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A. Mottet

S. Jillard

J. Hauden

N. Grossard

et al.



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A. Mottet^{*a}, S. Jillard^a, J. Hauden^a, N. Grossard^a, H. Porte^a, J. Tchahame^a, D. Veyrie^b, O. Gilard^b
^aiXblue PSD Besançon, 3, rue Sophie Germain, 25000 Besançon, France; ^bCNES, 18, avenue Edouard Belin, 31401 Toulouse Cedex 4, France

ABSTRACT

This paper presents the technical solutions implemented with the support of the French Space Agency (CNES) to design and manufacture hermetic Lithium Niobate (LiNbO₃: LN) modulators, in the framework of a Research & Technology (R&T) project [1]. There is also presented some identified space-compatible raw materials that constitute modulators and some relevant results of a space evaluation program realized on about fifteen of these hermetic modulators (including hermeticity tests, mechanical tests and climatic tests).

Keywords: LiNbO₃, electro-optical modulators, space qualification, space communications

1. INTRODUCTION

A LiNbO₃ (LN) modulator is an optoelectronic component whose function is to modify the properties (phase, amplitude or polarization) of the light passing through it by an electro-optical effect [2]. This device, which is already used for terrestrial telecommunications systems to achieve very high data rates transmissions, is also increasingly required for space applications such as Fiber-Optic Gyroscope (FOG) [3], free-space optical communications [4, 5] or other space missions [6]. For these space operations, it is crucial to use proven components in an environment as hostile as space. Thus, the components must present a great robustness to handling, shocks, vibrations, chemical attacks, contamination, radiation and so on, which can cause severe failures. In few words, the embedded components must be “space compliant”. One of the first ramparts contributing significantly to ensure this robustness is the packaging, in metal or ceramic. In general, the more hermetic the package is, the more reliable it will be physically. In this regard, this recent year, iXblue has made numerous efforts to improve the hermeticity level of its modulators packages, made in kovar. This thanks to several R&T projects with the support of French Space Agency and through dedicated space projects with industrial or laboratories.

In the rest of the paper, we firstly present the technical improvements realized on modulators, in the frame work of this R&T, in instances, the optical fibers feedthroughs soldering and the identification of integrated elements space-compatible (e.g. the conductive adhesive). To validate these improvements, we have manufactured a series of fifteen modulators integrating the corrections. This batch of modulators has been subjected to a space evaluation program. The results of this space evaluation, focused on packaging hermeticity, are given in the third section of this paper.

*alexandre.mottet@ixblue.com; phone +33 1 30 08 87 28

2. PROCESS AND PACKAGING IMPROVEMENT

2.1 Highlighted initial problems

The pictures of the Fig. 1 show respectively, an amplitude (a) and a phase (b) standard modulator, manufactured by iXblue. The word “standard”, used here, means that the product is reliable and suitable for terrestrial applications. The main elements that constitute the modulator are: a LN chip, held in the housing by gluing, an input and output optical fiber, a Radio-Frequency (RF) connector and Direct Current (DC) pins.

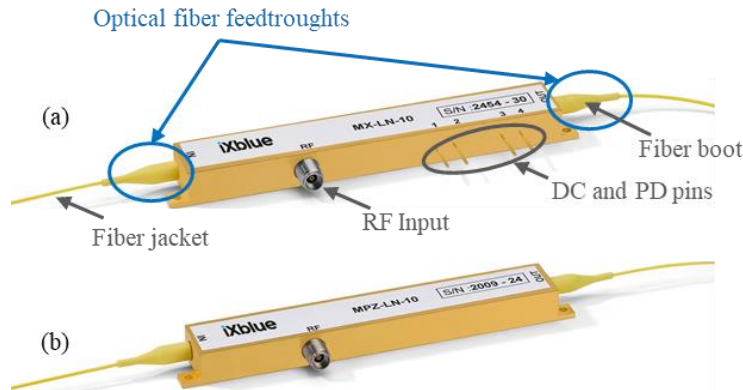


Figure 1. Lithium Niobate standard modulators, designed and manufactured by iXblue. (a) amplitude (or intensity) modulator; (b) phase modulator. RF: Radio-Frequency; DC: Direct Current; PD: Photodiode.

