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# High-energy, 100-ns, single-frequency all-fiber laser at 1064 nm

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## ABSTRACT

A high-energy, single-frequency fiber laser with long pulse duration of 100 ns has been experimentally investigated in an all-fiber architecture. Only 34-cm long heavily Yb-doped phosphate fiber was employed in power scaling stage to efficiently suppress the Stimulated Brillouin effect (SBS). In the experiment, 0.47 mJ single pulse energy was achieved in power scaling stage at the pump power of 16 W. The pre-shaped pulse was gradually broadened from 103 to 140 ns during the amplification without shape distortion.

**Keywords:** single frequency, fiber laser, high energy.

## 1. INTRODUCTION

High energy, high power, single-frequency nanosecond pulsed laser sources have seen broad applications in areas such as coherent lidar, remote sensing, and nonlinear frequency conversion [1-3]. Laser sources in all-fiber architecture as a practical technology have been widely investigated and developed due to the advantages on compactness, ruggedness and easy thermal management [4-6]. Since narrow-linewidth operation is demanded for the applications mentioned above, longer pulse durations are generally needed for a transform-limited pulse. However, power scaling on such long laser pulses is greatly hindered by the onset of nonlinear effects, especially SBS effect, which is governed by the phonon lifetime of ~10 ns [7, 8]. Therefore, most of the demonstrations on high power single-frequency pulsed fiber amplifiers in 1  $\mu\text{m}$  regime were focused on the laser pulses with duration smaller than 10 ns [9-11]. An average power of 913 W has been obtained on multi-stage cascaded power amplification under the high repetition rate of 10 MHz and short pulse duration of 3 ns, while the corresponding peak power was around 28.6 kW [12]. To achieve high energy single-frequency pulses amplification for long pulse duration, many techniques have been proposed to increase the threshold of SBS, such as shortening the length and increasing the mode area of active fiber, temperature and strain gradients, and acoustically tailored active PCF [13-15]. Employing the strain gradient on the active fiber in power scaling stage, Chen et al. achieved a single-pulse energy of ~260  $\mu\text{J}$  in a single-frequency pulsed Yb-doped MOPA configuration, where the SBS free peak power was successfully increased from 330 to 508 W [16]. In 2015, Wang et al. presented a double-passing amplification technology to suppress the SBS by linewidth broadening through cross phase modulation between the signals propagated in both directions [17]. The peak power of 2.2 kW was achieved in the demonstration with a laser linewidth of ~230 MHz. Highly rare-earth-doped multicomponent fiber has been greatly developed recently, in which sufficient laser gain can be provided with a short active fiber length [18, 19]. In 2010, Shi et al. achieved a pulse energy of 0.126 mJ for 105 ns pulses at a repetition rate of 8 kHz, where only two pieces of 15-cm long heavily Er/Yb co-doped phosphate fibers were employed in power amplification stages [20]. With highly Tm-doped germanate glass fiber boosting power and pulse energy in final amplifier, an average power of 16 W and pulse energy around 1 mJ were obtained by the same group in 2012 [21]. It can be found that, the SBS effect was significantly suppressed with the short active fiber length while the power/energy scaling can be achieved due to the high gain coefficient provided by the active fibers.

In this paper, we demonstrated a 1064-nm, high-energy, single-frequency all-fiber laser with long pulse duration of 100 ns. Five pulses amplification stages have been built up to gradually amplify the pulse energy while maintaining the pulse

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shape and spectrum purity. Heavily Yb-doped large mode area (LMA) phosphate fiber was employed in power scaling stage to effectively shorten the fiber and thus increase the SBS threshold. In the experiment,  $\sim 0.47$  mJ of single-pulse energy has been achieved under a pulse repetition rate of 5 kHz. The pulse duration was broadened from 103 to 140 ns during the amplification while the pulse shape was kept well through pre-shaping.

