RECENT PROGRESS ON THE RELIABILITY AND THE HERMETICITY OF SPACE GRADE $LiNbO_3$ MODULATORS

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Abstract
In collaboration with the French Space Agency (CNES), a reliability study of lithium niobate ($LiNbO_3$) modulators manufactured by iXBlue PSD, SA (former Photline Technologies), was previously reported. This study included a complete evaluation program and did validate lithium niobate modulators technologies for space applications ([1], [2]). However, the study has shown that hermeticity and outgassing properties could be further improved. Indeed, the optical fiber feedthrough created hermeticity issues and outgassing concerns arose from specific modulator materials. With the support of CNES [3], a new project has been initiated to address those issues and better the electro-optical modulators reliability for space. This paper provides an overview of these study achievements.

I. INTRODUCTION

Photonic systems, sub-systems and components are found in an increasing number of applications of many high technology industry segments. This remark applies particularly to space-embedded systems, which rely on the versatility and reliability of photonic systems to realize many of the critical functions needed to insure their safe and durable operation. Many embedded space photonic systems use light modulators as key components to achieve intensity or phase modulation of various light sources at different operating wavelengths. In particular, the electro-optic lithium niobate ($LiNbO_3$: LN) modulators offer a unique combination of performances that makes them prime candidates, not only to satisfy the optical system specifications, but also to meet the stringent requirements of space operation.

In fact, among the different optical modulator technologies available such as polymer, III-V semiconductors, silicon, the well-known lithium niobate offers the best trade-off in terms of performances, ease of use, and power handling capability ([4], [5]). The LN technology is still widely deployed within the current high data rate fiber optic communication networks. This technology is also the most mature and guarantees the reliability required for space applications [5].

A number of applications can be listed:

- Fiber optic gyroscopes
- Inter-satellites communications
- On-board laser cavity stabilization
- Microwave photonic payload sub-systems

In order to supply space systems manufacturer optical modulators matching their requirements, it is necessary to develop space compliant devices.

The goal of this work is to improve reliability and hermeticity of the modulators manufactured by iXBlue PSD. For this study, the chosen reference is a standard 1550 nm intensity modulator “M20XTi1550” based on titanium in-diffusion in $LiNbO_3$ X-cut substrate.

II. IDENTIFICATION AND DEFINITION OF THE PACKAGING IMPROVEMENTS

A. Hermeticity

The carried out tests during the previous study helped define an improvement roadmap towards full hermeticity for the modulators packaging.

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The modulator lids were previously sealed hermetically with neutral and dry gas by seam welding operation. However, this process did not allow the packaging to reach the 10^{-8} atm.cc/s He level of leak rate needed to qualify for full hermeticity. In fact, leaky optical fiber feedthrough prevented the packaging to meet the appropriate leak rate level (Fig.1).

Note: the microwave feedthrough inserted for electrical access is hermetic.

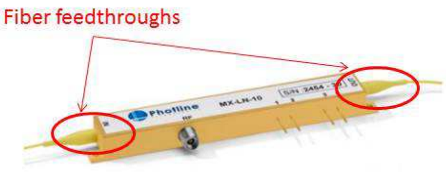

Fig. 1: Photography of a standard modulator

The research and development already implemented since the beginning of the project has allowed significant technical upgrades.

Optical fiber patchcords with hermetic metallic feedthrough have been selected to solve the packaging leakage issue. These fibers embed a hermetic Kovar ferrule with gold plating. One key advantage of these fiber pigtails is that they can be soldered to the modulator package (also made in gold plated Kovar) and provide higher hermeticity.

The relatively low meltdown temperature of indium makes it a good material pick for soldering the pigtail Kovar ferrule to the modulator package. Detailed analysis shows that indium provides superior material filling properties compared to other materials like SnBi or AuSn which also require higher solder temperature that may lead to collateral damages and deteriorate the long term reliability.

The induction soldering method is depicted in Figure 2. A Kovar tube is brazed to the modulator package sidewalls to offer support for the fiber Kovar ferrule. Indium is used to solder the ferrule to the tube. One can notice the custom inductor around the Kovar tube that generates the adapted magnetic field to produce a high quality soldering.

Alternative soldering techniques have been tested before opting for induction. This last method provides enhanced temperature homogeneity, fast rise to and fall from set temperatures. Temperature levels are also much better controlled than in any other technique and last but not least this is a contactless soldering method which provides an overall higher quality when the process is optimized (less likely to bring in contaminants).

