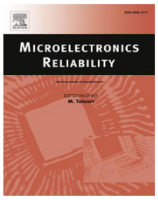
Microelectronics Reliability 138 (2022) 114753

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel



Reliability assessment of miniaturised electromechanical RF relays for space applications

I. Marozau [a,*], S. Unterhofer [a], M. Berry [b], G. Aubry [b], P. Gonin [b], R. Enquebecq [b], M. Dadras [a], O. Sereda [a]

[a] *CSEM SA, Jaquet-Droz 1, 2000, Neuchatel, Switzerland*
[b] *Radiall IDA, Rue de la Garenne 15, ZI Chesnes Tharabie - BP 709, 38295 Saint Quentin Fallavier, France*

ARTICLE INFO

Keywords:
RF relay
Space qualification
Reliability assessment
Failure mode analysis

ABSTRACT

A test programme was developed for the reliability assessment and evaluation of radiofrequency (RF) miniaturised electromechanical relays (MEMR) as required for space application. The test programme allows to carry out the required qualification of newly designed MEMR device for its use in space as well as in terrestrial applications (e.g. redundancy rings in telecom satellites or 5G technology equipment). It is aligned with the existing ESA standards for the direct current (DC) electromechanical relays. At the same time, the test and evaluation procedures are designed to meet the specific needs and requirements of the RF application domain. The developed test programme was successfully applied for the reliability evaluation of the MEMR developed within the framework of SELECTOR EU project (grant number 821973). The performed failure mode analysis allowed to improve the mechanical robustness of the device to match the qualification requirements.

1. Introduction to the project

SELECTOR project aims at developing for space sector of miniaturised, surface-mount technology compatible electromechanical switch called Miniature ElectroMechanical Relay (MEMR). MEMR is devoted to being used within reconfigurable microwave space subsystems in line with satellite evolution toward more digital satellites allowing high data capacity. Very High Throughput Satellite (VHTS) is the solution to decrease the cost per bit (€/Gbps) of satellite telecommunications. The satellite payload is constituted of a digital core, the digital transparent processor (DTP), surrounded by frequency converter units. For VHTS systems, the number of frequency converters channels is increased from few tens of equipment to several hundred compared to standard satellite architecture. Therefore, stronger constraints are then put on cost and mass of such equipment to remain competitive with no compromise on reliability. Redundancy rings are mandatory to achieve an operational lifetime of more than 15 years but are increasingly difficult to implement at a reasonable cost and weight, as they are centralized at payload level and consequently individually driven by telecommand and telemetry satellite bus.

The project aims at the development of a miniaturised RF relay for space applications, which shall replace the existing bulky RF switches. The main objectives were to drastically reduce the size and weight of such a relay. Another objective was to change the categorisation of the relay from equipment to component. The latter shall make the qualification and standardisation procedures significantly easier. Fig. 1 shows the size comparison of the currently used and newly developed devices.

Within the scope of the present work, a single pole double throw latching RF MEMR was developed. The relay operation frequency is from DC to 26.5 GHz (32 GHz for the upgraded version). The developed MEMR exhibits superior RF performances to its main state-of-the-art competitor Teledyne GRF121, as shown in Table 1. Both RF relays have comparable size and mass.

2. Miniaturised electromechanical RF relay

The developed MEMR is an electromechanical latching device used to connect the RF signal from one source to two output ports.

The developed MEMR is a surface-mount device (SMD). The command pulses are supplied through the Cmd pins soldered onto the solder pads on the customer PCB (see Fig. 2). The pulse latch connects the RF input port (**C**) to any RF output port (**1** or **2**) by applying the 6 V DC command signal pulses to the respective pair of the command pins (+1/ −1 or +2/−2) according to the switching diagram shown in Fig. 3.

---

* Corresponding author.
E-mail address: ivan.marozau@csem.ch (I. Marozau).

https://doi.org/10.1016/j.microrel.2022.114753
Received 8 June 2022; Received in revised form 16 August 2022; Accepted 18 August 2022

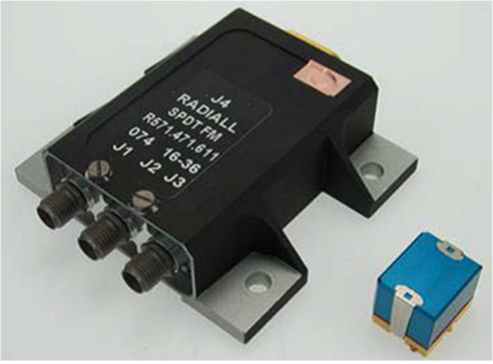


Fig. 1. Comparison of the size of the currently used RF relays for space applications (left, DC – 18 GHz) to the size of the developed MEMR (right, DC – 26.5 GHz).

