Comparison of phase modulation schemes for coherently combined fiber amplifiers

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Abstract: Optical linewidth broadening through both white noise (WNS) and pseudo-random binary sequence (PBRS) phase modulation are effective techniques for suppressing stimulated Brillouin scattering (SBS) in high-power fiber amplifiers. However, detailed studies comparing both coherent beam combining and SBS suppression of these phase modulation schemes have not been reported. In this study, a passive fiber cutback experiment is performed comparing the SBS threshold enhancement factor of a PRBS and WNS broadened seed as a function of linewidth and fiber length. Particularly, assuming an optimal PRBS pattern is chosen, pseudo-random modulation provides superior SBS suppression than WNS for a given fiber length and signal linewidth. Furthermore, two WNS and PRBS modulated 150 W fiber lasers are coherently combined to measure and compare the combining efficiency, beam quality, and coherence as a function of optical path length difference. Notably, the discrete spectral density of PRBS modulation provides a re-coherence effect where the lasers periodically come back into phase. Overall, this may reduce path length matching complexity in coherently combined fiber laser systems.

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1. Introduction

Power scaling of high-power fiber amplifiers is generally limited by nonlinear and thermal effects. In terms of nonlinear parameters, stimulated Brillouin scattering (SBS) is the lowest threshold effect in single-frequency and narrow linewidth continuous-wave (CW) fiber amplifiers. Towards that end, numerous SBS suppression techniques have been reported such as phase modulation [1], novel fiber designs [2], laser gain competition [3], and longitudinal thermal gradients [3]. Notably, due to the advent of low voltage fiber-coupled LiNbO₃ phase modulators, optical linewidth broadening has become the predominant method of suppressing SBS in high power fiber lasers. In particular, external phase modulation has led to the development of narrow-linewidth kilowatt class Yb-doped fiber amplifiers [4,5].

By phase modulating the optical signal on time scales shorter than the phonon lifetime, the Brillouin gain is reduced; leading to increased SBS thresholds. 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 [5–7]. Specifically, white noise (WNS) [5,6] and pseudo-random binary sequence (PRBS) [4] phase modulation have been the prevalent linewidth broadening schemes for high power fiber amplifiers. As such, theoretical models predicting the SBS enhancement factors of these phase modulation techniques have been reported [8, 9]. Here the SBS enhancement factors are normalized to the un-modulated (i.e. single-frequency) SBS thresholds. Towards that end, here we report detailed SBS threshold comparisons as function of fiber length and spectral bandwidth for both WNS and PRBS phase modulation.

Although SBS mitigation is required to scale the power of individual fiber lasers, beam combination of multiple fiber lasers is needed to ascend to even higher powers of interest. Whereas broader linewidths are generally preferred for optimal nonlinear suppression, larger linewidths may hinder efficient beam combining. In spectral beam combining (SBC), broader linewidths may reduce the number of channels that can be combined within the finite Yb gain spectrum and lead to beam quality degradation. In coherent beam combining, the coherence length is inversely proportional to the laser linewidth causing strict path length matching tolerances. Although CBC of different phase modulation schemes (and hence different spectral distributions) have varying path length matching requirements, detailed studies comparing their beam combining performance have yet to be reported.

Consequently, two separate experiments are performed to measure the SBS enhancement factor and the coherent beam combining performance of WNS and PRBS phase-modulated amplifiers. Cutback experiments are performed on polarization maintaining (PM) fibers; measuring their SBS enhancement factors as a function of fiber length and optical linewidth for a WNS and PRBS phase modulated signal. We demonstrate that for specific pattern lengths, the PRBS signal can have an appreciably larger SBS enhancement factor relative to the WNS. Furthermore, we demonstrate that the PRBS pattern length can be tuned such that the enhancement factor is nearly independent of the fiber length.

