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Study of Vibration Effects on Communication Filters in Substrate Integrated Technologies

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ABSTRACT The growing need of space communication systems forces the industry to innovate in order to provide more robust, economical and flexible solutions. The new substrate integrated technologies enable the development of on-board communications devices with less weight and volume than the traditional waveguide-based ones. However, it is necessary to analyse the performance of these devices in the particular working conditions of satellite communications. This work studies the integrity of the electrical response of advanced communication filters under mechanical stress conditions. Four realisations of a Ku-band microwave filter in different substrate integrated technologies were developed and tested. Two mechanical vibration tests were performed: sinusoidal sweep and random vibration. These tests emulate the transport and launching conditions of the satellite payload. Furthermore, the mechanical natural frequency of the filters and its variation after being exposed to the tests have been measured to evaluate the devices integrity. For all the filters, this frequency variation is lower than 5 %, the standard threshold. This proves that the developed filters can survive the launching conditions of satellite payload, thus qualifying the technology for spatial applications.

INDEX TERMS Filters, natural frequency, space communications, substrate integrated circuits, vibration.

I. INTRODUCTION

In the last decades, an unprecedented revolution has been going on in the field of information technology. There has been an exponential growth in the demand for internet access for multiple sensors, software, and other technologies, known as Internet Of Things (IoT) [1], as well as for the management of the generated big data [2]. IoT has been adopted for the development of intelligent systems in a wide range of applications [3]. Moreover, the increasingly high transmission rates required by these services impact the requirements of communication systems: higher signal-to-noise ratio and sensitivity, increasingly complex modulations, reduced size and weight, cheaper manufacturing, etc.

New fleets of satellites are needed in order to cope with this massive demand for high quality and ubiquitous internet access [4]. Low orbit and small size satellites (picosatellites, nanosatellites, and microsatellites) offer the advantage, compared to traditional satellites, of very low cost and mass production. A report by Northern Sky Research [5] estimates that small satellites will play an increasingly important role in the market of IoT. The small satellite segment has grown from 20 satellites launched in 2011 to more than 350 in 2021. It is estimated that between 1800 and 2400 nano and microsatellites will be launched between 2020 and 2024 [6] for applications such as earth observation, remote sensing, communications, scientific missions, technology, and novel applications. These new small-size satellites require the development of passive components and antennas of small size, with low manufacturing costs and with as high performance as possible.

Rectangular waveguides are the dominant technology for satellite payload filters operating at microwave frequencies. However, planar technologies are increasingly being

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considered for implementing these components. The need for reduction of weight and volume motivates this decision. In particular, substrate integrated technologies perform halfway between traditional waveguides and planar lines. Specifically, the use of H-plane rectangular cavity filters and the introduction of resonant cavities based on dielectric material are classic lines of research on substrate integrated circuits [7], [8]. Nevertheless, these new technologies do not yet reach the level of understanding that classical waveguide technology does. Therefore, little has been done to shed light on the behaviour of these new transmission technologies in the space segment.

Before launching a satellite, all its components must pass a set of tests defined by the different space agencies. The communications devices of the satellite payload must prove their viability in front of extreme conditions of temperature, power handling and mechanical stress, among others. This process is commonly known as "qualification for space applications". Examples of this process can be found in [9] where mechanical vibration was studied on a filter with a planar realization, and [10] where a complete space qualification is performed on a waveguide filter. Concerning Substrate Integrated filters, [11] performs temperature and power handling testing, but not mechanical tests, on Air-Filled SIW (AFSIW) filters and multiplexers. In [12] space temperature tests were performed on communication filters manufactured in different substrate integrated technologies. The results of these tests were remarkable. In order to continue with the validation process, the filters should also pass the rest of the tests.

This work aims to assess the performance of substrate integrated technologies for Ku-band communication filters under conditions of mechanical vibration stress. The tests emulate the stress levels under the mechanical vibratory conditions that these devices suffer during satellite transport and launching stages. For this purpose the same filters than in [12] were the object of the vibration tests described in the European Space Agency standard ECSS-E-ST-10-03C [13].

II. SUBSTRATE INTEGRATED TECHNOLOGIES AND FILTER REALISATION

The Substrate Integrated Waveguide (SIW) [14] was the first member of this family of transmission lines. It consists of a waveguide implemented in a Printed Circuit Board (PCB) substrate. The conducting layers of the PCB act as the top and bottom walls of the waveguide, and the lateral walls are implemented with two rows of metalized via holes close enough to form an electric field boundary, avoiding radiation almost completely.

