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Enhancing the efficacy of Noise Modulation for SBS suppression in High Power, Narrow Linewidth Fiber Lasers by the incorporation of Sinusoidal Modulation

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***Abstract*— Power scaling of continuous-wave, narrow-linewidth fiber lasers are limited by the onset of stimulated Brillouin scattering (SBS) which manifests at threshold as potentially damaging, peak power, backward propagating pulses. While several SBS mitigation techniques exist, optical linewidth broadening through external phase modulation using white noise is predominantly used for its simplicity. But the broadened line-shape is non-ideal and has a slow roll-off resulting in increased SBS seeding from reflections and hence limited power scaling. With better line-shape control, higher output powers can be achieved. In this work, we propose a simple and effective technique to improve the SBS suppression of these high power, narrow linewidth, noise broadened systems, by the addition of a sinusoidal modulation in cascade. The dual modulation results in an improved line-shape with a relatively flat topped-center and fast roll-off when compared to pure noise modulation at similar root-mean-square (RMS) linewidths. Using a multi-stage fully polarization maintaining, kW-class amplifier, we demonstrate >2.3X enhancement in SBS limited output power when compared to the pure noise modulated case at ~7.3 GHz and >1.029 kW output power at ~10.4 GHz RMS linewidth.**

***Index Terms*—Stimulated Brillouin Scattering, Phase Modulation, White noise source, Sinusoidal Modulation, High Power Fiber Lasers, Narrow Linewidth, Power Scaling, Kilo-watt class**

I. INTRODUCTION

HIGH power, narrow linewidth fiber lasers have garnered a lot of interest over the last decade due to their widespread use in beam combining applications [1-3], laser guide star [4], nonlinear frequency conversion [5], and light detection and ranging (LIDAR) [6]. Power scaling of these lasers is limited by nonlinear and thermal effects. Stimulated Brillouin scattering (SBS) is the lowest threshold nonlinear effect in narrow linewidth, continuous-wave (CW) lasers and occurs in the form of high peak power pulses propagating in the backward direction. These pulses cause catastrophic damage to the system and must be mitigated. Several SBS suppression techniques such as introducing thermal gradients [7] and longitudinal strains [8] along the fiber, novel fiber designs, laser gain competition [9], acoustic anti-guiding [10,11] and linewidth broadening have been reported [12,13]. But with the development of compact, low voltage, fiber-coupled Lithium Niobate phase modulators, optical linewidth broadening through external phase modulation has become the preferred method for SBS suppression in high power fiber lasers [12-15]. Spectral broadening of the seed laser through phase modulation with pseudo-random binary sequence (PRBS) [16], arbitrary waveform generator (AWG) [17] or filtered white noise (WNS) [18] can be used for obtaining high power narrow linewidth fiber lasers. Among these, AWG and PRBS techniques provide high SBS enhancement factor [16] by using customized line-shapes but result in increased system cost, complexity, and resource utilization. Additionally, in these systems the SBS threshold enhancement is significant only when optimized line-shapes or waveforms are used. A comparison study of WNS and PRBS modulation schemes for ~1.7 GHz linewidth in [15] shows that for a given length of fiber, WNS modulation offers a much higher SBS enhancement factor than PRBS (2^{15}-1), but when an optimized pattern with PRBS (2^{7}-1) is used, the overall enhancement factor is slightly higher than WNS. But, obtaining an optimized pattern or waveform is a complex iterative process. Phase modulation with WNS is the simplest and most prevalent technique to increase SBS threshold and allows for continuous tuning of linewidth through control of noise power and bandwidth. But the resulting lineshape has a central peak with slow roll-off and an extending signal tail seeding SBS. This results in lower experimental SBS threshold enhancement than the estimated theoretical value [18-20]. In this work, we propose a modulation technique to improve the performance of WNS broadened, narrow linewidth systems to achieve higher output power while preserving the simplicity of the technique.

