Space grade S-band high power isolator development

15-18 October 2024
ESA/ESTEC, Noordwijk, The Netherlands

E. Lakatos[(1)], I. Gyenes[1)]

[(1)] *TKI-Ferrit Kft*
Kis-Duna utca 3, 2030 Érd, HUNGARY
Email:erno.lakatos@tki-ferrit.com,
imre.gyenes@tki-ferrit.com

INTRODUCTION

Circulators and isolators are passive devices used in modern RF and microwave equipments since some decades. The microwave three port coaxial ferrite circulator is a nonreciprocal device that can be used as an isolator in microwave systems if we connect a matched load to one of the ports. Their applications include the decoupling between a generator and its load, the decoupling of several amplifiers, and the combining of two or more transmitters. By using them the stability, performance, and reliability of the systems can be improved. There is increasing need of the broadband S-band space qualified ferrite-based coaxial microwave isolator suitable for high power applications. The present proposal addresses a space grade 100W coaxial isolator development. The frequency range of the device will be 2000 MHz-2700 MHz in accordance with the requirements given in ESCC No. 3202/022 [1]. The first phase of the development aims to move from the TRL4 (Technical Readiness Level) to the TRL5. As a first step the expectations and specifications were defined based on related ESA requirements. The development was then continued with various simulations (thermal, multipactor, high frequency). Finally, the development samples were prepared and several tests were carried out according to the characterization plan.

DESIGN ASPECTS , SPECIFICATION AND SIMULATIONS

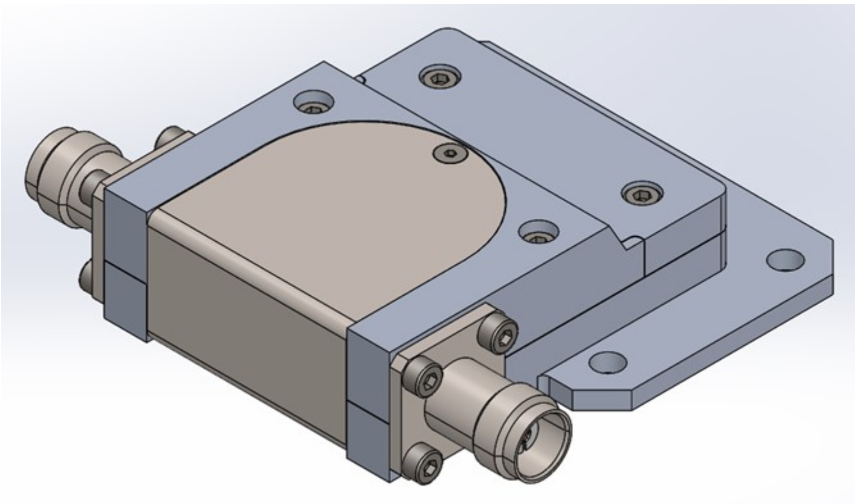

Fig.1. The EBB (elegant breadboard) mechanical design concept

The main requirements of the EBB mechanical design were as follows: reduced and robust house, reduced mass, increased heat transfer area to improve heat dissipation, improved multipactor and corona level, high power handling with TNC female connector usage. Table 1. provides comprehensive summary of the product specification.

Table 1. Specification summary

Parameters	**Values**
General Frequency Specification	
Centre Frequency, Fc (GHz)	2,0-2,7
Operating Frequency Fop (GHz)	Fc+- 0,2
General Technological Specification	
Component Type Variants: ISO101 / ISO102	Clockwise/Anti-clockwise
Nominal Impedance (Ohm)	50
Rated RF Power (Forward, W)	100
Rated RF Power (Reverse, W)	100
Corona level (Output Port Loaded)	60
Multipaction Level (Output Port Loaded, Classification type:2)	400
Voltage Standing Wave Ratios (VSWR)	1,22
Isolation (dB)	20
Insertion losses max.(dB)	0,4
Connector types	TNC Coaxial Female
Maximum Weight (g)	300
Physical Dimensions (mm) max.	88 x 86 x 25
Environmental Specification	
Functional Temperature Range (°C)	-30… +120
Operating Temperature Range (°C)	-30… +90
Storage Temperature Range (°C)	-40… +125
Vibration Environment Specification	50grms

The thermal design consideration is particularly important for high power isolators. The dissipated power will cause heating of the ferrite junction and degradation in performance. Heat is generated in the isolator because of insertion losses, and reflections. Most of the reflected microwave power is converted to heat by the load block. The insertion loss generated thermal power (Q) can be calculated from the input power (Pin) and the insertion loss (Ins loss dB) using the formula (1).

$$Q = Pin\ (1-10^{-Ins\ loss/10}) \tag{1}$$

In our case Pin= 100 W, Ins loss = 0,2 dB and the calculated Q = 4,5 W. In order to test the EBB samples as high power as possible the power of the load resistor will be 250W. The final mechanical sizes of the housing will be defined after the successful thermal analysis. The aim of the thermal analysis is to determine the temperature of isolator's components during normal, and worst case (short-circuit) operation conditions. In each condition the temperature of the components should be under their maximum allowable temperature. With the support of the Solidworks Simulation Professional [2] thermal analysis software, we could determine the maximum and the average temperatures of the components. Fig.2. shows the temperature distribution in normal and short-circuit operation condition. Table 2. shows the temperature values of the temperature sensitive components and the temperature reference point (TRP) located on right side screw hole of the house. All temperatures are below their maximum allowable temperature.

