73 nJ, 109 fs Yb-doped fiber laser at 19 MHz repetition rate in amplifier similariton regime

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We report femtosecond pulse generation in an amplifier similariton oscillator and a prechirped fiber amplifier system. The final output power is 1.4 W, and the fundamental repetition rate is 19.1 MHz after a single state fiber amplifier. The pulsewidth is 109 fs.

OCIS codes: (320.7090) Ultrafast lasers; (140.3510) Lasers, fiber; (140.4480) Optical amplifiers.

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1. INTRODUCTION

Femtosecond pulses with pulse energy of tens of nanojoules or higher have lots of amplifications in the waveguide writing, biological material processing, and imaging. There have been many solid-state lasers available to fit those applications [1–3]. Recent developments have enabled fiber lasers to deliver high pulse energy or short pulse duration with passive cooling, maintenance-free operation, and lower cost compared with solid-state lasers. A mode-locking regime exploiting self-similar pulse propagation has been demonstrated, and these lasers generate sub-100-fs pulses with less than 20 nJ of energy at repetition rates of more than 30 MHz [4–6]. High pulse energy will rely on the lower repetition rate dissipative soliton mode locking with a 31 nJ pulse before compression to 80 fs from a dissipative soliton fiber laser at 70 MHz repetition rate with the double-clad Yb:fiber that was reported in [7].

For the application such as the newest flap-making in cornear LASIK operations, a pulse energy of >50 nJ at a pulsewidth <200 fs is required. For higher pulse energy, one would have to reduce the pulse repetition rate so as to maintain low average power and to avoid thermal damaging. If not enough, a pulse amplifier has to be applied for a higher pulse peak power [8]. However, in the fiber amplifier, one must cure the high-order dispersion problem in the pulse compression.

Building a fiber laser at a repetition rate below 20 MHz is not easy, because a long fiber cavity is difficult in mode locking starting with nonlinear polarization evolution (NPE) [9,10]. In terms of the amplifier, it is also difficult to maintain the pulse shape with low high-order dispersion, so that the output pulsewidth is short and clean for maintaining the high peak power of the pulses. The other problem is long-term stability. Low repetition rate fiber lasers contain very long fibers. The environmental perturbation induced birefringence can ruin the mode-locking condition in NPE mode locking.

In this paper, we demonstrate 73 nJ, 109 fs pulse generation at a repetition rate of 19 MHz with a single stage fiber amplifier. The optimized prechirp and dechirp interplay with the fiber nonlinearity makes the pulse clean without side lobes. The long-term stability is improved by employing long polarization-maintaining (PM) fibers in the cavity.

2. EXPERIMENTS SETUP AND ANALYSIS

The schematic of the laser oscillator and the amplifier is shown in Fig. 1. The fiber laser cavity was 10.6 m long including a 5.4 m 10/125 μm PM single-mode fiber (SMF), a 4.4 m 10/125 μm Yb-doped double-cladding gain fiber (3.9 dB/m), a 0.4 m 10/125 μm SMF, and 0.4 m free space. The pulse shaping mechanism was the amplifier similariton due to the long gain fiber and all normal dispersion. The PM fiber takes more than half of the fiber length in the cavity to reduce the laser susceptibility to the ambient environment to improve the environmental stability and obtain a stable narrow spectrum with a sharper edge [11]. The remaining SMF was kept for NPE mode locking. Two half waveplates, two polarization beam splitters (PBSs), and a Farady rotator (FR) were employed to build a free-space isolator to ensure unidirectional operation.

To operate the laser in amplifier similariton [12–17], a spectral filter has to be employed. The spectral filter was a double-pass through a single transmission grating (1000 lines/mm) and the limited aperture of the collimator (0.85 mm). The double-pass through the grating was for enlarging spectrum spreading spatially so that the filtering bandwidth was narrow enough to shape the spectrum. The spectral width of the filter was measured to be about 0.47 nm. Then the light was coupled into the PM fiber. The output from the PM fiber was spatially coupled with the SMF and the gain fiber with a waveplate in between. The rest of the cavity is the same as a standard fiber laser for NPE mode locking. To avoid excessive intra-cavity pulse power leading to pulse splitting, an additional half-waveplate and a PBS were inserted into the cavity for controlling the intra-cavity power. This power control is independent of the NPE setup.

