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High-Performance Free-Space Optical Communications System Based on High-Power Fiber Amplifiers

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***Abstract*—A high-performance free-space optical communications system is designed around the capabilities and limitations of high-power large-mode-area Yb-doped fiber amplifiers.**

Keywords—free-space optical communications, fiber amplifier

I. Introduction

Closing deep-space optical communications links at greater than lunar ranges requires overcoming enormous propagation losses. For terrestrial transmitters, the benefits of increasing the transmit aperture are limited by atmospheric turbulence. Size, weight, and power (SWaP) considerations limit how large a receive aperture is practical on a satellite. Detectors require at least one photon of received light per transmitted symbol, which encourages the use of waveforms that encode multiple bits of information on each received photon. High-order pulse-position-modulation (PPM) waveforms provide the required photon efficiency, but have practical limitations. Ultimately, deep-space optical uplinks will require a powerful transmitter, preferably one that operates with a diffraction-limited beam and can provide high-energy pulses in a low-duty-cycle communications waveform that takes maximum advantage of the amount of information a transmitted pulse can convey.

This study was motivated by the desire to optimize the performance of large-mode-area (LMA) Yb-doped-silica fiber amplifiers for applications in deep-space optical communications. The performance of the amplifiers is optimized by balancing the effects of Stimulated Brillouin Scattering (SBS), Stimulated Raman Scattering (SRS), and Transverse Mode Instability (TMI). The capabilities and limitations of LMA fiber amplifiers are discussed in Section II.

To operate at its maximum pulse energy and average power, a fixed-frequency short-pulse amplifier must operate at a fixed repetition rate with pulses of fixed amplitude. To encode information on the output of the amplifier, either the pulse amplitude or timing must be modulated. Section III begins with a discussion of a communications waveform that allows the amplifier to operate close to its maximum output power — a sparse, low-order PPM waveform. It concludes by proposing a communications system concept that takes advantage of that waveform.

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Section IV discusses how to fully characterize a high-power Yb-doped fiber amplifier for applications in deep-space optical communications once it is in hand, under the assumption that it will be used to generate a sparse PPM waveform as discussed in Section III.

II. Capabilities and Limitations of LMA Fiber Amplifiers

The performance of a pulsed, high-energy LMA Yb-doped-silica fiber amplifier operating in the nanosecond pulse regime is limited by SBS, SRS, and TMI. The thresholds for each of these effects are discussed in this section. With the proper selection of pulse width, it is possible to eliminate SBS as a limiting factor in the performance of the amplifier and to maximize the pulse energy. The maximum average power can then be achieved by optimizing the fiber core diameter. The resultant performance capabilities are discussed at the end of this section.

A. SBS Threshold

If a fiber amplifier is operated in the short-pulse regime, with a pulse length shorter than twice the transit time of light through the fiber, the SBS-limited peak signal power in the fundamental mode of the fiber is

$$P_{\mathrm{lim,SBS}} = \left[\frac{\pi d_{\mathrm{mode}}^2}{8}\right]\left[\frac{2\left(\theta_{\mathrm{B}}-\theta_{\mathrm{O,B}}\right)\mathrm{n}}{\mathrm{g_B} c\tau}\right]\left[\frac{\mathrm{T_B}\left(\theta_{\mathrm{B}}-\theta_{\mathrm{O,B}}\right)}{\tau}+1\right]\left[\frac{\Delta\nu_{\mathrm{S}}}{\Delta\nu_{\mathrm{B}}(I_{\mathrm{signal}})}+1\right] \quad (1)$$

(based on Keaton [1] and Agrawal [2]). In this equation, the first bracketed term on the right side converts intensity to power and d_{mode} is the $1/e^2$ diameter of the fundamental fiber mode.

The second bracketed term of (1) corresponds to the cw expression for the SBS limit, where the effective interaction length for the forward-propagating signal pulse and backward-propagating Brillouin pulse is one half the pulse width τ multiplied by the speed of light in the fiber, c/n. The Brillouin gain coefficient is $\mathrm{g_B}$ and the threshold parameter $\left(\theta_{\mathrm{B}}-\theta_{\mathrm{O,B}}\right)$ contains two terms. The first term, θ_{B}, is the natural logarithm of the total gain for the backward-propagating pulse. If the pulse builds up from noise,

$$\theta_{\mathrm{B}} = \ln\left(\mathrm{P_{par,B}}\frac{2\pi\mathrm{T_B}}{\alpha h\nu_{\mathrm{B}}}\right), \quad (2)$$

where $h\nu_B$ is the energy of a photon at the Brillouin frequency, $\alpha/2\pi T_B$ is the Brillouin bandwidth (full-width at half maximum), T_B is the phonon lifetime in the fiber, α reflects inhomogeneous broadening in the fiber glass matrix, and $P_{par,B}$ is the peak parasitic Brillouin power the system can tolerate coming out of the input end of the fiber. Often, the power that matters is the average power and the peak power is given by the average power divided by the duty cycle. The second term in the threshold parameter, $\theta_{O,B}$, is the natural logarithm of the optical gain seen by the Brillouin pulse as it propagates from the output to the input end of the fiber. Since the Brillouin frequency is not shifted from the signal frequency by much, the optical gain seen by the Brillouin pulse is the same as the gain seen by the forward-propagating signal pulse, and

$$\theta_{O,B} = \ln\left(G_{amp}\right), \tag{3}$$

where G_{amp} is the amplifier gain for the signal light. An implicit assumption is that a single signal pulse does not significantly deplete the amplifier gain.

The third bracketed term in (1) corresponds to the enhancement of the Brillouin threshold that results from the amplification of short pulses, and can be interpreted as an increase in the Brillouin bandwidth that results from the dynamics of short-pulse amplification [1].

The final bracketed term accounts for the bandwidth of the input signal, $\Delta\nu_S$, relative to the effective Brillouin bandwidth $\Delta\nu_B(I_{signal})$, which, for high-peak-power pulses, is a function of the signal intensity I_{signal}. For most of this section, we will assume a single-frequency, narrow-bandwidth signal and ignore it. We will return to it in Section II.G.

Equation (1) assumes that the backward-propagating Brillouin pulse does not interact with any pulse as it travels backward through the fiber other than the pulse that generated it. For this to be true, the separation between pulses must be greater than $2nL/c$, where $L = L_{active} + L_{passive}$ is the total length of fiber in the amplifier, L_{active} is the length of the active fiber, $L_{passive}$ is the length of passive fiber added to the end of the active fiber, often called the pigtail, and we are allowing for the possibility that SBS is initiated in the pigtail. Equation (1) also assumes that the phonon field associated with the Brillouin pulse builds up from noise. The phonon field sees the same Brillouin gain as the optical field. For stable operation at the maximum possible pulse energy, it must be allowed to decay back to noise between pulses. The time required for the phonon field to fully decay is $T_B(\theta_B - \theta_{O,B})$. Therefore, for a maximum-energy pulse the maximum pulse repetition rate is

$$R_{max} = \mathrm{Min}\left[R_{max,L}, R_{max,phonon}\right], \tag{4}$$

where the Min operator returns the minimum value of its arguments,

$$R_{max,L} = \frac{1}{\frac{2n}{c}L + \tau}, \tag{4a}$$

and

$$R_{max,phonon} = \frac{1}{T_B(\theta_B - \theta_{O,B}) + \tau}. \tag{4b}$$

(See Section II.H for a discussion of the trade between pulse energy and pulse rate for less-energetic pulses.)