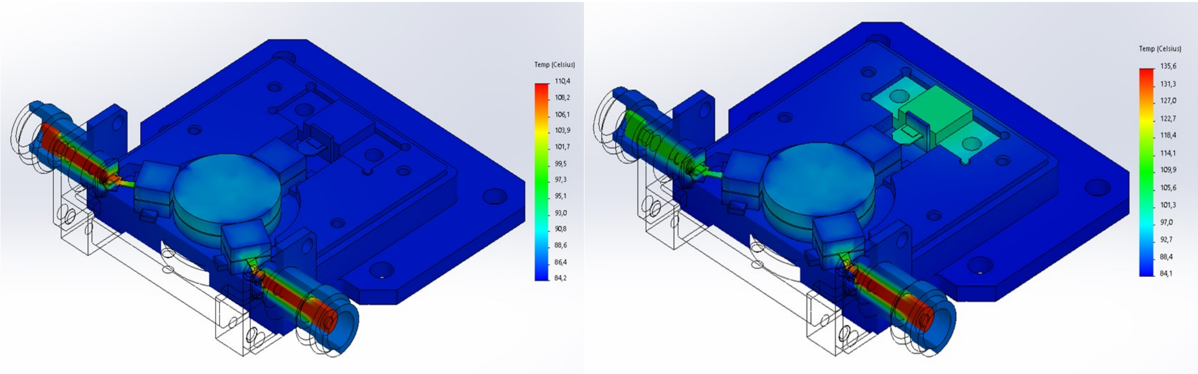

Fig.2. Temperature distribution in normal and short-circuit operation condition

Table 2. Temperature values in short circuit conditions

Surface	Max temperature [°C]	Temperature average [°C]	Maximum allowable temperature [°C]	Margin [°C]
TRP	85	85	-	-
Resistor	102.2	97.5	134	31.8
Ferrite	94.0	91.6	160	66.0
Ceramic plate	102.9	90.4	200	97.1
Tuning ceramic	134.4	106.1	200	65.6
Central conductor	131.9	95.4	200	68.1
Connector central part (IN)	111.6	111.4	165	53.4
Connector central part (OUT)	135.6	135.1	165	29.4

In order to reduce the multipaction and corona effect, to have better breakdown power margins, the whole inner space is filled with space grade silicon filler. Consequently vacuum or air cannot be formed in inner space therefore the multipaction and corona effect is reduced strongly. The simulated maximum electric field strength was 626,66 V/mm. vs. 19 kV/mm electric field strength of filler material.

The HFSS (High Frequency Simulation Software) analysis made by Ansys software [3]. The aim of the analysis is to determine the proper operation, the S-parameters, the powers and losses of the designed ferrite isolator. The isolator had to be analyzed in two different circumstances: normal operation with matched 50Ω output terminal and short-circuit operation with short output terminal. HFSS uses tetrahedral adaptive meshing, which means it sets up an initial mesh, solves the fields on the solution frequency and after that re-meshes the model based on the data obtained. Each re-meshing step is a Pass. The Maximum Number of Passes value is the maximum number of mesh refinement cycles that you would like HFSS to perform. This value is a stopping criterion for the adaptive solution; if the maximum number of passes has been completed, the adaptive analysis stops. If the maximum number of passes has not been completed, the adaptive analysis will continue unless the convergence criteria are reached. The delta S is the magnitude of the change of the S-parameters between two consecutive passes. The solver reports the worst case violation. The value you set for Maximum Delta S is a stopping criterion for the adaptive solution. If the magnitude of the change of all S-parameters are less than this value from one iteration to the next, the adaptive analysis stops. Otherwise, it continues until the requested number of passes is completed. Setting the Maximum Delta S too small wastes computer resources and time.

Setting it too large jeopardizes accuracy. We decreased the value of Delta S until it had no significant effect on the results. With the value of 0.005 and 0.002, we got almost the same S-parameters, so 0.002 is small enough to get accurate results. The Scattering (S) parameters Plot Fig.3. represents the insertion loss (S21 - green), isolation (S12 - blue) and the return losses (S11 - red, S22 - orange).

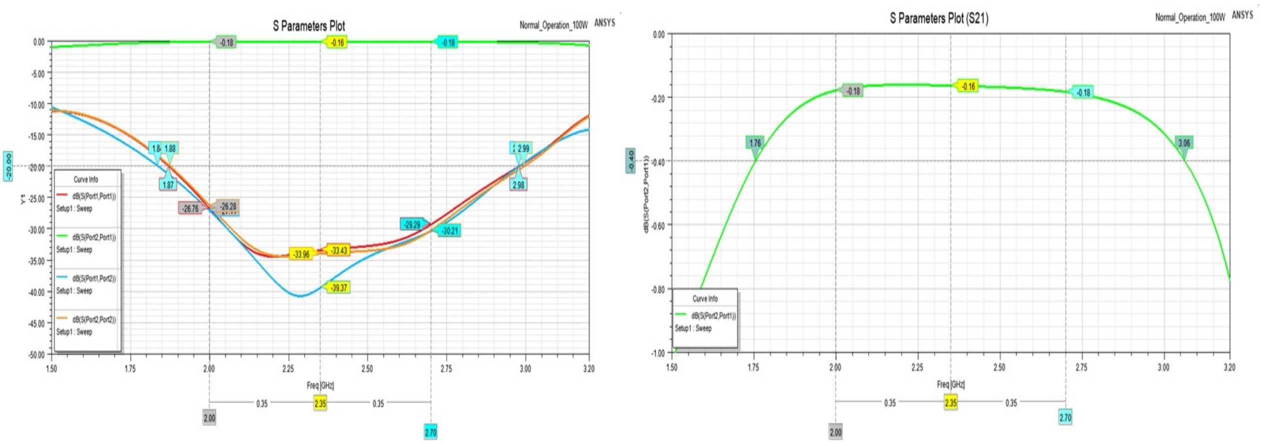

Fig.3. S parameters of the isolator

The Table 3. shows the comparison data of S parameters. It can be seen that all the parameters meet the requirements defined in product specification. The margin is big enough to accept these results with high certainty.