The beam combining performance of the PRBS and WNS phase modulated signals are then compared by measuring the visibility as a function of optical path difference (OPD). Notably, the measured visibilities agree well with expected coherence lengths for both modulation schemes. We coherently combined two 150 W lasers, and demonstrated that both PRBS and WNS can be coherently combined to produce a single beam with 91% combining efficiency and near diffraction limited M² beam quality. We note that due to its discrete frequency comb, PRBS exhibits a re-coherence effect where the lasers periodically come back into phase. In contrast, WNS modulation exhibits no re-coherence. As such, re-coherence effects at PRBS modulation frequencies of 5 GHz and 12 GHz are demonstrated. Significantly, the re-coherence effect in PRBS modulated systems may potentially simplify path length matching complexities in fiber laser CBC systems.
2. Theory

2.1 Stimulated Brillouin Scattering

Theoretical SBS models have been developed based on the transient coupled wave equations. The coupled equations for the amplitudes of the laser, Stokes and acoustic waves are the following [8]:

\[
\frac{c}{n} \frac{\partial A_L}{\partial z} + \frac{i \omega \gamma_e}{2 n^2 \rho} \rho A_s = 0
\]  
\[ (1) \]

\[
\frac{c}{n} \frac{\partial A_s}{\partial z} + \frac{i \omega \gamma_e}{2 n^2 \rho} \rho^* A_L = 0
\]  
\[ (2) \]

\[
\frac{\partial^2 \rho}{\partial t^2} + (\Gamma_B - 2i \Omega_B) \frac{\partial \rho}{\partial t} - i \Omega_B \Gamma_B \rho = \varepsilon_0 \gamma_e q^2 A_s A^*_s - 2i \Omega_B f
\]  
\[ (3) \]

\[
A_L(z=0,t) = A_L^0 e^{i \phi(t)}
\]  
\[ (4) \]

Here, \( \gamma_e \) is the electrostrictive constant, \( \Gamma_B \) is the phonon decay rate, \( \Omega_B \) is the resonant acoustic frequency, and \( f \) is a Gaussian random variable with zero mean used to initiate the SBS process from noise. After phase modulation, the input electric field amplitude is given by Eq. (4), where \( \phi(t) \) is the time-dependent phase modulation and \( A_L^0 \) is the unmodulated input electric field amplitude. The time-dependent phase term increases the average spectral bandwidth of the signal, reducing the nonlinear gain and increasing the SBS threshold. For different types of phase modulation, the spectral distribution changes, affecting the SBS threshold. Consequently, for our SBS suppression and beam combining experiments we utilized the prevalent modulation schemes (WNS and PRBS) in high-power fiber lasers. Experimental results to validate the time-dependent SBS simulations were also conducted using sinusoidal modulation and are also briefly discussed below. For WNS, it was shown in [8] that the SBS enhancement factor has a dependence on the fiber length. For telecom length fibers (several km), this length dependence is very small, and the SBS threshold can be approximated analytically. In contrast, for typical fiber amplifier lengths (fiber length < 20m), significant deviations are expected [8,9].

2.1 Coherent beam combining

In addition to their SBS mitigation properties, applicability of phase modulation schemes towards efficient beam combining is essential for high-power applications. Thus, to test the path length matching requirements and visibilities of WNS and PRBS phase modulation schemes, an actively stabilized CBC system was constructed using a non-polarizing 50/50 splitter as the combining element. The combining architecture, similar to a Mach-Zehnder interferometer is shown in Fig. 1. The master oscillator was a non-planar ring oscillator (NPRO) from JDSU operating at 1064 nm with a nominal linewidth of <5 kHz. Subsequently, a fiber-coupled LiNbO\(_3\) electro-optic modulator was used to broaden the effective linewidth of the seed through both WNS and PRBS phase modulation. The phase modulated source is then split and phase stabilized using the LOCSET phase locking technique [10]. The seed signals are then power scaled through two 150W fiber amplifiers.
Fig. 1. Two beam, actively stabilized coherent beam combining system to measure the coherence of either a WNS or PBRS phase modulated master oscillator (MO).

Based on the optical path length difference and phase noise introduced by the amplifiers, each arm of the interferometer accumulates a different amount of phase. Consequently, phase errors can be stabilized through the LOCSET control system, and optical path length differences (OPD) can be controlled through the use of a variable delay line (VDL). At the combining port, the transmitted intensity is determined by the square of the sum of the electric fields. Here based on the coherence of the lasers and the optical length between the two paths, the intensity fluctuates between a maximum, \( I_{\text{max}} \), and minimum, \( I_{\text{min}} \), intensity. The combined intensity of the two channels is therefore given by:

\[
I(\tau) = I_1 + I_2 + 2\sqrt{I_1 I_2} |V(\tau)| \cos(\alpha \tau - \delta)
\]

