Kilowatt-level stimulated-Brillouin-scattering-threshold monolithic transform-limited 100 ns pulsed fiber laser at 1530 nm

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We demonstrate a high-stimulated-Brillouin-scattering-threshold monolithic pulsed fiber laser in a master oscillator power amplifier configuration that can operate over the C band. In the power amplifier stage, we used a newly developed single-mode, polarization maintaining, and highly Er/Yb codoped phosphate fiber with a core diameter of 25 μm. A single-frequency actively Q-switched fiber laser was used to generate pulses in the hundreds of nanoseconds at 1530 nm. We have achieved peak power of 1.2 kW for 105 ns pulses at a repetition rate of 8 kHz, corresponding to a pulse energy of 0.126 mJ, with transform-limited linewidth and diffraction-limited beam quality. © 2010 Optical Society of America
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For coherent lidar and active remote sensing applications, high-precision measurements depend on the linewidth or coherence length of the laser pulses [1,2]. Therefore, the laser pulses should have a pulse duration long enough to take full advantage of the narrow linewidth in a transform-limited pulse. For longer nanosecond single-mode (SM) narrow linewidth pulses, laser power scaling in fiber amplifiers has been difficult due to optical nonlinearities, primarily from stimulated Brillouin scattering (SBS) [1–3]. There are three main approaches to increase the SBS threshold: reducing the overlap integral between the optical and acoustic fields, using a temperature gradient or strain gradient to alter the SBS spectrum, and directly using large mode area fibers [3–8]. In pursuing the high SBS threshold for the pulsed fiber laser and amplifier, we use large-core highly codoped phosphate fibers with SM performance. Recently, we reported a high-SBS-threshold, single-frequency, SM, polarization maintaining (PM) monolithic pulsed fiber laser source based on SM PM highly Er/Yb codoped phosphate glass fiber (LC-EYPhF) with a core diameter of 15 μm, which can generate 332 W peak power for 153 ns pulses at 1538 nm [3]. In this Letter, we have designed and fabricated a new LC-EYPhF fiber 25/400 and demonstrated transform-limited 105 ns pulses with peak powers of 1.2 kW at 1530 nm in a master oscillator power amplifier (MOPA) configuration. The core and cladding sizes are 25 μm and 400 μm, respectively. It has core doping concentrations of 3 wt.% Er and 15 wt.% Yb, core NA of ~0.0395, and a V number of ~2. This low NA large-core fiber has been achieved based on a rod-in-tube technique under precise refractive index control for core and cladding glasses.

Figure 1 shows the implemented monolithic pulsed fiber laser system based on a MOPA architecture. The fiber laser consists of a single-frequency Q-switched fiber laser seed [3,9,10], two preamplifier stages using commercial active fibers, and two power amplifier stages using the LC-EYPhF fibers 15/125 and 25/400. The fiber lengths for the two large core fibers are 12.5 cm and 15 cm, which have been theoretically and experimentally optimized. Most important, the whole fiber laser is a monolithic system. The LC-EYPhF fibers have been successfully fusion spliced with the silica fibers based on an asymmetric fusion splicing technique [3]. Two LC-EYPhF fibers were fixed by using a low-index polymer in the V grooves on the separate copper plates and cooled by forced air.

Compared with the most narrow linewidth submicrosecond pulsed fiber laser seeds obtained by using acousto-optic modulators to externally modulate the narrow linewidth CW laser seeds [11,12], the single-frequency Q-switched fiber laser seed is very simple, stable, lightweight, compact, rugged, and low cost, as well as capable of high signal-to-noise ratio [3]. Figure 2 shows the seamless tunability of the longer pulse duration and the typical pulse shape (inset) at 1530 nm with a pulse width of 125 ns and a repetition rate of 8 kHz. When the pulse duration is longer than 100 ns, the pulse duration tunability is very sensitive to the pump power change due to the very short lasing fiber medium (2 cm) for the population inversion recovery in Fig. 1. It is worth noting that the Q-switched pulses exhibit a nearly temporal Gaussian

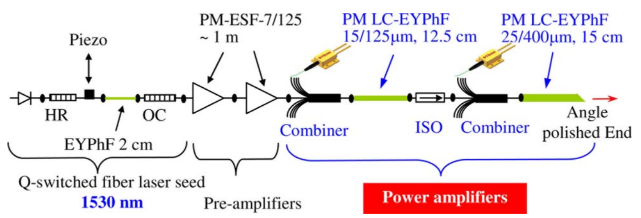

Fig. 1. (Color online) Schematic of the SM PM narrow linewidth pulsed monolithic fiber laser: HR, high-reflective fiber Bragg grating; OC, fiber Bragg grating output coupler; ISO, isolator.

