Pseudo-random binary sequence phase modulation for narrow linewidth, kilowatt, monolithic fiber amplifiers

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Abstract: We report on pseudo random binary sequence (PRBS) phase modulation for narrow-linewidth, kilowatt-class, monolithic (all-fiber) amplifiers. Stimulated Brillouin scattering (SBS) threshold enhancement factors for different patterns of PRBS modulated fiber amplifiers were experimentally analyzed and agreed well with the theoretical predictions. We also examined seeding of the SBS process by phase modulated signals when the effective linewidth is on the same order as the Brillouin shift frequency. Here ~30% variations in SBS power thresholds were observed from small tunings of the modulation frequency. In addition, a 3 GHz PRBS modulated, 1.17 kW fiber amplifier was demonstrated. Near diffraction-limited beam quality was achieved (M^2 = 1.2) with an optical pump efficiency of 83%. Overall, the improved SBS suppression and narrow linewidth achieved through PRBS modulation can have a significant impact on the beam combining of kilowatt class fiber lasers.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (060.4370) Nonlinear optics, fibers; (290.5900) Scattering, stimulated Brillouin.

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1. Introduction

Fiber lasers offer several advantages over bulk solid state lasers; including compactness, near diffraction-limited beam quality, and high efficiencies. However, due to small core sizes and long interaction lengths; high-power, single-mode fiber lasers are limited by the onset of detrimental effects, such as stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS). The latter phenomenon is the lowest threshold nonlinear effect in single-frequency and narrow-linewidth continuous-wave (CW) fiber amplifiers. This process is a phase-matched third-order nonlinear interaction that couples acoustic phonons to the photons of the optical field and the backscattered Stokes light. Consequently, optical power is transferred from the laser light and into the Stokes light; thus degrading amplification of the signal light and possibly damaging the fiber amplifier through pulsation.

An effective SBS mitigation technique revolves around spectral linewidth broadening [1]. In the 1980s, SBS suppression through phase modulation was investigated in the telecommunication industry for long haul applications [2]. In this case, the broadening is commonly achieved through RF frequency modulation and suppression occurs when the phase variation is on a time scale shorter than the phonon lifetime. Along those lines, narrow-linewidth, kW class Yb-doped fiber amplifiers have been recently demonstrated through external phase modulation [3]. Although the effective linewidth of the laser would no longer be single-frequency, beam combining of high-power fiber amplifiers modulated at the GHz level has been demonstrated for both spectral and coherent beam combining (CBC) architectures [4–6]; further driving interest in kW class narrow-linewidth fiber amplifiers.

For monolithic (all-fiber) Yb-doped amplifiers, fiber-coupled $LiNbO_3$ electro-optic modulators with low insertion loss, large frequency bandwidth, and low π-phase shift voltage are commercially available. Subsequently, to suppress SBS, standard phase modulation techniques include driving the phase modulator with a sine wave [7] or a white noise source (WNS) [8]. In sinusoidal phase modulation, the spectral power exhibits a series of discrete sidebands at integer multiples of the modulation frequency. Yet, once the modulation frequency increases appreciably beyond the spontaneous Brillouin gain bandwidth, there is no further increase in the SBS threshold [7]. While increasing the modulation depth can further increase the SBS enhancement factor, this is limited by the electrical handling capability of the phase modulator. As a result, more spectrally efficient linewidth broadening schemes are desired. To that end, linewidth broadening via a filtered WNS is the standard approach towards SBS mitigation in kW class amplifiers. Specifically, WNS modulation creates a continuum spectrum around the carrier with lineshape depending on the voltage amplification and filtering setup. Optical linewidth can be controlled by varying the RF filter range. Notably, WNS modulation has been employed to attain kilowatt class, monolithic fiber amplifiers at 10-15 GHz linewidths [3].

