Single-frequency high-energy Yb-doped pulsed all-fiber laser

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A single-frequency pulsed all-fiber laser with a master oscillator power amplifier configuration is presented. While maintaining the properties of single mode, linear polarization, and narrow linewidth, a single-pulse energy of 260 μJ and over 500-W peak power is experimentally demonstrated at 1 kHz by employing tensile strain gradient and pulse-shape control methods. In addition, approximately 55 dB of optical signal to noise ratio is also achieved.

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Single-frequency linearly polarized and high-energy pulsed laser sources have wide applications, such as coherent lidar, active laser remote sensing, and spectroscopy[1−4]. Meanwhile, fiber sources with all-fiber architecture have attracted much attention due to their advantages of being rugged, reliable, compact, and lightweight[5]. In many applications, high-precision measurements depend on the linewidth or coherence length of the pulsed laser. Therefore, the laser pulse duration should be sufficiently long to obtain narrow linewidth in a transform-limited pulse. However, due to limitations, such as those from the stimulated Brillouin scattering (SBS) nonlinear effect[6], laser power scaling is difficult for longer pulses (>100 ns) with a single spatial mode and narrow linewidth in fiber amplifiers. Many investigations have been conducted on SBS suppression in fibers[7−10]. When using common silica fibers and to prevent damaging the narrow spectral linewidth of the laser, two techniques are mainly used to increase the SBS threshold: reducing the SBS gain coefficient with a SBS-suppressing fiber or broadening the SBS gain bandwidth by temperature or strain gradients along the fiber. Employing a SBS-suppressing fiber, Carlson *et al.* reported a Yb-doped fiber (YDF) master oscillator power amplifier (MOPA) system that obtained 500-W peak power pulses with space-coupling counter-pumped configuration[4]. By using an active fiber with core and inner cladding diameters of 30 and 90 μm, Chen *et al.* presented a single-frequency fiber laser at 1 563 nm, and pulses with over 500-W peak power were obtained with beam-quality factor of $M^2 < 1.6$[7]. Jeong *et al.* reported a single-frequency fiber laser at 1 060 nm that reached over 400-W continuous wave (CW) radiation, with the temperature difference between the fiber ends estimated to be 190 K[8]. Rothenberg *et al.* introduced a narrow linewidth Yb-doped fiber source with a strain gradient along the active fiber that achieved 190-W CW radiation[9]. For this letter, the SBS-suppressing fiber is difficult to fabricate because its temperature gradient is not convenient to realize and its magnitude is practically limited. In addition, although the counter-pumped configuration is helpful to increase the SBS threshold, it is not appropriate for an all-fiber architecture because the inevitable passive fiber reduces the SBS threshold and there is risk of component damage. Hence, a co-pumped all-fiber configuration is set up with a tensile strain gradient applied to the active fiber to increase the SBS threshold. In addition, a pulse-shape control method is used to increase the pulse energy. Pulses with 260-μJ pulse energy and 508-W peak power are obtained with near diffraction-limited performance. To our knowledge, our experiment is the first to use a strain gradient to suppress SBS in a single-frequency pulsed fiber laser. The value of the peak power is the highest for narrow-linewidth, single-mode (SM), polarization-maintaining (PM) all-fiber lasers operated at 1 μm. In addition, in order to obtain good spectral performance, a non-planar ring oscillator (NPRO) is used as the seed laser and the amplified spontaneous emission (ASE) is suppressed in the amplifiers. As a result, the amplified pulses are very close to being transform-limited pulses.