The resulting waveguide has the same height as the substrate, and it is perfectly integrated into the planar circuit, with a performance midway between the microstrip line and the waveguide.

The integration with a planar line (for example, the microstrip line) is achieved thanks to a tapered transition that feeds the SIW. Although this structure has far better performance than a microstrip line, it presents higher loss than a waveguide due to the substrate tangent loss, the loss in the conductors, and the non-perfect electric walls created by the via holes. As an attempt to reduce the loss of the SIW structure, the Empty Substrate Integrated Waveguide (ESIW) [15] appeared, where the substrate is removed from the path of the fields and the metalized via holes are substituted by continuous metalized walls. This structure needs top and bottom covers to confine the fields inside the line.

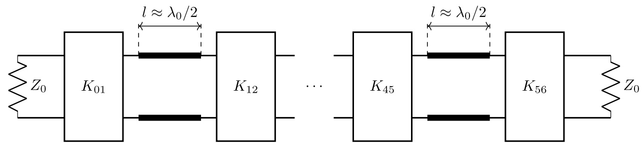


FIGURE 1. Equivalent network of the band-pass filter based on series resonators and impedance inverters. The normalized inverter values are $\bar{K}_{01} = \bar{K}_{56} = 0.2134$, $\bar{K}_{12} = \bar{K}_{45} = 0.0353$ and $\bar{K}_{23} = \bar{K}_{34} = 0.0247$.

A similar proposal is the Empty Substrate Integrated Coaxial Line (ESICL). It implements a square cross-section empty coaxial by stacking five layers of PCB substrate [16], all integrated into a printed circuit board and connected to planar lines. The central layer contains the active conductor of the coaxial, the microstrip (or coplanar) feeding line, and the transition between the two technologies. The top and bottom layers perform the upper and lower parts of the outside conductor, and the intermediate layers create the air gaps between inner and outer conductors. This five-layered structure allows the integration with planar circuits in a seamless way while maintaining the performance of the coaxial line.

High-frequency circuits can be built on these integrated technologies following the same design procedures used in the classical waveguide or coaxial line-based technologies.

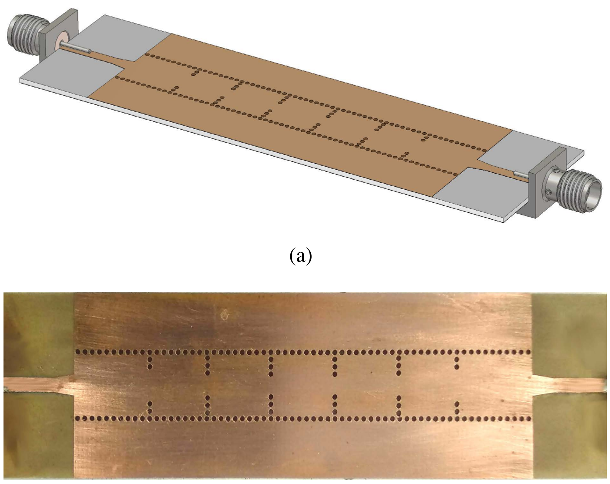
A. FILTER DESIGN

In this work, four substrate integrated technologies have been used to implement a Ku-band bandpass filter with the following electrical response: a five poles Chebyshev response centred at 13 GHz, with 400 MHz bandwidth and 25 dB of return loss (0.1 dB of ripple) in the pass-band.

Filters have been designed by using the well-known insertion loss method [17]. Firstly, a low-pass filter prototype is computed, and then the final pass-band response is obtained by applying a frequency transformation. These prototypes are based on lumped elements that are difficult to construct at high frequency. Consequently, the filter circuit should be redefined by using half-wavelength resonators and impedance inverters, Figure 1.

Once the values of resonator lengths and impedance inverters are computed [18], these must be implemented in a distributed way. For this purpose, a numerical electromagnetic simulator (CST Studio Suite) was used [19].

