DEVELOPMENT OF HIGHLY INTEGRATED W-BAND CIRCULATORS/ISOLATORS BASED ON SUBSTRATE INTEGRATED WAVEGUIDE (SIW) TECHNOLOGY

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INTRODUCTION

The objective of the activity was to design, manufacture, and test highly integrated W-band circulators and isolators for frequency band 81 – 86 GHz using the Substrate Integrated Waveguide (SIW) technology. This recently emerged technology allows a direct integration of an effective rectangular waveguide inside the microstrip substrate of standard PCBs. Hence, it responds to the bulkiness, integrability and cost issues related to standard rectangular waveguide technology. SIW is considered an attractive choice for integrated communication and radar systems in space applications. For example, development of SIW circulators/isolators will allow their integration within RF chains and their implementation on the same board at lower cost. The use of SIW is expected to lead to a drastic reduction in mass, volume, and cost, and it should ease the assembly and integration of RF parts on one board compared to standard coaxial and waveguides solutions currently used in telecommunication at high frequencies.

In this activity, the SIW structures were chosen to be implemented using the Low Temperature Co-Fired Ceramic (LTCC) technology. LTCC allows constructing 3-dimensional structures within a ceramic substrate being hence very suitable for realizing especially substrate integrated waveguides

It is noteworthy that, in the literature, we did not find reports on any existing SIW circulators that would operate at W-band frequencies. The closest examples were designs for 38 GHz [1] and for 24 GHz [2], both implemented on a PCB substrate. For lower frequencies, LTCC based circulators were found, but they were fully based on microstrip topologies. Overall, no previous examples of their combinations, i.e., LTCC-SIW circulators, were found.

DESIGN

A Y-junction circulator is a non-reciprocal 3-port component based on a ferrite resonator in the junction of three waveguide, or transmission line, arms. A photograph of designed and manufactured LTCC-SIW circulator is seen in Fig. 1. The permanent magnet on top of the junction creates a static H-field, which is required for biasing the ferrite into a correct mode of operation.

For probing purposes, the device terminals are equipped with additional transitions to 50 Ω Grounded Co-Planar Waveguide (GCPW) interfaces. The component has three GCPW ports, whose numbering is indicated in Fig. 1. The coplanar lines at ports 2 and 3 have additional 30-degree bends in order to align all ports on a rectangle, which makes the device probing more feasible and enhances the overall integrability.

A 2-port isolator is obtained by terminating one of the circulator ports. In practice, the planar LTCC technology requires the chosen termination to be integrated in the component. In our case, the most elegant and symmetrical choice is to terminate the circulator port 1. The remaining ports 2 and 3 are re-numbered as port 1 and port 2, as seen in Fig. 2, which presents two studied variants of SIW isolators. In the first variant, the termination is implemented with a discrete 50 Ω thin film resistor and in the second one, the termination is based on a distributed absorber, which is manufactured by LTCC technology using conductive paste. The inner structure of the isolators is identical to the circulator design.

The LTCC structure consists of a stack of dielectric layers, which are sintered together into a uniform substrate. That is, the thickness of the substrate can only be varied in discrete steps. However, thin conductor layers can be sintered inside the substrate in between the ceramic layers. These conductor layers are connected by vias, which are also used to form the sidewalls of the effective, substrate integrated, waveguides.

The most essential element in the circulator is the biased ferrite disk, which is located in the middle of the Y-junction. In order to enable the assembly of the ferrite after the LTCC process, the ferrite is placed against the bottom of the component surrounded by an air cavity with a slightly larger radius. A piece of copper tape is used to seal the cavity. The bottom of the component is supplemented with a steel plate. Steel has very high (nonlinear) permeability and hence the plate at the bottom behaves as a magnetic mirror, which attracts the magnetic field lines and enhances the applied flux in the vicinity of the ferrite. A cross-cut through the junction is illustrated in Fig. 3.

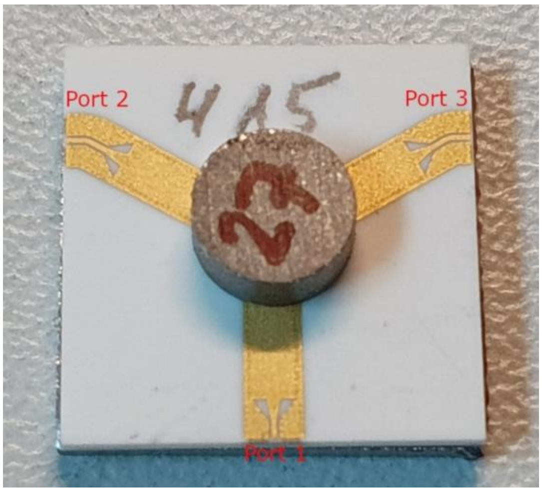

Fig. 1. LTCC-SIW Y-junction circulator.

