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Functional, mechanical and thermal vacuum qualification testing of G&H Proto-flight Erbium Doped Fiber Amplifier

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ABSTRACT

We present the development and qualification testing of G&H multi-channel fiber amplifier unit developed for satellite to ground free space laser communications. The qualification results show robust functional and structural performance following stress at all 3 possible excitation axes with high level sine vibration, random vibration and mechanical shock as well as thermal cycling between survival and operating temperatures in vacuum condition.

Keywords: free space laser communications, satellite to ground optical downlink, erbium doped fiber amplifier

1. INTRODUCTION

The recent success of 1.55 um laser communication demonstration missions is driving the development of space qualified laser modems that rely on hi-rel fiber optic components used in the modern terrestrial long-haul and submarine networks. Current R&D efforts are focused on the design and space qualification of elements and units that will constitute the next generation high-speed 1.55um laser communication terminals. The space qualification requires typically an electronic and optical circuit design that complies with the mission radiation level as well as the rigorous thermo-mechanical testing to verify the unit capability to withstand the mechanical stress and the temperature variations in a vacuum environment.

In this paper we present for the first time the extensive test results obtained during the space qualification of G&H multi-channel, 1.55 um Erbium Doped Fiber Amplifier (EDFA) Proto-flight Model (PFM). The-PFM EDFA is built using ESCC-qualified EEE parts and up-screened fiber optic components exploiting G&H heritage in manufacturing hi-rel active and passive fiber optic components. The electronics and optical circuit design complies with ionizing and non-ionizing radiation levels found in LEO orbits. The PFM has been subjected to a qualification test campaign as per the ECSS "Space Engineering Testing" specification which foresees full functional testing (FFT), high-level sine vibration, random vibration, mechanical shock and temperature cycling in thermal vacuum condition for optical equipment. The approach for subjecting a PFM in qualification test levels and durations has been selected to both qualify the design and at the same time deliver a unit that can be used in an In-Orbit Demonstration (IOD) mission.

The PFM FFT test results demonstrate robust optical and electronic control/monitoring performance. The PFM mechanical test results include complete optical and electronic function performance during vibration and shock stress in all three possible excitation axes. In addition, thermal vacuum test results include optical and electronic performance characterization during a total of 7 temperature cycles within the survival and operating temperature extremes with demonstration of "hot" and "cold" turn-ON and OFF as well as a Reduced Function Test at the temperature plateaus to demonstrate all the unit major functions. The PFM-EDFA FFT was performed at the beginning and at the end of thermo-mechanical testing; the comparison of the two FFT results has verified that there was no opto-electronic performance degradation. The PFM-EDFA passed the delivery review board (DRB) and was shipped for system integration into the Optel-u terminal and subsequent IOD.

2. PFM-EDFA BUILD AND VERIFICATION

2.1 Erbium doped fiber amplifier proto-flight model

Figure 1 shows the multi-channel PFM-EDFA unit. The unit is built with space grade electronic parts assembled on a printed circuit board (PCB) which complies with ECSS-level standards for the procurement and fabrication of hi-rel space-grade electronic assemblies. The pump lasers are hermetic devices, they are manufactured in-house, they comply with TELCORDIA GR-468 and MIL standards, they exhibit a small form factor and wide temperature range and have sufficient space evaluation heritage to be characterized as suitable for flight hardware integration [1]. Before their system assembly, the opto-electronic parts are screened as per ESCC Basic Specification No. 23201 (evaluation of laser diodes). The screening tests, complying mostly with MIL-STD-883 standard, involve:

- Internal, external and pre-cap visual inspections (MIL-STD-883 Method 2010, MIL-STD-883 Method 2009)
- Temperature cycling (MIL-STD-883 Method 2010)
- Particle Impact Noise Detection (PIND - MIL-STD-883 Method 2020)
- Burn-in (MIL-STD-883 Method 1015)
- Hermetic seal - Fine/Gross leak test (MIL-STD-883 Method 1014)
- Electrical measurements at different stages of device development

The surface mount and through hole EEE and opto-electronic parts were soldered according to hi-rel ECSS standards for soldering and assembly of space-grade electronic assemblies. In order to comply to these standards and guarantee high quality solder joints, the though hole EEE and opto-electronic parts were de-golded and re-tinned before the soldering operation. Electrical and seal tests were performed before and after the parts processing to ensure no impact on hermeticity and functional performance. The fiber optic parts are predominantly produced in-house and have both hi-rel terrestrial as well as space heritage. The fiber optic circuit is spliced together according to G&H internally approved and verified procedures for fiber handling, fiber optic splicing and component fixing suitable for hi-rel industrial and space grade modules. The integration of the PFM-EDFA sub-assemblies was performed in a Class 10,000 clean room (ISO7). The declared material list (DML) complies with stringent requirements for materials outgassing whereas the Declared Component list (DCL) and Declared Process List (DPL) are available and documented.

