Ku/K-Band LTCC SMD Circulator for Space Applications

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INTRODUCTION

In light of the increasing need to meet the RF systems requirements, circulators, as key components, have been the subject of research for several years. Conventional circulators are commonly based on Y-junction shape designed in stripline or microstrip technology. Stripline circulators are simple to integrate and induce low losses. This circulator topology can be connectorized through coaxial connectors, realized in a Drop-in technology or built in a Surface Mount Device (SMD). Despite their higher cost, coaxial circulators have higher EMC shielding and power handling capabilities than others. Furthermore, Drop-in devices handle less power and have no EMC shielding. Finally, SMD circulators have lower power handling capability than coaxial circulators but have better EMC shielding than Drop-in. Facing the growing need of miniaturization, integration, and cost reduction, the LTCC (Low Temperature Co-fired Ceramics) technology is a promising candidate to meet these challenges. LTCC technology is a technique for housing integrated circuits through a multilayer structure. It consists of stacking tapes, which prevents air gaps in the junction, and reduce multipaction risks for high power space applications. In the past years, many published studies focused on the design of LTCC circulators [1]-[2]. Nevertheless, most of them were theoretical and only a few focused on industrial purposes [3]. Hence, Exens-Solutions, in collaboration with CNES, Thales TRT and IMT Atlantique, have proposed LTCC technology to develop a K-band circulator to protect active antennas. The circulator is designed by Exens-Solutions based on specifications agreed with CNES. IMT Atlantique is in charge of the circulator manufacturing process. The ferrite and dielectric materials tapes are developed by Thales TRT.
Thus, the present paper is divided into four sections. The first section presents the LTCC circulator specifications and details the materials properties. A dry run to establish the design rules is described in the second Section. The design steps and simulations of the LTCC circulator are discussed in the third Section. The manufacturing steps and measurement results are reported in the last Section.

LTCC CIRCULATOR SPECIFICATIONS

Preliminary proposed topology

The stripline topology is adopted for the design of LTCC circulators housed in their packages. This topology has the advantage of miniaturizing the circulator and avoiding any damage of the metal paths. As shown in Fig.1, signal and ground vias are added to the LTCC structure to ensure its interconnection with an SMD surface.

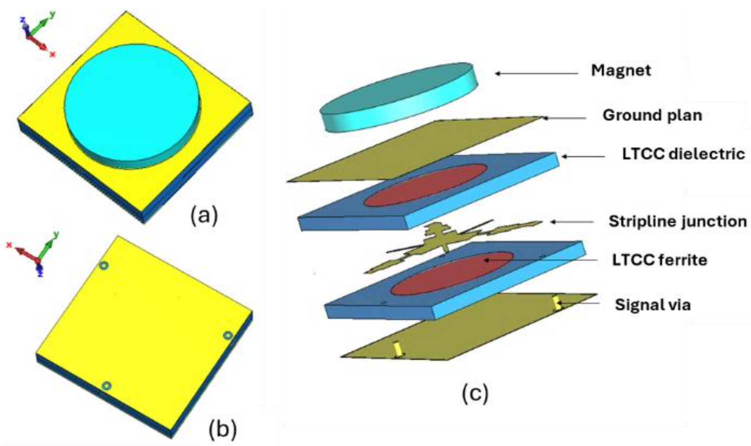


Fig. 1. Preliminary illustration of the stripline LTCC circulator, (a) top view, (b) bottom view and (c) detailed view.

RF characteristics

The selection of ferrite and dielectric characteristics is made to achieve the requested performances detailed in Table 1. To ensure an optimum functioning of the LTCC circulator in the desired frequency band (16GHz-22GHz), a weak-field polarization is required. The choice of the ferrite saturation magnetization is based on the Equation (1):

$$\frac{f}{3\gamma} < M_s < \frac{3f}{4\gamma} \qquad (1)$$
$$2261 < M_s < 5089$$

Table 1. LTCC circulator specifications

		Initial target		Long term target	
Parameters	Unit	Min	Max	Min	Max
Frequencies	GHz	17.3	20.2	16	22
Insertion loss	dB	-	0.7	-	0.5
Losses variation	dBpp	-	0.1	-	0.1
Isolation	dB	15	-	20	-
Return loss	dB	15	-	20	-
Power handling	W	-	1	-	10
Dimensions	mm3	5x5x4		5x5x3	

For this first development, a power handling of 1W is required, hence the choice of a non-doped ferrite that will minimize insertion losses. Given these characteristics, an NZC38 (Nickel-Zinc-Copper) ferrite is proposed by THALES TRT with a high saturation magnetization (*Ms*) and a permittivity of 14. As for the dielectric, two materials have been suggested: the first with permittivity of 14 and 21 for the second. The material selection will be done after electromagnetic simulations.

