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High-Efficiency Fiber Optic Amplifiers for New Space Constellation Applications

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ABSTRACT

In this paper, we describe progress in development of both single-mode-fiber and polarization-maintaining fiber optic Erbium-Ytterbium-doped-fiber booster optical amplifiers, as well as single-mode-fiber optic low-noise Erbium optical amplifiers operating in the 1535-1565nm wavelength range, optimized for low-earth-orbit (LEO) spacecraft applications. The SMF boosters operate in the range of 1 W to 10 W output power, while the PMF amplifiers operate in the 1-3 W range. Both types of boosters can be co-packaged with low-noise/high-gain SMF Erbium-doped-fiber pre-amplifiers, and utilize highly efficient common pump-control, telemetry and power-supply circuitry, in rugged housings. The amplifiers utilize uncooled pump laser diodes, commercial-off-the-shelf optical components and electronics, as well as radiation-tolerant Er and ErYb fibers and microprocessors. The combined booster/LNA units exhibit up to 20% electrical wall-plug efficiency at beginning of life at operating power levels in the 5-10 W range. Environmental testing in thermal vacuum and from -10C to +60C was performed to demonstrate that these modules meet or exceed many of the requirements of space applications. In this presentation we will discuss the design approach, show performance characteristics, predicted reliability and preliminary environmental test results for these amplifiers.

Keywords: Spacecraft Datalinks, Free Space Optical (FSO) Links, Laser Communications Terminal (LCT), Spacecraft Electronics, Spacecraft Photonics, Avionics.

1. INTRODUCTION

Space-grade fiber optic amplifiers are required in large numbers to enable free-space-optical links for many planned "new-space" satellite constellations. Requirements include low noise figure, high-gain, wide wavelength range from 1535-1565 nm, high output powers (1W-10W or more), high wall-plug-efficiency, low cost, small package size, rugged construction to survive launch and the on-orbit environment, including radiation tolerance. An overarching requirement is the need for a cost-effective solution to provide large numbers of optical amplifiers, economically, on expedited schedules. The prior approaches of long development and qualification cycles, hand-crafted in small numbers, do not satisfy the commercial imperatives of new space constellation applications.

There are multiple challenges to be overcome to produce cost-effective optical amplifiers that can survive space missions. The 1535-1565 nm wavelength band is typical of many new spacecraft constellation applications, which has been difficult to address with ErYb optical amplifier designs. Also, novel approaches are required to heat-sink the various high-power optical components in vacuum environments. Both single-mode (SM) and polarization-maintaining (PM) fiber amplifiers are needed to support traditional DWDM NRZ intensity-modulation links, as well as links employing polarization diversity, coherent DP-QPSK transmission, and quantum communications applications with polarization extinction ratios > 20 dB.

We have conducted a development program for "COTS" aerospace-grade optical amplifiers since 2018, addressing the increasing data transmission requirements between spacecraft. In a previous ICSO paper[1], we discussed development of aerospace grade parallel optics transceivers and DWDM transceivers, with excellent results for space applications when using COTS components coupled with screening and qualification tests. In this paper we will describe the most recent results of these developments for aerospace-grade optical amplifiers.

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2. REQUIREMENTS FOR SPACE-GRADE OPTICAL AMPLIFIERS FOR FSO TERMINALS

A typical FSO lasercom terminal block diagram is illustrated in Figure 1, showing various optical transceivers and optical amplifiers. Just like optical transceivers, optical amplifiers for new-space constellations have unique requirements, with some key differences compared to optical amplifiers intended for earth-based applications.

