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Space qualification of a 10W single-mode PM optical amplifiers in the 1.5- μ m region



Space Qualification of a 10W single-mode PM optical amplifiers in the 1.5- μ m region

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ABSTRACT

MPB has developed a 10W Polarization Maintaining Optical Fiber amplifier (1550 nm) for space applications. The prototype is based on three stages of optical amplification with photodiodes at each stage, monitoring the output power. It includes the control electronics and software with feedback loops to dynamically control and monitor the amplifier. The design had to overcome many challenges to comply with the mechanical, thermal, radiation, and vacuum requirements for the LEO satellite space environment, while at the same time meeting the price targets for LEO constellations by maximizing the use of commercial off the shelf (COTS) components.

The following were the main challenges: a) to effectively dissipate the heat generated (75-90 W); b) to select radiation-tolerant electronics to drive the needed electrical current; c) to source and effectively implement components, such as the combiners and isolators, in the high power optical path compatible with vacuum at 10W output.

The major challenge with regard to heat management was to find an optimal method to dissipate the heat from the third stage (high power) Erbium Ytterbium Doped Fiber. Commonly, this fiber is spooled on an Aluminium spool. The difference in the Constant Temperature Extension (CTE) between the fiber (low) and Aluminium (high) leads to a detachment of the fiber at low temperature with a high risk of breaking the fiber when passing from OFF to ON. At high temperatures, the Aluminium extends much more than the fiber, leading to an over tension on the fiber with a high risk of mechanical breakage. Different designs of the spool, supports inside the box, selection of materials, and process implementations were tried. An innovative, proprietary method was developed to satisfy this requirement.

The unit successfully passed performance testing between -20°C and +40°C in vacuum with 10W output, with a wall plug efficiency of 11%. The lower temperature limitation was due to the specification of the high-power laser diodes. The higher temperature was limited by the local heating and risk of mechanical breaking of the third-stage COTS combiner and isolator. Vibration and mechanical shock are not foreseen to be an issue. The simulation demonstrated the prototype is complying with these requirements. Moreover, MPB has built similar instruments at lower power levels that have successfully passed these qualification tests.

The components used were available as COTS products, including the radiation-tolerant electronics. All the components were qualified individually for > 30 krad, in vacuum, and for the temperature range -35°C to +65°C except for the high-power laser diodes which were limited to -25°C. MPBC is continuing the qualification, implementing minor design changes, in order to satisfy the complete temperature range (-35°C to +65°C).

Keywords: Optical Intersatellite link- satellite-Ground link, High power EDFA, 100 Gbps Transmitter.

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1. INTRODUCTION

Three main groups were competing to provide the internet from satellites through optical communications: Google, Facebook, SpaceX-Airbus. Now, about 12 major players are planning to populate the space with about 55,000 to 60,000 satellites by 2029 [1]. The first generation of satellite constellations using optical communications is planned for deployment in 2022 with service in 2023 (e.g. Tesat, Telesat, SpaceX). While these constellations will offer Gbit/s capacity, there is already a desire to see Terabit/s capacity, in order to seamlessly integrate with the existing terrestrial infrastructure. The market requires also flexible and focused Capacity to obtain >100Gbps in concentrated areas, low cost, low latency (30-50 msec), interference resistance, and inter-satellite links.

It is expected that the 10 W EDFA will permit ≥ 100 Gbps EDFA. This is a key device in optical communications. A recent study by NASA [2] showed the need for the 10 W to reach the 100 Gbps unless the diameters of the telescopes are considerably increased than those suggested by the Interagency Operations Advisory Group [3]

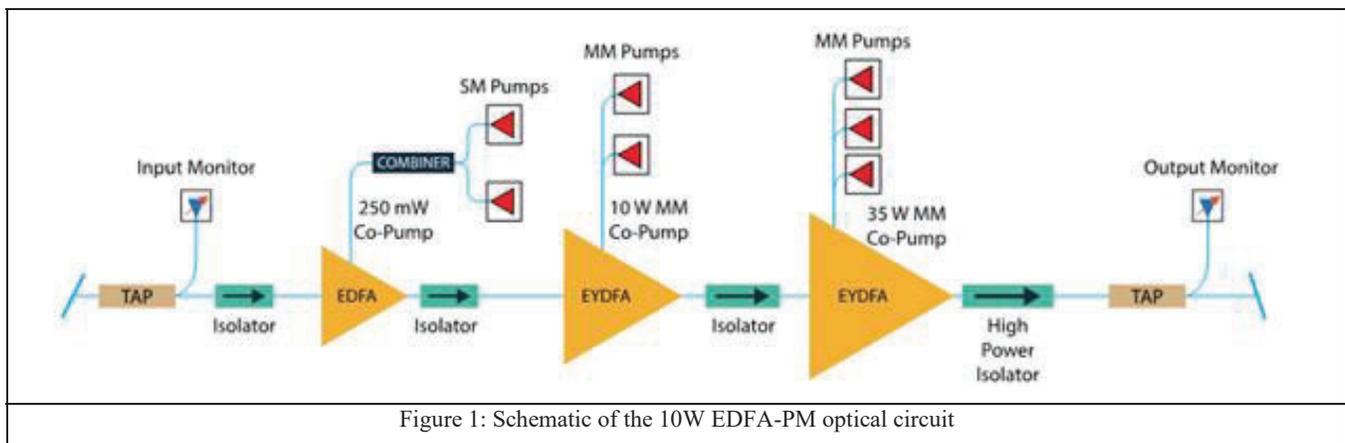
MPBC built the first Erbium Doped Fiber Laser in space which is flying on the ESA PROBA-2 Satellite. It has been completely functional for 11 years, within MPB’s fiber sensor interrogator [4].

