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1550 nm combined transmission booster amplifier and receiver preamplifier for satellite to satellite laser communication

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ABSTRACT

Satellite-to-satellite laser communication technology underpins high-speed l0-Gbps optical links for the new generation of satellite constellations that will serve as global telecommunications networks. LEO satellite-to-satellite links may extend over distances of >5000 km, necessitating an optical-power budget of ~70 dB to compensate for diffraction-limited optical-beam divergence. This can be achieved by boosting the transmitted laser diode signal to around 1 W, and by amplifying the received signal by 40 dB. Such performances are attained by terrestrial fiber amplifiers, operating in the telecom 1550-nm wavelength window, which are produced in volume of thousands and are (in relative terms) of low cost. Based on MPBC's large volume production experience of fiber amplifiers and its heritage of space system design and manufacturing, a new product line of Laser Communication Terminals (LCTs) for space is presented. It is designed to be lower cost, exploiting commercial off-the-shelf (COTS) components whenever possible. Most of these fiber-optic components are extensively employed in large terrestrial telecom equipment and are already qualified to telecommunications standards. However, additional tests are required to ensure reliable long-term operation in a space environment. We have subjected the components, both active and passive, to gamma- and proton-radiation tests including total ionization doses of up to 100 kRad, Temperature vacuum cycling over extended temperature range have been performed and are still ongoing. Finally, considering manufacturing costs, we are packaging both the transmission optical booster unit and receiver optical amplification unit in the same housing, in order to co-locate both the transmit and receive functions of the link. These units are compact and stackable and save on the enclosure weight.

Keywords: 1550 nm optical fiber amplifiers, laser communications, 10 Gbits satellite-to-satellite laser links, COTS for space, space component qualification, fiber optic module, integrated booster and preamp fiber optic unit, low cost space technology

1. INTRODUCTION

Satellite-to-satellite laser communication[1] will enable multi gigabit data transfers in space that will surpass present microwave systems. With these high-speed links, new satellite constellations will become global telecommunications networks. LEO satellite-to-satellite links may extend over distances of more than 5000 km, necessitating an optical-power budget of ~70 dB to compensate for diffraction-limited optical-beam divergence. This can be done by boosting the transmitted laser diode signal to around 1 W, and by amplifying the received signal by 40 dB. Such performances are achieved by terrestrial fiber amplifiers, operating in the telecom 1550-nm wavelength window, which are produced in large volume and at relatively low cost. However, they are not space qualified.

Space technology is usually more expensive, on account of the more rigorous tests and controlled-environment manufacturing environment and because, until recently, the number of satellites is traditionally small (often one), thus preventing economies of scale. This is changing with the proposed new constellations for which hundreds, and even more than 1000 satellites, will be launched, each often comprising four laser communications terminals (LCT). Low-cost LCT are now required as satellite constellation providers seek more affordable solutions for their very large constellations.

Based on MPBC's extensive production experience with fiber amplifiers and its history of space system design and manufacturing, the Company has proposed and begun development on a new line of lower-cost space-borne LCT terminals. We designed a package to hold both the transmission optical booster unit and receiver optical pre-amplification unit, because all links need both a powerful transmitter and a sensitive receiver. These units are compact and stackable. This allows weight savings and provides superior radiation shielding. This design also helps the control costs in assembly and testing. To improve reliability, all active components are redundant. They are built using of commercial off-the-shelf (COTS) components whenever possible. The fiber optic components used in large volume for our terrestrial amplifiers are already qualified to telecommunications standards. However, additional tests are required for operation in a space environment. We have subjected the components, both active and passive, to Gamma and proton radiation testing, to total ionization doses of up to 100 krad, which can be accumulated over 15 years is space. We are also performing temperature vacuum cycling over extended ranges of temperatures, i.e., -25 to 70 ◦C, to understand the behavior of the COTS components. Finally, they must be tested to more severe vibration and shock tests. We can thus select COTS that will work in our space applications. Accordingly, the amplifier is designed with power in reserve to compensate any anticipated degradation over the lifetime (5 to 15 years) of operation.

