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Power scaling of high-power linearly polarized fiber lasers with <10 GHz linewidth

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In this work, an all-fiberized polarization-maintained (PM) fiber laser has been demonstrated with a near-top-hat-shaped spectrum. By optimizing the modulation signal to generate near-top-hat-shaped spectrums, a 3-kW PM fiber laser has been achieved at <10 GHz linewidth with the polarization extinction ratio of 96% and beam quality of 1.156, which is the highest output power ever reported with approximately 10 GHz linewidth, and further scaling of output power is limited by stimulated Brillouin scattering. By decomposing the mode content, the proportion of the fundamental mode in the output laser is above 97%. The stimulated Raman scattering suppression ratio reaches 62 dB at the maximal output power.

KEYWORDS

polarization-maintained fiber lasers, stimulated Brillouin scattering, mode instability, high-power fiber lasers, phase modulation

1 Introduction

High-power linearly polarized fiber lasers with a narrow linewidth and near-diffraction-limited beam quality are required in various scientific, industrial, and advanced applications, such as the coherent LiDAR system, non-linear frequency conversion, and beam combining [1, 2]. Due to the high demand for high-power linearly polarized fiber lasers, researchers have made great progress on power scaling of narrow-linewidth polarization-maintained (PM) fiber lasers in the last few years, and even a 5-kW PM fiber laser has been reported [3]. To suppress the onset of detrimental stimulated Brillouin scattering (SBS) effects, the linewidth of these multi-kilowatt linearly polarized fiber lasers has been broadened to several tens of GHz, which is a key factor in the penetration of fiber lasers in the aforementioned applications. Taking the beam combining applications, for example, which is an opportune method to break through the brightness limitation of the fiber laser system, the linewidth of PM laser is generally required to be within 10 GHz to achieve higher combining efficiency and better beam quality [4]. Specially designed spectral broadening formats have been proposed to achieve high-power PM lasers with 10 GHz linewidth, including pseudo-random binary sequence (PRBS) [5–7], filtered white noise signal (WNS) [8–12], multi-phase coded signal (MPCS) modulation [13], and near-top-hat-shaped spectrum [14–18]. In recent years, great progress has been made in power scaling of PM fiber laser within 10 GHz linewidth [5–19], and the highest output power reaches 2.3 kW with 8.5 GHz linewidth using a near-top-hat-shaped spectrum seed laser in public reports [15].

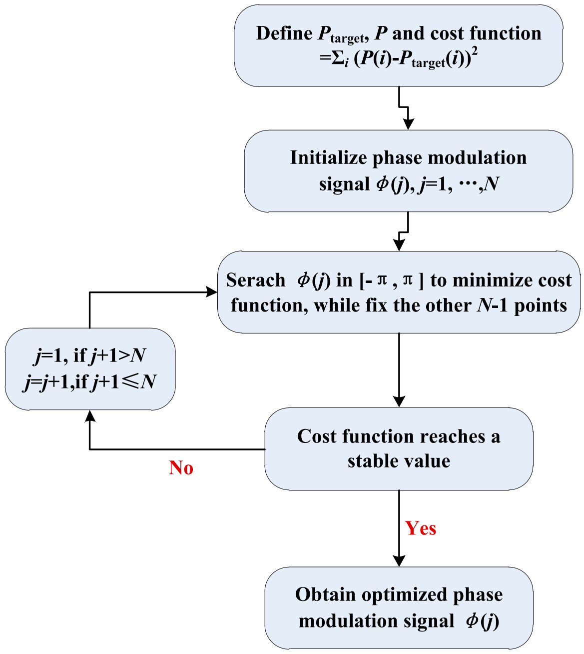

FIGURE 1
Optimization method of the phase modulation signal.

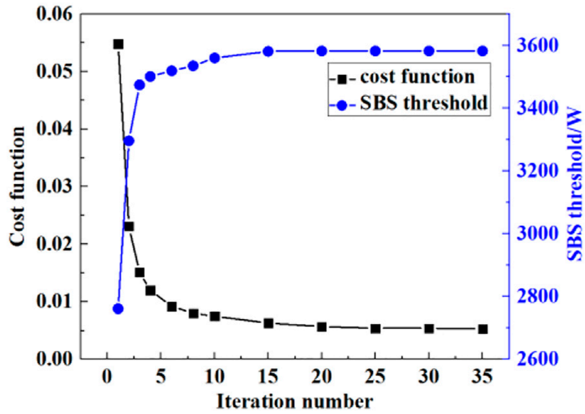

FIGURE 2
Cost function and SBS threshold versus iteration number.