Figure 1 shows the scheme of the pulsed fiber laser based on an all-PM fiber MOPA configuration consisting of a seed laser and four amplification stages. An isolator and a narrow band filter are inserted between the adjacent amplification stages to eliminate the feedback light and the ASE. Rather than the commonly used diode

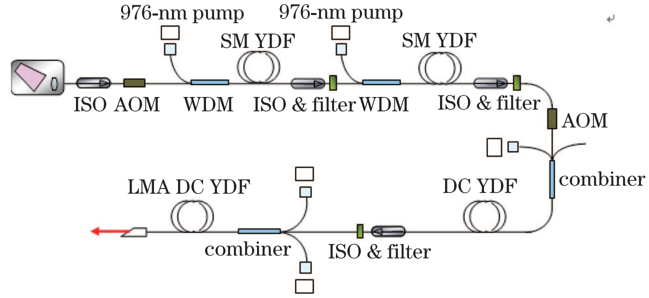

Fig. 1. Diagram of the experimental setup. ISO: isolator.

laser, the seed laser is an in-house-built NPRO laser[11]. By virtue of its monolithic cavity design, this type of laser is well known for its capability of providing an ultrastable single-frequency emission. The NPRO laser is operated in CW mode to guarantee narrow spectral linewidth and provide approximately 500 mW of linearly polarized radiation at 1 064 nm with a linewidth of several kilohertzs. Next, the seed light is coupled into an SM PM fiber, and an isolator is used to protect the seed laser from any feedback originating in the following amplification stages. The pulses are obtained by modulating the CW seed laser using a fiber pigtailed acousto-optic modulator (AOM) with preset pulse shape. Then, a pulse train with 500-ns pulse duration and single-pulse energy of 50 nJ is obtained. The seed pulses are firstly amplified via two stages of SM, and PM Yb-doped fiber amplifiers (YSF-5/130, Nufern). The active fibers are core-pumped using wavelength division multiplexers (WDM) for 976/1 064-nm wavelengths. Because the seed pulse energy is very small, the pulse repetition frequency is set to be 10 kHz with the first AOM, although the final repetition rate needed is 1 kHz. With this method, the optical–optical conversion efficiency is improved, and the ASE effect is reduced. After the second amplification stage, an additional AOM is used to set the pulse repetition rate to 1 kHz, which eliminates build-up of the optical power emitted within the same bandwidth of the ASE filter. After the second AOM, approximately 4.5-mW average power is obtained. The active fiber used in the third amplifier stage is a double-clad (DC) fiber with a core diameter of 10 μm and a core numerical aperture (NA) of 0.08 (YDF-10/130, Nufern), which is pumped by a 975-nm multi-mode diode laser. At the end of this amplifier stage, single-pulse energy of 15 μJ becomes available to seed the final amplifier stage.

The SBS threshold is determined by the peak SBS gain when integrated over the length L of the fiber. In the simple case of constant power and gain over the fiber length, the threshold power $P_{\rm SBS}$ can be expressed as[6]

$$P_{\rm SBS} \approx 21\frac{A_{\rm eff}}{K \cdot g_{\rm B} \cdot L}, \quad (1)$$

where $A_{\rm eff}$ is the optical effective mode area, $g_{\rm B}$ is the peak SBS gain coefficient[12], and K is the polarization dependence factor. Because the SBS threshold is proportional to the ratio of the mode field area divided by the effective length of the fiber and the peak SBS gain, the SBS threshold can be increased by maximizing the fiber diameter and minimizing the fiber length. However, the maximum core diameter is limited by the requirement of good beam quality. Taking into account all of the factors above, the large mode area (LMA) DC fiber used in the final amplification stage has a core diameter of 25 μm and a core NA of 0.06 (YDF-25/250, Nufern). The pump absorption in the inner cladding is approximately 4.5 dB/m at 975 nm, and the threshold power-length product $P_{\rm SBS} \cdot L$ is approximately 260 W·m. A commercial PM (2+1)×1 signal pump combiner is used to combine two fiber pigtailed diode lasers at 975 nm, which are operated in pulse mode with pulse width of 240 μs and pulse repetition rate of 1 kHz. Approximately 1.57-W average pump power is launched into the active fiber. The length of the LMA active fiber is set as 1.3 m, and 70% of the pump power is absorbed.