2. 10W-EDFA-PM AMPLIFIER DESIGN (40 DBM EOL)

Requesting 10W EDFA in PM under space radiation, in vacuum, functional over a wide range of temperature, in limited volume, with the risk of Stimulated Brillouin back-Scattering, presents strong and challenging with many potential issues to predict and solve. Table 1 summarizes the potential challenges and the proposed methods to mitigate them

Table 1: Challenges encountered during the design, and how to mitigate them

Challenge	Mitigation Approach
Radiation on doped fibers	<ul style="list-style-type: none"> • Design with shielding • Simulation of expected dose • Testing to determine required design margins
Stimulated Brillouin Scattering (SBS)	<ul style="list-style-type: none"> • Limiting delivery fiber length • Measurement of threshold • MPBC expertise in previous fiber laser (Guidestar technique)
Pump diodes	<ul style="list-style-type: none"> • <u>Carefully</u> selected candidates • Qualification for radiation, thermal cycling, vacuum, vibrations, and shock
Control electronics radiation	<ul style="list-style-type: none"> • Qualification of radiation-tolerant processors • Possibility to control with system processor
Power consumption	<ul style="list-style-type: none"> • Optimize the heat dissipation interface between the radiator and EDFA box • Use of uncooled components • Cold redundancy
Reliability	<ul style="list-style-type: none"> • Redundancy of high FIT components • Qualification for expected lifetime
Environmental conditions	<ul style="list-style-type: none"> • Design according to space standards • Radiation, Thermal and structural simulations • Component and unit-level qualification for radiation, thermal cycling, vacuum, vibration, and shock



The mechanical structure and thermal balance analysis were performed using ANSYS Finite Element Analysis (FEA) code. The materials and mechanical parts were selected based on:

- MPB smaller power EDFAs (2W) for space applications
- MPB EDFA products for terrestrial and submarine
- Detailed simulation with Ansys code

A margin of safety based on the safety factor was considered when taking the parameters Material Properties and Parameters. A modal analysis simulation was performed in ANSYS 17.1 to identify the natural frequencies of the system at which the system will naturally resonate. For the Random Vibrations we used three Power Spectral Density (PSD) spectra for our analysis, The first, used by Alter Technology in a previous contract for EDFA testing, proposed by ESA (ECSS-E-HB-32-26A, Chapter 9, Fig. 9-4, and Page 243, Grms =24 G), the second was the PSD proposed for MPB's Fiber Sensor demonstrator on Proba2 (ESA-Verhaert, Grms =23 G), and the third by a private client for 1W EDFA.

The simulation permitted an iterative design improvement to:

- Have an optimal homogeneous distribution on the bottom surface of the EYDFA enclosure
- Optimize the distribution of the components inside the enclosure to reduce the thermal
- Compare our results with others who are building amplifiers for NASA at 40dB[5]
- Compare our results with the requirements of primes client of 1W EDFA and YDFA amplifiers, who are giving useful information on the parameters to consider for the thermal control
- Get maximum heat dissipation, a main challenge with the 10W EDFA, with 75-90 W of heat to dissipate

The electronic circuit to control and monitor the 10W EDFA-PM is based on MPB commercial product Laser P33 (33dBm, 2W). The generic-design circuit at MPB, developed for the commercial products permits the control of every individual laser diode pump. There are a total of seven pumps (2 in stage-1, 2 in stage-2, and 3 in stage3)

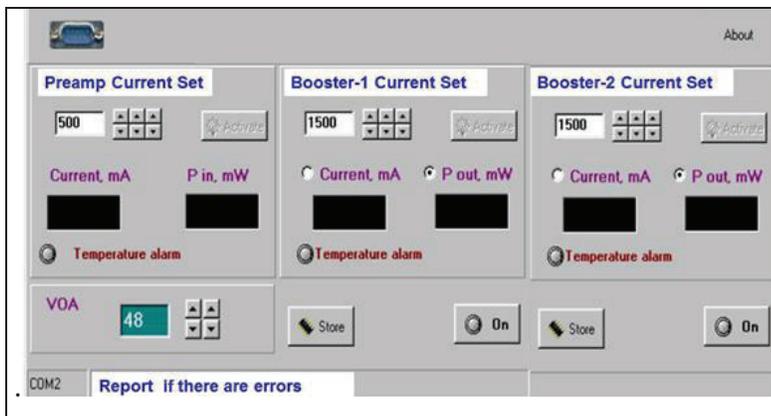


Figure 2: Control interface software to monitor the current set of each stage

There are mainly two modes of monitoring:

- a) Amplifier Current Control (ACC) where the current is set as per the calibration to obtain the required output power. In this case, if during the time the pump aging decreases its optical efficiency, a new current will be set and verified
- b) Amplifier output Power Control (APC) where the output photodiode signal is used in a feedback loop that monitors the current to obtain the desired output power.

MPB is integrating Dynamic Power Management that permits to have different functional modes at different selected output power levels and duration depending on the dynamic inter-satellite link. The code includes a Standby mode at 0 or a minimum output power.