2. OBJECTIVES

The large constellations, with their hundreds of identical satellites, are a game changer for the production of space hardware. The new onboard systems must still be reliable and able to survive years in the space environment, but they must also be produced in large volume over periods of months or years. This becomes very similar to the production of high-quality terrestrial systems, which achieve lower cost because of volume. In order to produce large volumes of satellite subsystems, one must not only consider the design for space, but also the lowering the cost coming from the manufacturing processes and the supply chain. Therefore, to address the 10 Gbits LCT application, the baseline design was based on terrestrial amplifiers that are produced in volume but with these additional space related requirements.

- The fiber amplifiers are based on the 1550-nm ("C-band") wavelength window

  Due to the ubiquitous deployment of Erbium (Er)- or Erbium-Ytterbium (ErYb)-doped amplifiers in terrestrial networks, the underlying technology is well developed.

- Use of COTS components

  The COTS components used in terrestrial systems already exhibit a high level of reliability and are tested to Telcordia standards, but the space operational conditions are often more severe. Consequently, additional testing must thus be performed on the COTS devices. Such testing includes extended temperature range, gamma and radiation exposure, vacuum exposure and shock and vibration. For traceability, the testing must be performed per manufacturing lot. It would be preferable to produce all the satellite subsystems from the same lot, but it is unrealistic the expect that to be the case, especially if production extends over several years and when the total number of satellites to be ultimately deployed is unknown. Therefore, qualification must be done repeated on each different lot of manufactured components.

- Redundancy of critical active parts and de-rating

  Laser diodes are the parts most likely to fail. Redundancy is thus essential to ensure the long-term reliability of the systems. Furthermore, the design normally limits their use to less than half of their power rating, thereby also improving reliability and extending their life. As well, it is important that photodiodes for monitoring the signals (or other system parameters) must provide reliable information throughout the LCT lifetime. Finally, electronics can be affected by radiation, and hence redundancy will help maintain the system robust to, and able to recover from, isolated events.

- Single unit for Transmission Booster and Receiving Pre-amplifier

  Redundancy improves reliability, but it also increases the number of parts. The subsystems will therefore be larger. In order to reduce the weight, the booster and preamp are package in the same unit. The saving of material by eliminating a wall of an enclosure may in turn be used to improve the shielding from radiation. The detail design actually calls for two "half units", one containing the preamp and the other containing the booster, that are joined together during final integration. This simplifies the manufacturability and thus the cost of the unit, both for assembly and test.

- Passive thermal control

  Passive thermal control allows simplification of the system, but it does put more stress on the component performances, some of which will need to operate below or above their usual temperature range. The qualification is essential in evaluating their performance and predict the power consumption needs of the system.

- Qualification and end-of-life margin

  The qualification of the COTS components will enable the determination of the loss of performance the targeted space environment. This is especially true for gain fibers that undergo degradation due to gamma irradiation. The LCT design thus must have sufficient backup power to compensate with this loss of performance

The design and testing will be detailed in the following sections.