B. SRS Threshold

The threshold set by SRS is determined by a parasitically generated Raman pulse that copropagates with the signal light. As a result, the effective interaction length L_{eff} is the same for pulsed and cw light, and the SRS-limited peak signal power is given by

$$P_{lim,SRS} = \frac{\pi d_{mode}^2}{8}\frac{(\theta_R - \theta_{O,R})}{g_R L_{eff}} \tag{5}$$

(based on Smith [3] and Agrawal [4]). In this equation, g_R is the Raman gain coefficient and

$$L_{eff} = \frac{\int_0^{L_{active}} P_{signal,max}(z)dz}{P_{signal,max}(L_{active})} + L_{passive}, \tag{6}$$

where $P_{signal,max}(z)$ is the maximum signal power at position z in the fiber. For fiber amplifiers pumped in the forward direction, the effective length of the active fiber, $L_{eff,active} = L_{eff} - L_{passive}$, is typically about two-thirds of its actual length. The threshold parameter $(\theta_R - \theta_{O,R})$ contains two terms. The first term, θ_R, is the natural logarithm of the total gain for the Raman pulse. If the pulse builds up from noise,

$$\theta_R = \ln\left(\frac{P_{par,R}}{h\nu_R \Delta\nu_R}\right), \tag{7}$$

where $h\nu_R$ is the energy of a photon at the Raman frequency, $\Delta\nu_R$ is the Raman bandwidth, and $P_{par,R}$ is the peak parasitic Raman-shifted power that we are willing to accept coming out of the output end of the fiber amplifier. The second term in the threshold parameter is the natural logarithm of the optical gain seen by the Raman pulse as it propagates along the fiber,

$$\theta_{O,R} = \frac{\sigma_R}{\sigma_S}\ln\left(G_{amp}\right), \tag{8}$$

where σ_R/σ_S is the ratio of the gain cross-sections for Raman-shifted and signal light.

C. Maximum-Energy Pulse Width

The maximum-energy single-frequency pulse that can be obtained from a fiber amplifier has a pulse width that is determined by setting the SBS threshold equal to the SRS threshold. For a narrow-linewidth pulse (neglecting the fourth bracketed term on the right side of (1)) in the limit $\tau \ll T_B(\theta_B - \theta_{O,B})$,

$$\tau_{opt} = \left[\frac{2(\theta_B - \theta_{O,B})^2}{(\theta_R - \theta_{O,R})}\frac{g_R}{g_B}\frac{T_B L_{eff} n}{c}\right]^{1/2}. \tag{9}$$

To stay below the SBS threshold, pulses longer than τ_{opt} will have a lower peak power and a lower pulse energy. The peak power of pulses shorter than τ_{opt} will be limited by SRS.

D. TMI Threshold

TMI sets a limit on the average power that a fiber amplifier can stably produce in the fundamental transverse mode. There is no simple equation based on material properties for the TMI-limited power from a fiber amplifier. However, there are some scaling rules that can be inferred from the literature. Before articulating those rules, it is helpful to define two terms:

> *Radially normalized refractive-index profile (RNRIP)*: The refractive-index profile of a fiber with the distance from the center of the fiber normalized such that the core radius is equal to one. For the discussion below, we only care about the refractive-index profile over the portion of the fiber that determines the properties of the guided core modes.

> *Normalized heat-deposition profile (NHDP)*: The longitudinal heat-deposition profile along the length of the fiber normalized such that the peak heat load (J/m in MKS units) is one and the fiber length is one. The NHDP is dependent on fiber parameters, the pump power and wavelength, and the signal input power and wavelength. The NHDP of different fibers should only be compared if they have the same total pump absorption.

The TMI threshold for a fiber amplifier will depend on the RNRIP, NHDP, and other system parameters (OSP), including the coiling diameter of the fiber and the pump and signal stability. For the rest of this discussion, we will assume that the OSP, and their effects on the operation of amplifiers, are repeatable from system to system.

From the literature, the TMI threshold for Yb-doped LMA fiber amplifiers appears to scale inversely with the heat load per unit length and the cross-sectional area of the fiber core. To maintain a fixed amount of pump absorption, the length of the active fiber scales as the ratio of the squares of the cladding and core cross-sections:

$$L_{\text{active}} \propto \frac{d_{\text{clad}}^2}{d_{\text{core}}^2}, \tag{10}$$

where d_{core} is the fiber core diameter and d_{clad} is the cladding diameter. For a fixed pump absorption, the heat load per unit length scales inversely as L_{active} and

$$P_{\text{lim,TMI}} = K(\text{RNRIP}, \text{NHDP}, \text{OSP}) \frac{d_{\text{clad}}^2}{d_{\text{core}}^4}, \tag{11}$$

where $P_{\text{lim,TMI}}$ is the TMI-limited average power and $K(\text{RNRIP}, \text{NHDP}, \text{OSP})$ is a constant determined by the fiber's RNRIP and NHDP, and OSP.

From a practical point of view, all fibers drawn from the same preform, or similar preforms, will have the same, or similar, $K(\text{RNRIP}, \text{NHDP}, \text{OSP})$, independent of the final core diameter. A measurement (or calculation) of the TMI threshold for one core diameter will determine the value of $K(\text{RNRIP}, \text{NHDP}, \text{OSP})$ for all core diameters. The core-to-cladding ratio can be independently controlled by varying the diameter of the sleeving on the preform. For maximum compatibility with existing fiber components, we will assume that the cladding diameter is maintained at an industry-standard dimension, nominally 400 µm. With this assumption,

$$P_{\text{lim,TMI}} = P_{\text{lim,TMI}}(25) \frac{25^4}{d_{\text{core}}^4}, \tag{12}$$

where $P_{\text{lim,TMI}}(25)$ is the TMI threshold for a fiber with a 25-µm core diameter and d_{core} is in units of microns.

The SRS threshold equation, (5), can be written in a form similar to (12):

$$P_{\text{lim,SRS}} = P_{\text{lim,SRS}}(25) \frac{d_{\text{core}}^2 d_{\text{mode}}^2}{25^2 d_{\text{mode}}^2(25)}, \tag{13}$$

where $P_{\text{lim,SRS}}(25)$ and $d_{\text{mode}}(25)$ are the SRS threshold and mode-field diameter for a fiber with a 25-µm core. If we make the simplifying approximation that the mode diameter is proportional to the core diameter, (13) becomes

$$P_{\text{lim,SRS}} = P_{\text{lim,SRS}}(25) \frac{d_{\text{core}}^4}{25^4}. \tag{14}$$

(This approximation results in an error of less than 0.2 µm in the core diameters and about 5% in the peak powers and pulse energies in the calculations below.)

It is also convenient to rewrite the expression for the optimized pulse width, (9), as

$$\tau_{\text{opt}} = \tau_{\text{opt}}(25) \frac{25}{d_{\text{core}}}, \tag{15}$$

where $\tau_{\text{opt}}(25)$ is the optimized pulse width for a 25-µm-core fiber.