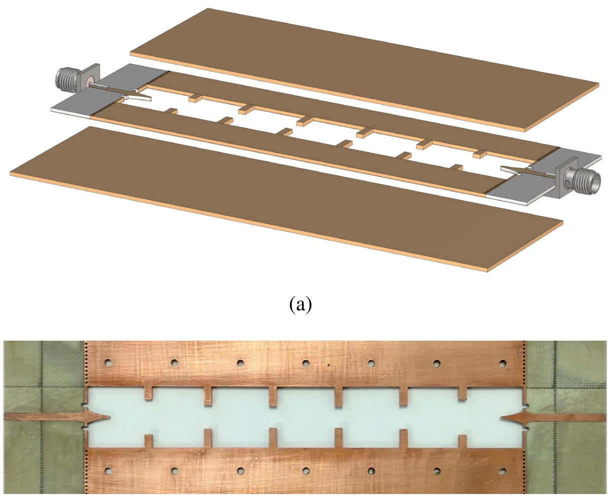
In the case of the SIW [20], and ESIW [15] filters implemented in this work (see Figure 2 and 3), a classical H-plane rectangular cavity filter topology was used. These filters are based on half-wavelength cavity resonators coupled through



(a)

(b)

FIGURE 2. **Layout of the proposed SIW filter: (a) 3D view and (b) top view of the manufactured devices.**



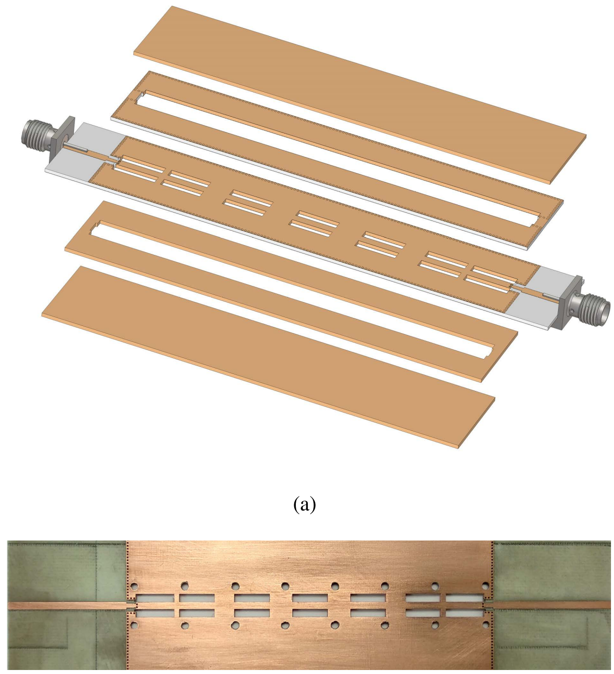
(a)

(b)

FIGURE 3. **Layout of the proposed ESIW filter: (a) 3D view and (b) top view of the middle layer of the manufactured devices.**

shunt inductive windows. These windows act as impedance inverters whose dimensions were computed using CST. The structure of the filter is performed similarly for both of them. In the case of SIW, the half-wavelength cavity resonators are sections of a SIW line separated by inductive windows, which are performed by a series of metalized via holes, as shown in Figure 2 (a). In the case of the ESIW filter, the cavities are performed with metalized walls, see Figure 3. These metalized walls are done by cutting and metalizing channels using standard manufacturing processes for PCBs.

For the ESICL filter [21] (Figure 4), the resonators are implemented by short-circuited transmission lines with a length of half-wavelength. These resonators are coupled by shunt inductances achieved by connecting the active and ground conductors of the structure. The inductance value can



(a)

(b)

FIGURE 4. **Layout of the proposed ESICL filter: (a) 3D view and (b) top view of the middle layer of the manufactured devices.**

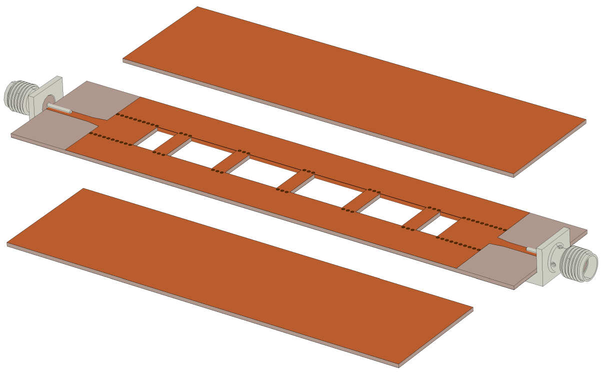
be adjusted by changing the length of the shorted sections, thus achieving the desired response for each inverter.

