International Conference on Space Optics—ICSO 2022

Dubrovnik, Croatia

3–7 October 2022

Edited by Kyriaki Minoglou, Nikos Karafolas, and Bruno Cugny,

High power optical amplifier at 1.5 µm for GEO and LEO optical feeder links

International Conference on Space Optics — ICSO 2022, edited by Kyriaki Minoglou, Nikos Karafolas,
Bruno Cugny, Proc. of SPIE Vol. 12777, 127773J · © 2023 ESA and CNES · 0277-786X · doi: 10.1117/12.2690533

High power optical amplifier at 1.5 µm for GEO and LEO optical feeder links

T. Schmitt[a*], R. Cousty[a], T. Dumont[a], P. Morin[a], F. Soulabaille[a]
[a]CILAS, 8 Avenue Buffon, CS 16319, 45063 Orléans Cedex 2 - FRANCE

ABSTRACT

In the frame of the FOLC2 project, in cooperation with Airbus Defence and Space, CILAS developed, manufactured and qualified an in-orbit demonstrator model (IODM) of a 5-W space-grade high power optical amplifier (HPOA), at 1.5 µm, for both LEO and GEO laser communication terminal feeder links. It is designed to amplify single-channel or multi-channel signal, from 1555 to 1565 nm, up to 5 W with limited noise, limited gain flatness and very good efficiency, with its own space-grade electronics. The IODM HPOA will be embedded in the GEO optical terminal demonstrator TELEO, developed by Airbus Defence and Space.

Keywords: high power optical amplifier, fiber amplifier, space qualification, optical feeder link, LCT

1. INTRODUCTION

The growing need for high data rate, independency from spectrum congestion and more secure communication in space has triggered the development of laser communication terminals (LCT), especially for space-to-ground communication, also called optical feeder links. The use of a high power optical amplifier (HPOA) is required to reach the target output power necessary to have efficient optical feeder links.

In 2018, the FOLC project, supported by ESA ARTES program and led by Airbus Defence and Space, consisted in the development of the main building blocks at breadboard level of an optical feeder links as well as the performances assessment of the whole communication chain [1]. CILAS was in charge of the development, manufacturing and test of an elegant breadboard of a 5-W HPOA. The optical concept chosen for the HPOA was successfully validated through functional tests in laboratory environment, by CILAS at equipment level and by Airbus Defence and Space once integrated in the communication chain breadboard, including 5 optical channels to be amplified.

In 2020, in the continuity of this success, the FOLC2 project started to address the evolution and the qualification of a generic optical communication chain and its constituents, such as the HPOA, to be embedded onto TELEO, a hosted payload of an optical terminal demonstrator. The in-orbit demonstrator is planned to be launched in 2023. CILAS manufactured two models of HPOA: an engineering model (EM) and an IODM. The EM differs from the IODM only in regard of reliability and traceability aspects, in order to reduce procurement and manufacturing time, e.g. pump diode in the EM did not undergo upscreening. The EM of the HPOA was manufactured first and tested by CILAS, before being tested by Airbus Defence and Space in the communication chain. The IODM HPOA was manufactured, tested and qualified by CILAS before shipment to Airbus Defence and Space. More information on the overall communication chain performance can be found in [2].

The following sections present the design and performances of the IODM HPOA, and the qualification tests conducted to validate its compatibility with the mission requirements.

* tschmitt@cilas.com; phone: +33238644101

2. DESIGN

The HPOA is a single-polarization fiber amplifier, with its own space-grade electronics and is made up with two amplification stages: a first stage to shape the input signal and a second stage to reach the target output power.

The optical architecture was designed according to the "Newspace" approach: all fiber components are component off-the-shelf (COTS), pre-selected through specific analysis and individually qualified, when necessary, to be compatible with the 2-years GEO demonstration environments. Analyses have been carried out to quantify the acceleration levels (Figure 1), total dose levels and maximum temperature of the components, in order to ensure they can withstand the qualification level expected. The qualification tests on the components cover both TELEO demonstrator and generic 15 years GEO mission requirements. More information on the Newspace approach is given in [3].