(5)

where \( \tau \) is the optical delay, \( \alpha \) is the angular frequency, \( V \) is the visibility function, and \( \delta \) is the phase offset. For a narrow linewidth laser source the visibility function is defined by the Wiener-Khinchin theorem, imparting a Fourier transform relationship between the visibility and power spectral density (PSD) [11]:

\[
|V(\tau)| = \left| \int_{-\infty}^{\infty} P_{SD}(\nu) e^{-i\nu \tau} d\nu \right| = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}
\]

(6)

For a WNS phase modulated system, the broadened optical signal follows a Gaussian function due to the random distribution of voltage amplitudes applied to the modulator. In a PRBS system, the binary data pattern generates a sinc\(^2\) spectral envelope with nulls located at the digital clock rate, \( \nu_c \). Accordingly, the power spectral density of a white noise and PRBS modulated laser can be represented, respectively, as follows:

\[
P_{SD,WNS}(\nu) = \frac{2\sqrt{\ln 2}}{\sqrt{\pi \Delta \nu}} \exp \left[-\left(2\sqrt{\ln 2} \frac{\nu}{\Delta \nu}\right)^2\right]
\]

(7)

\[
P_{SD,PRBS}(\nu) = \frac{1}{\nu_c} \sin^2 \left(\pi \nu / \nu_c\right)
\]

(8)

where \( \Delta \nu \) is the full width at half maximum (FWHM) of the optical spectrum. Based on Eqs. (6-8), we can characterize the WNS and PRBS visibility functions as

\[
V_{\text{WNS}}(x) = e^{-\pi(\Delta \nu)^2 x^2 / (4\ln 2) \nu_c^2}
\]

(9)

\[
V_{\text{PRBS}}(x) = Tr\left(\frac{x}{c} \nu_c\right)
\]

(10)
where $x$ is the optical path difference.

The coherence length, $L_c$, is defined as the delay for which the visibility is decreased by $\sqrt{2}$ compared to no delay. Although other metrics are sometimes used when defining the coherence length (e.g. 0.5 or 1/e drop in visibility), the $\sqrt{2}$ decrease still maintains the high visibilities required for efficient beam combining; with an absolute combining efficiency of $>85\%$. Based on these definitions, the coherence length of a white noise modulated spectrum can be characterized as $L_{\text{WNS}} = c\sqrt{2\ln 2} / \pi \Delta \nu$. Conversely, a PRBS modulated system with a sinc$^2$ PSD, results in a triangular visibility function Eq. (10). The corresponding PRBS coherence length is $L_{\text{PRBS}} = \left(\sqrt{2} - 1\right)c / \sqrt{2\nu}$.

3. SBS Suppression: experimental results

As an initial experiment, in order to validate the time-dependent model described in [8], a sinusoidal phase modulation was applied to an 1064 nm amplifier that utilized an Yb-doped fiber with a core diameter of 10 µm. SBS thresholds were experimentally determined for various modulation frequencies and depths, and are shown in Fig. 2 (red dots). In the figure, the SBS threshold is normalized to the single-frequency case and referred to as the enhancement factor. The horizontal axis represents the modulation frequency and is normalized to the spontaneous Brillouin gain bandwidth. Also plotted are the results of the simulations in [8] (black dots and best fitting curves). The analytical solutions (dashed lines) are based on neglecting SBS cross interactions among the sidebands which are expected to become exceedingly smaller as the modulation frequency is increased. Thus, one would expect both the simulations and experimental data to converge to the analytical solutions at high modulation frequencies.

Fig. 2. Numerical results (black dots) of SBS threshold enhancement factor vs. normalized modulation frequency for various sinusoidal modulation depths. Solid curves represent best fit for numerical results. Red dots depict experimental data points. The dashed lines are based on analytical solutions.

The results shown above represent good agreement between the experimental results and the time-dependent simulations for sinusoidal phase modulation. They also show an increasing SBS threshold with increasing modulation depth. In practice, there is an upper limit to the voltage that can be applied to the electro-optic modulator to achieve the desired SBS suppression. Both WNS and PRBS are more effective techniques and we proceeded to experimentally quantify the SBS suppression for these approaches. For this work, a
monolithic, all-fiber amplifier was constructed as shown in Fig. 3. A low-power single-
frequency seed laser (NRPO) is phase modulated, and subsequently amplified through three
stages. The final stage of amplification utilized Yb-doped PM 10/125 fiber and provided up to
90 W of output power at 1064 nm. This fiber was subsequently spliced onto a 0.01% tap
coupler and passive test fiber (PM 10/125 Nufern fiber). As there were no reliable fiber-
coupled isolators that could handle >30 W of power, there was no isolation between the
passive fiber and the final stage amplifier. The tap coupler was capable of measuring the
backwards traveling Stokes and Rayleigh scattered signal traveling through the passive fiber.
By normalizing the backwards traveling power to the power emitted from the passive fiber,
the reflectivity was calculated. Backward power measurements are a standard metric for SBS
characterization in optical fibers. Experimentally, we have found a reflectivity of ~0.01-0.1%
to be characteristic of operation near SBS threshold.