In this paper, we conducted a PM narrow-linewidth all-fiber laser experiment with near-top-hat-shaped signal modulation formats. The PM laser delivered 3-kW single-mode laser at < 10 GHz linewidth by applying the near-top-hat-shaped signal modulation format. At 3 kW output power, the polarization extinction ratio (PER) was 96%, and the beam quality was 1.156. A high optical signal-to-noise ratio (OSNR) was achieved with the stimulated Raman scattering (SRS) suppression ratio of approximately 62 dB, and further power scaling of the laser was limited by the onset of SBS.

2 Materials and methods

2.1 Optimization of the phase modulation signal

For fiber lasers with a narrower linewidth, the match of the optical length can be simplified for coherent combining systems [20], and the systems can be more robust against environmental perturbations. In order to scale the output power of the PM fiber laser system with narrower spectral linewidths, the modulation signal is optimized. Comparing it to common WNS and PRBS modulation formats, the top-hat-shaped spectrum can reach the highest SBS threshold with the same linewidth [21, 22], and the top-hat-shaped spectrum has a longer coherent length [18], so we optimize the phase modulation signal to obtain the top-hat-shaped spectrum.

The generation of the top-hat-shaped spectrum by phase modulation is to make the spectrum of modulated lasers rectangular in theory. The spectrum of the modulated laser $P(v)$ is expressed as the Fourier transform of the modulated laser:

$$P(v) = fft\left(E_0 e^{i\varphi(t)}\right) = \text{rectangular},$$

where E_0 is the amplitude of the laser and $\varphi(t)$ is the phase modulation signal. Since the Fourier transform of the sinc function is rectangular, $E_0 e^{i\varphi(t)} = \sin t/t$, but the equation has no real number solution. Therefore, it is impossible to modulate a single-frequency laser to a perfect top-hat-shaped spectrum by phase modulation. We can only optimize the modulation signal to make the phase-modulated spectrum as close to the top-hat-shaped spectrum as possible. The optimization method is established, as illustrated in Figure 1.

First, we define the target spectrum $P_{target}(v)$ and the modulated spectrum $P(v)$. Next, the cost function is established as $\Sigma_i\ (P(i)\text{-}P_{target}(i))^2$, and the phase modulation signal $\varphi(j)$, $j = 1, 2 \ldots N\text{-}1, N$ is initialized. Then, we optimize the phase modulation signal by the grid search method to make the cost function reach a stable value. The specific method is to search $\varphi(1)$ in [-π, π] to minimize the cost function, while fixing the other N-1 points, and $\varphi(1)$ is determined followed by $\varphi(2)$ and $\varphi(3)$ until $\varphi(N)$ by using the same method; this is the first iteration process. We repeat several iterations until the cost function reaches a stable value, and then, the optimized phase modulation signal $\varphi(j)$ is obtained. By this optimization method, the arbitrary-shaped modulation spectrum can be realized theoretically by changing the target spectrum. When the target spectrum is the top-hat-shaped spectrum, the cost function and SBS threshold versus iteration number is shown in Figure 2. With the increase in the iteration number, the cost function decreases and the SBS threshold increases. When the iteration number is above 25, the cost function and SBS threshold remain stable, which indicates that the phase modulation signal has reached the optimal state.

When the iteration number is 25, the optimized phase modulation signal and spectrum produced by optimized phase modulation are shown in Figures 3A, B. It can be seen that the near-top-hat-shaped spectrum is realized by optimizing the phase modulation signal.

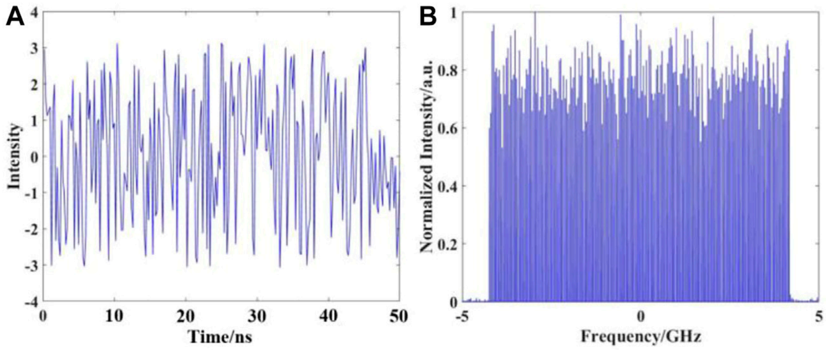

FIGURE 3
(A) Optimized phase modulation signal and **(B)** near-top-hat-shaped spectrum.