The figure below (left) shows the PFM-EDFA during the integration phase. The figure (middle) shows the finished unit with the lid-on and the fitted electrical (high density 44-pin D-sub) and optical (MiniAVIM adaptors) interfaces. The figure (right) shows the unit on the vibration shaker with the fitted space-qualified MiniAVIM patchcords.

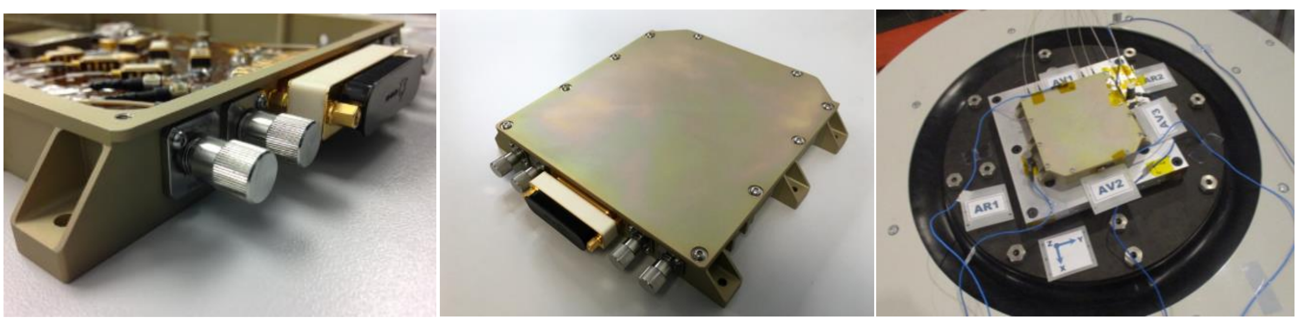


Figure 1. (left) PFM-EDFA during integration, **(middle)** finished unit with the lid and D-sub saver on, (right) unit mounted on shaker during out-of-plane axis vibration test

The unit dimensions - excluding the mounting flanges are 143mm x 153mm x 24mm, the unit mass - without the MiniAVIM connectors - is 645 grams. In terms of mechanical stiffness, the unit was designed to demonstrate a fundamental mode frequency of >500 Hz. The figure below (left) illustrates the result of the low level sine sweep that was performed to measure the fundamental mode frequency before the start of the vibration test campaign. The measurement verified the design stiffness; the fundamental mode frequency is 659 Hz with amplitude of 14.47 gn.

With respect to electrical functions the unit is controlled and monitored through a built-in digital interface that includes on-board LVDS transceivers and ADC/DAC ICs. Voltage regulation is also performed within the unit. The electrical functions include enable/disable of the pump laser currents as well as Loss-of-Input (LOI) and LOI override. The LOI causes an automatic shut down of the pump diodes in case of a sudden loss of optical input power. The monitors are: a) optical input / output power, b) pump laser driving current and temperature, c) unit chassis temperature.

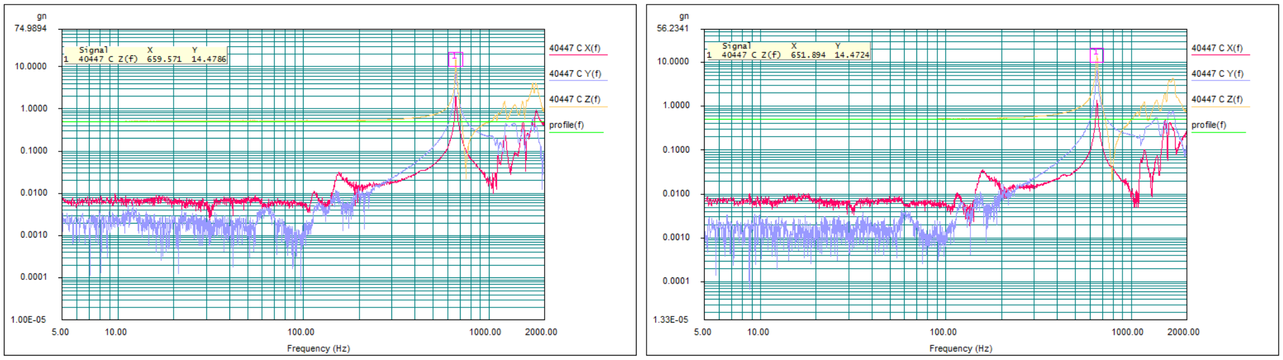


Figure 2. Low level sine response plots: (left) before vibration testing and (right) at the end of the vibration test campaign

