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51 W, 1.5 um, 7 WDM (25 nm) Channels PPM Downlink Transmitter and 500 W, 1 um, Uplink PPM Transmitter for Deep Space Lasercom

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ABSTRACT

This paper describes progress toward a space -based 51 W average power amplifier for deep space PPM and Earth GEO links. We demonstrated a broadband WDM amplification at 50W with flat gain across a 25 nm bandwidth. Similarly, for 5 W amplifier we demonstrated a flat gain across a 32 nm bandwidth. These amplifiers demonstrate the feasibility for multi-channel space optical communications links. To increase the bandwidth GEO links to multi-Tbps and deep space links to > Gbps. The laser supports kW/channel SBS limited peak power for PPM and achieves an optical-to-optical efficiency of > 40%.

In a separate but related effort for a deep space uplink beacon, we achieved 500 W average power, 2.6 kW peak power PPM (2,2) for a 1 um uplink transmitter. Reliable SBS free operation is achieved with phase modulation resulting in 26 GHz transmitter linewidth. Uplink transmitter is optimized for 65 usec (pulsewidth) slot size—achieving fastest possible rise/fall times (<10 usec) and pulse uniformity.

Keywords: Lasers and laser optics; fibers, erbium, free-space optical communication, nonlinear optics, EDFA, space based, space qualified, PPM, GEO.

1. INTRODUCTION

This paper describes the development of deep space laser technologies including a 50 W downlink laser to support Gbps from deep space and a 500 W binary pulse position modulation (BPPM) uplink beacon and BPPM laser to support NASA missions, The downlink laser is high power, and the design is traceable to space and supports a wavelength division multiplexing (WDM) channel with flat spectral response. The uplink 500 W laser meets all NASA requirements with 10 lasers being used to uplink 5 kW of average power and 20 kW of peak power.

The space-based 50 W WDM communications transmitter supports serial concatenated pulse position modulation (SCPPM) deep space and geosynchronous earth orbit (GEO)-GEO and GEO-Earth cross-links. The goal is to support 1-5 Gbps for deep space downlinks and Tbps core space GEO optical links using cross-correlated phase shift keying (xPSK), on-off keying (OOK), or coherent waveforms. The laser is capable of high peak powers needed for PPM. The laser has been demonstrated at 32 nm flat spectral response at 5 W of total power and 25 nm flat spectral response at 50 W of average power. We achieved > 40% electrical-to-optical (e-o) efficiency and project very high wall-plug efficiency.

Fibertek has previously developed a series of space-based FSO transmitters including a CubeSat-sized 0.5 W laser, a 6 W deep space transmitter, and 20 W Er fiber amplifier tested to TRL-6 and TRL-7 as shown in Figure 7 in Part 4 of this paper. With the addition of this 50 W amplifier heading toward Technology Readiness Level 5 (TRL-5), Fibertek now has TRL-4 to TRL-7 laser technology to support the full spectrum of laser performance needed to satisfy NASA Space Communications and Navigation (SCaN) space optical communications roadmap requirements. The transmitters are capable of supporting single channels or WDM.

This paper also reports the results of our deep space uplink laser effort with NASA. Fibertek has designed and tested a breadboard 500 W average power and 2.6 kW peak power 1064 nm uplink Yb fiber laser that satisfies NASA's need for deep space communications for the Deep Space Optical Communications (DSOC) Psyche mission. The design is compact, meets all requirement and is 75% optical-to-optical (o-o) efficient. NASA plans to use 10 of these lasers to generate 20 kW peak power and 5 kW average power.

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Europeans are deploying a Space Data Highway system, with laser communication links of up to 1.8 Gb/s, between GEO-GEO and GEO-low earth orbit (LEO) satellites[1]. The Lunar Laser Communication Demonstration (LLCD) mission demonstrated 622 Mbps data rate from lunar orbit to earth ground station using a 1.5-um telecom derived, $P_{avg} < 0.5$ W fiber-amplifier [2].

