Journal of
Ceramic Science
and Technology

J. Ceram. Sci. Tech., **06** [04] 267-272 (2015)
DOI: 10.4416/JCST2015-00058
available online at: http://www.ceramic-science.com

Tolerance-Optimized RF Structures in LTCC for mm-Wave Frequencies Applications

J. Balcells-Ventura*, T. Klein, P. Uhlig, C. Günner, R. Kulke

IMST GmbH, Kamp-Lintfort, Germany

received September 8, 2015; received in revised form October 30, 2015; accepted November 6, 2015

Abstract

Low-Temperature Co-fired Ceramic (LTCC) is a well-established technology for microwave space products and RF structures and it is a good candidate for these new frequency bands. Embedded passives are available to increase the density of integration even more. At higher frequencies, structures become smaller and more prone to process tolerances. This challenge is addressed here with two novel mm-wave tolerance-optimized RF concepts in LTCC: load termination and Gysel power splitter. The concept presented here minimizes the effect of fabrication tolerances to provide stable RF response.

Keywords: LTCC, tolerances, Gysel power splitter

I. Introduction

Communication systems are migrating towards mm-wave frequencies in order to achieve larger channel capacity. This migration requires new materials and technologies in order to fulfil accuracy and tolerance requirements. Low-Temperature Co-fired Ceramic (LTCC) has proven to be one technology candidate. It provides advantages such as size reduction and 3D integration, but process tolerances introduce difficulties at high frequencies.

One area of interest is satellite communications systems at Ka-band. The aim of the system is to cover large areas with high efficiency. To increase the efficiency, different capacity is required depending on the region: high traffic is required in highly populated areas and low traffic in rural regions. One approach to increase the efficiency is to divide the service area into cells and use an efficient frequency-reuse technique such as a four-colour topology [1]. The four-colour topology uses for adjacent cells, either four different frequencies or two frequencies with two different polarisations. The first approach to implement such a topology would require a complex system where each cell would require an independent antenna feed and at least four reflectors would be needed. A very compact solution was presented in [2] with the Multiple Feed per Beam (MFB). This solution proved to reduce the reflector positioning system complexity using fully steerable beams with phase shifters. Also, the use of LTCC provided a high integration level and reduced weight and dimensions. One of this solution's drawbacks is that the Beam Forming Network (BFN) is very sensitive to amplitude and phase variations.

The work presented here aims to show alternative structures for the feeding networks used at BFN, which provide stable amplitude and phase with regard to manufacturing tolerances. Tolerance-optimized RF loads and a Gysel power splitter in LTCC have been designed to operate at the frequency band of 27.5 to 31 GHz.

II. RF Load Tolerances in LTCC

A proof of concept for the BFN manufactured on LTCC was presented in [2]. The feeding network was based on stripline with Wilkinson power dividers. A -35dB isolation level between adjacent ports of the network was reported. This value was achieved by using a cascade of three power divider stages and is limited by a single divider's performance.

Manufacturing stripline 50Ω Wilkinson power dividers in LTCC, two critical points are observed. First, the buried resistors' tolerances are very high. The resistor paste presents a ± 20 % tolerance of the sheet resistivity (Ω/sq) which has to be added to the LTCC process tolerances (printing, layer stacking and shrinkage). When the resistor is on the top layer, the tolerances may be compensated by means of laser fine tuning, but this solution is not possible for buried resistors. The second critical point is the minimum conductor width printable on LTCC, which is 100 μm for standard processes (lower line widths may be achieved with fine line techniques [3]). This is combined with the fact that the substrate thickness for a single layer is limited in order to avoid any spurious waveguide or parallel plate modes. Both limitations result in a maximum characteristic line impedance of 50 to 55 Ω, away from the 70.71 Ω required in a Wilkinson power divider at 50 Ω systems. A solution to compensate for the printing accuracy is to transform the system to 25 Ω characteristic impedance, but that would need an impedance transformer at the network input and output ports [1].

In the case under study, the sheet resistivity tolerance influences on a stripline Wilkinson divider have been analyzed. Fig. 1 shows the ports' isolation for the resistor

* Corresponding author: balcells@imst.de

paste nominal resistivity and for the tolerance extremes. It can be seen how at the frequency band of interest (27.5 to 31 GHz), the isolation drops from 20 dB to 16 dB and the resonant frequency is shifted. Also, the insertion loss has a variation owing to the resistivity. The simulations (not shown in figure) presented an insertion loss variation of 0.1 dB, which is a big contribution to the overall amplitude variation of 0.25 dB targeted for the BFN.