2.2 PFM-EDFA functional verification

A full functional test (FFT) was performed at the beginning and the end of the test campaign to verify functionality over a number of different operating modes. The initial FFT was performed at three different case temperatures (0, 21, 30ºC) in ambient pressure condition in order to verify the thermal design. The figure below shows the output power of one of the EDFA channels as a function of the laser diode driving current (left) and as a function of the input power (right). The input wavelength was 1565 nm. The measurements show a very uniform response to the different case temperatures. The saturated output power which did not vary with temperature was >21 dBm and the noise figure (NF) was 7 dB. A heat rise of +7 degC was measured between case temperature and pump laser temperature when the pumps were driven at the maximum de-rated driving current.

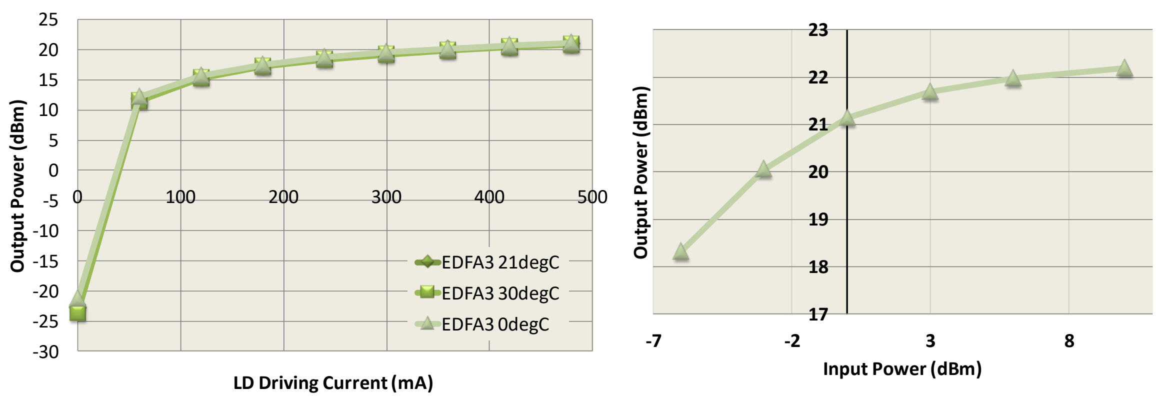
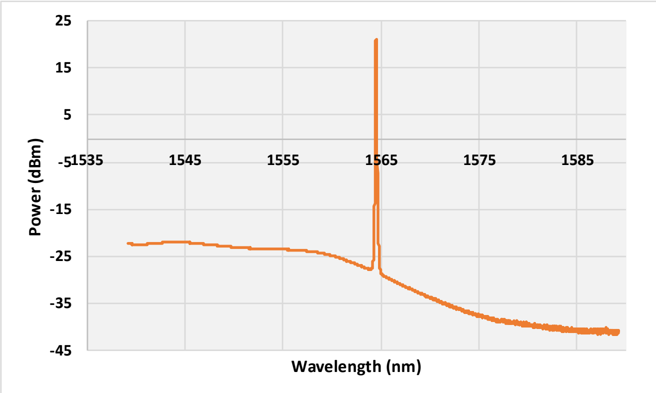


Figure 3. Output power as a function of: (left) driving current and temperature and (right) input power

Figure 4 (left) shows the Optical Spectrum Analyzer (OSA) trace recorded at 0 dBm input indicating an OSNR >45 dB. The PFM-EDFA was tested against its polarization dependent gain (PDG). The polarisation of the input signal to the PFM-EDFA was scanned using a digital polarisation controller in autoscan mode. The measurements of the output power were logged for 10 minutes which was sufficient enough time that the min and max polarisation states were found. The table below (right-top) shows the PDG measurements of the PFM-EDFA output at the three different case temperatures. The PDG is temperature independent and was as low as 0.25 dB. The table below (right-bottom) shows the input/output optical power monitor measurements for the min and max output power at 21ºC case temperature. The input monitor values are insensitive to the input signal polarization state. The output monitor values change but this reflects the change in the measured output signal. The monitors responded uniformly for the different case temperatures.

