

ENABLING NEXT-GENERATION OPTICAL SATELLITE COMMUNICATIONS WITH HIGH-PERFORMANCE AMPLIFIERS

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ABSTRACT

Optical satellite networks require compact, efficient, and reliable amplifiers capable of maintaining high optical performance throughout launch and long-duration operation in space. This paper presents the design and qualification of MPB Communications' Pulsar Optical Amplifier Unit (OAU) for low-Earth-orbit satellite constellations. The unit integrates an 8W Booster, a low-noise amplifier (LNA), and radiation-tolerant control and power electronics within a single enclosure. The Booster delivers more than 5 W of output power across the full in-orbit operating range while maintaining greater than 50% pump-current derating and efficiently suppresses amplified spontaneous emission (ASE). The LNA provides received-signal-strength monitoring down to -53 dBm and provides over 40 dB of gain. CAN-based, model-driven firmware provides precise power regulation, synchronized telemetry and event logging, fault protection, and fail-safe in-orbit updates. Qualification included EMC/EMI, vibration, shock and thermal-vacuum testing, as well as 30,000 cold switch-on cycles at -30 °C, and gamma irradiation to 31 krad. These results support the suitability of the Pulsar architecture for 10-year LEO missions. The paper also presents ongoing developments of a compact 2 W OPA for CubeSat and SmallSat terminals and a radiation-hardened 20 W Pulsar OAU for long-duration Medium-Earth Orbit (MEO) and Geostationary Earth Orbit (GEO) applications, demonstrating a scalable amplification platform for emerging multi-orbit optical networks.

Keywords: Free-space optical communication, Laser Communication Terminal, High-Power Optical Amplifier, Fiber Optics, Satellite Communication

1. INTRODUCTION

Optical satellite communications have advanced rapidly over the past decade and are becoming a fundamental element of space-based communication networks. Low-Earth-orbit (LEO) satellites equipped with optical inter-satellite links (OISLs) are increasingly being deployed in large constellations developed by organizations such as SpaceX, Amazon Kuiper, the Space Development Agency, Telesat Lightspeed, and Europe's IRIS² program. In parallel, multi-orbit optical connectivity architectures are being developed to provide terabit-per-second capacity and extend terrestrial fiber-optic infrastructure into space, as illustrated by ESA's HydRON program and the ESA Specification for Terabit/sec Optical Links (ESTOL) [1]. These developments are driving demand for scalable, efficient, and reliable laser communication terminals (LCTs) and optical amplification technologies capable of extending link distances, improving link margins, and supporting multi-wavelength transmission.

Spaceborne optical amplifiers must deliver telecom-grade optical performance while satisfying stringent size, mass, power, thermal, and reliability constraints. They must also withstand launch vibration and shock, repeated thermal cycling and cold start-up in vacuum, and cumulative radiation exposure throughout the mission. Large constellation programs introduce additional requirements for design repeatability, manufacturability, and production scalability. Addressing these combined constraints requires the optical, electronic, mechanical, thermal, firmware, and manufacturing architectures to be developed as an integrated system.

Within this context, MPB Communications has developed a portfolio of space optical amplification technologies with flight heritage and Technology Readiness Level 9 (TRL 9). Approximately 700 flight models have been delivered to date for commercial, military, and defense programs, including units supporting Space Development Agency (SDA) programs. Design, development, manufacturing, integration, and testing are performed at MPB's headquarters in Montréal, Canada. This vertically integrated approach enables close control of design evolution, configuration, qualification, and volume production.

This paper presents MPB's optical amplifier developments across a broad range of spacecraft classes and orbital regimes. The main focus is the Pulsar OAU for LEO satellite constellations, including its 8W Booster and LNA architectures, electronics, optical performance, and qualification campaign. The paper also presents two ongoing developments: a compact 2W optical power amplifier (OPA) for CubeSat and SmallSat terminals, and a radiation-hardened 20W Pulsar OAU for long-duration MEO and GEO missions. Together, these systems illustrate how a common optical amplifier technology base can be scaled to address diverse optical satellite communication applications.