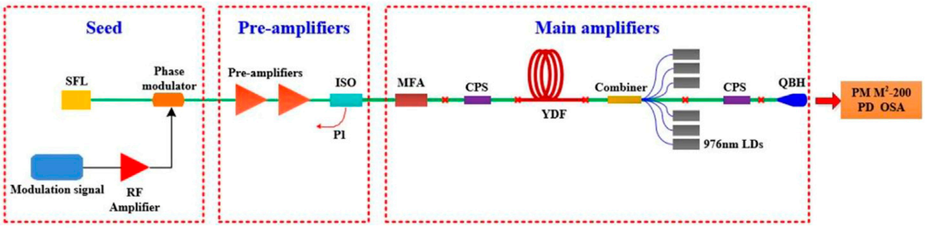

FIGURE 4
Experimental setup of the PM narrow-linewidth fiber laser (SFL, single-frequency laser; RF, radio frequency; ISO, isolator; MFA, mode field adaptor; CPS, cladding power stripper; YDF, Yb-doped fiber; QBH, quartz block head; PD, photo-detector; OSA, optical spectrum analyzer; PM, power meter).

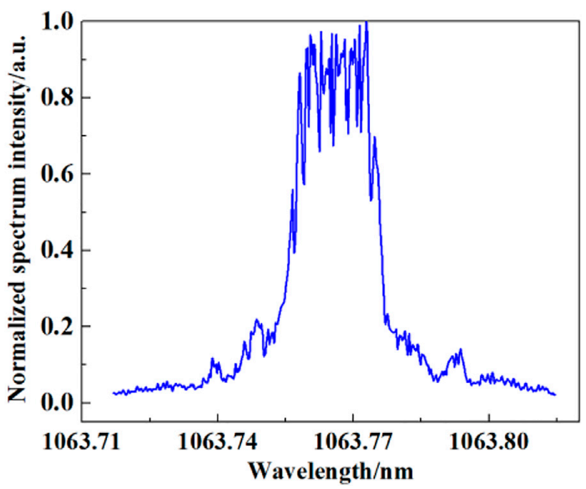

FIGURE 5
Measured normalized spectrum of the seed laser.

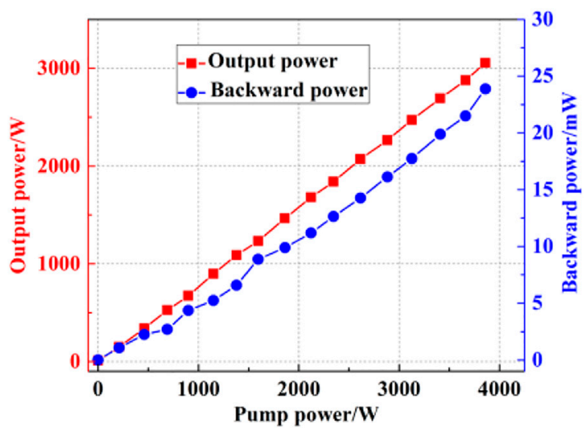

FIGURE 6
Output power and backward power versus pump power for the PM fiber laser system.

2.2 Experimental setup

Figure 4 shows the experimental setup, which is based on a master oscillator power amplification (MOPA) structure. The seed was a 1064-nm single-frequency linearly polarized fiber laser with a linewidth of 10 kHz, delivering an output power of 20 mW. The seed was phase-modulated by a phase modulator, driven by an amplified modulation signal to broaden the linewidth of the seed to suppress SBS in an amplifier. The

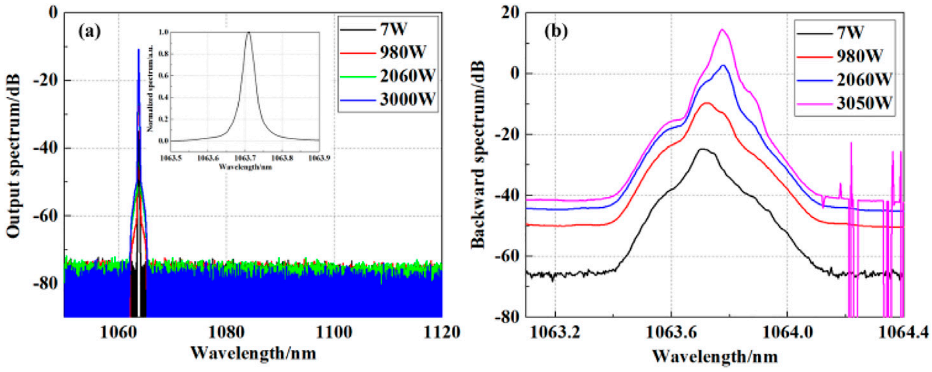

FIGURE 7
(A) Output spectrums and **(B)** backward spectrums at different output powers for the PM fiber laser system.