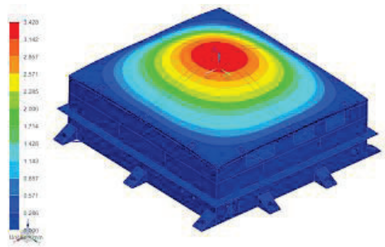

Figure 1 – Mode visualization from mechanical analyses (FEM) of the HPOA

Derating and redundancy rules have been implemented in order to ensure sufficient reliability for both the TELEO demonstration (2 years) and a 15 years generic GEO mission. The electronics (control and DC/DC converter) integrated in the HPOA has been designed by Airbus Defence and Space and is hardened to resist space environments, such as radiations. Its main functions are to power the pump diodes, to process internal securities as well as telemeasures (TM) and telecommands (TC) to and from the satellite. The HPOA is operated in automatic power control mode (APC) thanks to a monitoring photodiode. The current of the pump diodes is adjusted automatically to allow a fixed output power set point. Thermistor are also implemented inside the HPOA to monitor internal temperatures and prevent overheating.

The HPOA footprint is 217 x 197 mm², including fixing brackets, and its height is 64 mm with a total mass of 2.1 kg. Its electrical interfaces are made up of one power connector and one communication connector. Its optical interfaces are Mini-AVIM adapter for the input and a polarization maintaining (PM) fiber for the output.

3. PERFORMANCES

The performances of the HPOA, as detailed in Table 1, meet the demonstration needs as well as future generic mission needs.

Table 1 – HPOA performances

Parameter	**IODM HPOA performances**	**Comments**
Operational temperature	[+10 ; +56°C]	At temperature reference point (TRP)
Operating wavelength	[1555 nm ; 1565 nm]	-
Input power	≥ 4 mW	-
Output power	[0 W ; 5 W]	Stability <±0.3% @ 5W and 20°C
Power consumption	≤ 46 W	@ 5W beginning of life (BOL)
Wall plug efficiency	≥ 11 %	@ 5W BOL Including space-grade electronics
Polarization extinction ratio (PER)	≥ 14 dB	@ 5 W
Flatness	≤ 0,4 dB	For 2 channels, with 200 GHz spacing
Noise figure	≤ 10 dB	@ 5 W

The IODM HPOA was tested in different test configuration in CILAS laboratory, as shown in Table 2.

Table 2 – Test configuration of the DM HPOA

Configuration	Number of channel	Mounting plate temperature (MPT)
1	1	20
2	1	50
3	2	20
4	2	50

The number of channel and the associated wavelength are related to the channel configuration of the TELEO in-orbit demonstration. Minor differences of performances were measured between the different test configurations.

Regarding end of life (EOL) performances, only power consumption and wall plug efficiency are expected to change. Radiations are the main factor of efficiency degradation over time in a fiber amplifier. In fact, gamma radiations induce additional losses in the fibers that lead to an increase of the consumption in order to keep the output power to its nominal target value. Shielding optimization and use of rad-hard fibers are solutions to mitigate doses and its impact on performances respectively.

3.1 Spectrum

To measure the spectrum, the output signal of the HPOA was collimated. A fraction of the collimated beam was taken by a wedge prism and focalized in a fiber patchcord, connected to an optical spectrum analyzer (OSA).

The HPOA introduces limited noise with a noise figure (NF) below 10 dB. The NF is defined as the additional noise introduced by the HPOA and it was calculated thanks to the global input and output optical signal-to-noise ratio (OSNR):

$$NF = OSNR_{in} - OSNR_{out}$$

The OSNR is the ratio (in dB) between the channels power and ASE power in the operating wavelength range (1555-1565 nm). The output OSNR is 61 dB at 5W output power, for both single and dual-channel configurations.

Regarding non-linear effects (NLE), stimulated Brillouin or Raman scattering were not detected. FWM was the only NLE observed at 5W output power: it is a Kerr effect that appears when multiple channels propagate in a fiber, causing crosstalk between channels. The main parameters influencing its intensity are the output power per channel, the total fiber length, the channel spacing as well as the number of channel.