Table 3. Summary of S-parameters

S-parameters	Simulated result [dB]	Specified result [dB]	Margin [dB]
S21	-0.18	-0.4	0.22
S12	-27.11	-20	7.11
S11	-26.76	-20	6.76
S22	-26.28	-20	6.28

The power handling capability of the isolator is most critical when the output port is short-circuited, since full reflection occurs and all reflected power is transferred to the terminating resistor. The Fig.4. shows the simulation results of the electric field, the surface loss density and the volume loss density in short circuit operation.

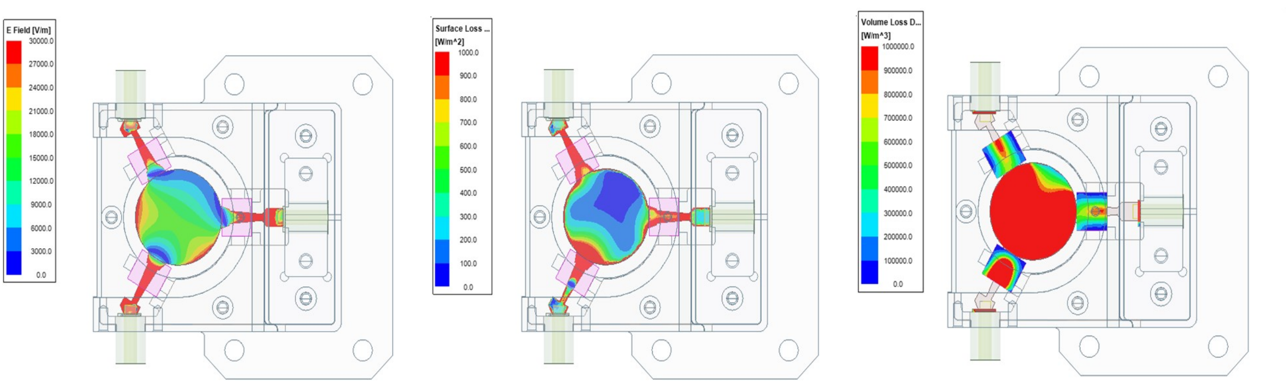

Fig.4. Distribution of electric field, surface loss density and volume loss density in short circuit operation

The Table 4. summarizes the calculated powers and losses of the isolator components in short circuit operation.

Table 4. Calculated powers and losses in short circuit operation

Name	Powers / Losses [W]
Output port	0
Termination load	89.84
Ferrites	4.04
Ceramics	1.05
Central conductor	1.08
Input connector	1.33
Output connector	2.66

With the application of the Ansys HFSS software we managed to specify the parameters of the components. This way we could tune the device to the optimal magnetic point with the specified value of the magnetic bias. By adjusting the dimensions of the components, fine-tuning could be performed in order to obtain the best S-parameters. The simulation was accomplished both in normal operation and in short circuit operation. After completion all the operations in iterative mode it can be concluded that the isolator model meets all the parameters of the specification. By fulfilling these requirements, we could step forward to the next phase of the development.

TESTING OF EBB SAMPLES

The testing processes of EBB samples shall be prepared according to characterization plan Fig.5.