There are different software (e.g. Satellite Tool Kit (STK)) that provide the distance and elevation based on the satellites orbit parameters The software can take into account pointing acquisition and tracking procedure as well, so that when the link is established the actual communication starts, if power requirements are satisfied. If all distances have been calculated with high accuracy, all the other parameters can be found from the geometry properties of the link and from the way it changes. The main points of the Dynamic control design, developed by MPB, are the following Modes:

- Off mode (no power applied),
- On power up the system goes into standby mode.
- From standby mode, the system can go to any operational or test mode.
- Operational modes are accessible from one to the other directly, only if, to get into a particular mode, it is efficient to go through an existing mode to get there. e.g. if Mode-n is a low powered version of Mode-m so it makes sense that it is possibly most efficient to go to Mode-n by traversing through Mode-m first.
- Once the system is up and running any off-nominal behaviour can send the system to the Error/Exceptions mode. From the Error/Exceptions mode the system may be commanded to shut down or go back to Standby if the error is of the kind that will allow for further system operation.
- The transitions may be very different in terms of their entry/exit criteria and the actions done within the mode to enable the transition.
- The Standby Mode shall be used as an intermediary mode when transitioning from one mode to another to safely change data rate, power, or the signal source (lambda0).

The enclosure dimension is: 277.5 x 216.5 x 32 (Thickness 3 mm) The total mass including the electronics is 2.6 kg

3. ERBIUM AND ERBIUM-YTTERBIUM FIBER EVALUATION

The Erbium Doped Fibers (EDF) and Erbium-Ytterbium doped fibers (EYDF) are the components that would be most affected in a space environment, by the radiation.

MPB's experience in the irradiated fibers is a built-up knowledge, since 2013, with 10 gamma radiation tests performed in three laboratories, Ecole Polytechnique in Montreal (Canada), ESA-ESTEC (Netherlands), and Alter Technology (Spain). The irradiated items included more than 50 kinds of active fiber, EDFs, Polarization Maintaining EDFs (PM-EDFs), EYDFs, and PM-EYDFs. The tests followed the ESA Basic irradiation specification document ESCC22900 [6]. Since 2013, MPB has performed about 10 radiation tests of optical fibers and EDFA components tested in gamma radiation at different doses between 10 and 100 krad. At least one kind of fiber was submitted in all the tests, and many fibers were submitted in a few tests to compare the effects of different doses and dose rates on the same kind of fiber. Dose rates between 85 and 400 rad/h no major difference or trend of the gamma effects on the EDFs or EYDFs could be deduced from this decreasing of the radiation dose rate.

The major result from these tests is the capability to mitigate the radiation effects by photobleaching, i.e. pumping the active fibers at their nominal power during a convenient period after irradiation. Moreover, as shown in Figure 4 to Figure 6, the COTS fibers' performance can be better than that of a radiation-tolerant expensive fiber. The radiation effects in combination with the gain recuperation by photobleaching releases us from the necessity of using the radhard and allows the use of Commercial EDF-PM fibers.

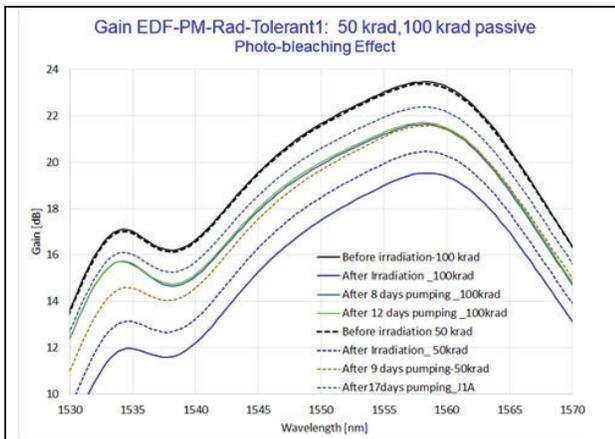


Figure 3: Radiation tolerant (expensive) EDF-PM-Rad-Tolerant1 Gain Spectra before and after radiation and post-pumping for bleaching

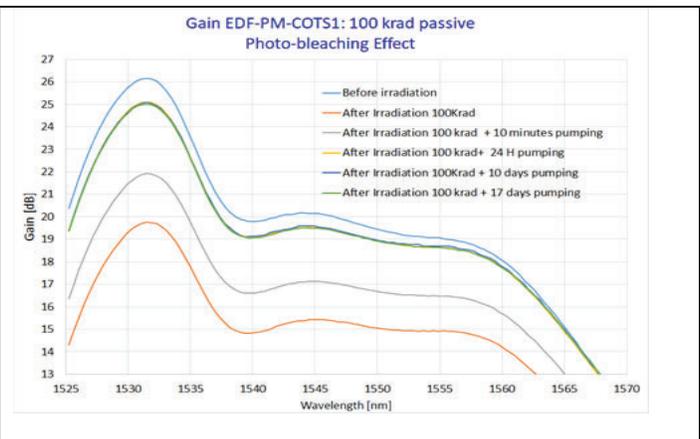


Figure 4: Commercial EDF-PM-COTS1 special core Gain before/after radiation and photo-bleaching