Despite promising results, scaling to multi-kW levels has proven difficult, with broader linewidths (>20 GHz) envisioned at 2 kW. Such linewidths may hinder efficient beam combining, due to added path length matching complexities in CBC and beam quality degradation in spectral beam combining (SBC). Thus, to further reduce SBS in high power fiber amplifiers an alternative digital scheme, pseudo random bit sequence (PRBS) modulation has been theoretically investigated [9]. PRBS is a periodic, deterministic, pseudo random signal widely used in digital communications. In contrast to WNS, PRBS generates a well-defined discrete optical power spectral density with features that are a function of the modulation frequency and pattern length. Moreover, phase shift keying (PSK) with pseudo random patterns has been shown to provide significant SBS suppression in long distance optical communication systems [10]. Similarly, we believe PRBS modulation can deliver considerable linewidth reduction in kilowatt class fiber lasers.

To that end, we report on PRBS modulated high-power narrow-linewidth, monolithic fiber amplifiers. Advantages of discretely modulated amplifiers with respect to continuously broadened sources are discussed. Subsequently, SBS enhancement factors for specific PRBS patterns are investigated and compared to recent theoretical models and simulations [9]. Furthermore, we discuss seeding of the SBS process by phase modulated signals. Specifically, we show how Rayleigh scattering and other sources of back reflected light can substantially alter the SBS threshold in high-power fiber amplifiers. Mitigation of the seeding process is demonstrated through appropriate PRBS modulation frequency tuning. Finally, a 3 GHz PRBS modulated, 1.17 kW near diffraction limited, all-fiber amplifier with 83% optical-to-optical efficiency is demonstrated. This represents a significant reduction in effective spectral linewidth for kW class fiber amplifiers.

2. Implementation of PRBS in kW class amplifiers

2.1 Comparison to numerical simulations

Recently, a theoretical study of transient SBS in optical fibers seeded with phase modulated light was presented [9]. SBS suppression via phase modulation is examined in the time domain using a triply coupled set of nonlinear partial differential equations. These equations describe a three-wave interaction of two optical fields and an acoustic field. The temporal and spatial evolutions of the acoustic phonon, laser, and Stokes fields are determined by the following coupled three-wave interaction system:

$$\frac{c}{n}\frac{\partial A_L}{\partial z}+\frac{\partial A_L}{\partial t}=\frac{i\omega\gamma_e}{2n^2\rho_o}\rho A_S \tag{1}$$

$$-\frac{c}{n}\frac{\partial A_S}{\partial z}+\frac{\partial A_S}{\partial t}=\frac{i\omega\gamma_e}{2n^2\rho_o}\rho^* A_L \tag{2}$$

$$\frac{\partial^2\rho}{\partial t^2}+\left(\Gamma_B-2i\Omega_B\right)\frac{\partial\rho}{\partial t}-i\Omega_B\Gamma_B\rho=\varepsilon_O\gamma_e q^2 A_L A_S^*-2i\Omega_B f \tag{3}$$

where A_L, A_S, and ρ represent the amplitudes of the pump, Stokes, and acoustic fields, respectively. Here ω ($\omega=\omega_L\simeq\omega_S$) and Ω_B represent the laser and acoustic angular frequencies, respectively and q is the acoustic wavenumber. The electrostrictive constant, γ_e, relates the electrostrictive pressure to the electric field and ρ_0 is the background density of the fiber medium. Moreover, Γ_B is the phonon decay rate and f is a Gaussian random variable with zero mean that accounts for the initiation of the SBS process from a Langevin noise source. Phase modulation effects are accounted for by including appropriate initial and boundary conditions for the laser, Stokes, and phonon fields.

Experimental validation of the time-dependent model has been conducted for sinusoidal phase modulation, with results agreeing with the model and simulations [7]. Similarly, we have been experimentally investigating more spectrally efficient phase modulation schemes, such as PRBS modulation. Recently we performed an experimental study of SBS suppression in passive fiber via WNS and PRBS [11]. Through a cutback experiment we investigated SBS suppression as a function of spectral linewidth and fiber length. For a certain PRBS pattern, we observed superior SBS suppression compared to the WNS at fiber lengths < 20 m.

In digital communications, PRBS is an ideal test signal as it simulates the random characteristics of a digital signal and can be easily generated through linear shift registers. Specifically, it allows one to generate repeatable noise of known spectrum and amplitude, with adjustable linewidth (via clock frequency adjustment), using prevalent and reliable digital circuitry. As such, robust, high-speed PRBS generators are widely available. In

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contrast to the continuum spectra generated by a WNS, PRBS modulation exhibits a periodic and discrete optical frequency comb. The spectral frequency comb is due to the indefinitely repeating psuedo-random pattern lengths. A nominal spectrum of an optical field modulated with a PRBS pattern is presented in Fig. 1.

