Robust short-pulse, high-peak-power laser transmitter for optical communications

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ABSTRACT

We report on a pulsed fiber based master oscillator power amplifier laser at 1550 nm to support moderate data rates with high peak powers in a compact package suitable for interplanetary optical communications. To accommodate pulse position modulation, the polarization maintaining 1 W average power laser transmitter generates pulses from 0.1 to 1 ns with variable duty cycle over a pulse repetition frequency range of 10 to 100 MHz.

Keywords: Free space optical communications, laser, fiber amplifier

1. INTRODUCTION

Fiber based laser transmitters are a key component of a deep space optical communications system and have been under development for several years [1-3]. Previous work has concentrated on the high efficiency required for photon starved links without sacrificing the high peak powers required for pulse position modulation (PPM) waveforms. Due to the low quantum defect, pump coupling efficiency of double clad fibers, efficient pump diode development and the extensive work on high power systems for material processing Yb doped fiber amplifiers at 1.06 μm have been the system of choice [4,5]. However, current transmitter systems have included sources at 1.5 μm to leverage the robust terrestrial fiber optic telecommunication and near Earth high rate optical communications systems developed primarily for other applications [6]. Although there are overlapping requirements for planetary applications with terrestrial telecommunications, it is important to note that there are significant differences in the laser transmitter requirements which necessitate separate development. In particular, the PPM format with high peak powers and low pulse duty cycle requires high pulse extinction-ratio (ER) and stable, high polarization-extinction-ratio (PER) at high average power which extends that required by fiber optic telecommunications. Similarities include reliable, long term operation, short pulses for high bandwidth modulation and good mode quality for fiber coupling on the ground and pointing stability in free space systems.

The current work extends the development of previous 1064 nm fiber based laser transmitters to 1550 nm with sub-nanosecond pulse-widths while maintaining high peak powers in a master oscillator power amplifier (MOPA) architecture [1,3]. This enables high order PPM formats applicable to long range optical links [7]. Due to the large range variations of interplanetary optical communication links and wide range of background conditions encountered during day versus night time operations, selectable PPM orders and pulse-widths are needed to maximize the achievable return data rates. Using sub-nanosecond pulses, average data rates up to several hundred Mb/s can be accommodated for M-ary PPM for M = 16 to 256. The modular system shown in Fig. 1 was developed by Nuphoton to meet our requirements and comprises a pre-amplified seed laser followed by a separate booster amplifier to give 1 W of average power over a nominal pulse repetition frequency (PRF) range of 10 to 100 MHz utilizing pulse-widths from 0.1 to 1 nsec. A high data rate FPGA based PPM encoder has also been developed at JPL to supply the test patterns for various PPM orders and to support real time PPM encoding at data rates up to 1.2 Gb/s.

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2. LASER DEVELOPMENT

2.1 Architecture

The oscillator module consists of a directly modulated seed laser polarization maintaining (PM) fiber coupled to a single stage external modulator to improve the ER. The modulator bias control is a non-dither type to limit the influence of locking to the dither frequency by the receiver. A PM fiber pre-amplifier boosts the power to an average 30 mW output over the entire PRF range with a narrow band filter inserted to limit the amplified spontaneous emission (ASE). The wavelength of the narrow line-width DFB diode laser source is around 1550 nm.

The booster amplifier is a single stage device with both input and output isolation and a 2-nm narrow band pass filter for ASE cleanup at the input. Uncooled wavelength stabilized 975 nm pump diodes with 40% overall electrical-optical efficiency are used. Pump diodes at 1480 nm were investigated but the lower efficiency offset the smaller quantum defect from pumping at the higher wavelength. The active fiber used in the booster stage is PM Er-Yb co-doped dual clad fiber with an 8 µm single mode core diameter. The overall efficiency of the MOPA is on the order of 3%, slightly below the goal of 5% due to the lower efficiency of the preamplifier stage.