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The sub-normal SBS threshold enhancement in noise broadened systems can be attributed to the stochastic nature of WNS broadening and the enhanced SBS seeding resulting from line-shape and reflections (including Rayleigh scattering and end facet) [16,18, 21-22]. The role of reflections influencing SBS threshold has been explored by many groups [23-26]. For better SBS suppression, an improved line-shape having a flat-topped center (ensuring uniform power distribution) and fast roll-off at the edges (for reduced spectral overlap and hence SBS seeding) is required. PRBS modulation and techniques using AWG also strive towards this goal. Here we demonstrate that SBS threshold enhancement with improved lineshape can be achieved in a simple configuration by using a cascade of noise and sinusoidal modulation. With this novel modulation, we demonstrate >2X enhancement in SBS limited output power when compared to the pure noise modulated case achieving an output power of >1029 W at ~10.4 GHz RMS linewidth in a polarization maintaining, narrow-linewidth fiber amplifier assembled with off the shelf components.

Improved power scaling using multiple modulation blocks in cascade has been demonstrated previously in [27] using non-polarization maintaining (non-PM) architecture and in [28,29] with fully polarization maintaining (PM) architectures. In [28] the authors use cascaded sinusoidal modulation and demonstrate 3-dB spectral linewidth and output powers of 6 GHz and 477 W (single-stage), 18.5 GHz and 1040 W (two-stage) and 45 GHz and 1890 W (three-stage modulation) respectively. Similarly, in [29] cascaded WNS modulation is used with 3 dB spectral linewidth and output power of 12.8 GHz and 1230 W (single-stage), 20 GHz and 1790 W (two-stage) and 32 GHz and 2620 W (also two-stage). It is important to note that the increase in output power corresponds to a significant increase in linewidth after each stage of the cascade. This is a key difference because in this work, we aim to demonstrate an improvement in output power of a WNS broadened system by the addition of sinusoid modulation while keeping the overall linewidth same for both cases. Thus, the enhancement obtained is attributed solely to the change in line-shape introduced by the cascade.

In [27] a brief account of SBS-limited output power of 1.4 kW at 26 GHz in a non-PM architecture using a combination of sinusoid and noise is given but does not discuss the effect of this modulation scheme on lineshape and power scaling. Further, SBS threshold in non-PM narrow linewidth systems is significantly higher than in PM systems. In this work, we examine the effect of dual modulation with sinusoid and noise on lineshape and optimize the modulation parameters to demonstrate superior results with >1 kW output power at ~10 GHz linewidth in a fully PM architecture. This is a >2X enhancement in output power compared to the single-stage noise modulated system at similar linewidths.

Linewidth measured as 3 dB spectral linewidth does not fully account for the effect of line-shape on SBS seeding. To understand and compare the line-shapes obtained by different modulation schemes, RMS linewidth of the line-broadened signal $\Delta\nu_{RMS}$ is calculated as:

$$\Delta\nu_{RMS} = 2*\sqrt{\frac{\sum\left(pow*(freq)^2\right)}{\sum pow}} \qquad (1)$$

Here, “pow” is the spectral power measured in linear scale. The RMS linewidth considers not only the line-shape at the central region of the laser, but also roll-off and is a better metric for the distribution of spectral power. Further, it allows for comparison with other modulation techniques such as sinusoidal or AWG modulation where the spectrum has ripples or is discontinuous [17]. In this work, we propose a “dual modulation with sinusoid and noise” (referred to as DMSN) to increase the SBS threshold and output power of a simple WNS broadened system at similar RMS linewidths.