2. 8W PULSAR - SATELLITE CONSTELLATION OAU

Design overview

The 8 W Pulsar OAU was developed to meet the stringent size, mass, and power constraints of large LEO constellations. Its key specifications are summarized in Table 1. Within a single enclosure, the unit integrates an 8W Booster amplifier, a low-noise amplifier (LNA), and radiation-tolerant control and power electronics. Figure 1(a) shows the architecture of the SDA-compliant variant and identifies its principal optical and electrical interfaces. These interfaces are adaptable to meet different standards (such as ESTOL) or specific customer requirements. A photograph of the Pulsar unit is shown in Figure 1(b).

Table 1: Key specifications of the SDA variant of the 8W Pulsar

Spec	Value	Spec	Value
Booster		Interface and operation	
Operating wavelengths	1536.61 nm, 1553.33 nm	Fiber type	Non-PM, SMF-28e+ bare fiber or sacrificial connector
Pass band filter	ITU Grid 100 GHz	Operation mode (OPA & LNA)	ACC, APC
Minimum input power	-10 dBm	Communication interface	2 x CAN 2.0A Bus
Output power range	16 to 39 dBm (8W)	Supply voltage	12 V (10 V to 15 V)
Low-Noise Amplifier (LNA)		Mass	≤ 1300 g
Operating wavelengths	1536.61 nm, 1553.33 nm	Size	182 mm x 182 mm x 29 mm
Pass band filter	ITU-T 100-GHz Grid	Operating case temperature	-5°C to 55°C
Output power	≥ -10 dBm (≥ -50 dBm input power)	Radiation TID	30 krad
Gain	≥ 40 dB	Radiation DSEE	LET _{th} ≥ 38 MeV·cm ² /mg
Noise figure	≤ 5 dB (> 30 dB of gain)	Vacuum compatible	Yes
Input power monitor range	-53 to -30 dBm		

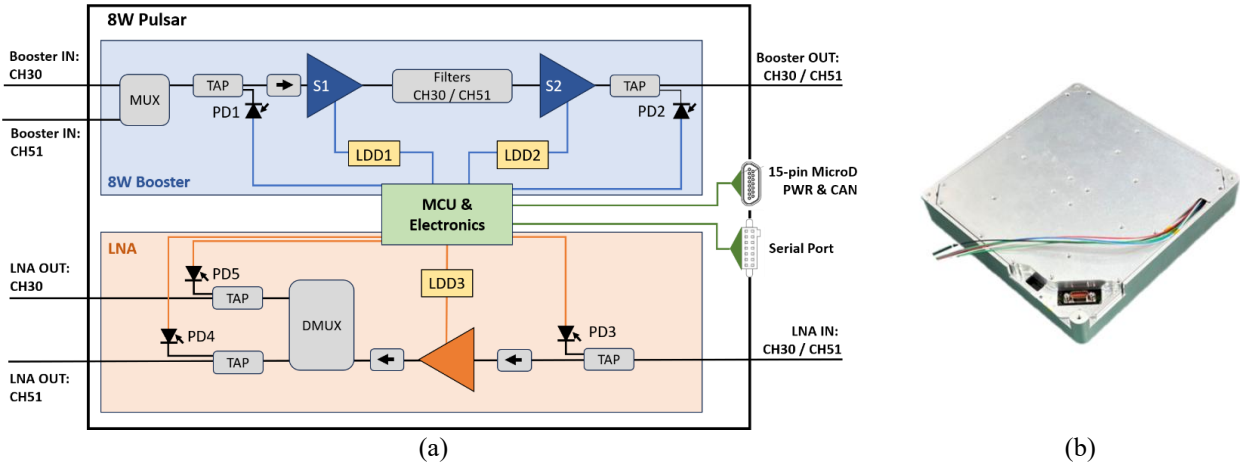


Figure 1: (a) Block diagram of the 8W Pulsar architecture. MUX – Multiplexer; DMUX – Demultiplexer; PD – Photodiode; TAP – Tap coupler; LDD – Laser Diode Driver. (b) Picture of the 8W Pulsar unit.