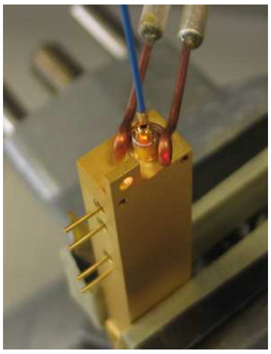

Fig. 2: Indium Induction soldering

In this case, a new manufacturing flow chart has been adopted. Indeed, the inductive soldering requires the chip pigtailing to be performed within the housing (Fig. 3). This in turns has led to the development of a specific modulator packaging design which is shorter than standard SFF (Small Form Factor): 85mm length instead of 95 mm for standard SFF (Fig. 4). Moreover, the obtained packaging mass reduction aligns with the new-generation spacecrafts requirements.

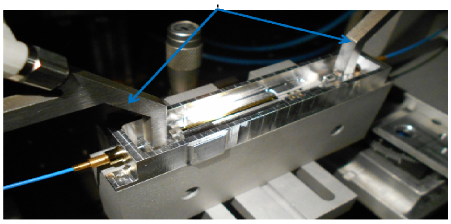

Fig. 3: Pigtailing process within prototype housing

The seam welding process has also been optimized to allow modulators packaging to successfully pass the fine leaks test. The sealing environment has been modified: a gas mix of helium and neutral and dry gas is now used during the process.

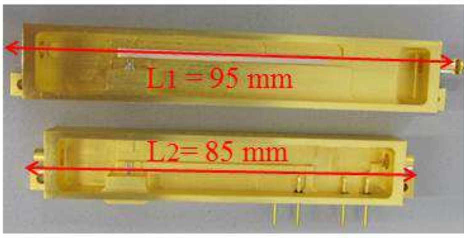

Fig. 4: New hermetic modulator housing

Fiber constraints can seriously degrade both optical insertion loss (IL) and polarization extinction ratio (PER). It is therefore crucial to monitor the evolution of optical fiber patchcords (with hermetic metallic feedthrough) after the packaging underwent the new soldering and pigtailing processes.

Figure 5 represents the in-situ follow-up of IL evolution with temperature. The following temperature plateau :-30°C, -20°C, 0°C, 20°C, 40°C and 70°C last 2 hours each. In this test, IL are primarily targeted because that would be the first parameter to be affected by temperature induced damage.

The obtained results ($\Delta(IL) \leq 0.1$dB) demonstrate that the new optical pigtails are not subjected to any variations when the packaging is placed under temperature stress.

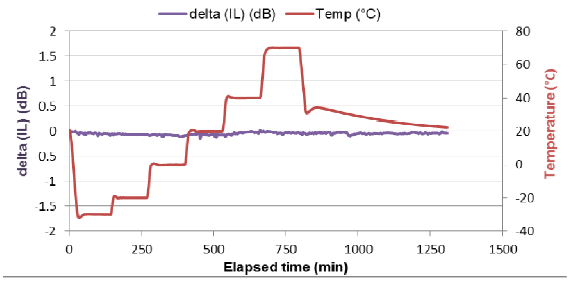

Fig. 5: In-situ follow-up of the optical insertion loss variation vs temperature

B. Outgassing aspect

Outgassing (also known as “offgassing) is an important concern in space systems. The effects of outgassing can impact a wide range of application areas, from satellites to space-based equipments.

In the vacuum of deep space, outgassing could contribute to degrade the performance of some systems. This phenomenon prompts the space community to develop exacting procedures for evaluating materials prior to their use in space.

The total mass loss (TML) and collected volatile condensable materials (CVCM) are considered as key material parameters to gauge the changes in mass of different materials in a vacuum environment which would occur due to outgassing. NASA and ESA’s acceptable target number is less than 1% for TML and less than 0.1% for CVCM [6].

In some cases when a material is known to outgas in a vacuum environment, the potential for usage still exists if the outgassing occurs in a portion area of a space craft such that these materials could not degrade the performance of any existing system.

For these reasons, the need to minimize environment contamination drives the materials selection. Hence, the following measures have been taken:

- The Hytrel fiber jacket used in standard modulators was replaced by polytetrafluoroethylene (PTFE) which is compliant with space specification ECSS-Q-ST-70-02C [6]. The PTFE outgassing analysis results are listed in Table I. Besides its outgassing properties, PTFE high resistance to temperature stress is of particular interest for soldering.

