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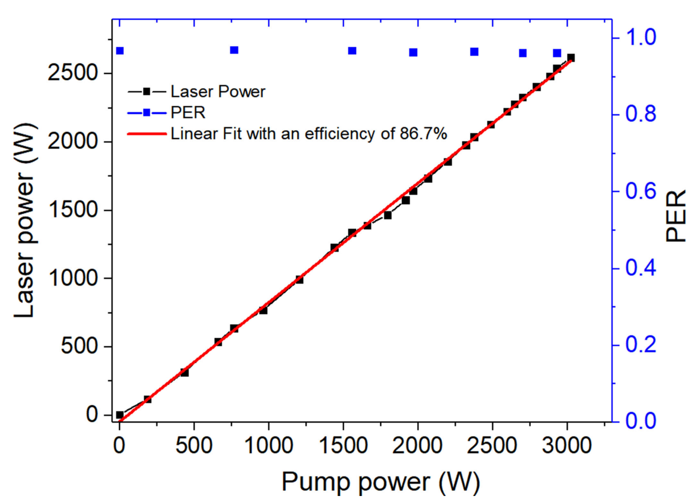

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2.5 kW Narrow Linewidth Linearly Polarized All-Fiber MOPA With Cascaded Phase-Modulation to Suppress SBS Induced Self-Pulsing

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Abstract: As a major limitation for power scaling of high power narrow linewidth fiber master oscillator power amplifiers (MOPAs), Stimulated Brillouin Scattering (SBS) induced self-pulsing in polarization maintaining (PM) fiber amplifiers is well characterized and analyzed in this paper by comparing different white noise signal (WNS) phase-modulated modes in experiments. It is found that the self-pulsing effect is not observed in the PM-amplifier with single-frequency laser seed injection, and cascaded WNS modulation provides superior self-pulsing suppression than single WNS modulation with similar output linewidth. Moreover, the experimental results indicate that the self-pulsing threshold can hardly be predicted only by the output linewidth or the defined SBS threshold in a WNS phase modulated fiber amplifier system. As self-pulsing is originated from the spectral spikes in WNS modulated system, we theoretically analyzed characteristics of these spikes in different phase-modulation modes. It indicates the spectral peak intensity can be reduced by cascaded modulation, for which self-pulsing can be suppressed. The theoretical predictions agree well with the experimental results. At the same time, in order to suppress the mode instability effect, a plum blossom shaped bending mode selection device is used in this high-power narrow linewidth fiber amplifier system. Finally, a 32 GHz cascaded WNSs modulated, over than 2.5 kW linearly polarized all-fiber amplifier with a slope efficiency of 86.7% is demonstrated. The polarization extinction ratio (PER) is measured larger than 14 dB and the beam quality factor M^2 maintains lower than 1.3 in the power scaling process.

Index Terms: High power fiber laser, narrow linewidth, linear polarization, self-pulsing.

1. Introduction

High power linearly polarized all-fiber lasers or MOPAs with narrow linewidth and near diffraction limited beam quality have important applications for nonlinear frequency conversion [1], spectral beam combining (SBC) [2]–[5] and coherent beam combining (CBC) [6]–[8]. However, nonlinear effects (NLE) such as SBS [9], four-wave-mixing (FWM) [10], [11] and mode instability (MI) [12] effects have limited the power scaling of this type of narrow linewidth fiber laser systems. Over the past decade, several methods were employed in these systems for NLE and MI suppression. For the NLE, using large mode area (LMA) and short length fiber [13], [14], counter pumping structure [15]–[17], phase modulated seed [18]–[21] are effective suppressing techniques. As for the MI, the various optimizing methods have been presented [22]–[25]. By now, the output power of all-fiber narrow-linewidth non-PM fiber laser has achieved 3.7 kW with a linewidth of 79 GHz [21]. However, obtaining of a high power PM-fiber laser output is more challenging compared with the non-PM fiber laser because of the lower SBS and MI threshold [20], [26]. The Table 1 shows the typical experimental results on narrow linewidth linearly polarized all-fiber amplifiers in recent years. In 2008, Nufern company achieve a kilowatt linearly polarized laser output with a linewidth less than 10 GHz based on 25/400 μm LMA PM gain fiber and WNS phase modulation [27]. In 2010, G. Goodno *et al.* reported a 1.43 kW linearly polarized laser based on active polarization control of a non-PM fiber amplifier, the linewidth is 25 GHz [28]. In 2016, P. Ma *et al.* based on three-level sinusoidal phase modulation and PM fiber amplifier, obtained a 1.89kW linearly polarized laser output with the linewidth of 45 GHz [20]. In 2017, R. Su *et al.* obtained a 2.43 kW output laser power with 68 GHz linewidth based on WNS phase modulation [33]. In 2018, N. Platonov reported 2 kW, 22 GHz linearly polarized all-fiber laser [26], the further increasing of laser power is limited by the MI effect. In 2019 [38], we reported a 1.5 kW PM fiber amplifier with 13 GHz linewidth and near diffraction-limited beam quality based on WNS phase modulation.

Besides, the Table 1 shows that WNS phase modulation technology plays an important role in high power narrow linewidth fiber lasers. However, in recent years, researchers find that except the NLE and MI, the self-pulsing effect has become another serious limitation for power scaling of these narrow linewidth continuous wave fiber laser systems with WNS phase-modulation. As self-pulsing has the features of high peak power, short pulse duration and strong randomicity, it has become a critical threat to fiber components. In 2017, we found that the self-pulsing limits the power scaling of WNS phase modulated kilowatt high power narrow linewidth fiber amplifiers [31]. According to our both theoretical and experimental analysis, it is found that self-pulsing is associated with the SBS pulses induced by the spikes of phase modulated spectrum [40]. Generally, the optical spectrum generated by WNS phase modulation will have a random profile, which contains spectral spikes with different and random intensities. During the amplification process, the high intensity spikes in signal can reach the SBS threshold. By further increasing the pump power, the power of 1st Stokes wave can dramatically increase by SBS gain from these spikes. Together with laser dynamic process, this forms some pulses with high peak power, even when most of the signal with different spectral content has not reached the SBS threshold. Therefore, comparing to normal considering 1st Stokes induced by continuous wave, the self-pulsing can be a more notable threat to the fiber laser system, as it appears before normal considering SBS threshold. Since self-pulsing is induced by SBS, common SBS suppression methods [15]–[17], [20], [41]–[42] can also be suitable for suppressing these self-pulses. In 2019, by using three common SBS suppression methods (counter-pumping, larger mode area passive fiber and wider spectral linewidth), the self-pulsing threshold of our experimental fiber laser system was increased by a factor of 1.5 [38]. However, these methods can only have limited improvement on a practical narrow linewidth fiber laser system, as applications may have some requirements on linewidth or beam quality. As the self-pulsing is caused by the WNS modulated spectral spikes, thus by directly optimizing the modulation spectrum to suppress the spectral spikes can hopefully increase the self-pulsing threshold while maintaining the linewidth and gain fiber mode area size.