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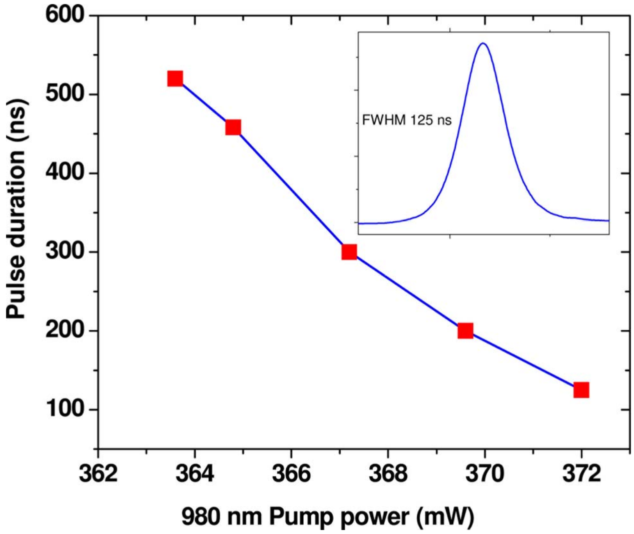

Fig. 2. (Color online) Pulse duration tunability at different 980 nm diode pump powers and typical pulse shape of the implemented Q-switched fiber laser seed (inset) at 8 kHz repetition rate.

shape. From the spectrum of the Q-switched fiber laser seed measured by using an OSA with a resolution of 0.06 nm, the signal-to-noise ratio of the Q-switched fiber laser pulses is up to ~55 dB.

In order to characterize the performance of the monolithic pulsed fiber laser in Fig. 1, the single-frequency Q-switched fiber seed with a pulse duration of 112 ns and a repetition rate of 8 kHz was used at 1530 nm. In this experiment, we kept the peak power after the second amplifier below 30 W in order to avoid the SBS effect by monitoring the temporal pulse trace, OSA spectrum, and Fabry–Perot scanning spectrum. For the SBS-free pulses after the second amplifier, the pulse shape stays nearly the same as the Q-switched pulse seed before amplification. After the first power amplifier stage, the peak power was scaled to 100–200 W by optimizing the pump power of the first power amplifier stage without obvious pulse steepening or distortion. The pulse energy after the second power amplifier stage was accurately measured by using a fast pyroelectric energy meter. This pulse energy meter is insensitive to the ASE background and CW signal component. Figure 3(a) shows the output pulse energy without SBS at different pump powers at 975 nm for the second power amplifier stage when the input pulse duration is 112 ns at 1530 nm with a repetition rate of 8 kHz. One can see that the highest pulse energy can reach 0.126 mJ without SBS. The output pulse energy has very good stability: the fluctuation is ~2% over several hours. The amplified pulse width is about 105 ns, and the pulse shape is still Gaussian-like. Figure 3(b) shows the output peak power from the second power amplifier stage at different pump powers at 975 nm based on the measured pulse energies pulse widths. It is worth noting that the highest peak power can reach 1.2 kW for 105 ns pulses with a repetition rate of 8 kHz. However, the optical conversion efficiency (1.37%) is lower than that (~10%) of commercial fiber [1,2]. In this Letter, we used the large cladding size in order to get a safe and stable monolithic fiber laser system, especially for the high

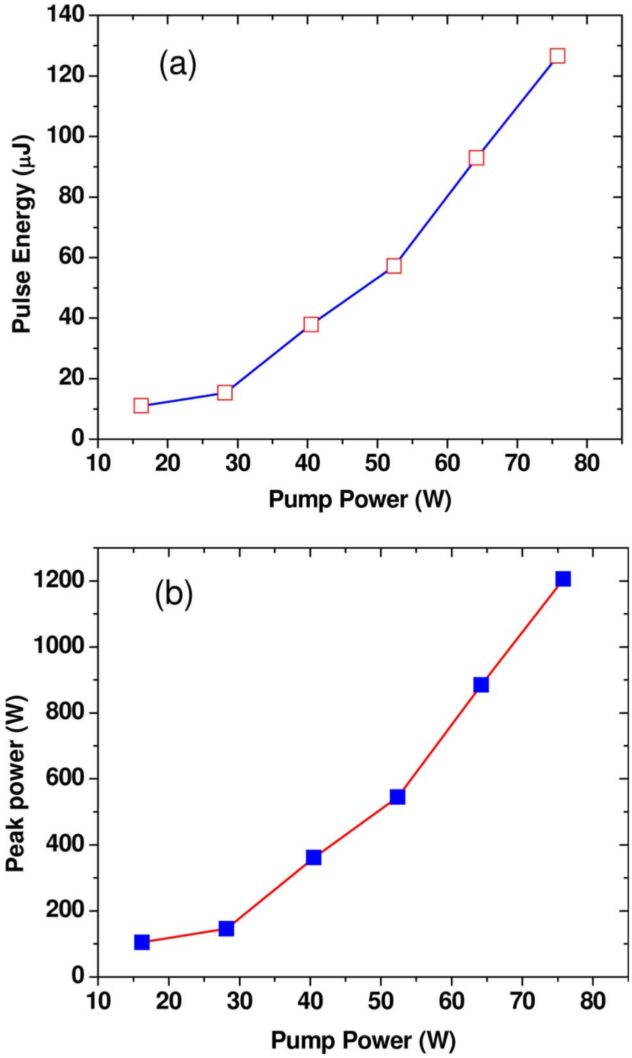

Fig. 3. (Color online) (a) Output pulse energy of the second power fiber amplifier at different pump powers at 975 nm and (b) output peak power of the second power fiber amplifier at different pump powers at 975 nm when the repetition rate is 8 kHz.