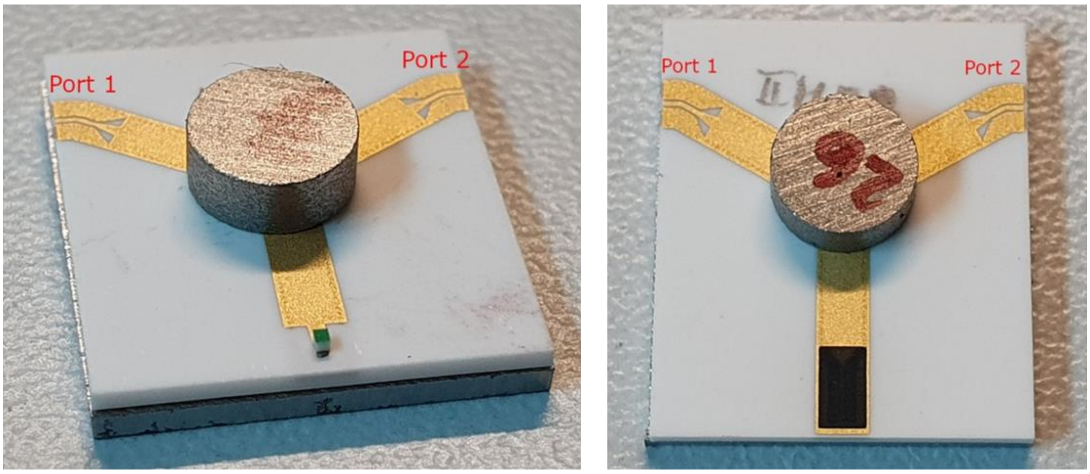

Fig. 2. Left: LTCC-SIW isolator with discrete resistor termination. Right: LTCC-SIW isolator with distributed absorber termination.

SIMULATIONS AND MEASUREMENTS

The simulated 3-port S-parameters of the designed LTCC-SIW circulator are plotted in Fig. 4.

Unfortunately, major issues in the measured performance of the manufactured circulators and isolators were observed. The level of matching turned out to be very poor and the required nonreciprocity was nearly completely missing. Some typical S-parameter measurement results are presented in the following.

Altogether 11 samples of circulators were assembled and tested. They all provided very similar results. Due to practical limitations, the circulator 3-port parameters were measured as 3 separate 2-port measurements, where the third port was terminated with a matched load (see the port numbers in Fig.1). The results of a typical sample are presented in Fig. 5.

Fig. 6 presents typical 2-port measurement results for both isolator variants. It is found that these results are more stable and more similar to each other, even though their performance is still far from the desired specifications. The similarity between the isolator variants indicates that the integrated terminations based on a discrete resistor and distributed absorber seem to work equally well. The termination in the third port, however, seems to affect the matching in the signal ports, as well. Whereas for the circulator, the best matching is observed around 81 – 82 GHz (see Fig. 5), for isolators this is observed close to 85 GHz.

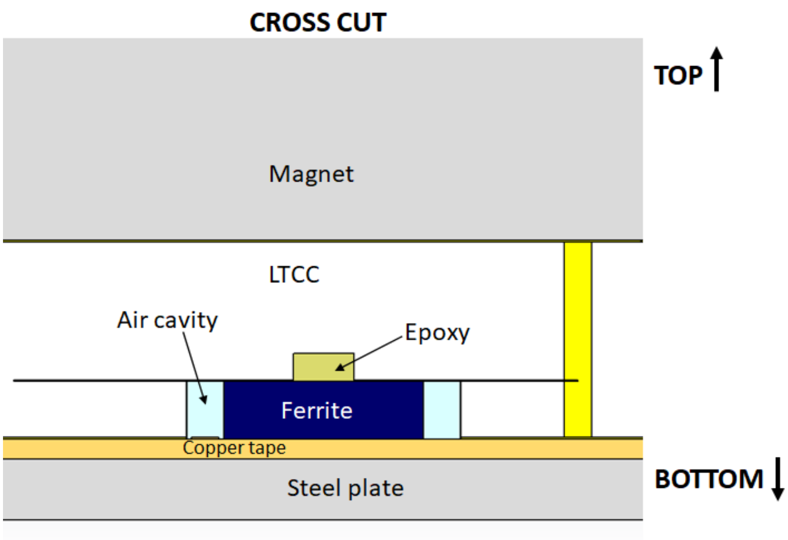

Fig. 3. Cross-cut of the circulator/isolator junction assembly.