NASA's SCaN roadmap for 2025 and beyond shows the need for optical links, for Earth, Lunar, inter-planetary, and relay networks, which needs development of such high-power, efficient fiber amplifier/laser-based transmitters. For eye-safe reasons, broad atmospheric transmission window, and to leverage high-reliability fiber-optic WDM component technology and supplier base, development of wideband, space-qualified 1.5-µm Erbium (Er)-doped fiber amplifiers is preferred.

2. 50 W WDM PPM SPACE DOWNLINK TRANSMITTER

Nominal requirements for each of the wavelength channels of a WDM DSOC downlink transmitter are taken to be consistent with the requirement of a single-channel downlink DSOC tranmistter[3-7]. A polarization-maintaining (PM) transmitter needs to generate 4-6 W per channel of average power with peak power as large as ~1 kW. For an 8-channel WDM downlink transmitter, total output power needs to be 32-50 W average power. The developed PM breadboard WDM transmitter consists of a WDM/PPM front-end and three 1.5-um fiber amplifier gain stages. The WDM/PPM front-end consists of 10 channels covering 1534-1572 nm.

Table 1 summarizes the achieved results from the four amplifier configurations. For all configurations measured, output beam quality was near diffraction limited $M^2 < 1.2$. From the third stage, o-o efficiency as high as 44% is achieved for wideband operation. Using the measured efficiencies for the amplifier stages, a preliminary system power budget is developed for an 8-channel, 50 W WDM PPM transmitter. **Including for the efficiencies of diode drivers and DC-to-DC converters, the laser is expected to consume 280 W, which is 18% wall-plug efficiency.**

Table 1. Characteristics of optimized WDM amplifier configurations tested.

Amp. Config. #	**# of Stages**	**# WDM Channels**	**Spectral Range**	**Average Output Power Level**	**Peak Power/Channel PPM (128,32)**
1	2	8	1543.8-1572 nm	6 W	120 W/channel
2	2	9	1534-1568 nm	4 W	80 W/channel
3	3	6	1549-1572 nm	52 W	1.5 kW/channel
4	3	7	1543.8-1568 nm	51 W	1.2 kW/channel

Figure 1 shows measured temporal and spectral data for the 4 W, 9 channel (34 nm wide) output of stage 2. Figure 1 (left) shows PPM (128+32) format with slot size (pulsewidth) of 2 nsec. In the temporal figure each of the 9 WDM channels is separated by ~12 nsec. Temporal data shows ~0.5 dB gain uniformity for the 9 WDM channels. The Figure 1 inset shows the output spectrum. Figure 1 (right) shows PPM (128+32) format with slot size 8 nsec. In this higher energy/pulse format 0.5 dB gain uniformity was maintained.

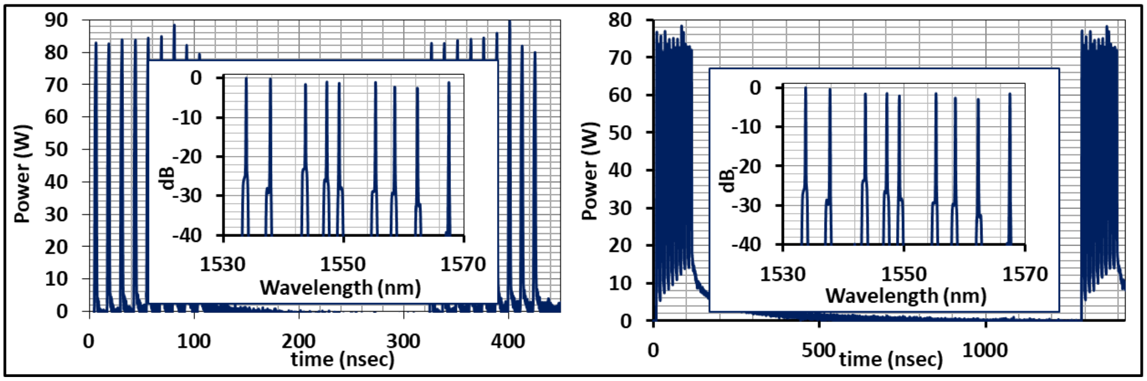

Figure 1. Two-stage output temporal and spectrum measurements for 4 W average power, 9 channel 34 nm amplifier bandwidth (Table 1, configuration 2). PPM (128+32) slot size (left) 2 nsec and (right) 8 nsec. Nine temporal pulses correspond to nine different wavelength channels spanning 34 nm amplifier bandwidth—gain uniformity <0.5 dB (inset: output optical spectrum).