Finally, the Alternating Dielectric Line Sections (ADLS) filter [22] is based on the alternation of sections of SIW and ESIW lines, see Figure 5. In this case, the dielectric-filled sections (SIW), with a length of approximately $\lambda_g/2$, act as resonators. The empty sections (ESIW) work below the cutoff frequency acting as impedance inverters, whose inversion ratio can be adjusted by controlling their length.

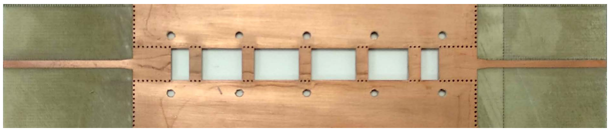
A different transmission line feeds each filter; SIW and ADLS use SIW feeding lines, while ESICL and ESIW filters are fed by ESICL and ESIW lines, respectively. Thus, transitions from microstrip to each of these transmission lines have been designed to interconnect them with planar circuits. The dimensions, topologies, and transitions of these filters are those presented more extensively in [12]. The ESIW and ESICL filters have been manufactured twice, one with the same length as in [12], and another with an extended length of the feeding lines. This was done to check the influence of the length in the vibration tests. The total dimensions of the six prototypes are shown in Table 1.

III. VIBRATION TESTS

Mechanical stress wave-based disturbances cause deformations in the media through which they propagate. These deformations can lead to irreversible structural changes depending on the stress amplitude and the mechanical characteristics of the materials that support them.



(a)



(b)

FIGURE 5. Layout of the proposed ADLS filter: (a) 3D view and (b) top view of the middle layer of the manufactured devices.

TABLE 1. Dimensions of the filters under test.

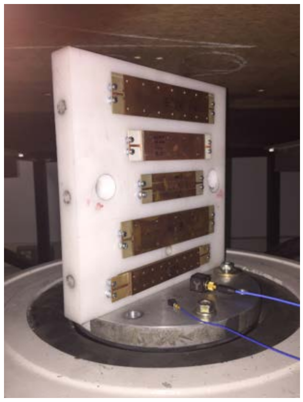
Filter	Height (mm)	Width (mm)	Total Length (mm)
ine SIW	1	25	90
ESIW Short	3	40	130
ESIW Long	3	40	140
ADLS	3	25	113
ESICL Short	4	20	116
ESICL Long	4	20	136

The objective of vibration tests is to ensure the structural and functional integrity of the devices when they are subjected to different types of mechanical stress. For space applications, the technical characteristics of these tests, as well as the associated tolerance margins, are described in the ECSS-E-ST-10-03C standard [13] of the European Space Agency. These stress phenomena are characteristic of any spatial application due to the intense vibrations during take-off and on-orbit operations. Therefore, three different tests are defined in the ECSS standard: sweep test, random vibration, and shock wave test.

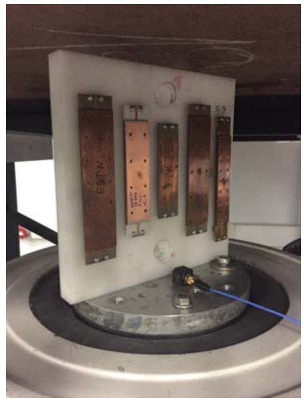
Additionally, it is of particular interest to point out the concept of natural frequency since the variation of its value is the indicator that the ECSS standard stipulates to consider whether a device has successfully passed the vibration tests. The natural frequency is the resonance frequency at which a system tends to oscillate without external forces.

A. GENERAL CONSIDERATIONS

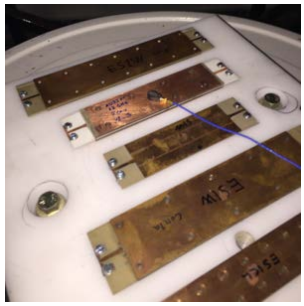
In this work, we performed sinusoidal sweep and random vibration tests on the devices under test (DUT). Likewise, the natural frequency of all of them was measured, before and after the tests, to verify their stability.



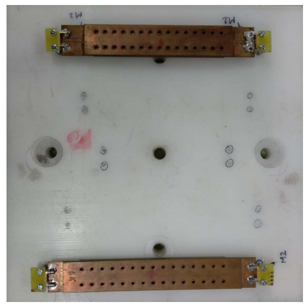
(a) Vibration on the x-axis.