Table I. PTFE identification card results

Results:	**Avg.**	1st sample	2nd sample	3rd sample
TML in %	**0.01**	0.02	0.01	0.01
CVCM in %	**0.01**	0.01	0.01	0.01

- The standard fiber boots were also replaced by space compliant ones (Table II).

Table II. The new optical fiber boots outgassing results

	Curing 24h @ 125°C, 1mbar	ECSS Outgassing measurement & additional curing 144h @ 125°C, 1mbar
TML in %	0.89	0.47
CVCM in %	0.16	0.05

- The conductive glue used inside the modulator packaging to mitigate the optical modulator’s pyroelectric effects has been updated to a space compliant one. This conductive glue is applied on the sides of the lithium niobate crystal substrate, to prevent and dissipate the pyroelectric charges accumulating during temperature variations.

Indeed, the new conductive glue meets the low outgas specifications outlined by NASA and ESA with a TML of ≤1% and CVCM of ≤0.1%.

- Residual Gas Analysis "RGA" within the framework of space standards is realized. The followed method is internal vapor Analysis. The purpose of this test method is to quantitatively measure the relative concentration of the internal vapor content, including water vapor, in hermetically sealed, gas filled devices using a mass spectrometric technique. This technique is destructive and is intended for the reporting of all volatile atomic and molecular species detected in the electro-optic device. A prebake of 12-24 hours at 100°C is recommended for the modulator because it contains polymeric materials (i.e. optical fiber jacket, boots) and organics in its cavity. The test is realized at 100°C.

III. VALIDATION TESTS ON NEW MANUFACTURED MODULATORS

The compatibility and reliability upgrades need to be thoroughly assessed by added verification testing. In that purpose, two prototypes have been manufactured with the new improved packaging. The standard chips "M20XTi1550" were used.

A recognized quality assurance system meeting space grade parts and packaging program assessment criteria was used all the way through the new modulators production.

A Process Identification Document "PID" was edited. The sub-elements that form the electro optical modulators are sourced from the same batch and are fully traceable.

A. Hermeticity and outgassing aspects

This new packaging method targets space environment compatibility. The hermeticity aspect is of main interest. The following tests place the focus on assessing the enhanced hermeticity brought by the fiber patchcord soldering and the modulator lid hermetic sealing. In that purpose, the produced prototypes have undergone a full hermeticity test (fine and gross leaks).

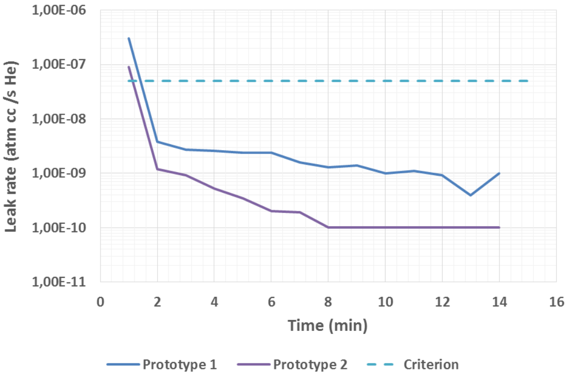

Fig. 6: Fine leak rate obtained during the prototyping phase

The hermeticity results (Fig.6), show that the prototypes succeeded the gross leaks test and score much lower fine leaks rates (now lower than 10^{-8} atm.cc/s He: which is the maximum allowed leak rate value).

An internal vapor analysis was performed. Low outgassing levels were recorded with the new manufactured prototypes. This largely stems from the integration of high-quality materials and from the well-controlled manufacturing processes.

These residual gas analyses results have shown that two steps may be improved:

- Prebake/ stabilization bake: Before sealing, the modulators are submitted to a vacuum bake. This operation forces any trapped water and remaining organic compounds to outgas. This usually lasts few hours at high temperatures. RGA results show that increasing the prebake duration or its temperature may improve the process yield. The prebake efficiency may benefit from temperature setpoints higher than the maximum temperature seen during fabrication and screening tests.

- The new sealing environment: It will be required to use an atmosphere control system during the sealing process.

B. Screening tests

The new conductive glue

After validation of the conductive glue outgassing, it was mandatory to verify the suitability of its physical properties. Therefore, an in-situ follow-up of the output optical power "Pout" and DC voltage "Vbias" (static modulator's bias) behaviors versus temperature (-30°C, -20°C, 0°C, 20°C, 40°C and 75°C) was performed for one prototype (Fig. 7).