Figure 2 shows measured temporal and spectral data for 51 W, 7 channel (25 nm wide) output of stage 3. Figure 2 (left) shows PPM (128+32) format with slot size (pulsewidth) of 2 nsec. In the temporal figure each of the seven WDM channels are separated by ~12 nsec. Temporal data shows ~0.5 dB gain uniformity for 7 WDM channels. The Figure 2 inset shows the output spectrum. Figure 2 (right) shows PPM (128+32) format with slot size 8 nsec. In this higher energy/pulse format 0.5 dB gain uniformity was maintained.

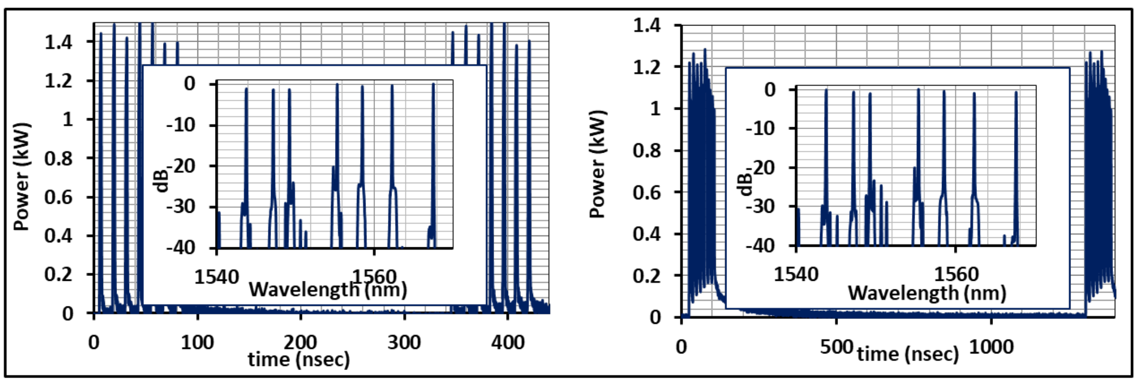

Figure 2. Third stage output temporal and spectrum measurements for 51 W average power, 7 channel 25 nm amplifier bandwidth (Table 1, configuration 4). PPM (128+32) slot size (left) 2 nsec and (right) 8 nsec. Seven temporal pulses correspond to seven different wavelength channels spanning 25 nm amplifier bandwidth—gain uniformity <0.5 dB (inset: output optical spectrum).

3. NASA UPLINK LASER BREADBOARD: 500 W, 2.6 kW PEAK POWER SUPPORTING BINARY PPM PULSE FORMAT

This section describes Fibertek's breadboard demonstration of an uplink beacon that satisfies all the requirements for NASA's DSOC program for deep space communication on the NASA Psyche mission.

Laser beacons with scalable power (multi-kW) are needed for earth-to-asteroid, interplanetary (Mars), and deep-space optical communication uplinks[8-10]. They serve as absolute reference for precise pointing, acquisition, and tracking (PAT) of spacecraft during the downlink laser communications. They also enable high-rate-signaling data commands (>0.5 Mbps). For such space communication link distances, especially beyond LEO, the beam spread due to diffraction is significant enough that only a few photons are collected by a moderate-size optical telescope on a spacecraft. This necessitates photon-counting detectors suited for the space environment, along with increasing the output power of the laser beacon[10]. High average powers (multi-kW) at 1064 nm with near-diffraction-limited beam quality (M^2 <1.2) are targeted for the "uplink laser beacon." Such a laser beacon encounters the atmospheric layers, and even under clear weather conditions the atmospheric turbulence causes significant scintillation (intensity variation) of the beam in the far-field[11]. It has been shown that instead of a single (large) transmit aperture, use of multiple sub-apertures with four to eight beams alleviates the scintillation and improves the fade characteristics for uplink laser communications[12]. Multi-apertures for the laser also eases the power requirements of single source and damage thresholds of telescope mirror optics[13]. For future DSOC systems higher power transmitters allow for more robust and reliable DSOC communication links including operation under small sun-probe-earth angle[14].