(b) Vibration on the z-axis.



(c) Vibration on the y-axis



(d) Vibration of ESICL filters.

FIGURE 6. Set up for vibration tests with the filters under test screwed to a methacrylate plate.

Therefore, a specific setup and a set of tools capable of carrying out both tests and measurements were necessary. The vibrational response of the filters is influenced by the type of setup used in the tests. In this case, each filter was screwed to a 21 mm thick methacrylate plate by using four M2 screws at the ends, in the same way as they are fixed in the satellite (see Figure 6). Screwing them is necessary to ensure a minimum distance between the filters and the plastic support to avoid blows during the tests. As shown in Figure 6, the methacrylate support allows it to be placed in different orientations, which enables the testing set for the three spatial axes. The following tools were used for the excitation and measurements:

- Electrodynamics vibration exciter LDS V721: together with a PA1000 amplifier constitutes the vibrating bed that transmits the stress waves to the filters.
- Triaxial accelerometer PCB 356A16 (100 mV/g): it will be placed on the vibrating bed or on the plastic support, depending on the test.
- Ultralight accelerometer PCB 352C22 (10 mV/g): precision accelerometer that depending on the measurement, will be placed on the vibrating bed or on the filters themselves.
- Photon Analyzer Dactron: used for processing the signals measured by the accelerometers.

Finally, to measure the above mentioned natural frequencies, an ultralight accelerometer was placed on the centre of each filter.

B. SINUSOIDAL SWEEP

Sinusoidal sweep consisted of applying narrow-band stress waves to the filters. During the test the device is subjected to an incremental (or decremental) frequency sine vibration. According to the standard, it tries to assess the behaviour of the devices under low frequency stress waves during the launching or ground transport processes.

The requirements of this test are:

1) The tests have to be carried out in launch configuration for the three spatial axes.
2) The x-axial acceleration at the anchor points must be limited.
3) The natural frequency of each device must be measured before and after the test, variation less than 5 %.
4) Visual check must be carried out to check the integrity of the devices.

For this test, we applied a sweep from 5 Hz to 140 Hz with an amplitude of 1 g (value extracted from measurements inside the Ariane 5 shuttle [23]) and a speed of sweep of 2 octaves per minute. The maximum amplitude of displacement was limited to 5 mm to preserve the integrity of the electrodynamics exciter between 5 Hz and 7 Hz, which implied that the applied acceleration was 0.5 g, reaching an acceleration of 1 g at 7 Hz.

C. RANDOM VIBRATION

This test supports the structural feasibility of the filters under broadband mechanical disturbances caused during the launching or ground transport processes. For this test, the requirements are the same as for the sinusoidal sweep one.

During the test the device is subjected to a pseudo random vibration signal, whose energy level is defined by a Power Spectral Density (PSD). PSD is the Fourier Transform of the autocorrelation of the random signal. The signal can be described as non correlated, and it is composed by multiple sinusoidal vibrations occurring simultaneously at different frequencies over a specific frequency range. The standard specifies that the PSD of the applied acceleration must be above the minimum workmanship PSD [13], which is defined by each Spatial Agency for the test [23], [24]. Minimum workmanship avoids peaks and does not present slopes greater than 25 dB/octave.

The PSD used in this test is shown in Figure 7 for each of the spatial axes. The duration of the applied vibration was 2 minutes for each direction, and root mean square (RMS) was 7.1 g.

D. SHOCK WAVE

The shock wave is a short duration wave of very high mechanical vibration frequency and energy, up to 1000 g. During this test, the devices are submitted to high mechanical forces during a short time, which may affect their structural integrity. This test is performed with the devices in "off" mode, since it emulates the effect of the launching stages when the payload is not operative. Consequently, when the device is propagating an RF signal, it is not under the effect of a shock wave.

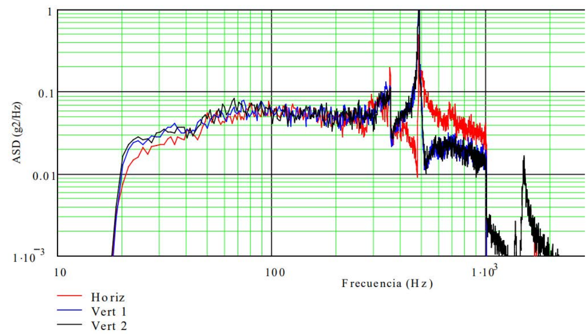


FIGURE 7. Spectral density of vibration amplitude applied to filters in random vibration tests.