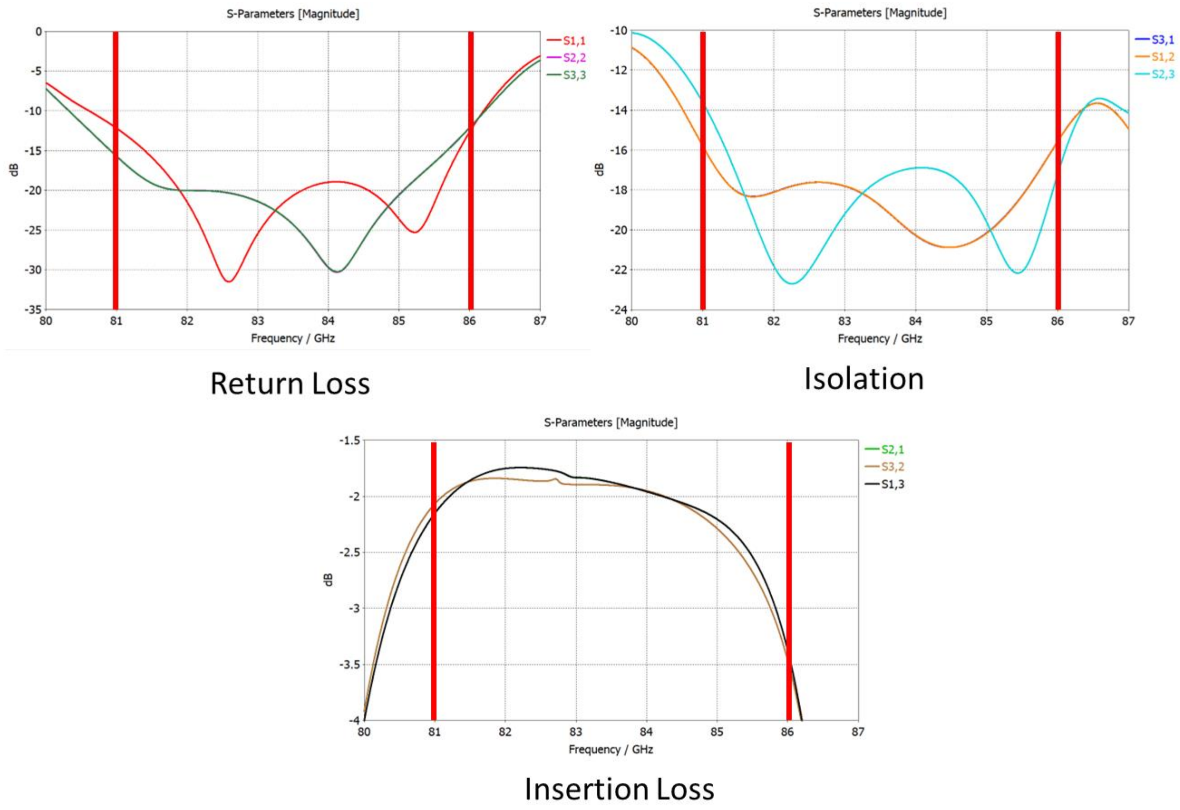

Fig. 4. Simulated 3-port S-parameters of LTCC-SIW circulator.