For the NASA DSOC program, a 10-aperture/channel uplink laser transmitter is being developed to be deployed as part of the NASA Psyche mission's DSOC technology demonstration[14]. The laser will output a total of 5 kW average power and >20 kW peak power at 1064 nm. A pulsed laser will be operated with BPPM format with 2 guard bands and slot size of 65.5 usec. From each of the 10 apertures this corresponds to 500 W average and >2 kW peak power and a pulse energy of 130 mJ.

The driving optical uplink laser requirements (per laser) are listed in Table 2. Each uplink channel needs to produce 500 W average power operating with BPPM format with 2 guard channels (25% duty cycle). Slot size of BPPM is 65.5 usec. More than 95% of the optical power for each pulse needs to be inside the slot size. The transmitter needs to put out an unpolarized signal with excellent diffraction limited beam quality M^2 <1.2. Stimulated Brillouin scattering (SBS) free operation needs to be achieved with 2-3 m delivery fiber length and <50 GHz linewidth. A single uplink transmitter channel breadboard is built and all the key optical requirements are demonstrated.

Table 2. Key per aperture/channel optical requirements for the 1064 nm uplink transmitter.

#	Requirement	Value	Status	Comment
1	Average Power (W)	500 W	Achieved	Measured, BPM operation
2	BPM Slot Size (μs)	65.5 μs	Achieved	Measured, >95% of pulse energy within slot
3	Max Peak Power (kW)	2 kW	Achieved	Measured, 2.6 kW, rise/fall times <10 usec/2 usec
4	Linewidth 3 dB (GHz)	<50 GHz	Achieved	Measured, 26 GHz with 2 m delivery fiber length
5	OSNR (dB loss in 0.8 nm)	< 0.04 dB	Achieved	Measured peak power with <0.04 dB loss in 0.6 nm
6	Output Mode Qua., M^2	< 1.2	Achieved	Measured, 1.1
7	Wall-Plug Power Eff.	> 10 %	13% Estimate	Measured, >75% o-o final stage efficiency

The breadboard uplink laser transmitter consists of a linewidth broadened continuous wave (CW) 1064 nm laser, two-stage CW Yb-doped fiber preamplifiers, and a two-stage Yb-doped power amplifier that are pulse pumped. In the front-end a 10 GHz phase modulator is used to broaden the linewidth of a 1064 nm distributed feedback (DFB) laser to ~26 GHz. All the fiber amplifier stages are built using non-PM mature commercial off-the-shelf (COTS) fiber-optic components. The first two stages are single-mode Yb fiber amplifiers. They are CW pumped outputting 1 W with ~33 dB of gain. The two power amplifier stages are pulsed pumped in order to generate the 65.5 usec BPPM pulses. Stage 3 is pulse or CW pumped, achieving up to 80 W of seeding peak power into the final amplifier stage. The flexibility in the stage 3 pulsing scheme allows for the study of final stage seeding power dependence on rise and fall. Stage 4 is pulsed pumped with 3.3 kW of peak pump power, using an ultra-fast (<5 usec rise time) high-power pulse diode driver.

Figure 3 (left) shows pump power versus output signal power where the pump diodes are pulsed with 55 usec pulsewidth and 262 usec period in order to guarantee that >95% pulse energy remains within the 65.5 usec slot size. Stage 4 achieves >75 o-o efficiency. A diffraction limited beam quality is measured out of the stage 4 at 520 W. Figure 3 (right) shows the output BPPM pulses at average power of 520 W and peak power of 2.6 kW.