## 2. EXPERIMENTAL SETUP AND RESULTS

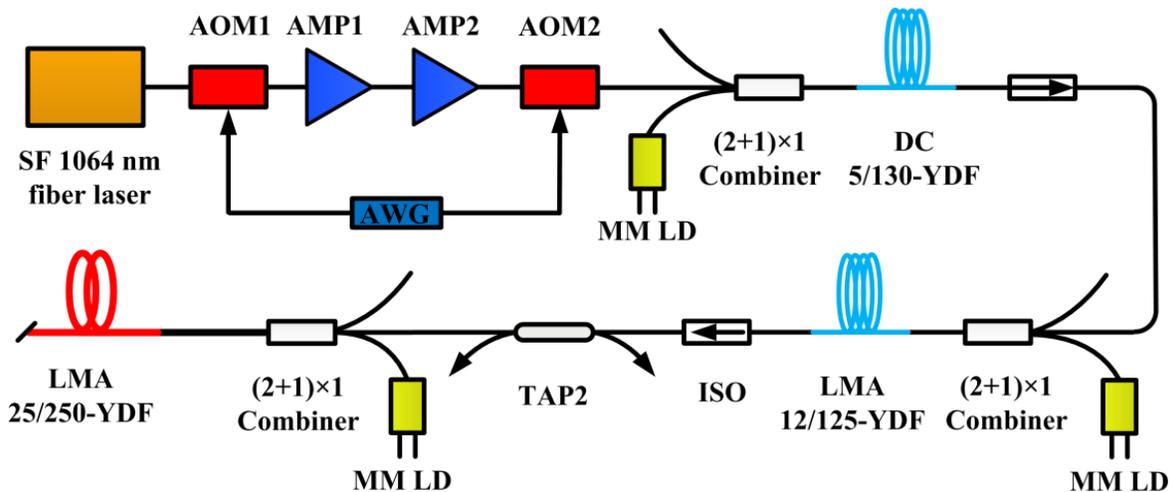


Figure 1. Experimental setup of the high-energy, single-frequency pulsed all-fiber laser at 1064 nm.

The experimental setup was shown in Fig. 1. The seed is a CW single-frequency fiber laser at 1064 nm with the output power of 20 mW. The laser linewidth was measured to be 7 kHz. It was modulated by an acousto-optical modulator (AOM) to generate the laser pulses with the repetition rate of 5 kHz and pulse duration of around 103 ns. The pulse was pre-shaped through parameter design of the driver signal from arbitrary waveform generator (AWG) to make the leading edge gently sloped to limit its gain or steepening. Since the AOM has an insertion loss of 2 dB and pulse repetition rate is only 5 kHz, the generated pulsed seed was rather weak. In this condition, the amplified spontaneous emission (ASE) rose up greatly, which would contain much CW component for the output signal and thus compromise the pulse amplification thereafter. So they were firstly amplified via two stages of core-pumped amplifiers. The length of the acti-

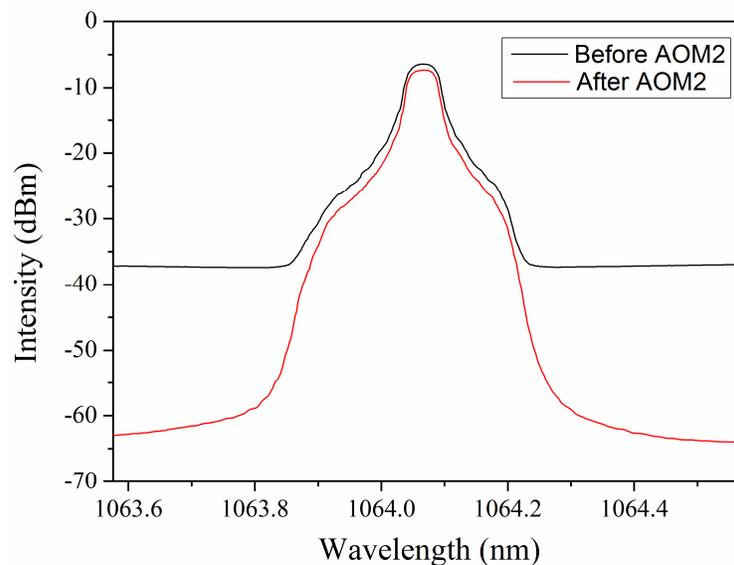


Figure 2. Optical spectra comparison of the amplified pulsed laser before and after AOM2.