E. Fiber Optimization for a Narrow-Linewidth System

To find the core diameter that maximizes the average power that can be achieved from a short-pulse fiber amplifier, we must account for the fact that the TMI threshold is a limit on the average signal power out of the fiber and the SRS threshold is a limit on the peak signal power that can be achieved. The optimal core diameter is then obtained by solving

$$P_{\text{lim,TMI}} = R\tau_{\text{opt}} P_{\text{lim,SRS}}, \tag{16}$$

where R is the pulse repetition rate, which must be equal to or less than $R_{\max}$. With the use of (12), (14), and (15), we find that

$$d_{\text{core,opt},R} = 25 \left[\frac{P_{\text{lim,TMI}}(25)}{P_{\text{lim,SRS}}(25)} \frac{1}{\tau_{\text{opt}}(25) R} \right]^{1/7}. \tag{17}$$

The optimized pulse width is

$$\tau_{\mathrm{opt},R} = \tau_{\mathrm{opt}}(25)\left[\frac{d_{\mathrm{core,opt},R}}{25}\right]^{-1}, \qquad (18)$$

the maximum TMI-limited average power that can be obtained at a given pulse repetition rate is

$$P_{\mathrm{ave,opt},R} = P_{\mathrm{lim,TMI}}(25)\left[\frac{d_{\mathrm{core,opt},R}}{25}\right]^{-4}, \qquad (19)$$

the corresponding SRS-limited peak power is

$$P_{\mathrm{peak,opt},R} = P_{\mathrm{lim,SRS}}(25)\left[\frac{d_{\mathrm{core,opt},R}}{25}\right]^{4}, \qquad (20)$$

and the maximum pulse energy is

$$E_{\mathrm{peak,opt},R} = \tau_{\mathrm{opt}}(25)P_{\mathrm{lim,SRS}}(25)\left[\frac{d_{\mathrm{core,opt,R}}}{25}\right]^{3}. \qquad (21)$$

If the length of active fiber required to obtain the desired amplifier efficiency is $L_{\mathrm{active}}(25)$ for a 25-µm-core fiber, the required length for a fiber with an optimized core diameter is

$$L_{\mathrm{active,opt},R} = L_{\mathrm{active}}(25)\left[\frac{d_{\mathrm{core,opt},R}}{25}\right]^{-2}. \qquad (22)$$

The maximum average power is obtained by operating the system at the maximum pulse repetition rate R_{max}. If we assume that the maximum pulse repetition rate is limited by fiber length and that τ_{opt} is always much less than twice the round-trip time of light in the fiber, we can make the approximation

$$R_{\mathrm{max}} = R_{\mathrm{max}}(25)\left[\frac{d_{\mathrm{core,opt},R}}{25}\right]^{2}. \qquad (23)$$

Substituting this for R in (17) results in

$$d_{\mathrm{core,opt},R_{\mathrm{max}}} = 25\left[\frac{P_{\mathrm{lim,TMI}}(25)}{P_{\mathrm{lim,SRS}}(25)}\,\frac{1}{\tau_{\mathrm{opt}}(25)R_{\mathrm{max}}(25)}\right]^{1/9}, \qquad (24)$$

which can be used in (18) through (22) to determine the pulse characteristics and fiber parameters for a maximum-energy pulse when the system is designed to operate at its maximum average power. (If the maximum repetition rate is limited by phonon relaxation, the exponent in (24) becomes 1/7.)

Optimization of the fiber diameter for repetition rates well below R_{max} results in short active fibers with a larger core diameter. It allows for significantly higher peak powers and pulse energies, but results in a significant decrease in average power.

F. The Numbers

All of the optimized performance parameters discussed above, R_{max}, $\tau_{\mathrm{opt},R}$, $P_{\mathrm{ave,opt},R}$, $P_{\mathrm{peak,opt},R}$, and $E_{\mathrm{peak,opt},R}$, along with the associated fiber parameters $d_{\mathrm{core,opt},R}$ and $L_{\mathrm{active,opt},R}$, can be calculated from basic material properties and knowledge of the TMI threshold and fiber length for any fiber amplifier with the same $K(\mathrm{RNRIP, NHOP, OSP})$. The basic material properties, particularly g_B, T_B, and g_R, are functions of fiber design and glass chemistry. The values used in the calculations below, listed in Table 1, are consistent with measurements made on commercially available high-power gain fiber and are in line with values reported in the literature.

TABLE I. INPUT VALUES USED FOR FIBER OPTIMIZATION

Parameter	Symbol	Value
Signal wavelength	λ_S	1064 nm
Brillouin gain coefficient	g_B	7.5×10^{-12} m/W
Phonon lifetime	T_B	1.07 ns
Inhomogeneous broadening factor for Brillouin linewidth	α	1
Brillouin photon energy	$h\nu_B$	1.87×10^{-19} J
Raman gain coefficient	g_R	2.5×10^{-14} m/W
Raman bandwidth	$\Delta\nu_R$	7 THz
Raman photon energy	$h\nu_R$	1.79×10^{-19} J
Speed of light in fiber	c/n	1.99×10^{8} m/s
Ratio of gain cross-sections at Raman and signal wavelengths	σ_R/σ_S	0.2
Amplifier gain	G_{amp}	150
Numerical aperture of fiber core	NA	0.06
TMI threshold for 25-µm fiber	$P_{\mathrm{lim,TMI}}(25)$	1.0 kW
Active fiber length for 25-µm fiber	$L_{\mathrm{active}}(25)$	7.5 m
Maximum average Brillouin power out of fiber input end	$P_{\mathrm{par,B}}/\text{duty cycle}$	5 W
Maximum peak Raman-shifted power from fiber output end	$P_{\mathrm{par,R}}$	100 W

The mode diameter used for all calculations is derived from the fiber core diameter using the Marcuse formula and the approximation of a step-index fiber:

$$d_{\mathrm{mode}} = d_{\mathrm{core}}\left(0.65 + \frac{1.619}{V^{2/3}} + \frac{2.879}{V^{6}}\right), \qquad (25)$$

where

$$V = \frac{\pi}{\lambda_S} d_{\mathrm{core}}\mathrm{NA}. \qquad (26)$$

The calculated values for the optimized performance parameters of a system operating at the maximum pulse repetition rate, and the associated fiber parameters, are:

TABLE II. OPTIMIZED PERFORMANCE PARAMETERS

Symbol	Amplifier with no Pigtail	Amplifier with 2.0-m Pigtail
R_{max}	14.6 MHz	12.2 MHz
$\tau_{\mathrm{opt},R_{\mathrm{max}}}$	2.12 ns	2.48 ns
$P_{\mathrm{ave,opt},R_{\mathrm{max}}}$	0.81 kW	0.63 kW
$P_{\mathrm{peak,opt},R_{\mathrm{max}}}$	26.1 kW	20.9 kW
$E_{\mathrm{peak,opt},R_{\mathrm{max}}}$	55.2 µJ	51.7 µJ
$d_{\mathrm{core,opt},R_{\mathrm{max}}}$	26.2 µm	27.6 µm
$L_{\mathrm{active,opt},R_{\mathrm{max}}}$	6.83 m	6.15 m