In this work, the self-pulsing characterization in a high-power PM fiber MOPA with three different phase modulation methods is researched, including no modulation, which is then actually single

TABLE 1
Typical Experimental Results on Narrow Linewidth Linearly Polarized All-Fiber Amplifiers, PC: Polarization Control, FBG: Fiber Bragg Grating, and PRBS: Pseudo-Random Binary Sequence

Year	Configuration	Power (kW)	Linewidth (GHz)	M^2	PER (dB)	Ref.
2008	Phase modulation and PM fiber	1.01	8	1.25	-	[27]
2010	WNS phase modulation and PC	1.43	25	-	-	[28]
2014	Phase modulation and PM fiber	1.14	12	1.08	16	[29]
2015	WNS phase modulation and PM fiber	1.03	20	1.18	20	[30]
2017	WNS phase modulation and PC	0.96	6.5	1.2	13	[31]
2016	Sinusoidal phase modulation and PM fiber	1.89	45	< 1.3	15.5	[20]
2017	WNS phase modulation and PC	1.43	45	-	11.1	[32]
2017	WNS phase modulation and PM fiber	2.43	68	-	18.3	[33]
2017	FBG seed and PM fiber	1.018	79	1.24	14	[34]
2017	Phase modulation and PM fiber	1.5	15	< 1.1	20	[35]
2018	Phase modulation and PM fiber	2	22	< 1.1	20	[26]
2018	Sinusoidal phase modulation and PM fiber	1.08	7.6	1.14	14	[36]
2018	FBG seed and PM fiber	1.1	47	1.25	15	[37]
2019	WNS phase modulation and PM fiber	1.5	13	1.15	13	[38]
2019	PRBS phase modulation and PM fiber	0.818	6.6	-	13	[39]

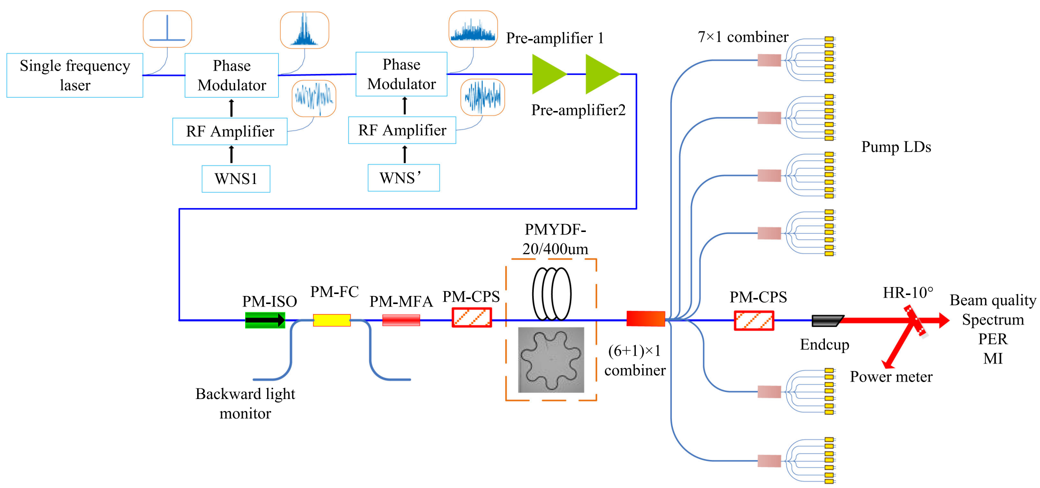

Fig. 1. Scheme of all-fiber PM-amplifier based on cascaded phase-modulated single-frequency seed.

frequency laser system, single WNS phase modulation and cascaded WNS phase modulation. The experimental and theoretical results show that cascaded modulation achieves an obvious suppression on the intensity of spectral spikes and the followed self-pulsing effects, while maintaining similar linewidth comparing to that of single modulation. With this method, we demonstrate a narrow linewidth linearly polarized all-fiber laser operating at maximum output power of 2.62 kW with a 3dB linewidth of 32 GHz by suppressing the self-pulsing effect. The PER is larger than 14 dB and the M^2 is lower than 1.3 along the whole power scaling process.

2. Experiment Structure

Fig. 1 shows the experimental setup of our PM all fiber laser system, which consists of a phase modulated single frequency laser seed, two PM-preamplifiers and a PM fiber amplifier. The seed