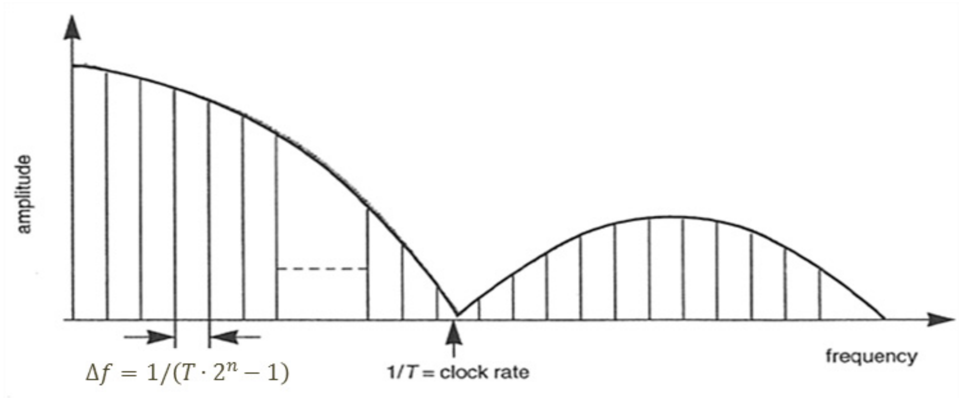

Fig. 1. Nominal PRBS pattern frequency spectrum exhibiting discrete frequency comb within $sinc^2$ envelope.

A PRBS pattern is typically denoted as 2^n-1. The power (n) indicates the shift register length used to create the pattern. The 2^n-1 patterns contain every possible combination of n number of binary bits ('0' and '1'), except the null pattern. For PRBS phase modulation, the binary '0' and '1' data bits represent phase shifts of '0' and 'π', respectively. Subsequently, a $sinc^2$ spectral linewidth is generated (Fig. 1), with the spectral nulls occurring at the bit or clock rate (1/T; T is the bit period). Furthermore, within the $sinc^2$ envelope generated by the bit rate the PRBS data pattern defines a discrete frequency comb. Here the frequency comb separation is given as $\Delta f = 1/(T \cdot 2^n - 1)$ and the FWHM linewidth is approximately equal to the PRBS clock rate. Thus, using PRBS modulation the SBS spectrum can be preferentially altered through appropriate bit rate and pattern length adjustments. This capability can be utilized to provide a means of utilizing phase modulation in conjunction with other SBS mitigation schemes such as longitudinal thermal [12] or strain [13] gradients. For WNS, simultaneous application with one of these techniques results in overlapping Stokes spectra; providing minimal further SBS suppression.

A monolithic, all-fiber, Yb-doped fiber amplifier, shown in Fig. 2, was built to experimentally investigate laser power scaling via PRBS phase modulated signals. The master oscillator was a non-planar ring oscillator (NPRO) from JDSU operating at 1064 nm with a nominal linewidth <5 kHz. Subsequently, a PRBS generator and fiber-coupled LiNbO3 electro-optic modulator were used to broaden the effective linewidth of the seed. Experimentally, to generate the '0' and 'π' binary phase shifts, the electro-optic phase modulator was driven at the appropriate half-wave voltage.

After spectral expansion, the broadened seed was then amplified in three stages to 12 W. The high-power amplifier was comprised of a (6 + 1) × 1 tapered fiber bundle (TFB) with non-polarization maintaining (non-PM) 20/400 µm feed through fiber and six 200/220 µm pump delivery legs from ITF Labs. Six 300 W (976 nm) fiber-coupled laser diodes, manufactured by nLight, were then used to pump the high power amplifier. The gain fiber which was comprised of a non-PM Yb-doped fiber from Nufern was fusion spliced to the pump combiner in a co-pumped configuration. The nominal core and inner cladding diameters were 25 µm and 400 µm, respectively. The fiber length used was ~8 m with manufacturer specified absorption of 1.71 ± 0.21 dB/m. We note the fiber length (and subsequent absorption) were chosen to approach the nominal 13 dB absorption required for

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adequate pump absorption. At the fiber output, the amplifier was terminated with a 400 μm diameter endcap. A dichroic mirror was used to separate and measure the unused 976 nm pump light.