The maximum pulse energy $E_{\mathrm{peak,opt},R}$ is plotted as a function of pulse repetition rate R in Fig. 1. In the calculations that generated Fig. 1, the passive pigtail was 2.0 m for $R = R_{\mathrm{max}}$ and allowed to scale with the active fiber length as the repetition

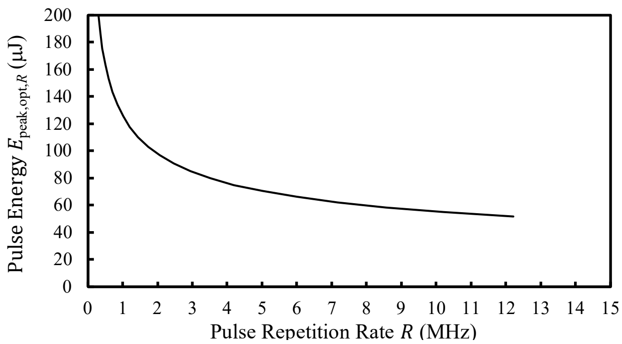

Fig. 1. Pulse energy vs. pulse repetition rate for an optimized fiber amplifier.

rate changed. The optimized pulse width $\tau_{\mathrm{opt},R}$ ranges from 1.70 ns at 1 MHz to 2.48 ns at 12.2 MHz.

In all calculations, the passive pigtail was assumed to be an unpumped section of the active fiber, with the same glass chemistry. The Brillouin gain coefficient for pure silica glass is 2.45×10^{-11} m/W. The use of a passive fiber with a pure silica core could significantly reduce the maximum obtainable pulse energy – the Brillouin pulse would be generated in the passive fiber where there would be a significantly lower Brillouin threshold.

It is worth noting that the calculated maximum signal pulse energy $E_{\mathrm{peak,opt},R_{\max}}$, the maximum pulse energy at the output end of the fiber, is well below the saturation energy E_{sat} for the fundamental mode in the fiber:

$$E_{\mathrm{sat}} = \frac{\mathrm{h}\nu_{\mathrm{S}}}{\sigma_{\mathrm{S}}} \frac{\pi d^2_{\mathrm{mode,opt},R_{\max}}}{8}, \tag{27}$$

where the gain cross-section at 1064 nm, σ_{S}, is $\sim2.7\times10^{-21}$ cm^2.

G. Spectral Broadening

It is common practice in high-power cw fiber amplifiers to spectrally broaden the signal in order to increase the SBS threshold. From (1), with spectral broadening the SBS threshold is increased by a factor of

$$f_{\mathrm{broadened}} = \left[\frac{\Delta\nu_{\mathrm{S}}}{\Delta\nu_{\mathrm{B}}(I_{\mathrm{signal}})} + 1\right]. \tag{28}$$

At low powers the Brillouin gain bandwidth $\Delta\nu_{\mathrm{B}}(I_{\mathrm{signal}})$ is independent of signal intensity and can be expressed as

$$\Delta\nu_{\mathrm{B}}(0) = \frac{\alpha}{2\pi \mathrm{T_B}}. \tag{29}$$

For Yb-doped-silica fiber, $\Delta\nu_{\mathrm{B}}(0)$ is typically in the range from 50 to 150 MHz. For high-peak-power pulses the dynamics of phonon generation increase the Brillouin bandwidth [1]. In the high-peak-power limit

$$\Delta\nu_{\mathrm{B}}(I_{\mathrm{signal,lim}}) = \frac{1}{2\pi}\sqrt{\frac{2\mathrm{g_B} I_{\mathrm{signal}}\mathrm{c}}{\mathrm{T_B n}}}. \tag{30}$$

More generally, it is reasonable to approximate the Brillouin bandwidth as

$$\Delta\nu_{\mathrm{B}}(I_{\mathrm{signal}}) = \left[\Delta\nu_{\mathrm{B}}(I_{\mathrm{signal,lim}})^2 + \Delta\nu_{\mathrm{B}}(0)^2\right]^{1/2}. \tag{31}$$

SBS will be initiated in the portion of the fiber that sees the maximum signal intensity, near the fiber output. For a maximum-energy pulse, the signal intensity in the fiber is at the Raman threshold and

$$\Delta\nu_{\mathrm{B}}(I_{\mathrm{signal}}) = \Delta\nu_{\mathrm{B}}(0)\left[\frac{2\mathrm{g_B T_B c}}{\alpha^2 \mathrm{n}}\frac{(\theta_{\mathrm{R}}-\theta_{\mathrm{O,R}})}{\mathrm{g_R} L_{\mathrm{eff}}} + 1\right]^{1/2}. \tag{32}$$

For the waveforms that we are considering, typical values for $\Delta\nu_{\mathrm{B}}(I_{\mathrm{signal}})$ are between 2 and 4 GHz.

In the presence of spectral broadening, the optimized pulse width and maximum pulse energy are increased by a factor of

$$\frac{\tau_{\mathrm{opt}}(\Delta\nu_{\mathrm{S}})}{\tau_{\mathrm{opt}}(\Delta\nu_{\mathrm{S}} \ll \Delta\nu_{\mathrm{B}})} = \left[\frac{\Delta\nu_{\mathrm{S}}}{\Delta\nu_{\mathrm{B}}(I_{\mathrm{signal}})} + 1\right]^{1/2}. \tag{33}$$

This gives a system designer an additional tool to tailor the system performance. However, it should be kept in mind that as the pulse energy is increased, it will become increasingly necessary to preshape the input seed pulses to ensure a uniform peak power over the duration of the pulse and from pulse to pulse in a PPM waveform.

Spectral broadening can be considered in the optimization of a fiber design; applied to commercial, nonoptimized fiber designs to increase their pulse energies; or added as an additional mode of operation in optimized unbroadened systems to extend their range. Fig. 2 shows the operational space available when spectral broadening is applied to a fiber, using the same parameters as were used to generate Fig. 1. It is discussed in detail in the figure caption.

H. Trading Pulse Energy for Pulse Rate

The above discussion focused on optimizing a system for maximum-energy pulses, with pulse energy $E_{\mathrm{lim,SBS}} = \tau_{\mathrm{opt}} P_{\mathrm{lim,SRS}}$. The same system can be operated at higher pulse rates if the pulse energy is reduced by reducing the pulse width.