The table below shows the results of the enable/disable verification test. The test was performed by ramping up the pump drive current to 50 mA whilst the PFM-EDFA is disabled and measuring the output to ensure that the amplifier is not operating. The pump current is then ramped down, the PFM-EDFA is enabled and the current is ramped up to 50 mA to verify that the amplifier is functioning. Whilst operating, the unit is then disabled and tested to verify no operation.



	Pout (21degC) (dBm)	Pout (30degC) (dBm)	Pout (0degC) (dBm)
Pmin	20.97	20.95	21
Pmax	21.2	21.18	21.25
Pavg	21.07	21.06	21.08
Pmax-Pmin (dB)	0.23	0.23	0.25

Pout (dBm)	**Monitors (21degC)**			
	IN		OUT	
	Bits	mW	Bits	mW
20.98	348	1	1809	126.41
21.18	349	1.01	1890	132.07

Figure 4. (left) PFM-EDFA output OSA trace and (right): (top) PDG measurements of the amplifier output at three different temperatures, (bottom) PDG measurement of the amplifier IN/OUT monitors at 21ºC

EDFA ENABLE	**OUTPUT POWER (dBm)**	**IN_PWR_MON**		**OUT_PWR_MON**	
		Bits	**mW**	**Bits**	**mW**
0	-23.27	326	0.99	0	0
1	10.39	326	0.99	212	10.93
0	-23.27	326	0.99	0	0

Table 1. Measurements during EDFA ENABLE/DISABLE function

The results in table 1 show that the enable/disable control is operating properly; no output power is measured when the amplifier is disabled but output power is measured when the EDFA is enabled. This allows on/off control of the PFM-EDFA without it being powered down fully. This function has been tested over temperature without change.

The PFM-EDFA is designed to automatically shutdown the pump diodes if there is an interruption (LOI) of the input signal. The status of the LOI trigger can be directly read through the unit digital interface as a binary value. In order to verify the LOI response the input power is tuned from 0dBm to -10dBm and the LOI trigger point is detected. In order to find the LOI release point, the input power is then increased back to 0dBm.

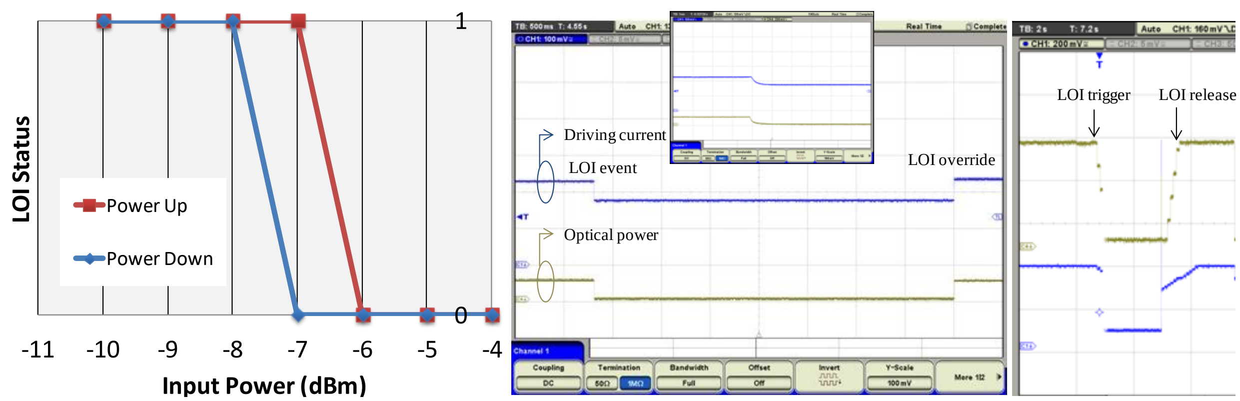


Figure 5. (left) LOI trigger point detection, (middle) LOI override measurement, (right) LOI trigger & release measurement

Figure 5 (left) shows that the LOI triggers when the input power falls to -8dBm. The LOI releases when the input power has increased to -6dBm. The trigger and release values are designed to be separated to avoid any oscillatory effects if the power level is close to the trigger level. The test was repeated at the three different case temperatures and the LOI trigger and release values were not affected. The unit includes an LOI-override function that is used to bypass the LOI function at a loss of input event. Figure 5 (middle) shows the captured oscilloscope trace of the driving currents and optical power emitted by the PFM-EDFA. The Figure shows a loss on the amplifier input port that triggers an LOI event. After a short duration an LOI override is performed that restores the optical output power. The corresponding shutdown timing is shown in the inset. The timing shows that the output fall time is less than 1ms. Figure 5 (right) shows the logged data when an LOI event occurs and is then released i.e. the input power is restored. The trace shows that when the input power drops (LOI trigger point) the output power drops. When the input power is restored (LOI release point) the LOI event clears and the output power is restored.