The peak SBS gain $g_{\rm B}$ is inversely proportional to the SBS gain linewidth. For a given fiber, the natural SBS gain has a Lorentzian lineshape

$$g(\nu) = g_0/[1 + 4(\nu - \nu_B)^2/\Delta\nu_B^2], \quad (2)$$

where $\nu_{\rm B}$ is the SBS resonance frequency and $\Delta\nu_{\rm B}$ is the SBS gain linewidth, which is approximately 50 MHz in the YDF. The result of a strain gradient along the position z in the fiber is a concomitant shift of the SBS resonance frequency

$$\nu_{\rm B}(z) = \nu_{\rm B} + \beta\varepsilon(z), \quad (3)$$

where the strain $\varepsilon \equiv \Delta L/L$ and the coefficient $\beta = \frac{\partial\nu_{\rm B}}{\partial\varepsilon} \approx 0.464$ GHz/%[13]. Hence, when a strain gradient is applied, the integrated gain bandwidth over the fiber length is effectively broadened, and the threshold power should be increased

The strain distribution along the 1.3-m active fiber is shown in Fig. 2. The maximum strain is limited by the worry of fracture failure. Along the direction of the laser, the fiber is divided into four segments: the first has a length of 40 cm, with no strain applied; the second is 50-cm long, with 8-N force applied, which corresponds to a strain of $\varepsilon = 0.11\%$; the third is 25-cm long, with a force of 16 N applied, which corresponds to a strain of $\varepsilon = 0.22\%$; the fourth is 15-cm long, with no strain applied. The onset of SBS is detected by the depletion in the temporal lineshape of the amplified signal. Beyond the SBS threshold, pulse amplitudes become erratic due to the stochastic nature of SBS triggered by thermal/phonon fluctuations in the fiber. In the absence of any strain gradient, the SBS free peak power is approximately 330 W, and depletion in the amplified pulses will become evident if the peak power is further increased by 5%. When the strain gradient is applied, the SBS free peak power is scaled to 508 W, and an increase of 1.87 dB is achieved.

In pulsed fiber amplifiers, for square seed pulses, the pulse often becomes steep at the leading edge, which increases the peak power significantly. Therefore, such pulses are adverse for increasing the pulse energy because the peak power is limited by the SBS effect. Considering this phenomenon, a special seed pulse shape is designed with the first AOM, and an approximate top flat pulse shape at the output end is obtained. Figure 3 shows the output pulse shape of the final amplification stage and the modulated seed pulse shape (see insert). By means of this method, the output pulse energy is increased by approximately 80%. Figure 4 shows the output power with different pump powers. When the pump power is 1.57 W, the highest achievable power without the presence of SBS is 260 mW (i.e., 260 μJ) at 1 kHz, which

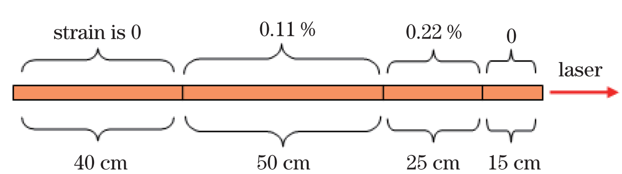

Fig. 2. Strain distribution along the active fiber.

corresponds to 508-W peak power. The optical–optical conversion efficiency is approximately 17%, and the measured polarization extinction ratio (PER) is better than 14 dB.

The spectrum of the amplified laser is shown in Fig. 5, which is measured using an optical spectrum analyzer (OSA, YOKOGAWA, AQ6370) with a resolution of 0.02 nm. The spectrum shows that approximately optical signal-to-noise ration (SNR) of 55 dB is obtained between the signal and the ASE peak at 1 032 nm, and that the SNR between the signal and the local ASE noise at 1 064 nm is more than 60 dB. This high SNR is primarily due to the 2nd AOM, which improves the SNR by more than 13 dB.