(a) **(b)**

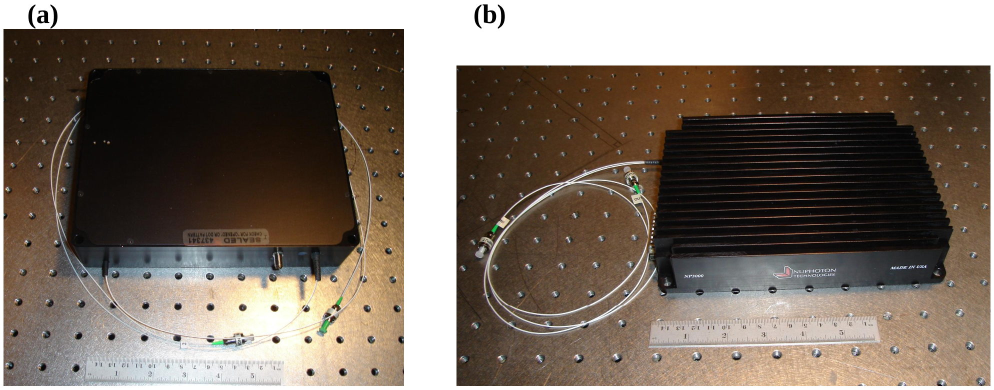


Fig 1. (a) Seed and (b) amplifier modules

With the emphasis on a compact and robust package for future field tests and as a precursor to a flight-like engineering model, Telcordia certified components were specified to the extent possible [8]. This included the seed diode, external modulator, fiber pump diodes, doped fiber, tap couplers, monitor PIN diodes, gain flattening filters and output isolator. Typical vendor data for the 980 nm pump diodes (low power devices in the pre-amplifier) showed wear out and random failures of 900 FITs and 2000 FITs respectively or mean time between failure (MTBFs) of up to 40 years. The high power multimode pump diodes in the booster stage have been certified to 10,000 hours MTBF minimum. However, a new design could employ the telecom graded pump diode which would offer Telcordia certified reliability. The other passive components have FIT values below 20 signifying device maturity applicable to a future space-borne optical communications transmitter.

The PPM encoder is based on a previous FPGA Virtex IV design upgraded with faster components and multiplexed serializers to generate a range of pulse widths in increments of 100 ps pulses at variable PRFs [2]. Since fiber amplifiers are peak power limited and the peak power increases with decreasing PRF, the PRF lower limit is determined by the maximum pulse delay that produces the peak output power to avoid fiber damage. Table 1 shows the limiting frequency for various pulse-widths and PPM orders. Taking a baseline pulse-width of 0.3 ns, 128-PPM and possibly 256-PPM can be supported with the Nuphoton laser PRF specification, depending on the measured ER. The laser was hence designed to support PRFs from 10 MHz to 100 MHz with variable DCs. These specifications were derived from the maximum and minimum pulse delay that one should expect to see under typical modulation formats using a PPM order of 64-ary as a baseline. As an example, different pulse formats are shown in Fig. 2 where, for instance, the maximum pulse delay for a 64-PPM word corresponds to a 1-bit word followed by a 63-bit word or 2 x 63 slots. A guard time for receiver synchronization is also included in our scheme, but is encoded into the actual word [9]. In addition to providing an energy free pattern for PPL slot and symbol clock recovery, the guard time mechanism also ensures that the laser transmitter never has to output a double pulse-width.

Table 1. Lower pulse repetition frequency limits (MHz) as a function of PPM order and pulse-widths. Shaded values supported by current laser specification.

Pulse-width, ns	16-PPM	64-PPM 1	28- PPM	256-PPM
0.1 333		79.4	39.3	19.6
0.3	111	26.5	13.1 6.	5
1.0	33.3 7.	9	3.9	2.0

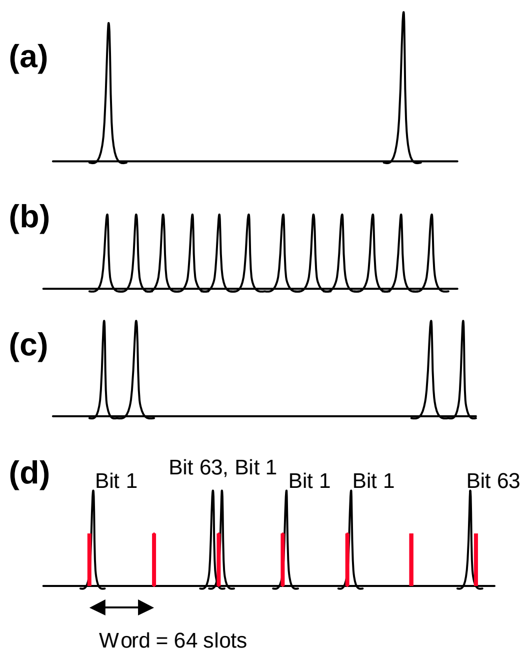


Fig. 2. Pulse modulation format for various PRFs on the same timescale; (a) 10 MHz, (b) 100 MHz, (c) 10/100 MHz, and (d) extreme case 64-ary PPM for 0.3 ns pulses. The hash marks represent 64-PPM word lengths.