The 8 W Booster uses a two-stage architecture to provide high performance and reliability across the specified operating envelope. In the first stage (S1), an erbium-doped fiber is pumped by a single-mode 980 nm laser diode powered by laser diode driver 1 (LDD1). The second stage (S2) uses a cladding-pumped erbium-ytterbium co-doped fiber and InGaAs multimode pump laser diodes powered by laser diode driver 2 (LDD2). For in-orbit operation, the Booster provides more than 5 W of output power across the full specified operating range while maintaining more than 50% pump-current derating, supporting reliable operation over a 10-year mission lifetime.

MPB's proprietary Booster architecture is also optimized to suppress out-of-band ASE, particularly in the receiver (Rx) band, as shown in Figure 2(a). The worst-case ASE occurs when the Booster is operated with a short-wavelength input signal, such as CH51 at 1536.61 nm. Under this condition, the ASE within the CH30 Rx passband centered at 1553.33 nm is maximized. Backscattering from optical components in the optical head can couple this ASE into the Rx subsystem, where it may degrade receiver performance. As shown in Figure 2(a), MPB's design reduces the ASE at 1553.33 nm by 24 dB, substantially mitigating this risk.

The Pulsar LNA uses a proprietary architecture based on a high-gain erbium-doped fiber pumped at 980 nm by a single-mode laser diode and provides over 40 dB of gain. The LNA input incorporates a dual-stage isolator together with a photodiode that enables received-signal-strength-indicator (RSSI) monitoring for input powers as low as -53 dBm. Figure 2(b) shows a representative LNA noise-figure (NF) measurement. The measured NF is typically 4.6 dB, because of the insertion losses of the dual-stage isolator and input photodiode. Customized LNA configurations can achieve NF values down to 3.5 dB.

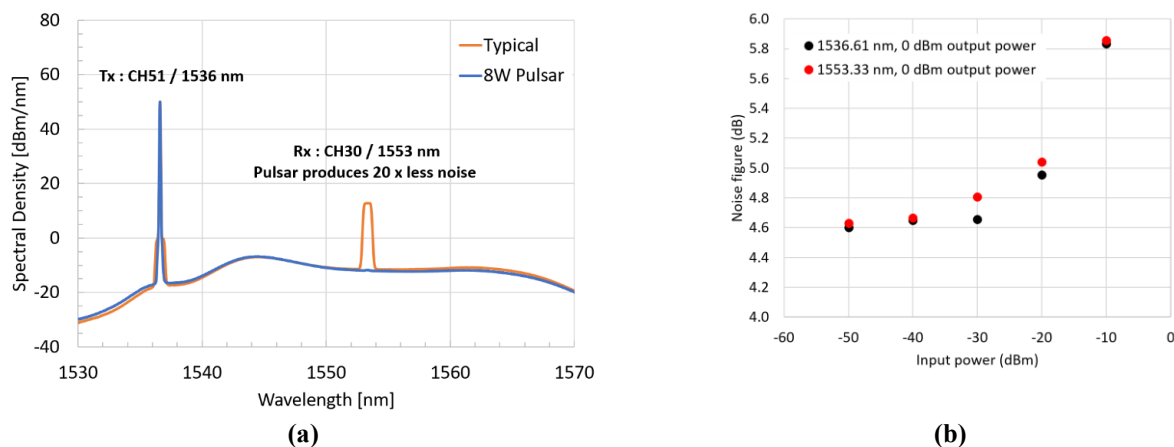


Figure 2: (a) Pulsar Booster output spectrum at 5W of output power and -5 dBm of input power at CH51 / 1536.61 nm. (b) Pulsar LNA Noise Figure as a function of input power.