Aiming to use these standard modulators for space applications, a previous study, also with the support of CNES, had revealed two negative points (points to improve). The first point was the non-compliance of the outgassing level for: the optical fiber boots, the conductive adhesive and the optical fiber jacket (hytrel jacket). The outgassing level of a material can be determined by the parameters named Total Mass Loss (TML), Recovered Mass Loss ($RML \leq TML$) and Collected Volatile Condensable Material (CVCM) [7,8]. The National Aeronautics and Space Administration (NASA) acceptable rate for materials outgassing is $TML \leq 1\%$ and $CVCM \leq 0.1\%$. The ESA acceptable rate for materials outgassing is $RML \leq 1\%$ and $CVCM \leq 0.1\%$ [7,8].

The second point to improve was the non-compliance of the package hermeticity (leak rate $> 10^{-8} \text{ atm.cm}^3.\text{s}^{-1}$), mainly due to the optical fiber feedthroughs.

2.2 Identified space-compatible raw materials

The Hytrel jacket initially used for standard modulators has been replaced by polytetrafluoroethylene (PTFE) jacket which is compliant with the ESA's requirements [8]. The use of materials with low outgassing level avoids eventual contamination problem in the space vehicle that embeds the device. The Tab. 1 shows the results of outgassing tests performed on 3 samples of PTFE jacket [9]. In addition to this low outgassing level, PTFE jacket has several others key features, interesting for space applications: an extreme chemical resistance, a wide range of temperature service and excellent dielectric properties [10].

Parameters	1 st sample	2 nd sample	3 rd sample	Average values
TML in %	0.02	0.01	0.01	0.01
CVCM in %	0.01	0.01	0.01	0.01

Table 1: PTFE outgassing analysis results [9].

As with the Hytrel jacket, we have also changed the type of optical fiber boot. The results of outgassing tests performed on the new optical fiber boot is presented in Tab. 2.

Parameters	Condition A: Curing 24 hours at 125°C and 1 mbar	Condition B = condition A with additional curing, 144 hours at 125°C and 1 mbar
TML in %	0.89	0.47
CVCM in %	0.16	0.05

Table 2: The new optical fiber boots outgassing analysis results [9].

Moreover, in our manufacturing process we have also replaced the usual conductive glue, for a space-compatible one. The conductive glue is a key constituent in LN modulator, because it helps to mitigate the pyroelectric effect generated by the temperature gradients. During the assembly process, the conductive glue is longitudinally deposited along the lateral faces of the LN chip, in direct contact with the metal housing (Kovar material). This electrical contact thus created, enables to dissipate the accumulated pyroelectric charges on the lateral faces. It is important to mitigate as much as possible this pyroelectric effect, because it generates a temperature dependence of the modulator operation point [11].

2.3 Solution for hermeticity

Since the optical fibers feedthroughs had been identified as the cause of the packaging non-hermeticity, we have developed a new technique to set-up the optical fibers in the housing. This method relies essentially on the use of optical fibers pigtailed with a metallized tube on a very precise area, as shown on Fig. 2 (a). The metallized part of this pigtailed is in kovar gilded with gold. One end of the pigtail is equipped with a ferrule in order to increase the contact surface between the optical fiber (pigtail) and the LN chip. A mechanical protection (jacket) is crimped to the kovar tube.

During the assembly process, the metallized area of the optical fiber is soldered to the housing tips by induction (Fig. 3 (b)).

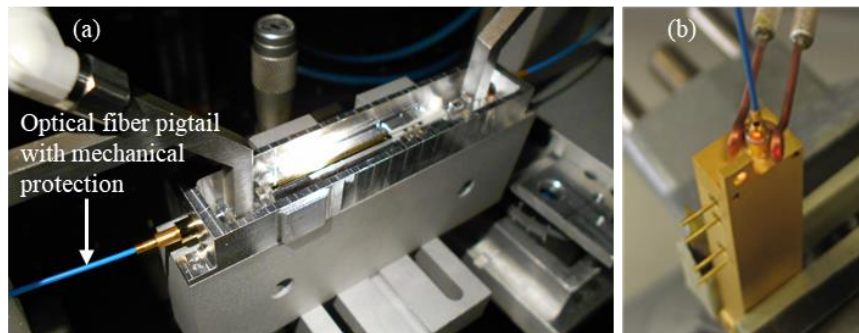


Figure 2. Set-up of optical fibers pigtailed in the modulator feedthroughs: (a) LN chip pigtailed process with a prototype housing; (b) Soldering process by induction on a serial housing.