TABLE 2
The Parameters of Four Different WNSs

	Frequency (GHz)	Power (dBm)
WNS1	0.01-2.5	27
WNS2	2-5	25
WNS3	2-6	25
WNS4	2-9	25

is a 1064nm single frequency laser, which is followed by two cascaded high speed $LiNbO_3$ electro-optic modulators driven by WNS generators (WNS1 and WNS'), respectively. The noise generated by WNS1 covers the band 0.01–2.5 GHz and with a radio-frequency (RF) amplifier, the RF power of this driven signal can reach 27 dBm. The noise generated by WNS' covers the band 2–18 GHz and with another RF amplifier, the RF power can reach 25 dBm. By switching on and off these two amplified WNSs separately, we can then analyze the self-pulsing characteristics in four cases, which are single frequency source, two single WNS phase-modulation separately and cascaded WNS phase-modulation. In order to further investigate the influence of modulation bandwidth on self-pulsing characteristics, three low-pass filters with cut-off frequency at 5 GHz, 6 GHz and 9 GHz are used to change the band of WNS' to 2–5 GHz, 2–6 GHz and 2–9 GHz, which are marked as WNS2, WNS3 and WNS4 in the following context, respectively. The parameters of these four different WNSs are shown in Table 2. After phase modulation, the power of laser signal is amplified to 0.3 W and then 7 W by using two PM-preamplifiers. Both preamplifiers are pumped in co-direction by the laser diodes (LDs) worked at 976 nm, and the gain fiber is PM Yb-doped fiber (YDF) with a core/inner cladding diameter of 10/125 μm. Through a PM mode field adaptor (MFA), the pre-amplified signal is injected into our final high power PM-amplifier. A PM fiber coupler is set between the second pre-amplifier and the PM-amplifier to monitor the backward light. The PM-amplifier is counter-pumped by two-stage pump-tree-based LD modules. Forty-two 90W wavelength-stabilized 976 nm LDs are divided into 6 groups. With 7×1 combiners, the 7 LDs in each group are combined as a pump module. Then the output of 6 these modules are coupled into the gain fiber through a $(6+1)\times1$ combiner. The gain fiber is a 20/400 μm double cladding PM-YDF ($\sim$9 m) with the core NA of 0.065, whose cladding pumping absorption is 1.5 dB/m (typical value). The gain fiber is fixed in a U-shape groove on a water-cooling aluminum heat sink. The cooling medium between the gain fiber and U groove is the silicone grease with the thermal conductivity of $\sim$5 W/(m·K). Ref [26] indicates that the MI threshold of PM fiber amplifier is lower than that of non-PM fiber amplifier. The bending mode selection technology can effectively increase the mode instability threshold. For example, ref. [33] using the aluminous cylinder for bending mode selection to achieve a 2.43 kW PM laser output. In this work, in order to suppress the MI effect, the gain fiber in PM-amplifier is coiled with a plum blossom shape on the aluminous plate with the minimum coiled diameter of 9 cm and the maximum coiled diameter of 11 cm, respectively, it is shown in Fig. 1. Compared with the aluminous cylinder, aluminum plate is more commonly used for fiber coiling. Two PM cladding power stripper (CPS) are used to strip the residual pump and cladding signal power, respectively. The $\sim$3.5 m long PM passive fiber (1.5 m 20/400 um fiber + 2 m 25/400 um fiber) is used at the end of the amplifier. The output laser is collimated via an all fiber end-cap with lens and then split by a highly reflected mirror placed at $\sim$10°. The high power reflected beam is dumped by a power meter (also for power measurement), the low power transmitted beam is used to measure the beam quality, spectrum, PER and MI. The output spectra are measured by an optical spectrum analyzer (AQ6373, manufactured by Yokogawa company). Two photodetectors with the bandwidth of 17 MHz and 30 GHz are used to capture the backward temporal profiles, which then are analyzed by the oscilloscope with 4 GHz analog bandwidth. The beam quality is measured by the M-200s beam quality analyzer (4sigama) manufactured by Spiricon Company. With the bending mode-selection, high-order mode generated by MI will be filtered out. Therefore,

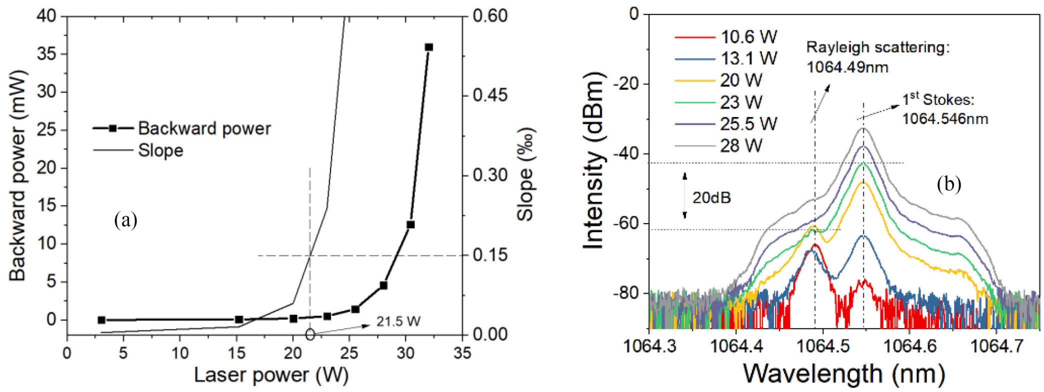

Fig. 2. (a) The backward power vs output laser power curve and its slope and (b) backward spectrum.

the MI effect can be easily detected by the forward power fluctuation, which is monitored by a 17 MHz photodetector (PD) in our experiment.

3. Experimental Results and Discussion

3.1 SBS Behavior of the PM-Amplifier With a Single Frequency Laser Seed

To show the different behavior of irregular self-pulsing caused by spectral spikes induced SBS, a normal SBS procedure in the PM-amplifier with a single frequency seed injection is investigated firstly. In this case, all WNS generators are switched off. The backward power as a function of the output laser power is shown in Fig. 2(a). The nonlinear increase of the backward power occurs at ~23 W signal output power, which can generally represent the SBS threshold. To be more quantitative, here we define the output signal power when the slope ($\Delta P_b/\Delta P_l$) of the fitted backward power vs laser power curve, reaches 0.15‰ as the SBS threshold. The ΔP_b and the ΔP_l is the increasing of the backward power and the laser power, respectively. Fig. 2(a) shows that the SBS threshold of the PM-amplifier with single frequency seed is about 21.5 W. Fig. 2(b) shows the backward spectra of the PM-amplifier at different laser power. The SBS 1st Stokes peak can be observed from the spectrum with 10.6 W output power. And with 13.1 W, the amplitude of Stokes peak is close to that of Rayleigh scattering peak. With 23 W laser power, the Stokes peak amplitude is already 20 dB higher than the Rayleigh scattering peak. Meanwhile, from the smooth spectra we can confirm that no self-pulsing emerges at or even slightly above SBS threshold in this PM-amplifier with the single frequency laser seed injection.

3.2 SBS Induced Self-Pulsing Behavior of the PM-Amplifier With Single WNS Modulation (WNS1/WNS2) and Cascaded Modulation (WNS1+WNS2)

In this section, we investigate the behavior of irregular self-pulsing caused by spectral spikes induced SBS in the PM-amplifier by using different phase modulation combination (WNS1, WNS2 and WNS1+WNS2) broadening the linewidth of the single frequency seed. The measured output spectra with different phase-modulation modes are shown in Fig. 3(a). With 2.5 GHz WNS (WNS1) phase modulation, the 3dB spectral linewidth of the signal is broadened to 12.8 GHz (0.048 nm). With 2-5 GHz (WNS2) phase modulation, the linewidth is broadened to 16.6 GHz (0.062 nm). By cascading both (WNS1+WNS2), the linewidth reaches 20 GHz (0.075 nm). Also, as in phase modulation spectral broadening scheme for SBS suppression with a single frequency seed, the signal seldom gets spectral broadening in the power scaling process [43], the linewidth of the seed can be treated as the linewidth of output laser after amplification.