Nevertheless, if the shock wave has damaged the structure of the device, this may affect its performance. Although this test was not performed due to a limitation in the testbed, the study of the structural problems that may appear in the particular case of substrate integrated filters is presented:

- For one-layer filters (SIW technology), the structure might only be damaged by a severe breakout of the PCB layer, which would compromise other parts of the circuit. This effect is improbable but not negligible.
- For three-layered filters (ESIW and ADLS filters), the structure might be compromised by an unstuck of the welded parts of the filters. Even small gaps between the three layers that compose these filters cause out of tuning and propagation loss. These effects are a consequence of the electric current distribution in these filters: gaps between layers interrupt it. Obviously, the risk of a breakout of the PCB layer is also present.
- For five-layered filters (ESICL filters), the unstuck of the welded parts is not so critical since the electric current distribution is different and small gaps between layers do not affect it. Nevertheless, the risk of a breakout of the PCB layer is always present when performing these tests.

E. NATURAL FREQUENCY

In the same way, electrical circuits with resonant elements have resonant frequencies; mechanical systems have natural frequencies. When a system is excited with a mechanical force that oscillates at the natural frequency, the system enters into resonance, and the amplitude of the vibrations increases substantially. Therefore, the measurement of this parameter is critical because it is representative of the structural integrity of a system.

The literature [25] shows how to calculate the natural frequencies of the different modes of solid objects, like beams, columns or shells. Nevertheless, the devices under test are complex: with a non-homogeneous material and noncanonical shapes. However, a first approximation can be made for the calculus of the natural frequency of the SIW filter by using

TABLE 2. Variation of the natural frequencies of the filters after carrying out the set of vibration tests.

Filter	Initial Frec. (Hz)	End Frec. (Hz)	Bias (%)
SIW	424	425	+0.2
ESIW Short	349	348	+0.3
ESIW Long	303	289	+4.6
ADLS	494	478	+3.2
ESICL Short	435	434	-0.2
ESICL Long	355	345	+0.3

the simply supported beam model in 1.

$$f_n = \frac{K_n}{\pi}\sqrt{\frac{EIg}{wl^4}} \tag{1}$$

where, K_n is a constant referring to the vibration mode, E is the modulus of elasticity, I is the area moment of inertia, g is the acceleration, w is the uniform force per unit length and l is the length. The SIW filter was manufactured with RO4003C substrate, whose $E = 0.01954$ GPa, the section of the filter is 0.92×25 mm, thus $I = 1197.92$ mm^4, the length of the filter is 90 mm, with an applied force of 0.00063 N/mm the calculated natural frequency for the first mode is 116.8 Hz and for the second one 467.5 Hz. As it can be seen in Table 2 the measured natural frequency of SIW filter is 424 Hz, thus the second mode, since the resonance of first mode was too weak for good accuracy. Unfortunately, the model cannot be used for all the filters, but it will provide an idea of the range where the natural frequencies can be.

During a vibration test campaign, the devices natural frequency is measured before and after each test is performed. According to the standard, the deviation in natural frequency after each test must be under 5%. Not fitting this constrain is a symptom of the loss of mechanical integrity of the system or device.

In this work, two vibration tests were performed (sinusoidal sweep and random vibration), the natural frequency was measured before and after having completed both tests. Therefore, the natural frequency variation was due not to one but two tests, thus adding an inherent safety margin to the ECSS standard.

In order to measure the natural frequency, the aforementioned ultralight accelerometer (weight: 0.5 g) was installed on top of each filter by using a non-permanent adhesive, see Figure 6.c. In this way, we obtained the mechanical transfer function between the acceleration measured at the device versus the acceleration applied to the base (and measured by a triaxial accelerometer). For this measurement, a noise signal was used as excitation. Its frequency was up to 1.3 kHz, and its amplitude was much lower than in the rest of the tests.