II. Simulations and Experimental Setup

In our previous work [26], we investigated the relative contributions to SBS seeding and found that end facet reflections and Rayleigh scattering assisted SBS seeding lowered the power scalability by over 20% at ~10 GHz linewidth. Thus, the line-shape induced enhancement of SBS due to signal tail overlap with Brillouin gain spectrum plays a dominant role in determining the maximum achievable power. The tailoring of laser line-shape with the proposed DMSN was initially investigated through simulations based on phase modulation. Transfer function of the phase modulator was used to incorporate the proposed modulation scheme and the spectra of filtered white noise was utilized to synthesize instances of noise voltage [29]. Sinusoid voltage is added to the noise to analyze the laser line-shape evolution for the proposed DMSN scheme with increasing sinusoidal power (1 GHz tone) as shown in Fig. 1. Starting from a 700 MHz bandwidth (BW) low-pass filtered noise with ~25.2 dBm noise power (Fig. 1, blue trace), with increasing sinusoid power which also increases the linewidth (Fig. 1, green to violet trace), the spectrum has improved flatness near the carrier resulting in reduced peak power.

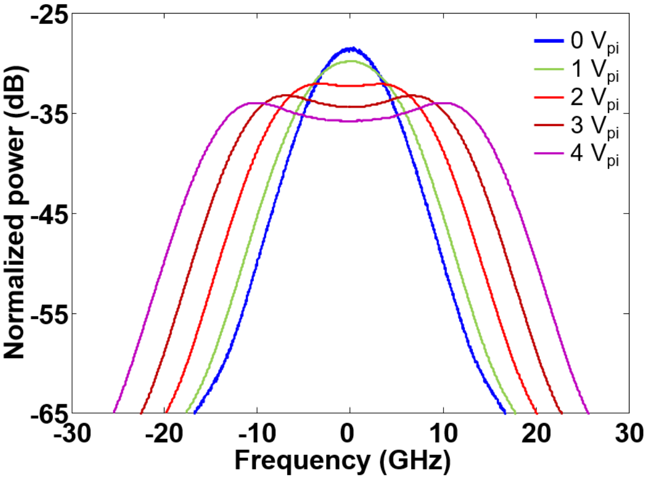

Fig. 1. Simulated line-shape evolution of the dual modulation with sinusoid and noise laser with increasing sinusoid power.

To target a specific linewidth, several combinations of the sinusoid and noise parameters can be used. Based on the combination of filters and attenuators available with us, we chose the 1 GHz tone to tune the linewidth from ~7 GHz to ~10 GHz. Fig. 2 shows a comparison between noise modulation only and DMSN with same RMS linewidth of ~10 GHz. With noise modulation only, the line-shape is sharp at the center and there is a significant overlap of the signal tail with the Brillouin gain spectrum leading to increased SBS seeding. This is mitigated by using DMSN where the line-shape has a relatively flat-topped center and a fast roll-off with significantly lower powers present at the SBS Stokes wavelength (shifted by 16 GHz). The combined effect of improved spectral flatness and reduced SBS seeding due to overlap results in an increase in SBS threshold and hence the maximum operating power of the system.

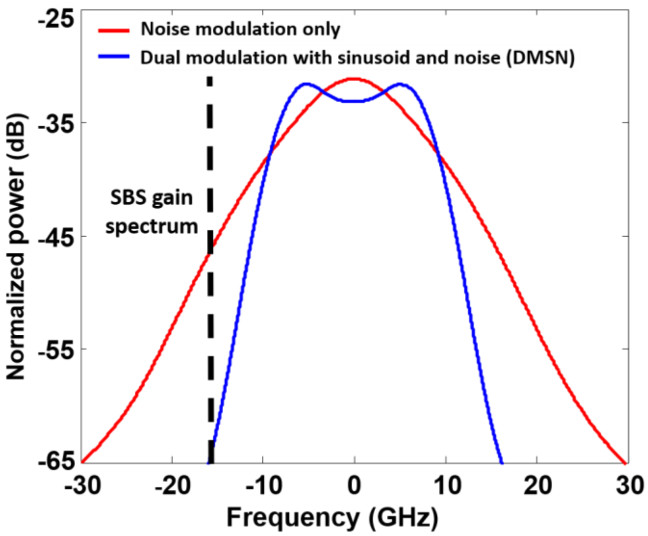

Fig. 2. Comparison of line-shape and SBS spectral overlap for noise modulation only (red) and proposed DMSN scheme (blue) for ~10 GHz RMS linewidth.

