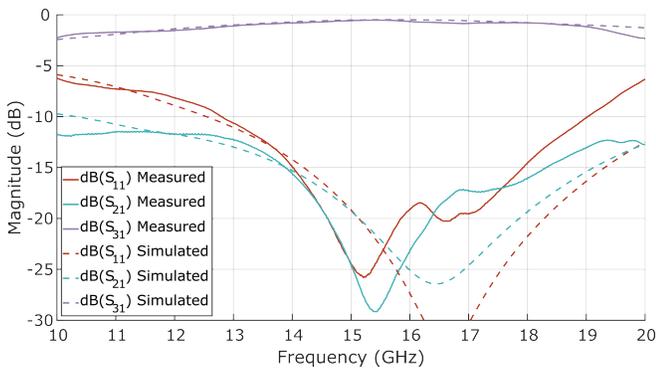


Fig. 6. Comparison between the measured and simulated S-Parameters for the Spinel3800 based circulator. Adaptation in red, Isolation in cyan and Transmission in purple.

The comparison between simulated and measured S-parameters of the Spinel3800-based circulator is presented in Fig. 5. Again, a frequency shift is observed. The broadband behaviour obtained in simulation has been confirmed in practice. A 3.91 GHz bandwidth at -15 dB has been achieved with insertion losses lower than 0.86 dB. The minimal insertion loss was of 0.53 dB at 15.36 GHz.

V. CONCLUSION

Two new LTCC compatible ferrites, a garnet and a spinel, have been developed. Co-firing the garnet with a commercial dielectric has been successful. For the spinel ferrite, a non-magnetic variation of the same material has been developed in order to fabricate the circulator.

Both ferrites were used to design and manufacture two LTCC circulators. The measurements were in good agreement with the simulations except slight frequency shifts. The spinel-based circulator provided the best performance with lower insertion losses and a wider bandwidth. These results demonstrate that LTCC technology can be used for the collective realization of low-cost circulators.

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