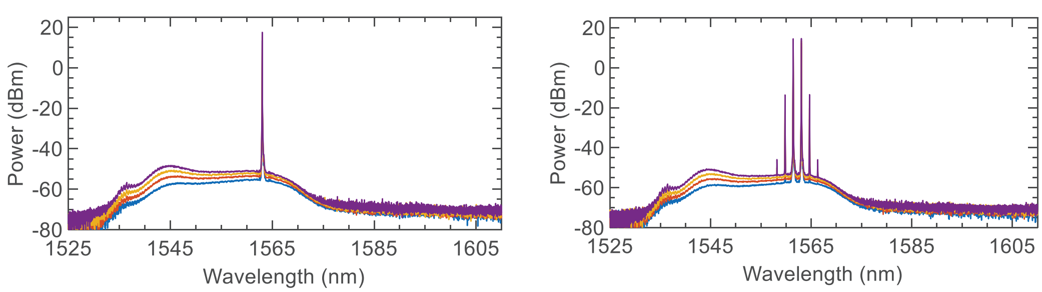

Figure 2 – Single-channel (left) and 2-channel configurations (right)
For different output power: purple = 5W / yellow = 4W / orange = 3W / blue = 2W

As illustrated in Figure 2, for the 2-channel configuration, at 5W output power, the minimum isolation between the external FWM spurious and the channels is above 25 dB. Isolation between the channels and the FWM spurious at the channel wavelengths was not characterized, as it would have required switching off one of the channel.

3.2 Power

The output power was measured using a powermeter. For each setpoint, electrical power consumption was also measured through the power supply interface. The nominal output power range of the HPOA is between 0.5W (27 dBm) and 5W (37 dBm), over the operating temperature range. The HPOA can deliver higher output power than 5W but it would increase the pump diode current setpoints and chip temperatures, causing a degradation of the HPOA reliability.

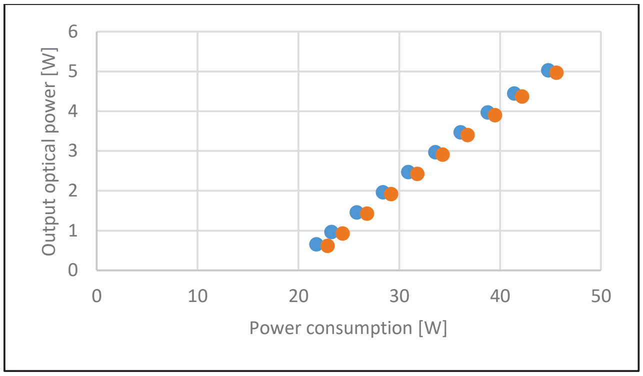

Figure 3 – Optical power vs electrical power for 20°C (blue) and 50°C MPT (orange)

Up to 5 W output power, the wall plug efficiency (WPE) is 11 % at the beginning of life (BOL) of the HPOA mission, with no radiations. The WPE includes the space-grade electronics, integrated inside the HPOA.

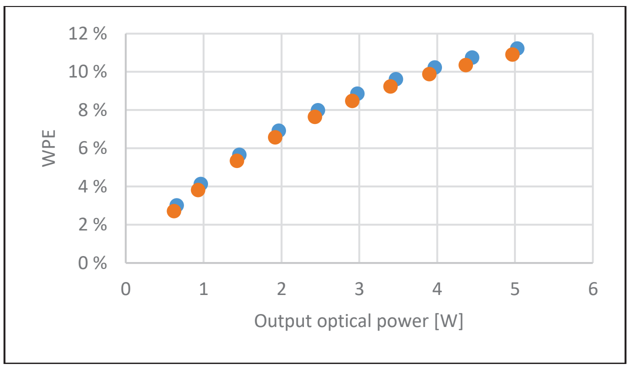

Figure 4 – WPE vs output optical power for 20°C (blue) and 50°C MPT (orange)

Based on previous radiation test results on a similar HPOA manufactured by CILAS, the EOL wall plug efficiency (for 15 krad) is expected to be around 10 %, corresponding to a maximum power consumption of around 50 W.