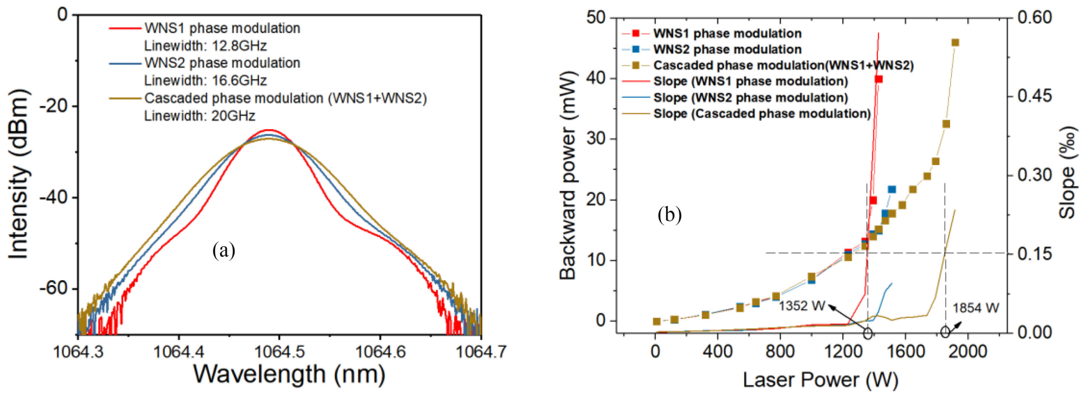

Fig. 3. The laser characteristics of the PM-amplifier with WNS1, WNS2, and WNS1+WNS2 phase modulation, respectively, (a) the measured spectra and (b) the backward power vs output laser power curve and its' slope.

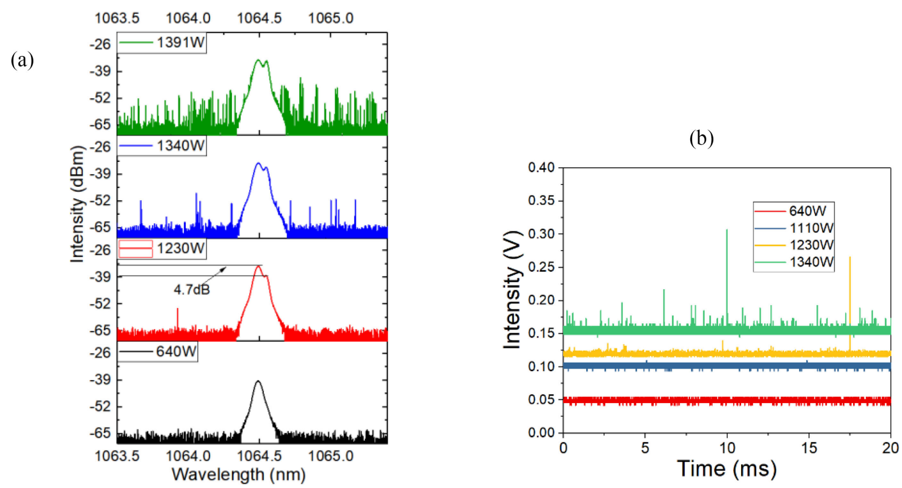

Fig. 4. (a) The backward spectra and (b) temporal profiles of backward light of the PM-amplifier at different laser power level with WNS1 phase modulation.

Based on our previous works [38], [40], the backward self-pulsing of WNS modulated fiber amplifier will occur earlier than the forward self-pulsing. Thereby, we monitor the backward self-pulsing for the safety of our laser system. And in this work, the self-pulsing threshold is defined as the signal output power when backward self-pulsing occurs. Fig. 3(b) shows the backward average power vs the output signal power curve and its' slope with three different modulation schemes. It can be seen that the defined SBS threshold is reached when the output laser power reaches 1352 W and 1854 W, corresponding to WNS1 and WNS1+WNS2 modulation, respectively. With WNS2 phase modulation, as the backward power is quite unstable when the amplifier operating at the maximum output power, we did not further increase the pump power. So, it stops lower than the defined SBS threshold.

The backward spectral profiles of the PM-amplifier at different signal power levels with WNS1 modulation are shown in Fig. 4(a). It can be seen that with the output power reaching 1230 W, the self-pulsing occurs in the spectrum, when the Stokes peak is still 4.7 dB lower than the Rayleigh scattering peak. When the signal is amplified to 1391 W, the self-pulsing becomes

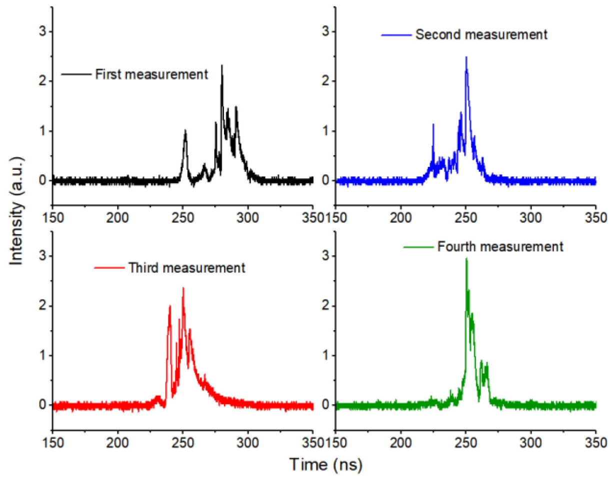

Fig. 5. Temporal details of some backward pulses.

severe. As self-pulsing randomly emerges on the time scale with random amplitude, there will be significant fluctuations in the backward power after self-pulsing emerging. Also random spikes in the spectrum could be a sign of the self-pulsing occurring. With the power further increasing, the emerging probability density of self-pulsing increases exponentially, leaving more spectral spikes on spectrum. As the high peak power, narrow pulse width and strong randomicity, self-pulses may damage fiber components in our amplifier, we do not further increase pump power. The temporal profiles of the backward signal are monitored by a PD with 17 MHz bandwidth. As show in Fig. 4(b), pulses with high peak power are observed when the laser power reaches 1230 W, and with further increasing on laser power, the pulses become denser on the time scale. “Zoom-in” features for temporal details of some backward self-pulses are measured by a 30 GHz bandwidth PD. The results are presented in Fig. 5. The full width at half maximum (FWHM) of these pulses is between 10–30 ns. These results are consistent with our previous theoretical analyses and experimental results [40]. As the self-pulsing can be detected both from temporal and spectral profiles. In the later discussion, for convenience we use spectral features to represent the severity of self-pulsing.