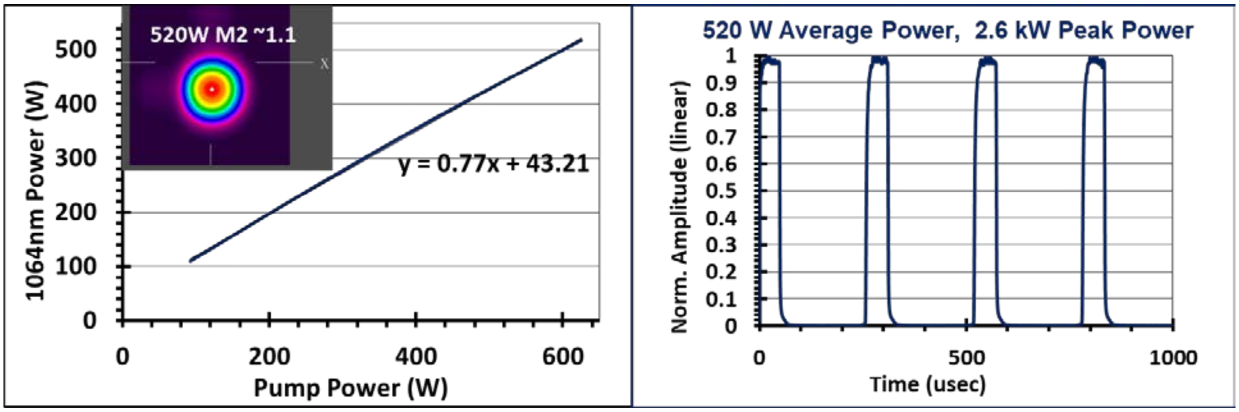

Figure 3. (left) Output 1064 nm signal power vs. average pump power (pump modulation 55 usec pulsewidth, 262 usec pulse period), (inset) far field optical beam at 520 W, and (right) measured temporal 1064 nm signal pulse waveform with 520 W average power and 2.6 kW peak power.

Figure 4 (left) shows measured 1064 nm signal pulse shape at 520 W average power and 2.6 kW peak power. The 10/90% rise and fall times are 6 usec and 4 usec, respectively. Rise and fall time dependence on seeding power is studied. It is found that fall times <2 usec can be achieved as the seeding peak power is increased 80 W. Figure 4 (right) shows the output pulse train in logarithmic scale. Pulse extinction ratio well over 20 dB is achieved resulting in >1% optical power being outside the BPPM slot.

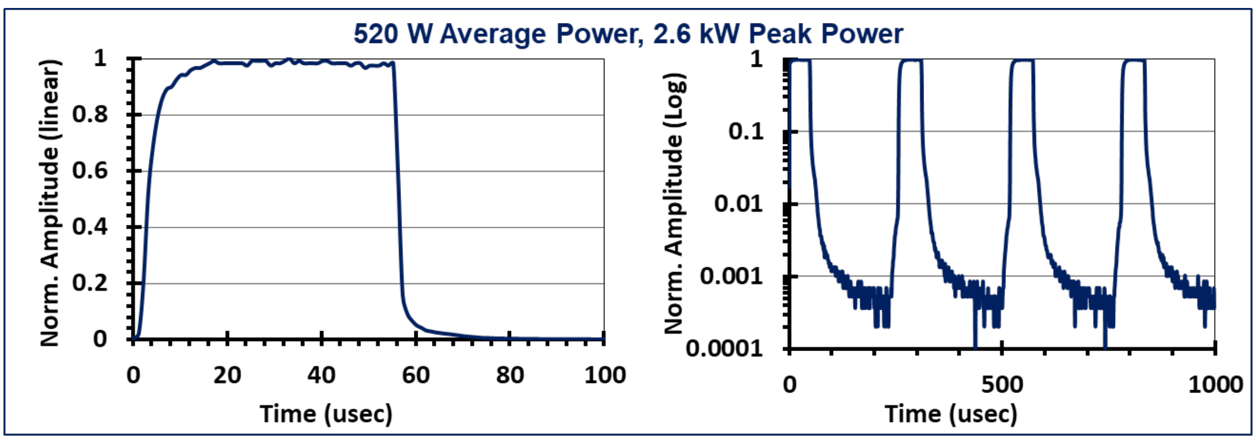

Figure 4. (left) Measured temporal 1064 nm signal pulse waveform with 520 W average power and 2.6 kW peak power, slot size 65.5 usec, period 262 usec; (right) measured temporal 1064 nm signal pulse waveform in logarithmic scale with 520 W average power and 2.6 kW peak power. Pulse extinction ratio >20 dB is achieved.