In order to measure the spectral width of the amplified laser, an optical heterodyne beat method is utilized[14]. A small portion of the seed NPRO laser is separated out, after passing through 10-km SM fiber, mix on a photodiode with the amplified pulses. The fast Fourier transform (FFT) spectrum calculated from the beat signal is shown in Fig. 6, and the spectral width $\Delta\nu$ is approximately 1.98 MHz. Because the pulse width Δt is approximately 500 ns, the product of $\Delta\nu$ and Δt is approximately 1. The approximately rectangle pulse shape indicates that the amplified pulses are very close to transfom-limited pulses.

For a coherent laser transmitter, near diffraction-limited beam-quality performance is usually required. In this work, the active fiber of the final amplifier stage is coiled at a diameter of 8 cm to improve the beam quality[15], and the measured M^2 values are approximately 1.2 in both horizontal and vertical directions.

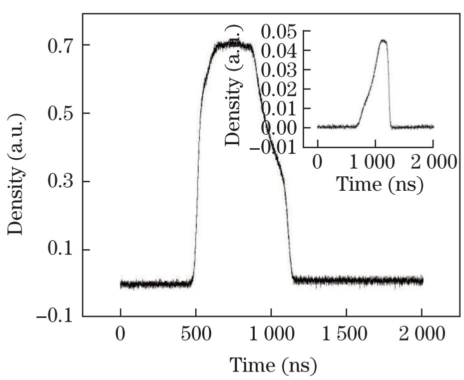

Fig. 3. Temporal pulse shape of the amplified laser after the final stage. Inset is modulated seed pulse shape.

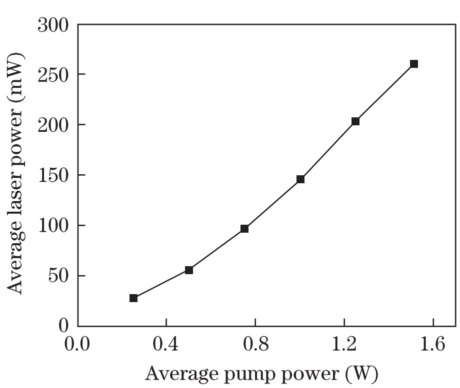

Fig. 4. Average output power versus the pump power.

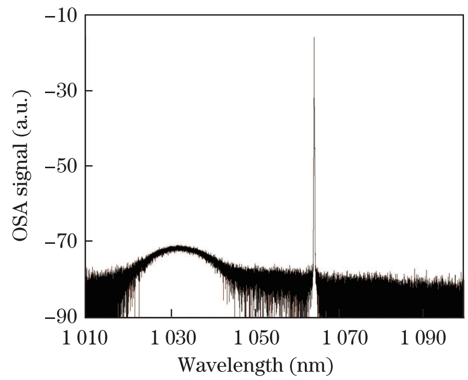

Fig. 5. Output spectrum recorded with a OSA resolution of 0.02 nm.

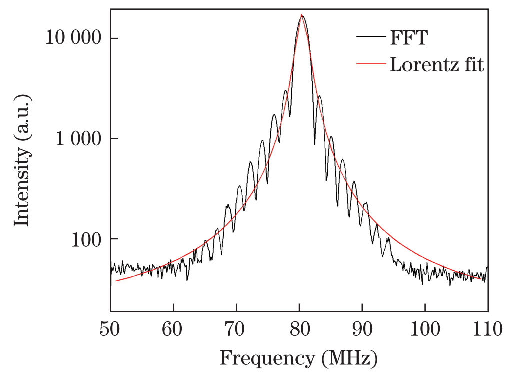

Fig. 6. FFT spectra of the heterodyne beat signal with Lorentz fitting.

In conclusion, we present a single-frequency high-energy pulsed fiber laser based on an all-PM fiber MOPA configuration. Using the methods of tensile strain gradient and pulse-shape control, a single-pulse energy of 260 μJ, which corresponds to over 500-W peak power, is obtained at 1 kHz. Close to transform-limited spectral width and near diffraction-limited beam quality are also achieved. In this system, changing the pulse repetition frequency and the pulse width is convenient to meet different applications. The peak power further scaling of the single-frequency pulsed fiber laser remains under study.

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