Table 1
Specifications comparison of the developed MEMR from Radiall with the state-of-the-art competitor device Teledyne GRF121 (USA).

Parameter	MEMR from Radiall	Teledyne GRF121
Max frequency	26.5 GHz	18 GHz
Typical insertion loss	0.5 dB at 18GHz 1dB at 26.5GHz	1.1 dB at 18GHz
Typical VSWR	1.2 at 18GHz 1.4 at 26.5GHz	2.0 at 18GHz
Typical isolation	50 dB at 18GHz 45dB at 26.5GHz	30 dB at 18GHz
Power handling	18 W at 18GHz	No specification

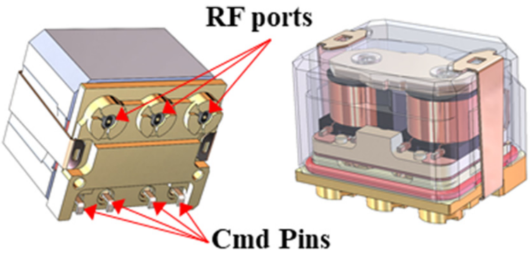


Fig. 2. Global overview of the MEMR.

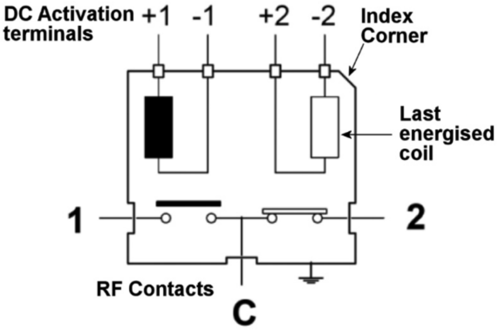


Fig. 3. MEMR Functional diagram [5,6].

The RF signal is supplied through the RF ports soldered on a PCB (see Fig. 2). The RF signal is transmitted from the input to the output ports/antenna through the RF cavity in the following way:

1. To the RF contact which is a circular coaxial transmission line
2. Then to a RF blade in "transmission position" which is a rectangular coaxial transmission line
3. Finally, to the output RF contact/port which is a circular coaxial transmission line as well.

The command signal duration can be from 20 to 1000 ms. The relay switching time is 5 ms maximum (typically <2 ms).

The internal switching function is based on two electromagnetic coils (55 Ohm resistance). Each coil can push a "paddle" when subjected to a DC current pulse (6 V, 144 mA max). The paddle then indirectly pushes the RF blade into RF contact (see Fig. 4).

The other RF path remains in "isolation position". The RF blade in "isolation position" is pushed on the RF cavity top side using an isolation blade that work as a spring, see Fig. 4.

The RF line and cavity were designed to provide the best RF performances in the wide frequency range from DC to 32 GHz.

MEMR is assembled in clean room environment. The assembly is done in 3 main steps:

1. Purchase of machined and moulded sub-parts following incoming specification to comply with electrical, mechanical, reliability and RF performances
2. Manual assembly of all the sub-parts by operator using different shims with different width to adjust the forces applied inside the switch
3. Screening test (vibration, run-in, electrical performance in temperature, etc…).

3. Reliability assessment test programme

The developed MEMR device shall be qualified for the space application domain. Up to date, there are no existing ESA standards for the qualification of electromechanical RF relays at the component level. Within the scope of this work, a test programme for the reliability assessment and evaluation of the RF MEMR components was developed. This test programme is aligned with the existing ESA standards for the reliability assessment of direct current (DC) electromechanical relays [1–3]. It addresses the main environmental and operational severities applicable for the usage in space. The test programme consists of the following reliability tests:

- Random mechanical vibration (step-stress)
- Sine sweep mechanical vibration (step-stress)
- Mechanical shock (step-stress)
- Hot switching life (high DC load applied)
- Coil life temperature cycling
- Coil voltage (step-stress)