The 8 W Pulsar electronic subsystem uses a semi-redundant, microcontroller-based architecture to control the unit, stabilize and monitor its optical output power, manage modulation frequencies, and acquire internal voltage, current, and temperature telemetry. Its power architecture incorporates a redundant 1+1 input DC/DC step-down converter supplying the internal 7 V buses, a linear single-event-latchup-free 3.3 V supply for the processor and analog circuitry, and a redundant 1+1 DC/DC step-down converter supplying the linear laser-diode drivers. The control and measurement functions are provided by the processor unit, ADC acquisition circuitry, and transimpedance amplifiers used for optical-power monitoring. Dedicated laser-diode drivers (LDDs) power the pump lasers used by the LNA and the Booster's first and second amplification stages, with a redundant 1+1 driver architecture implemented for the second-stage of the Booster.

The Pulsar is managed by firmware running on a radiation-tolerant microcontroller and communicates through a 1 Mbit/s CAN bus with the LCT. The firmware receives setpoints, operating limits, calibration coefficients, and synchronization frames while continuously reporting optical powers, currents, temperatures, and operating states. Its model-based control architecture combines nested state machines with an automatic power-control loop based on self-calibrated and unit-specific models. Feedforward control, slew-rate limiting, conditional integration, anti-windup, and adaptive current-step limiting enable the Booster to reach an output power setpoint of 5 W in less than two seconds without overshoot and

maintain the output power within 1% of the setpoint; an open-loop automatic current-control mode is also available. System protection is provided through 64 monitored alarm conditions linked to the fault-tree analysis and FMEA, with synchronized events stored in a non-volatile log for post-anomaly reconstruction. A dual-image, CRC-verified bootloader enables safe in-orbit firmware updates while retaining a validated backup image.

Design Qualification

The Pulsar qualification campaign was structured to reproduce the principal environmental stages encountered during launch and a typical space-mission lifecycle, as summarized in Figure 3. After each qualification test, the Booster and LNA output power and telemetry were fully characterized to identify any performance or parameter shifts. The Pulsar qualification model (QM) was manufactured on MPB's space-production line in its ISO 7 cleanrooms. It then underwent electromagnetic compatibility and electromagnetic interference (EMC/EMI) testing at MPB's Electronic Test Center (ETC) in Airdrie, Alberta, Canada, in accordance with MIL-STD-461G.

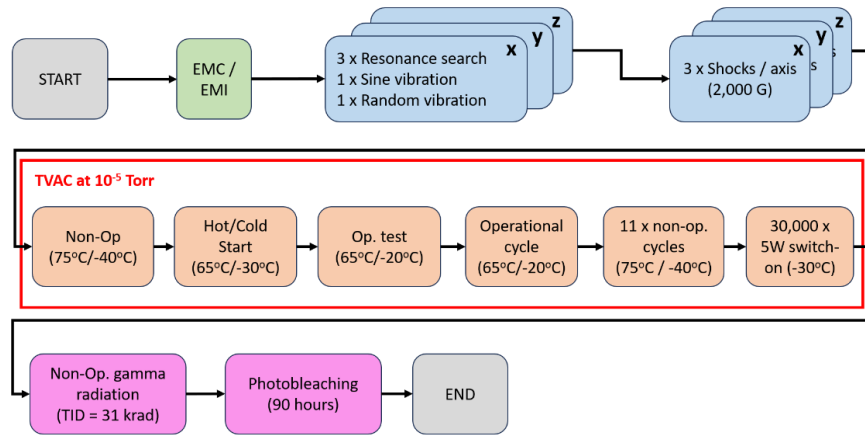


Figure 3: Pulsar qualification campaign

After EMC/EMI testing, the QM underwent sine and random vibration testing along the x, y, and z axes. For each axis, the unit was first subjected to sine vibration at a 10 mm displacement level from 5 to 28.6 Hz and an acceleration level of 33 g from 28.6 to 100 Hz. It was then exposed to 30.67 g RMS random vibration for 150 s. Figure 4(a) shows the measured acceleration spectral density for the x-axis test. A 0.5 g sine-resonance search from 20 to 2,000 Hz at a sweep rate of 4 oct/min was performed before and after the sine and random vibration exposures for each axis. The pre- and post-test responses were compared to confirm the unit's structural integrity and verify that its resonance characteristics remained unchanged.