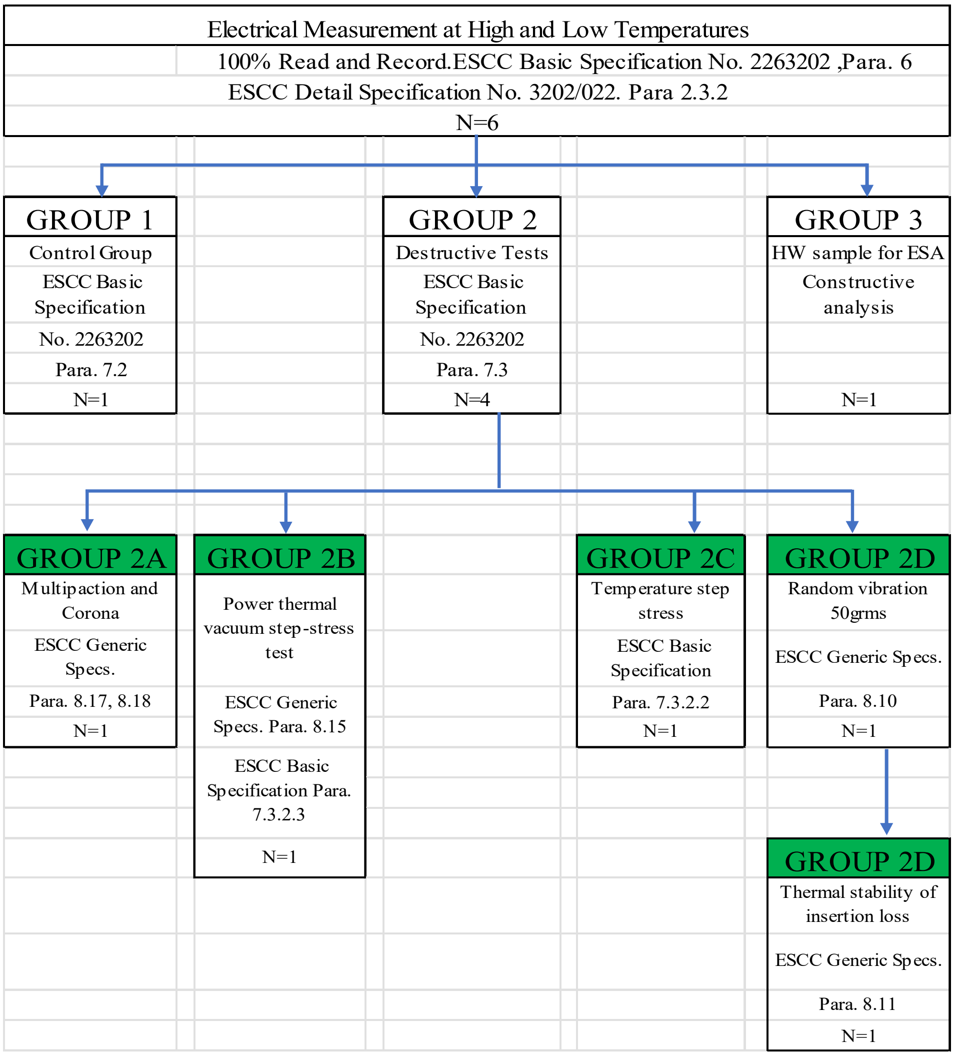

Fig.5. Characterization plan of the EBB samples

RF Measurement

Based on the characterization plan the specified S-band is covered by two type of isolator samples, each with 400MHz bandwidth. The RF measurements have been made at low (-30°C), at high (+85°C) and at ambient (+25°C) temperatures. Fig.6. shows the low temperature results, insertion loss (S21) is better than -0.32 dB, isolation (S12) is better than -20.2 dB and return losses at input and output port are better than -24.2 dB.

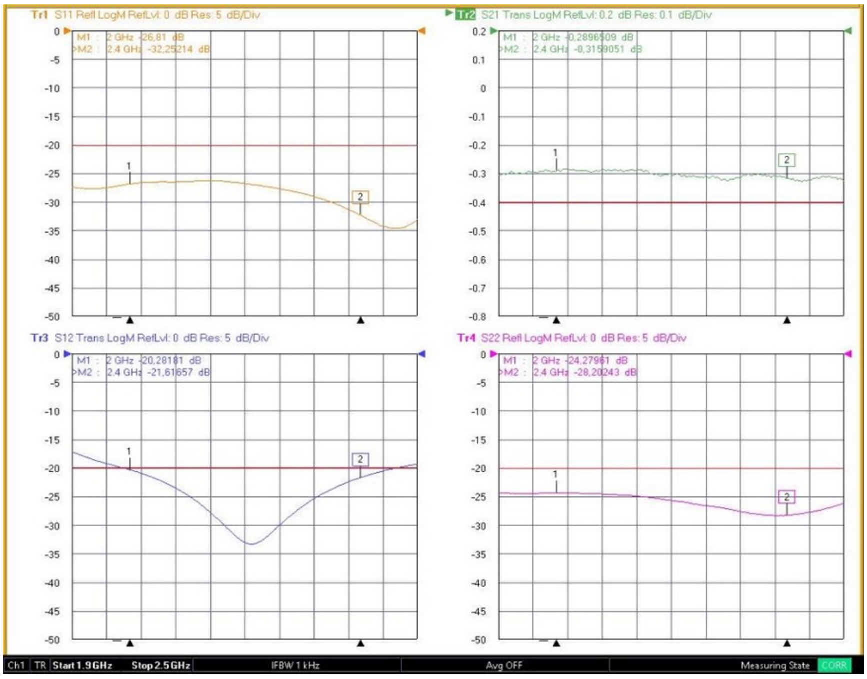

Fig.6. RF measurement at low temperature

Fig.7. presents the S parameters measured at high temperature. The results are shifted due to the ferrite and ceramics temperature dependent behavior, the insertion loss (S21) slightly improved to -0.27 dB.