3. UNIT DESIGN

3.1 Pre-amplifier optical design

The pre-amplifier is a two-stage design as shown in the figure below

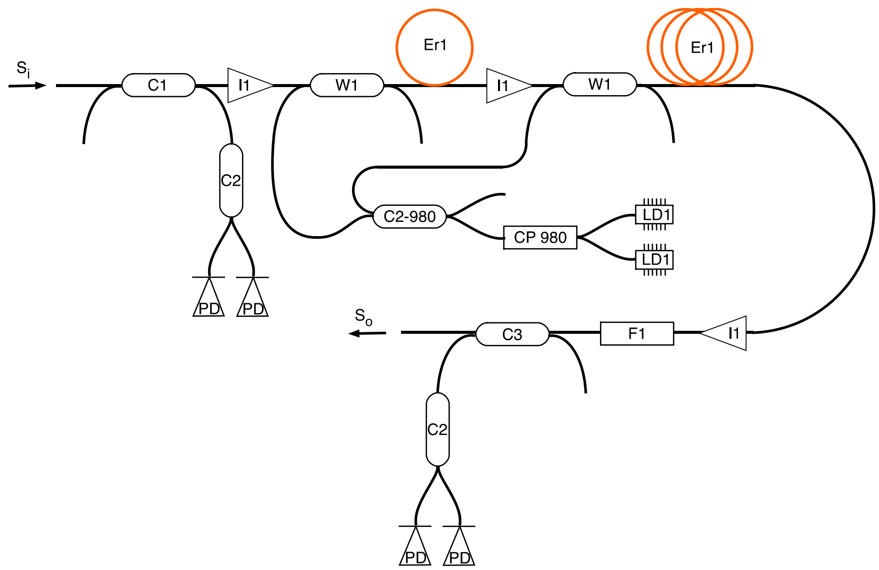


Figure 1: Schematic of the fiber pre-amplifier

The first stage is a low-noise high-gain amplifier optimized for amplification of very weak signals (in the range of -40 dBm). The second-stage booster the signal to 1 dBm. The laser diodes are 400 mW single-mode 980-nm pump lasers that are normally limited to operate at half their power rating. In this schematic, the pump power is shared between the two stages, but each stage could have its own separate lower-power pumps. The preamp has an input signal monitor to detect the presence of an incoming signal, and, if yes, to indicate to the control electronics to “turn on” the preamp. It also has an output power monitor, so the gain may be adjusted. Depending on customer requirements, this schematic can be modified. An example would be the elimination of the input power monitor if the satellite can supply to the preamp a receiving signal command.

Part	Description	Function
C1	2x2 90%/10% tap fused fiber coupler	Tap 10% of input power for monitoring
C2	2x2 50%/50% fused fiber coupler	To provide redundant signal to photodiodes
PD	Photodiode	To monitor signal
I1	Isolator	To prevent amplified stimulated emission (ASE) or back reflection propagating in the system
W1	2x2 980/1550 nm fused fiber coupler WDM	To combine laser pump power to signal at the input of the gain fiber
LD1	980 nm grating stabilized pump laser diode	To pump the gain fiber
CP 980	Polarization combiner at 980 nm	To combine the 2 redundant pumps
C2-908	2 x2 fused fiber coupler	To split the pump power to the 2 gain stages
ER1	Single-mode Erbium-doped fiber	Gain fiber
F1	100 GHz thin film filter	To filter out ASE
C3	2x2 98%/2% tap fused fiber coupler	Tap 2% of input power for monitoring

Table 1: Parts list for pre-amplifier

Description	Units	SPA-CR40
Operating Spectral Range	nm	1536 - 1565
Input Dynamic Range	dBm	-45 - -35
Small Signal Gain	dB	> 40
Noise Figure	dB	< 5
Operating mode		ACC, APC
Operating temperature	˚C	-25 to +70
Storage temperature	˚C	-40 to +85
Fiber (Input and Output)		ITU G.652 (e.g., SMF-28)
Fiber Length	m	1

Table 2: Pre-amplifier operation specifications

3.2 Booster optical design

The booster is a two-stage design as shown in Figure 2.

The first stage is a single-mode amplifier to amplify the modulated signal (typically a few milliwatts) from the source laser. The pump lasers are 400-mW single-mode 980-nm laser diodes that are operated at half their power rating. The second-stage booster amplifies the signal to ~30 dBm. It is pumped by 10-W multimode pump laser diodes at 940 nm, use at a maximum of half their power rating. The booster has an input signal monitor to determine if a signal is coming in and turn on the amplifier. It also has an output power monitor, so the gain can be adjusted. Depending on customer requirements, this schematic can be modified. An example would be the elimination of the input power monitor if the satellite can supply to the booster a receiving signal command.