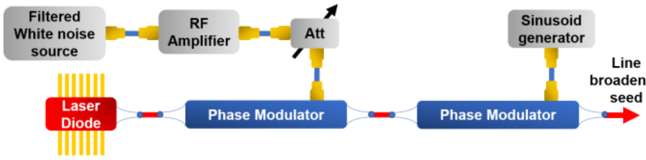

Fig. 3. Architecture for the proposed dual sinusoid and noise modulation scheme. RF: Radio Frequency, Att: Attenuator.

Fig. 3 shows the implementation of the proposed DMSN used in this work. A 1064 nm DBR seed laser with ~5 MHz linewidth (Thorlabs DBR1064P) is phase modulated with filtered WNS and sinusoid waveforms. The RF power handling limit of each phase modulator used is 500 mW and Vπ (at 1 GHz) is ~2.4 V. The noise source with 3 GHz bandwidth (1 mW power) is spectrally shaped by a low pass filter (LPF) bank, and the noise power is controlled by an amplifier and a suitable attenuator. The line-shapes were evaluated with an in-house built homodyne measurement setup. An alternate architecture to implement the proposed modulation scheme would be to use a single-phase modulator with higher power handling capability and a pick-off-tee to combine the sinusoid and noise signals in an optimal ratio.

We initially tested the effectiveness of DMSN in a CW narrow linewidth, polarization maintaining (PM) system at relatively low powers of 15 W. Since SBS does not occur at this power level for GHz linewidths, we used 50 m of PM 980 fiber (from Nufern) to increase the effective fiber length and terminated it by a small angle cleave (~2 degrees) to enhance reflective seeding and encourage early onset of SBS. The SBS limited output power (taken when pulses are recorded on the oscilloscope placed at the monitor port) was compared for the case with WNS broadening only and with DMSN at similar RMS linewidths. The results showed >2X enhancement in SBS limited output power with DMSN at ~13 GHz linewidths. We then tested the performance of this modulation scheme at kW power levels with an in-house built, multi-stage amplifier in a fully PM architecture.

The line-broadened seed laser with ~10 mW of power is power scaled using three-stages of cascaded PM, Ytterbium-doped fiber amplifiers (YDFA) as shown in Fig. 4.

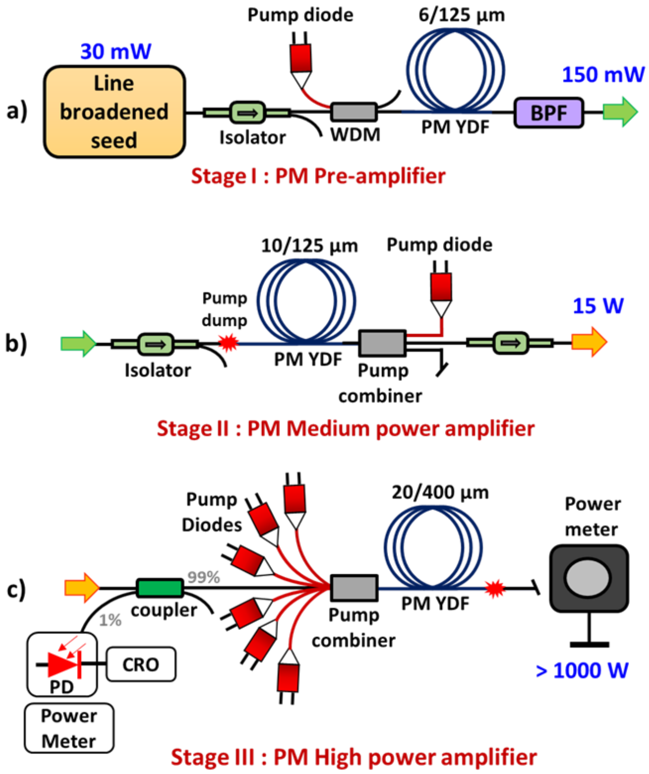

Fig. 4. Experimental setup of the kW-class, narrow linewidth, polarization maintaining Ytterbium-doped fiber laser. WDM: Wavelength Division Multiplexer, PM: Polarization Maintaining, YDF: Ytterbium Doped Fiber, PD: Photodiode, CRO: Cathode Ray Oscilloscope.