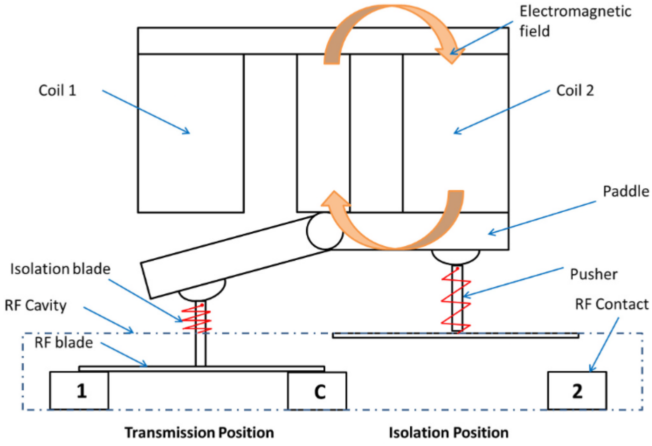


Fig. 4. Internal view of the switching function.

- Resistance to solder heat (step-duration)
- High temperature operation life (step-stress)
- Low temperature operation life
- Temperature cycling (step-stress)
- Humidity resistance (step-stress)
- Hermeticity

Some of the tests above were carried out in a step-stress mode, meaning that the corresponding load (e.g. mechanical shock acceleration) was progressively increased from low to high values in order to identify the device robustness limits. A total of 77 devices were subjected to the test programme (6 per each test listed above +5 in the control group).

The main difference of the test programme developed in this work in comparison to the existing ESA standards for the DC relays is related to the RF characterisation of the tested components. Thus, the failure assessment procedure consisted of:

- DC characterisation: measurements of the contact resistance for each of the two RF paths
- RF characterisation: measurements of the insertion loss, isolation and voltage standing wave ratio (VSWR) for each RF path
- Switching time: minimum pulse duration required to open and close the contacts for each RF path.

The abovementioned electrical and RF characteristics of the MEMR were measured at the beginning of the reliability tests, during the required interim characterisations, and at the end of each test. The failure criteria were defined as: 1) complete loss of the device functionality (catastrophic failure) or 2) as a deviation of the measured characteristics beyond the specified limits (non-catastrophic failure).

An innovative testing approach for the mechanical testing was developed. It allows to perform in-situ electrical characterisation of the tested relay during the mechanical impact, thus enabling the detection of any micro-opening or micro-closing of the relay's contacts caused by the applied mechanical load. Dedicated test benches were designed and constructed for these tests, as well as for the switching cycling tests at high and low temperatures (Fig. 5).

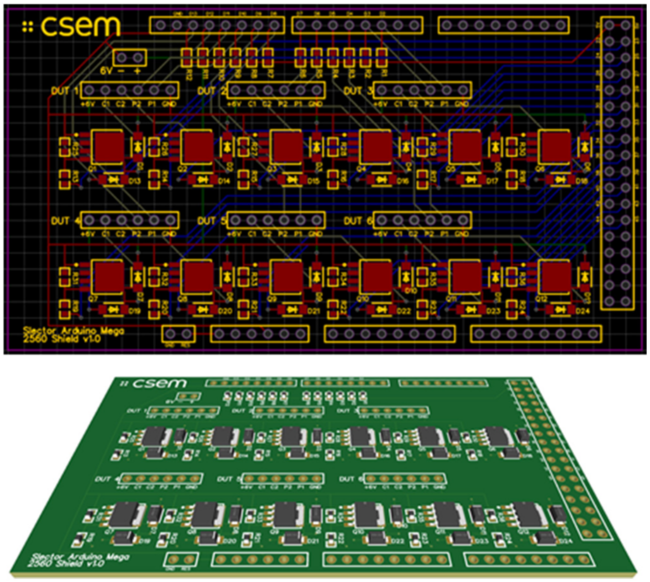


Fig. 5. Developed test bench PCB and its schematics.

