

High-Rate High-Power Uplink Laser Transmitters for Future Deep Space Optical Communications

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ABSTRACT

Current uplink laser transmitters have demonstrated kbps uplink data rates for deep space optical communications systems with a multi-beam transmitter consisting of over 500 W average powers from a single transmitter in the Deep Space Optical Communications (DSOC) project. The primary JPL ground station in California used multiple custom devices that were modified from commercial continuous wave (cw) systems and co-propagated as sub-aperture beamlets arrayed though a single transmit aperture. Future NASA mission requirements for supporting human exploration of deep space call for higher data rates while maintaining up to kW class average powers for the long-range applications. We will present performance data and results of some recent laboratory work to support data rates over 1 Mbps with kW class average powers in fiber-based lasers using recently available fiber designs. Peak powers up to 50 kW were demonstrated using OFS fiber, limited by the fiber optical nonlinearities which can support over 20 Mbps uplink data rates depending on the actual link range.

I. INTRODUCTION

The DSOC project has successfully demonstrated bidirectional optical communications from deep space ranges on the Psyche mission. The uplink transmitter supported a 1.8 kbps uplink pulse position modulation (PPM) data rate using ten lasers synchronized to provide over 5 kW of average uplink power at nominally 1064 nm wavelength in the technology demonstration up to 3 AU distances [1]. The uplink laser operational performance was summarized previously [2]. However, future optical communications to deep space, in particular, to Mars type ranges for human exploration, will require much higher uplink data rates greater than 1 Mbps and with similar average powers. The data rate of the current DSOC uplink laser transmitter was enabled by modulation of the pump laser diodes at the kHz repetition rates in the third high power stage with low order binary PPM and a two-slot inter-symbol guard time. This effectively led to a peak to average power ratio of 4 which can be supported by the individual laser units operating at nominally 500 W of average power or 2 kW of peak power and pulse widths of 65 μ sec. Higher data rates require a different architecture to support higher order PPM with nanosecond pulses at higher pulse repetition rates and hence much higher peak powers. Seed laser modulation is required along with novel fiber amplifier designs that can accommodate the peak powers to avoid fiber nonlinearities that can limit the spectral power in the laser line pass band. Though at much lower average powers, it is worth noting that the recent lunar optical communication experiment on the Artemis II spacecraft, Optical to Orion or O2O project, demonstrated up to 20 Mbps uplink data rates with 5 individual commercial laser transmitters capable of 10 W average power each at 1550 nm and synchronized with nanosecond pulsewidths [3]. However, extending these data rates with kW class laser transmitters requires development above what is commercially available.

The present paper addresses recent development and testing of high-rate, high power fiber based optical amplifiers as part of the uplink laser transmitter configuration to meet the future NASA mission communication requirements for long range applications. PPM is assumed, similar to that used for the downlink laser transmitter, to support the photon starved optical links.

The first section compares and summarizes the various high power laser transmitter designs to meet the high-rate data requirements as summarized in a recent Mars architecture study and starting with modification of the DSOC laser transmitter design developed by Attalon, formerly, Coherent. MIT-LL has also developed a high power, high-rate uplink laser transmitter utilizing a new OFS (now Lightera) fiber that can support much higher peak powers [4]. The next section describes the performance data from the Attalon and MIT-LL systems that have been tested including comparisons with modeling efforts reported in [5]. Finally, we will conclude with implications of these results on future mission opportunities.

II. HIGH-RATE HIGH POWER LASER DEVELOPMENT

A. High-rate high power uplink laser optical communication requirements

Link budgets for uplink communication at Mars-type ranges for future human exploration missions assume high-rate photon counting receivers that can support from 2 to 20 Mbps using higher order PPM with nanosecond pulsewidths using current GM-APDs or future flight qualified SNSPD detectors, respectively. Average uplink transmit powers are on the order of 5 kW from an array of ten lasers for each of these cases or 20 kW peak power from individual laser transmitters. This is the baseline used in the current study to demonstrate the laser technology required to support the data rates above. Other key parameters include GHz or less laser linewidth to ensure sufficient laser pulse energy through the receive filter to eliminate background light and high pulse extinction ratio of > 20 dB for slot detection.