The first stage of power scaling is done in the PM pre-amplifier. Fig. 4(a) shows a simplified schematic of stage I. The pump is a 976 nm butterfly diode. The line broadened seed is amplified to 150 mW by core-pumping a section of 6/125 µm PM Yb-doped fiber (YDF) from Nufern with 80 dB/m pump

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absorption in the core. Amplified spontaneous emission (ASE) from the pre-amplifier stage is suppressed by a low power PM band pass filter (BPF) with 2 nm pass band before further amplification. The pre-amplifier output is then power scaled in the cladding pumped PM medium power amplifier (MPA) (Fig. 4(b)). A counter-propagating pump scheme is utilized as it provides higher powers and better ASE suppression in comparison to the co-propagating scheme. A semiconductor laser diode with maximum output power of 30 W at 976 nm is used to pump ~4.5 m of 10/125 µm PM YDF to yield 20 W which reduced to 15 W after the isolator. The polarization extinction ratio (PER) at each stage is >20 dB.

The third stage is a cladding pumped PM high power amplifier (HPA) with ~8 m of 20/400 µm PM YDF and ~1.5 m of angle-cleaved matched passive delivery fiber (from Nufern). The fiber geometry was chosen to provide power-scalability with high beam quality. The effective length of the high-power amplifier stage plays a crucial role in determining the onset of SBS. Longer fiber lengths cause an early onset of SBS, shorter gain fiber lengths result in incomplete pump to signal conversion and difficult thermal management. Thus, the length of gain and passive delivery fiber was optimized to yield >1 kW output power. For this, 976 nm semiconductor diode packages capable of delivering 210 W - 220 W at full power are used at each of the six pump ports of the pump combiner (from Lightcomm) (Fig. 4(c)). They are mounted on a cold plate that is externally water cooled to ensure stable operation over an extended period of time.

Isolators with suitable power handling capabilities are placed between every stage to protect the system from backward propagating light. Tap ports of the low-power isolators in stage I and II are used to constantly monitor the output power at key junctions, since failure of any stage during ON operation would result in catastrophic damage to the subsequent amplifier sections. The entire setup is carefully monitored using a high-resolution thermal camera to detect temperature changes of components and splices and identify stable operating points of the system.

To monitor the onset of SBS, a tap port in the form of a bi-directional coupler is introduced between the medium and high-power amplifier stage as shown in Fig. 4(c). A fast photodiode (PD) with 17 MHz BW and a cathode ray oscilloscope (CRO) is used to detect the SBS pulses. A power meter is also placed in the tap port to measure the average backward power entering the MPA (stage II).

SBS threshold is usually defined based on the ratio of average backward power to input power. For high power narrow-linewidth fiber lasers, SBS manifests as pulses [30] and a theoretical -3 dB, -10 dB or -20 dB threshold for quantifying the onset of SBS is not practical since the components used will reach their damage threshold well before that. Through our experiments which resulted in damage events, we identified, that pulses of peak powers as low as tens of watts to hundred watts could potentially result in system damage. A definitive measure of threshold depends on the maximum SBS limited output power ensuring safe system operation. Owing to the chaotic nature of these pulses, we conservatively set our SBS threshold as the recurrence of pulses of peak powers at the 10 W level. It is to be noted that further scaling in output power is possible, but since our aim is to compare the performance of the two modulation schemes (i.e., noise only and DMSN), we set this 10 W pulse peak power limit as our threshold measure to ensure reliable system operation over linewidths ranging from 7 GHz to 10 GHz. The oscilloscope was calibrated to identify the voltage level corresponding to the appearance of these threshold defining pulses.