For maximum-energy pulses, the separation between pulses must be greater than $2\mathrm{n}L/\mathrm{c}$ in order to avoid SBS. For less-energetic pulses, the SBS limit can be avoided as long as

$$2\int_0^{\mathrm{n}L/\mathrm{c}} P_{\mathrm{signal}}\left(L - \frac{\mathrm{c}}{\mathrm{n}}\mathrm{t}\right)\mathrm{dt} \le E_{\mathrm{lim,SBS}}, \tag{34}$$

where $P_{\mathrm{signal}}(\mathrm{z(t)})$ is the signal power at position z(t) in the fiber at time t and the leading edge of a pulse arrives at $\mathrm{z} = L$, the output end of the fiber, at time $\mathrm{t} = 0$. If the signal waveform consists of pulses of length τ_{opt}/x and peak output power $P_{\mathrm{lim,SRS}}$, this condition is always satisfied when x is a positive integer and the duty cycle of the system remains the same as it was when the system operated with output pulses of energy $E_{\mathrm{lim,SBS}}$. The stipulation that x is an integer is sufficient to avoid SBS, but not always necessary. With a small reduction in pulse

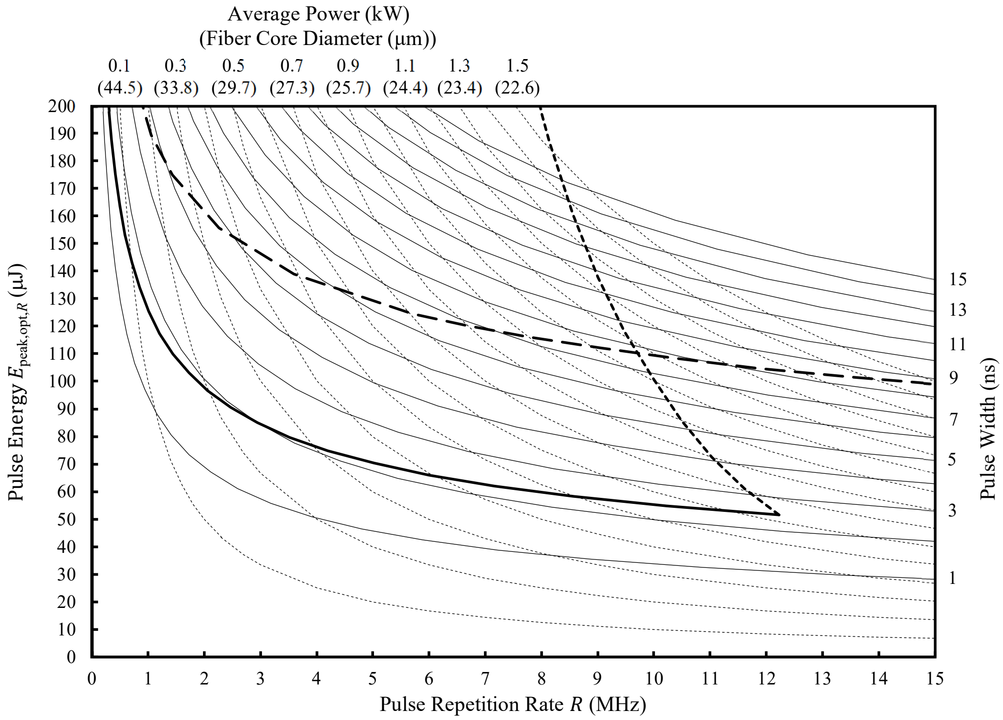

Fig. 2. Operational space available for a fiber amplifier with spectral broadening.

The thick solid curve traces out maximum pulse energy vs. pulse repetition rate for an unbroadened signal in a fiber amplifier optimized for narrow-bandwidth operation (the same curve as in Fig. 1). It is an implicit function of the fiber core diameter.

The thin dashed curves trace out maximum pulse energy vs. pulse repetition rate for an amplifier with a fixed fiber core diameter. They are curves of constant, SRS-limited peak power and constant, TMI-limited average power. They are labeled by both average power and fiber core diameter at the top of the figure. Above the thick solid curve, these curves trace out what can be achieved with spectral broadening. Below the thick solid curve, they correspond to reducing the pulse energy as discussed in Section II.H. Amplifiers with a given fiber core diameter can be operated below or to the left of these curves, but not above them or to the right.

The thick short-dashed curve traces out the maximum pulse repetition rate that can be achieved with a maximum-energy pulse. It is an implicit function of the fiber core diameter.

The thin solid curves trace out the minimum pulse width that is needed to operate at a given point in this two-dimensional space. They are implicit functions of fiber core diameter. Fifteen-nanosecond pulses require several tens of GHz of spectral broadening.

The thick long-dashed curve traces out the saturation energy for the gain fiber in the amplifier. It is an implicit function of the fiber core diameter. If the system is operated well below this curve, minimal preshaping of the seed pulses is needed.

energy, it can always be relaxed to x being any number greater than one.

A second requirement for operating at the maximum pulse energy is that the phonon field in the fiber amplifier be allowed to decay back to noise between pulses. In the limit $\tau \ll \mathrm{T_B}(\theta_\mathrm{B} - \theta_\mathrm{O,B})$, the SBS threshold increases as $1/\tau^2$ (1). If we start with a maximum-energy pulse and reduce its duration by a factor of two, while maintaining the same peak power, the peak power of the pulse is a factor of four below the SBS limit. Two such pulses could occur arbitrarily close to each other without raising concerns about the SBS threshold, despite the fact that the phonon field has not been allowed to decay. Any time between the pulses allows for some decay of the phonon field and gives margin with respect to the SBS threshold. It is safe to operate the system at a repetition rate of $2R_\mathrm{max}$ if the pulse duration is reduced from τ_opt to $\tau_\mathrm{opt}/2$ while maintaining the peak power at or below $P_\mathrm{lim,SRS}$. More generally, considering only the phonon field, the system can by operated at any repetition rate xR_max if the pulse duration is reduced to τ_opt/x, for $x \geq 1$.

The bottom line is that the pulse rate of the system can be increased by reducing the pulse energy. A system designed to operate at M pulses per second for maximum-energy pulses can typically operate at xM pulses per second if the transmitted pulse energy is reduced from $E_\mathrm{lim,SBS}$ to $E_\mathrm{lim,SBS}/x$ by reducing the pulse width from τ_opt to τ_opt/x while maintaining the same duty cycle and average power. In some cases, a small additional decrease in pulse energy may be required, depending on the gain profile of the amplifier. This is true for narrow-linewidth and spectrally broadened pulses.

I. Can we do better?

The results discussed above are the best that can be obtained with conventional LMA Yb-doped-silica fiber amplifiers for the input values used. The easiest parameters to leverage for improved system performance are the amplifier efficiency, through the active fiber length $L_\mathrm{active}(25)$, and the pigtail length. All of the input values should be validated before any serious effort is put into a system design, and all of the values should be determined for a single fiber design and glass chemistry.

One approach that is attracting attention for the generation of high-energy pulses is the use of tapered fiber amplifiers. In Yb-doped fiber amplifiers, TMI originates in a short length of fiber near the maximum heat load. This region is close to the pump end of the fiber. SRS builds up more quickly toward the output end of the fiber where the intensity is greatest. The idea is to taper the fiber such that it has a small core diameter at the location of the maximum heat load, with increasing diameter as the pulse is amplified. This relaxes, but does not eliminate, the trade-off between TMI and SRS. The taper must be gentle enough to allow for adiabatic expansion of the fundamental mode, and the diameter of the fiber at the pump end must be consistent with the brightness of available pump sources. An optimized taper can be designed based on the equations presented above and the fiber's NHDP. The design can be translated into a real fiber — tapered Yb-doped fiber is commercially available — but sophisticated fiber drawing capabilities are required.

It remains to be seen what can be achieved with tapered fiber amplifiers. A preliminary analysis indicates that for an optimized tapered fiber the maximum increase in pulse energy, relative to an optimized untapered fiber, is about a factor of two. However, that benefit is only achievable in fibers with no parasitic absorption at the signal wavelength. For a real system, the taper should be designed to optimize system performance at end of life. Even small amounts of photodarkening quickly reduce the benefits of a taper.