B. Extending current DSOC laser transmitter performance –Attalon, formerly Coherent.

The current DSOC laser transmitters were based on the cw commercial SPADE systems developed by Attalon and were limited to a 2.7 kW peak power, corresponding to the cw power. To enable higher pulse repetition rates and hence higher peak powers with the shorter nanosecond pulsewidths, the fiber in the final stage has been upgraded by the manufacturer Attalon, for the current laser testbed. This testbed uses similar components to those used in the delivered Uplink Laser Assembly (ULA) units with modification by the manufacturer, Attalon, and tested under various pulse parameters. The modifications included three different configurations. The first change involved shortening the passive output fiber, initially delivered with approximately 3m lengths in order to rack mount the units separate from the uplink optical assembly bench. The second configuration change involved reducing the length of the third stage active gain fiber that is being pumped. The final configuration change involved replacing the shorter gain fiber with a slightly larger fiber core diameter. Each of these configurations was tested with a fixed pulse repetition frequency of nominally 12 MHz, 4 ns pulsewidth and also with a pseudo random pulse sequence (PRBS) to emulate real data with the variable pulse delays between pulses corresponding to PPM with m=16 typically. A summary of the data will be shown in the next section. Along with the power measurements, spectral power in the laser linewidth was noted for broader 30-nm bandpass as well the more applicable bandpass of 1 nm that was used in the DSOC demonstration. Pulse extinction ratio and pulse stability were also monitored up to the onset of the fiber nonlinearities such as stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) and compared with previously modeled systems [5]. Typically, the threshold for the nonlinearities was determined by 90% of power in either the 30 nm or 1 nm bandpass. The pass bandwidth was chosen to isolate the impacts of different non-linearities on the optical spectrum. With the 30nm bandpass, out-of-band power was attributable primarily to SRS and could be benchmarked against theoretical SRS gain models, while with the 1nm bandpass, amplified spontaneous emission and self-phase modulation also contributed. Considering both pass bandwidths enabled optimization of seed laser pulses to mitigate all of these effects.

C. MIT-LL laser testbed

The short pulses required for use in high data rate transmitters can cause undesirable nonlinear effects in fiber amplifiers when used at high power, thereby limiting the pulse energy that can be produced. The dominant nonlinear effects are Stimulated Raman Scattering (SRS) and Stimulated Brillouin Scattering (SBS) and the critical power levels for onset can be estimated as [6]:

$$P_{crit,SRS} \approx 16 \frac{A_{eff}}{g_R L_{eff}} \text{ and } P_{crit,SBS} \approx 21 \frac{A_{eff}}{g_B L_{eff}}, \quad (1)$$

where A_{eff} is the effective mode area, g_R and g_B are the Raman and Brillouin gain coefficients, and L_{eff} is the power-weighted length of the fiber:

$$L_{eff} = \frac{1}{P(L)} \int_0^L P(z) dz. \quad (2)$$

SRS and SBS are both related to the propagation length and local irradiance levels inside the optical fiber and their effects can be reduced by increasing P_{crit} , i.e. increasing the mode-field diameter (MFD) of the light propagating in the fiber and/or shortening the length of the fiber. Increasing the MFD can also cause the

waveguide to support higher order modes, which impacts the beam quality and can also cause instabilities related to mode beating, known as transverse mode instability (TMI) [7,8]. Specialty fibers have been created to try to increase the MFD without leading to TMI issues. Shortening the fiber leads to lower efficiency, which to a point, is typically not a concern for ground-based applications.

A testbed system was constructed (

Figure 1) to characterize the performance of a new fiber from OFS (now Lightera) having a large (24.5 mm) MFD that is also able to suppress TMI effects. The testbed consists of a narrow, kHz-class linewidth CW seed laser, which is amplified from 5 mW to 100 mW by a ytterbium-doped fiber amplifier (YDFA) before being chopped into pulses with an electro-optic Mach-Zehnder modulator to create transform-limited-linewidth pulses of variable pulse length, typically 1 – 10 ns. This is followed by a phase modulator, which is optionally used to line-broaden the transform-limited pulses. Line broadening can be used to suppress SBS for pulses longer than ~2 ns in order to concentrate investigations to purely SRS, or purely SBS effects, and could also be used in fielded systems if pulse lengths longer than ~2 ns are expected to be used.