2.3 PFM-EDFA environmental verification

The PFM-EDFA was subjected to a series of thermo-mechanical qualification tests with the test plan and procedures complying with [2]. The vibration test block comprises high level sine (25g) and random vibration (19.2g RMS - freq. range 20-2000 Hz) that are conducted sequentially for the out-of-plane (Z) and the in-plane excitation (X/Y) axes with a low level sine sweep and limited performance test (LPT) in-between them to monitor the unit structural and functional performance. The low-level sine sweep is performed over the frequency range 5-2000 Hz (sweep up from 5 Hz to 2000 Hz and down from 2000 Hz to 5 Hz), using an input of 0.5 G at 2 octaves/minute. The success criteria of the low level sine sweep are as per [2], i.e less than 5% in frequency shift and less than 20% in amplitude shift for modes with an effective mass greater than 10%. The random vibration test was performed in three steps suppressing the PSD firstly by -6 dB (test duration 20 seconds) then by -3 dB (test duration 20 seconds) and finally subjecting the unit to the 0 dB condition to the qualification duration of 2 minutes. A total of 5x tri-axial accelerometers (2 control and 3 response) are used. Vibration strategy is peak control with 2 control signals.

Figure 6 shows the super-imposed low level sine spectra recorded during the out-of-plane vibration testing by the tri-axial accelerometer that captures the unit fundamental mode. There is a very strong overlap of the spectra in all the measurement steps which indicates a robust structural performance. The initial and final low level sine results are shown in Figure 1. Te main resonance frequency drift was <1.2% whereas the amplitude drift was <6%.

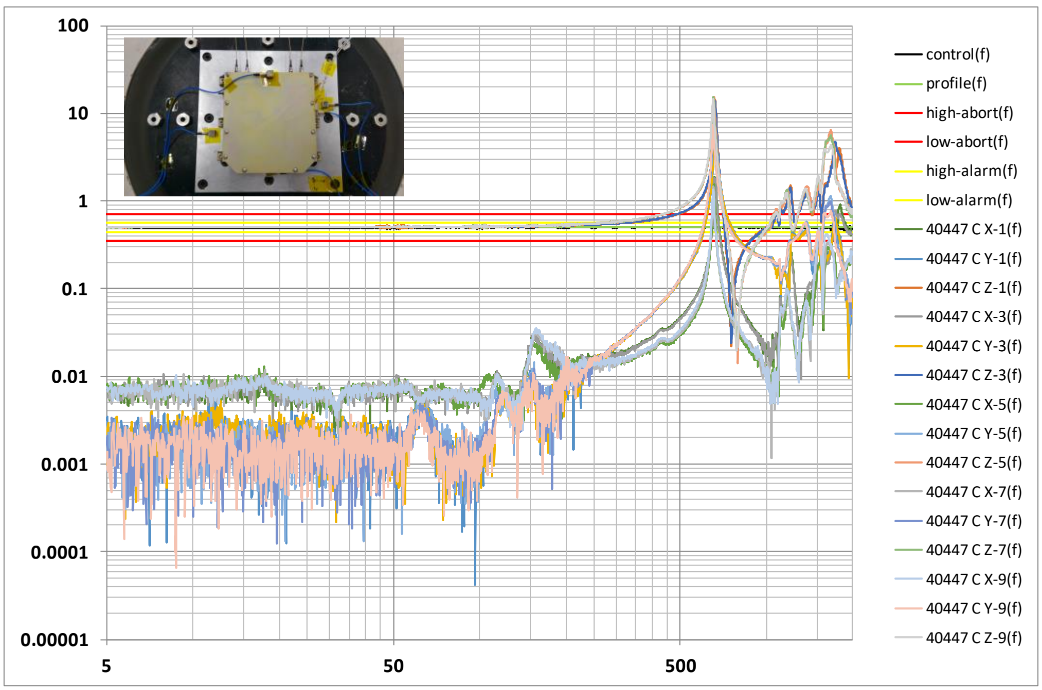


Figure 6. Overlapped low level sine response plots during out-of-plane vibration test. Steps: 1) initial, 3) after high level sine, 5) after - 6 dB random vib, 7) after -3 dB random vib, 9) after 0 dB random vib. Axes: Z-out-of-plane, X/Y in-plane