Figure 5 shows output spectral measurements at 520 W average power and 2.6 kW peak power. Figure 5 (right) shows that output has negligible amplified spontaneous emission (ASE) content with optical signal-to-noise ratio (OSNR) >35 dB. Figure 5 (right) shows measured full width at half maximum (FWHM) linewidth of 0.1 nm (26 GHz). Of the optical power, 0.04 dB is within a 0.6 nm bandwidth centered on 1063.96 nm.

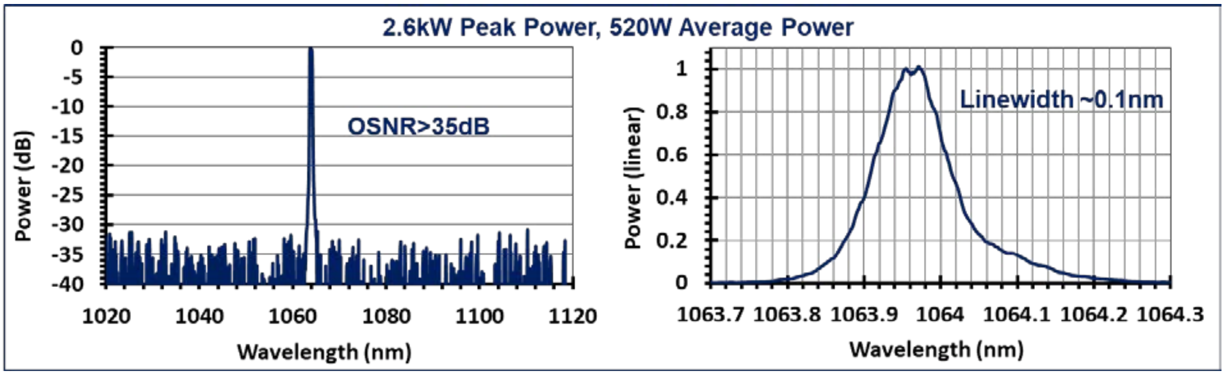

Figure 5. Output spectrum at 520 W average and 2.6 kW peak power BPPM modulation operation. (left) Wide spectrum with 2 nm resolution measurement showing negligible ASE content >35 dB, and (right) high-resolution (0.01 nm) spectral measurement showing a FWHM linewidth of 26 GHz.

Figure 6 (left) shows measured temporal profile with min-max pattern PPM (2,2) at 520 W average and 2.6 kW peak power. Negligible pulse variation is achieved between pulses occupying slots 1 and 2. Figure 6 (right) shows measured temporal profile for a 50% duty cycle waveform at 700 W average and 1.6 kW peak power. Operation with the additional formats in Figure 6 shows that the laser architecture is capable of achieving all the required waveforms.