Both WNS and PRBS phase modulation were studied in these sets of experiments. The
results for PRBS are shown further below. WNS modulation utilizes an RF thermal noise
source to produce a Gaussian broadened signal. The RF signal is amplified and filtered with
low-pass filters before being applied to the electro-optic phase modulator. A corresponding
RF spectrum and optical power spectral density of a 1 GHz (FWHM) white noise signal is
shown in Fig. 4. The optical bandwidth was measured through a (unmodulated-to-phase-
modulated) heterodyne measurement with a fast photo-detector and a radio-frequency
spectrum analyzer (RFSA).

Fig. 3. Block diagram of cutback experiment. A single-frequency seed laser is phase
modulated and amplified, and the SBS threshold is measured in a passive fiber as a function of
optical linewidth, phase modulation type, and fiber length.

Fig. 4. Left) RF spectrum for a WNS which has been filtered by a 225 MHz low pass filter.
Flatness is approximately 2dB, and suppression of higher frequencies is > 40dB. Right)
Measured Gaussian spectral distribution of the phase modulated optical signal with a FWHM
of 1.0 GHz. The optical bandwidth was measured using a heterodyne measurement with a fast
photo-detector and RFSA.
Accordingly, through WNS, the optical signal was modulated at several FHWM bandwidths between 0.225 GHz and 1.47 GHz. The SBS enhancement factor was then measured at varying passive fiber lengths from 70m to 15m. In Fig. 5, we show the enhancement factor vs. FWHM spectral width for lengths of 70m, 20m, and 15m. At each fiber length, a linear dependence on the linewidth and enhancement factor was found; in accordance with the simulations in [8]. For fiber lengths greater than 20m, the enhancement factor remained nearly unchanged with a slope of 11.7 GHz\(^{-1}\), and a maximum enhancement factor of 18.0 for an optical bandwidth of 1.47 GHz. As the fiber is cutback to 15m, the slope of the enhancement factor is sharply reduced by ~30% to 8.3 GHz\(^{-1}\), producing a maximum enhancement factor of 13.0 for an optical linewidth of 1.47 GHz. It is expected the enhancement factor will be further reduced at shorter fiber lengths [8, 9].

![Graph showing enhancement factor vs. FWHM spectral width for lengths of 70m, 20m, and 15m.](image)

**Fig. 5.** Enhancement factor for phase modulation via WNS measured for the cutback experiment using a passive PM 10/125 with fiber length of 1) 70m, 2) 20m, 3) 15m.

The lack of isolation between the final stage amplifier and the passive test fiber precluded us from conducting reliable experiments at lengths below 15 m. The main issue was pulsations induced in the amplifier due to the backward travelling light initiated in the passive fiber. To conduct studies below 15m, we began another set of cutback experiments using an active PM 5/130 fiber that can provide up to 80 W of output power. The experimental setup is shown in Fig. 6.
The results of this cutback experiment are shown in Fig. 7. Again, for WNS there is a remarkable decrease in the enhancement factor. High-power fiber amplifiers typically have lengths of \( \sim 10 \) m, and therefore utilization of WNS for phase modulation may hamper power scaling at linewidths that are amenable to beam combining, be it spectral or coherent combination.

The length dependent behavior of the WNS is due to the transient terms in the time-dependent equations. This can be interpreted in terms of the time averaged optical spectrum across a given length of fiber [9]. For short fibers, the effective optical spectrum appears sparse and random due to the small number of samples. As the fiber length is increased, the optical spectrum as seen by Stokes light that traverses the fiber approaches an ideal Gaussian distribution. Thus, for fiber lengths greater than 20m, the effect of these transient terms is small. However, for fiber lengths shorter than 15m, the sparse time averaged spectrum reduces the enhancement factor (with further enhancement reductions expected at shorter lengths). Practically, this means that when designing fiber amplifiers (typical lengths of \( \sim 10 \)m), broader optical bandwidths are required to achieve a particular enhancement factor. It is worthwhile to point out that the available pump power precluded us from conducting this study at higher modulation frequencies. It is expected that, at higher modulation frequencies approaching the Brillouin shift frequency (\( \sim 16 \) GHz), phase modulation can seed the SBS...
process and therefore lower the enhancement factor. Due to the continuous nature of its spectrum, WNS may be quite susceptible to this seeding process [4].