The pulse chopping has a duty factor of ~1%, thereby reducing the average optical power by > 100x when also accounting for insertion losses of the modulators, so a second YDFA pre-amp is needed to increase the output power of the laser front end to ~5 mW. The high-power YDFA consists of 3 stages having optical isolators between stages. The third stage contains the large-MFD specialty fiber, which amplifies the average power from ~5 W to as much as 1 kW, limited in power by the available pump diodes.

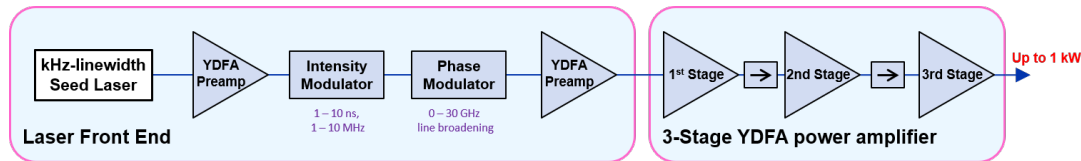


Figure 1 Block diagram of MITLL laser testbed. YDFA = Ytterbium-doped fiber amplifier

D. Other high-rate high power laser development

Other separate developments include Hamamatsu (formerly NKT Photonics) that delivered a high-power uplink beacon laser which supported the ESA demonstration to the DSOC flight terminal on the Psyche spacecraft transmitting a total of 6.5 kW as a tracking source from 5 units [9]. Though not used as a communication uplink in the experiment, it was capable of modulation at 1 MHz but only tested at significantly lower average power of 150 W with 50 % duty cycle for a single unit. Further development is being pursued using novel fiber designs with much higher peak power thresholds. Under a NASA SBIR, PSI is also seeking to develop a high-power uplink laser transmitter using an alternative fiber design to support the high peak powers and fabricated at MIT-LL, separate from the above work.

III. RESULTS and DISCUSSION

A. Modified DSOC laser testbed from Attalon.

Using the initial design wherein a cw seed laser was followed by the electro-optic intensity modulator (EOM), measurements using PPM 16 and 4 ns pulsewidths compared the in-band powers for the four different configurations (including the base configuration). The 90% inband powers increased for each successive configuration change with up to approximately 150% increase in configuration 4 compared to the base design though still limited to around 245 W average power with PRBS modulation. However, it was observed that the measured inband powers were limited by the ASE from the seed amplifier. Placing the intensity modulator after this seed amplifier improved the performance and gave the following results. The inband power fraction remains above 99% for average powers up to 665 W or a mean peak power of 10.9 kW for the final configuration with shorter large mode area fiber in stage 3 as shown in Fig 2(a), with the peak to average power ratio shown in Fig 2(b). The pulse extinction ratio is shown in Fig 2(c) and is fairly constant up to full power. A histogram of the intrapulse or peak powers is shown in Fig 2(d).