The backward spectral profiles for our PM amplifier with WNS2 and WNS1+WNS2 phase modulated seed are shown in Fig. 6. The self-pulsing threshold with WNS2 and WNS1+WNS2 modulation is 1340 W and 1790 W, and the peak intensity ratios between Stokes and Rayleigh scattering is −1.4 dB and 2 dB, respectively.

3.3 SBS Induced Self-Pulsing Behavior of the PM-Amplifier With WNS3 Modulation

In the previous section, we found that cascading modulation has a higher self-pulsing threshold than single modulation, however, it may due to the SBS suppression by further broadening on spectrum from 16.6 GHz to 20 GHz. In this section, the self-pulsing characteristics under 2–6 GHz WNS (WNS3) modulation with a nearly same linewidth (compared with the WNS1+WNS2 cascading) is studied. The measured output spectra with WNS3 phase-modulation is shown in Fig. 7(a). The 3dB spectral linewidth of the signal is broadened to 21.4 GHz (0.08 nm). As shown in Fig. 7(b) and Fig. 7(c), the self-pulsing occurs (1574 W) before the PM-amplifier reaches the defined SBS threshold. Even if the linewidth under WNS1+WNS2 modulation is a little smaller than that under WNS3 modulation, the self-pulsing threshold is still 216 W higher than that under WNS3 modulation. These experimental results confirm that the cascaded modulation can achieve a higher self-pulsing suppression compare to single modulation with a nearly same linewidth. Meanwhile, the results in section 3.2 and 3.3 prove that the self-pulsing threshold can hardly be predicted only by the output linewidth.

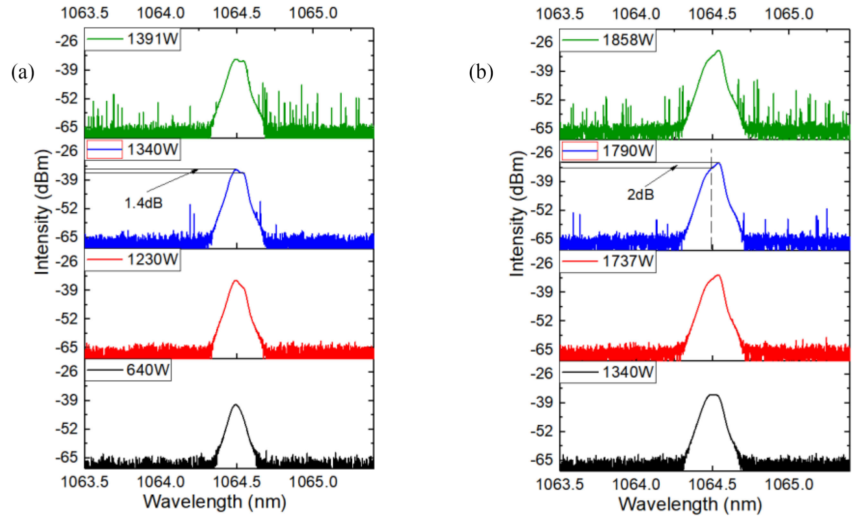

Fig. 6. The spectrum of backward light of the PM-amplifier at different laser power levels with the seed phase modulated by (a) WNS2 and (b) WNS1+WNS2, respectively.

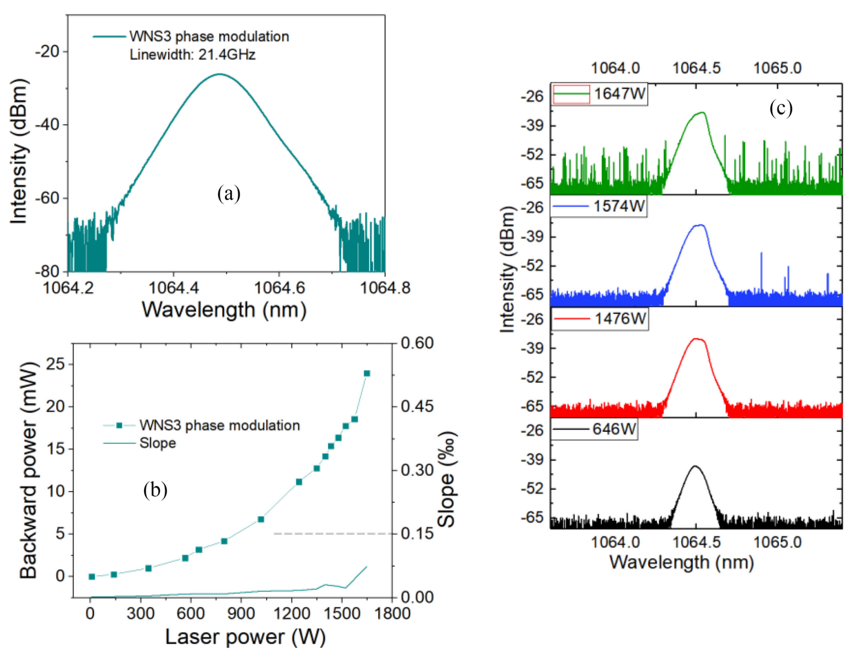

Fig. 7. The laser characteristics of the PM-amplifier with WNS3 phase modulation, (a) measured spectra, (b) the backward power vs output laser power curve and its' slope, (c) the backward spectra.

3.4 SBS Induced Self-Pulsing Behavior of the PM-Amplifier With Single WNS Modulation (WNS4) and Cascaded Modulation (WNS1+WNS4)

In order to further improve the self-pulsing threshold and output laser power, we broaden the linewidth of the seed source by using the 2–9 GHz WNS (WNS4), and studied the self-pulsing characteristics of the PM-amplifier under WNS4 single modulation and WNS1+WNS4 cascading modulation. The backward spectra of the PM-amplifier with WNS4 and WNS1+WNS4 cascaded

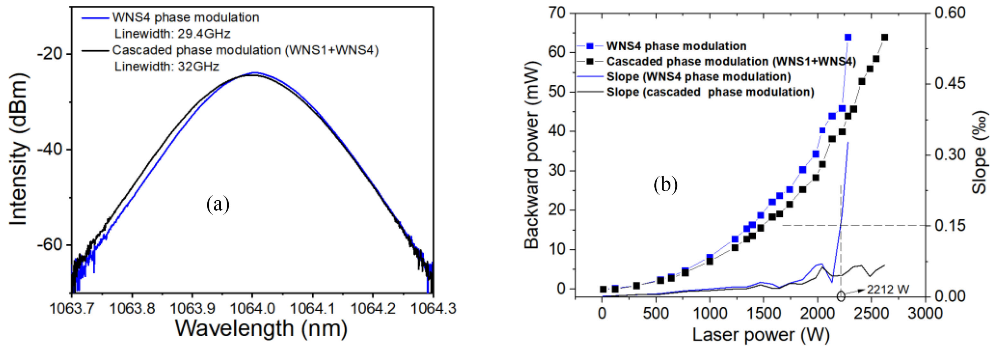

Fig. 8. The laser characteristics of the PM-amplifier seeded by the WNS4 and WNS1+WNS4 phase modulation, respectively, (a) the measured spectra and (b) the backward power vs output laser power curve and its' slope.