The installation of the optical fibers pigtailed is followed by an x-rays inspection of the optical fibers feedthroughs (Fig. 3).

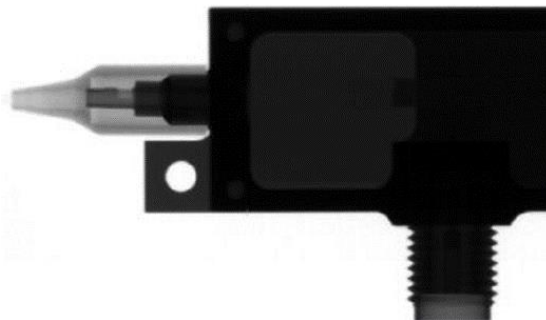


Figure 3. x-rays image of a fiber feedthrough (image made after the optical fiber pigtail installation).

After the soldering of optical pigtailed, several other steps are completed according to our Process Identification Document (PID). One of the crucial steps of this manufacturing process is the housing seal welding. For this operation, we carry out beforehand a curing of the modulators (bake), with the aim of eliminate as much as possible the organic residues and the water vapors trapped in the adhesives used. At the sealing stage, the environment consists essentially of a mixture of nitrogen (N₂). For this study, we added He in the sealing atmosphere to increase the leak test sensitivity.

3. SPACE EVALUATION AND VALIDATION

3.1 Presentation of the evaluation program

Following the improvements mentioned in the previous sections, to verify the reliability of the modulators for space applications, we have carried out a space evaluation on a dedicated batch of these hermetic modulators (made of 15 pieces). This evaluation paid a particular attention to the hermetic nature of the housings.

The full evaluation program conducted is depicted on the diagram shown on Fig. 4. This evaluation program includes a screening phase. The aim of this screening is to detect and discard atypical devices that will present early failures. Following the screening tests, a fine leak test is performed, and the modulators are grouped in several stream tests.

A modulator from the batch, set aside and used as reference sample has undergone no tests, but only the EO characterizations. 3 modulators of the batch had undergone mechanical tests and 5 others had undergone climatic tests. Following these environmental tests, a second campaign of fine leak tests has been performed to investigate their impact on the hermeticity. As also shown on the diagram, 3 Electro-Optical Modulators (EOMs) had been subjected to Destructive Physical Analysis (DPA) and 4 EOMs had been subjected to Residual Gas Analysis (RGA). Since the main objective of the R&T was to evaluate the hermeticity of the packaging, we do not present the results of the DPA analysis in this paper.