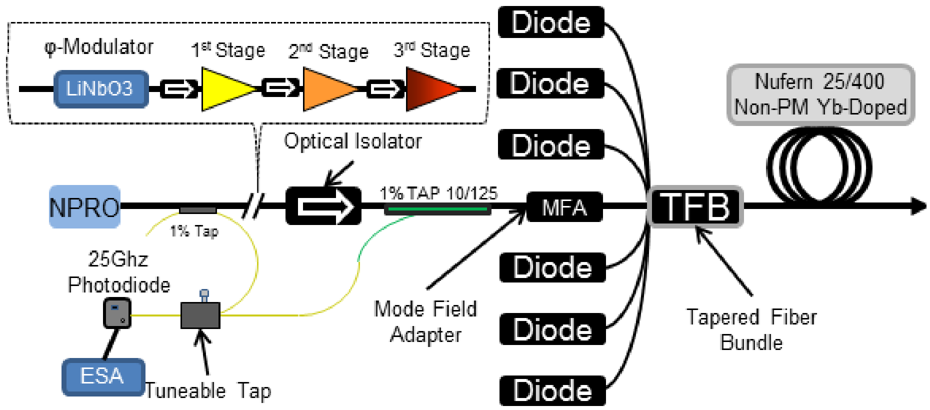

Fig. 2. Experimental arrangement for PRBS modulated monolithic, fiber amplifier. Amplifier included three intermediate stages and a backward power heterodyne diagnostic for Stokes light characterization. The fiber used in the final stage was a non-PM Yb-doped Nufern 25/400.

Consequently, numerical and experimental investigations of SBS threshold enhancement for different PRBS pattern lengths as a function of modulation frequency were compared. For example, normalized SBS threshold enhancement simulations as presented in [9] and experimental data points for the n = 3 and n = 5 patterns are shown in Fig. 3. As shown in Fig. 2, a 1% tap coupler was inserted to monitor the forward and backward propagating light. In order to characterize the SBS response, the backward tap was spliced onto a 50/50 splitter to allow us to simultaneously monitor the power of the backward light on a photodiode and its spectral content using a 0.01 nm resolution bandwidth optical spectrum analyzer (OSA). Backward power measurements are a standard metric for SBS characterization in fiber amplifiers. Experimentally, we have found a reflectivity of 0.05-0.1% to be characteristic of operation near SBS threshold [12]. The SBS threshold enhancement is normalized to the un-modulated (i.e. single-frequency) SBS threshold for the same amplifier configuration.

In addition, we implemented a self-heterodyne technique capable of capturing the Brillouin gain spectrum (BGS) while the amplifier was running. The experimental setup for the self-heterodyne is shown in the bottom left portion of Fig. 2. Through the use of a tap coupler, 1% of the un-modulated NPRO seed is interfered with a sample of the backward travelling light from the high power amplifier. This interference signal is then coupled to a high-speed 25 GHz photodiode and monitored with an RF spectrum analyzer (RFSA). This setup was found to be valuable in investigating the effect of the SBS process being seeded due to phase modulation as discussed in more detail in Section 3.

The experimental results qualitatively agree with the time-dependent SBS model and simulations. The minor variations may be due in part to the finite rise time (non-instantaneous response) of the PRBS system. The numerical model described above does not take into account self-seeding of the SBS process. However, at modulation frequencies well below the Brillouin shift (i.e. modulation frequencies 5 GHz or less) reduced self-seeding is expected. Due to the TFB power handling limitations (1200 W), we were not able to reach the SBS power threshold at modulation frequencies above 3 GHz for the n = 5 pattern. For this pattern, an enhancement factor of ~23 was experimentally obtained at a modulation frequency of 3 GHz as compared to an initially predicted enhancement factor of 25 [9].