4. Test results

4.1. Mechanical tests

Mechanical random and sine sweep vibration tests were carried out in the frequency range from 5 to 2000 Hz. The tests were performed in step-stress mode with increased vibration accelerations. The devices under test (DUTs) were subjected to vibration in 3 orthogonal directions. Test results showed that the MEMR is capable of withstanding the vibration accelerations up to 50 g rms (random) and 50 g peak (sine sweep) without any degradation of the electrical and RF characteristics. In-situ electrical monitoring of the samples revealed micro-second short opening of the closed RF contacts during vibration with the acceleration levels of 30 + g (random) and 40 + g (sine sweep). This phenomenon is not considered as a failure since for the target application in space domain such high vibration levels can only be experienced during the launch and stage separation flight segments, where the MEMRs are idle (not operating).

Mechanical shock tests were also carried out in step-stress mode with a stepwise increase of the shock acceleration (and corresponding decrease of the shock pulse duration). It was found that the most vulnerable direction is *Z*- (acceleration acting down on the top face of the MEMR device shown in Fig. 1). In-situ electrical monitoring of the DUTs during the test revealed micro-opening and micro-closing of the contacts at accelerations up to 2000 g and flipping of the relay state (e.g. path-1 open turns to path-2 open) at accelerations 2000-4000 g. Both phenomena are not considered as failures, as the relay retains its full functionality and can be normally reset to its original state. The limit of the catastrophic failure occurrence ranges from 3000 g to 4000 g, which is above the target specification of 2900 g.

Two failure modes were observed:

1) Relay cannot switch its position (while being structurally intact). This is a less common failure mode. The performed analysis reveals that the root cause for this failure is detachment of the permanent SmCo magnet. A stronger adhesive can be used as a mitigation solution.

2) Metal bracket holding the relay case is destroyed (see Fig. 6). This is a more common failure mode, which leads to a complete structural disintegration of the relay as the lid becomes loose. The probable root cause is the stress applied to the metal bracket by the used elastic sealing gasket. Possible mitigation solutions could be utilisation of a stronger bracket and/or adjustment of the gasket thickness to reduce the tensile force acting on the bracket.

4.2. Endurance tests

The tests from this group aim at the assessment of the relay's

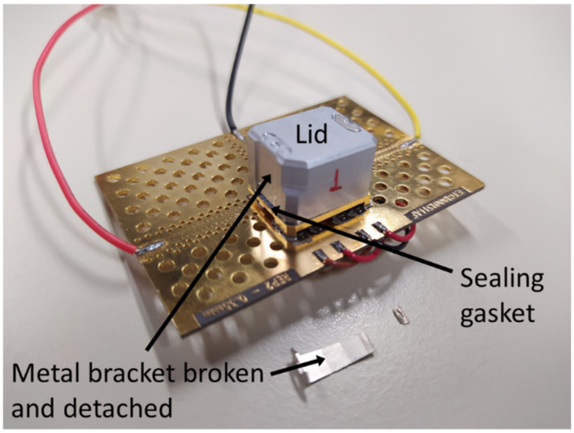


Fig. 6. MEMR DUT failed during the mechanical shock test at the peak acceleration of 4000 g.

performance under high functional electrical loads (e.g. high commutated currents, coil overstressing). Hot switching life test was performed at the maximum specified operation temperature of 95 °C by actuating the relays with a high applied commutated DC load (power of 1 W) at a switching frequency of 20 cycles per minute. The contact resistance was monitored throughout the test at several interim time intervals. It remains nearly constant throughout the test with no degradation trend observed (Fig. 7). The RF parameters were measured before and after the test completion. No deterioration of the RF performances was also observed (Fig. 8). Thus, all 6 DUTs successfully passed the test of 500′000 switching cycles.

The coil endurance was assessed by carrying out a special coil life temperature cycling test (defined in ESA standard [2]). The DUTs were subjected to 10 temperature cycles between the max and min operation temperatures (+95 °C and −55 °C, respectively). During the time at +95 °C the coils were fully energised with the nominal voltage of 6 V (during the usual operation this voltage is only applied for a few milliseconds to switch the bistable state of the relay). 11 of the 12 tested coils (6 DUTs, each has two coils) have successfully passed the test. One coil has failed early in the test after the 2nd temperature cycle (out of 10 cycles). This was considered as an early mortality failure. Normally this kind of failures can be avoided by the implementation of a burn-in procedure. The DUTs used in this work were not subjected to any burn-in or pre-selection processes.