Ferrite material validation: test vehicle

A test vehicle is suggested to validate the operation of the ferrite proposed by THALES TRT in the targeted frequency band.

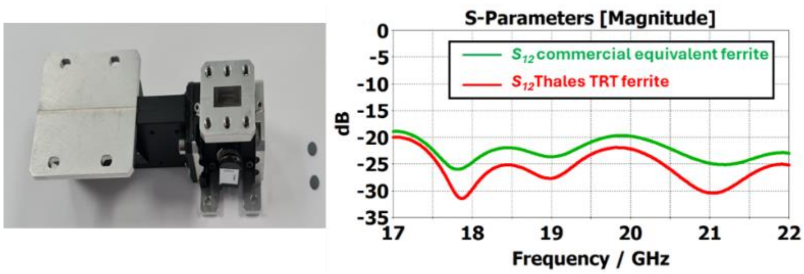


Fig. 2. Test vehicle isolation comparison results between commercial equivalent ferrite and Thales TRT ferrite.

Thanks to its low manufacturing dispersion effects due to limited mechanical and assembly tolerances, a rectangular waveguide isolator (RWG) with a WR51 flange is chosen. The RWG offers greater flexibility in gluing and ungluing the ferrite, which facilitates comparison between the ferrite proposed by THALES TRT (NZC38) and a conventional ferrite from Exxelia [5]. The latter was chosen for its characteristics, which are sufficiently close to those of THALES TRT to allow a better comparison. These two ferrites were tested on the same RWG after in-house machining. The measured isolations, with each ferrite, are shown in the Fig.2. The measurements comparison shows a good agreement between these two configurations. A slight non-conformity is observed due to the difference in *Ms* and ε_r of the two materials. The performance of the RGW remains satisfying and validates the correct operation of the TRT ferrite in the targeted frequency band.

DRY RUN & DESIGN RULES

This preliminary study was carried out by IMT Atlantique to acquire a better understanding of the manufacturing phases and constraints of LTCC circulators in stripline technology. The developed prototypes are not fully functional and are based on LTCC tapes already available at IMT Atlantique (A6M-E). The coplanar structure consists of a stack of 15 layers of A6M-E (Fig.3), the last 5 layers are fugitive tapes with inserts to house the magnets.

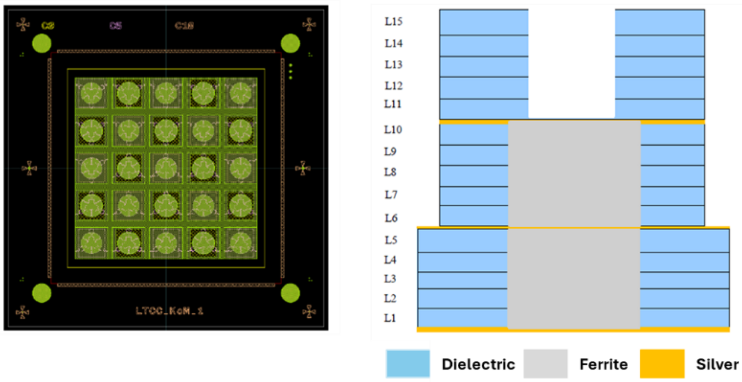


Fig. 3. Dry Run: Preliminary realization of a stripline LTCC circulator based on A6M-E layers.

This prototype highlighted several issues to be considered during the final phase of the circulator's development. The non-planarity of the surface of the ferrite layers led to a metallization problem during the screen-printing and drying phases, as shown in Fig.4. However, this problem is unlikely to occur with the tapes made by Thales TRT. For a more reliable design, the L6-L10 layers will be replaced with dielectrics. The minimum number of layers is set at 5 with a thickness of 102,5µm after the circuit firing process. The metallized layers are connected through vias with a minimum diameter $Ø_{via}$=80µm. To ease their filling with conductor material, the vias are surrounded with catch pad ($Ø_{catch\_pad}$= $Ø_{via}$+100µm) on each layer.