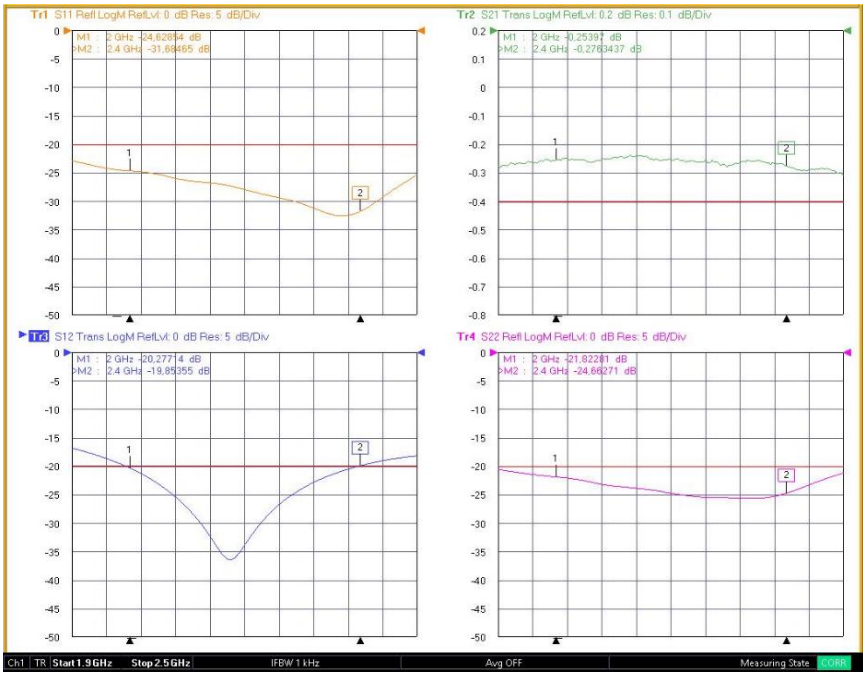

Fig.7. RF measurement at high temperature

Multipactor and Corona Tests

The tests were conducted with the following parameters:
Pressure: < 1.5 x 10^{-5} mbar for Multipactor test, and from 1013 mbar to the range of 10^{-2} mbar for Corona test
Test temperature: +22 °C and aborting Temperature: +90 °C
Frequency: 2,0 GHz
Max. RF power: 400 Wpeak for Multipactor test and 60 Wpeak for Corona test
Pulse width: 20 µs, Pulse frequency of RF: 1000 Hz
Fig.8. shows the test setup integration before multipactor and corona tests.
The tests were completed successfully in thermal vacuum chamber.

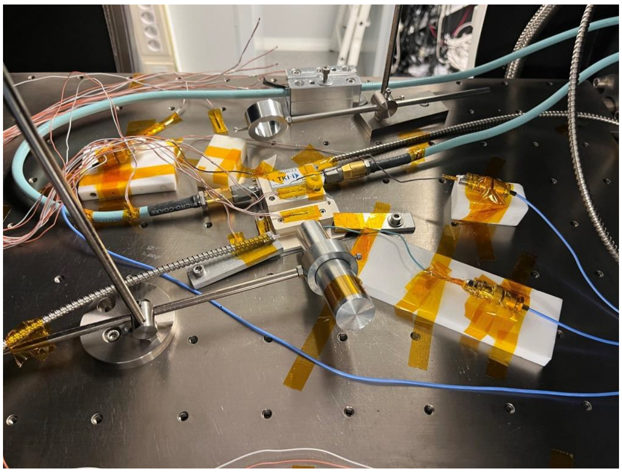

Fig.8 Integration before Multipactor and Corona tests

Power Thermal Vacuum Step-stress Test

Test parameters are as follows:
Pressure: < 1.5 x 10^{-5} mbar
Test temperatures: +80°C, aborting Temperature: +90°C
Frequency: 2,2 GHz, maximum RF power:140 W continuous wave
Two Strontium-90 radioactive isotopes were used as beta sources at the critical areas. Prior starting test , the isolator was left under high vacuum for around 70 hours. At the last RF power step (140 W) and at the end of the phase points, a second sliding short 0-180 degrees sequence was performed over the full range of the phase shifter. This action was implemented to ensure full phase coverage along the whole range and at maximum RF power. Fig.9. shows the test setup integration before the test started. No discharges were recorded up to maximum RF power (140 W).

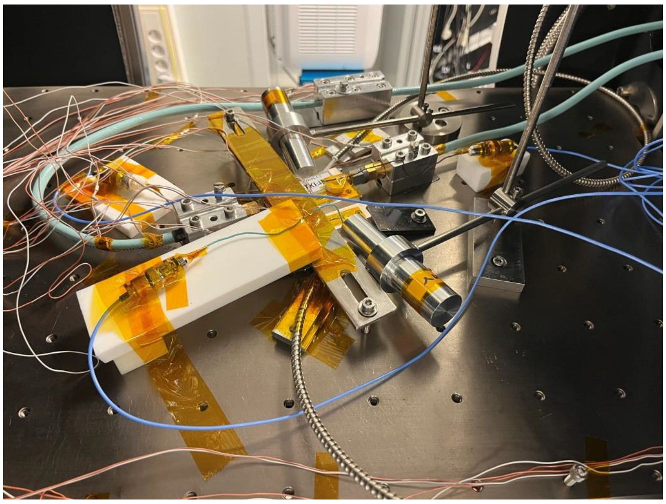

Fig.9. Integration before power thermal vacuum step-stress test

Temperature Step-stress Test

The tests were performed at the maximum rated power:100W. RF measurements were made in every cycle at room temperature (25°C) in the center frequency of the isolator operational frequency band 2.2 GHz. The starting temperature at temperature reference point (TRP) of the isolator was 85 °C and the temperature steps were 5°C. The thermal profile of the test is shown in Fig.10.

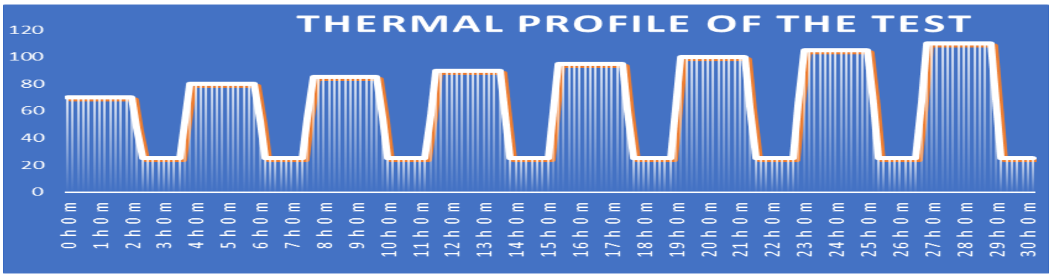

Fig.10.The thermal profile of the tests

Fig.11. Measurement setup of the temperature step-stress test

Fig.11. presents the testing setup. The final summary of the temperature step-stress tests results are shown in Table 5. The test finished at 120°C with a failure of the incorrect input reflection parameter. The root cause of the failure was: tuning ceramic element cracked at input port.