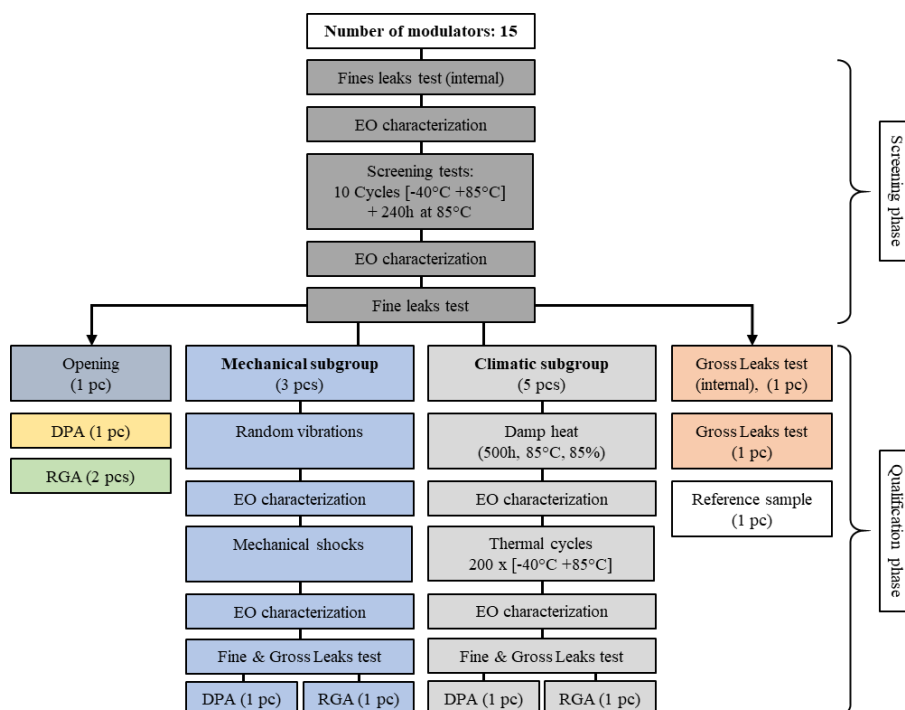


Figure 4. Space evaluation program. EO characterization: Electro-Optical characterization; Destructive Physical Analysis (DPA) and Residual Gas Analysis (RGA). Random Vibrations test conditions: Frequency range: 50 Hz – 2 000 Hz; PSD slope: 6 dB/octave from 50 Hz to 100 Hz, 0.3 g²/Hz at 1 000 Hz, -6 dB/octave from 1 000 Hz to 2 000 Hz; G_{RMS} = 20.5 g; direction: in the 3 axis. Mechanical shocks test conditions: acceleration of 500 g, pulse duration: 1 ms; number of shocks per direction: 5; 3 axis.

EOMs Serial numbers	6537-03	6537-22	6537-12	6538-06	6538-17	6540-10	6538-18	6540-14
Subgroups	Ref. sample	Climatic	Climatic	Climatic	Climatic	Climatic	Mecha.	Mecha.
EOMs Serial numbers	6737-07	6537-21	6538-02	6538-20	6537-08	6540-03	6537-02	
Subgroups	Mecha.	Gross leaks test	Gross leaks test	DPA & RGA	RGA	RGA	Opening	

Table 3: distribution of modulators according to the tests undergone. Ref. sample stand for Reference sample.

3.2 Initial RGA and leaks tests

The Fig. 5 shows the results of fine leak test performed on the fifteen modulators at the end of the screening step.

In order to increase the hermeticity measurement accuracy and avoid outgassing issues with the fiber jacket and boot, the devices had been sealed with approximately 16% He inside the cavity, and the leak test has been performed directly without He bombing.

The device 6540-03 presents an atypical measured He leak rate R of 2×10^{-8} atm.cm³.s⁻¹. The equivalent standard leak rate of this device can be assessed to 4.9×10^{-8} atm.cm³.s⁻¹ using Eq. 1 [12].

$$L = \sqrt{\frac{M_{He}}{M_{Air}} \frac{P_0}{P_E}} R \quad (1)$$

With L the standard leak rate of the device in atm.cm³.s⁻¹, M_{He} the He molar mass (4 g.mol⁻¹); M_{Air} the air molar mass (28 g.mol⁻¹), P_0 the atmospheric pressure (1atm) and P_E the internal He pressure (assessed to 0.16 atm).

This device is not hermetic according to method 1014.16 of MIL-STD-883 [13] (maximum standard leak rate of 1×10^{-8} atm.cm³.s⁻¹ for $V > 0.4$ cm³ for class K hybrids). We attribute this failure to a slight deviation of the manufacturing process during the seal welding or optical pigtail sealing. It has been decided to store it during the evaluation activities, and to perform additional leak tests and RGA at the end of the study.

For the 14 other devices, the measured He leak rate is lower than 4×10^{-10} atm.cm³.s⁻¹, close to the background of the He leak tester. It corresponds to a standard leak rate of 9.3×10^{-10} atm.cm³.s⁻¹, compliant with the MIL standard. 93% of modulators in the batch are hermetic.

For device 6537-08, the time to reach background is more important. It can be due to the test set-up. This device has been used for initial RGA, and the obtained results were similar to the final RGA results obtained after evaluation tests on 2 additional parts, proving there was no gross leak (15.3% He in the cavity for this device, 15.2% and 15.9% He for the 2 RGAs performed after evaluation tests).