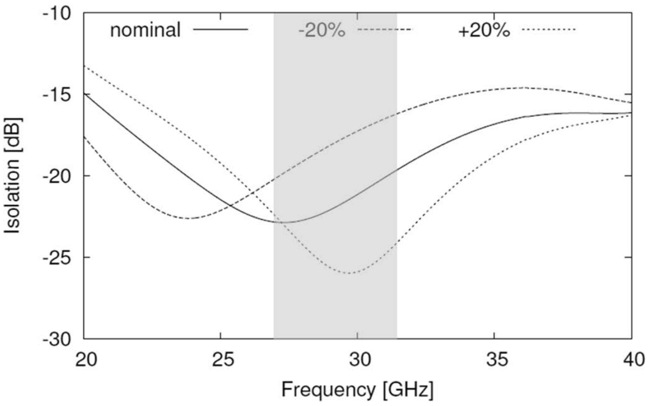

Fig. 1: Wilkinson power dividers ports isolation: nominal resistivity and extreme tolerances.

III. Tolerance-Optimized RF Loads in LTCC

To overcome the tolerances of the LTCC resistor paste, a tolerance-optimized RF load has been designed. Fig. 2 shows a 3D model of the proposed structure, based on the LTCC multilayer characteristics. The RF load concept has been simulated and optimized for DuPont 9K7 system (ε_r =7.1 tanδ =0.0015 @ 40 GHz), with a stack of two layers, each 225 µm thick.

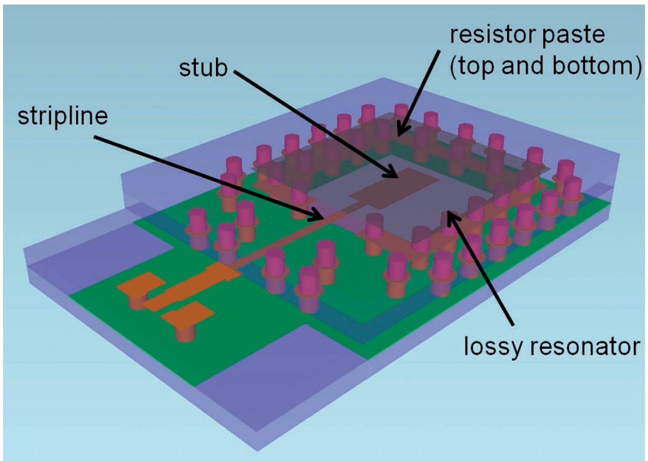

Fig. 2: RF load model.

The RF load consists of a stripline stub that ends into an LTCC lossy resonator. The resonator side walls are defined by two rows of metal-filled staggered vias. Technological limitations impose a minimum distance of 2.5 x via diameter (in the example presented it is 500 µm) between two consecutive vias. A surrounding metal frame in all layers, not shown in the model for the sake of clarity, interconnects all the vias to ground. The resonator top and bottom planes define an area of 2 mm x 2 mm and are printed with resistive paste of 120 Ω/sq±20%. The resistive planes are overlapped (300 µm) with the surrounding metal frame. Relaxed design rules have been applied by printing a larger resistive paste area. Also, the fact that both planes are overlapped with the surrounding metal frame lays the dimensions precision on the conductor paste printing process, which is higher than resistor paste printing.

Three different approaches have been designed. The first approach has been designed to work at high frequencies, the second approach is designed to have a larger bandwidth and the third approach is designed to work from DC to high frequencies. All structures have been modelled and optimized with the commercial software Empire XPU[4] based on the Finite Difference Time Domain method (FDTD).

(1) Stub fed lossy resonator

The first approach is based on the original idea where the stripline stub is ended into a lossy resonator. Length and width of the stub have been optimized to obtain a broadband load at high frequencies. Fig. 3 shows the current distribution on the top lossy plane at 25 GHz. It can be seen how the active area at this frequency is mainly concentrated above the stub. Fig. 4 shows the simulated return loss of the structure for the paste nominal resistance and its maximum variations. The design with the nominal value shows an RF load impedance matching 15 to 50 GHz. The different resistor paste values present large variations on the return loss for the lower frequencies of the bandwidth while not much influence is observed for frequencies higher than 35 GHz. In this structure, no variations of the resonant frequency are observed when the resistor paste is changed. That proves a more stable performance despite the large tolerances.