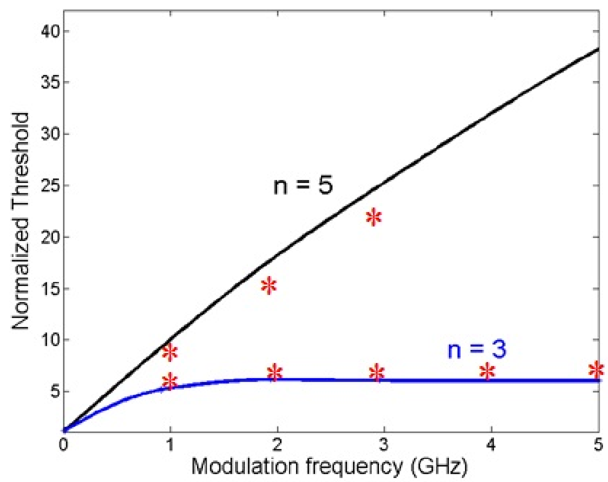

Fig. 3. Normalized SBS threshold enhancement vs. modulation frequency for the PRBS patterns, n = 3,5. Solid lines represent time-dependent SBS simulation with * depicting experimental data.

Moreover, phase modulation with a 2^3-1 PRBS pattern provides a maximum enhancement factor of approximately 6. We note that there is saturation in the enhancement factor at modulation frequencies greater than ~1.5 GHz. At this modulation frequency, the separation among the adjacent sidebands lying within the sinc^2 envelope is appreciably more than twice the spontaneous Brillouin bandwidth. As a result, the sidebands generated by the PRBS act independently and thus the SBS threshold is dictated mainly by the modes carrying the highest amount of optical power. Any further increase in the modulation frequency beyond this point is minimal. Similarly, this was observed in sinusoidal phase modulation when the modulation frequency (and the comb frequency separation) is much larger the Brillouin bandwidth [7], as expected in discretely modulated systems. In contrast, the higher PRBS pattern lengths with smaller separation between discrete tones require larger modulation frequencies before SBS enhancement rollover occurs.

2.2 Characterization of 1170 W monolithic amplifier

At a modulation frequency of 3 GHz, the 2^5-1 pattern allowed scaling to 1170 W of output power at SBS threshold. A plot of the output power and reflectivity vs. pump power is shown in Fig. 4. As shown, an output power of 1170 W was attained at a reflectivity slightly above 0.1%; thus indicating operation at SBS threshold. The optical efficiency of the amplifier was estimated to be 83%. Further power scaling can be achieved by increasing the modulation frequency beyond 3 GHz and optimizing the PRBS pattern as shown in the numerical work of [9]. However, our power levels are currently limited by the TFB pump combiner. Although our six nLight diodes are each capable of providing up to 300 W of pump power, our ITF TFB combiners are rated for 200 W power handling per leg. Thus, we did not push the diodes to full power (stopped at 220-230W) which precluded us from scaling beyond 1.2 kW.

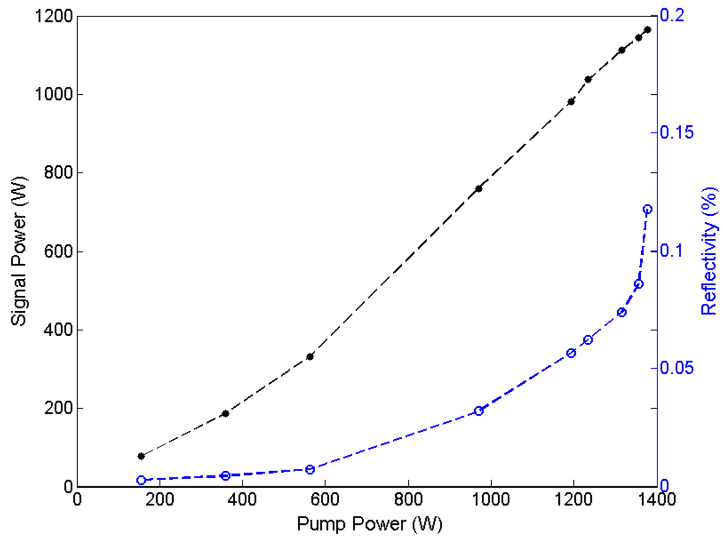

Fig. 4. Signal power (left axes, black curve) and reflectivity (right axes, blue curve) vs. pump power for 3 GHz, 1170 W fiber amplifier. The gain fiber was comprised of a non-PM Yb-doped Nufern 25/400.