Table 5. Final summary of the test results

Measure Start		Measure End		Input Power	Temp of Thermal reference	Result	comment
2023.05.09	11:53:53	2023.05.09	13:53:35	50dBm $\frac{+0,7dBm}{-0dBm}$	70C° ± 0.5C°	OK	Chart 01
2023.05.11	10:41:29	2023.05.11	12:41:59	50dBm $\frac{+0,7dBm}{-0dBm}$	80C° ± 0.5C°	OK	Chart 02
2023.05.12	10:12:36	2023.05.12	12:16:26	50dBm $\frac{+0,7dBm}{-0dBm}$	85C° ± 0.5C°	OK	Chart 03
2023.05.15	9:46:11	2023.05.15	11:49:48	50dBm $\frac{+0,7dBm}{-0dBm}$	90C° ± 0.5C°	OK	Chart 04
2023.05.16	9:39:42	2023.05.16	11:40:49	50dBm $\frac{+0,7dBm}{-0dBm}$	95C° ± 0.5C°	OK	Chart 05
2023.05.16	13:30:50	2023.05.16	15:28:22	50dBm $\frac{+0,7dBm}{-0dBm}$	100C° ± 0.5C°	OK	Chart 06
2023.05.17	10:19:53	2023.05.17	12:21:22	50dBm $\frac{+0,7dBm}{-0dBm}$	105C° ± 0.5C°	OK	Chart 07
2023.05.18	10:05:05	2023.05.18	12:06:48	50dBm $\frac{+0,7dBm}{-0dBm}$	110C° ± 0.5C°	OK	Chart 08
2023.05.19	9:51:23	2023.05.19	11:45:09	50dBm $\frac{+0,7dBm}{-0dBm}$	115C° ± 0.5C°	OK	Chart 09
2023.05.22	10:02:47	2023.05.22	12:02:06	50dBm $\frac{+0,7dBm}{-0dBm}$	120C° ± 0.5C°	NOK	Chart 10

Random Vibration Test

The random vibration spectra parameters for each axis are:

10Hz to 50 Hz: +3dB/octave;   50Hz to 1000 Hz: $1.5g^2/Hz$;   1000Hz to 2000 Hz: -3dB/octave
Overall acceleration: 50 g_{RMS},
Test time :180s for each axis
Succes criteria: to have the same, unchanged RF parameters before and after the test, as it is described in ESCC Detail Specification [4].
The X-Y-Z axis setup for random vibration tests are shown on Fig.12.

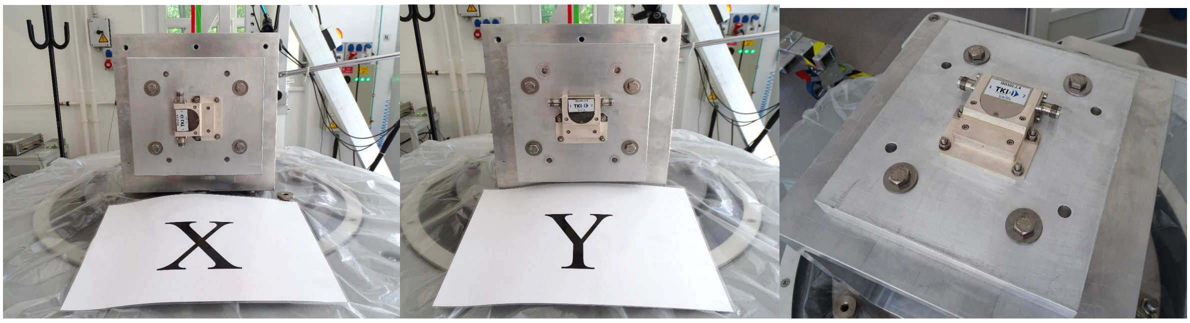

Fig.12. X-Y-Z axis setup for random vibration tests

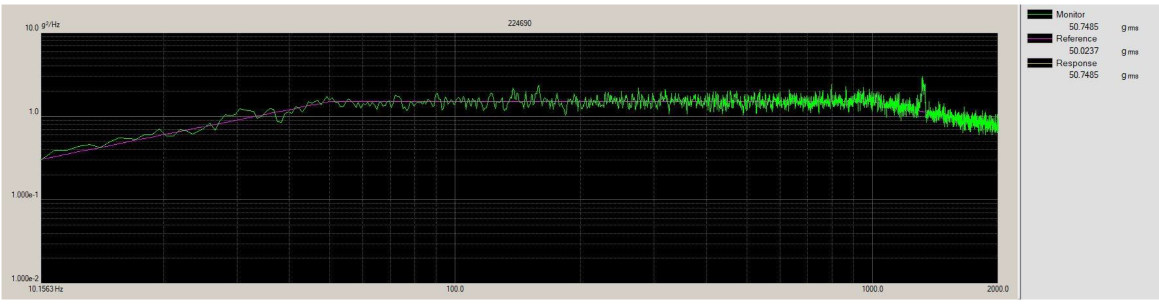

Fig.13. Random vibration test results on Z-axis

The results of random vibration test on Z-axis are shown on Fig.13. The figure shows the reference and response results as well. Fig.14. shows no changes of the measured RF parameters before and after tests.