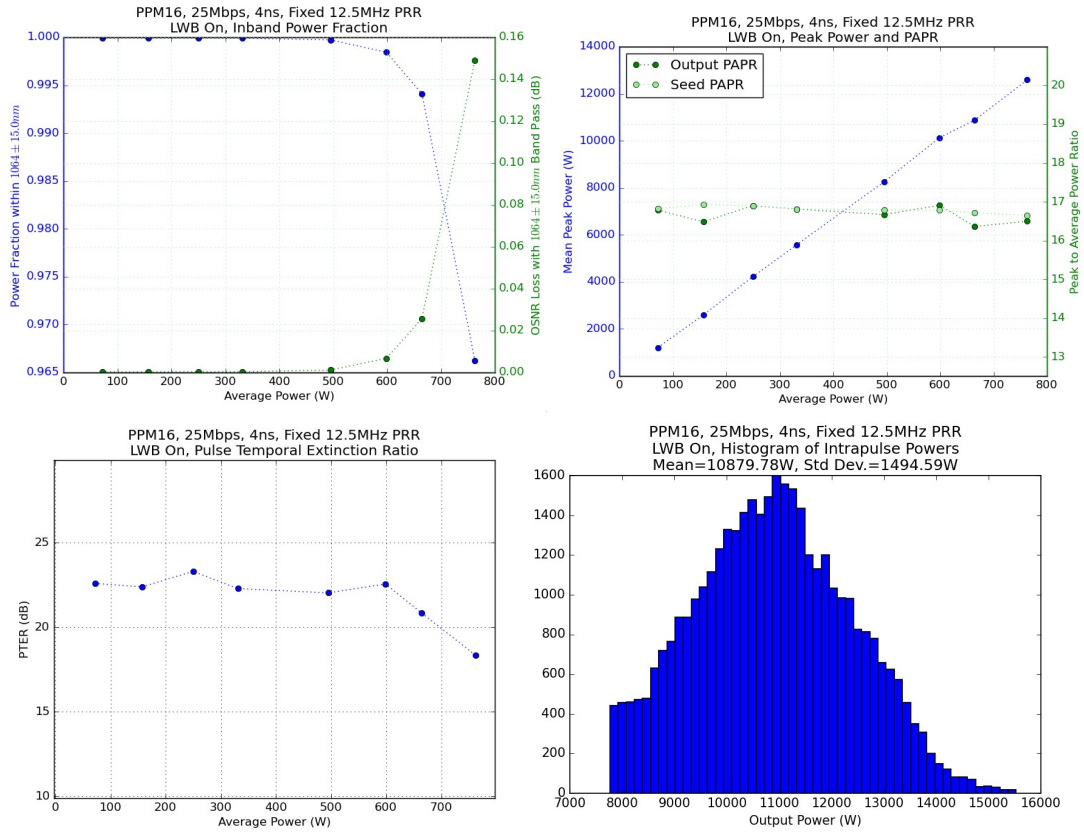


Figure 2. Inband power measurements from final configuration 4. (a) Inband power, (b) peak to average power, (c) pulse extinction ratio and (d) intrapulse power histogram at 665 W average power. Data courtesy of Attalon

However, if we use a narrow bandpass that eliminates power outside a 1 nm passband, the inband power does not exceed 80% as seen in Figure 3.

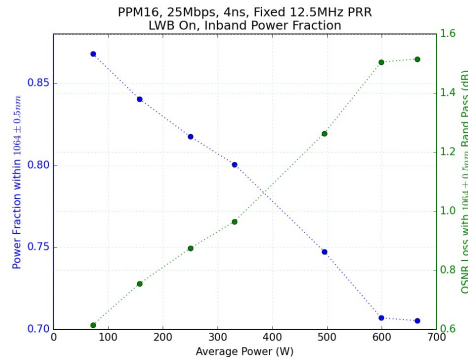


Figure 3. Inband power with more applicable 1 nm bandpass with reduced power due to ASE. Data courtesy of Attalon

To understand this discrepancy, we can look at the output spectrum seen in Fig. 4(a) with zoomed in profile in Fig. 4(b), which shows ASE around 1064nm and SRS primarily at 1115 nm. The 1064 nm signal peak can also be seen to broaden with increased average power, likely due to self-phase modulation. This implies that the dominant contributor to out-of-band power in this configuration is not SRS, but instead is ASE and self-phase modulation. Further work can be done to optimize seed power and seed temporal characteristics to mitigate these effects.