ve fibers in AMP1 and AMP2 should be well controlled for the balance between pulse amplification and ASE suppression. It can be observed in the experiment that the ASE component generated once the pump incident into the active fiber in AMP1&2. Even the bandpass filters with a bandwidth of 2 nm have been used after the amplification stage to filter out most of the ASE, the CW component in the transmission bandwidth still existed. Another AOM, which was time synchronized to the former, was arranged after that to remove the in-band ASE and increase the extinction ratio. The laser spectra were measured with an optical spectrum analyzer (OSA, YOKOGAWA, AQ6370D) under the resolution of 0.02 nm. The output spectrum after two stages of core-pumped amplification stages has a signal-to-noise ratio (SNR) of around 30 dB while serious ASE was generated on both sides of the central wavelength. When the second AOM was employed after the AMP2 to filter out the light between the neighbor pulses, the SNR was greatly improved to 55 dB. The average power of the laser pulses after AOM2 was  $\sim 0.9$  mW.

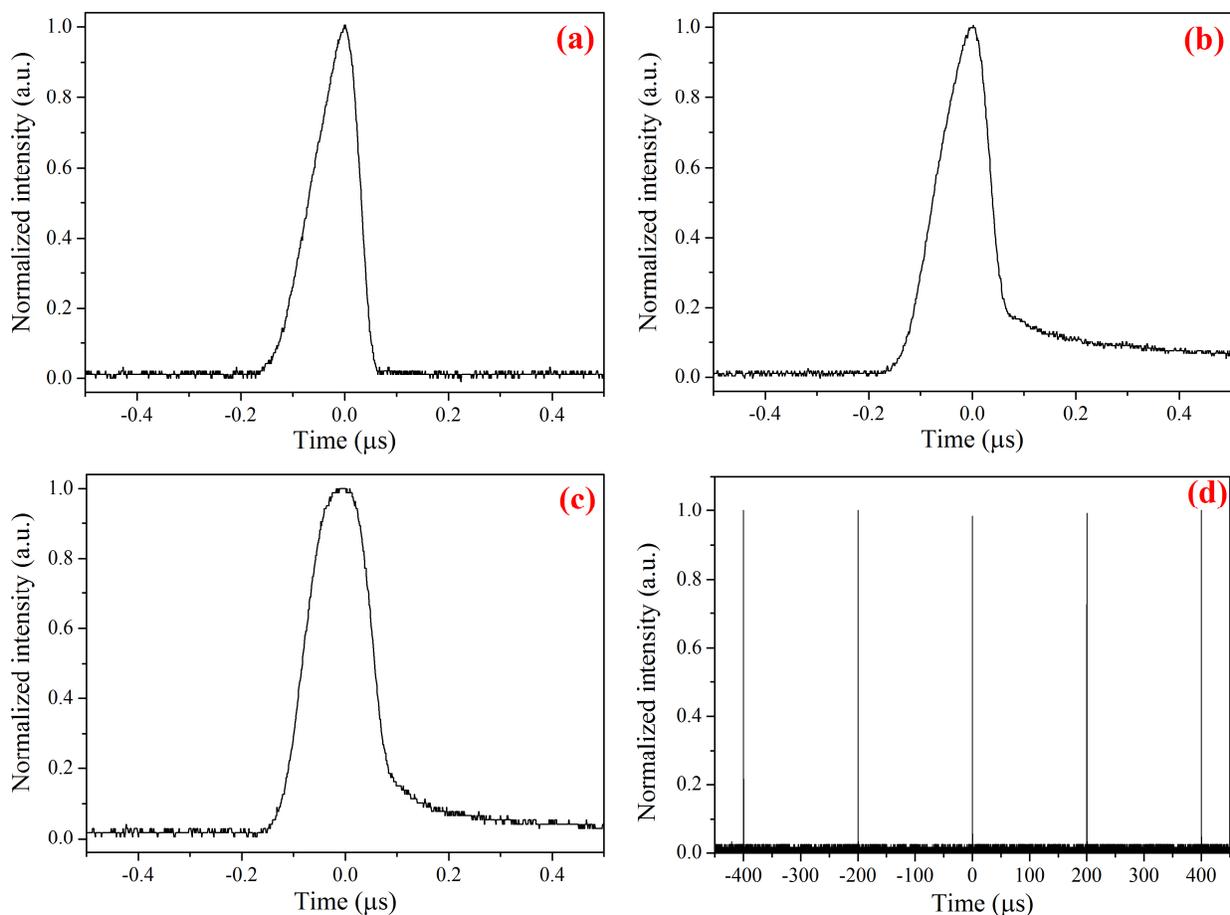


Figure 3. Pulse evolution during the amplification: (a) the modulated seed; (b) pulse before the power amplification; (c) pulse after the power amplification; (d) pulse trains at the highest output power.