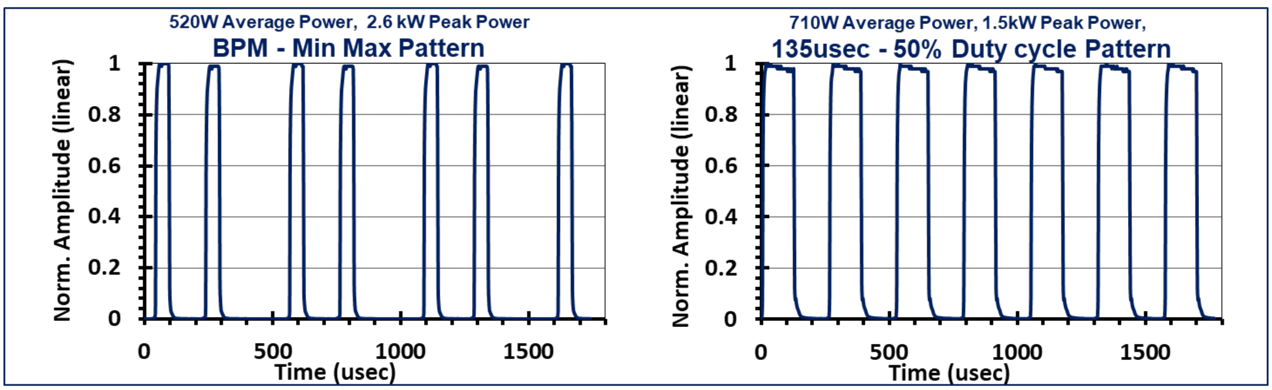

Figure 6. Measured temporal profiles with (left) min-max PPM (2,2) pattern at 520 W average and 2.6 kW peak power; (right) 50% duty cycle, 135 usec pulsewidth, and 700 W average and 1.8 kW peak power.

4. CONCLUSIONS

This paper describes the development of a high-efficiency space-tracible 50 W Erbium amplifier that supports high peak power suitable for Gbps data rates from deep space using SCPPM along with WDM. This new technology is enabling for planetary and small body science missions and planetary orbiters and for deep space core optical relays. This transmitter is architected for very high reliability and 24/7 operation for 10-year missions.

The same 50 W amplifier can support Tbps GEO-GEO and GEO-Earth cross-links using OOK, xPSK, and coherent waveforms with our polarization maintaining capability. This amplifier, together with Fibertek's previously developed Erbium amplifiers (Figure 7), supports the full spectrum of NASA SCaN's roadmap for space optical networking. Lasers have included CubeSat sizes, 0.5 to 3 W transmitters, space VPX versions, deep space 6 W downlink, and 20 W and the new 50 W amplifier reported here.

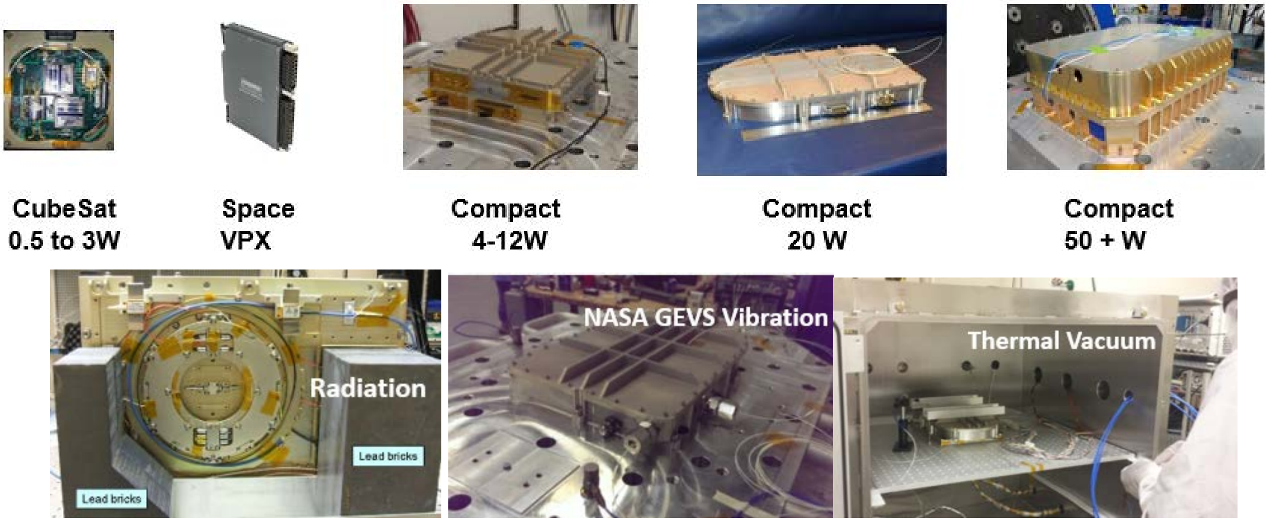

Figure 7. (top) Fibertek FSO transmitters covering the full spectrum of space requirements from CubeSat to GEO-GEO link to deep space laser communications, and (bottom) environmental testing of various space amplifiers. Note: Photo of 50 W amplifier is actually that of a 100 W Fibertek space fiber laser that will eventually house the 50 W Erbium amplifier.

5. ACKNOWLEDGMENTS

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