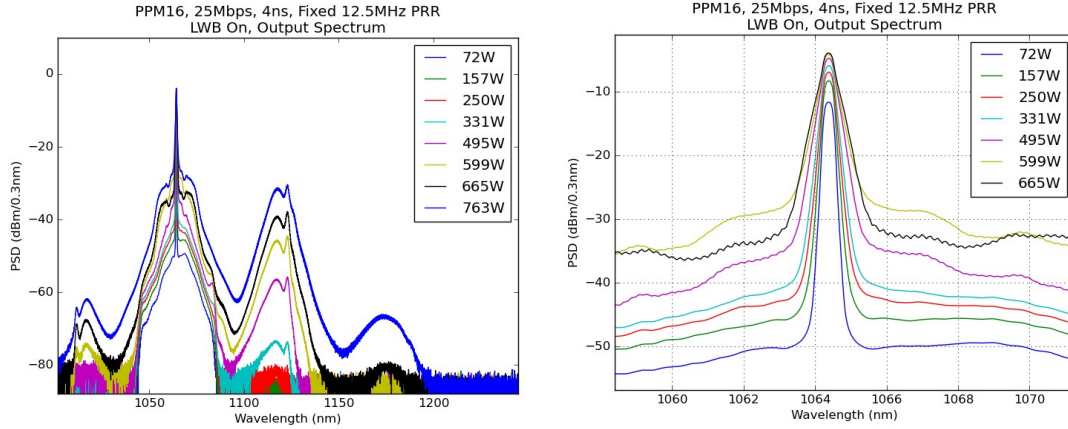


Figure 4. Laser spectrum from final configuration, and magnified line center (right). Data courtesy of Attalon

Overall, we were able to improve the peak power capacity of the current DSOC laser amplifier up to 10.9 kW by upgrading the fiber configuration in the final amplifier stage of the commercial devices. Paths to optimizing out-of-band power and scaling beyond 10.9 kW have been identified and may be pursued in future work.

B. MITLL test results on OFS (now Lightera) fiber laser transmitter

A variety of fiber lengths were used for the large-MFD fiber under test, ranging from 4 – 8 meters.

Figure 5 shows the beam profile and gain model for a 4.1-m gain fiber. The beam profile is near-Gaussian at the 600-W output power, as desired. The gain model shows the pump and signal power evolution along the length of the fiber, as well as the 68% optical-to-optical (o-o) efficiency and the 2.3-m effective fiber length (eqn. 2) that is relevant to SRS and SBS effects.

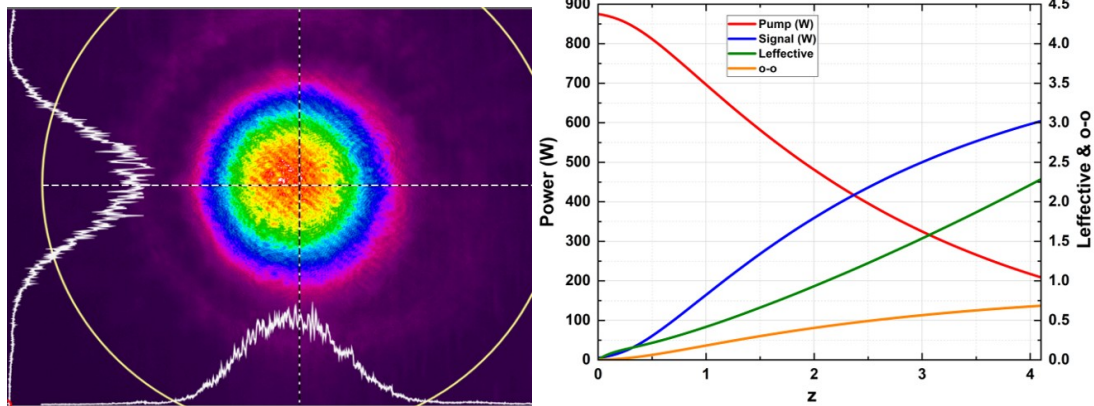


Figure 5. Output of the laser has near-Gaussian beam profile (left), modelled performance of the laser (right).

Figure 6 illustrates the effects of SRS and SBS on the laser. As a rule of thumb, when 2% of the laser power is in the Raman peak, we label this as the SRS threshold. Figure 7 shows the fraction of power in the signal decreasing as SRS becomes more dominant for higher peak power. The SRS threshold for a 7.4-m gain fiber ($L_{eff} = 4.8$ m) is 26 kW and for a 4.1-m gain fiber ($L_{eff} = 2.3$ m) it is 53 kW, which is consistent with the effective fiber length scaling suggested by equation 1.