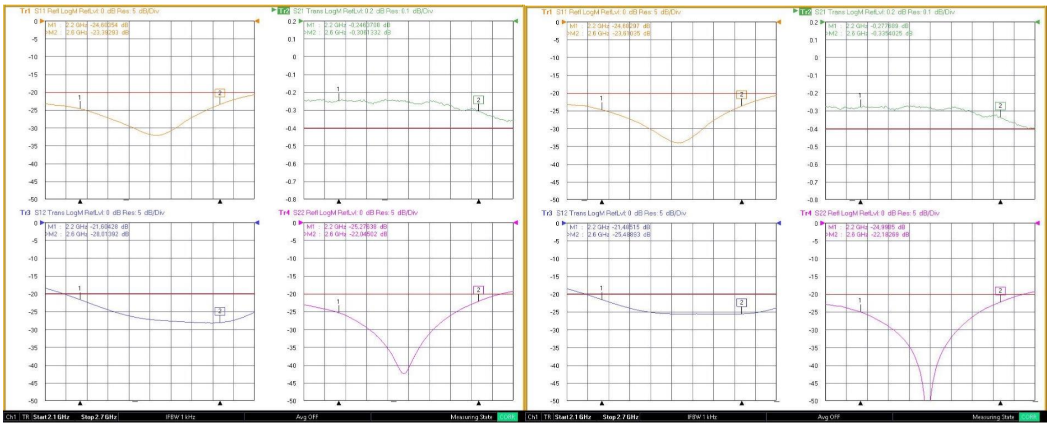

Fig.14. RF parameters before and after tests

The RF parameters did not change after the random vibration tests for each axis, therefore the test resulted successful completion.

Thermal stability of insertion loss test (Glitch test)

The insertion loss parameter of the isolator was continuously monitored and recorded every 100 milliseconds during the 5x2 temperature cycles as it was defined in thermal profile Table 6. The expected result of this test is the continuity of the insertion loss parameter during 5x2=10 thermal cycles. In other words, there is no spike or step which exceeds 0.1 dB level. The RF power applied during cycling was 0 dBm and the test frequency was 2.4 GHz.

Table 6. The thermal profile of two thermal cycles

- T_0= 0 (10 min) TEMP= +25°C
- T_1= 10min (18 min) TEMP= -30°C T_{grad}= -3°C/minute
- T_2= 28min (45 min) TEMP= -30°C ΔT= 45 minutes
- T_3= 73min (38 min) TEMP= +85°C T_{grad}= 3°C/minute
- T_4= 111min (45 min) TEMP= +85°C ΔT= 45 minutes
- T_5= 156min (38 min) TEMP= -30°C T_{grad}= -3°C/minute
- T_6= 194min (45 min) TEMP= -30°C ΔT= 45 minutes
- T_7= 239min (38 min) TEMP= +85°C T_{grad}= 3°C/ minute
- T_8= 277min (45 min) TEMP= +85°C ΔT= 45 minutes
- T_9= 322min (20 min) TEMP= +25°C T_{grad}= -3°C/ minute
- T_{10}= 342min (45 min) TEMP= +25°C ΔT= 45 minutes
- T_{11}= 387min END of 2 test cycles