In PRBS, a pseudo-random binary voltage (0 or \(V_\pi\)) is applied to a LiNbO\(_3\) phase modulator. The pseudo-random pattern is determined from a linear feedback shift register consisting of \(n\)-bits, producing a pattern with a length of \(2^n-1\) bits. For a given clock frequency \(\nu_c\), each bit has a width of \(1/\nu_c\), and the finite pseudo random pattern repeats itself. This is shown in Fig. 8, where a \(2^{23}-1\) PRBS pattern modulated at 1 GHz was simulated. The resulting optical spectrum consists of a sinc\(^2\) envelope with nulls located at integer multiples of \(\pm \nu_c\). In general, the clock rate controls the size of the sinc\(^2\) envelope, while the pattern length controls the number of discrete spectral components within that envelope. The separation of the sidebands, \(\nu_s\), is given by \(\nu_c/(2^n-1)\). For short lengths (typical of high power fiber amplifiers), shorter patterns provide better SBS suppression as the long patterns take much longer to develop than both the phonon lifetime and the roundtrip time of the light in a fiber.

Previous theoretical work has shown that larger clock rates typically increase SBS suppression. However, once the spacing between adjacent sidebands is appreciably greater than the spontaneous Brillouin bandwidth, no further increase in the SBS enhancement factor is seen [8]. In contrast to WNS, through pseudo-random modulation the pattern length can be adjusted to compensate for the length of the fiber. To validate this and to compare to WNS phase modulation, our cutback experiments included a study of PRBS using the patterns of \(2^{23}-1\) and \(2^{15}-1\). We note that based on previous theoretical and experimental observations, the \(2^{23}-1\) pattern is near optimal for typical high-power fiber amplifier lengths (~10m) [4,8]. Through PRBS phase modulation, the SBS enhancement factor for clock frequencies ranging from 0.275 GHz to 2.0 GHz was analyzed here; corresponding to FWHM spectral widths of 0.25 GHz to 1.78 GHz. Similar to the WNS experiments, the enhancement factor for the passive PM 10/125 fiber was measured for several lengths between 70m and 15m; with the corresponding measurements at 70m and 15m shown in Fig. 9.
Fig. 9. Cutback experiment plots showing the enhancement factor at 70m and 15m using a passive polarization maintaining 10/125 fiber with phase modulation achieved via PRBS patterns 2^7-1 and 2^15-1. Experimental data measured at 70m, 2^7-1 (red); 15m, 2^7-1 (black); 70m, 2^15-1 (blue); 15m, 2^15-1 (green).

Clearly, the 2^7-1 PRBS pattern is superior to 2^15-1 in suppressing SBS. It is also superior to the experimental WNS results obtained for comparable frequencies and fiber lengths. For L = 70m (red and blue lines), both patterns provide approximately the same enhancement factor with a minor increase for the 2^7-1 pattern. Nevertheless, at L = 15m the SBS enhancement factor diverge significantly, with the 2^7-1 pattern demonstrating minimal dependence on the fiber length. For the 2^7-1 pattern at 70m (red line), the enhancement factor is a linear function of the optical spectral width, with a slope of 9.97 GHz$^{-1}$. Moreover, a maximum enhancement factor of 21.8 is attained for a FWHM linewidth of 1.78 GHz. Cutting back to 15m (black line) reduces the slope to ~9 GHz$^{-1}$, and the maximum enhancement factor is only reduced by 12% to 19.2.

Conversely, the 2^15-1 pattern experiences a considerable SBS enhancement factor decay as the length is reduced (similar to WNS). Cutting the fiber back from 70m to 15m reduces the enhancement factor vs spectral width by ~30% from 9.5 GHz$^{-1}$ to 6.6 GHz$^{-1}$. Notably, the fiber length SBS dependence can be minimized by adjusting the PRBS pattern length. While the clock frequency and fiber length might be fixed by other requirements (coherence length, delivery fiber length, etc), adjusting the pattern provides an additional freedom to maximize the enhancement factor; allowing for higher output powers to be achieved.