The SBS gain has a linewidth of ~ 100 MHz for 1-mm wavelength light in fused silica so linewidths larger than this cause a large drop in the SBS gain coefficient, thereby suppressing SBS effects. For high-power CW lasers, the linewidth is intentionally broadened using a phase modulator and similar benefits can be achieved for pulsed lasers. Figure 8 shows modelled lines and experimental points where the critical SBS power is reached for transform-limited linewidths (“Unbroadened” red and blue data) and for 30-GHz broadened linewidth (purple and yellow). Above these values it is likely that damage to the laser will occur. There are additionally

two lines showing where the SRS threshold is reached for the two different fiber lengths discussed earlier. Above the green lines, laser operation will be limited by SRS rather than by SBS. For short pulses, the transform-limited bandwidth increases sufficiently to suppress SBS such that SRS becomes the dominant nonlinearity.

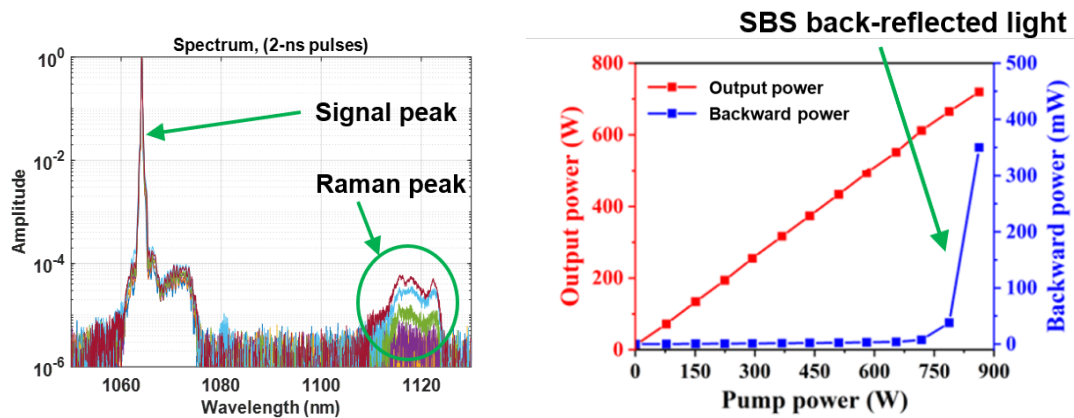


Figure 6 SRS and SBS nonlinearities become evident as the laser power is increased. SRS robs power from the desired signal, SBS can generate large backward pulses, damaging the laser

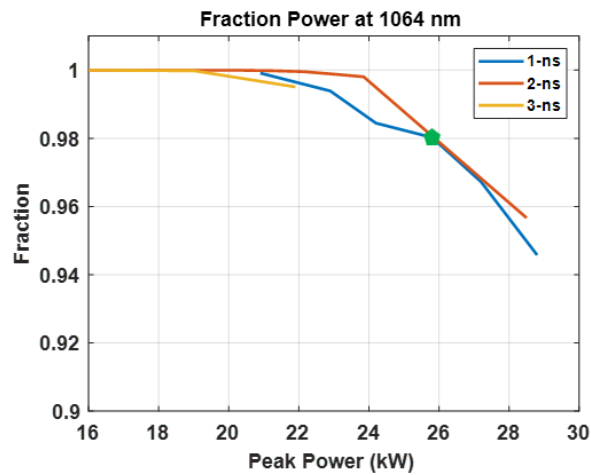


Figure 7 The fraction of power in the signal decreases as peak power is increased, leading to more power being converted to the Raman wavelength. At 26 kW peak power, 2% of the signal is lost to SRS for this 7.4-m gain fiber.