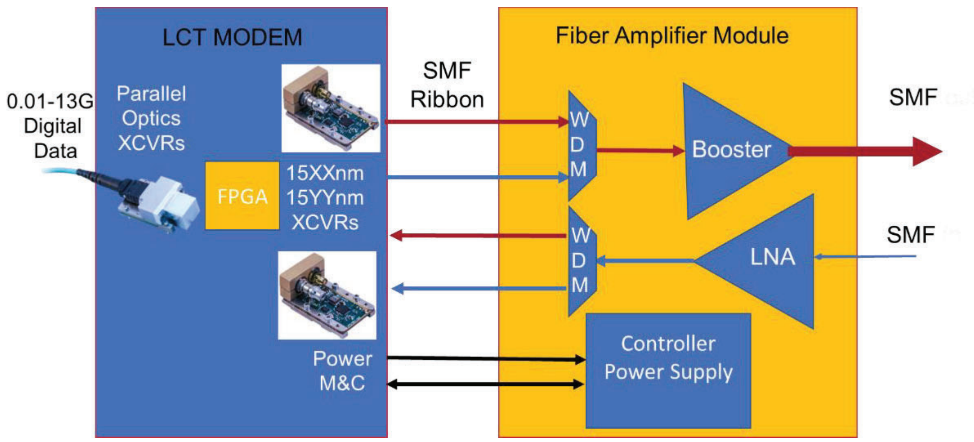

Figure 1: Functional block diagram of typical FSO laser communications NRZ 10G dual-wavelength MODEM and optical amplifier modules. Telescope and gimbaling mechanism not shown.

Typical spacecraft FSO links operate on two wavelengths, to provide for full-duplex bi-directional operation. As illustrated in Figure 1, two optical transceiver outputs are combined in a WDM before introduction to the booster amplifier. The input levels are typically in the -10 dBm to +3 dBm range per channel. The booster inputs can be provided via single-mode optical fibers using space-grade optical connectors. The single-fiber optical output is typically provided via a bare fiber that is spliced into the telescope assembly, due to the inability of single-mode fiber-optic connectors to handle such high-power levels.

In some cases, the WDM may be located inside the booter amplifier chassis. Specific requirements for booster amplifiers include operating wavelength range from 1535-1565 nm, high output powers (1W-10W or more), high wall-plug-efficiency, operation in thermal vacuum, and operation with either single-mode fiber (SMF) or polarization-maintaining fiber (PMF). Functionality includes both constant-current operation of the pump lasers as well as automatic power control (APC) of the output power. Due to the high-power levels for the pumps, protection circuitry is needed to sense the input power level and shut the pumps down if there is no input signal present, to prevent self-lasing. The amplifier is commanded via a serial digital interface such as RS-422, CANbus or USB. Typical key optical specifications for booster amplifiers are listed in Table 1.

In the LNA, the received signal is input from the telescope on a single mode fiber in the range of typically -50 dBm to -30 dBm. After amplification, the signal is separated into individual output channels with a WDM and fed to the photodiode receivers in the MODEM. Amplified spontaneous emission (ASE) noise of the amplifier is filtered by these WDM filters to provide for optimum receiver sensitivity. Automatic power control (APC) is typically required to level the output power and limit it so that the photodiode receiver is not damaged.

Specific requirements for LNAs include low noise figure, high-gain, ASE filtering for one or more ITU channels, operation from 1535-1565 nm, APC mode. Typical key LNA specifications are listed in Table 2 below.

Other key requirements for LEO spacecraft optical amplifiers include low-outgassing materials, rugged construction to survive launch, good thermal performance in vacuum, radiation tolerance, and high-reliability to survive in 3–10-year mission lifetime. Typical storage temperature requirement is -40C to +85C, and operating temperature is -5C to +55C at the unit baseplate in vacuum on orbit.

Table 1. Optical Characteristics – Booster Amplifier

Parameter	Symbol	Min	Typ	Max	Units	Notes
Wavelength	λ	1535		1565	nm	ITU Ch 30 and Ch 51 combined at input, only one present at a time
Input Power	P_{IN}	-10	0	+6	dBm	
Output Power	P_{OUT}	-30	36	37.5	dBm	BOL, 55°C thermal interface.
Noise Figure (HIGH OUTPUT)	NF_{HI}	-		9	dB	Pin=0dBm, Pout = +36 dBm, Pin= 0dBm, BOL λ = 1536.6nm, 25°C thermal interface
Input/ Output Return Loss		40	50		dB	
Output Isolation		35			dB	

Table 2. Optical Characteristics – Low-Noise Amplifier

Parameter	Symbol	Min	Typ	Max	Units	Notes
Wavelength	λ	1535		1565	nm	only one channel present at any time
Input Power	P_{IN}	-50	-45	-40	dBm	
Output Power per channel	P_{OUT}	-13	-	-3	dBm	At Pin_max, adjustable via APC settings and/or output attenuation
Gain	G		37		dB	</= Pin_max
Noise Figure (HIGH GAIN)	NF_{HIG}	-	4.5	5	dB	For Pin = -40 dBm, no input isolator
Output Isolation		35			dB	
ASE Filter Bandwidth	BW_{ASE}		100		GHz	-3dB BW, at specified channel