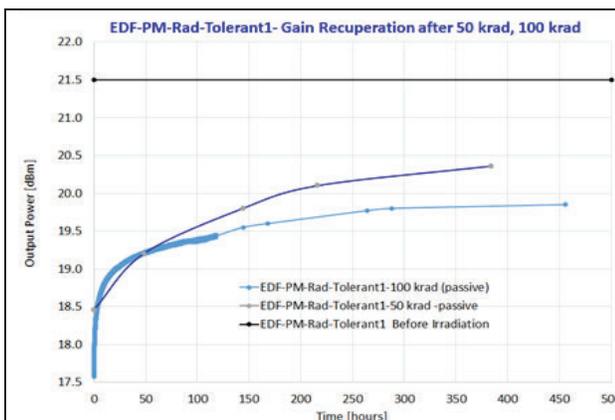


Figure 5: Radiation tolerant (expensive) EDF-PM-Rad-Tolerant1 Gain recuperation with pumping

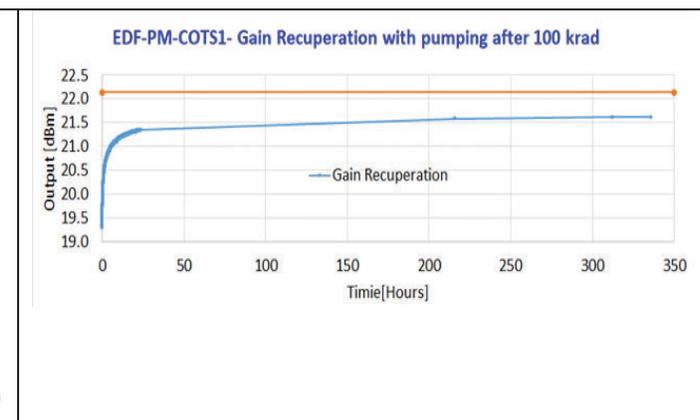


Figure 6: Commercial EDF-PM-COTS1 special core Gain recuperation by photo-bleaching

The estimation of radiation received on the components is deduced from the ESA’s operational software “The Space Environment Information System (SPENVIS)”, combined with a Monte Carlo ray-tracing code that considers the attenuation caused by the detailed materials inside the EDFA enclosure box. Figure 7 presents the Total Ionization Dose (TID) and their attenuation by Aluminium spheres with various thicknesses, as calculated by Spenvis for various orbits; it shows also the TID inside the payload considering the attenuation by the enclosure.

Figure 8 illustrates the rays traced by Monte Carlo code ray tracing to find the TID received on the Fiber enrolled on the spool. Combined with the Spenvis the code calculates the final amount received by the different portions of the fiber. The estimation from the two codes shows the fiber would receive between 10 and 30 krad during the satellite lifetime.

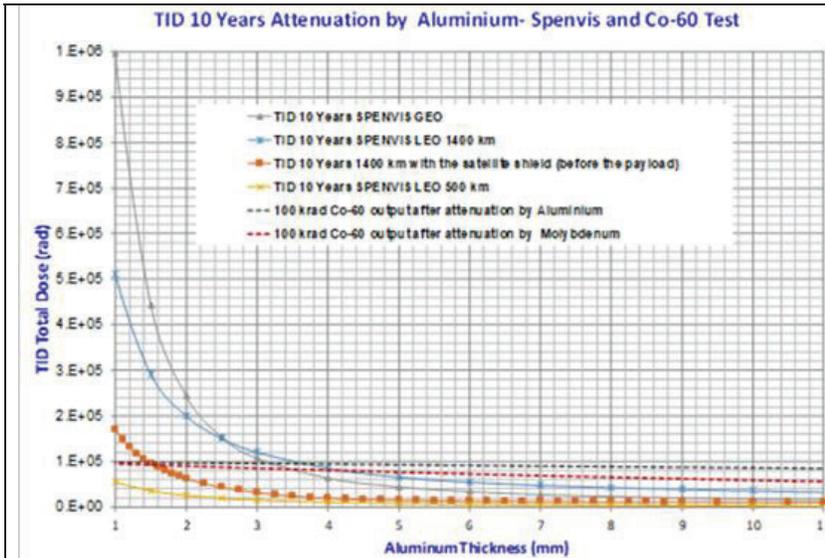


Figure 7: Amount of Total Ionization Dose (TID) radiation predicted by Spenvis code, for different orbits and the radiation attenuation by the different thicknesses of the Aluminium shield.

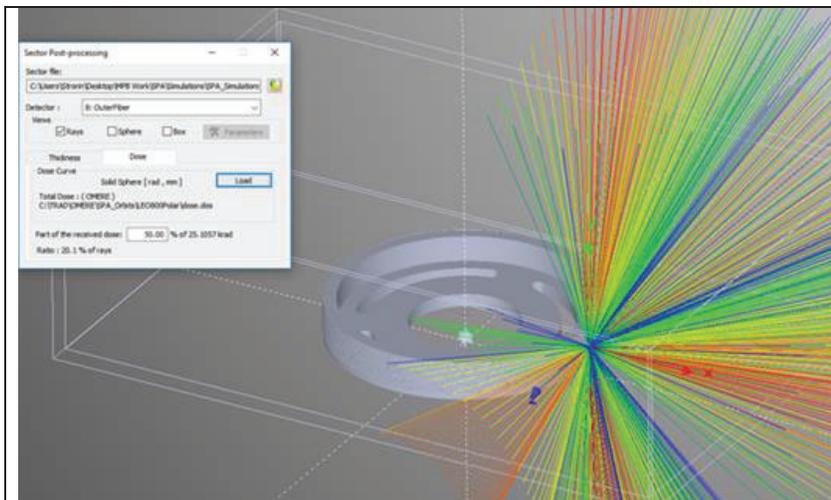


Figure 8: Amount Schematic showing the Monte Carlo Ray Tracing with Radiation Code to estimate the attenuation at detailed locations