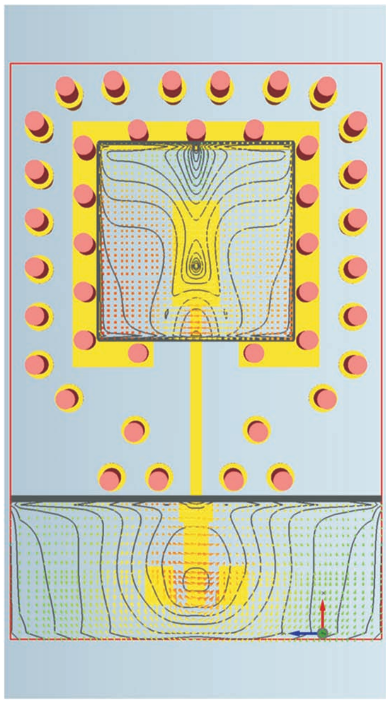

Fig. 3: Current distribution on the top lossy plane at 25 GHz for stub fed lossy resonator.

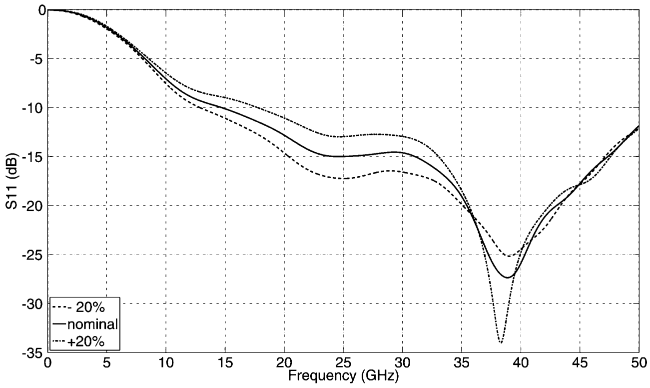

Fig. 4: RF load approach A simulated return loss.

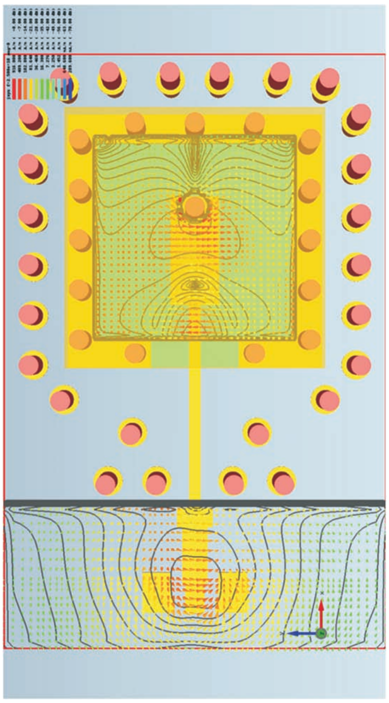

Fig. 5: Current distribution on the top lossy plane at 25 GHz for stub via connection.

(2) *Stub via connection*

A second approach pursuing a larger bandwidth and also a less sensitive performance has been designed. In this case, the centre stub is connected to the top and bottom resistor planes by a metal-filled via. Length and width of the stub together with via positions have been optimized. Fig. 5 shows the current distribution at 25 GHz on the top lossy plane. It can be seen how the active area at this frequency is mainly concentrated on the vias. Fig. 6 shows the simulated reflection coefficient. A wider band than with the first approach is observed with a frequency band from 5 to 47 GHz. Also, the influence of the resistor paste variations is much lower for all the frequencies.

(3) *Resistor aperture*

The third approach aimed at an RF load with a larger bandwidth that could operate from DC to 50 GHz. This approach is a variation on the second approach. In this case, an aperture on the resistor plates has been opened, as shown in Fig. 7. That way, the current distribution has been optimized to reduce the return loss for the lower frequencies. The simulated reflection coefficient is shown in Fig. 8. The designed RF load presents a S_{11} lower than -10 dB from DC to 50 GHz. Variations on the resistor paste show small variations of the load performance.