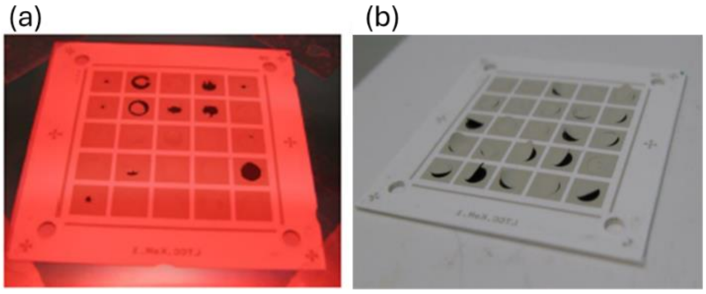


Fig. 4. (a) Metallization default after screen printing process, (b) Metallization removal problem and ferrite detachment during the drying phase.

All these manufacturing constraints allowed to define design rules to be applied for the final phase of the LTCC circulator manufacturing.

DESIGN AND SIMULATION OF LTCC CIRCULATOR

Circulators in LTCC technology are a good alternative for more robust and automated design. As a result, it is crucial to strengthen the simulation reliability. Unlike for other topologies, LTCC circulators are not tunable once prototyped. Therefore, their optimization process should be controlled, and all simulation constraints must be considered.

Stripline junction

The first simulations aimed to define the stripline topology. The number of ferrite and dielectric layers and the junction dimensions are optimized to obtain better performances in the operating frequency band. The chosen structure consists of a stack of 2 dielectric ($\varepsilon_r=14$) bottom layers with 3 upper ones separated by a stripline junction. Two ferrite NZC38 layers are embedded into the bottom dielectric and two ground planes are placed at the upper and lower sides of the circulator. The whole structure is shielded by adding ground vias, which reduce-insertion losses (Fig.5). The device is fed through waveguide ports with an input impedance of 50Ω.

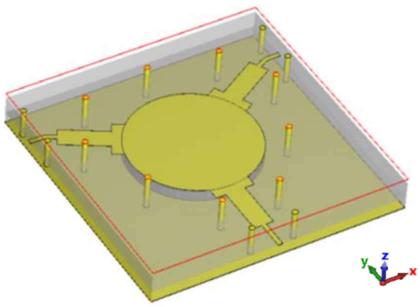


Fig.5. Preliminary design of the LTCC circulator.

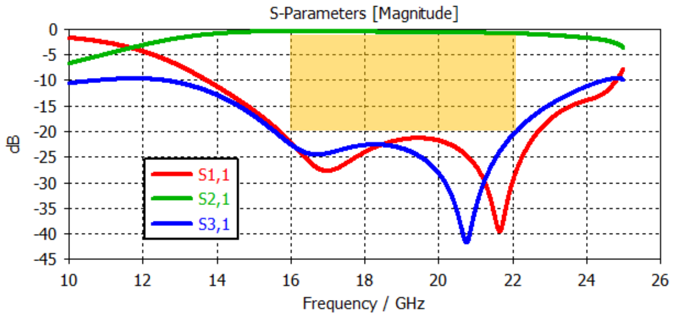


Fig. 6. Preliminary LTCC design simulation results.

The simulation results, in terms of return loss, isolation and insertion losses are illustrated in Fig.6. From these curves, it is obvious that the results are compliant with the specifications. The return loss on the 3 ports is less than -20dB over the entire frequency band. The isolation also meets the specifications (<-20dB). Regarding the insertion loss, they are lower than 0.5dB. However, they remain approximative and should be confirmed after measurements.

LTCC circulator fed through CPW-to-stripline vertical transition

Once the preliminary approach is validated, the challenge is to develop an LTCC circulator optimized for reliable production. The idea was to consider a coplanar waveguide (CPW) to stripline vertical transition to ease the device integration into SMD technology [4]. The parameters of the CPW-stripline transition are set to respect the design rules and to obtain an impedance of 50Ω. Consequently, an intermediate ground plane is designed on the third dielectric tape layer. Ground vias are also added to the structure to obtain a better shielding. The designed LTCC circulator with the CPW-stripline transition is shown in Fig. 7.