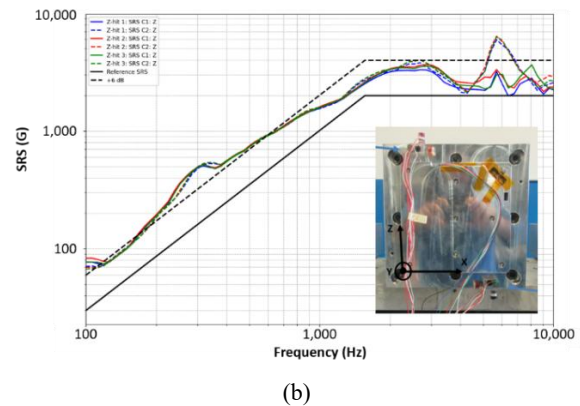
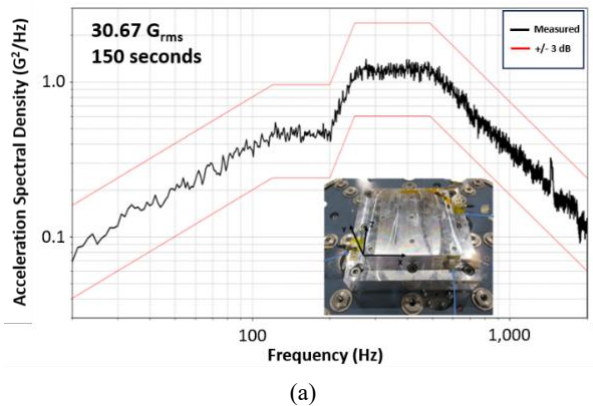


Figure 4: (a) Measured random-vibration acceleration spectral density for the Pulsar QM along the x-axis. (b) Measured shock response spectrum (SRS) for the three shock events along the z-axis.

After vibration testing, the QM underwent three shock events along each axis. As shown in Figure 4(b), the measured shock response spectrum (SRS) exceeded the specified Ariane 6 and Falcon 9 profiles, demonstrating the design's mechanical robustness.

Following the mechanical test campaign, the Pulsar QM underwent thermal-vacuum (TVAC) testing at a pressure below 10^{-5} Torr. Conducting TVAC testing after vibration and shock reproduces the sequence of environmental loads experienced during a mission and helps reveal potential latent defects initiated by the mechanical tests. The unit was tested across its full operational, non-operational, and switch-on temperature ranges to verify compliance with its specifications.

In addition, the QM completed 30,000 switch-on cycles at $-30\text{ }^{\circ}\text{C}$ in vacuum, with each cycle driving the Booster to its nominal output power of 5 W. This test was intended to expose cold-start failures, harmful electrical or optical startup transients, intermittent behavior, and degradation of components or interconnections caused by repeated low-temperature power cycling. Typical optical amplifiers can be particularly vulnerable to degradation of fiber splices and other fiber-optic assemblies under these conditions, potentially leading to system-level failure. In contrast, the Pulsar's optical, electronic, mechanical, and firmware architectures were co-designed to withstand extreme temperature events and mitigate the associated degradation risks.

After TVAC testing, the QM underwent total-ionizing-dose (TID) testing. Irradiation was performed using a cobalt-60 gamma-ray source at a dose rate of 272 rad(Si)/h, in accordance with ESCC 22900 (Issue 5) [2], to a cumulative dose of 31 krad. The Pulsar remained non-operational during irradiation, representing a conservative condition since no concurrent photobleaching of the active fibers could occur. In orbit, by contrast, continuous operation of the Booster and LNA would promote photobleaching throughout the irradiation period. Following irradiation, the Booster and LNA were operated to quantify their photobleaching recovery, as shown in Figure 5. Before photobleaching, the measured radiation-induced attenuation (RIA) was 1.5 dB for the Booster and 2.2 dB for the LNA. After approximately 90 h of photobleaching, the residual RIA had decreased to 0.5 dB and 0.8 dB, respectively. These results are consistent with MPB's previous gamma-irradiation tests on active fibers [3]. The Pulsar design accounts for this limited residual radiation penalty, which is the main contributor to the unit's end-of-life (EOL) performance degradation.