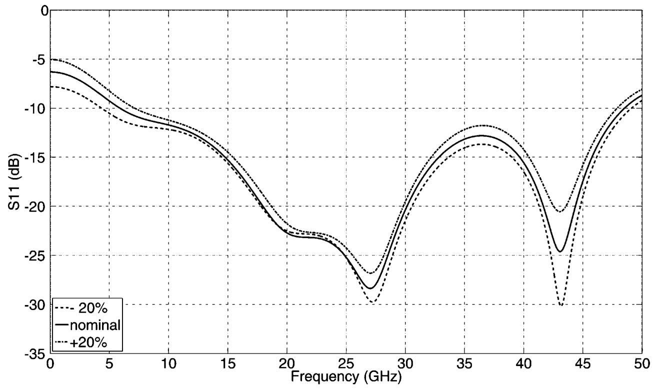

Fig. 6: RF load approach B simulated return loss.

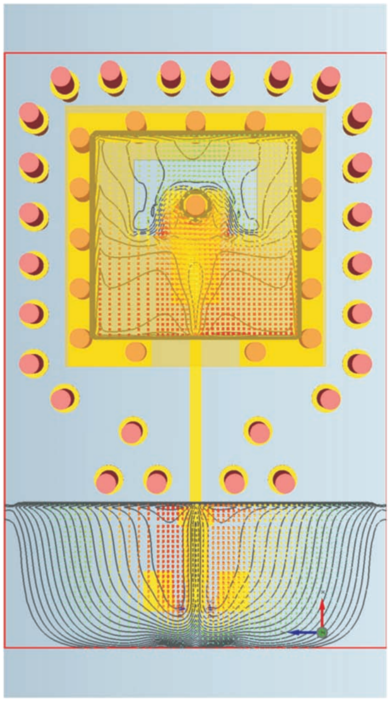

Fig. 7: Current distribution on the top lossy plane at 25 GHz for resistor aperture.

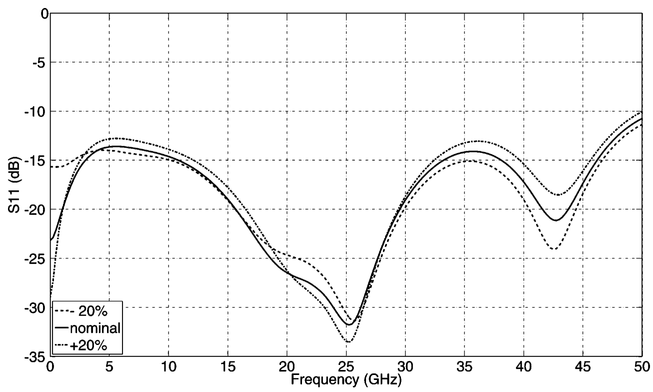

Fig. 8 : RF load approach C simulated return loss.

IV. Optimized feeding networks using Gysel power splitter

The challenges observed when designing and manufacturing stripline Wilkinson power dividers in LTCC lead to the necessity to find alternative structures without such sensitivity to resistor paste variations as well as to the LTCC linewidth printing precision and tolerances. One candidate for such structures is the Gysel power splitter [5]. This structure has more degrees of freedom than the Wilkinson divider design and the LTCC design rules in terms of linewidth may be relaxed [6]. In addition, the transmission line length that connects the RF loads may be arbitrary, thus the position of the loads may be placed as best fit to the design without any influence on the final performance. The use of one port RF loads lead to the use of the tolerance-optimized RF loads in LTCC presented in the previous section.

A Gysel power splitter in DuPont 9K7 has been modelled (Fig. 9) and designed with Empire XPU. The RF loads have been optimized for the targeted frequency band (27.5 – 30 GHz) and integrated to the model. Transitions from stripline to coplanar waveguide (CPW) have been also included so the structure can be measured using a ground-signal-ground (GSG) probe.