4. MODULE COMPONENTS VALIDATION (40 DBM EOL)

More emphasis was given to the Laser diodes, the Isolators, and combiners the two potential components to be affected by thermal vacuum cycling (TVAC). The laser diodes have a limited temperature range due to the high power required from them and the isolators may change due to evaporation of some epoxy used to fix its part in particular at relatively high temperature in vacuum The TVAC test was performed at MPB in a small vacuum Chamber

- For the laser diodes pumps, the output power was measured for different electrical input current before and after the tests, and the results were compared with the original calibration line
- For the photodiodes, the output current was measured vs input optical power at different levels

- For the Isolators, and combiners the Insertion Loss and the transmitted power were measured at different conditions
 - For many passive components, the insertion loss was measured before and after the tests.
 The isolators and the laser diode pumps of the second stage were cycled within the temperatures [-30°C to +60°C] in active form, with the nominal electric current applied to them. The third stage isolators were tested from -40°C to +60°C in active form, and the laser diodes from -15°C to +40°C due to the limitation set by the supplier. These diodes were the best ones available commercially, the supplier did not reply to our request on what happens when the temperature goes outside this range. The Insertion Loss and the Isolation of Isolators stayed the same. The laser diode changed slightly.

Figure 9 to Figure 12 gives examples of the radiation and TVAC effects on some representative components.

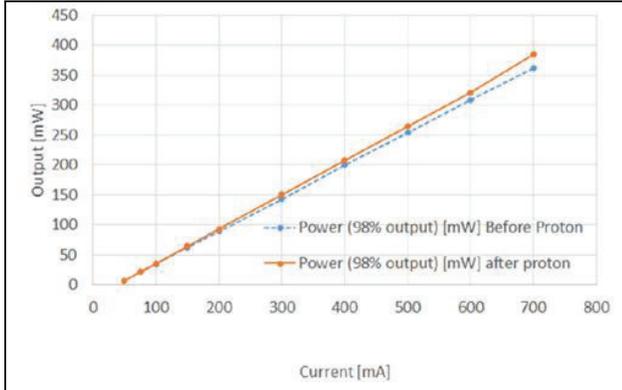


Figure 9: First Stage Laser Diode Response to current before and after $2 \times 10^{11}/\text{cm}^2$ protons (20 MeV) It was tested for 100 krad gamma radiation during a previous contract. Its response stayed the same

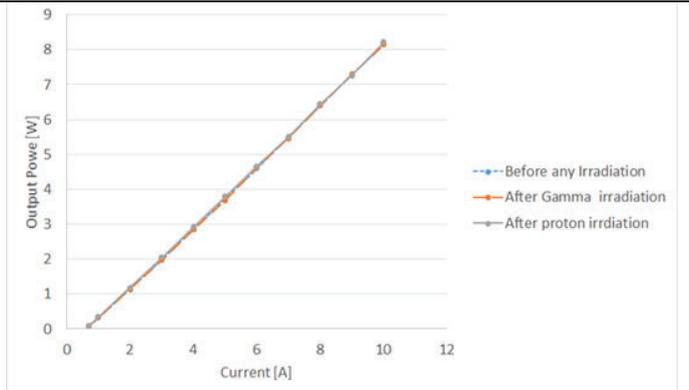


Figure 10: Second-stage Multi-Mode Laser Diode Response to current before, after 100 krad (gamma) and after $2 \times 10^{11}/\text{cm}^2$ protons (20 MeV)

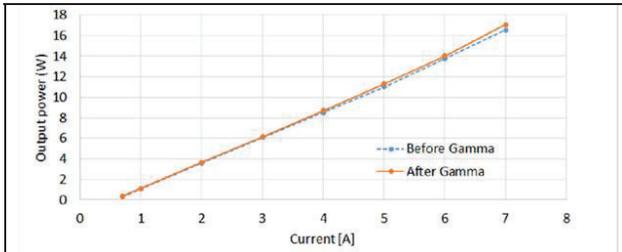


Figure 11: Third-stage Laser Diode Response to current before and after 100 krad (gamma) radiation

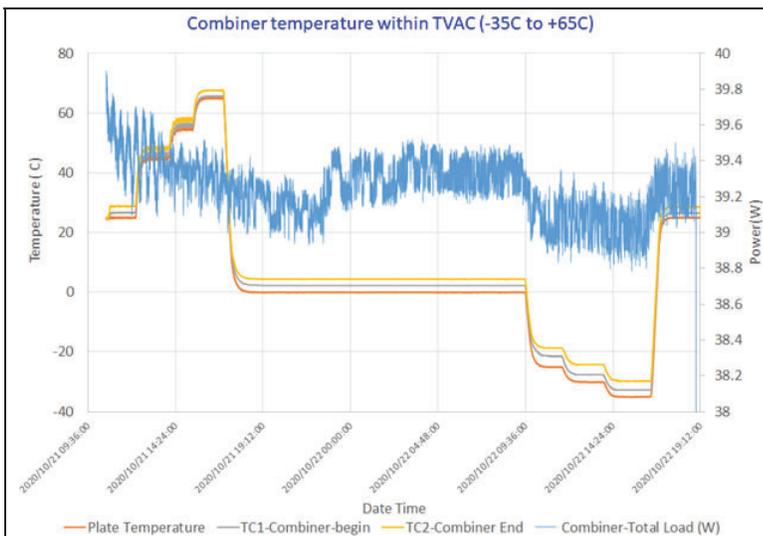


Figure 12: Temperature Evolution of the third stage (1+2x1) PM combiner, and total power loaded, when the vacuum chamber temperature is changed between -35°C and +65°C