3.3 PER

The HPOA has been designed with polarization maintaining components and fibers, but also with a few polarizing components to enhance the PER and limit the dependency of the HPOA to the PER of the input signal. PER is defined as the ratio between the optical power along the fast axis and the slow axis of the PM fiber. The signal at the output of the HPOA was split along the two polarization axis thanks to a polarization beam splitter. Each axis power was measured by independent power meters.

The minimum PER at 5W output power is 14 dB (Figure 5). Even if this result is sufficient for the TELEO demonstration, upgrades to improve the PER at the HPOA output have already been identified and are being implemented in future upgrades of the HPOA.

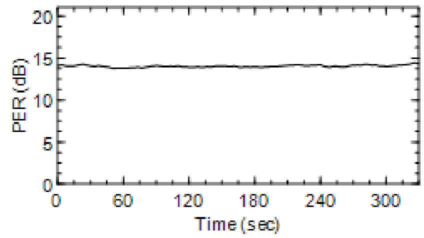

Figure 5 – PER at 5W output power

4. QUALIFICATION

The overall qualification strategy was defined to meet the stringent constraints of the TELEO demonstration. The HPOA has undergone environment tests in order to validate its design is fully compatible with the mission constraints, from launch to service in orbit (Table 3). The whole performances of the HPOA (output power / PER / spectrum) have been tested, before and after the environment tests, to verify no internal degradation occurred. A limited performance test (output power measurement only) was also performed between TVAC and mechanical tests.

Table 3 – Qualification test list

Test sequence	Description
Performances test	All parameters measured (output power / consumption / PER / spectrum)
Thermal vacuum (TVAC)	Non-operational & operational cycling
Performances test	Only output power / consumption
Vibrations test	Sinus / quasi-static / random vibrations
Shocks test	SRS shocks
Performances test	All parameters measured (output power / PER / spectrum)

No radiations tests were performed on the HPOA. Radiation analysis and test at component level are sufficient to justify the compatibility of the HPOA with the total ionizing and non-ionizing dose expected for the in-orbit demonstration as well as generic GEO missions. Furthermore, in the frame of a CNES R&T project, CILAS had already quantified the impact of gamma radiation on the performances of an elegant breadboard HPOA up to 70 krad, with the same fibers as in the TELEO HPOA, which covers the radiation level expected on the TELEO demonstration (around 15 krad).

4.1 TVAC

TVAC test consisted in both non-operational and operational cycling, under secondary vacuum.

Table 4 –TVAC test characteristics applied to the IODM HPOA

Test	Characteristics
Non-operational cycling	MPT / TRP = [-30 ; +70 °C] HPOA switch OFF Pressure < 10-5 mbar
Operational cycling	TRP = [+10 ; +56°C] HPOA switch ON Pressure < 10-5 mbar

As shown in Figure 6, the HPOA was mounted on the regulated baseplate of the vacuum chamber. Radiative panels were also activated in order to minimize the duration of thermal stabilization. The TRP of the HPOA was monitored during the entire test. The mounting plate temperature (MPT) of the HPOA was regulated to ensure the TRP to reach the temperature range extrema, without exceeding the acceptable tolerances. Temperature difference between the MPT and the TRP was below 2 °C.

During non-operational cycling, the HPOA was electrically switched off. On the contrary, for operational cycling, the HPOA was electrically and optically switched on during the entire test sequence. Its output power was continuously measured during the entire sequence, as well as temperature and pressure. Operators measured other functional parameters, such as power consumption and internal temperatures, during working hours. The dwell time for each extreme levels was at least 1 hour to allow complete thermal stabilization of the HPOA.