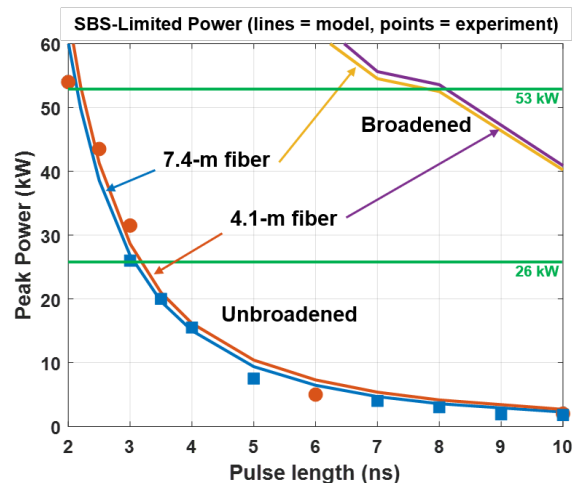


Figure 8. SBS-limited peak power as a function of pulse length. “Unbroadened” (red and blue) data is transform-limited-linewidth pulses, and “Broadened” (purple and yellow) data uses 30-GHz linewidth from the phase modulator. Above the green 53 kW and 26 kW lines SRS will become the limiting nonlinearity for the two fiber lengths, rather than SBS being the limiting factor.

The discussion on SBS so far has been with respect to a single pulse propagating in the optical fiber. Now we consider the effects from a train of pulses as would be present in a PPM-style modulation as shown in Figure 9. SBS consists of acoustic waves generated by the electric field of the light, which cause density variations in the medium that in turn reflect some of the light, creating a runaway feedback effect. The reflected SBS light always propagates in the opposite direction of the signal light. When pulses are closely spaced in time, and therefore in space, it is possible for the backward propagating SBS light to seed SBS in a subsequent pulse if the next pulse enters the fiber before the previous SBS light pulse has exited the input end of the fiber. This effect sets a minimum pulse separation (t_{min}) equal to the round-trip time of flight through the fiber ($\sim 10 \text{ ns} \times \text{length of the fiber in meters}$). Additionally, the acoustic phonon lifetime is $\sim 10 \text{ ns}$, so acoustic energy is present even at times somewhat longer than the round-trip time of flight, but for practical purposes, t_{min} can be set to the round-trip time of flight.

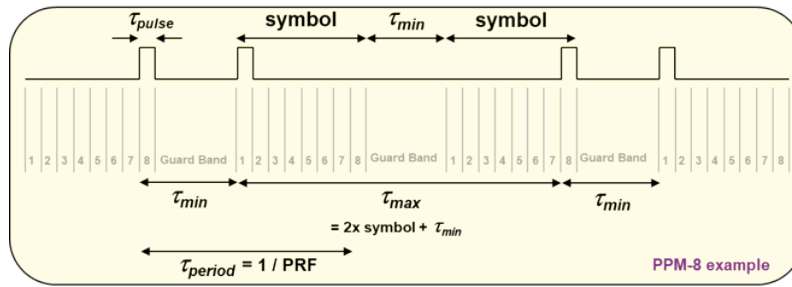


Figure 9. Definitions for PPM waveform modulation.

There is also a maximum allowable pulse separation (t_{max}) that is set by variation in the pulse amplitude related to gain dynamics in the fiber. During a laser pulse, energy is being extracted from the upper state of the laser transition, and between pulses this population is being replenished. For small pulse energies, there is little effect on the upper state population, but if the extracted energy approaches the saturation energy (eqn. 3), then a variation in pulse energy will become evident when two closely spaced pulses are followed by a large delay before the next pulse arrives. This effect is apparent in Figure 10.

$$E_{sat} = \frac{A h \nu}{\sigma_{em} + \sigma_{abs}} = \frac{\pi (12.25 \times 10^{-6})^2 \times 1.87 \times 10^{-19}}{3.5 \times 10^{-25} + 0} \approx 250 \mu\text{J} \quad (3)$$

As the peak power increases, the pulse energy is obviously increasing as well, leading to a reduction in the maximum allowable pulse separation. For a 7.4-m fiber having 24.5 μm MFD operating at the SRS threshold, t_{max} was found to be $\sim 240 \text{ ns}$ to maintain a pulse amplitude variation of less than 10%, and for a 4.1-m fiber operating at the SRS threshold, t_{max} was found to be $\sim 180 \text{ ns}$.