We also conducted beam quality measurements using a Spiricon M^2 beam analyzer. A plot of the beam profile at 1 kW is shown in Fig. 5. An M^2 value of 1.2 was measured; thus indicating near-diffraction limited operation. In addition, the spectral content of the forward travelling light was sampled using an OSA. Here an amplified spontaneous emission (ASE) suppression of better than 50 dB at 1 kW of power was observed (Fig. 6), which indicated negligible ASE. Therefore, a 1.17 kW, 3 GHz modulated near diffraction-limited fiber amplifier with 83% pump efficiency and excellent ASE suppression was constructed. We note that this represents a significant reduction in linewidth for monolithic kW class fiber amplifiers.

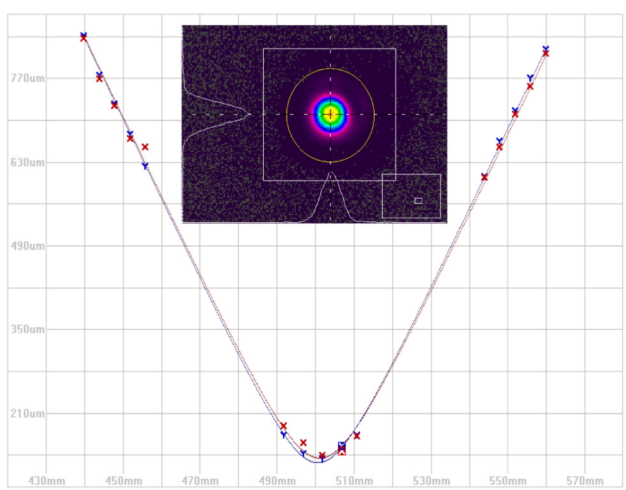

Fig. 5. M^2 beam quality and beam profile (inset) measurements of our kW class monolithic fiber amplifier. Notably, excellent beam quality with M^2 of 1.2 was attained.

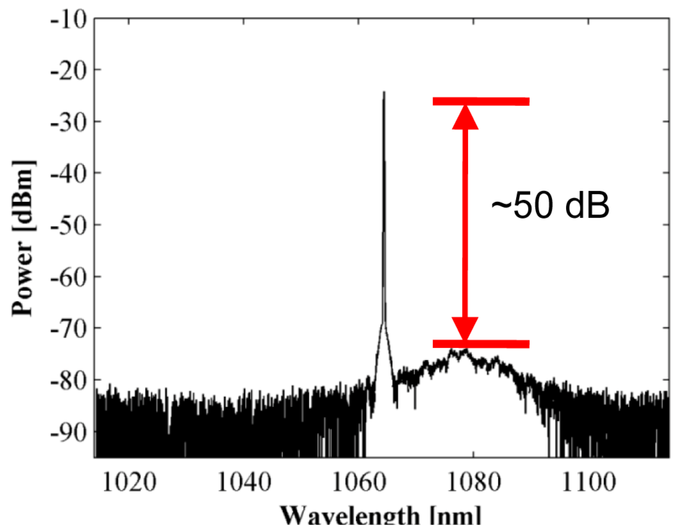

Fig. 6. Forward power spectrum showing amplified spontaneous emission (ASE) suppression of better than 50 dB was achieved at 1 kW of output power.

3. SBS seeding through phase modulation

In single-frequency amplifiers, the backward propagating light oscillating at or near the frequency of the signal is predominantly comprised of two distinct components: 1) Rayleigh scattered light and reflections occurring at the output fiber facet (and/or splice locations within the system) and 2) the Stokes light due to the Brillouin process. The former oscillates at the frequency of the signal while the latter oscillates at a frequency that is downshifted from that of the signal. Accordingly, the Brillouin frequency shift is given by $v_B = 2n_{eff} v_A / \lambda_L$, where n_{eff} is the effective index of refraction and v_A is the acoustic velocity of sound in the medium, respectively. Through this relationship, one can approximate the Brillouin frequency shift as 16 GHz at 1064 nm.