The coil robustness against overvoltage was evaluated by stepwise increase of the driving voltage from the nominal 6 V up to 18 V (3× nominal). At each voltage step the relay was actuated 100 times at the maximum operation $T = 95$ °C. All 6 DUTs successfully passed the test without any degradation of the electrical and RF parameters.

4.3. Environmental tests

A series of the tests was carried out in order to assess the MEMR robustness against typical environmental stresses (e.g. high and low T, T cycling, humidity) and in order to identify the reliability limits.

Fig. 9 shows the typical results of the high T switching cycling life test performed at a low signal-level commutated DC current of 1 mA (at 5 V). The cycling rate was 120 switching cycles per minute.

The obtained results (also the performed RF characterisation) indicate that the MEMR can withstand a prolonged operation at the nominal maximum operation T of 95 °C. No degradation of the electrical and RF performance was observed up to 3’000’000 switching cycles. The test performed at an increased T of 125 °C reveals a degradation trend of the contact resistance (as well as RF performance) that becomes significant beyond 1′000’000 switching cycles (see bottom chart in Fig. 9, please note the log scale). This suggests that the relays can still operate at increased temperatures, but at the cost of a gradual degradation of characteristics. A possible reason for the observed degradation could be a gradual contamination of the RF contacts surface by the decomposition products of the used organic materials (e.g. adhesive) when the MEMR is heated above the maximum specified T of 95 °C.

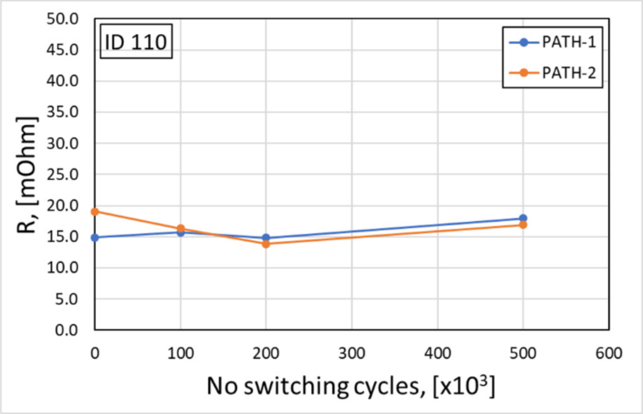


Fig. 7. Evolution of the contact resistance with the number of hot switching cycles at 95 °C (typical example).

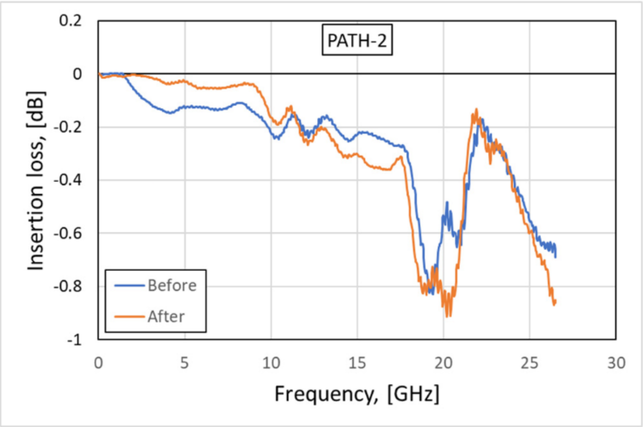


Fig. 8. Typical example of the RF insertion loss measurements before and after the hot switching life test.