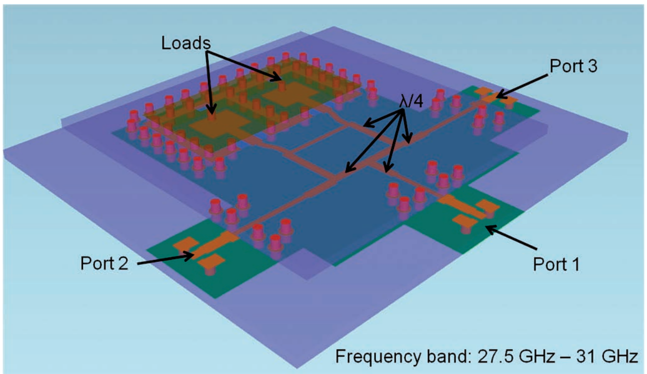

Fig. 9: Gysel power splitter model.

Fig. 10 shows the simulated transmission coefficient (S21/S31) and isolation coefficient (S23/S32). For clarity, not all measurements have been plotted. All three ports present a reflection coefficient lower than -12 dB at the frequency band of interest. Concerning the transmission coefficient, it can be seen that there is a symmetrical signal distribution between both ports (S21 and S31). Also, the tolerances on the resistor paste have been studied (nominal and ± 20 %). Variations lower than 0.05 dB are observed in the transmission coefficient. When focusing on the isolation coefficient, it has a value lower than -20 dB in the frequency band. Also, no critical variations are observed when the resistor paste values are changed.

V. RF Measurements

The designed RF structures on DuPont 9K7 have been fabricated and characterized. The S-parameters have been measured with 250 µm pitch GSG probes (Z050-A3N-GSG-250) connected to a vector network analyzer (VNA) from Rohde & Schwarz (R&S-ZVA 40). Fig. 11 shows the measurement set-up used.

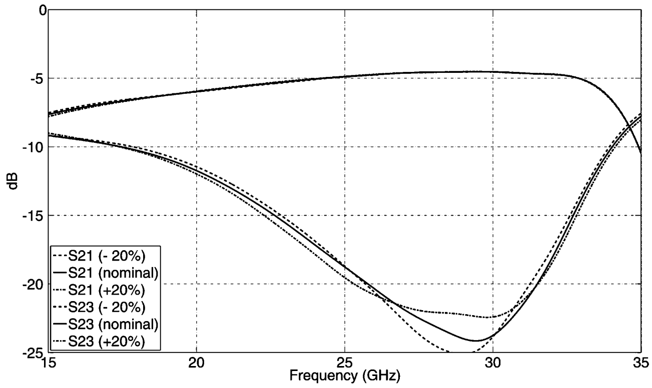

Fig. 10: Gysel power splitter simulated transmission- and isolation-coefficient.

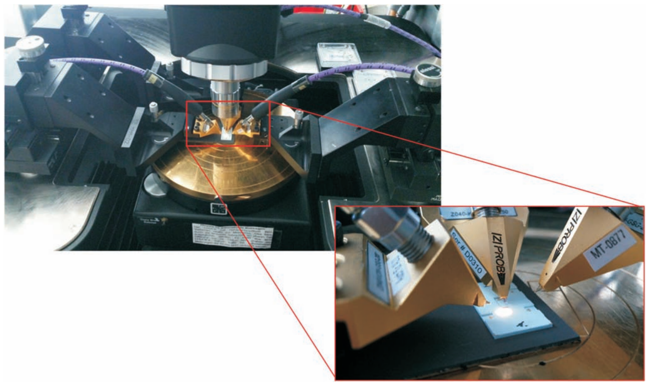

Fig. 11: GSG probe measurement set-up.

The first structures to be characterized were the RF loads. Fig. 12 shows the measured reflection coefficient for the three approaches. Approach 1 presents an operating frequency band between 20 and 40 GHz. Approach 2 increases the frequency bandwidth and improves the performance at lower frequencies. Approach 3 presents a broad band performance from DC to 40 GHz.

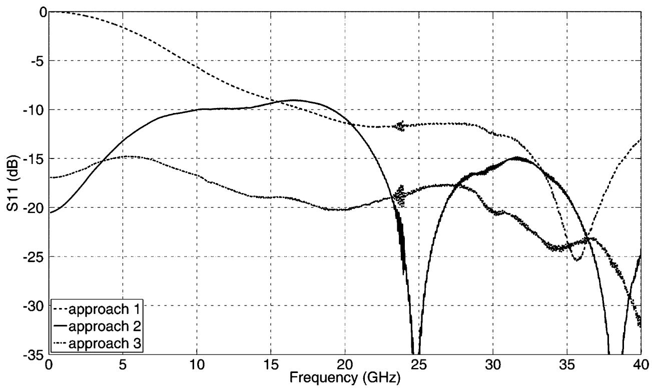

Fig. 12: RF loads measured return loss.