Optical power at the output of the HPOA was above 5W. However, the different optical connection (e.g. optical vacuum feedthrough, patchcord…) involved optical losses of 0.27 dB: the optical power measured outside the chamber was 4.7 W (Figure 7). Thanks to the APC mode, the output power variation over the entire temperature qualification range was limited, below +/- 1,5 %. The dependency of insertion loss with the temperature, as well as the difference of insertion loss variation between the monitoring port and the main output of the HPOA can explain the residual variation of output power.

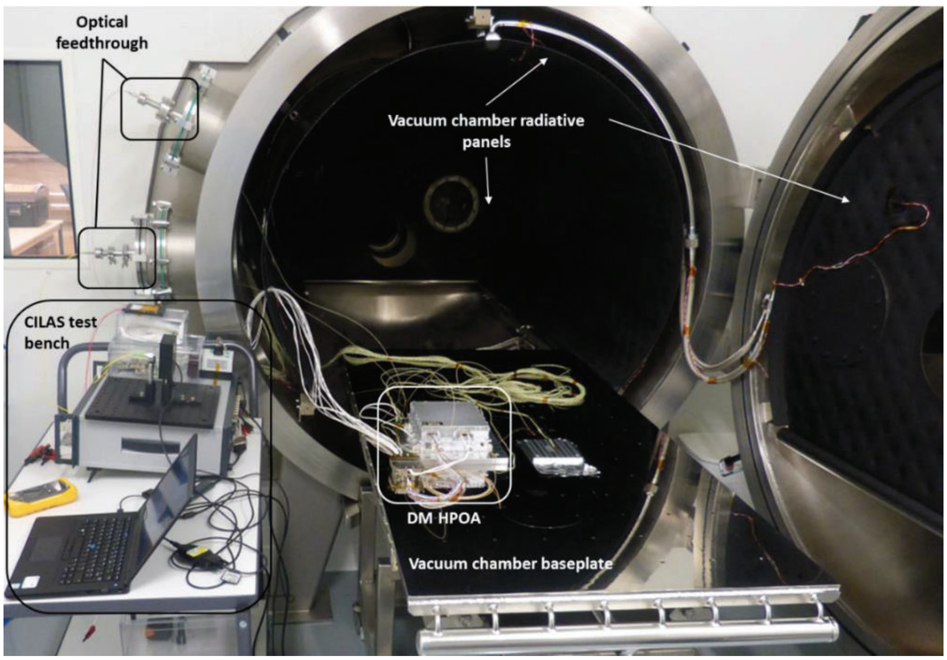

Figure 6 – TVAC test configuration

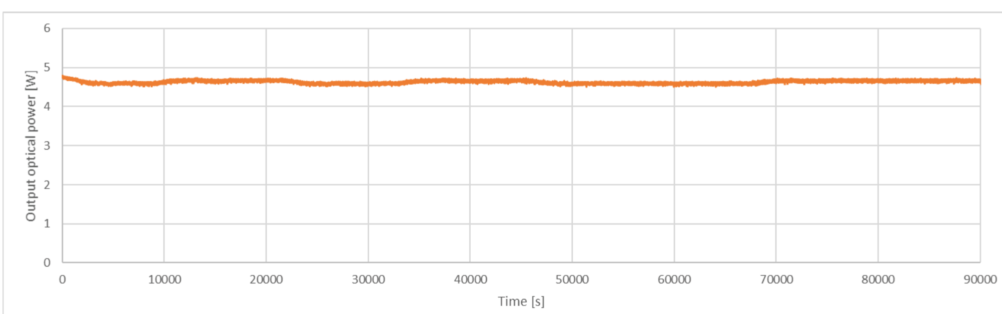

Figure 7 – Power variation over time, for operational cycling (TRP = [+10; +56°C])

4.2 Vibrations tests

The HPOA has undergone vibrations along all axes, as part of the mechanical acceptance tests, with characteristics presented in Table 5.