The table below lists the main results of the LPT tests. At each LPT point two tests are performed, one immediately after the PFM-EDFA switch ON and one after a dwell time of 5 minutes to make sure that the unit output power and pump laser temperature has reached a plateau. Results indicate negligible drifts in all the PFM-EDFA monitors that were measured through the EGSE interface. The PFM-EDFA optical performance (gain) was measured through the OSA and has shown drifts that are within the measurement accuracy of the instrument. Similar performance was obtained when testing the two in-plane axes.

	OFA on SHAKER BEFORE Z	OFA on SHAKER BEFORE Z	OFA ON SHAKER AFTER HIGH LEVEL SINE-Z	OFA ON SHAKER AFTER HIGH LEVEL SINE-Z	OFA ON SHAKER AFTER RANDOM -6dB	OFA ON SHAKER AFTER RANDOM - 6dB	OFA ON SHAKER AFTER RANDOM -3dB	OFA ON SHAKER AFTER RANDOM 0 dB	OFA ON SHAKER AFTER RANDOM 0 dB	OFA ON SHAKER AFTER RANDOM 0 dB
Meas 1 GAIN	20.4	20.45	20.45	20.43	20.51	20.5	20.54	20.53	20.58	20.56
Meas 2 GAIN	21.1	21.1	21.12	21.16	21.14	21.14	21.13	21.11	21.14	21.14
Meas 3 GAIN	17.66	17.68	17.65	17.69	17.72	17.73	17.74	17.75	17.93	17.83
Input 1 (mW)	0.83	0.83	0.83	0.83	0.83	0.83	0.84	0.84	0.84	0.84
Input 2 (mW)	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.05	1.04	1.05
Output 1 (mW)	182.31	183.63	183.29	183.29	181.75	182.59	181.4	182.24	181.26	182.17
Output 2 (mW)	123.17	121.95	122.87	122.66	123.48	123.17	123.99	123.63	124.09	123.79
Pump current (mA)	482.49	483.48	482.89	483.28	482.3	483.09	482.1	482.89	482.1	482.89
Pump temperature (degC)	31.49	39.41	35.58	37.51	28.59	34.87	27.1	33.07	26.64	32.89

Table 2. LPT results during out-of-plane vibration steps

The unit was then subjected to a 100Hz/40g and 2000-10000 Hz/1000g shock. 3 shocks per axis in one direction were applied, i.e. the unit was subjected to a total of 9 shocks. 7 accelerometers were used, i.e. 4 mono-axial piezo-electric charge accelerometers as control for shock test, 2 ICP mono-axial accelerometers as control for pre and post shock low level sine sweep and 2 ICP tri-axial and 1 mono-axial as response for pre and post shock low level sine sweep.