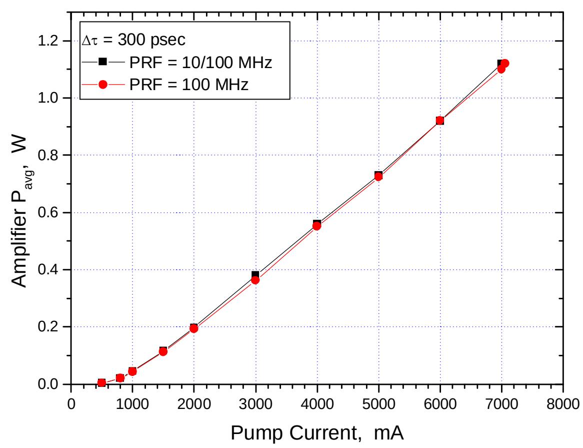
2.2 Measurements

Pulse measurements were obtained with a 5 GHz detector coupled into an 8 GS/s digitizing oscilloscope. Optical spectra were recorded in an Optical Spectrum Analyzer with 0.01 nm resolution. The beam quality measurements were taken with a coated silicon CCD and beam analyzer software. Polarization measurements were taken with a 1000:1 polarization beam splitter (PBS) cube coated for 1550 nm. Extinction ratios (ER), defined as the P_{on}/P_{off}, were measured directly and inferred from the average power along with the duty cycle and pulse width. Although the system was capable of 100 ps pulses, due to available detectors and the jitter limitations of present photon counting detectors and the impact of deep space optical link efficiency, testing was predominantly performed with pulse-widths above 300 ps [10].

3. TEST RESULTS AND DISCUSSION

Initial average power measurements (Fig.3) for the MOPA laser transmitter as a function of the amplifier diode pump current for various PRFs show no variation in power with PRF. The output power of the seed and amplifier were also monitored separately as a function of the pulse-width in Fig. 3(b). Wavelength spectra exhibit negligible influence of fiber nonlinearities. Figure 4 shows an example case for 300 ps at 104 MHz with other spectra taken under high peak power associated with the lower PRF and shorter pulse-widths in the amplifier giving similar results. Some slight spectral broadening at the higher peak powers and shorter pulse-widths due to self phase modulation was apparent when the relative pulse energies were plotted as a function of spectral width around the laser line in Fig. 5.

(a)



(b)

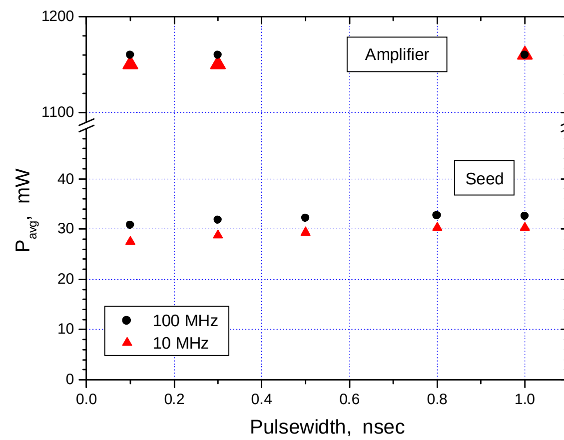


Fig. 3. Average output power (a) as function of amplifier pump current and (b) input pulse width, $\Delta\tau$.

The temporal pulse shape was fairly uniform down to the detector limit and is shown in Fig. 6 for 300 ps to 1 ns. Although not calibrated absolutely, the variation in peak power can also be seen for the range of PRFs in Fig. 7. The 64-ary PPM worst case represents a maximum pulse delay of 26.45 MHz [= 1/(2 x 63 x 300 ps)]. An important aspect of optical links with photon counting receivers is that the pulse energy should be uniform over the various pulse delays associated with PPM. As the PPM order increases, the pulse delays can be significant, and are limited ultimately by the energy state lifetime of the laser amplifier media. For the desired PPM orders, the variation of the pulse energy in the laser, also referred to as gain ripple modulation, was measured for a worst case pulse pattern Figure 8 demonstrates a minimal variation of 0.3 dB in the peak powers for 1 ns pulses with the variable pulse delay associated with interleaving a 10 and 100 MHz PRF.