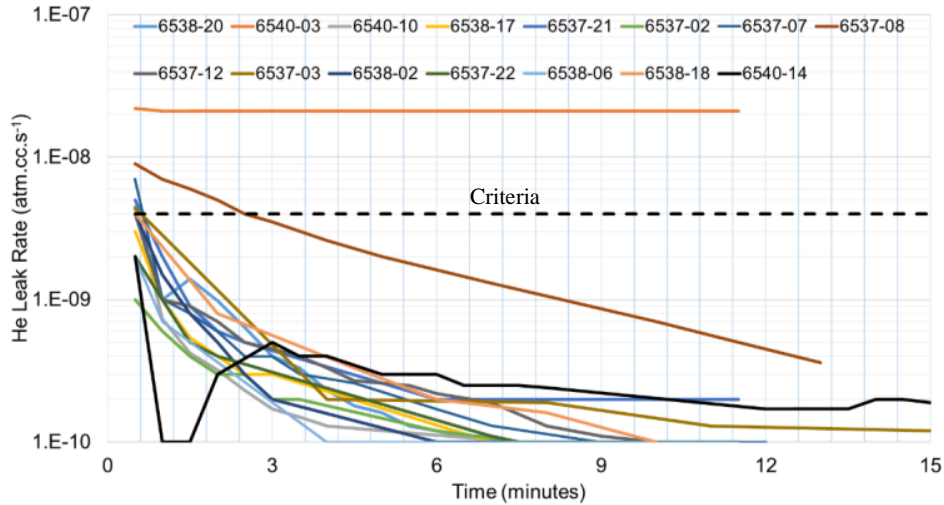


Figure 5. Fine leak tests results after screening step (during the screening phase).

3.3 Mechanical tests

The objective of mechanical tests is to reveal the impact of static or dynamic forces on modulators properties. To do this, the modulators are installed on a vibrating pot (or shocks table). The accelerometers placed on modulators enable to measure the corresponding vibrations spectrum.

On the Tab. 4, we show the EO characterizations results of one of the three modulators that have been subjected to the mechanical tests (random vibrations and mechanical shocks), according to the tests conditions given on Fig. 4. The comparison of measurements before and after the mechanical tests enables to appreciate the parameters evolutions. In the table, the specifications of the modulator remain excellent. For example, the optical Insertion Losses (IL) remain lower than 4 dB, before and after the mechanical tests. Furthermore, after these tests, an external visual inspection (magnification of 1X to 10X) of the modulator(s) did not reveal any physical damages. We also did not note anything as a disqualifying point on the other 2 modulators of this subgroup.

S/N: 6540-14	A: before Mechanical tests	B: after Mechanical tests	A-B
Optical Insertion Loss, IL (dB)	3.83	3.66	0.17
Static Extinction Ratio, SER (dB)	24.39	32.77	8.38
RF half-wave voltage, $V_{\pi RF}$ (V)	5.62	5.5	0.12
DC half-wave voltage, $V_{\pi DC}$ (V)	6.51	6.46	0.05
Electrical reflection, S_{11} (dB)	-10.1	-12.57	2.47
Electro-optical bandwidth (GHz)	26.6	23.25	3.35

Table 4: Electro-optical measurements of the hermetic modulator 6540-14, before and after mechanical tests. The characterization made at the wavelength of 1550 nm.

3.4 Damp heat test

The aim of the damp heat test is to investigate the ability of modulators to withstand long-term exposure to high temperature and humidity penetration. For this test, the modulator (modulators) has (have) been placed in a dedicated climatic chamber as depicted on Fig. 6. A linearly polarized laser beam, at the wavelength of 1550 nm, is injected into the modulator. A DC bias voltage is applied to the modulator through a Modulator Bias Controller (MBC). The bias voltage is set so that the modulator emits a maximum of optical power (It means that the operation point is set at the maximum of the modulator's transfer function). A power-meter and an acquisition software are used to record the output optical power and deduce the modulator's optical losses. The applied DC bias voltage is also recorded during the test. The conditions used for this test were as follow: 85°C and 85% of relative humidity (RH). An example of results is shown on Fig. 7, for the sample 6537-22. On the Fig. 7(a) which represents the optical insertion losses variation versus time, we can note that the modulator's transmission remains stable along the whole test (IL maximum deviation = 0.44 dB). The Fig. 7(b) shows the corresponding DC bias voltage applied to lock the modulator at the maximum of transmission. We can see a jump on curve at the 325th hour (MBC reset). This is not due to the modulator failure, but to the fact that the voltage delivered by the MBC has reached the maximum value available (± 9 V).