The fiber laser was pumped by a multimode fiber coupled high-power laser diode. The mode locking was started by the standard NPE, which was realized by rotating waveplates. The strong spectral filtering compresses the pulse duration by cutting off the spectral bandwidth [18,19] and improves the

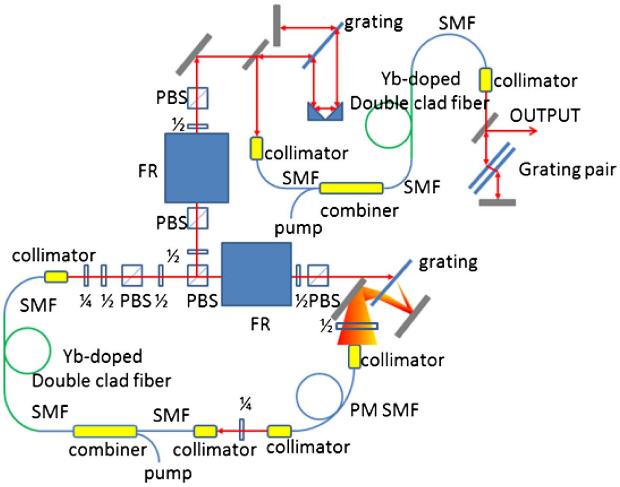

Fig. 1. Schematic of the Yb-doped fiber laser.

stability of the laser by attenuating the low-amplitude wings that can grow over the fiber cavity [20].

Under a pump power of 3 W, the output power of the mode-locked fiber laser was 320 mW at the repetition rate of 19.1 MHz. The corresponding pulse energy was 16 nJ.

The output power as a function of the pump power is plotted in Fig. 2. The mode-locking threshold was 1.4 W and was self-starting. As the pump power was increased to more than 3 W, the pulse started to be unstable, even with the intra-cavity power controller. The average output power of the oscillator can reach 1 W when the pump power is increased to more than 7 W; however, the pulse was very easy to break up. Therefore we maintain the pulse energy to less than 16 nJ.

The pulse spectrum in linear scale is shown in Fig. 3(a) and is a typical amplifier similariton. The intensity autocorrelation trace shown in Fig. 3(b) of the output pulse was 4.6 ps and was highly chirped. The FWHM of the linear spectrum output from the mode-locked laser was 7 nm. The time–bandwidth product was 9.66.

To boost the pulse energy, a fiber amplifier has to be employed. In the amplifier, a 1.8 m long 10/130 μm Yb-doped double-clad gain fiber was chosen and was pumped through a high-power beam combiner (105/125 μm pigtail for the 980 nm multimode pump, 10/130 μm pigtail for signal fiber).

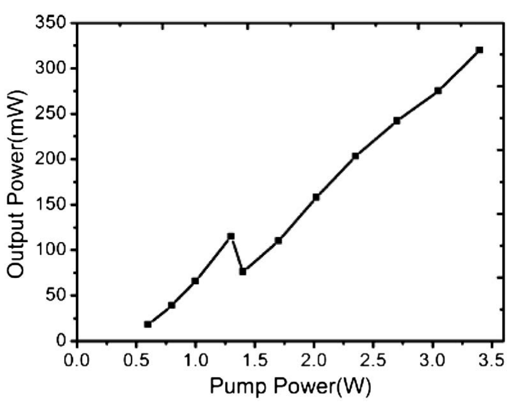

Fig. 2. Output power of the fiber laser oscillator as the pump power. The mode-locking threshold is 1.4 W.

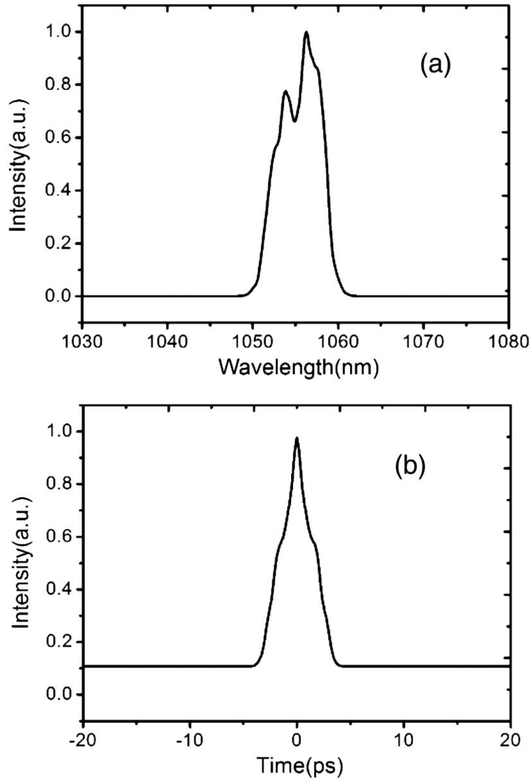

Fig. 3. (a) Linear spectrum of the output pulse from the mode-locked laser. (b) Measured density autocorrelation trace of pulses from the mode-locked fiber laser.

The input and output of the fiber amplifier were all spliced with collimators (50 cm working distance).