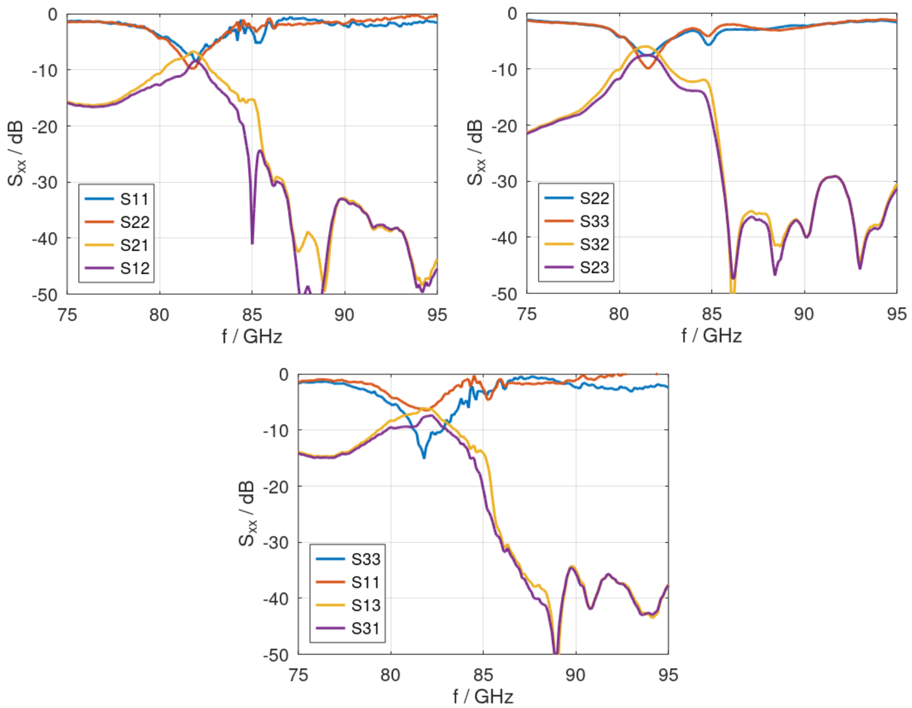

Fig. 5. Typical measured S-parameters of manufactured LTCC-SIW circulator. Top left: 2-port measurement between P1 and P2 with P3 terminated. Top right: 2-port measurement between P2 and P3 with P1 terminated. Bottom: 2-port measurement between P3 and P1 with P2 terminated.

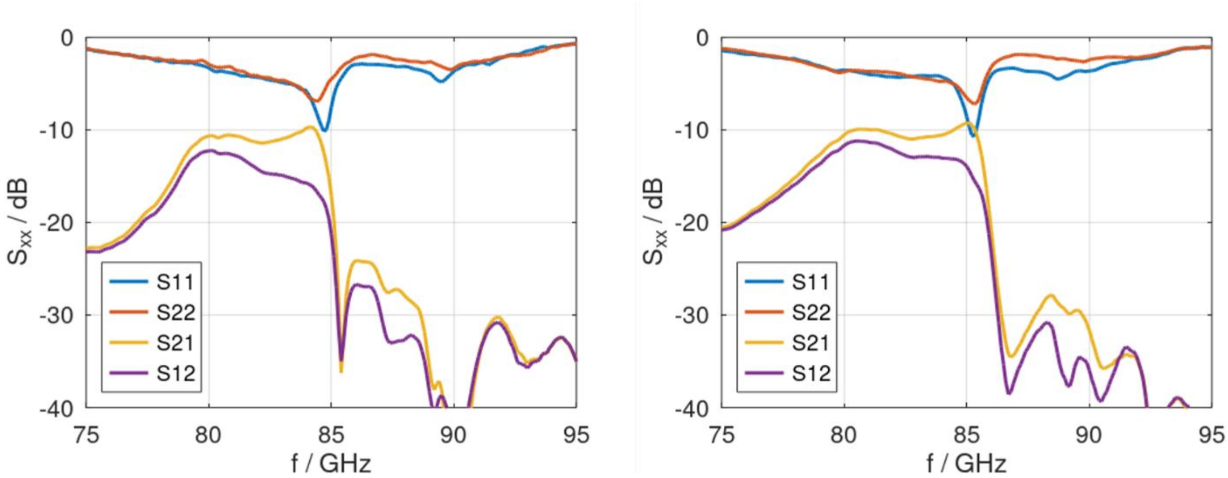

Fig. 6. 2-ports S-parameter measurements of typical samples of LTCC -SIW isolator. Left: variant with discrete resistor. Right: variant with distributed absorber.

TROUBLESHOOTING

By specific measurements, we were able to rule out the problems in the ferrites and the magnets. It was hence deduced that the issues must be related to the various sensitivities and tolerances of the LTCC process and the manual assembly of the ferrite. The differences between circulators and isolators also indicate that there are potential issues with the GCPW interface matching and termination.