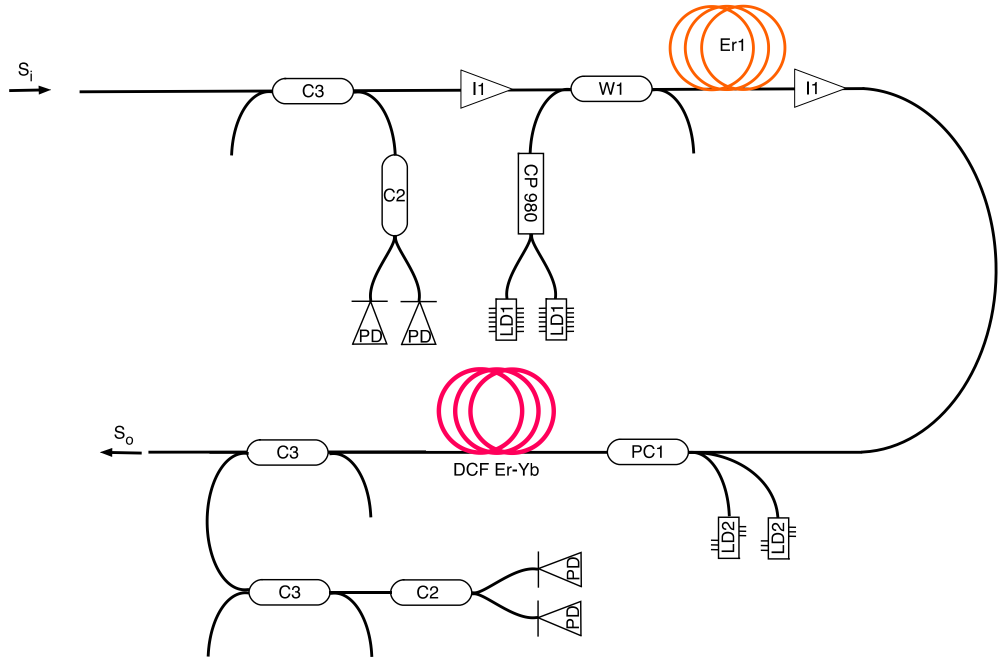


Figure 2: Schematic of the fiber booster amplifier

Part	Description	Function
C3	2x2 98%/2% tap fused fiber coupler	Tap 2% of input power for monitoring. In the last stage, also used to attenuate the signal to the monitoring photodiodes
C2	2x2 50%/50% fused fiber coupler	To provide redundant signal to photodiodes
PD	Photodiode	To monitor signal
I1	Isolator	To prevent amplified stimulated emission (ASE) or back reflection propagating in the system
W1	2x2 980/1550 nm fused fiber coupler WDM	To combine laser pump power to signal at the input of the gain fiber
LD1	980 nm grating stabilized pump laser diode	To pump the gain fiber
CP 980	Polarization combiner at 980 nm	To combine the 2 redundant pumps
ER1	Single-mode Erbium-doped fiber	Gain fiber
PC1	(2+1) x 1 pump combiner	To combine the multimode laser pump power to signal at the input of the gain fiber
DCF Er-Yb	Double-clad Erbium-doped fiber (DCF)	High power gain fiber
LD2	940 nm multimode pump laser diode	To pump the DCF gain fiber

Table 3: Parts list for booster amplifier

Description	Units	SPA-CT30
Operating Spectral Range	nm	1536 - 1565
Input Dynamic Range	dBm	-5 - +5
Saturated output power	dBm	30
Noise Figure	dB	< 10*
Operating mode		ACC, APC
Operating temperature	˚C	-25 to +70
Storage temperature	˚C	-40 to +85
Fiber (Input and Output)		SMF-28
Fiber Length	m	1

Table 4: Booster operation specifications

*(It should be appreciated that, when used for transmission of digital optical signals, the specified noise figure (NF) above is not particularly meaningful, since the shot noise comprising the noise figure is also attenuated by the same link-loss value as the signal level. This is generally true for all optical power amplifiers.)

3.3 Mechanical design

The single unit box is the assembly of two halves made of aluminum. One of the halves contains the booster and the other the preamp. They are both joined together to form the unit, as illustrated in Figure 3.

As illustrated in Figure 4 (a), the larger side of the booster box is used as the optical tray. All the passive optical components are mounted in that space. There are two angled protected fiber outputs, one for the input signal and the other for the output signal. It also includes a spool for the DCF gain fiber. The pumps are mounted on the smaller side. They are connected via an electronics board that also includes the photodiodes, but they are directly thermally interfaced to the side. Once the unit is assembled, this small side actually becomes the bottom of the unit and is the heatsink surface, thus enabling he high-power pumps to be directly and passively cooled. On top of the fiber spool, an aluminum shield is put in place. The shield helps control the radiation exposure for the most sensitive component, which is the gain fiber. We have simulated the exposure of the gain fibers and with a proper choice of the shield and enclosure thickness, we can limit the total radiation dose to under 20 krads for the operational lifetime of the system. The shield also serves as support and heat sink to the controller electronics board.