Table 5 – Vibrations characteristics applied to the IODM HPOA

Test	Characteristics
Sinus vibrations	5-20 Hz / max shaker amplitude 20-100 Hz / 20 g
Quasi-static vibrations	35 Hz / 10 s / 20 g
Random vibrations	Z axis: 20-2000 Hz / 18.3 gRMS X or Y axis: 20-2000 Hz / 9.5 gRMS

Accelerometers were located on the HPOA to verify mechanical model predictions and ensure internal components were not overstressed. Abort criteria have been set to secure the test. Pilot accelerometers were located on the HPOA interface tool plate.

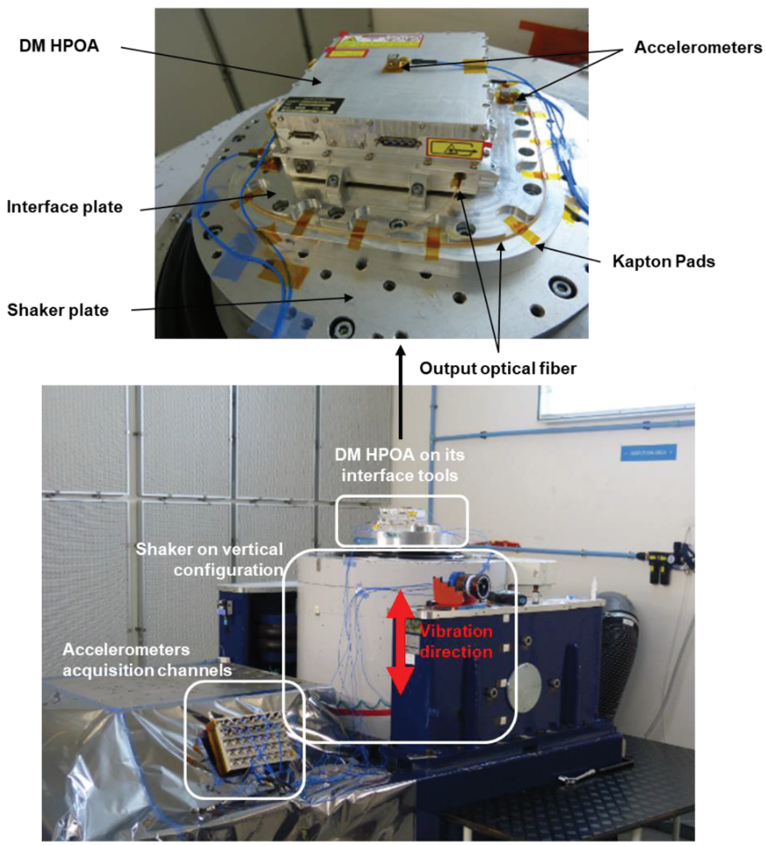

Figure 8 – Vibrations test configuration (Z-Axis)

The output fiber has been spooled around the HPOA and secured to avoid the fiber to be damaged on sharp edges during vibration test.

Critical frequency survey were carried out after each axis, no mechanical deterioration of the DM HPOA occurred. No frequency or amplitude shifts were measured, outside acceptable tolerances. The resonance frequency of the main mode is around 1434 Hz (Figure 9), in accordance with the computed value of 1350 Hz. No external degradations were observed after the different vibration environments.

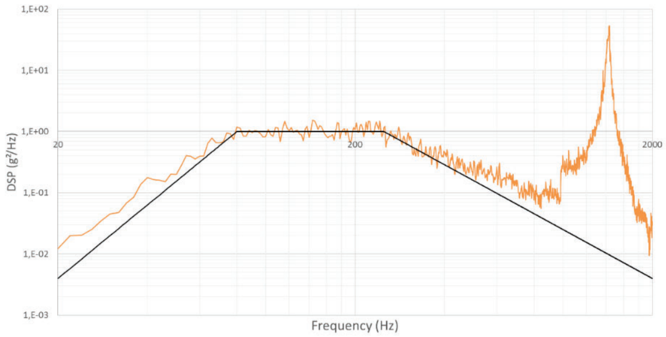

Figure 9 - Frequency response of the DM HPOA (orange)
Spectrum applied at equipment level (black)

No functional tests were carried out between vibrations and shocks, as the risk of failure associated with the vibration test was considered acceptable and agreed with the customer.