3. COTS FIBER OPTIC AMPLIFIER DESIGNS FOR SPACE

Erbium and Erbium-Ytterbium fiber optic booster amplifiers for space applications were developed to support the ITU C-band grid frequencies between 1535 nm and 1565 nm, responsive to the requirements listed in the previous section. The optical amplifiers are designed for space vacuum applications with up to 10 W of optical output power and support multiple transmitter and receiver optical inputs and outputs to enable dual-wavelength communications systems for simultaneous bi-directional links. The amplifiers are configured as dual booster + LNA, or single booster or single LNA. All designs employ a common microprocessor-controller chip available in radiation-tolerant and standard versions, with the same footprint and plastic package, as well as a switching DC-DC power supply. The firmware provides automatic control of the pump lasers responsive to commands from a serial digital interface.

The amplifiers utilize COTS components and ruggedized packaging to realize adequate performance in LEO satellite constellation missions, at reasonable cost, targeting limited lifetime of typically 5-7 years. COTS optical components, including optical couplers, gain fibers, photodiodes, isolators, WDMs and pump laser diodes were evaluated for suitability in the space vacuum environment. Both rad-tolerant and standard gain fibers are employed, with the specific fiber selected depending on the application and expected radiation total ionizing dose.

The booster amplifier employs either SMF or PM Erbium-doped single-mode fiber in a first stage with 980nm single-mode pump, and cladding-pumped Erbium-Ytterbium-doped-fiber second high-power stage with one or two

20W 940nm multi-mode pump laser diodes, depending on the required power levels and need for redundancy. The LNA employs SMF Erbium-doped-fiber and a single 980nm pump laser diode. All lasers are uncooled and hermetically sealed. Hermeticity is tested by the manufacturer and has been verified in He-leak and gross-leak testing by the authors. The high-level block diagram of the amplifier module is shown in Figure 2.

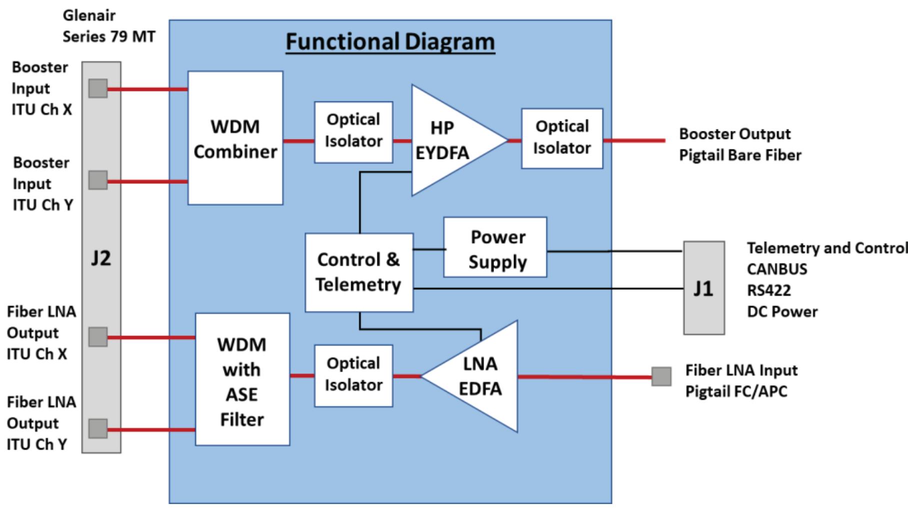

Figure 2. Optical amplifier functional block diagram.

All high-power optical components in the booster amplifier (pumps, multi-mode pump combiner, output optical isolator and coupler) are heat sunk to a common aluminum baseplate. The high-power ErYb fiber is also heat sunk using a method to permit thermal expansion and contraction of the fiber over a wide temperature range. Continuous operation in thermal-vacuum conditions with ambient pressure < 5E-6 torr for up to 900 hours has been demonstrated, as well as repeated thermal excursions from -10C to +60 C baseplate temperature while maintaining excellent optical power stability.