The cutback experiment performed on the active 5/130 fiber also exhibits a similar trend of strong length dependence in the enhancement factor for the 2^15-1 pattern as opposed to a milder dependence for the 2^7-1 pattern. Figure 10 shows the enhancement factor plots for the two patterns at a FWHM of 1.77 GHz for fiber lengths varying from 15m to 8m. We point out that at 15m, the enhancement factors for both PRBS patterns are noticeably lower than the respective enhancement factors measured using the passive 10/125 fiber. This discrepancy may be attributed to the difference in the spontaneous Brillouin bandwidth of the two fibers and warrants further investigation. Also shown in Fig. 10, for comparison purposes, is the enhancement factor for the WNS at a similar FWHM. Again, the enhancement factor for the WNS shows a more pronounced dependence on length than that of the 2^7-1 PRBS pattern. The SBS threshold was not measured for WNS at 8m length due to pulsation in the amplifier. In general, the amplifier was more prone to pulsation near the SBS threshold when seeded with a WNS phase modulated source. At 8m and FWHM of 1.77 GHz, the pulsations were too severe at 53 W and precluded us from reaching our 0.015% reflectivity metric for SBS
threshold for this active fiber study. On the other hand, with the $2^7$-1 pattern, we were able to achieve 71 W at SBS threshold.

Fig. 10. Enhancement factor as a function of fiber length for ~1.7 GHz WNS and PRBS ($2^7$-1 and $2^{15}$-1) phase modulated systems. A 5/130 PM Yb-doped fiber was utilized for these measurements.

Overall, assuming an optimal pattern is chosen, PRBS modulation provides superior SBS suppression than WNS for a given fiber length and signal linewidth. We also note that PRBS modulation has additional advantages at broader linewidths approaching the Brillouin shift frequency (~16 GHz), where spectral overlap between the broadened linewidth and the Stokes shifted wave can lead to seeding of the SBS process. As stated above, this seeding cannot be controlled with continuously broadened WNS modulation. On the other hand, it was shown that this process can be controlled through the digital PRBS modulation format by small tunings of the clock rate [4]. Therefore as we scale to broader linewidths, this seeding mitigation can lead to even greater SBS suppression performance for PRBS modulation.

4. Coherent beam combining

4.1 Beam quality and combining efficiency

For phase modulated linewidth broadening, applicability towards efficient beam combining is another critical metric. In CBC, the dissimilar optical spectra lead to distinct coherence properties. Thus, to compare their respective coherence length and coherent combining performance, a CBC experiment was configured for both WNS and PRBS phase modulation, as shown in Fig. 1. Here the variable delay line was adjusted to optimize path length matching of the two channels and to maximize the combined output power.

Through WNS modulation, a Gaussian broadened optical signal with 4.5 GHz FWHM was implemented. The combined two-channel output power was measured to be 273 W, resulting in ~91% combining efficiency. Slight deviations from the ideal combining efficiencies are due in part to non-optimal beam overlap/pointing and lower than expected polarization extinction ratio (PER) of ~15 dB from the fiber amplifiers. Nonetheless, near diffraction limited beam quality was obtained with an $M^2 = 1.05$ (Fig. 11, left). Similarly, a $2^9$-1 PRBS pattern at a modulation frequency of 5 GHz was applied resulting in a sinc$^2$ spectrum with FWHM of 4.42 GHz. The combining efficiency was identical to the WNS case, producing 273 W of combined power (~91% efficiency). Moreover, near diffraction limited beam quality with an $M^2$ of 1.06 (Fig. 11, right) was also achieved for PRBS beam combining.
4.2 Visibility

Subsequently, we investigated the coherence length properties of PRBS and WNS modulated signals. Through modification of the variable delay line, the visibility was measured as a function of optical path difference. These measurements were compared to the expected WNS and PRBS visibilities using the time averaged spectral distributions as provided by Eqs. (7-8). While both phase modulated signals have near equal spectral widths, the different spectral shapes of the modulation formats (WNS-Gaussian; PRBS-sinc$^2$) lead to different visibility curves and coherence lengths. The subsequent normalized visibility versus optical path difference for the 4.5 GHz (FWHM linewidth) WNS is plotted in Fig. 12. The measured signal has strong correspondence with the theoretical Gaussian PSD, and ~20.8 mm coherence length (visibility reduction of $1/\sqrt{2}$) was determined.