Figure 13 shows the temperature of the isolator at its input and output when transmitting 10W output optical power as in the prototype

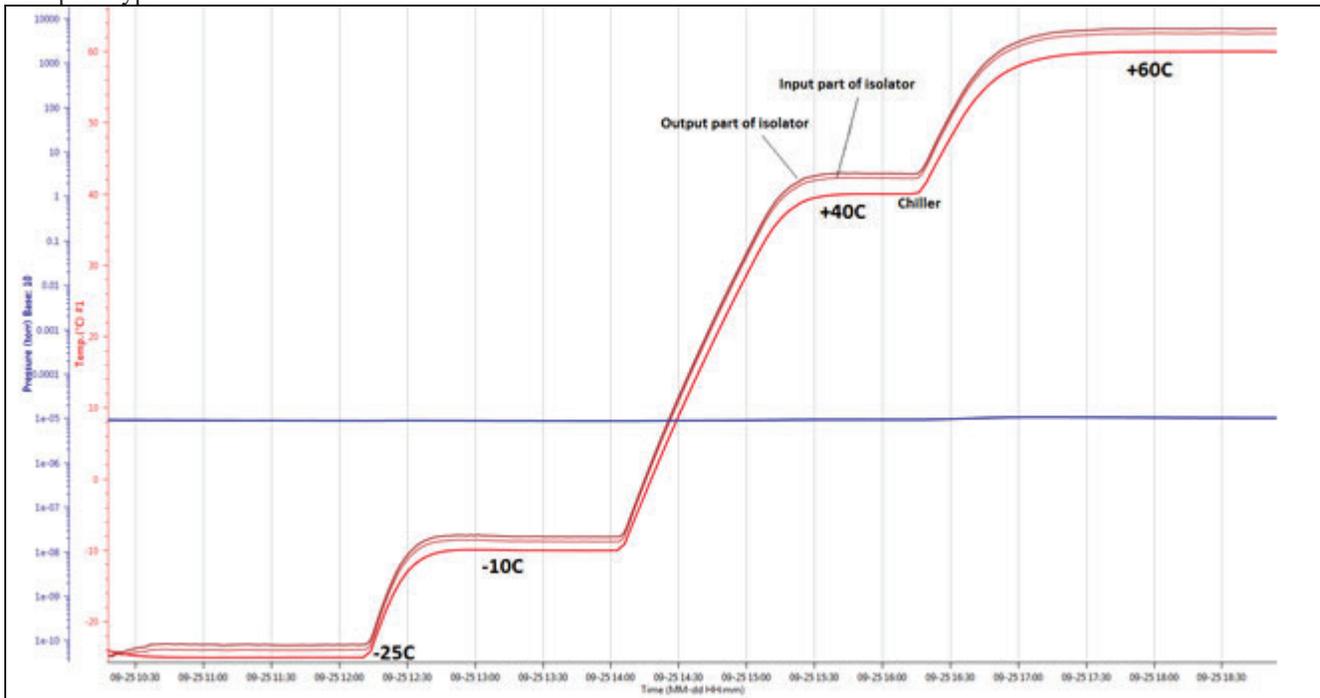


Figure 13: Temperature Evolution of the isolator in vacuum when it transmits 10W signal power for temperatures of +25°C, +45°C and, +60C.

5. OPTICAL AMPLIFIER MODULE PROTOTYPING

Figure 14 shows the wall-plug power conversion efficiency Figure 15 presents the power consumption in the prototype amplifier in term of different parts contribution after design improvement, and Figure 16 compares the improvement of the output power of the 10W PM-EDFA (Dec2019, Feb2020, And Mar2020) in vacuum at 10°C

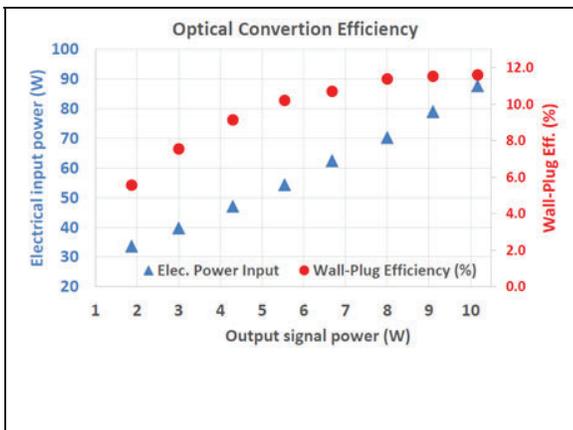


Figure 14: Wall-plug Power conversion efficiency of the (1552nm) output power. Blue points are electrical input and red points are wall-plug efficiency.