Pump power control for both constant current and automatic power control (APC) modes is managed by an onboard microprocessor that controls current sources for up to four pump lasers. The electronics design has been refined over four years of continuous design and evaluation efforts, and a stable bill-of-materials now exists for all parts in the design. These parts are stockpiled in quantities to enable rapid evolutions of new form-factor designs and circuit board layouts. The circuitry can employ both radiation-tolerant and non-radiation-tolerant versions of the microprocessor in the same plastic IC package footprint, allowing for supporting qualification and integration testing in non-radiation environments at reduced cost. The microprocessor manufacturer's datasheet states the parts have been lot-tested to verify no Single Event Latch-up (SEL) below an LET threshold of 60 MeV.cm2 /mg @125°C, and to withstand Total Ionizing Dose (TID) of 30 krad(Si).

A high efficiency switching power supply design is also included in the modules. This power supply design has ~ 95% efficiency and accepts a wide range of input voltage from 10V to 32V, providing regulated 5V, 3.3V and 1.8V power for the current sources and sensing circuits as well as the microprocessor.

Serial digital interfaces for telemetry and control that are supported include USB, RS-422 and CANbus. The microprocessor has flexibility to support other interfaces as well for future applications.

The booster design has been demonstrated in single-mode-fiber and polarization-maintaining fiber versions. One physical implementation of the 5-10 W booster + LNA unit is shown in Figure 3. Other configurations can be accommodated. In this implementation, a single microprocessor controls both the LNA and booster amplifier pumps and provides for APC functionality. In the LNA, output power is sensed via a 1% tap coupler after the WDM output corresponding the operation wavelength. This output is compared to the commanded output power and the 980nm pump laser current is adjusted to maintain the output power at the desired level. Similarly, in the booster, the second stage 940nm pump lasers are adjusted in response to the sampled output power via a 0.1% tap coupler to maintain the output power to the commanded level. The photodiode/coupler combinations are calibrated during manufacturing against an external reference optical power meter, and the unique calibration constants are stored in the microprocessor non-volatile memory to insure accurate optical output power. Over 50 dB of optical output power adjustment range has been demonstrated to be possible by varying the first stage and second-stage pump laser power levels.

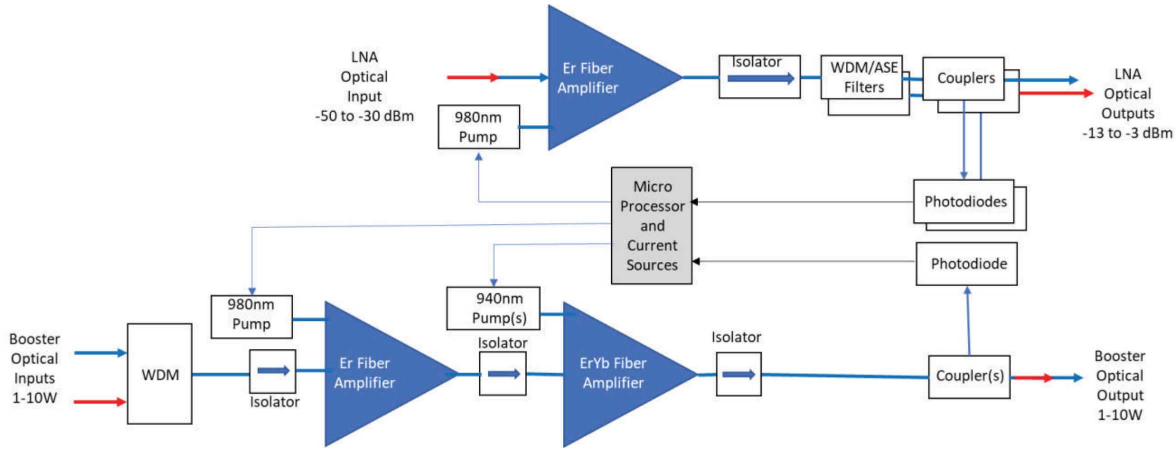

Figure 3. Optical amplifier block diagram for booster + LNA showing common microprocessor control and photodiode taps to enable APC loops. Switching power supply block not shown for clarity.

Extra care has been taken to replace or eliminate sources of outgassing in the materials used as well as the COTS fiber-optic components, including replacing epoxies, thermal interface materials and elastomeric boots for fiber strain relief with lower-outgassing types. Extensive outgassing testing according to ASTM-E595 was completed for many materials used in the internal components, including the optical fiber and coatings, to arrive at a reduced outgassing load for the overall assembly.

Both commercial-grade and radiation-tolerant fibers have been employed in various iterations of the amplifier designs. Preliminary results indicate that the radiation-tolerant fibers have lower efficiency than the non-radiation tolerant fiber that has been tested. More work is in process to establish the optimum fiber lengths and composition for best radiation tolerance and wall-plug-efficiency. Other workers have reported multiple sources of supply of radiation tolerant fibers and pump lasers suitable for LEO spacecraft applications[2].