Eventually, the most apparent problem was found to be the mechanical assembly of the ferrite to the LTCC junction. Additional tests were made to improve the quality of the junction assembly, which was illustrated in Fig. 3. Some silver epoxy was added also under the ferrite to improve the galvanic contact with the steel plate (the copper tape was removed at this point). Fig. 7 presents a comparison between the original (P2-P3 2-port) measurement and an updated measurement after the same component was re-assembled using silver epoxy. It is found that the circulator matching becomes significantly improved by the additional epoxy, and the insertion losses are much smaller. Even though the gyrotropy effect also becomes more prominent, the isolation, seen as difference between S_{32} and S_{23}, unfortunately remains rather low.

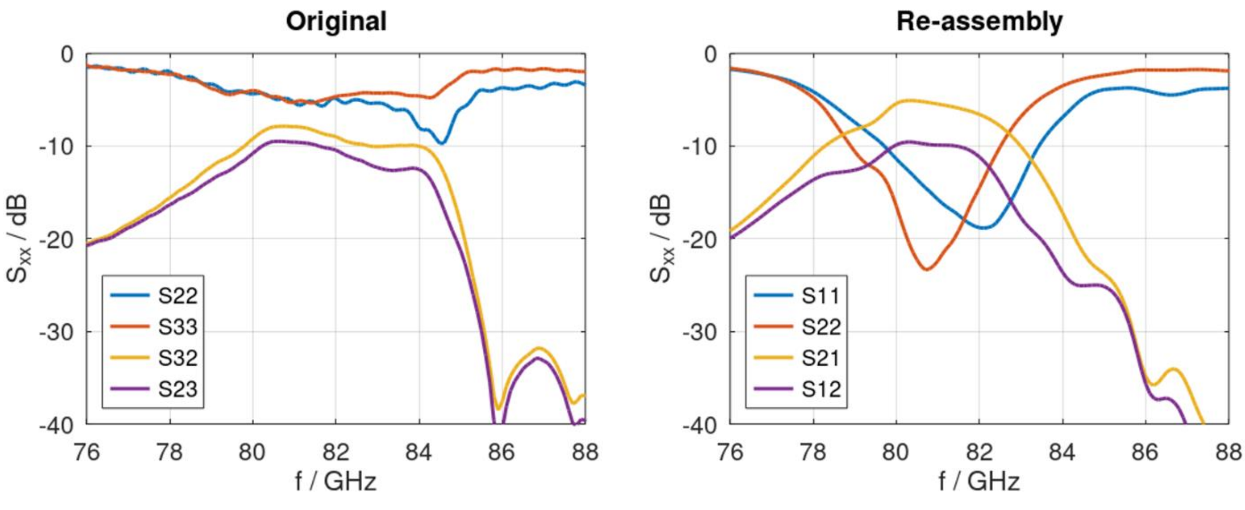

Fig. 7. 2-port measurement of the same circulator sample. Left: Original measurement. Right: measurement after re-assembly of the component with additional silver epoxy to improve the ferrite contacts.

CONCLUSIONS

After two manufacturing rounds and manufacturing process assessment and optimization, the designed and manufactured LTCC-SIW circulators and isolators did not yet perform according to specifications. Notable differences between simulated and measured performance were observed, but a single unambiguous root cause for these discrepancies was, however, not found.

The most apparent problem is the mechanical assembly of the ferrite to the LTCC junction. The design model assumes the ferrite bottom and top have both a good galvanic contact with conducting surfaces, that is, the ferrite disk is supposed to act as a resonator, which is short-circuited from both ends. Based on the studies of realized dimensions, this condition is very difficult to achieve. The achievable machining and assembly tolerances simply just do not meet the requirements. After a careful junction re-assembly with additional silver epoxy, a very promising matching was obtained within a broader band at correct frequencies. Nevertheless, the main features of the similar and measured curves are rather similar.

As light-weight and highly integrable components, SIW circulators and isolators appear very attractive and cost-effective for many space applications. Further design and optimization rounds are, however, needed to improve the current circulator/isolator performance. Considering possible future steps, a more feasible approach could be to try to repeat the design task for a notably lower frequency. This would make the physical dimensions larger and mitigate the required tolerances in manufacturing and assembly. Moreover, the efficiency of ferrites is supposedly better at lower frequencies. For instance, LEO inter satellite links at V-band between 59 – 71 could be a potential application.

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