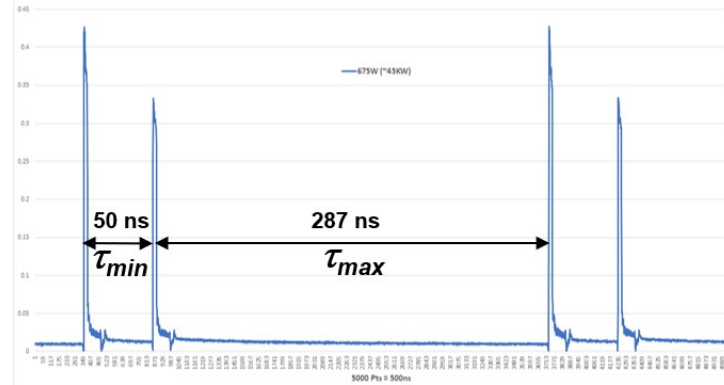


Figure 10. Pulse height variation caused by gain dynamics. Pulse energy variation of 19% illustrated with $\sim 110 \text{ mJ}$ pulses.

Now we discuss how these physics effects: 1) SRS, 2) SBS, and 3) saturation energy; affect the overall data transmission rate that can be achieved for a high-power uplink transmitter. Figure 11 illustrates achievable data rates for various PPM orders vs pulse length. If the physics effects are ignored, the data rate would be:

$$R_0 = C * PRF * \log_2(m) \quad (4)$$

where C is the code rate (nominally 0.5), PRF is the average pulse repetition frequency, and m is the PPM order. When the peak power limitations of SRS and SBS are imposed, along with minimum and maximum pulse separation constraints, the maximum data rates are reduced, with the two fiber lengths producing somewhat different results in the 20 – 30 Mbps range.

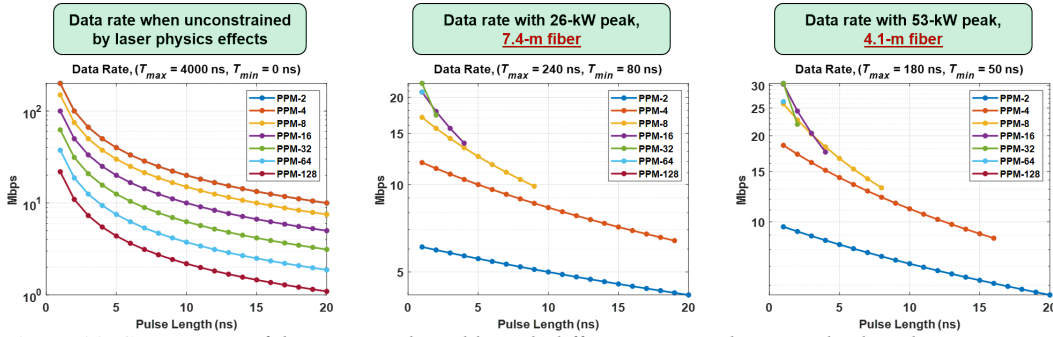


Figure 11. Comparison of data rates achievable with different PPM orders vs pulse length, unconstrained by physics (left), physics constraints of a 7.4-m fiber (center), and physics constraints of a 4.1-m fiber (right).

The laser pulse energy here is $\sim 100 \mu\text{J}$ per fiber laser. In a ten-laser array as is currently in use for the DSOC uplink transmitter, the aggregate pulse energy is $\sim 1 \text{ mJ}$, which is sufficient energy to close the link at an Earth – Mars distance. This supports data rates of up to 30 Mbps depending on the actual link ranges required and the receiver design.

IV. CONCLUSION

The DSOC experiment has demonstrated uplink optical communication to deep space ranges at low data rates with current high power laser technology. Increasing the performance of the high-power uplink laser design using novel optical gain fibers to support higher peak powers and hence higher data rates has been demonstrated in this report with laboratory prototypes and continues to be developed. Using higher order PPM, data rates over 20 Mbps with nanosecond pulsewidths at over 500 W average power and up to 50 kW peak powers have been implemented to support uplink optical communication for future NASA human exploration to Mars.

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