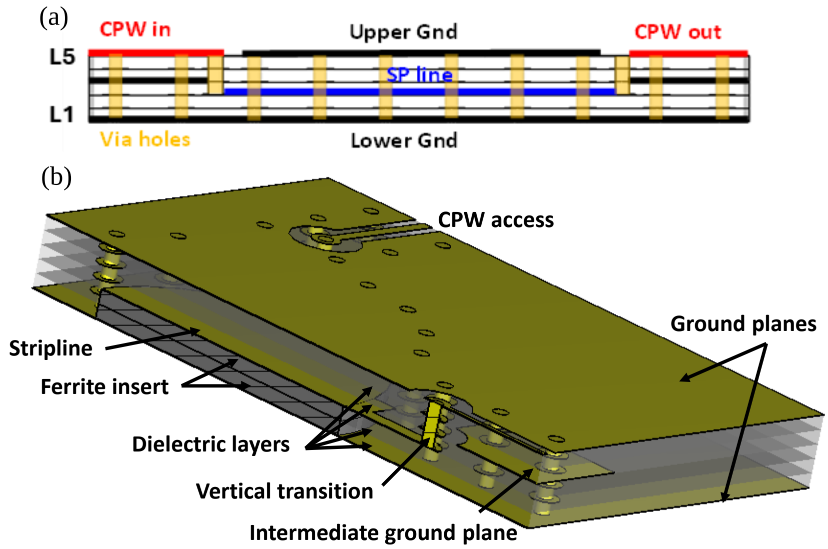


Fig. 7. Design of the LTCC circulator fed with a CPW-Stripline transition. (a) layer view, (b) Section view.

The S parameters of the circulator are shown in Fig.8. These results show good impedance matching in the full operating frequency band with return loss and isolation below -20 dB up to 21.5 GHz. Regarding insertion losses, they are approximatively lower than 0.5dB.

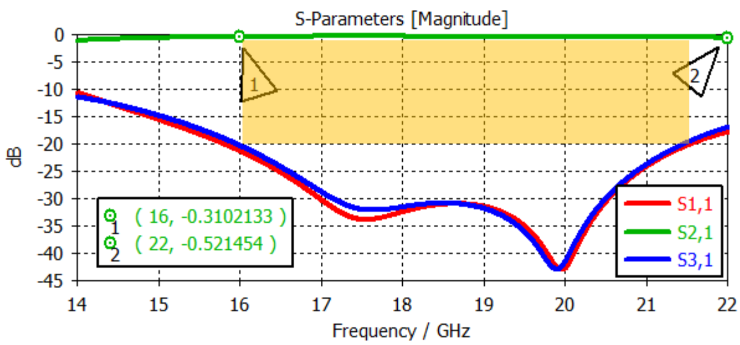


Fig. 8. LTCC circulator simulated S parameters.

Once the simulation results are compliant with specification, the manufacturing process can start.

MANUFACTURING OF THE CIRCULATOR

The device layers configuration is transmitted to IMT Atlantique to implement production. The circulators are built with five layers, which include ferrite inserts in two of them. On the same wafer, the test transmission lines (Fig.9 (a)) are integrated to measure the CPW-stripline typical transmission loss. The first realization step consists in cutting the via holes and cavities using a Nd:YAG 1064nm laser (Fig.9 (b)-(c)). The vias are then filled with conductive material (Fig.9 (d)). Conductor patterns are subsequently screen-printed using gold paste, which is more suitable for ferrite material (Fig.9 (e)). Screen printing is followed by stacking the different layers, which allows them to be assembled and better aligned. Before that, the ferrite inserts are placed in the dedicated cavity. The structure is then laminated to avoid any air gaps between its different layers. The top gold on the ferrites is screen printed before the circuit is fired at a temperature of 920°C (Fig.9 (f)). Finally, measurements are done on a probe station with thermal chuck, using 150 µm pitch GSG probes and a 67 GHz VNA. These CPW measurements aim to validate the LTCC circulator topology. Although, for commercial purpose, SMD pads will be added to the device to ensure interconnexion with the end user RF system.