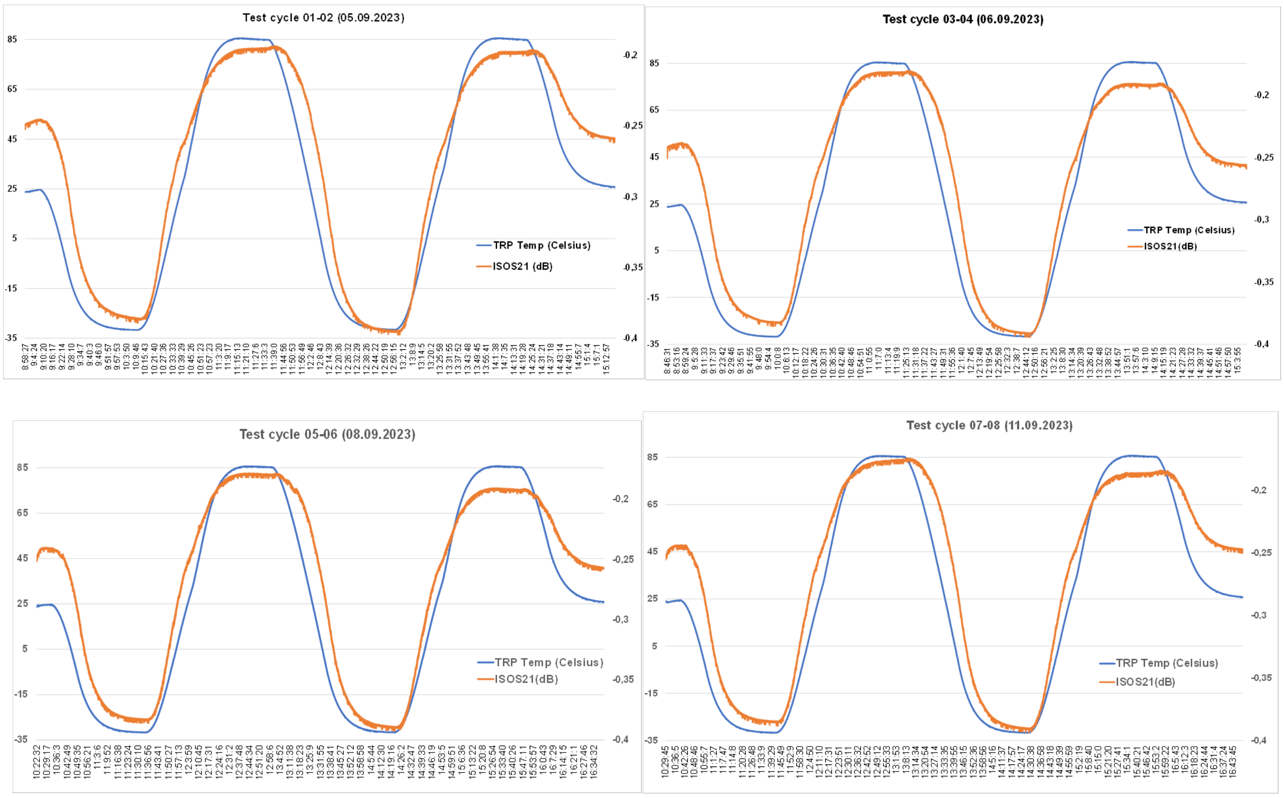

Fig.15. Glitch test results of test cycle 01-08

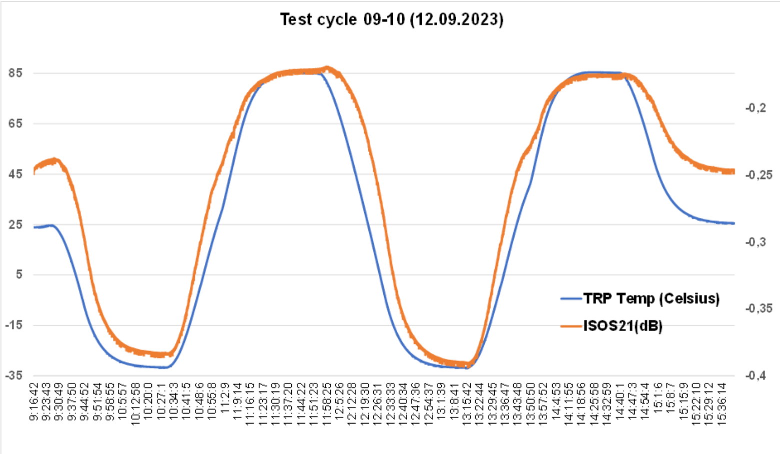

Fig.16. Glitch test results of test cycle 09-10

Table 7. Maximum glitch results of test cycles

Maximum glitch results of test cycles	
Test cycle 01-02	0,0114 dB
Test cycle 03-04	0,0108 dB
Test cycle 05-06	0,0104 dB
Test cycle 07-08	0,0111 dB
Test cycle 09-10	0,0112 dB

Table 7. shows the summary of the calculated glitch results of the test cycles. We have recorded 1.161.000 data points. Out of that we got the maximum glitch value 0,0114 dB, which is far below the acceptance criteria (0,05 dB). The tested isolator fully met the acceptance criteria.

CONCLUSION

High power isolators will continue to play a major role in the RF telecommunication systems. We have designed and tested an S-band 100W isolator for space applications. The technical readiness level was TRL4 at the beginning of the development activity and it was TRL5 at the end of this project. Finally we could improve several parameters like decreased mass, 400 MHz bandwidth, 0.3 dB insertion loss, 24 dB return loss and 20 dB isolation. It has been also demonstrated that the isolator can handle 140 W continuous wave power in forward and reverse mode under vacuum environment. The expected parameters of multipactor and corona discharge tests were validated as well. The 10 cycles glitch tests completed successfully meaning that the device is glitch free. The temperature stress-step test finished at 120°C, proven that the maximum operation temperature has 40% margin. All in all, the development activity has resulted a high power isolator with parameters that has met the requirements and specification of the development project.

REFERENCES

[1] Isolators, High Power, S-Band (2.0GHz to 2.7GHz), with Non-integral TNC Coaxial Connectors, ESCC Detail Specification No. 3202/022, Issue 1

[2] Solidworks Simulation Professional software, https://www.solidworks.com/domain/simulation

[3] Ansys HFSS High Frequency Simulation Software, https://www.ansys.com/products/electronics/ansys-hfss

[4] Ferrite Microwave Components, Isolators and Circulators, ESCC Generic Specification No.3202, Issue2

AUTHORS

Ernő Lakatos holds a Telecommunication Engineering degree from the Szechenyi Istvan University Hungary. He has worked for Videoton Company for 10 years as FM tuner and receiver developer. Ernő also worked for IBM Data Storage System Ltd for 18 years in various roles in new product intoduction, HDD yield improvement and high reliability testing areas. Ernő joined to TKI-Ferrit Ltd. (Hungary) in 2017 as head of the development group of the ferrite-based microwave passive devices. He has developed several waveguide and stripline circulators and isolators up to 40 GHz.

Imre Gyenes received his MsC degree in electrical engineering in 1983 at Budapest Technical University Hungary. He was the scientific member of the Research Institute for Telecommunication (TKI) for 11 years. The main engineering and research activities were here: fast PLLs, microwave mixers, and IF circuits. He also worked for Sanmina-SCI Hungary Ltd. as functional testing, failure analyser engineering and operations manager on the microwave radio link production lines more than 10 years. Imre had the repairing manager of networks repair role at CTDI Budapest Ltd. for 6 years. He joined to TKI-Ferrit Ltd. in 2021 as the head of ferrite based microwave device production group.