When the input light is no longer single-frequency due to phase modulation, a spectral overlap between the two light components occurs which can lead to the Brillouin process being seeded; thus reducing the SBS threshold. In this case, discrete spectrum phase modulation schemes can have an advantage over WNS as they provide the tunability to preferentially alter the BGS to reduce this spectral overlap. Towards that end, the self-heterodyne technique described above was utilized to investigate this effect in a fiber amplifier seeded with PRBS phase modulated light.

It is expected that the spectral overlap would become more significant as the modulation frequency approaches the Brillouin shift. Consequently we conducted our experiments at a modulation frequency of ~10 GHz. The 10 GHz modulation bandwidth is pertinent and resembles the linewidth of current WNS phase modulated kW class fiber lasers (~10-15 GHz). For the 25/400 fiber (length ~8 m) described above, a PRBS modulation frequency of 10 GHz could lead to pump-limited (rather than SBS limited) outputs. Consequently, for this study we utilized a non-PM Yb-doped Nufern 20/400 fiber of length 12 m. For this configuration, it is expected that the SBS limit would be reached at relatively low power; on the order of a few hundred watts.

As a first step, to demonstrate the utility of this self-heterodyne technique in characterizing the BGS while the amplifier is running, the seed light was left un-modulated. The Stokes response of the amplifier is shown in Fig. 7. The spectrum was obtained at an amplifier output power of 30 W; which is close to the SBS threshold. Here the measured data is fit with a Lorentzian line shape to give an estimated FWHM bandwidth of 22 MHz. The measured bandwidth of the Brillouin spectrum is 2.5x less than the spontaneous bandwidth (~60 MHz) due to gain narrowing. This concurs with theoretical simulations of the Brillouin gain bandwidth in the high gain regime [12].

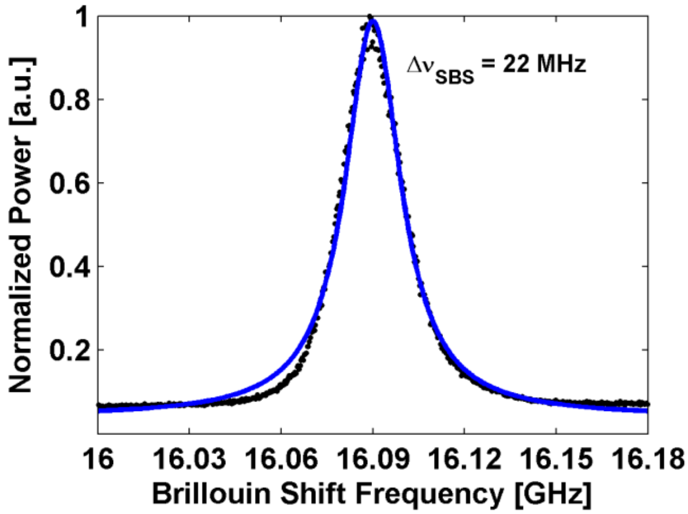

Fig. 7. Brillouin gain spectrum obtained from self-heterodyne of single-frequency fiber amplifier. In this case, the gain fiber was comprised of a non-PM Yb-doped Nufern 20/400. The measured data is fit with a Lorentzian lineshape (solid line) to give an estimated gain-narrowed FWHM of 22 MHz.

The self-heterodyne technique was then applied to PRBS modulated signals. In this case, a PRBS bit pattern of 2^5-1 modulated at ~10 GHz was applied. Three modulation frequencies were investigated: 9.979 GHz, 10 GHz, and 10.084 GHz. The choice of these frequencies will be explained further below. The results, presented in Fig. 8(a), show the Stokes response centered on the resonant Brillouin frequency of the fiber ($\nu_B \approx 16.09$ GHz), as expected. The relatively broad spectral components are associated with the Brillouin response of the PRBS signal. In contrast, the narrow peaks are related to the back reflected or Rayleigh scattered signal light. Due to the discrete nature of PRBS modulation, a frequency comb with numerous optical sidebands is created. Here the frequency separation of the Stokes sidebands is expected to be $10/(2^5-1)$ GHz. Therefore, this separation should be ~320 MHz as confirmed by the spectra shown in Fig. 8(a).