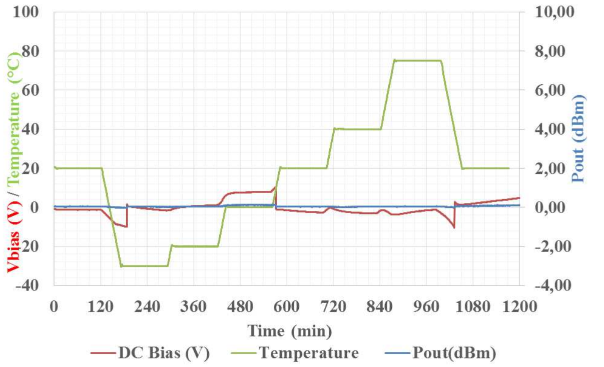

Fig. 7: In-situ follow-up of Pout and Vbias of a prototype modulator "M20XTi1550" during a thermal test (from -30°C to +75°C)

During the test, the electro-optical modulator was placed inside a climatic chamber and was monitored in order to perform an in-situ measurement of the Vbias drift and the output optical power variations versus temperature steps. The initial room temperature (20°C) is switched down to -30°C during two hours, then to -20°C, 0°C, +20°C, +40°C and +75°C, two hours for each step. The climatic chamber is then returned to 20°C.

One can see from Figure 7 that the output power of the modulator remains constant even if some variations of the DC voltage were noticed. The modulator bias controller compensates for the bias setpoint variations. According to the obtained results, the new conductive glue seems to be a good solution to prevent from pyroelectric effects.

The new pigtailing process

The thermal annealing main purpose is the modulator's reliability assessment. The custom fiber patchcords, the modulator chip and the packaging design will be evaluated as a set.

Indeed, because of thermal expansions coefficient mismatch between silica fiber, lithium niobate chip and Kovar housing, non-adapted relative lengths could potentially lead to a fiber pull in case of strong temperature variations. This stress may induce coupling degradations at the fiber to lithium niobate waveguide interface; this degradation is usually irreversible, and thus optical losses increase after thermal cycling.

The applied screening test consists in thermal cycles, from -40°C to +85°C, with ramps of 2°C/min and plateau of 30 minutes at constant temperature.

The two prototypes have shown highly stable optical output power during the test (Fig. 8). Moreover, optical insertion loss measurements before and after the thermal test show no degradation in this matter. Table III summarizes the obtained values.

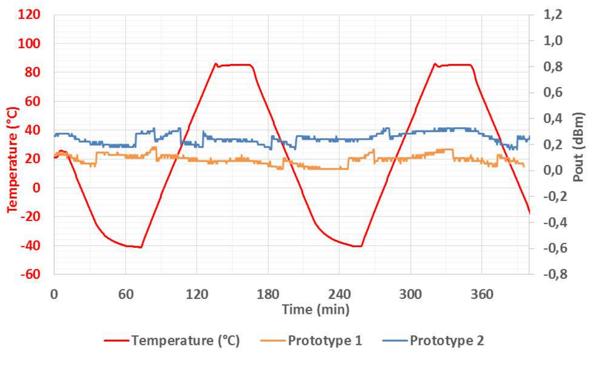

Fig. 8: Optical output power behaviour vs temperature

The test results demonstrate that the packaging design hermeticity is significantly improved. The choice of new materials (better space compliance and lower thermal expansion mismatch) and the new control processes are the main reasons for progress.

Table III. IL measured values before and after a thermal test

	Insertion Loss before annealing (dB)	Insertion Loss after annealing (dB)
Prototype 1	3.5	3.3
Prototype 2	4.14	4.12

The components electro-optical parameters remain correct and stable after undergoing all the tests.

Ongoing program

Following the optimization steps validation, fifteen identically manufactured $LiNbO_3$ modulators with part number "HERM-M20XTi1550" have started an evaluation program. This program consists on several tests: thermal, mechanical, …

Several Destructive Physical Analysis "DPA" and Residual Gas Analysis "RGA" are planned at the beginning and the end of the evaluation campaign to guarantee the packaging improvements.

Before starting and after each of the main evaluation test steps, the modulators electro-optical performances will be thoroughly verified (i.e. initial, intermediate and end-point characterizations have to be carried out).

IV. CONCLUSION

$LiNbO_3$ modulators are finding an increasing number of applications for future space flight missions. These components have to meet space requirements which are different from those of ordinary consumer modulators.

Two of the most particular requirements are the outgassing and the hermeticity properties. The current work reports on the recent progress made to address these issues.

Based on the favorable results from the initial screening tests, further space flight qualification testing could be conducted on the new packaged modulators.

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