Then the pulses were launched into a cladding pumped amplifier through a  $(2+1)\times 1$  combiner. The gain fiber is a piece of 1.5 m double cladding fiber (DC-5/125-YDF), which has a cladding absorption coefficient of 1.65 dB/m. Even though the active fiber length was insufficient, it is restricted by SBS effect due to the small core size. In this stage, the average power of the pulsed laser was amplified to 8.5 mW. Further increase of the laser power was limited by the pulse instability induced by the SBS effect. To ensure the pulse stability without timing jitter for the following stages, the laser power was kept to 8.5 mW. In the second cladding-pumped amplifier, the active fiber was changed to the LMA-12/125-YDF, where the larger core diameter indicated the higher SBS threshold. The active fiber has a cladding absorption coefficient of 11 dB/m and thus 1 m of the fiber was used in the experiment. The residual pump power was removed through a pump stripper home-made on a passive matched fiber. After the isolator, a maximum output power of 34 mW was achieved at the pump power of 1.1 W and further increase of the laser power was restricted by the SBS observed through the other port of the  $(2+1)\times 1$  combiner. As shown in Fig. 3(b), the pulse duration was broadened to 116 ns in

this stage due to the self-phase modulation effect. A 2×2 tap coupler was spliced thereafter to monitor the signal in the forward direction and the SBS in the backward direction.

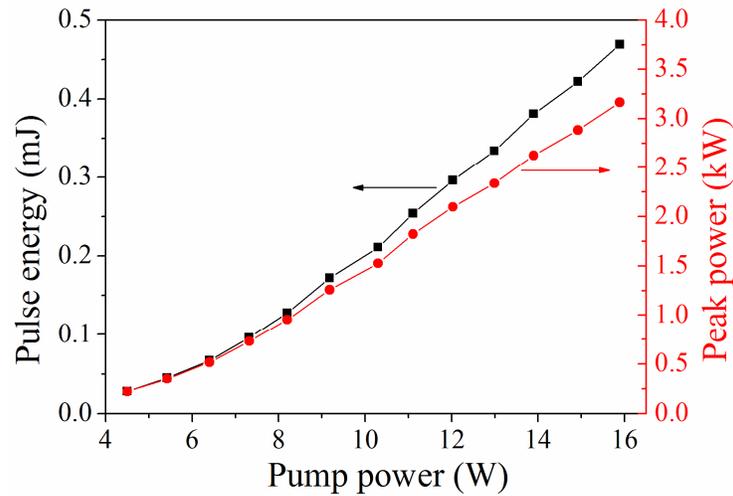


Figure 4. The relationship of the measured single pulse energy, corresponding peak power and the launched pump power.