The production of the units employs a modular design approach to support high-volume production. Four major subassemblies (LNA optical block, booster first stage, booster second stage and PCBA) are built and tested individually, then integrated prior to final test. All optical splices are proof tested to 100 KSI, and fiber recoating process is used to eliminate all splice tubes. This provides for smaller packaging and easier fiber routing. The modular approach results in higher production throughput at final assembly, by virtue of minimizes coupled-yield issues.

Reliability calculations performed according to MIL-HDBK-217F indicate the MTBF of the 5W design at average temperature of 35C in spaceflight conditions to be approximately 194,000 hours, or 22 years. This is well in excess of the typical 5–7-year lifetime requirements.

The optical amplifiers are designed for high shock and vibration environments to withstand launch conditions. Testing is underway and results will be reported in a future publication.

Final testing includes temperature cycling, burn-in and thermal vacuum testing over the full operating temperature range. Several completed form-factors for the amplifiers are shown in Figure 4.

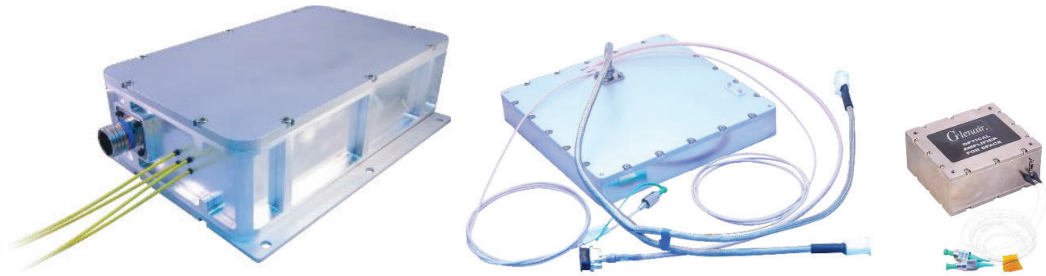

Figure 4. Optical amplifier types approximately to scale: first generation 5-10W booster + LNA (left, approximately 150mm x 200mm x 100mm), second-generation 5W booster + LNA (middle), 2W booster or LNA for 1U CubeSats (right, approximately 90 mm x 80mm x 40mm). All booster designs can be executed in either SMF or PMF.

4. OPTICAL AMPLIFIER PERFORMANCE DATA

All fiber optic amplifier products undergo a rigorous Environmental Stress Screening (ESS) process at the conclusion of production. Typical testing regimen includes, but is not limited to:

- Non-operating Thermal Cycling (-40C to +85C), ambient oven, 10 cycles, 30-minute dwell
- Functional test, full parametric screening at baseplate temperatures (-5C, 20C, 55C), 30-minute dwell
- Thermal-Vacuum testing, parametric testing, at the indicated supply voltage (typ. 12VDC or 28VDC) at 2 baseplate temperatures, -5C (-5C to +0C) and 55C (-0 +5C), 30-minute dwell
- Inspection, ESD Packing, Secondary packing for Shipping, and Certificate of Conformance.

Typical test data plots for a 5W Booster + LNA amplifier are shown in Figures 5-11. The booster amplifier output spectrum exhibits typical broadband ASE, but with proper choice of gain fiber lengths and pump power, adequate output power and signal-to-noise performance across the range of 1535 – 1565nm has been obtained. Typical noise figures are in the range of < 8 dB at power levels of > 4 W.