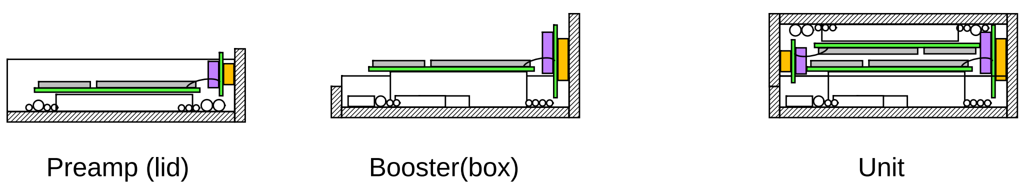
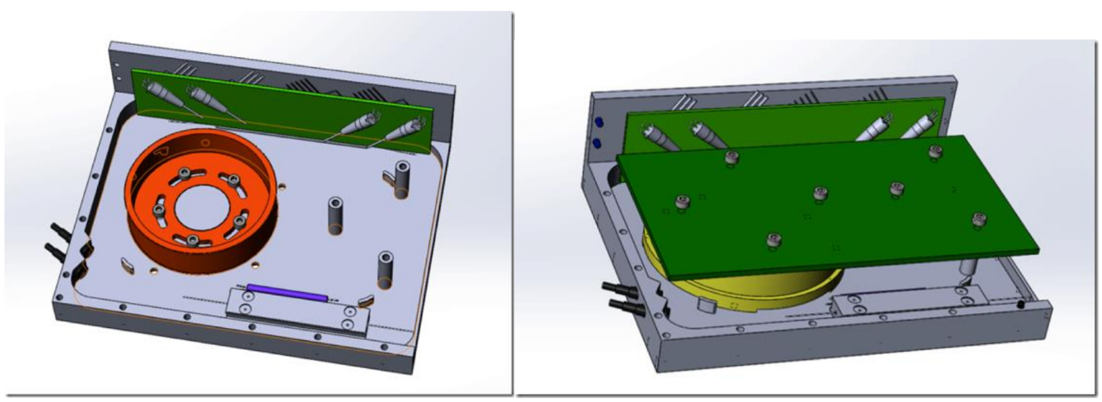


Figure 3



(a) (b)

Figure 4: Booster box with (a) fiber spool and pump and photodiode board and (b) with fiber shield and controller board

The design concept is also applied to the preamp lid portion of the unit. The large side serves as the optical tray and the small side is for mounting the pump and photodiode board. The pumps are again directly thermally coupled to the side, but the heat dissipation is much smaller than for the high-power pump. The heat is dissipated through the lid and conducted through the booster box to the heat sink.

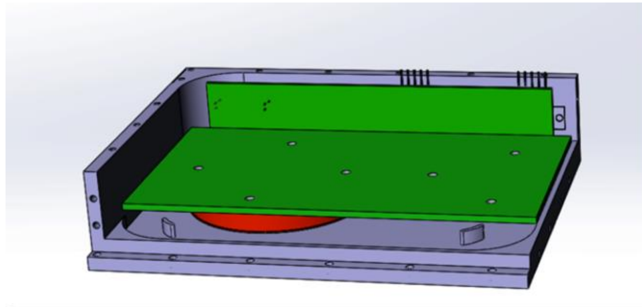


Figure 5: Preamp lid

The two halves are optically and electronically independent, so they can both be assembled and tested separately. When they are assembled, a back panel is added to complete the enclosure and provide the back support for the electrical connector, as shown in Fig 6. The fiber outputs are in the front of the unit, the heat sink surface is at the bottom. The unit dimensions are 160 mm x 120 mm x 50 mm. Additional features can be added to the unit so that it can be mounted to a frame in the satellite. Depending on the shielding required, the weight of the unit is typically between 800 g and 1000 g.