4.3 Shocks test

After vibrations, the HPOA has undergone shocks along all axes, as part of the mechanical acceptance tests. One shock per axis was done, for all three axes, according to the characteristics presented in Table 6. For information, all fiber components are qualified up to a minimum level of 1300g in order to cover both generic GEO mission and TELEO mission.

Table 6 – Shocks characteristics applied to the IODM HPOA

Test	Characteristics
Shocks	100 Hz / 20 g 1500 Hz / 500 g 10000 Hz / 500 g

The HPOA was mounted on an interface plate as shown in Figure 10. Accelerometer were positioned on the interface plate and on the plateau of the shock machine to verify the level reach at each shock. As for the vibration test, the output fiber was secured on the interface plate.

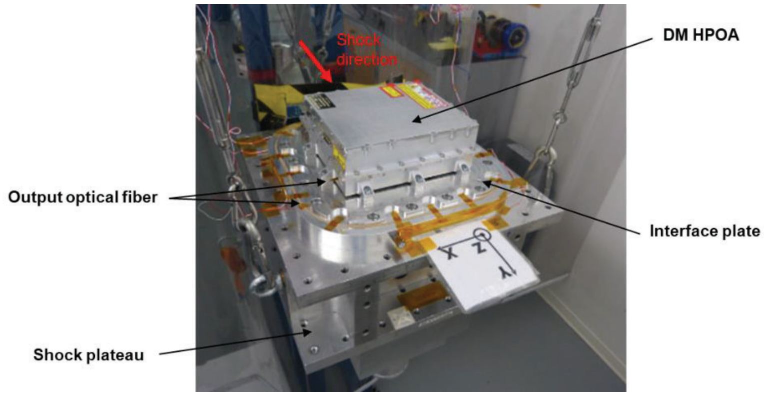

Figure 10 – Shocks test configuration (Y-Axis)

No external degradations or performances shift were observed after the shock test sequence. A critical frequency survey was also carried out after the shock test. No frequency or amplitude shifts were measured outside acceptable tolerances.

5. CONCLUSION

We have successfully developed and manufactured a HPOA for the TELEO optical terminal demonstrator, with its own space-grade electronics (including DC/DC converter), qualified to withstand all GEO and LEO space environments such as shocks, vibrations and radiations. Minimal design upgrades have already been identified, e.g. to maximize the PER of the HPOA, and they will be integrated on future HPOA for future GEO mission.

Another HPOA, with identical optical design as the TELEO HPOA, will be manufactured and tested by CILAS by the end of the year. It will be part of the LASIN demonstration in low earth orbit, led by Airbus Defence and Space.

ACKNOWLEDGEMENTS

We thank the Europeans Space Agency, the French space agency (CNES) and Airbus Defence and Space for their financial and technical support.

REFERENCES

[1] Thomas Anfray et al. (Airbus Defence and Space), Alexandre Mottet et al. (iXblue Photonics), Thomas Schmitt et al. (CILAS), “Assessment of the performance of DPSK and OOK modulations at 25 Gb/s for satellite-based optical communications” ICSOS, 2019

[2] Sylvain Poulenard, Thomas Anfray, Michael Crosnier, Jean-Frédéric Chouteau, Jordane Thouras, Charles-Ugo Piat, Jean-Adrien Vernhes, Laurent Coret, Walid Atitallah, Alassane Dupuy, Louis Barbier, Lyonel Barthe, Benjamin Gadat, Thomas Dreischer, Etienne Samain, Erick Bondoux, Thierry Lanz, Fredéric Lacoste, Julien Sommer, “10 Gbauds digital optical link and analog link from/to geostationary satellite”, ICSO 2022

[3] A. Salomon, L.Bouet, S. Mariojouls , Clement Guyot , Joël Tchahame, Arnaud Laurent, Stephane Ustaze, Raphael Cousty , Thomas Schmitt, O.Gilard, C.Bringer, “Optoelectronics parts NewSpace qualification aboard FOLC2 optical modem mission”, ICSO 2022