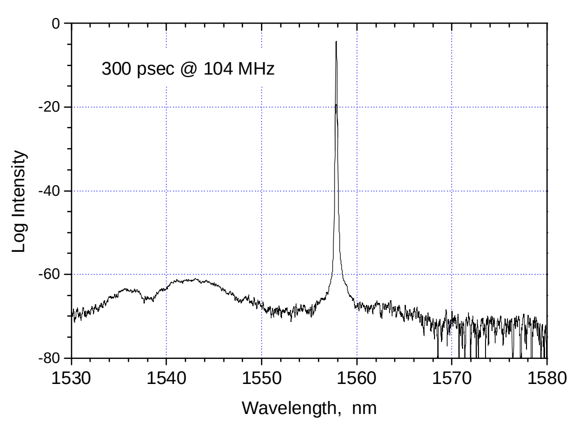


Fig. 4. Wavelength spectrum. ASE and nonlinear effects are over dB down from the laser line peak.

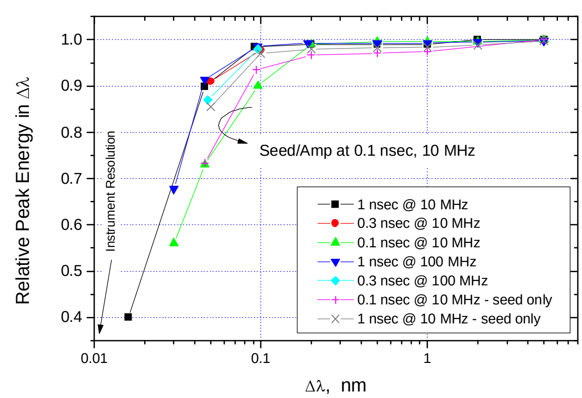


Fig. 5. Relative pulse energy vs.laser linewidth

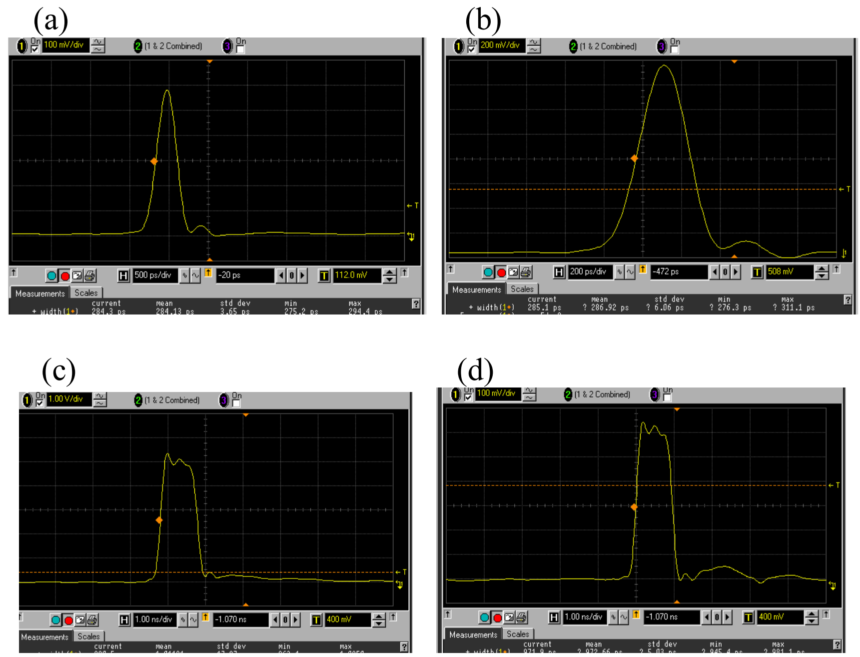


Fig 6. Temporal output pulse shape (a) seed laser output for 0.3 ns at 10 MHz; (b) amplifier output for 0.3 ns at 10 MHz; (c) amplifier output for 1 ns at 10 MHz and (d) amplifier output for 1 ns at 104 MHz