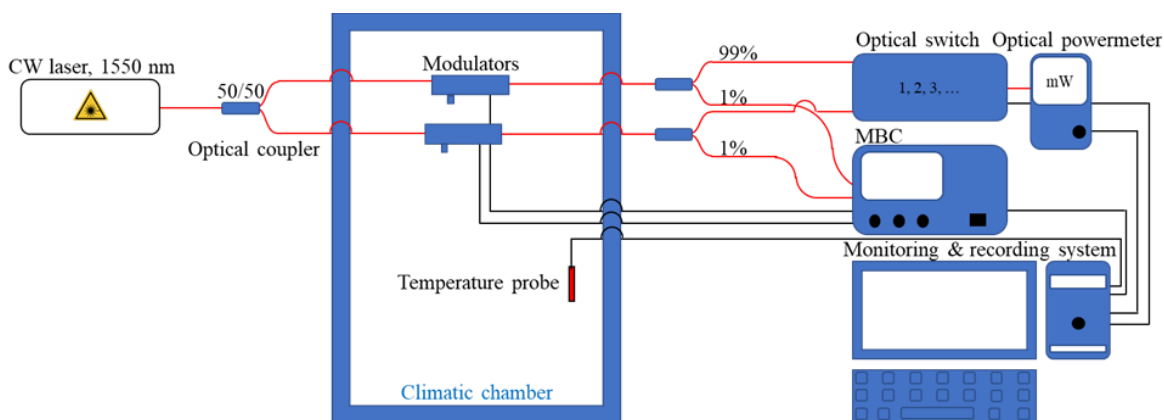


Figure 6. Experimental set-up for Damp heat test (and temperature cycling test). To simplify the illustration, we have considered only 2 modulators. MBC: Modulator Bias Controller.

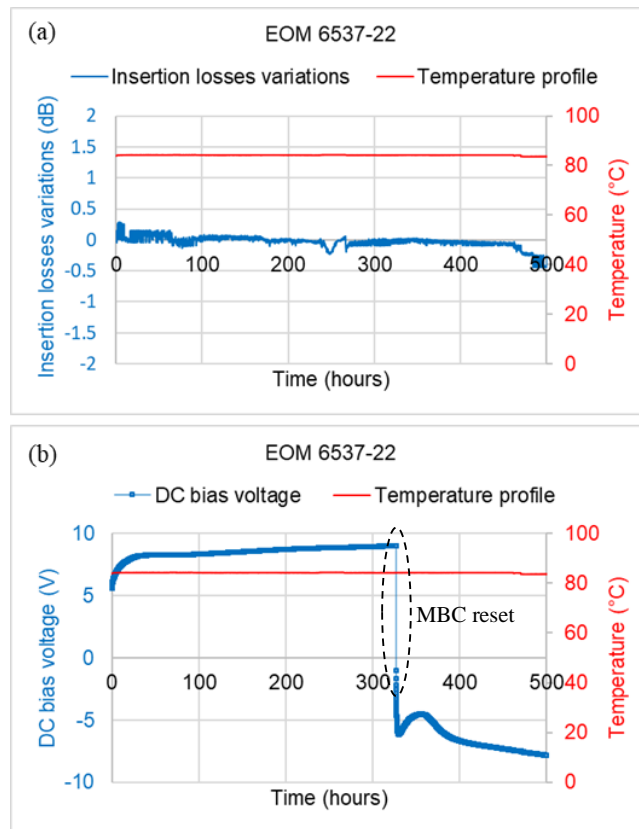


Figure 7. Damp heat test performed on electro-optical modulator (EOM) 6537-22 (85°C, RH=85%). Optical insertion losses variation (a) and DC bias voltage (b) versus time. The temperature profile is superimposed on the figure, in red color. MBC: Modulator Bias Controller.