Other options for increasing power and pulse energy from fiber amplifiers include novel glass chemistries, crystalline fibers, and novel fiber structures, including trench fibers, large flat-mode fibers, and photonic-crystal fibers. All of these are beyond the scope of this study.

III. Application to Free-Space Optical Communications

A. *Turning the Output of a Fiber Amplifier into a Communications Waveform*

To encode information on the pulse stream exiting a fiber amplifier, the output pulses must be modulated in some way. For a uniform train of pulses, it is a straight-forward task to preshape the seed pulses in order to obtain square output pulses, especially when the pulse energy is below the saturation energy of the gain fiber. The gain of the fiber sees only a modest decrease during a pulse and each pulse sees the same inversion density. The required preshaping of the seed pulses is modest and each seed pulse gets preshaped in exactly the same way.

Any modulation of the pulse stream will affect the inversion density such that subsequent pulses see different gains. Although this can, in principle, be corrected by preshaping the seed pulses based on the history of the pulse stream, it becomes more difficult as the impact of the pulse modulation increases. Fluctuations in pulse amplitude are unavoidable, and are particularly detrimental when the amplifier is operated near the nonlinear SRS and SBS thresholds. In order to accommodate amplitude fluctuations, the amplifier will need to be operated below its maximum pulse energy. Small modulations in the position of a pulse will have less impact than turning a pulse on or off, suggesting that a sparse PPM waveform, as illustrated in Fig. 3, may be ideally suited to the properties of the amplifier.

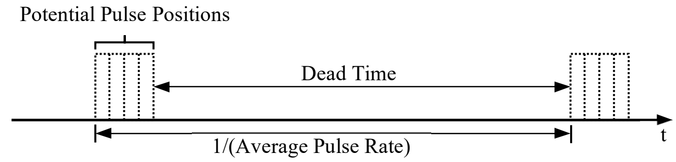

Fig. 3. Sparse PPM waveform, shown with a PPM order of four.

As a strawman design, we will use an amplifier consisting of 6.5 m of active fiber with the characteristics listed in Table 1, a 27-μm core diameter, and a 2-m-long passive pigtail. For this amplifier, the TMI threshold is 0.74 kW, the SRS-limited peak power is 19.5 kW, and the round-trip time of light in the fiber is 85 ns. With spectral broadening, it can produce 100-μJ pulses with 5.2-ns duration at an average pulse rate of 7.4 MHz. This is sufficient pulse energy to close a data link from Earth to Mars (see Appendix A). We will use a communications waveform that consists of a dead time of 111 ns followed by a PPM signal with four possible pulse positions, each having a temporal width of 6 ns. The 111-ns dead time ensures that only one pulse is present in the amplifier at a time. Each signal pulse transmits two bits of information, resulting in a data rate of 14.8 Mbps. (Operating the same amplifier with less-energetic pulses would enable higher data rates. See Section 2.H.)

For the strawman waveform, the maximum variation in the time between pulses is ±14%. Additionally, the pulse energy is below the saturation energy of the gain fiber. As a result, there will be minimal pulse amplitude fluctuations. If these small fluctuations are not acceptable, the amount of history-dependent preshaping required will be modest.

B. *High-Performance Free-Space Optical Communications System Concept*

Fiber amplifiers based on conventional Yb-doped-silica fiber are fundamentally limited in the single-frequency pulse energy they can produce. High-data-rate free-space optical communications over extremely large distances, such as to our neighboring planets and beyond, will require small clusters of fiber amplifiers to close the link. The outputs from all of the amplifiers can be incoherently combined at the distant receiver.

Multiple amplifiers can be used to increase the data rate as well as the link distance. The communications waveform described above has dead time between the PPM time slots. The dead time is long enough to accommodate the temporal interleaving of the outputs from five amplifiers, all operating at the same wavelength. Together they would bring the data rate for that wavelength to 74 Mbps. As the link distance increases, the timing and data content of the amplifiers can be adjusted to go from a 74-Mbps channel to a 14.8-Mbps channel with five times the pulse energy at the receiver. The gain bandwidth of Yb-doped fiber amplifiers is sufficient to support numerous such channels.

Small adjustments to system parameters would allow for a larger number of amplifier outputs to be interleaved, or for a different PPM order for the communications waveform. Ideally, these system-level decisions would be made before the final optimization of the fiber parameters. If the duty cycle for the amplifiers is reduced, the optimized core diameter and maximum pulse energy will increase.

C. Size, Weight, and Power Considerations

Most of the size, weight, and power draw (SWaP) of high-power fiber amplifiers is attributed to the pump diodes and scales linearly with the average output power of the system. As a result, most of the SWaP penalty for having multiple fiber amplifiers is borne by the beam-combining system, or the transmit aperture of the system and its gimbal, not by the amplifiers themselves. This SWaP penalty needs to be evaluated at the system level. Since fiber amplifiers have a large SWaP advantage relative to competing amplifier technologies, we would expect that they remain an attractive option for a variety of high-energy systems.

IV. Characterization of High-Power Fiber Amplifiers for Applications in Deep-Space Optical Communications

When using a high-power Yb-doped fiber amplifier for deep-space optical communications with a sparse PPM communications waveform, the intent is to transmit square-wave pulses with peak powers limited only by SRS. The maximum pulse width and energy at the SRS-limited peak power are determined by SBS. At maximum pulse energy, the minimum spacing between pulses is determined by the length of the fiber in the amplifier, the phonon relaxation time, or TMI. The maximum PPM order (number of potential PPM time slots for each pulse) for operation at maximum pulse energy with minimum dead time between possible PPM pulse positions is determined by the peak power, pulse width, minimum spacing between pulses, and saturation fluence of the amplifier. The four key parameters – peak power, maximum pulse width at peak power, minimum pulse separation at maximum pulse energy, and maximum PPM order at maximum pulse energy and minimum dead time – can be determined with four sets of measurements. Once they are known, they can be used to map out the achievable pulse energy vs. transmitted data rate for the amplifier. The four sets of measurements are discussed below.

Measurements made on a commercial 1.2-kW Yb-doped-silica fiber amplifier, purchased from Nufern in 2014, are included in the discussion below. All of the values in Table 1 are consistent with the performance of that amplifier.

A. Initial Considerations

Before getting to the measurements, there are a few issues that should be considered. The ideal situation would be to work with the producer of the amplifier and design the gain fiber according to the principles discussed in Section II. However, even if that is not possible, commercially available high-power cw Yb-doped fiber amplifiers support high-data-rate deep-space optical communications. Minor modifications to their nominal configuration, which may be available from vendors, could improve their performance for this application.

What efficiency is required from the amplifier? Most commercially available cw fiber amplifiers are designed for high efficiency. There are diminishing efficiency gains as the length of the active fiber is increased. On the other hand, increases in fiber length have a large impact on the SRS threshold. To maximize the peak power and pulse energy that can be obtained from the amplifier, the amplifier should be built with the shortest length of gain fiber that satisfies the efficiency requirement. The SRS threshold is also strongly dependent on the length of the amplifier's passive pigtail. It too should be kept as short as possible.