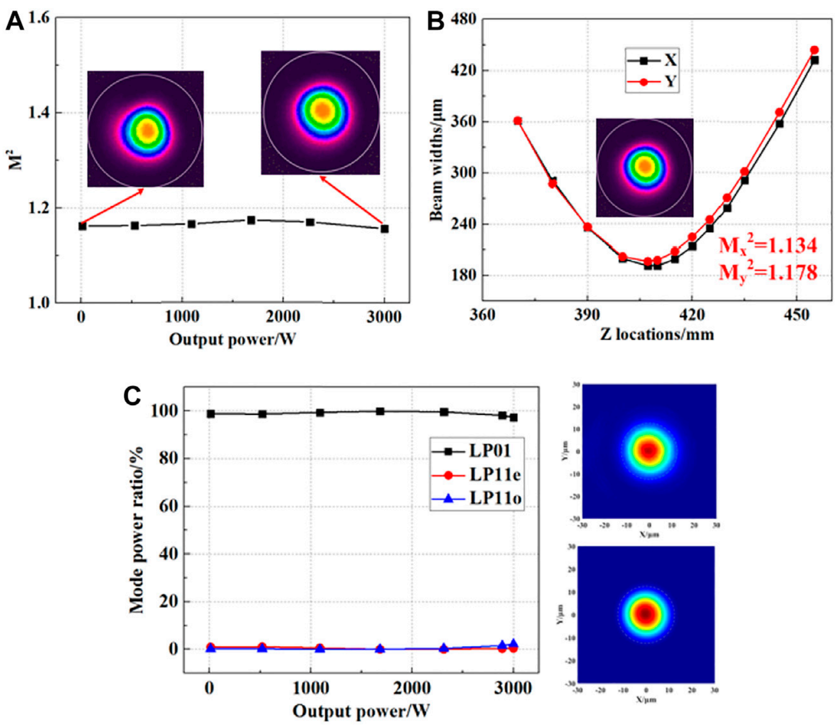

FIGURE 8
(A) M^2 factors at different output powers, **(B)** beam quality at 3 kW, and **(C)** power proportion of LP01, LP11e, and LP11o modes at different output powers and the output spot (top) and mode reconstruction spot (bottom) at 3 kW.

broadened seed laser was amplified by a three-stage all-fiber amplifier. Two pre-amplifiers boosted the laser seed to approximately 20 W, where a PM Yb-doped fiber (YDF) with a core/inner-cladding diameter of 10/125 μm was used. Then, the pre-amplified laser was injected into the main amplifier through a PM mode field adaptor (MFA). Between the PM MFA and pre-amplifiers, a PM isolator (ISO) was inserted to prevent damage from the backward light, and the multi-mode fiber port of ISO was used to monitor the backward power and backward spectrum. The main amplifier was constructed by PM YDF with a mode field diameter of 20 μm, which was coiled on a water-cooled aluminous plate. To enhance MI suppression, the backward pump configuration was employed in the main amplifier stage, and six laser diode modules centered at 976 nm were coupled into the YDF through a (6 + 1) × 1 PM signal/pump combiner. Two home-made PM

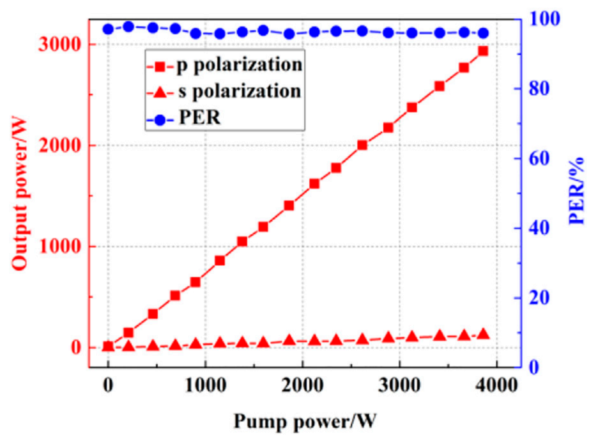

FIGURE 9
Polarization power and PER of a fiber amplifier at different pump powers.

cladding power strippers (CPSs) were used to strip the residual pump light and cladding signal light. An anti-reflection coated end cap was used to deliver and collimate the amplified laser.