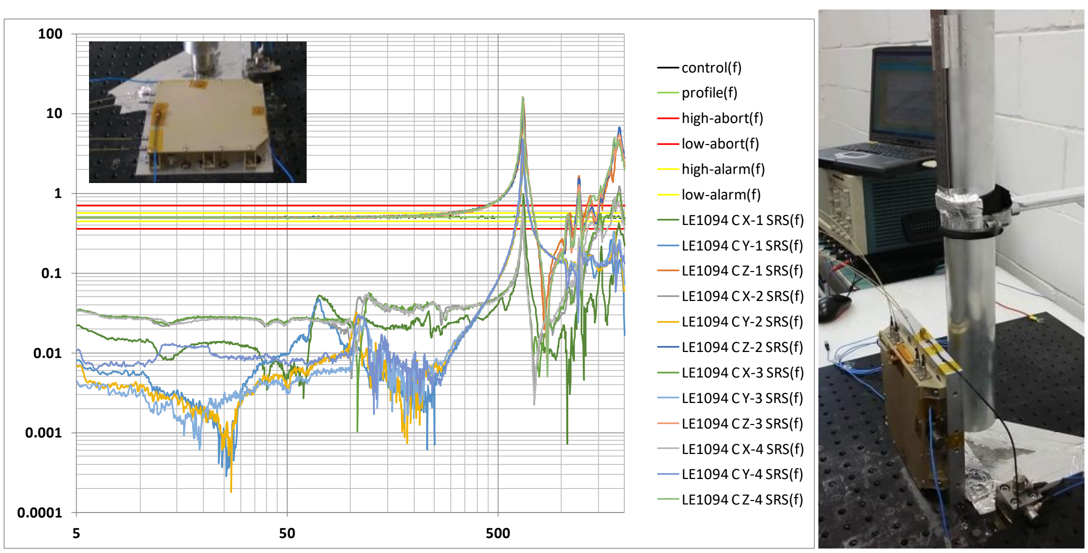


Figure 7. Overlapped low level sine response plots during out-of-plane mechanical shock. Steps: 1) initial, 2) after mechanical shock out-of-plane axis, 3) after mechanical shock in-of-plane axis, 4) after mechanical shock in-plane axis

Figure 7 shows the super-imposed low level sine spectra recorded before, in-between and after the out-of-plane mechanical shock testing by the accelerometer that captures the unit fundamental mode. There is a very strong overlap of the spectra in all the measurement steps which indicates a robust structural performance. The main resonance frequency drift was <1.16% whereas the amplitude drift was <14%. The inset shows the test configuration for out-of-plane mechanical shock. The figure below (right) shows the test configuration for one of the in-plane axes.

An LPT test was performed - as in the case of the vibration test. The results were similar to the ones obtained during vibration and have verified stable optical performance and robust monitoring functions. The table below summarizes the LPT measurements.

	OFA on SHAKER BEFORE SHOCK	OFA on SHAKER BEFORE SHOCK	OFA ON SRS TABLE AFTER SHOCK Z-axis	OFA ON SRS TABLE AFTER SHOCK Z-axis	OFA ON SRS TABLE AFTER SHOCK X-axis	OFA ON SRS TABLE AFTER SHOCK X-axis	OFA ON SRS TABLE AFTER SHOCK Y-axis	OFA ON SRS TABLE AFTER SHOCK Y-axis
Meas 1 GAIN	20.15	20.09	20.25	20.24	19.92	19.87	20.5	19.93
Meas 2 GAIN	21.02	21.02	21.00	20.99	20.94	20.96	20.88	20.89
Meas 3 GAIN	17.91	17.89	18.02	17.93	17.75	17.72	17.8	17.81
Input 1 (mW)	0.96	0.96	0.97	0.97	0.96	0.96	0.96	0.96
Input 2 (mW)	1.05	1.05	1.02	1.02	1.06	1.06	1.04	1.04
Output 1 (mW)	182.94	183.43	181.89	182.52	181.75	182.73	181.82	182.87
Output 2 (mW)	121.85	122.05	122.97	123.07	123.43	123.12	123.12	122.61
Pump current (mA)	483.28	483.48	482.49	483.09	482.3	483.09	482.3	483.09
Pump temperature (degC)	33.04	35.02	28.77	30.76	26.95	31.76	27.54	32.32