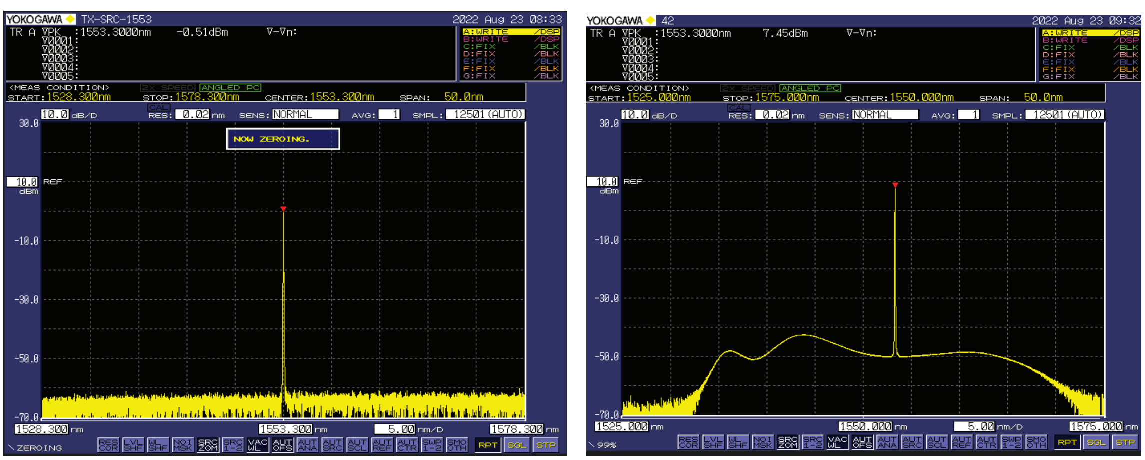

Figure 5. Typical optical spectrum analyzer plot of booster input (left) and output (right) signals near 1550nm.

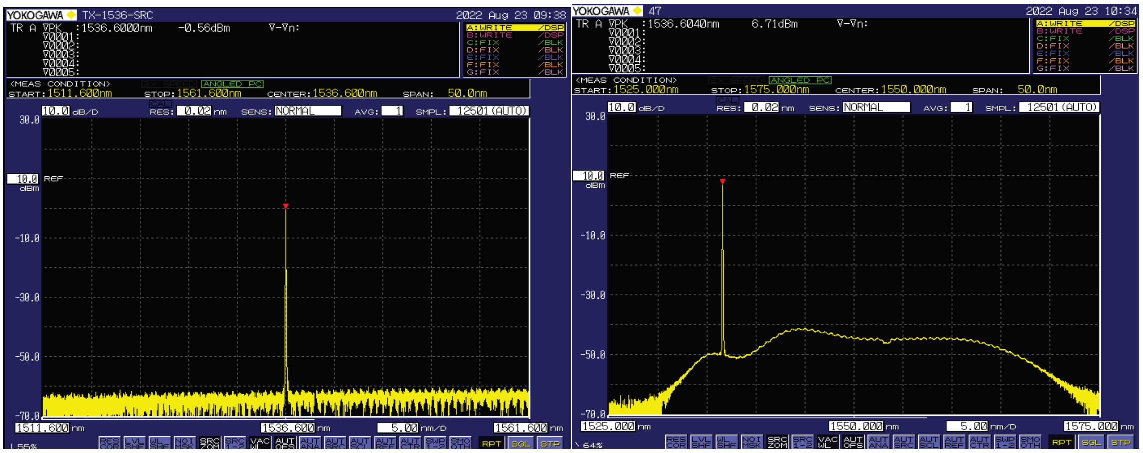

Figure 6. Typical optical spectrum analyzer plot of booster input (left) and output (right) signals near 1535nm.

Table 3: LNA measurement data. Note that MT test cable loss is subtracted from OSA measurement data to get calculated noise figure (NF) in right-most column.

	Source	980nm			OSA		
Input Power (dBm)	**Wavelength (nm)**	**Pump4 Current (mA)**	**Power OSA (dBm)**	**Gain (dB)**	**NF (dB)**	**Test Cable IL (dB)**	**Calculated NF (dB) NF-Test Cable Loss**
-40	1553.3	370	-2.93	**37.07**	**4.08**	0.37	3.71
-50	1553.3	370	-11.95	**38.05**			
-40	1536.6	650	-4.12	**35.88**	**3.93**	0.30	3.63
-50	1536.6	650	-13.31	**36.69**			