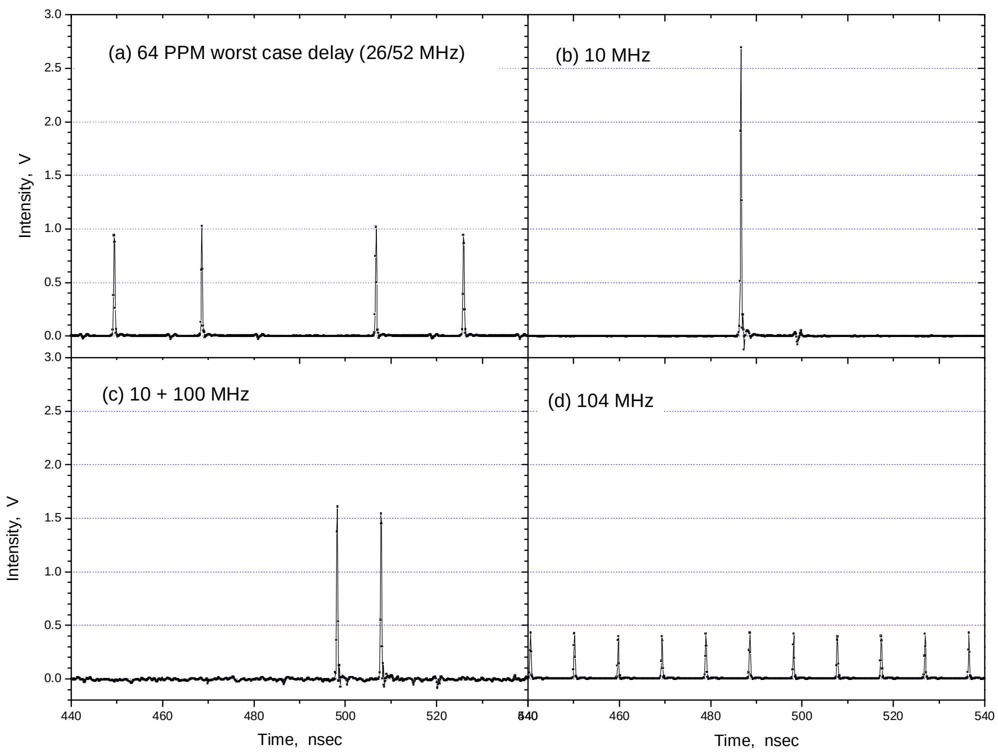


Fig 7. Amplifier output with 0.3 ns pulse-widths at variable PRFs showing the variation in peak power with variable pulse DC.

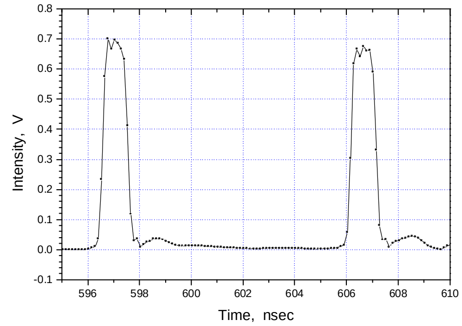


Fig. 8 Amplifier output with 1 nsec pulses for bit pattern corresponding to 10 and 100 MHz PRF showing slight gain depletion.

The pulse ER was measured directly and found to be 25 +/- 1 dB over the range of PRFs. Since the 'off' states are difficult to measure, the relative peak heights for different fixed PRFs could also be measured and compared to the analytical forms in Fig. 9 to derive the ER [11]. An estimate for ER = 27 dB was derived by comparing the relative peak powers at 10 and 100 MHz for each pulse-width and duty cycle and is consistent with the direct measurement. For the 0.3 ns pulses, this corresponded to a peak power of 200 W at 10 MHz and 31 W at 100 MHz. Comparing to the measured peaks of Fig. 7, the worst case of 64-PPM gave a peak power of around 70 W. Experimentally, the goal of 30 dB could be obtained over a limited PRF range but optimizing the ER over all the pulse formats and PRF meant that the maximum achievable ER was reduced to the measured values. The effect on the optical link can be seen by noting that with a measured ER = 23 dB, the actual peak power would be reduced by a factor of 2 from that with no power in the off state or perfect ER at 10 MHz. For higher PPM orders (and hence lower DC) this is a significant issue in limiting the measured received pulse energy in a PPM symbol.