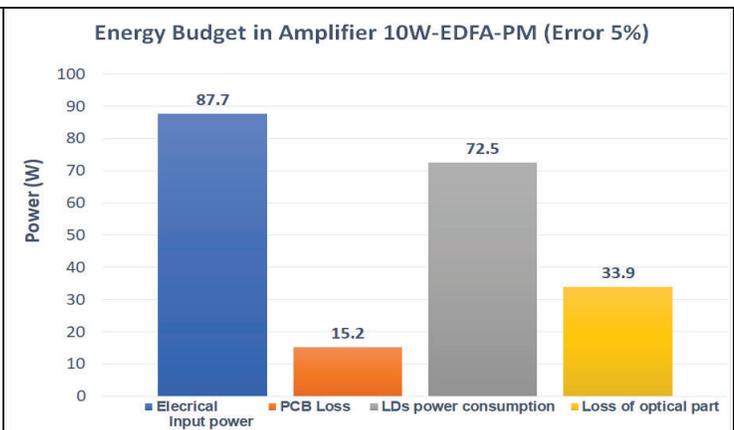


Figure 15: Power consumption in the 10WEDFA-PM amplifier in term of different parts contribution after design improvement

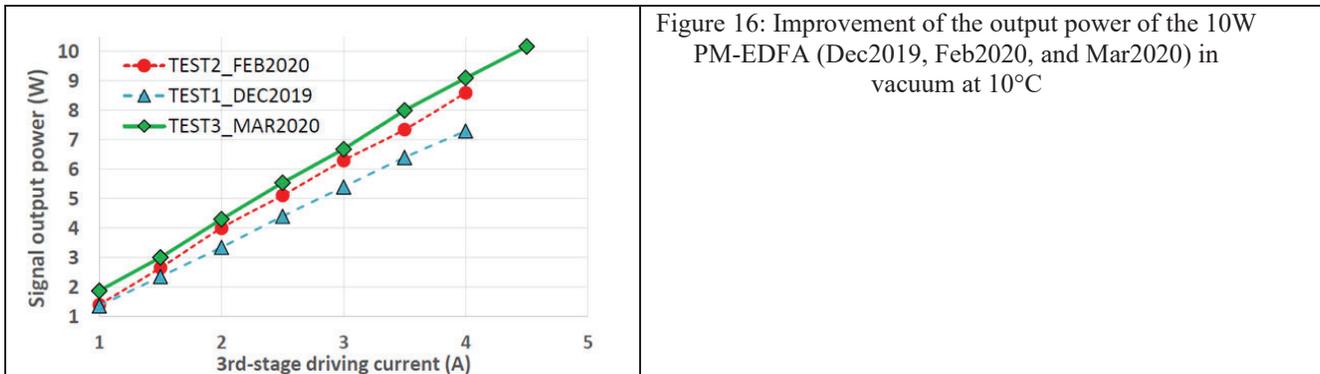


Figure 16: Improvement of the output power of the 10W PM-EDFA (Dec2019, Feb2020, and Mar2020) in vacuum at 10°C

Table 2 summarizes the first estimation of the power needed and the plug efficiency. These values were later improved during the prototype development

Table 2: Experimental Efficiency 10 W-PM and 10W non-PM

	Loss Power (W)	Loss Power (W)	Last (2020)	Loss Power (W)	Initial (2019)
Nominal output Power(W)	-	-	10.4	-	10.4
Er:Yb-doped fiber efficiency	25	-	32%	35	27%
Combiner efficiency signal	0.07	-	93%	0.1	88%
Combiner pump transmission	1.5	-	95%	2.6	93%
Isolator efficiency	1	-	89%	1.5	85%
Laser Diode Pump power	35.5	-	51.5%	45	51.5%
Driver and control board efficiency	15	-	83%	19	83%
Total electrical power needed(W)	-	-	87	-	112
Total Loss (W)	77	-	89.6%	101.5	91%
Wall-plug efficiency	-	-	11.4 %	-	9%

Figure 17 shows the evolution of the output power (at1552nm) after the third stage amplification in vacuum

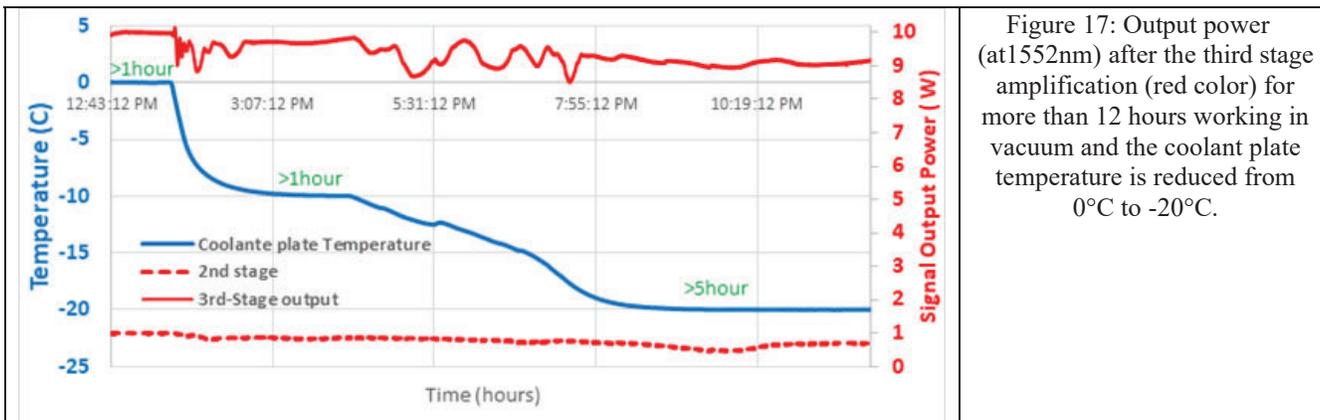


Figure 17: Output power (at1552nm) after the third stage amplification (red color) for more than 12 hours working in vacuum and the coolant plate temperature is reduced from 0°C to -20°C.