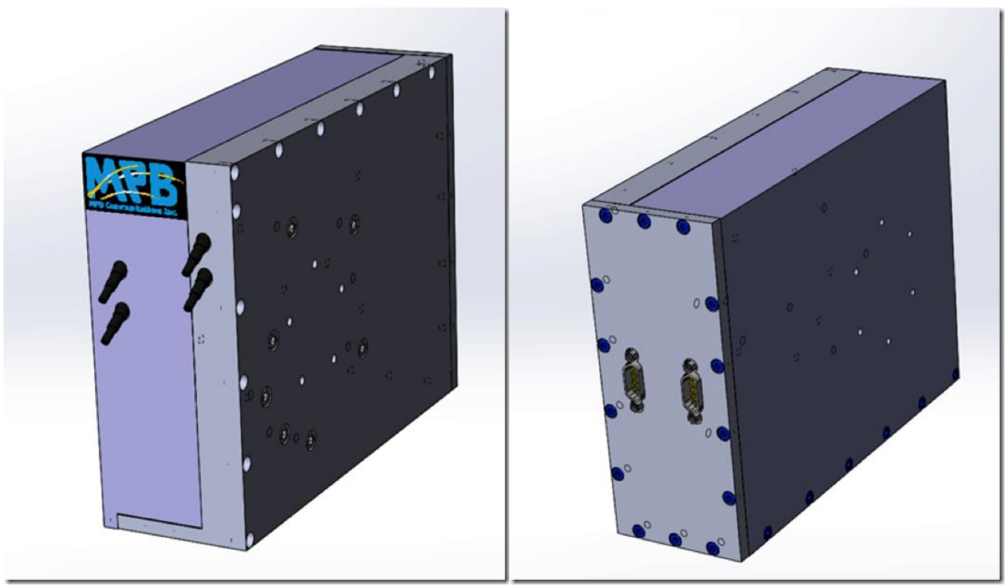


Figure 6: Assembled preamp and booster unit

Figure 7: Prototype unit, 160 mm x 120 mm x 50 mm.

3.4 Electronics design

The electronics design includes two electronics boards for each half of the unit. Each half includes a pump and photodiode board 133 mm x 33 mm. It can hold up to 4 high power multimode pump laser diodes, 2 single-mode 980 nm pump laser diodes, and 4 photodiodes. The board details depend on the selected pumps. This board provides wiring to the different opto-electronic component pins but does not have any other function. The control is effected through the primary larger board, illustrated in Figure 8.

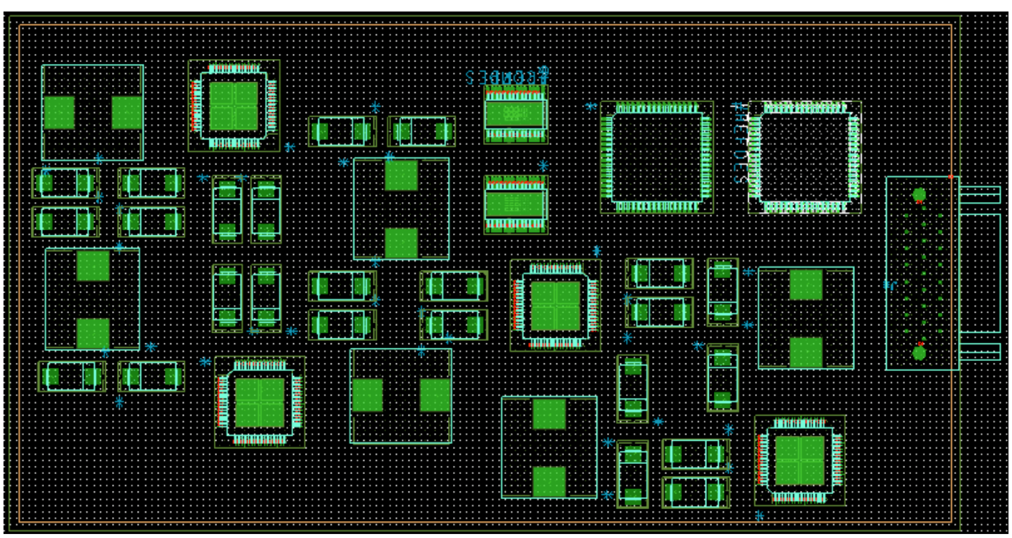


Figure 8: controller electronics board

This board support laser driver for each redundant pump diodes, 2 redundant CPUs for control and a 25 Pin MIL-DTL-83513 connector. The connector can be changed depending on customer requirement. Its dimensions are 148 mm x 80 mm.

For cost reduction and production purposes, both the preamp and the booster use the same electronic boards. The only difference is that the preamp boards are not fully populated as it requires fewer elements. The serial interface can be LVTTL, RS 232 or RS-485 (preferred) depending on customer requirements.

4. QUALIFICATION TESTING

For the space environment and reliability, testing is essential. Though we use COTS components that have been fully tested for terrestrial applications, extra tests have to performed, both for qualification and quality assurance. We summarize these in this section

4.1 Qualification test plan

The additional test that we implemented for the space product qualification are summarized in Table 5.