The core diameter of the gain fiber affects all aspects of the amplifier's performance. Larger core diameters result in higher SRS thresholds and saturation energies, at the expense of lower TMI thresholds. For high-power cw amplifiers, it is TMI that limits how large a core diameter is used. High-power cw amplifiers typically have a TMI threshold well above the average power achievable with the type of communications waveform being discussed. Before purchasing a commercial cw amplifier for this application, one should look into the option of using a larger fiber core diameter than is typically employed.

There were no modifications to the specifications of the Nufern amplifier used as an example in the discussion below.

B. Measuring the Four Key Parameters

1. Peak Power (P_{peak})

To measure the peak power that a fiber amplifier can support, the amplifier should be seeded with a short, square pulse at a low repetition rate. The pulse width must be short enough to avoid SBS (potentially as short as 1 ns), the pulse energy exiting the amplifier should be well below the saturation energy, the average power from the amplifier must be below the TMI threshold, and the pulse repetition rate should be below $R_{\max}$ (this is essential for the measurement of the critical pulse width discussed in Section 2 below). Under these conditions, the peak power of the amplifier will be limited by SRS. The amount of SRS that is acceptable is determined by the end user, and will typically correspond to around 1% of the output power Raman shifted out of the signal band.

To perform the measurement, increase the pump power to the amplifier until the SRS limit is reached. Record the total output power, signal power (power in a small spectral band centered on the signal wavelength), and Raman-shifted power (forward-propagating power outside of the signal band). Also record the shape of the output pulse. To the extent that it does not remain square, the output pulse shape will inform the need to preshape the seed pulses. Monitor the backward-propagating power (SBS and amplified spontaneous emission (ASE)). Stop the measurement if the SBS limit is reached (see 2.a below) or if TMI becomes an issue. If SBS is observed, repeat the measurement with a shorter pulse; if TMI is observed, decrease the pulse repetition rate. The peak power determined in this way is the Raman threshold, $P_{\text{peak}} = P_{\text{lim,SRS}}$.

The SRS-limited peak power for the Nufern 1.2-kW fiber amplifier was measured to be 9 kW using a 2.9-ns pulse.

2. Maximum Pulse Width at Peak Power

2.a. Unbroadened Critical Pulse Width (CPW(0))

For this measurement, the amplifier should be seeded with a narrow-bandwidth, square pulse of variable width and

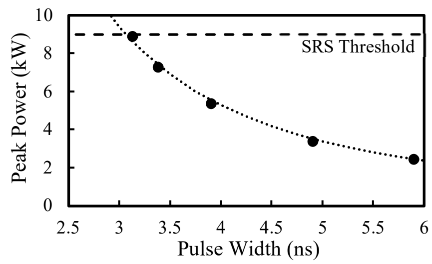

Fig 4. CPW(0) measurement. The large dots are measurements of the SBS threshold, the dotted curve is calculated from (1).

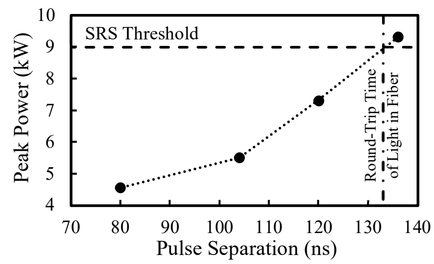

Fig. 5. MPS(0) measurement. The large dots are measurements of the SBS threshold for a 3-ns pulse. The dotted lines are a visual aid.

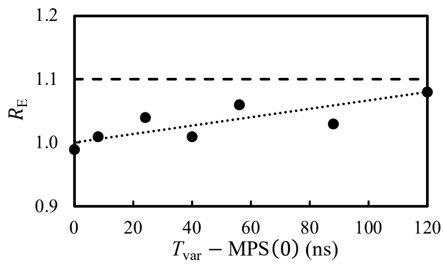

Fig. 6. R_E as a function of $T_{var} - \mathrm{MPS}(0)$ for the Nufern amplifier. The dotted lines are a visual aid.

operated at the SRS limit. It must be operated at a repetition rate below R_{max} (potentially as low as 5 MHz).

To qualify as a narrow-bandwidth seed, the bandwidth of the seed pulses should be small compared to the effective SBS bandwidth of the amplifier (see Section II.G). This could be challenging for gain-switched seed pulses due to thermal chirping, but is readily achievable with pulses carved from a cw source using an intensity modulator. If a narrow-bandwidth seed is not available, see Section 2.b below.

The SBS threshold is defined by the maximum output power that the high-power stage of the amplifier can be safely operated at without causing a problem to the input isolator or preamplifier. Typically, it will be the output power that results in a backward-propagating pulse with a peak power comparable to that of the seed.

The SBS threshold decreases as the pulse width increases. For very short pulses, it exceeds the SRS limit. CPW(0) is the pulse width where the system transitions from being SRS limited to SBS limited when seeded with a narrow-bandwidth source. To perform the measurement, start with a short pulse and increase the pulse width until the SBS limit is reached. If TMI is observed, repeat the measurement at a lower repetition rate. Check to make sure that the measured CPW(0) does not change as the repetition rate is decreased. If it does, reduce the repetition rate and repeat the measurement.

$\mathrm{CPW}(0) = \tau_{opt}(\Delta\nu_S \ll \Delta\nu_B)$. The product of CPW(0) and P_{peak} is the maximum pulse energy that can be obtained from the amplifier with a narrow-bandwidth seed.

Fig. 4 shows the SBS threshold as a function of pulse width for the Nufern amplifier. The measured CPW(0) is ~3.1 ns and the maximum unbroadened pulse energy is ~27 μJ.

2.b. Spectrally Broadened Critical Pulse Width ($\mathrm{CPW}(\Delta\nu_S)$)

$\mathrm{CPW}(\Delta\nu_S) = \tau_{opt}(\Delta\nu_S)$ is measured in the same way as CPW(0), except that the seed pulses are broadened to a spectral width of $\Delta\nu_S$. The product of $\mathrm{CPW}(\Delta\nu_S)$ and P_{peak} is the maximum pulse energy that can be obtained from the amplifier with a signal bandwidth of $\Delta\nu_S$.

For most applications, there is no downside to using a spectrally broadened signal and spectral broadening can be used to increase the available pulse energy. As the energy is increased, preshaping of the seed pulses becomes more important.

For 44 GHz of white-noise broadening, the measured $\mathrm{CPW}(\Delta\nu_S)$ for the Nufern amplifier is 14 ns and the maximum pulse energy is ~120 μJ.

3. *Minimum Pulse Separation at Maximum Pulse Energy*

3.a. Unbroadened Minimum Pulse Separation (MPS(0))

For this measurement, the amplifier should be seeded with narrow-bandwidth, square pulses at a variable pulse repetition rate. The pulse width should be slightly less than CPW(0) and the peak power should be just below P_{peak}. To perform the measurement, start at a repetition rate below R_{max} and increase the repetition rate until the SBS or TMI limit is reached. MPS(0) is the inverse of that repetition rate.

MPS(0) determines the maximum average power that can be obtained from the amplifier operated in pulsed mode with maximum-energy pulses for an unbroadened seed. In the absence of TMI, $\mathrm{MPS}(0) \approx 1/R_{max}$.

Fig. 5 shows the measured SBS threshold for a 3-ns pulse as a function of pulse separation. The minimum pulse separation for an SRS-limited pulse is 136 ns, roughly the round-trip time of light in the fiber of the amplifier (gain fiber plus pigtail).