Installing an accelerometer on a device (even if it is ultralight) is a method that affects the measurement of its natural frequency. This effect is assumed to be the same in each measurement. Since the required parameter is a variation of two measurements, i.e. a subtraction, the effect of the accelerometer is compensated. Nevertheless, if the effect of the accelerometer were not the same in each measurement, this would artificially increase the variation of natural frequency. The obtained results (see Section F. Results) show

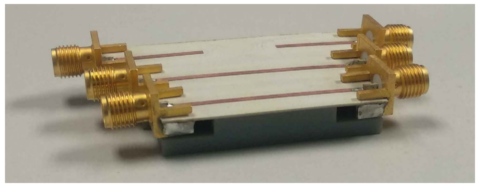


FIGURE 8. TRL calibration kit: open, line and through.

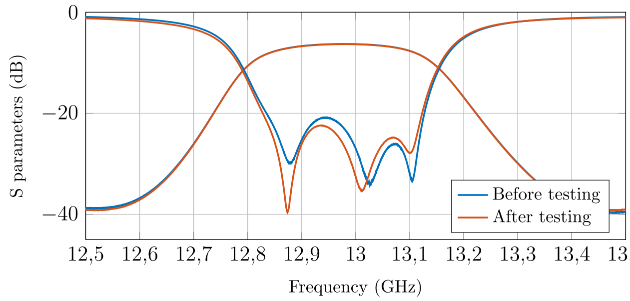


FIGURE 9. Frequency response of the filter in SIW technology before and after vibration tests.

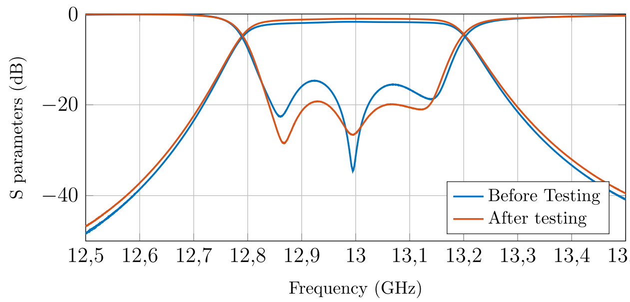


FIGURE 10. Frequency response of the filter in ESIW technology before and after vibration tests (ESIW Long).

that, in all cases, this variation is less than 5%; even with the negative effect introduced by the accelerometer, the parameter fits the requirements of the standard.

F. RESULTS

Before and after the vibration tests, the electric frequency response of every filter was measured by using a Vectorial Network Analyzer, in ambient temperature (25° C). A TRL calibration kit was used to eliminate the effect of connectors and microstrip feeding lines, see Figure 8. Then, the data were presented using a Matlab function, as can be seen in Figures 9, 10, 11 and 12.

The results show that the changes in the frequency response are negligible and go through unimportant variations in the values of the return loss in the passband, not observing, in any case, significant frequency shifts or increases in insertion loss.

On the other hand, Table 2 shows a comparison between the natural frequencies of the devices before and after performing the tests.

To study the behaviour of the devices based on their dimension, for ESIW and ESICL filters, these tests were carried out for two different lengths. As previously mentioned, the ECSS standard established a maximum variation of 5 % in the natural frequency for the viability of the DUT. Table 2

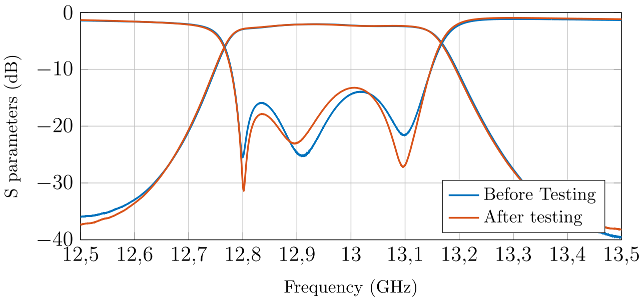


FIGURE 11. Frequency response of the filter in ESICL technology before and after vibration tests (ESICL short).