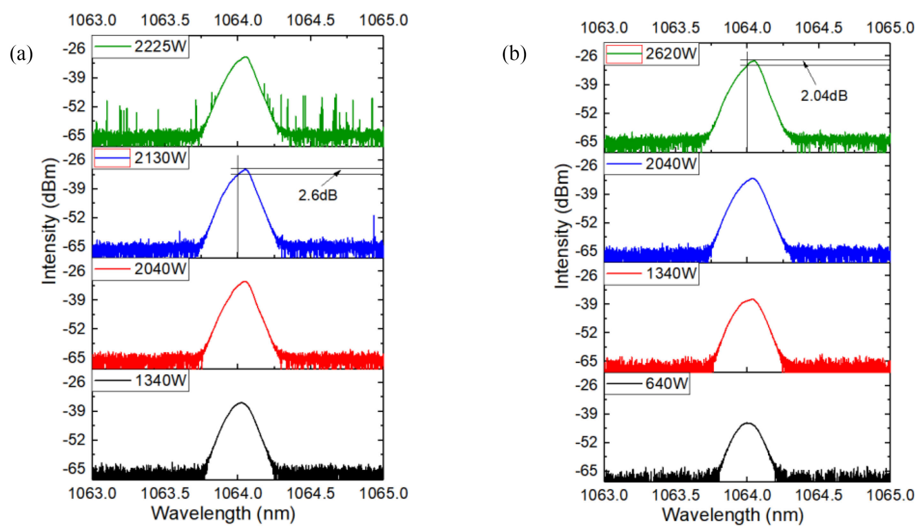

Fig. 9. The spectrum of backward light of the PM-amplifier at different laser power levels with (a) WNS4 and (b) WNS1+WNS4 phase modulation.

phase modulation are shown in Fig. 8(a). With WNS4 phase modulation, the 3dB spectral linewidth of the signal is broadened to 29.4 GHz (0.11 nm). While with cascaded (WNS1+WNS4) phase modulation, the linewidth is broadened to 32 GHz (0.12 nm). The backward power vs the laser power curve and its' slope with above two modulation schemes are shown in Fig. 8(b). It shows that the PM-amplifier reaches the defined SBS threshold at laser power of 2212 W with WNS4 modulation. With cascaded WNSs modulation, however, the PM-amplifier not reaches the defined SBS threshold.

The backward spectral profiles with WNS4 modulation are shown in Fig. 9(a). It can be seen that the self-pulsing occurs at the output laser power reaching 2130 W. With further increasing laser power to 2225 W, self-pulsing became severe. Fig. 9(b) demonstrates the spectra with WNS1+WNS4 cascaded modulation, which indicates no self-pulsing appears even when the output signal power reaches 2620W. Therefore, after cascading WNS1 to WNS4 the self-pulsing threshold increases from 2130W to over 2620 W, while the linewidth only increases from 29.4 GHz to 32 GHz.

TABLE 3
The Linewidth and Self-Pulsing Threshold at Different Phase Modulated Modes

	No modulation	WNS1	WNS2	WNS1+WNS2	WNS3	WNS4	WNS1+WNS4
Linewidth	~70kHz	12.8GHz	16.6GHz	20GHz	21.4GHz	29.4GHz	32GHz
Self-pulsing threshold	No self-pulsing	1230W	1340W	1790W	1574W	2130W	＞2620W

The linewidth and self-pulsing threshold characteristics of PM-amplifier with different phase modulation modes are shown in Table 3. According to Table 3 and experimental results above, two conclusions can be drawn. First, cascaded phase modulation of a WNS with low frequency and a WNS with high frequency achieves better self-pulsing suppression compare to single high frequency WNS modulation though their linewidth is quite similar. Second, the self-pulsing threshold can hardly be predicted only by the output linewidth or the defined SBS threshold in a WNS phase modulated fiber amplifier system. Next, we will theoretically discuss the different roles of low frequency WNS and high frequency WNS in broadening linewidth and suppressing self-pulsing.

It is worth noting that the suppressing of SBS effect based on cascade modulation has been reported in ref [44] and ref [20]. Such as in the ref [44], they used a combination of a sinusoidal signal and WNS to driven the phase modulator. And they obtain a 1.4 kW SBS-limited output power at the linewidth of 26 GHz, and 2.3 kW output power at the linewidth of 45 GHz. In the ref [20], they used three-stage cascaded sinusoidal signal phase modulation systems. The linewidth and output power at single modulation, two-stage cascaded modulation, three-stage cascaded modulation are 6 GHz and 477 W, 18.5 GHz and 1040 W, 45 GHz and 1890 W, respectively. In these two references, they used cascaded modulation realized obvious power increasing, but the spectral linewidth also increased significantly. While in our work, we achieve a substantial power increasing while maintaining approximate linewidth by cascading modulation. For example, in our work, the limited output power increases from 2130W to over 2620 W, while the linewidth only increases from 29.4 GHz to 32 GHz after cascaded phase modulation.

3.5 Discussion

Our previous work revealed that the self-pulsing is originated from the spectral spikes caused SBS in phase modulation. And as the cascaded WNS modulation can obtain a higher self-pulsing threshold compare to the single WNS modulation in a nearly same linewidth, it may indicate the cascaded modulation can effectively suppress spectral spikes. However, the resolution of the optical spectrum analyzer used for linewidth measurement in the experiment is 0.018 nm (1064 nm), which does not support measuring fine structure of the modulation spectrum. So, we numerically analyzed the fine spectral structure with different modulation schemes. Figs. 10(a) and 10(b) show the temporal and spectral profiles of the two WNSs used in calculation. The bandwidth and signal power are same with the modulating parameters we used in experiments (2–9 GHz, 25 dBm and 2.5 GHz, 27 dBm, respectively). Then the fine spectral profile is calculated by Fourier transforming autocorrelation of the temporal traces.