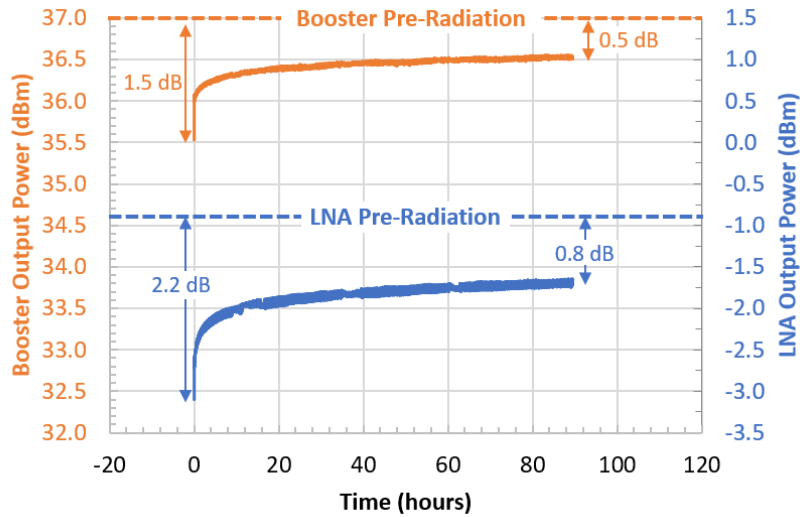


Figure 5: Pulsar QM Booster and LNA output power during photobleaching following 31 krad TID exposure.

Figure 6 shows the evolution of the Pulsar QM power consumption throughout the qualification campaign. For these measurements, the Booster was operated at its nominal output power of 37 dBm (5 W), while the LNA was operated at an output power of -1 dBm . The unit consumed between 35 W and 40 W across the different qualification phases, except during the final room-temperature measurement following irradiation and photobleaching, when the power consumption reached 40.6 W. Compared with the 36.7 W measured previously in vacuum at $20\text{ }^{\circ}\text{C}$ (VAC $20\text{ }^{\circ}\text{C}$), this represents a

modest increase of 10.6%, or 0.44 dB. This increase is consistent with the Booster radiation-induced attenuation (RIA) reported in Figure 5. Before radiation testing, the unit’s power consumption was also measured at room temperature with the Booster operating at an output power of 39 dBm (8 W). The resulting power consumption of 59.2 W indicates that the unit’s power consumption scales approximately linearly with Booster output power.

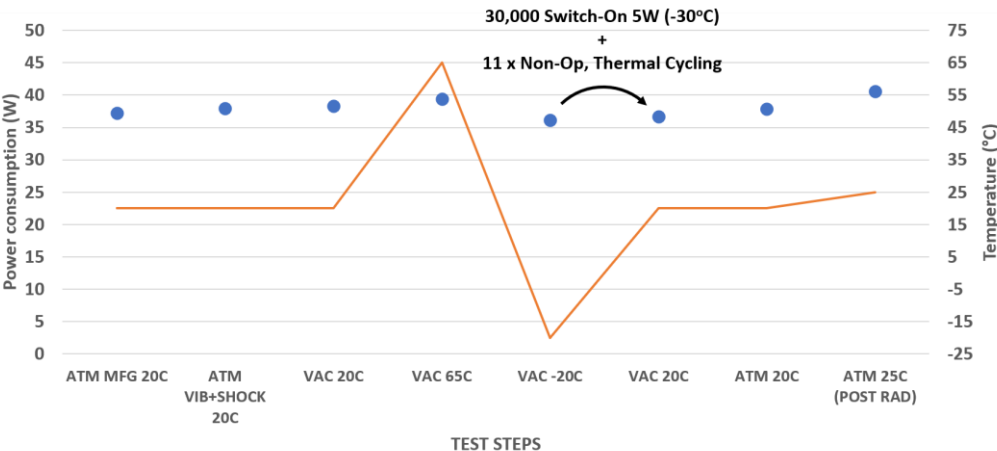


Figure 6: Power consumption of the Pulsar QM unit when the Booster is operated at 5 W (37 dBm) of output power and the LNA is operated at -1 dBm of output power.