The device was built with PM components throughout to ensure a polarized output. However, the PER varied considerably over time up to a maximum of over 20 dB. The origin of this variation is currently being investigated and is thought to arise in the direct pulsing of the seed laser source.

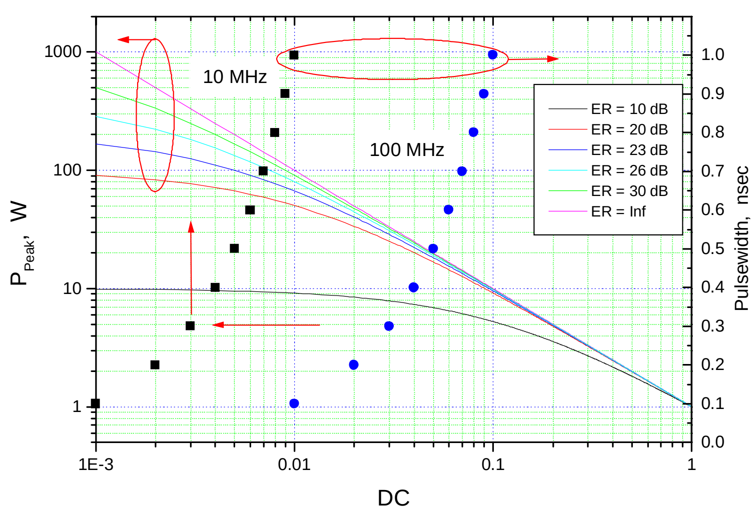


Fig. 9. Peak power as a function of duty cycle (DC) and extinction ratio (ER) for various pulse-widths. P_{avg} = 1 W

Pulse jitter is also a key parameter in PPM formats where timing of the pulse encodes the data transmitted. The main contribution of the measured rms jitter of 3.53 ps of the laser at 1 W average power and at 10 MHz was from the PPM encoder (3.43 ps) and well within the specification of 10 % of the pulse-width.

The output quality of the beam was also measured using the M^2 method. Values of 1.16 and 1.17 in the x and y direction respectively at 1 W output power are seen in Fig. 10 demonstrating that the beam is essentially single-mode.

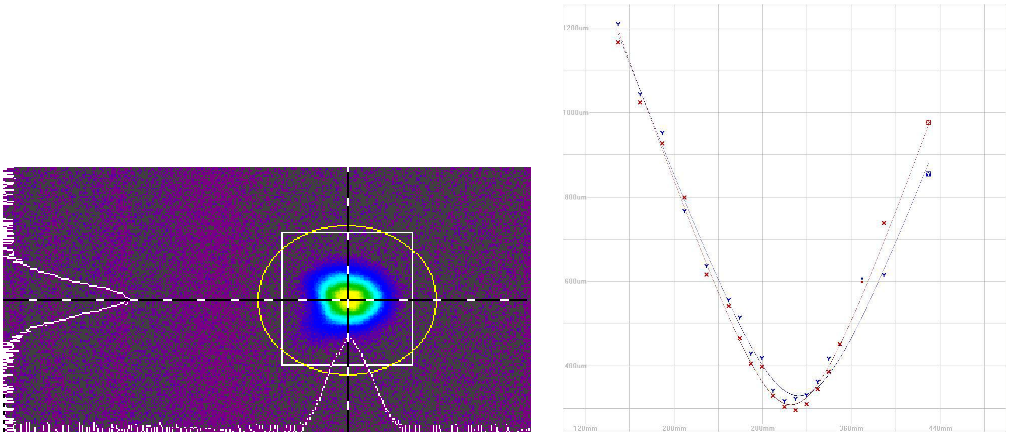


Fig. 10 Beam quality measurement with sample beam profile and M^2 data. Beam diameter vs. camera-lens `distance with y-axis 0.1 mm divisions and x-axis 40 mm divisions.

4. CONCLUSION

A fiber based MOPA laser was developed in partnership with industry to meet the requirements of a prototype deep space optical communications transmitter in the 1550 nm wavelength region. The power and modulation rate would support lunar, Lagrange, Venus and Mars ranges for at least M = 16 to 64 M-ary PPM with a robust package derived from Telcordia certified components to the extent possible. A full space-qualified design would require further screening and thermal vacuum and radiation testing in a comprehensive test plan.

5. ACKNOWLEDGEMENTS

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