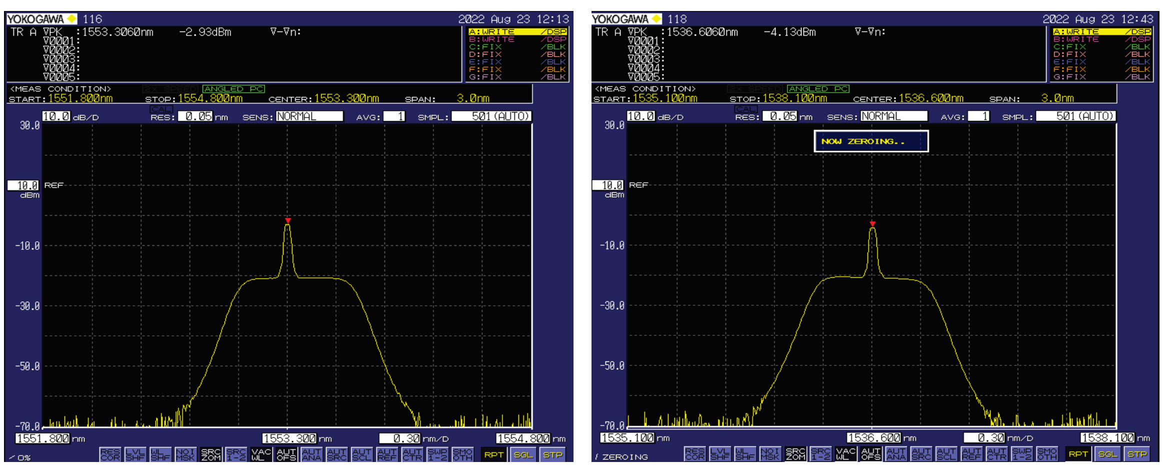

Figure 7. Typical LNA output near 1550nm (left) and 1535nm (right) for input level of -40 dBm, span = 3 nm. Note the ASE noise pedestal that is passed through the filter of approximately 0.8 nm => 100 GHz.

Figure 8. Typical optical spectrum analyzer LNA Noise Figure measurement display near 1550nm (left) and 1535nm (right) for input level of -40 dBm, span = 3 nm. Input signal is yellow trace, output signal is magenta trace. Note that NF measurement includes optical test cable losses of ~ 0.35 dB.

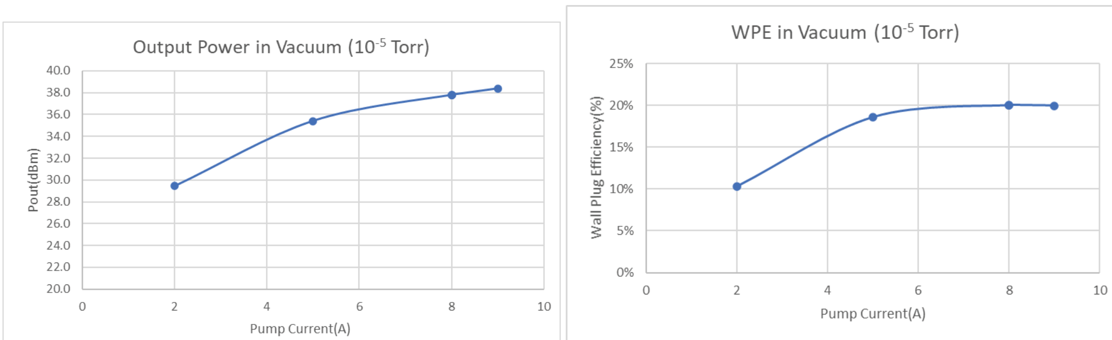

Figure 9: 5W Booster amplifier power vs second-stage pump current (left) and Wall Plug Efficiency (WPE) vs second stage 940nm pump current, in vacuum at 25C.

WPE = "Wall Plug Efficiency", defined as optical output power measured at signal wavelength peak divided by the supplied electrical power to the amplifier. Supply power is defined as the voltage x current supplied to the switching power supply input at 28V. The output optical signal wavelength peak is measured using an optical spectrum analyzer via a 0.1% fiber optic coupler. The OSA peak power measurement are checked using a clean DFB laser signal and a NIST-traceable optical power meter, because the OSA peak marker reading is typically less accurate than a power meter reading.

It is interesting to note that for lower output power levels in the range of 1-2W, the WPE is in the range of 10-15%. However, as the second-stage pump power is increased so that output power reaches 5W or higher, the WPE continues to increase until a ceiling of approximately 20% is reached when using non-radiation-tolerant ErYb and Er fiber in the booster. For radiation-tolerant fiber tested so far, the WPE ceiling appears to be in the range of 14-15% in preliminary measurements. We note that other work on radiation-tolerant fiber amplifiers has reported WPE in the range of 10-12% [3]. Careful power measurements and calibrations have been conducted on multiple units, and even verified by third party customers, obtaining WPE in the 20% range for non-radiation-hardened fibers at 5W power levels and above. More study is ongoing to determine the source of this discrepancy, examining the influence of fiber type, exact length and pump power on the wall-plug-efficiency.