The Gysel power splitter has also been measured on the probe station. Fig. 13 shows the transmission coefficient S21 and S31. Both coefficients are very similar, showing a good symmetrical signal distribution beside possible LTCC fabrication tolerances. Fig. 11 shows the measured isolation coefficient (S23/S32), with values lower than -17 dB for the frequency band of interest. The resulted isolation is higher than the -20 dB desired. A frequency shift between the simulated and measured results has been observed. This shift may be due to variations between the material permittivity in the 3D model and the real device. Final tuning of the Gysel splitter is required in order to achieve the required isolation. All ports have shown a good impedance together with a reflection coefficient lower than -13 dB at the studied frequencies.

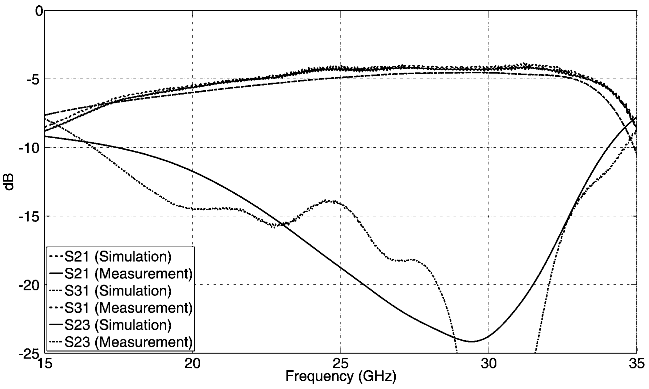

Fig. 13: Gysel power splitter measured transmission- and isolation-coefficient.

VI. Conclusions

The performance of stripline Wilkinson power dividers in LTCC are limited at mm-waves frequencies by the printing resolution and the resistor paste tolerances. As an initial step to compensate for such limitations, a tolerance-optimized RF load concept in LTCC has been presented. Three different approaches have been designed depending on the desired load performance. Good agreement between simulations and measurements proves the stability of the new structures with regard to fabrication tolerances.

A Gysel power splitter has been presented as an alternative to the Wilkinson power divider for very sensitive systems. The optimized RF load concept has been included in the final design. Measurements of the Gysel power splitter have proven its good performance in terms of transmission, insertion loss and isolation. Fine tuning is required in order to correct the isolation frequency shift. These are important figures of merit for the implementation of beam forming networks with multiple antenna outputs.

Acknowledgement

This work has partly been funded by the German Federal Ministry of Education and Research (BMBF) and executed by the German Space Agency (DLR) in the scope of the Ikersatec project (grant number 50YB1304) and OK-Tech project (grant number 50YB1224).

References

1 Rao, S.K.: Parametric esign and analysis of multiple-beam reflector antennas for satellite communications, *IEEE Antenn. Propag. M.*, **45**, 26 – 34, (2003).

2 Klein, T., Günner, C., Kassner, J., Kulke, R., Wolf, H.: Multiple Feed per Beam networks for Ka-band satellite communication systems in LTCC technology, Microwave Symposium Digest (MTT), 2011 IEEE MTT-S International, 5 – 10 June 2011.

3 Müller, J., Uhlig, P. *et al.*: Comparison of high-resolution patterning technologies for LTCC microwave circuits, *Journal of Microelectronic and Electronic Packaging*, **4**, [3], 99 – 104, (2007).

4 Lauer, A., Simon, W., Wien, A.: XPU technology for fast and efficient FDTD simulations using modern CPUs cache memory bandwidth, IEEE Conference Publications, 9th European Conference on Antennas and Propagation (EuCAP), 2015.

5 Gysel, U.H.: A new n-way power divider/combiner suitable for high-power applications, Microwave Symposium IEEE-MTT-S International, 1975.

6 Klein, T., Uhlig, P., Günner, C., Kulke, R.: Substrate-integrated divider networks in LTCC with optimized tolerance/isolation properties for Ka-Band satellite systems, International Symposium on Microelectronics (iMAPS), 47th San Diego, October 2014.