Slight modifications to the PRBS drive frequency can move the narrow peaks such that the overlap between these peaks and the peaks due to the Brillouin process is radically altered. Evidently, the Rayleigh signals at 10 GHz (red curve) are in resonance with the Brillouin response. This is detrimental since having the laser field from these weak reflections overlap with the SBS gain can seed the SBS process and reduce the SBS threshold. As we tuned the modulation drive frequency to 10 GHz (green curve), the overlap was decreased. Figure 8(b) shows both the reflectivity vs. the signal power for the three different modulation frequencies. As shown, the SBS threshold we obtained was higher at 10 GHz than that obtained at 9.979 GHz. By tuning the modulation frequency a little further to 10.084 GHz (blue curve), the spectral overlap was eliminated. Consequently, the SBS threshold was raised even higher; approximately 30% higher than that at 9.979 GHz. We note that WNS modulation with its fixed continuous spectral response does not offer such seeding control. In contrast, through the use of PRBS modulation and the self-heterodyne techniques, we are able to accurately tune the modulation frequency to minimize this seeding process; thus offering an advantage over WNS.

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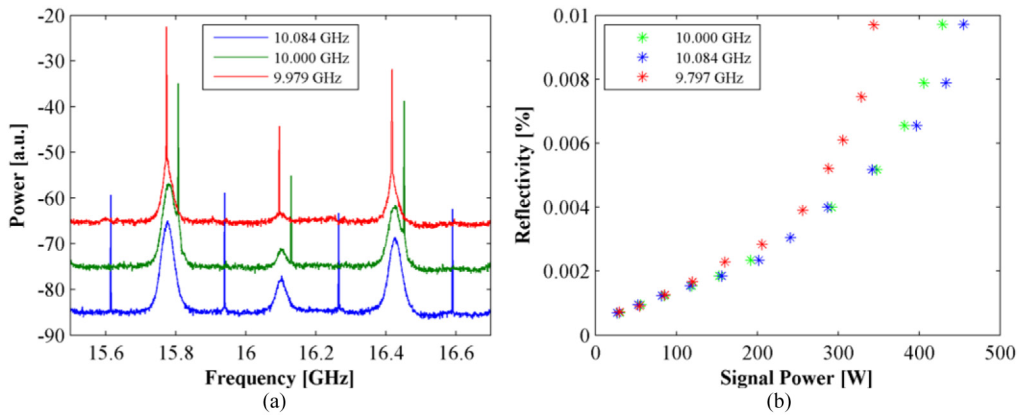

Fig. 8. a) Backward power measurements made with self-heterodyne experimental setup. The broad spectral components are associated with the Stokes response of the PRBS signal. The narrow peaks are associated with back reflected signal light. b) Fiber amplifier reflectivity for the three modulation frequencies inferring phase modulation can lead to seeding of SBS process.

5. Summary

In summary, we have presented PRBS phase modulation for narrow linewidth, kilowatt class, monolithic (all–fiber) amplifiers. Discretely broadened modulation techniques offer advantages over schemes with a continuum spectrum (e.g. WNS). One such advantage is that they provide, through tuning of the modulation frequency, the ability to reduce the seeding of the SBS process. SBS enhancement factors for different patterns of PRBS modulated fiber amplifiers were experimentally verified and agreed well with expected SBS theoretical simulations. Using a 2^5-1 PRBS pattern, we demonstrated at a modulation frequency of 3 GHz, a fiber amplifier with an output power of 1.17 kW. This represents a significant reduction in spectral linewidth for monolithic kilowatt fiber amplifiers. We also investigated seeding of the SBS process by PRBS phase modulated light. Although this seeding process is difficult to control with continuously broadened WNS modulation, we show that the SBS threshold can be tuned and optimized through PRBS modulation. The use of other SBS mitigation techniques (e.g. thermal or stress gradients) in conjunction with phase modulation, is expected to be much more compatible with PRBS than WNS. Overall, the improved SBS suppression and narrow linewidths achieved through PRBS modulation can have significant impact on the beam combining of kW class fiber lasers; where broader linewidths may hinder efficient coherent and spectral beam combining.

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