To get an accurate measure of the effectiveness of the proposed modulation technique, we kept the entire 3-stage MOPA set-up as is, and compared the system performance (i.e., output power at SBS threshold) by only changing the modulation on the initial seed from pure noise to the proposed DMSN for similar RMS linewidths.

III. Results

For the SBS threshold defined in this work, the output power at a linewidth of ~7.3 GHz with pure noise modulation was 319 W. Keeping the entire set-up as is and by only changing the modulation scheme to DMSN for similar linewidths (700 MHz LPF with 25.2 dBm noise power and 1 GHz sinusoidal modulation at 21.2 dBm), the output power increased to 751 W (scaled by a factor >2.3).

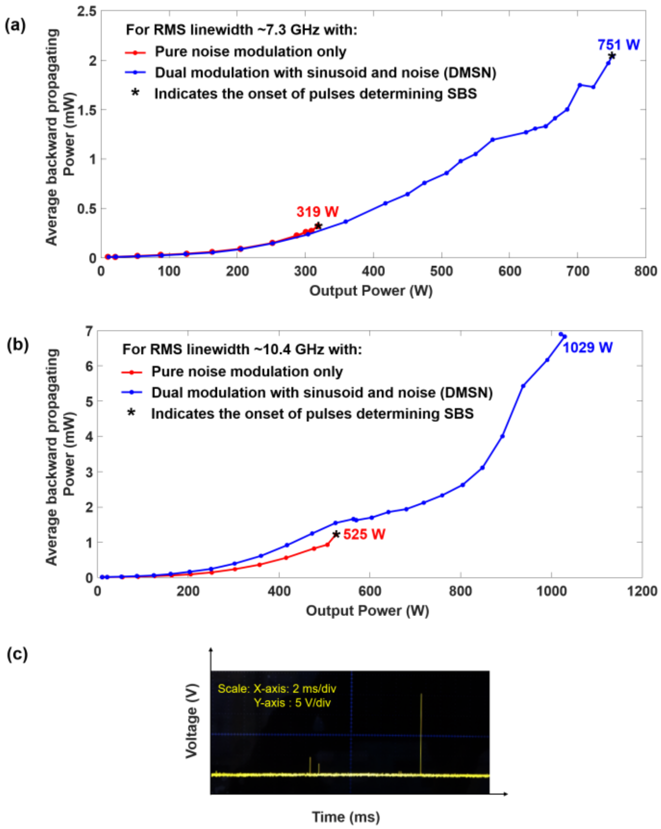

Fig. 5. Comparison plot of output power vs. average backward power entering the MPA with white noise modulation only (red) and dual modulation (blue) for (a) ~7.3 GHz RMS linewidth and (b) ~10.4 GHz RMS linewidth (* indicates the onset of pulses determining the SBS threshold); (c) Oscilloscope trace showing SBS pulses.

Figure 5 shows the plot of average backward power entering the MPA with increasing output power. Although we recognize that average backward propagating power does not fully define the onset of SBS in high power systems, we use it here to indicate the point of occurrence of pulses determining SBS threshold defined previously (denoted by * in Fig 5(a) and 5(b) and shown as an oscilloscope trace in 5(c)).

The average backward power with DMSN is ~55 dB below the output power level of 751 W. In the pure noise broadened case these threshold SBS pulses occur at much lower levels of average backward power indicating that the proposed modulation technique offers improved lineshape that effectively suppresses the early onset of peak SBS pulses, thereby enabling stable system operation with higher output powers. Further power scaling is achieved by increasing the linewidth of the seed. At ~9.4 GHz, output power is scaled from 388 W (noise only) to 879 W (DMSN with 700 MHz LPF and 1 GHz sinusoidal modulation at 26.8 dBm). By broadening the signal to ~10.4 GHz, as indicated in Fig. 5(b) we could easily scale the output power from 525 W (noise only) to 1029 W (DMSN) without reaching the SBS threshold limit. In Fig. 5(b) the average backward power for the ~10.4 GHz with dual modulation is slightly higher (by less than 0.5 mW) than the noise broadened case but lies within the error tolerance of the power measurement. However, it is clear that the slope of the backward power increases sharply for the noise broadened case (Fig. 5(b) red trace) beyond the 500 W level. The manifestation of peak power pulses determining SBS threshold occurred at much higher output powers for the dual modulation case (Fig. 5(b) blue trace) allowing for power scaling to kW-level.