3.b. Pulse-Width Dependent Minimum Pulse Separation ($\mathrm{MPS}(\tau)$)

If the amplifier is operated with a spectrally broadened signal and the pulse width τ is greater than CPW(0), the minimum pulse separation will be greater than MPS(0). The difference will be small if the minimum pulse separation is determined by SBS, but could be significant if it is determined by TMI. Repeat the measurement discussed in 3.a spanning the range of pulse widths the system will see.

For the Nufern amplifier, MPS(10 ns) is 143 ns.

4. Maximum PPM Order at Maximum Pulse Energy and Minimum Dead Time

4.a. Maximum Unbroadened PPM Order (MPPMO(0))

For this measurement, the amplifier is seeded repetitively with pairs of pulses. Both pulses should be unbroadened, of equal amplitude, and have a pulse width equal to CPW(0). The repetition rate of the pairs and the timing between the pulses in the pairs should be such that the resulting waveform consists of pulses that are alternately separated by MPS(0) and T_{var}, where T_{var} is variable. Throughout this measurement, the peak output power of the amplifier should be maintained at P_{peak}. The ratio of the output energies in consecutive pulses, R_E, defined to be greater than one, will change as a function of T_{var}.

To perform the measurement, start with T_{var} = MPS(0) and increase it until R_E reaches its maximum acceptable value (determined by the end user). The maximum PPM order for the amplifier operating with maximum pulse energy and minimum dead time between PPM time slots for an unbroadened seed is

$$\mathrm{MPPMO}(0) = \mathrm{Trunc}\left[\frac{T_{\mathrm{var,max}}(0) - \mathrm{MPS}(0)}{2\ \mathrm{CPW}(0)} + 1\right], \tag{35}$$

where Trunc is the truncation operator and $T_{\mathrm{var,max}}(0)$ is the value of T_{var} that corresponds to the maximum acceptable R_{E} for a pulse width of CPW(0). If the end user is able to appropriately preshape the seed pulses depending on the timing of past pulses, MPPMO(0) will be greater than it otherwise would. Increasing the dead time between PPM pulse positions also has the potential to increase the usable PPM order.

Fig. 6 shows R_{E} as a function of $T_{\mathrm{var}} - \mathrm{MPS}(0)$ for the Nufern amplifier. Without history-dependent preshaping of the seed pulses, MPPMO(0) is greater than 20 for a maximum acceptable variation in pulse energy of 10%.

If the intent is to use the output of the amplifier as part of a temporally interleaved channel, as discussed above in Section III.B, the highest data rate for the channel is achieved if each amplifier in it uses a PPM order of two or four.

4.b. Pulse-Width Dependent Maximum PPM Order (MPPMO(τ))

The output pulse width and pulse energy from the amplifier will impact the maximum PPM order. If the system will be operated with pulse widths other than CPW(0), to take advantage of the increased pulse energies available with spectral broadening or the increased data transmission rates that can be obtained with shorter pulses, the maximum PPM order MPPMO(τ) should be mapped out over the range of pulse widths of interest:

$$\mathrm{MPPMO}(\tau) = \mathrm{Trunc}\left[\frac{T_{\mathrm{var,max}}(\tau) - \mathrm{MPS}(\tau)}{2\tau} + 1\right]. \tag{36}$$

Shorter pulses could enable higher-order PPM waveforms.

C. The Performance Space of the Amplifier

The measurements discussed above allow for a complete mapping of the performance space, pulse energy vs. transmitted data rate, of a high-power Yb-doped fiber amplifier used for the generation of a sparse PPM waveform. The amplifier can be operated with output pulse energy

$$\mathrm{E}_{\mathrm{out}} = \tau \mathrm{P}_{\mathrm{peak}} \tag{37}$$

for any pulse width τ less than CPW(0) for an unbroadened signal or CPW($\Delta\nu_{\mathrm{S}}$) for a spectrally broadened signal. The data transmission rate, in bits per unit time, is

$$\mathrm{DTR} = \mathrm{R}_{\mathrm{ave}} \log_2(\mathrm{PPMO}), \tag{38}$$

where the average pulse transmission rate $\mathrm{R}_{\mathrm{ave}}$ must be less than the maximum average pulse transmission rate

$$\mathrm{R}_{\mathrm{ave,max}} = \frac{1}{\mathrm{MPS}(\tau) + \tau(\mathrm{PPMO} - 1)} \tag{39}$$

and the PPM order PPMO cannot exceed MPPMO(τ).

As an example of what can be done with comercially available amplifiers, without history-dependent preshaping of the seed pulses, Fig. 7 shows an eye diagram for the Nufern amplifier operating at a data rate of 10.75 MHz with a PPM order of four. The pulse energies range from 92 to 103 μJ, with an average value of 99.3 μJ.

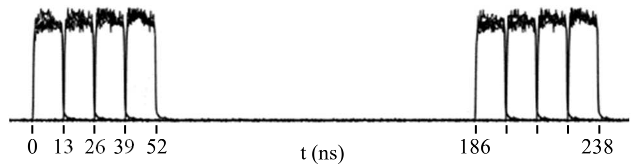

Fig. 7. Eye diagram for the Nufern amplifier operating at a data rate of 10.75 MHz with a PPM order of four and an average pulse energy of 99.3 μJ.

Appendix A: Link Analysis, Earth to Mars

At its furthest distance, Mars is 400,000,000 km from Earth. If we send a diffraction-limited optical pulse of energy E_{Tx} and wavelength λ_{S} through a transmit aperture of diameter d_{Tx}, over a distance R_{TxRx} to a receiver with an aperture diameter d_{Rx}, the energy received is

$$E_{\mathrm{Rx}} \approx E_{\mathrm{Tx}} \left(\frac{\pi d_{\mathrm{Tx}} d_{\mathrm{Rx}}}{4 R_{\mathrm{TxRx}} \lambda_{\mathrm{S}}}\right)^2 T_{\mathrm{Tx}} T_{\mathrm{A}} T_{\mathrm{Rx}}, \tag{A1}$$

where T_{Tx} is the transmission of the transmit telescope, T_{A} is the transmission of the atmosphere (including effects related to atmospheric beam distortion), T_{Rx} is the transmission of the receive telescope, and the approximate sign allows for small errors in pointing. For d_{Tx} = 0.5 m, T_{Tx} = 0.5, T_{A} = 0.5, d_{Rx} = 0.25 m, T_{Rx} = 0.5, and R_{TxRx} = 400,000,000 km, a 100-μJ pulse from a 1064-nm fiber amplifier results in an average of ~3.6 photons per pulse incident on the detector at the receiver.

One caveat to the values used in the above calculation is that a diffraction-limited 0.5-m-diameter transmit beam has a $1/e^2$ divergence of ~0.8 μrad. Pointing a transmitter to that accuracy (especially through the atmosphere) is at the edge of what can be done. Additionally, such a small beam divergence would require exquisite knowledge of the receiver's position. For those reasons, it might be necessary to increase the beam divergence, which would reduce the number of photons incident on the detector.

Together, the transmitted pulse rate, the number of photons received per transmitted pulse, data encoding, and the desired bit error rate will determine the data rate that can be achieved in a free-space communications channel. Having a few received photons per pulse is a good place to start.

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