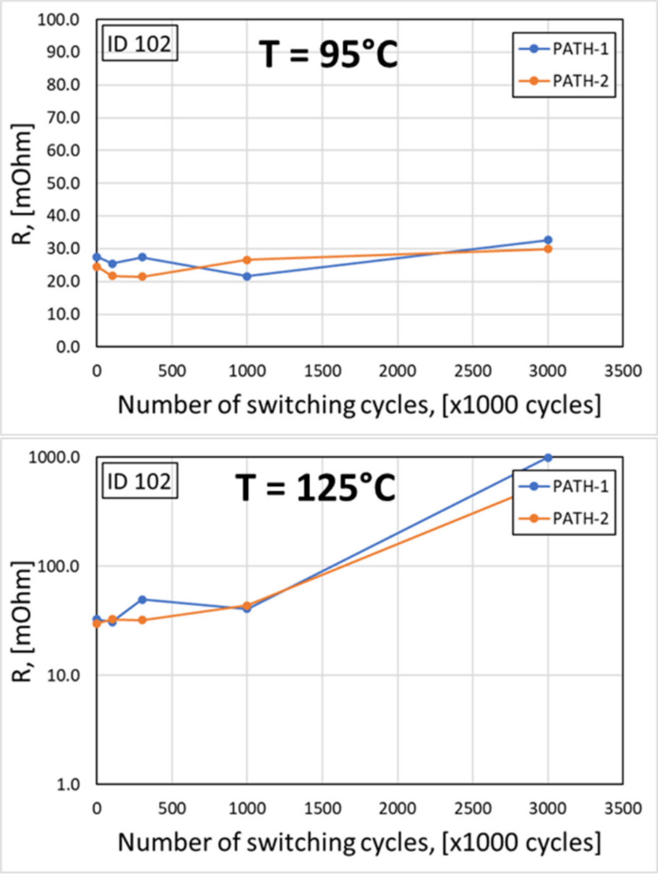


Fig. 9. Evolution of the contact resistance with the number of switching cycles at 95 °C and 125 °C (typical example). The observed non-monotonous variation of resistance is caused by the quality of electrical mechanical spring contact between the MEMR and the evaluation socket.

Results of the high temperature operation life test were used for the switching-related MEMR lifetime estimation using the Arrhenius law (see Eq. (1)). The lower bound of the lifetime at different operation conditions can thus be estimated from the number of switching cycles with no failures ($N_{cycl} = 3'000'000$) at the test temperature $T_t = 95$ °C. The activation energy of 0.15 eV was taken from [4].

$$FR(T) = A_T{}^{*}exp.(-E_a/kT) \tag{1}$$

$$Lifetime = [N_{cycl}/f_u]{}^{*}exp.(E_a/k^{*}[1/T_u - 1/T_t]) \tag{2}$$

where FR is failure rate; T is temperature; A_T is pre-exponential term; E_a is activation energy; k is Boltzmann constant; *Lifetime* is the lower bound for the lifetime in years; f_u is frequency of use in number of switching cycles per year (e.g. $f_u = 365$ year^{-1} if the device is switched once a day); T_u is temperature of use. The estimated lifetime as function of the operation temperature and actuation frequency is shown in Fig. 10.

The estimated device lifetime in terms of switching is demonstrated to be at least 10 years at the switching frequency of 1 cycle per minute up to the maximum rated operation temperature of 95 °C.

Low temperature operation life test was performed in a similar manner at the minimum specified T of −55 °C. The test was successfully passed by all 6 DUTs. Fig. 11 shows a typical example of the RF insertion loss measurement performed before the test and after 3'000'000 switching cycles at −55 °C. No degradation of the RF performance occurs between the two measurements. The observed value of the insertion loss of up to −2 dB is higher than the device specification (−1 dB) because the MEMR was not soldered to the PCB, but was connected mechanically to the characterisation RF socket. This causes the additional losses in the points of mechanical connection.

Temperature cycling test was carried out by moving the unpowered DUTs between the hot and cold chambers. Thus, the rapid change in temperature accelerates potential failure mechanisms related to the poor matching of the thermal expansion coefficients of the utilised materials. The test results showed an outstanding robustness of the MEMRs, which have successfully passed the test at 4 different T gradient levels up to the highest conditions of −55 °C/+175 °C.

Both, humidity resistance and hermiticity tests have also shown high reliability levels. The humidity resistance was demonstrated at 95 °C and 95 % relative humidity for 1000 h (unpowered DUTs). The improved MEMR hermiticity allowed to reach the IP67 level requirements. This was strictly required by the space-sector indented customer to comply with their liquid cleaning procedures after SMT soldering. It was also demonstrated that the developed MEMR can withstand the required SMT soldering thermal profile with an increased duration of 30 s at the maximum temperature of 250 °C (required is 10 s).

5. Conclusions

Performed reliability assessment and evaluation allows to conclude that the developed MEMR component is fully compliant with the target reliability levels (Table 2). The device exhibits high robustness against mechanical shock and vibrations. It also shows a very high endurance of the coils at the highest specified operation conditions. The component also demonstrates a high robustness against the environmental loads, such as operation temperature, high temperature gradients and humidity.