In order to evaluate similar PRBS coherence lengths, a 2$^9$-1 PRBS pattern at clock rate of 4.25 GHz was implemented. Here a 4.25 GHz modulation frequency (3.78 GHz FWHM) is required to generate a coherence length similar to that of the 4.5 GHz WNS ($\nu = c(\sqrt{2} - 1)/(\sqrt{2} L_{\text{na}})$). As expected, the corresponding visibility versus OPD exhibits a linear dependence as captured by Eq. (10), with ~20 mm coherence length as shown in Fig. 13. This is within 4% of the theoretical prediction. In general, for similar
spectral FWHM, small path length mismatches lead to less severe drop in visibility for WNS than PRBS, while the opposite is true for longer path mismatches (~50% visibility). In practice, the linear drop in the visibility for the PRBS can be altered by filtering out the spectral side lobes lying within the sinc² envelope. Preliminary experimental data indicate that this approach will have almost equal SBS suppression to that of unfiltered PRBS phase modulation. On the other hand, our simulations of visibility vs. OPD as shown in Fig. 14, indicate a filtered PRBS will appreciably have a less severe drop in visibility at small path length mismatches; comparable to the drop for a WNS. The SBS suppression and coherent beam combination properties of filtered PRBS will be investigated thoroughly in future work.

4.3 PRBS Re-coherence

The periodic nature of the pseudo-random pattern allows for a re-coherence in the visibility; a phenomenon not seen with the continuous spectral distributions of WNS modulation or typical broadband sources. By increasing the path length difference to an integer multiple of the spacing between spectral lines, i.e. integer multiple of \( c (2^{n-1}) / \nu \), coherence is restored.
This re-coherence is illustrated in Fig. 15 for both a 5 GHz (left) and 12 GHz (right) PRBS modulated 2³⁻¹ pattern. For the 5 GHz signal, the re-coherence distance is ~420 mm, agreeing well with the expected distance based on the pattern separation frequency of 0.714 GHz (5GHz/2³⁻¹). More importantly, there is no drop in visibility or combining efficiency as the lasers periodically come back into phase. By increasing the clock rate to 12 GHz, the pattern repetition frequency increases to 1.71 GHz, corresponding to the measured re-coherence distance of 175 mm. Visibility measurements were also repeated using a 4.5 GHz WNS phase modulated signal for a path length difference of up to 500 mm and no re-coherence was observed as expected. In contrast to WNS modulation, which is based on random RF signals (no periodicity), re-coherence is an intrinsic property of periodic signals such as sinusoid and PRBS modulation. As a result, instead of absolute path length matching to one beam combining maximum, path length matching to any one of the periodically repeating maximum is sufficient. Significantly, this property may greatly simplify path length matching complexities in fiber laser CBC systems.

![Fig. 15. Re-coherence measurements where re-coherence distance can be controlled by modifying the pattern repetition rate. (Left) 2³⁻¹ PRBS pattern at 5GHz with re-coherence distance of 420mm. (Right) 2³⁻¹ PRBS pattern length at 12GHz with re-coherence distance of 175 mm.](image1)

4. Conclusion

In conclusion, we have experimentally compared both the SBS enhancement factor and coherent beam combining properties of WNS and PRBS phase modulated fiber amplifiers. We have shown that the SBS enhancement factor of the WNS has a strong dependence on the fiber length, while PRBS phase modulation can partially correct for this length dependence by altering the pattern length. Cutting back to even shorter fiber lengths and further optimizing the pattern length, it is expected the relative performance of PRBS will improve. Subsequently, visibility as a function of OPD was analyzed for both PRBS and WNS. Here the dissimilar spectral densities cause disparate visibility curves; in agreement with the theoretical predictions. Furthermore, the discrete spectral lines of the PRBS modulated spectrum, indicative of a periodic phase modulation, cause a re-coherence effect where the lasers periodically come back into phase. Here re-coherence occurs when the path lengths differ by integer multiples of the spacing between the spectral lines. Specifically, we have demonstrated CBC of PRBS modulated fiber amplifiers for the first time and demonstrated PRBS re-coherence effects. This feature of the PRBS can offer a significant advantage for coherent beam combining of many lasers. Finally, for future work, we will investigate the SBS suppression and coherence properties of amplifiers seeded with filtered (i.e. spectral side lobes are eliminated) PRBS phase modulation.
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