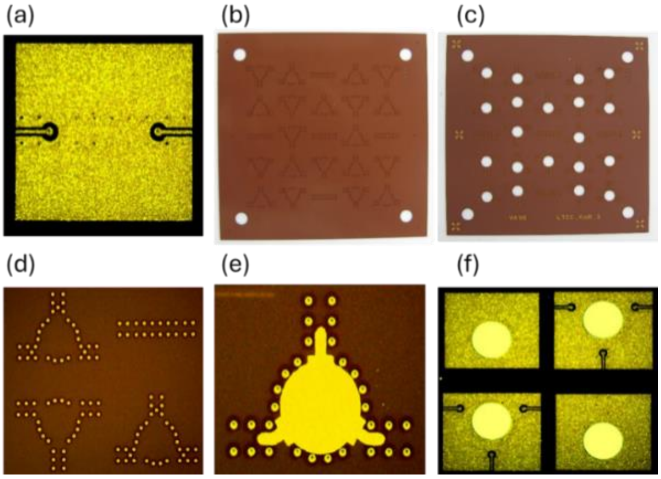
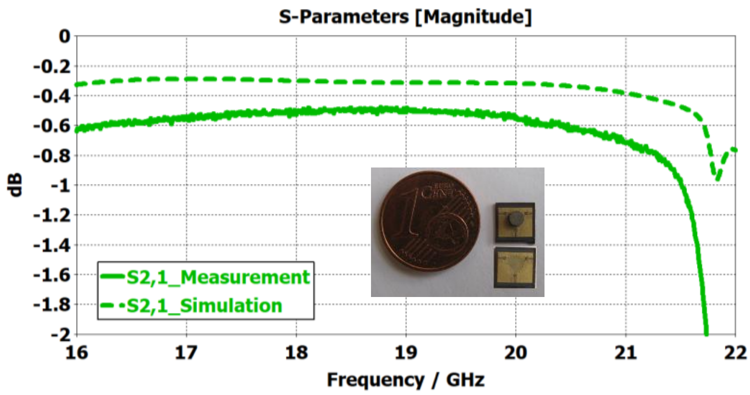
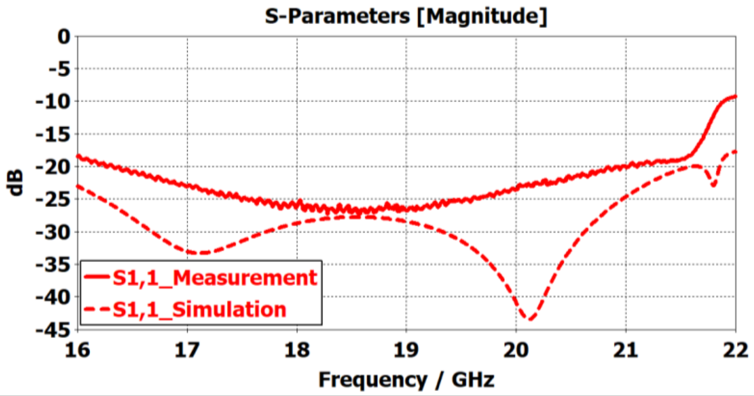


Fig. 9. Fabrication process, (a) test transmission line with ground plan vias, (b) via holes cutting, (c) ferrite cavity inserts creating, (d) via holes filling, (e) conductor patterns screen-printing, (f) top gold screen printed.





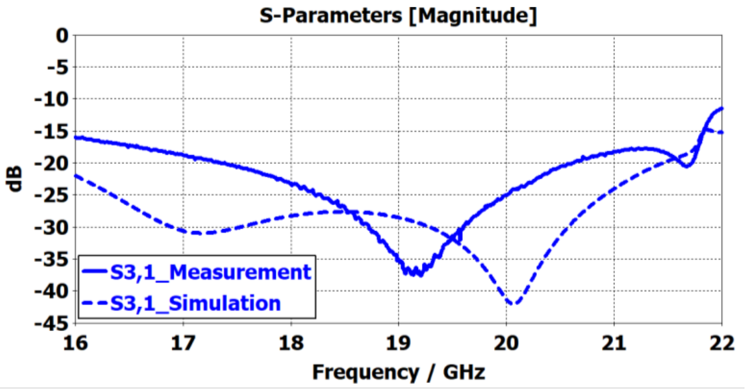


Fig. 10: Measured S parameters Vs simulated S parameters.

Table 1. Comparison of the requested and obtained LTCC circulator performances.

	Specification		**Measured results**	
	Typical	**Max**	**Typical**	**Max**
Frequencies (GHz)	[17-22]	[17.3-20.2]	[16-21]	[17-20.5]
Insertion Loss (dB)	0.5	0.7	0.6	0.57
Return Loss (dB)	20	15	19	22
Isolation (dB)	20	15	16	19
Dimensions (mm^3)	5x5x4	5x5x3	5.48x4.6x2.5	

CONCLUSION

A Ku/K-band LTCC circulator is presented in the current paper. The design process is also detailed, and the simulation results discussed. The device is built with 5 layers of dielectric and 2 ferrite disk inserts. The circulator is fed through CPW-stripline vertical transition for future integration purposes. The fabrication steps are shown, and the measurement results are in alignment with the simulated performances, meeting the initial target specifications.

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