3. ONGOING OPTICAL AMPLIFICATION TECHNOLOGY DEVELOPMENTS

2W Smallsat OPA

The market for CubeSats and Smallsats with optical satcom capabilities is growing as they will play a key role in multi-orbit optical connectivity. Furthermore, their small footprint is attractive in the context of mega-constellations as they offer a cost-effective access to space both in terms of unit and launch costs. Notable examples of small-form-factor LCT designs adapted to Cubesat and Smallsat platforms are DLR’s OSIRIS4Cubesat and CubeISL platforms [4-5] as well as TESAT Spacecom’s SCOT-20 and future SCOT-30 terminals [6]. While earlier CubeSat LCTs required a few hundred milliwatts of optical output power, current Cubesat LCTs are expected to rely on 1W to 2W of C-band optical output power to enable inter-satellite and direct-to-Earth laser links at data rates up to 2.5 Gbps.

To support such applications, MPB is developing a 2W Optical Power Amplifier (OPA) system in collaboration with the Canadian Space Agency (CSA) under the Science and Technology Development Program (STDP). The system’s specifications are provided in Table 2 while Figure 7 provides a rendering of the system.

Table 2: 2W Smallsat OPA specifications

Spec	Value
Operating wavelength range	1536–1565 nm
Minimum input power	≥ -3 dBm
Output power range	16–33 dBm
Input/ Output optical pigtails	SMF-28e+; bare fiber or sacrificial connector
Operation mode	ACC, APC
Communication interface	UART / RS-485
Supply voltage	5 V
Mass	≤ 250 g
Dimensions	85 mm x 65 mm x 25 mm
Operating case temperature	-5°C to 55°C
Total ionizing dose (TID)	30 krad
In-orbit lifetime	5 years
Vacuum compatible	Yes

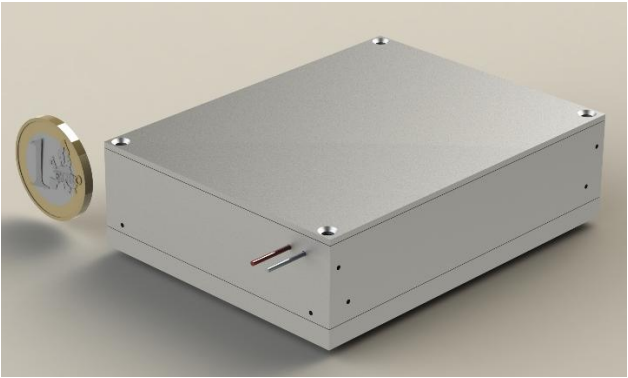


Figure 7: 2W Smallsat OPA system

The optical architecture of the 2 W OPA is derived from the Booster architecture shown in Figure 1 and has been optimized to meet the stringent size and mass constraints of Smallsat platforms. Its two-stage configuration is designed to provide high gain and output power while mitigating the risk of self-lasing compared with single-stage architectures. This approach retains the performance benefits of the established Booster architecture within a substantially more compact optical package.

The OPA employs a compact, microcontroller-based control architecture that integrates the control, monitoring, and power-management functions required for amplifier operation. This enables the unit to operate as a turnkey amplification system while simplifying its electrical integration within the LCT. Telcordia-grade components have been baselined for the optical subsystem, whereas electronic components have been selected according to the careful COTS approach [7]. This selection strategy ensures system reliability over the mission lifetime while simultaneously reducing overall cost. Communication with the telemetry and telecommand (TM/TC) subsystem is provided through a redundant UART interface, enabling robust system monitoring, configuration, and control.