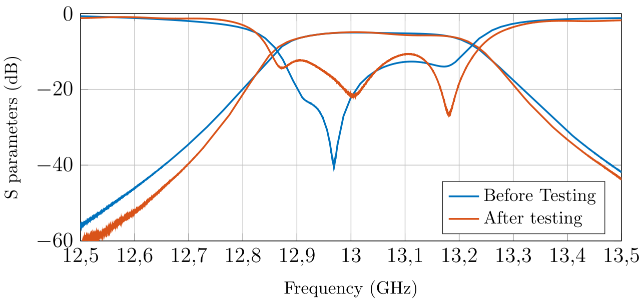


FIGURE 12. Frequency response of the filter in ADLS technology before and after vibration tests.

shows that none of the filters has suffered variations greater than the established limit, being the extended length ESIW filter the one with the higher variation with 4.6 %, followed by the ADLS filter, with a variation of 3.2 %. The rest of the filters remained at variations lower than 0.3 %, which shows their structural resistance.

To perform the tests, the filters were screwed to the test bench, and we discovered that screws loosen up during testing, affecting the measurement. Furthermore, the screws were tightened by hand, and the pressure was not always the same. SIW, ADLS and ESIW filters were tested screwed only, whilst ESICL filters were tested with screws fixed with glue. We discovered that it is recommended to fix the device carefully on the testing bench to avoid adding sources of uncertainty to the measurement.

In addition, as was expected, the longer versions of the filters present lower natural frequencies and higher variations. Nevertheless, Figures 10 and 11 show the electric response of an ESIW filter with a long input feeding line and an ESICL filter with a short one, respectively. As can be noticed, the length of the feeding line is not a key parameter to have into account regarding frequency response variation.

In relation to previous work made about vibration tests on satellite filters, [10] states that sinusoidal and random vibration tests were performed on a resonant cavities filter based on waveguide. The frequency response of the filter was: central frequency 11.7 GHz, bandwidth 200 MHz, insertion loss 0.5 dB, and return loss −19 dB. The filter dimensions: 166 × 27 × 14 mm. No information is provided concerning the test bench, the specifications of the random vibration and sinusoidal tests or the measured natural frequencies. No before and after frequency responses of the filters were provided. Nevertheless, the work declares that the filter passed the test successfully.

In [26] a high temperature superconducting filter was tested. The frequency response of the filter was: central frequency 1.74 GHz, bandwidth 54 MHz, insertion loss 0.1 dB, and return loss −22,5 dB. The filter dimensions were not provided. The work states that sinusoidal (10 to 100 Hz and 20 g of amplitude) and random vibration (100 to 2000 Hz and 17.6 g RMS of PSD) tests were performed. The natural frequency was not measured. The work shows the electric response of the filters, before and after the test, the differences in frequency and losses are negligible.

In [27] an optical filter assemblies is subject to complete space qualification, including vibration tests. The filter is composed of several lenses assembled in an Optical Filtering Module (OFM). The overall frequency response of the OFM is: central wavelength 532.27 nm and bandwidth 31.04 pm. The dimensions of the OFM are not specified. Two types of tests were conducted: sinusoidal and random vibration, both specified, and PSD levels for random vibration were provided. The work states that natural frequencies were measured before and after the tests, and they were within the tolerance; no numerical values were provided.

IV. CONCLUSION

Four different Substrate Integrated technologies for developing communication filters in Ku band have been tested under the mechanical stress requirements set in the ECSS standard for space missions. Ku band is used for broadcast and fixed satellite services.

The objective of the tests was to check if the filters survive to the launching process, i.e. their natural frequency did not change and neither their electrical response.

The electric frequency response of the filters has been measured before and after random vibration and sinusoidal sweep tests. The results show no significant changes in these responses, no matter the technology used or the length of the device.

Mechanical vibration does not directly affect the electromagnetic wave as the nature of both waves is different. Nevertheless, the electrical response of the device may be affected by vibrations because they produce micro-deformations when it is present. However, the tests emulate the mechanical stress suffered by the devices during the launching. According to the standard, devices which are not operational during launching do not need to be operational during vibration tests, which means that when the mechanical wave is present, the electromagnetic wave is not.

As it can be observed, the deviation of the mechanical natural frequency of the filters was measured. Although all results are under the 5% limit, they present a high diversity. The extended length ESIW filter has the higher variation 4.6 %, followed by the ADLS filter with 3.2 %. SIW, short ESIW and ESICL filters have lower than 0.3 % variations. Different results are mainly due to the fixation to the test bench, the length of the feeding lines and the soldering quality.

As it has been verified, the results obtained in the set of vibration tests support the use of the four transmission technologies presented and allow their performance under high levels of mechanical vibration stress. Thus, fostering the development of low cost, volume and weight devices in Ku-band satellite applications.

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