The achieved level of reliability enables the use of the developed component in the redundancy rings of the telecommunication satellites. For this application the switching rate is expected to be much less than 1 cycle per minute, thus enabling very high lifetime in terms of switching operations for more than 10 years.

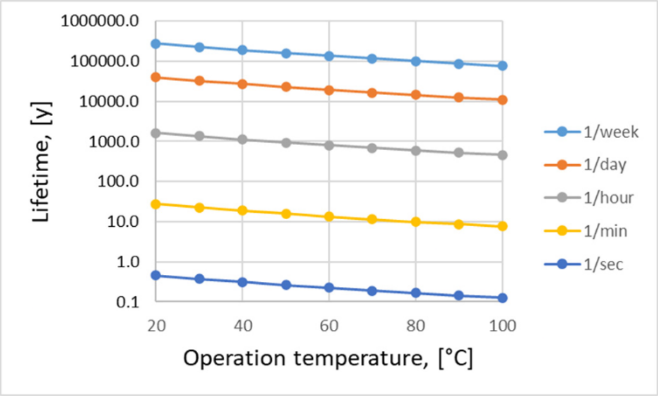


Fig. 10. Estimated lifetime of MEMR devices as function of operation temperature and switching frequency.

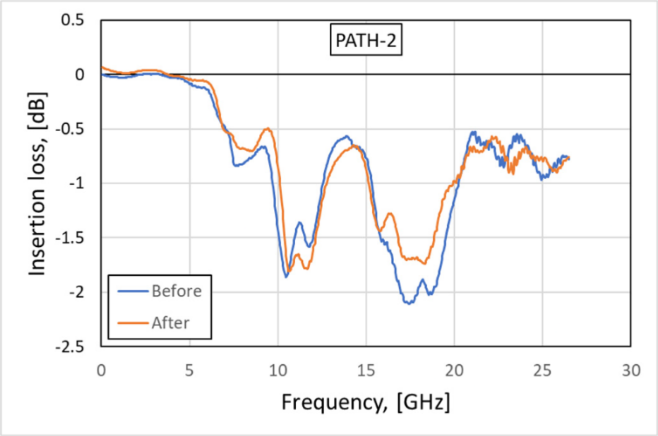


Fig. 11. Typical example of the RF insertion loss measurements before and after the low T operation life test.

CRediT authorship contribution statement

I. Marozau: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - Original Draft, Visualization

S. Unterhofer: Investigation

M. Berry: Conceptualization, Methodology, Formal analysis, Writing - Review & Editing, Visualization

G. Aubry: Methodology, Writing - Review & Editing, Visualization

P. Gonin: Methodology

R. Enquebecq: Conceptualization, Validation, Supervision, Project administration, Funding acquisition

M. Dadras: Conceptualization, Validation, Funding acquisition

O. Sereda: Conceptualization, Validation, Supervision, Funding acquisition

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table 2
Overview of the achieved reliability levels.

Test	Target spec	Achieved spec
Random vibration	50 g rms	50 g rms
Sine sweep vibration	50 g peak	50 g peak
Mechanical shock	2900 g	3000–4500 g
High T hot switching	500 k cycles	500 k cycles
High T cold switching	3 M cycles	3 M cycles
Low T cold switching	3 M cycles	3 M cycles
Temperature cycling	−55 °C/95 °C	−55 °C/175 °C
Humidity resistance	85 °C / 85% RH	95 °C / 95% RH
Ingress protection level	IP67	IP67
Solder heat	10s @250 °C	30s @250 °C
Coil overvoltage	6 V nominal	18 V

Data availability

The data that has been used is confidential.

Acknowledgements

This work has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821973.

References

[1] ESCC Basic Specification No. 2263600: Evaluation test programme for electromagnetic relays.
[2] ESCC Generic Specification No. 3601: Relays, electromagnetic, latching.
[3] ESCC Generic Specification No. 3602: Relays, electromagnetic, non-latching.
[4] IEC TR 62380: Reliability data handbook – Universal model for reliability prediction of electronics components, PCBs and equipment.
[5] ESCC Generic Specification No. 3603: Relays, electromagnetic, RF switch, latching.
[6] ESCC Detail Specification No. 323 (3603/007): RF electromagnetic relay, latching, SMT, micro-SPDT, break-before-make, low power, DC to 32Ghz.