3.5 Temperature cycling test

After the damp heat test, the modulators have been also subjected to a temperature cycling test with these conditions: 200 cycles with a temperature range of -40°C to 85°C, 10 min of dwell time and 3°C/min as the temperature rate of change. The purpose of this test is to determine the ability of the components to withstand extreme temperatures variations. The modulators installation is done in the same way as in the case of the damp heat test. An example of results are shown on Fig. 8, for the modulator 6537-22. On the Fig. 8, we can notice that the Insertion Losses (IL) of the modulator do not vary significantly during the test ($\Delta IL < 1.5$ dB).

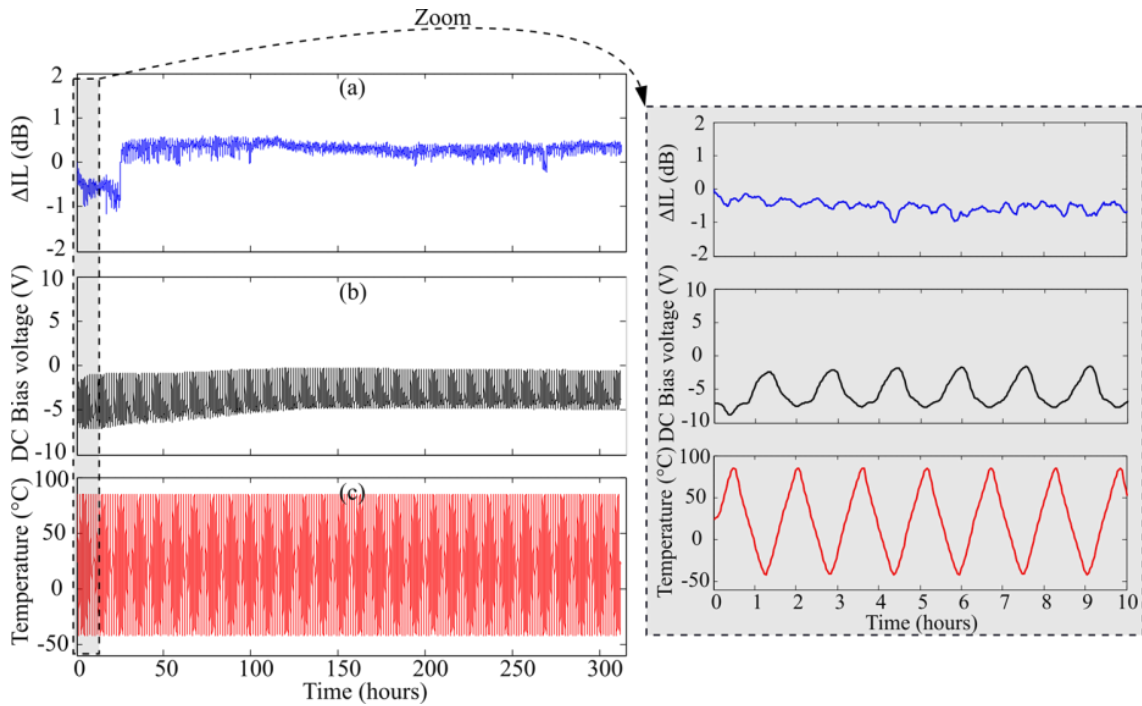


Figure 8. Results of the temperature cycling tests performed on the electro-optical modulator 6537-22. Optical insertion losses variations (a) and the corresponding applied DC bias voltage (b) versus time. (c) Temperature cycling profile. The data recording frequency is one point every 2 minutes.

In the Tab. 5, we compare the results of electro-optical characterizations (pre-test and post-test) of the modulator 6537-22, stemming from the climatic subgroup. After subjecting to the temperature cycling test, we can note that the modulator still has an excellent transmission and an excellent SER. Since, this R&T project was essentially dedicated to the packaging improvement, we did not dwell too much on the characterization of other electrical parameters.