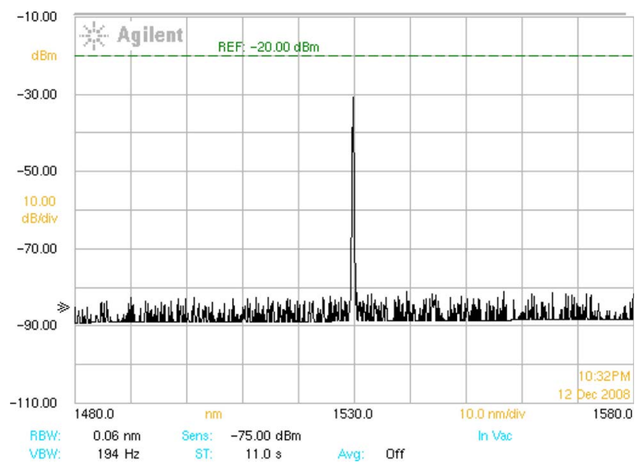

Fig. 4. (Color online) Spectral trace of 0.126 mJ pulses with 105 ns duration at 8 kHz repetition rate using an optical spectrum analyzer with a resolution of 0.06 nm.

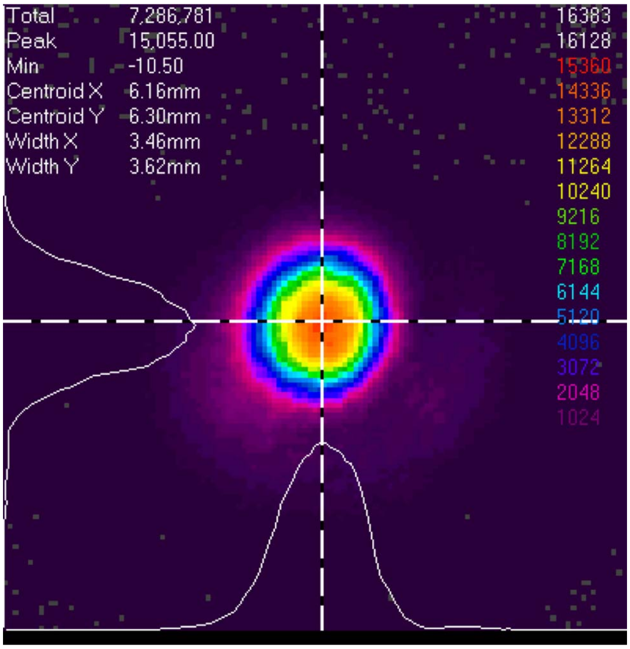

Fig. 5. (Color online) Image of the pulsed fiber laser beam profile displayed in 2D view.

power handling of the fiber fusion splicing joint. Therefore, the low core and cladding ratio of 25/400 is the main reason for the low efficiency.

The spectral trace for 0.126 mJ pulses with 105 ns duration at 8 kHz repetition rate was measured by using an optical spectrum analyzer with a resolution of 0.06 nm, shown in Fig. 4. It is evident that these amplified SM pulses have a signal-to-noise ratio of ~50 dB. Figure 5 shows the beam profile image of the fiber laser pulses with 0.126 mJ per pulse, which indicates the fiber laser pulses have near-diffraction-limited beam quality. The measured M^2 value is in the range of 1.2–1.4 for the different final output pulse energy levels in Fig. 3(a) in both the vertical and the horizontal directions, obtained by scanning the beam size around the waist position and far-field diameters of the focused propagation beam. Temperature and stress inside the active fiber, and seed launching at the splicing joint, can affect the beam quality, which can be further improved by optimizing the fusion splicing and decreasing the temperature inside the 25 μm core phosphate fiber. The transform-limited linewidth for the amplified fiber pulses were verified by using a scanning Fabry–Perot interferometer [3].

In conclusion, we have implemented a monolithic pulsed fiber laser system based on MOPA configuration with a pulse width of hundreds of nanoseconds, Gaussian-like pulse shape, and transform-limited linewidth, which can be operated in the C band. A newly developed SM PM LC-EYPhF 25/400 was used in the second power amplifier stage. We have achieved the highest peak power of 1.2 kW for 105 ns pulses at 1530 nm with a transform-limited linewidth, and the corresponding pulse energy is about 0.126 mJ, which is the highest value for the monolithic fiber laser pulses with transform-limited linewidth.

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