3 Experimental results and discussion

The optimized modulation signal is used to drive the phase modulator to broaden the linewidth of the single-frequency laser, and the spectrum is measured by an optical spectrum analyzer (OSA) with the spectral resolution of 2 pm, as shown in Figure 5. The spectrum presents a near-top-hat-shaped profile, and the full width at half maximum (FWHM) is 18 pm. However, compared with the theoretical results, there are some large power fluctuations and obvious sidebands in the spectrum. The main reason is that the RF amplifier and phase modulator used in the experiment have non-linear response coefficients at different frequencies, leading to the distortion of the experimental results.

The seed laser is amplified to approximately 20 W using two pre-amplifiers. By injecting the pre-amplified seed into the main amplifier, the output power and backward power of a PM fiber amplifier versus the pump power are shown in Figure 6. With the scaling of pump power, the output power of the fiber laser increases linearly. When the pump power is 3,860 W, the output power reaches 3,050 W, and the optical-to-optical efficiency is approximately 78%. At 3 kW output power, the backward power is approximately 25 mW.

The spectrum is also measured by an OSA with a spectral resolution of 0.02 nm, and output spectrums and backward spectrums at different output powers are shown in Figure 7. The output spectrums are shown in Figure 7A, and the fine output spectrum from 1,063.5 nm to 1,063.9 nm is shown in Figure 7A. Due to the limitation of the spectral resolution, the measured FWHM of the seed laser is 0.04 nm, and the linewidth slightly broadened to 0.04 nm at the maximum output power. The broadening of the spectral substrate is due to amplified spontaneous emission (ASE), and no Raman light has been observed at the maximal output power, meaning that the SRS suppression ratio is >62 dB. The backward spectrums at different output powers are shown in Figure 7B. SBS increases obviously with the scaling of the output power, and the laser produces random intensity peaks in the backward light spectrum at 3,050 W output power, which indicates that laser power has reached the SBS threshold [23].

The beam quality factors M^2 at different output powers are shown in Figure 8A. The beam quality of the seed laser is $M^2 = 1.19$, and the fiber laser maintains the near-diffraction-limited beam quality with the scaling of the output power. The beam quality at 3 kW is shown in Figure 8B, which is $M_x^2 = 1.134$ and $M_y^2 = 1.178$. M^2 is calculated as $M^2 = \sqrt{((M_x^2)^2 + (M_y^2)^2)/2}$, which is 1.156 at 3 kW, and no MI has been observed. For narrow-linewidth fiber lasers, M^2 cannot characterize the mode content accurately [24]. In order to further confirm the power ratio of the high-order mode (HOM), we decompose the output spot at different output powers. The output laser combines three modes: LP01, LP11e, and LP11o. Based on the stochastic parallel gradient descent (SPGD) algorithm [25, 26], the power proportion evolutions of the three modes have been studied and plotted in Figure 8C. In addition, the output spot and mode reconstruction spot at 3 kW are also shown in Figure 8C, and the cost function is 0.998, which proves the accuracy of mode decomposition. According to the results of mode decomposition, the proportion of the fundamental mode LP01 in the output laser reaches 97% at 3 kW. According to [24], M^2 should be less than 1.1 when LP11 is 3%, which is less than the measured M^2. This is because of the presence of residual cladding signal light due to the limited stripping efficiency of CPS [27], which was not considered during mode decomposition.

The output power of the p-polarization light and s-polarization light and the PER at different pump powers are shown in Figure 9, which are measured using the assemble components of a half-wavelength plate and a polarization plate. The measured PER changes between 95.77% (14.91 dB) and 97.52% (18.31 dB) for PM fiber amplifiers with approximately 2% fluctuation with the increase in the output power. At the maximum output power, the PER is measured to be approximately 96%.

4 Conclusion

In this paper, a high-power PM narrow-linewidth fiber laser based on the MOPA structure was built. Based on this system, we optimized the modulation signal by using the grid search method to obtain the near-top-hat-shaped spectrum. With the near-top-hat-shaped spectrum modulation signal, a 3-kW linearly polarized laser was realized with <10 GHz spectrum linewidth and near-diffraction-limited beam quality, which is the highest output power for the PM fiber laser reported so far, with a linewidth of approximately 10 GHz.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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