S/N: 6537-22	A: before climatic tests	B: after temperature cycling	A-B
Optical Insertion Loss, IL (dB)	3.25	2.85	0.4
Static Extinction Ratio, SER (dB)	20.2	25.54	5.34
DC half-wave voltage, $V_{\pi DC}$ (V)	6.54	6.57	0.03

Table 5. Measurements of hermetic modulator 6537-22 before and after climatic tests.

3.6 Final RGA and leak tests

At the end of these mechanical and climatic tests, quite representative of the space environment, we have again checked the housings hermeticity, in order to evaluate the impact of these evaluation environments.

Unlike the initial hermeticity tests, these final tests have been performed in accordance with the MIL standard method, with a 3bar 10 hours Helium bombing before leak measurement. This method is longer and less accurate due to He outgassing from the fiber jacket and boot after bombing, but the results demonstrate that it could be used to discard leaky parts, and so that it could be possible to avoid the addition of He in the sealing atmosphere.

For all the tested parts except ref. 6540-03 identified leaky after screening, 5 hours after bombing the measured He leak rate is below 4×10^{-9} atm.cm³.s⁻¹. For ref. 6540-03, 5 hours after bombing the leak rate is still 4×10^{-8} atm.cm³.s⁻¹, confirming it is atypical. The results are noted in the Tab. 6 below.

EOMs Serial numbers	6537-03	6537-22	6537-12	6538-06	6538-17	6540-10	6538-18	6540-14
Subgroups	Ref. sample	Climatic	Climatic	Climatic	Climatic	Climatic	Mecha.	Mecha.
Fine leaks test	NA	P	P	P	P	P	P	P

EOMs Serial numbers	6737-07	6537-21	6538-02	6538-20	6537-08	6540-03	6537-02
Subgroups	Mecha.	Gross leaks test	Gross leaks test	DPA & RGA	RGA	RGA	Opening
Fine leaks test	P	NA	NA	NA	NA	F	NA

Table 6: Fine leaks test results. P: Pass, F: Fail, NA: Not Applicable, Ref. sample: reference sample. The sample 6540-03 had already been identified at the beginning of the campaign, as non-hermetic modulator. 100% of tested modulators are hermetic after evaluation.

Residual Gas Analysis (RGA) have been performed on refs. 6540-10 (from climatic subgroup), 6537-07 (from Mechanical subgroup) and 6540-03 (leaky after screening, not used for evaluation).

For refs. 6540-10 and 6537-07, the internal cavity contained respectively 15.9% and 15.2% He, and a low quantity of oxygen. These results, similar to those obtained for the initial RGA performed on ref. 6537-08 after screening, confirm the high level of hermeticity of these 2 devices.

On the contrary, for ref. 6540-03, there is only 5% Helium remaining. The presence of Oxygen (11%) also reveals that air entered inside the cavity during the 1-year storage. Taking into account the standard leak rate of $4.9 \times 10^{-8} \text{ atm.cm}^3.\text{s}^{-1}$ assessed for this device after screening, according to Eq. 2 [12], after one-year storage, the helium percentage in the internal cavity should be 6.2%, which is close to the 5% obtained in RGA.

$$P = P_i e^{-\frac{L \sqrt{\frac{M_{\text{air}}}{M_{\text{He}}}} t}{V P_0}} \quad (2)$$

With P the He partial pressure inside the package in atm, P_i the initial He partial pressure inside the package (0.16 atm), L the standard leak rate of the device in atm.cc.s^{-1} , M_{He} the He molar mass (4 g.mol^{-1}); M_{air} the air molar mass (28 g.mol^{-1}), P_0 the atmospheric pressure (1 atm), V the internal volume (4.4 cm^3) and t the storage duration in s (approximately 1 year).

4. CONCLUSION

By using a specific optical fiber pigtail and a new process of fibers feedthroughs soldering, we have improved the hermeticity level of modulators packaging. A space evaluation conducted on a first series of these hermetic modulators, demonstrates the reliability of our packaging improvements. Furthermore, we have also shown that the outgassing rate of the main integrated elements in the modulators is space compatible, which is an asset to prevent contamination issues in case of possible degassing.

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