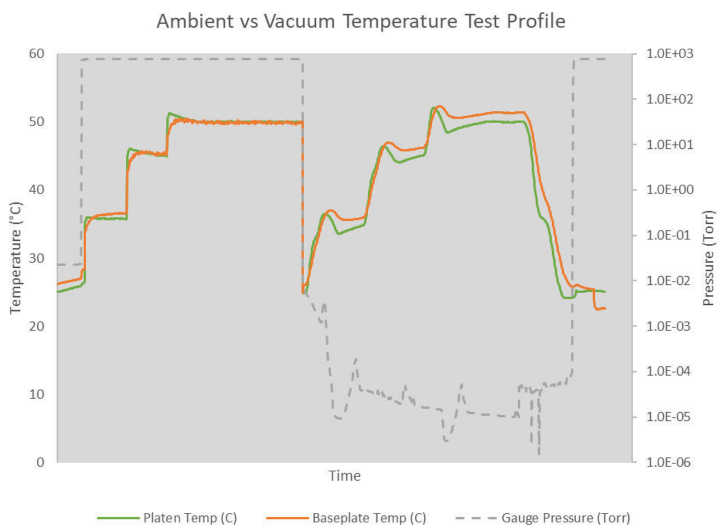

Figure 10: 2W Booster Amplifier TVAC testing temperature profile, indicating good tracking of unit temperature to thermal platen under vacuum.

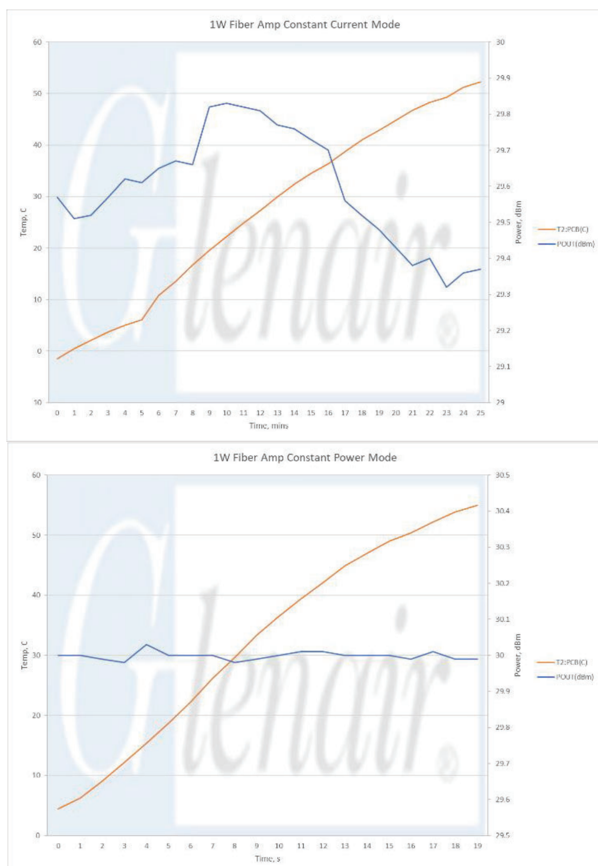

Figure 11: 1W Booster Amplifier comparison of output power stability in constant current mode (left) and APC mode (right). Note that optical power (right scale) is 1 dB full-scale over a temperature excursion (left scale) of approximately 50C. This indicates excellent power control in APC mode of well under 0.1 dB over this temperature range.

Typical variation of baseplate temperature in air vs vacuum is shown in Figure 10, indicating adequate thermal management. The output power stability of a 1W booster amplifier is shown in Figure 11 for both constant-current mode and automatic power control (APC) modes. In constant current mode, the optical power variations are approximately 0.5 dB p-p, which is half the amplitude of other reported results[2] . When APC mode is engaged, however, the optical power fluctuations are reduced dramatically, to well under 0.1 dB p-p over the 50C temperature range of this test. Similar results are obtained for higher-power boosters as well as LNAs operating in APC mode.

5. SUMMARY AND CONCLUSIONS

We presented requirements, designs and test data for optical amplifier modules designed for inter-satellite FSO spacecraft high speed digital datalinks. We discussed the results of various tests, including thermal cycling and thermal vacuum testing. Testing to date indicates that these parts can satisfy the environmental requirements of spaceflight applications, and further testing and product development is ongoing including radiation, vibration and shock; results will be reported in future publications.

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