Test	Description	Parameters	Duration	Purpose	Critical for
Gamma radiation	Expose components to Gamma radiation	Up to 100 krad TID	14 days	Measure degradation of performance due to change in material or packaging	Gain fiber (gain loss) Photodiodes Pump lasers Electronics
Proton radiation	Expose components to high energy protons	20.5 Mev 1.5 10e11 p/cm^2 47 krad	30 min.	Measure degradation of performance due to change in material or packaging	Photodiodes Pump lasers Electronics
TVAC Hi-Low	Cycle in vacuum chamber at the extreme temperature range	-40 ˚C to + 70 ˚C, 10^{-6} torr 8 cycles	2 days	Measure optical performance over temperature range Root out packaging issues (i.e., bubbles in expoxies causing stress on fibers)	All components except fibers Units
TVAC cycling	Long term cycling	-25˚C to + 70˚C 10^{-6} torr 500 cycles	35 days	Test reliability of pump lasers at full power Test long-term stability of passive component (measured before and after) Root out packaging issues	Pump lasers Units
TVAC High temperature	Long term high temperature	+70˚C 10^{-6} torr	2000 hours (84 days)	Test reliability of pump lasers at full power Test long term stability of passive component (measured before and after)	Pump Lasers
Vibration resonance search	Determine resonance frequencies	5-2000 hz, 0.5 g, 2 oct./min., all axes	<4 hours	Units must not have resonance frequencies which would increase strain on components	Units
Random Vibration	Submit unit to random vibration	20-1000 g 0.01-0.1 g^2/Hz	<4 hours	Root out assembly or bonding points issues for components in the units	Units
Sine vibration	Submit unit to random vibration	5-100 hz, 25g	<4 hours	Root out assembly or bonding points issues for components in the units	Units
Shock test	Submit unit to impacts	100 to 10000 hz, 50 -2000 g	<1 hour	Root out assembly or bonding points issues for components in the units and component reliability	Units

Table 5: Test plan

4.2 Radiation test

We have performed radiation testing on gain fiber, passive fiber component and the optoelectronics components. The results are qualitatively summarized in the following table.

Components	**Type of degradation**	**Severity**
Gain fiber[3]	Pump and signal loss Decrease in gain efficiency	High to moderate Observe more than 20 dB on some fibers Mitigation by selecting better performers 1 to 3 dB loss and shielding to reduce dose Partial mitigation of loss using photobleaching
Pump laser diodes	Loss in power	Very low, negligible effect
Photodiodes	Increase in dark current	Large increase but overall remains very small (pA to nA)
Thin-film filters	Increase in insertion loss	Very low, negligible effect
Fused couplers	Increase in insertion loss	Very low, negligible effect
Isolators	Increase in insertion loss	Very low, negligible effect

Table 6: Gamma radiation testing

We also performed high energy proton exposure and have not measured any performance degradation of the optical and optoelectronic parts. The problem is with electronics and especially isolated single events, perturbing the electronic data. This is mitigated by the redundancy of the electronics and robust firmware coding.

4.3 Temperature in vacuum test (TVAC)

We have performed thermal vacuum testing on relevant passive fiber component and the optoelectronics components. The results are qualitatively summarized in the following table.

Components	Type of degradation	Severity
Gain fiber	Decrease in gain efficiency	Low. The change in efficiency can easily be compensated by adjusting the pump power
Pump laser diodes	Loss in power	Very low, negligible effect in the short term. Long term tests to be performed
Photodiodes	Increase in dark current, low on sensitivity	Very low, can be calibrated
Thin-film filters	Increase in insertion loss	Very low, negligible effect
Fused couplers	Increase in insertion loss, change in coupling ratio	Small, 0.1 to 0.2 dB
Isolators	Increase in insertion loss, loss in isolation	Medium to large, increase in insertion loss to 1dB, larger is some cases, isolation can drop below 18 dB. Mitigation by selection, better-designed and more-stable components.

Table 7: Thermal vacuum testing

4.4 Production and quality assurance testing

Both amplifiers are tested during assembly. They are functional at room temperature before the unit assembly. However, once the two halves are integrated, an additional TVAC hi-low test is performed and the unit is characterized over the temperature range. This will root out assembly problems and provide calibration data for the system.

5. CONCLUSION

We have design a 1550 nm LCT amplifier unit that integrates both the preamp and the booster amplifier into a single enclosure weighing less than 1 kg. COTS components are used after being qualified in radiation and TVAC testing. When properly selected, they show little degradation in performance at the extreme of the temperature range and the system can accommodate the reduce efficiency with its power margin. The unit has also been optimized for volume manufacturing.

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