As shown in Fig. 11(a), we obtain the calculated power spectral density (PSD) of output signal with 2.5 GHz WNS, 2–9 GHz WNS and their cascade. It is indicated that the calculated RMS linewidths under 2.5 GHz WNS modulation, 2–9 GHz WNS modulation and cascade modulation are 11.7 GHz, 39 GHz and 40.8 GHz, respectively. With these three modulation schemes, there are a mass of spectral spikes found in the calculated spectra, and the relative peak intensity of spectral spikes is 0.00128, 0.00072 and 0.00051, respectively. By comparing the 2–9 GHz WNS modulated spectra and cascaded WNSs modulated spectra, we can see that the cascade modulation reduces the spectral peak intensity while the linewidth is not significantly broadened. Besides, the normalized power spectrum integrated within the SBS gain bandwidth (30 MHz)

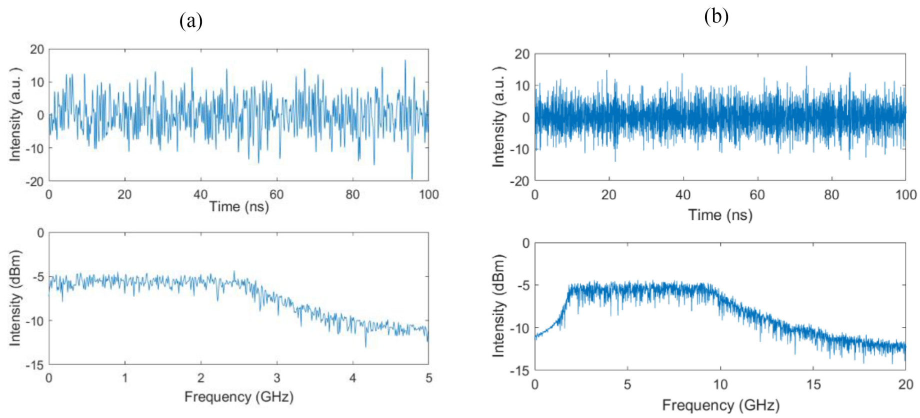

Fig. 10. Temporal and spectral profiles of WNS with (a) 2.5 GHz bandwidth and (b) 2–9 GHz bandwidth.

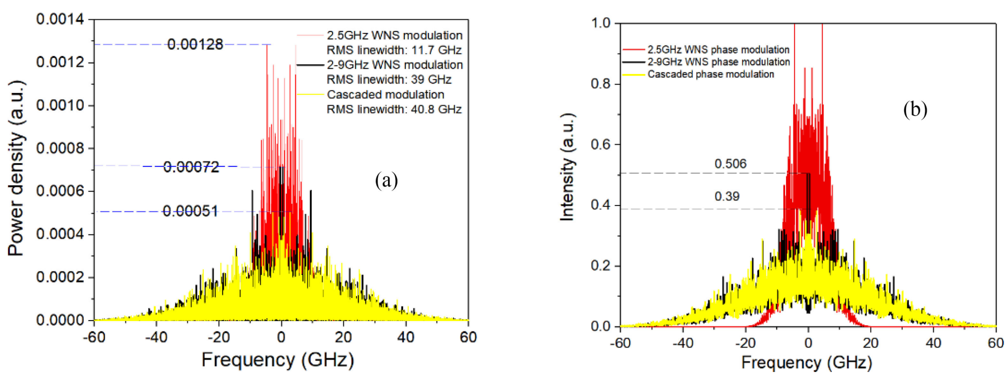

Fig. 11. (a) the calculated fine spectrum and (b) the normalized power spectrum integrated within the SBS gain bandwidth (30 MHz) window with three different modulation schemes.

window is shown in Fig. 11 (b). It is found that the peak value of the cascade modulation is reduced by about 23% compared to the single 2–9 GHz WNS modulation, which is close to the power increasing percentage in the experiment. It is proved that the higher frequency WNS dominates the linewidth of the modulated spectrum, while the low frequency signal can further reduce the spectral spike intensity and enhance the self-pulsing threshold without significantly broadening the spectrum.

4. 2.62 kW Narrow Linewidth Linearly Polarized All-Fiber Amplifier

The output power of PM-amplifier based on cascaded (WNS1+WNS4) phase modulation vs the pump power is shown in Fig. 12. The power of the seed is 7 W, which then is amplified up to the maximum power of 2620 W. The linear fitting shows a slope efficiency 86.7%. The measured PER is larger than 96% (∼14dB) during the power scaling process, marked as blue points in Fig. 12. Due to the using of plum blossom shaped bending mode selection, a near-diffraction-limited laser output is achieved. The measured M^2 factor at 2540 W is shown in the Fig. 13, the M^2 value is 1.219 in the x-direction and 1.294 in the y-direction, respectively.

The forward emission spectra of the PM amplifier at different laser power are shown in Fig. 14(a). The 3dB linewidth of forward signal maintains around 32GHz confirming no broadening in the power scaling process, which is an important advantage of phase modulated seeds for the high-power narrow linewidth fiber amplifiers. We could then control the linewidth of seed to exactly meet the

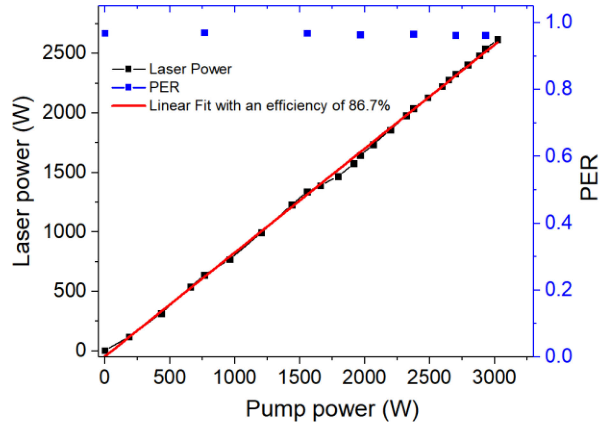

Fig. 12. Laser power and PER vs pump power.