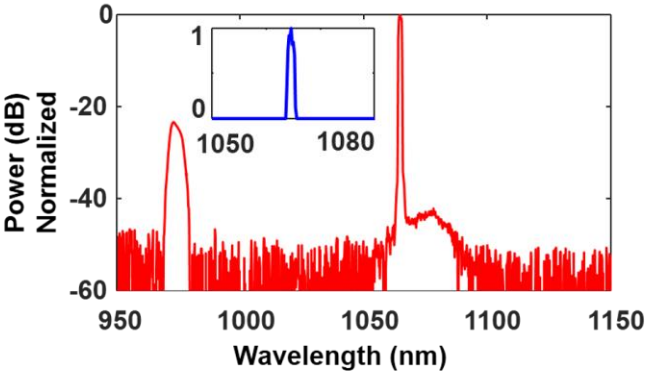

Fig. 6. Output spectrum of the laser at high power measured through scattered pick-up. Inset: Output spectrum in linear scale.

The output spectrum beyond the 500 W level is measured by scattered pick-up with an optical spectrum analyzer (OSA) and is shown in Fig. 6. The pump light picked up is more than 23 dB below and the ASE level is over 43 dB below the signal level at 1064 nm. The inset shown in Fig. 6 is a plot of output spectrum in linear scale demonstrating that nearly all of the output power is at the 1064 nm wavelength. While, peak power SBS pulses were not observed at 1029 W, power scaling beyond this point was restricted by the onset of modal instability, which is a higher threshold phenomenon in these systems. This was indicated by a drop in output power along with a sinusoidal fluctuation on the oscilloscope. By adopting simple methods of fiber coiling to overcome modal instability, further scaling in output power can be achieved. In addition, with an AR coated cable termination, we expect a further 20% increase in the SBS limited output power at ~10 GHz [26].

IV. SUMMARY AND CONCLUSION

In this work, we propose a simple technique to enhance the efficacy of SBS suppression of WNS broadened sources by adding sinusoidal modulation. This dual modulation scheme for line broadening has an improved line-shape (compared to the pure noise modulated case at similar RMS linewidths) with flat-topped central region and faster roll-off at the edges resulting in higher threshold for the onset of SBS pulses. The effectiveness of the proposed scheme was initially examined at medium powers and subsequently tested with a kW-class polarization maintaining, three-stage amplifier built by optimizing the MOPA architecture, gain fiber lengths, splices, and thermal management techniques. With the entire set up as is, and by only changing the modulation scheme (from pure noise to the proposed dual modulation) on the mW-class narrow linewidth DBR laser at 1064 nm, we experimentally demonstrate an improvement in SBS limited output power to 751 W for ~7.3 GHz linewidth (2.35X enhancement), 879 W at ~9.4 GHz (~2.3X enhancement) and >1029 W (>2X enhancement) for ~10.4 GHz linewidth. The lack of SBS threshold pulses at 1029 W is a testament to the superior SBS suppression obtained, making it a viable option for building multi-kW coherent beam combining systems. Systems with modulation using multi-tones, AWG and PRBS patterns are also capable of delivering high powers at narrow linewidths, but require several additional components of large form factor and increase the overall footprint of the system while also increasing the complexity of operation. The proposed dual modulation technique using simple and widely available sinusoid and noise sources provide a great alternative with enhanced system performance.

Thus, by the simple addition of a sinusoidal modulation in cascade, the efficacy of WNS broadened sources can be improved by over two times for a given linewidth in contrast to more complex modulation schemes implemented with AWGs and PRBS generators.

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