As long as the temperature of the chiller is constant, the amplifier output power is stable. It shows some instability when the chiller temperature is changed. The reason is the polarization of the transmitted light in the fiber optic line, including gain fiber and components, is sensitive to temperature change, due to the temperature dependency of PM fiber birefringence.

Figure 18 shows the optical and electrical parts temperature track of the unit under test (UUT) when the coolant plate is changed from 0°C to +40°C inside vacuum.

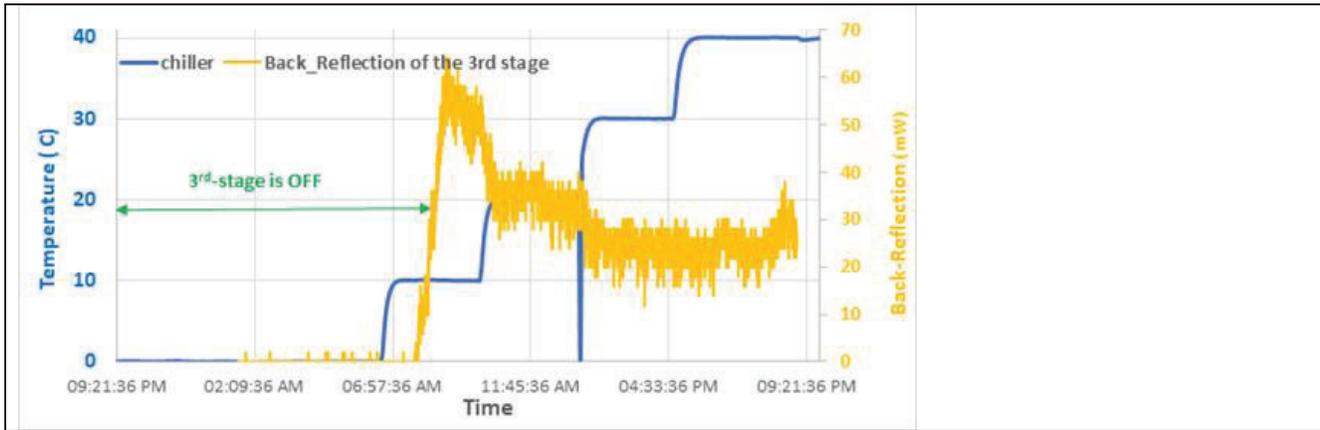


Figure 18: Back-Reflection light from 3rd-stage when the output power of the signal is 10W in vacuum and the coolant plate temperature is 10°C, 20°C, 30°C, 40°C

We compared two spools the first is the Aluminum commonly used spool and the other is an Innovative Proprietary Method (IPM) proposed by MPB. Also, MPB is using in both cases a highly Thermal Conductive Interface Layer (TCIL) that improves in all cases the thermal conductivity by keeping the active fiber attached to the spool.

Preliminary results are shown in

Table 3. The experiment is still ongoing

Table 3: Comparison of the thermal performance of Aluminum and an Innovative Proprietary Method (IPM) spools (Advantages in blue, Disadvantages in red)

Parameter	Al Spool	IPM Spool
Required Low Temperature (-35°C)	<p>At low temperature: Detachment of the EYDF 3rd stage (Difference in CTE) – No dissipation of the EYDF heat</p> <p>Adding a thermal conducting interface layer covering the fiber could keep the active fiber in contact with the spool</p> <p>Lowest Temperature Reached (-25°C, at 8.5 W output)</p>	<p>3rd stage fiber stays connected to the spool</p> <p>No Detachment IPM and EYDF have relatively close CTE</p> <p>Adding thermal conducting interface layer improves the heat dissipation</p> <p>Lowest Temperature Reached (-25°C, at 9.5 W output)</p>
Required High Temperature (65°C)	<p>At high temperature, the Al spool expands much more than the EYDF leading to over-tension applied on the EYDF and risk of its breaking</p> <p>Adding a thermal conducting interface layer permits the enrolling of the active fibers without tension at Room Temperature</p> <p>Highest Temperature Reached (+40 °C, at 10W output)</p>	<p>At High temperature, the IPM and EYDF expand similarly without over tension on the EYDF</p> <p>Adding the selected interface layer improves the heat dissipation</p> <p>Highest Temperature Reached (+40 °C, at 10W output)</p>

	(+50 °C, at 10W output)	
Heat Dissipation	Larger Thermal conductivity Add inner Al structure with more contact with the Al bottom box surface and inner wall of the Al spool	Lower heat conductivity, less heat dissipation Add inner Al spool with its base in larger area contact with bottom A surface, and Part of its wall in contact and pushing as strings on the IPM inner wall

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