Table 3. LPT results during mechanical shock test

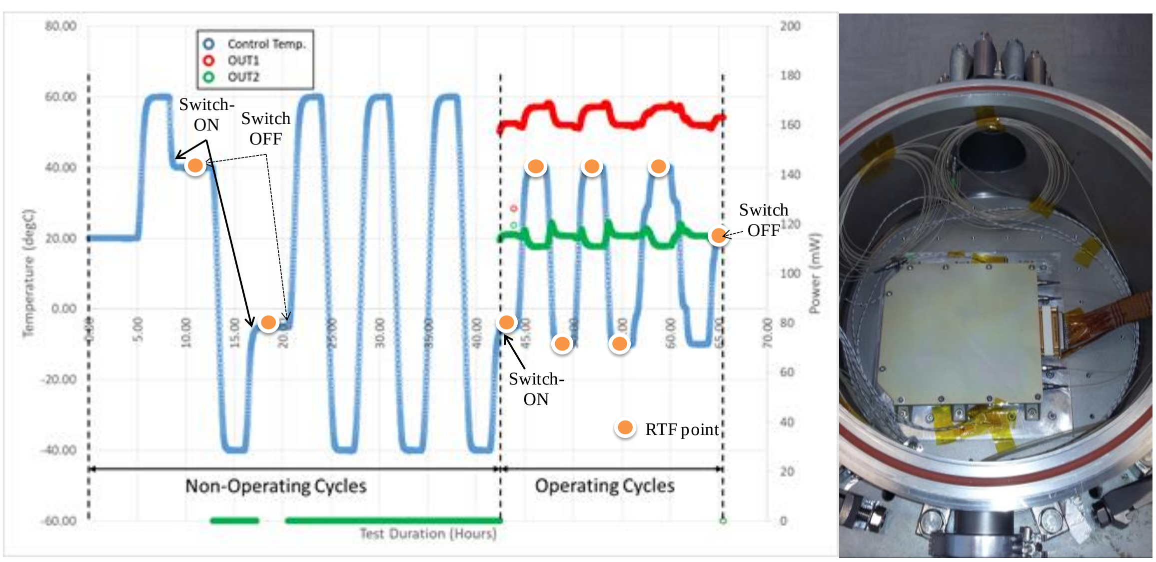


Figure 8. (left) output power of the three channels throughout the test (right) PFM-EDFA inside the vacuum chamber.

The PFM-EDFA was then subjected to a thermal vacuum test that involved a total of 7x temperature cycles (4 non-operating and 3 operating). The dwell time at the hot and cold temperature plateaus was 2h and the temperature rate of change was <3ºC. During the first non-operating cycle the hot and cold Turn-ON/OFF was tested together with a reduced function test (RFT). Figure 8 (left) shows the TURN-ON/OFF points and the RFT points - a total of 9 RFT tests were performed. The RFT involved ramping-up the pump laser driving currents to the maximum de-rated current value - i.e. worst case End-of-Life (EOL) condition - and measurement of the PFM-EDFA output power and recording all the monitors before and after the 2h dwell time. The result of the RFT conducted at the hot and cold TURN-ON points is shown in the Figure 9. The results indicate a very similar performance at the two different temperatures for all the three amplifier channels.

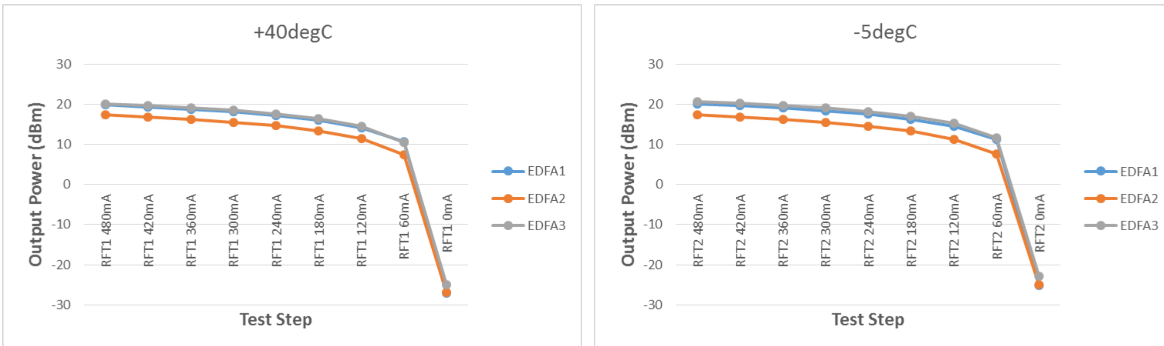


Figure 9. Output power as a function of driving current at: (right) hot TURN-ON and (left) cold TURN-ON points

With respect to the unit thermal behavior the internal pump laser thermistor measurements have shown that there is an average of 12ºC rise of the pump laser case temperature compared to the PFM-EDFA case temperature. For a unit operating temperature of 40ºC, this means that the pump lasers operate at a worst case condition (EOL driven at the maximum de-rated current) with a >20 ºC temperature margin with respect to the pump laser maximum operating temperature. This observation indicates that the PFM-EDFA could be operated at temperatures >40ºC.

3. CONCLUSION

We have reported a space-qualified 1550nm multi-channel amplifier unit designed for LEO to ground downlinks. A PFM (TRL 6/7) was developed following ECSS and internal G&H space-grade assembly processes that included ESCC screened lasers and ESCC EEE parts. The environmental campaign validated the functional performance of the system in the relevant environment. The module successfully passed 25g high-level sine vibration, 19.2g RMS vibration testing, 1.000g shock and temperature cycling in vacuum. An amplifier gain block using the same unit design has been shown to survive shock levels up to 2.500g [3] as such there is high confidence that the PFM could sustain higher mechanical shock stress.

4. ACKNOWLEDGMENT

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