To obtain a near-transform-limited pulse we must counteract against the high-order dispersion induced side lobes in the pulse. It is known that the interplay between self-phase modulation (SPM) and dispersion can remove the side lobes caused by the third-order dispersion acquired in the fiber and the grating pair [21]. Therefore we employed two grating pairs that offer negative chirp to the pulse.

The prechirp was made by a single grating (1000 lines/mm) in a round-trip configuration, to form a grating pair that offers anomalous dispersion. After the amplification, the pulses were compressed by a grating pair with a grating groove density of 1000 lines/mm.

The distance of the first grating pair for the prechirp was initially designed for setting the zero-chirp right at the middle of the gain fiber. Before this point, the pulse was gradually narrowing with a spectrum compression due to the SPM with a negatively chirped pulse. After that the pulse experiences both spectrum and pulse broadening due to the SPM and the positive dispersion in the fiber. Then the output pulse with is positively chirped. The second grating pair was employed to remove this chirp and compress the pulse.

Both the prechirp and dechirp grating pairs have a grating groove density of 1000 lines/mm. The grating distances were optimized when watching the pulse autocorrelation trace until the side lobes disappeared.

The output power of the amplifier is presented in Fig. 4. The maximum average power was 2.2 W under the pump power of 8.5 W. After the compressor, the power was reduced to 1.4 W corresponding one pulse energy of 73 nJ.

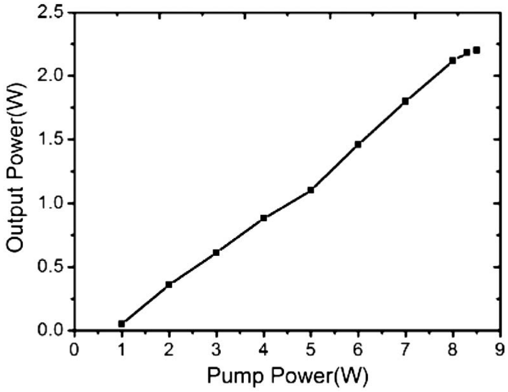

Fig. 4. Output power of the fiber laser amplifier as the pump power.

The output pulse spectrum is shown in Fig. 5(a). It appears highly modulated, showing that strong SPM indeed occurred inside the gain fiber. The FWHM of the spectrum was 14 nm.

The shortest pulse was obtained by optimizing the grating distances of both grating pairs. The autocorrelation of the best compressed pulse is illuminated in Fig. 5(b) and was deconvoluted to be 109 fs. It can be seen that the pulse profile was clean without side lobes. The grating slant distances of the prechirp and the compressor in this case were 72 and 7 mm, respectively.

The laser and the amplifier sustain for more than a week in an open-air environment without interruption, due to the PM fiber. A clean pulse has been applied for drilling holes inside the glass, demonstrating the capability of this laser amplifier.

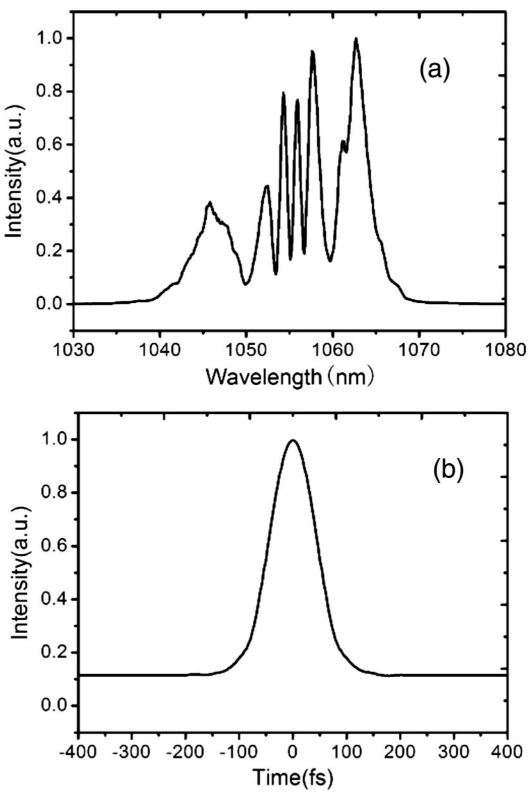

Fig. 5. (a) Linear spectrum of final output laser. (b) Measured density autocorrelation trace of the final output laser.

3. CONCLUSIONS

In conclusion, we have developed a 19 MHz amplifier similariton ring cavity fiber laser that delivers an output of 340 mW. Employing the PM fiber and the spectral filter ensures that the laser works stably against environment perturbations. The pulses were amplified in a double-cladding fiber amplifier. The pulse was negative chirped before being seeded into the amplifier and compressed after amplification. The final compressed pulse was 109 fs at a pulse energy of 73 nJ. The high pulse energy and the clean pulse demonstrated that the system qualified for precision processing of bio-materials.

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