In the former amplification stages, power scaling of the pulsed laser was mainly limited by the SBS effect. Before launched into the power scaling stage, 34 mW of the output power was achieved in case of the onset of SBS effect. To efficiently increase the SBS threshold in the single-frequency laser with such long pulse duration, the LMA heavily Yb-doped phosphate fiber was applied in the power amplifier, with a core/inner-cladding diameter of 25/250  $\mu\text{m}$ . The length of the active fiber is only 34 cm. The numerical aperture (NA) of the core is designed to be 0.04 in order to confine the mode of this LMA fiber for better beam quality. In this stage, the SBS effect was monitored by the 1% port of the tap coupler. As the pump power increased, the power scaling effect is much obvious when compared with the commercial active fiber []. The pulse energy was measured with the energy sensor (Ophir, PE10-C and PE50-DIF-C) so that the continuous wave part can be effectively excluded. As shown in Fig. 4, before the SBS effect was built up in the backward direction, the pulse energy was boosted up efficiently and the maximum single-pulse energy of 0.47 mJ was achieved at the pump power of 16 W. What should be noted is that the pulse was greatly broadened in the power scaling stage. As shown in Fig. 3(c), the pulse duration was around 140 ns at the maximum pulse energy while the pulse shape was kept well without pulse distortion. The pulse sequences were also shown in Fig. 3(d). The peak power can be approximately calculated to be 3.15 kW.

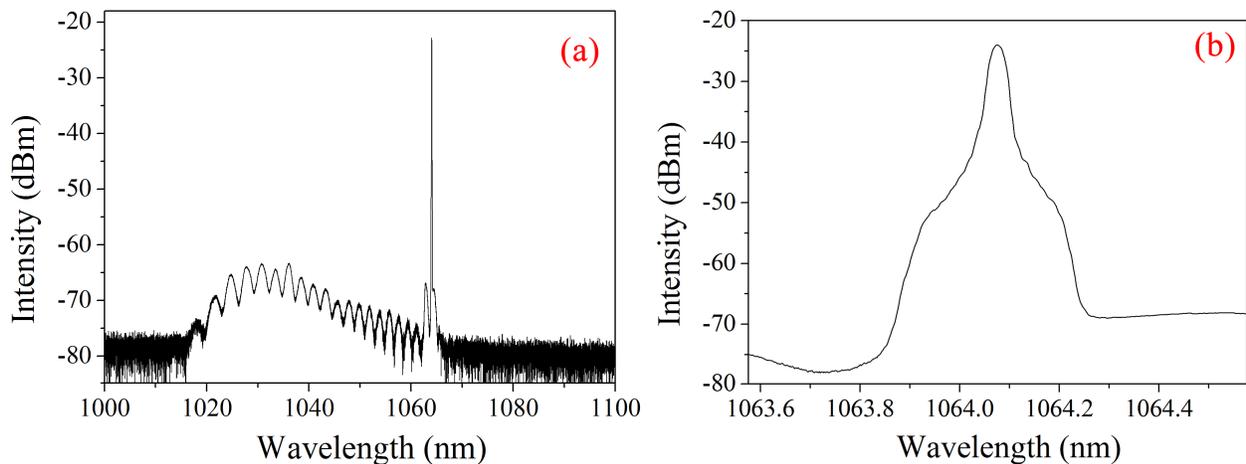


Figure 5. (a) Optical spectrum of the single-frequency pulsed fiber laser at the maximum output power in a broad range. (b) Optical spectrum of the pulsed laser with a scanning range of 1 nm under the OSA resolution of 0.02 nm.

The laser spectrum was also measured at the maximum output power with an OSA. Figure 5(a) showed the optical spectrum in a broad range from 1000 to 1100 nm. Considering the ASE around 1030 nm, the signal-to-noise-ratio can be around 45 dB. The sub-peaks around the signal were the ASE generated in the bandwidth of the filter used in the experiment. Figure 5(b) showed the spectrum measured in a range of 1 nm with a resolution of 0.02 nm and no spectrum broadening was observed in the whole pump range.

### 3. CONCLUSIONS

In conclusion, we have demonstrated a high-energy, single-frequency all-fiber laser at 1064 nm with pulse duration of hundred ns. 34-cm long heavily Yb-doped LMA phosphate fiber was applied in power scaling stage to efficiently increase the SBS threshold. In the experiment, maximum single-pulse-energy of 0.47 mJ at a repetition rate of 5 kHz was achieved and the corresponding peak power was around 3.1 kW. The short gain fiber in power scaling stage also resulted in a signal- to-noise-ratio of around 40 dB. Through pre-shaping, the pulse shape was kept well even at the maximum pump power.

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