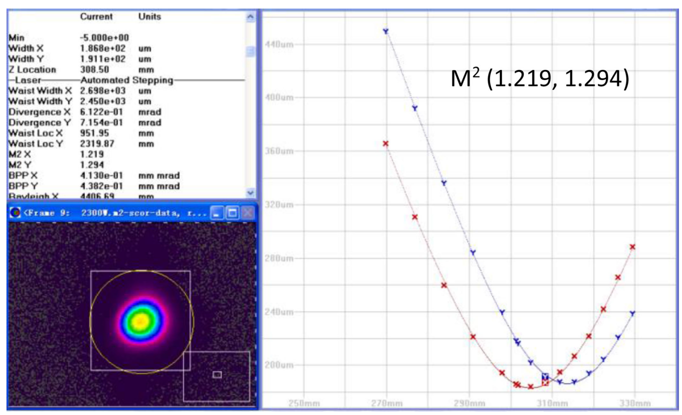

Fig. 13. Measured beam quality at 2540 W.

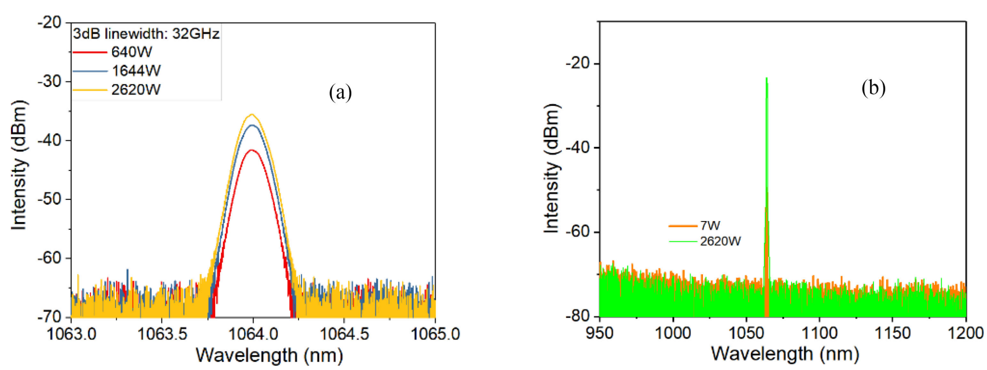

Fig. 14. (a) Forward emission spectra at different laser power and (b) output spectrum in a wide range.

requirement of certain applications without worrying spectral broadening in amplifiers. The output spectra in a wide range is measured by another optical spectrum analyzer (Yokogawa Corp. model AQ6370), as shown in Fig. 14(b), in which neither stimulated Raman scattering (SRS) effect nor amplified spontaneous emission (ASE) can be observed. Due to the counter-pumping scheme, the output is residual pump free, for which no pump can be seen from the spectrum.

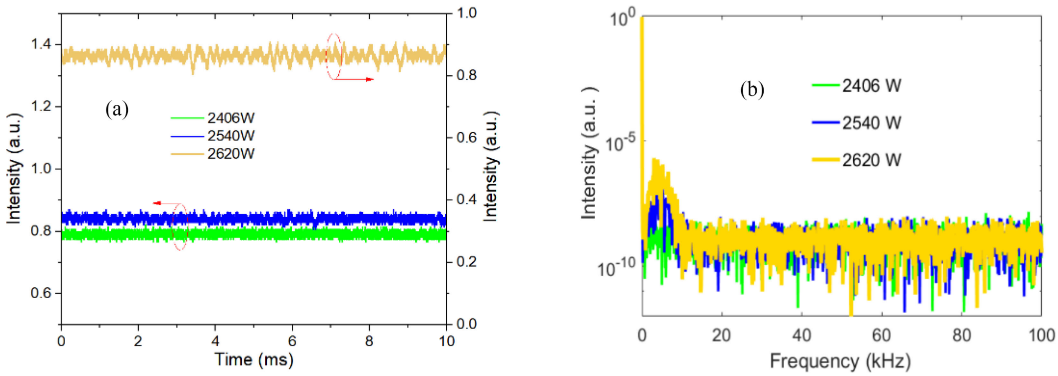

Fig. 15. (a) The temporal traces and (b) calculated spectra at different output powers.

Fig. 15(a) shows the ∼10 ms scale power stability of the output signal from our amplifier. With output power reaches 2406 W, the time domain is stable. And the output power reaches 2540 W, the slight power fluctuates is observed. While the laser power reaches 2620 W, the obvious power fluctuates is found. With fast Fourier transform (FFT) on the temporal traces, the calculated spectra at different output powers are shown in the Fig. 15(b). It is shown that there is no obvious peak at 2406 W output power. However, when the output power reaches 2540 W, a peak at several kHz appears. With the output laser increases to 2620 W, the amplitude of this peak increases significantly. This indicates the MI threshold of our amplifier is ∼2540 W. With bending mode selection of the PM-YDF in our amplifier, the MI will lead to power in high-order mode leaking to cladding, which then will increase the burden of the reverse combiner and the output CPS. That restricts further increasing pump power to achieve a higher output signal power in this PM fiber amplifier.

5. Conclusion

Phase modulation with WNS is a well-known method to achieve a high power narrow linewidth fiber amplifier. However, in recent years, researchers found self-pulsing has become a serious limitation for power scaling of narrow linewidth fiber amplifier based on WNS phase-modulation. In order to analyze and solve this issue, in this work, a high power narrow linewidth linearly polarized all fiber amplifier based on WNS phase-modulation was set up. And detailed characteristics of self-pulsing with different phase modulation schemes are investigated, which includes the single frequency seed without modulation, with single WNS modulation and cascaded WNS modulation. The experimental results show that no self-pulsing emerges in the amplifier with single frequency laser seed injection. And cascaded WNS modulation provides superior self-pulsing suppression comparing to single WNS modulation, while maintaining a similar linewidth. Besides, we found that the self-pulsing threshold can hardly be predicted only by the output linewidth or defined SBS threshold. As self-pulsing is caused by SBS generated from spectral spikes, spectral spikes in different phase modulation schemes are numerically analyzed, which confirmed the spectral peak intensity can be weakened by cascaded modulation. The theoretical predictions agreed with the experimental results. Finally, based on cascaded WNS modulation to suppress the self-pulsing and plum blossom shaped bending mode selection device to suppress the mode instability, we demonstrate a narrow linewidth linearly polarized all-fiber laser operating at maximum output power of 2.62 kW with a 3dB linewidth of 32 GHz by suppressing the self-pulsing. The PER is measured larger than 14 dB and the M^2 is lower than 1.3 in the whole power scaling process.

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