20W Pulsar OAU

As part of the Viasat-led Aidan Next consortium, MPB is developing a radiation-hardened, higher-power variant of the Pulsar OAU. In collaboration with the CSA and ESA under ESA's Optical & Quantum Communications - ScyLight Strategic Program Line, which forms part of the Advanced Research in Telecommunications Systems (ARTES) program, this optical amplifier system will enable optical satellite communication applications in MEO and GEO. The new unit builds on the established Pulsar OAU architecture while introducing the optical, electronic, thermal, and radiation-hardness enhancements required for higher output power, longer mission durations, and the more demanding operating environments associated with MEO and GEO missions. The unit is being designed for an operational lifetime of at least 10 years in orbit and an operational temperature range from -10 °C to 60 °C.

The higher-power Booster expands the existing Pulsar Booster architecture by adding a third high-power optical amplification stage. This additional stage will enable the Booster to deliver 20 W of output power while maintaining greater than 50% pump-current derating, thereby providing sufficient operating margin to support reliable long-term operation. Both the Booster and the LNA will support the four primary ESTOL wavelengths: U1 (1536.61 nm), U2 (1537.40 nm), L1 (1553.33 nm), and L2 (1554.13 nm).

The electrical architecture will also be adapted to operate from a nominal 28 V spacecraft power bus. The redundant CAN 2.0A interface inherited from the Pulsar OAU will be expanded to accommodate the additional command, telemetry, control, and fault-management functions required by the higher-power architecture. OAU control and housekeeping functions will be provided by an integrated radiation-hardened microcontroller, currently expected to be the Microchip SAMRH71. The microcontroller will coordinate Booster and LNA operation, acquire optical and temperature telemetry, control the laser-diode drivers, manage operating states and fault protection, and interface with the TECO through the CAN bus.

To support operation in the MEO and GEO radiation environments, the unit is being designed for a total ionizing dose (TID) of at least 50 krad and a destructive single-event effects (DSEE) threshold of 60 MeV·cm²/mg. Together, these enhancements extend the Pulsar platform to substantially higher optical output powers while preserving architectural commonality with the 8 W unit. The resulting 20 W Pulsar OAU will provide an integrated and radiation-hardened amplification solution for long-duration, high-capacity optical communication missions in MEO and GEO.

4. CONCLUSION

Optical satellite networks place simultaneous demands on amplifier performance, size, mass, power consumption, reliability, and manufacturability. The 8 W Pulsar addresses these demands within a single integrated OAU, combining a high-power Booster, an LNA, and radiation-tolerant control and power electronics. Its two-stage Booster delivers more than 5 W of output power across the full in-orbit operating range while maintaining greater than 50% pump-current derating. The LNA provides RSSI monitoring down to -53 dBm and achieves 40 dB of gain with a typical noise figure of 4.6 dB.

Built around bespoke electronics, the Pulsar's CAN-based, model-driven firmware facilitates LCT integration through rapid, overshoot-free output power regulation, synchronized telemetry and event logging, comprehensive fault protection, and fail-safe in-orbit updates. Combined with the unit's rugged design and receiver-band ASE suppression, these capabilities support stable optical performance and reliable system operation throughout the mission. The 8 W Pulsar was validated through a comprehensive qualification campaign encompassing EMC/EMI, mechanical vibration and shock, thermal-vacuum, and gamma-irradiation testing. These results demonstrate the suitability of the Pulsar architecture for 10-year LEO missions.

Ongoing developments are extending this technology across a broader range of missions, output powers, and orbital environments. The compact 2 W OPA targets laser communication terminals for CubeSat and SmallSat platforms, with a five-year orbital lifetime. At the opposite end of the power range, the 20 W Pulsar adds a third Booster amplification stage, ESTOL compatibility, a 28 V spacecraft interface, a lifetime of at least 10 years, and increased radiation tolerance for MEO and GEO missions. Together, these developments establish a scalable amplifier platform able to address the needs of current and future high-capacity, multi-orbit optical networks.

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