Ultra-short pulsed ytterbium-doped fiber laser and amplifier

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This paper investigates a high power all fiber ultrashort pulse laser system. This system consists of a mode-locking laser oscillator, a multi-stage amplifier, a pulse selector, and a paired grating pulse compressor. With pulse energy of 12 μJ at repetition rate of 30 kHz, the laser at center wavelength of 1.05 μm was obtained. Pulse width of 525 fs was achieved after the grating pair compressor.

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Laser systems based on fiber lasers and amplifiers are attractive due to their compact, robust, and reliable system compared with conventional solid-state lasers. In addition, good beam quality and high stability can be achieved in all-fiber laser from the combination of beam confinement and the excellent heat dissipation that is due to the large ratio of surface area to active volume. High efficiencies and high output powers are readily achieved with few thermo-optical problems, which make additional external cooling unnecessary. Ytterbium-doped fibers provide a number of attractive features, including a broad-gain bandwidth and a high efficiency. The generation of about 50-fs pulse from ytterbium-doped fiber lasers has been demonstrated[1,2]. However, energy from an oscillator is as low as nano-joule or pico-joule. A number of scientific and industrial applications such as ultrafast phenomena research and nonlinear optical research rely on high power short pulse laser system. It is necessary to amplify low energy pulse to micro-joule, even milli-joule. However, amplification of ultrashort laser in single-mode fibers is restricted by nonlinear effects, mainly self-phase modulation (SPM), stimulated Raman scattering, and nonlinear damaging. This limitation can be overcome by sufficient pulse stretching in the time domain and the enlargement of the mode-field diameter of the fiber to reduce the peak power intensity. Ytterbium-doped fiber lasers and amplifiers have been the focus of considerable research[3−11]. The generation of 650-fs pulses with a pulse energy of 100 μJ from an ytterbium-doped fiber chirped pulse amplification (CPA) system has been obtained[11].

In this paper, we experimentally study a self-starting mode-locked figure-eight fiber laser and fiber-based CPA system without stretcher, delivering pulse energies as high as 12 μJ at repetition rate of 30 kHz. The compression of these pulses down to 525 fs is achieved by using a paired diffraction grating compressor.

The experimental setup of our fiber-based CPA system is shown in Fig. 1, which consists of a diode-pumped passively mode-locked figure-eight fiber laser, three single-mode ytterbium-doped fiber preamplifiers, a pulse selector, two ytterbium-doped fiber power amplifiers (YDFAs) and a paired diffraction grating compressor.

The pump source of the fiber laser is a fiber-coupled single mode diode laser operating at the wavelength of 976 nm, which delivers a maximum power of 300 mW. Pump light is coupled into the optical loop through a 976 nm/1050 nm wavelength division multiplexer (WDM). The length of ytterbium-doped fiber (numerical aperture (NA) of 0.18, core diameter of 3.8 μm) is 4 m. The polarization insensitive isolator ensures a unidirectional operation cavity. Coupler 1 is the output coupler of the laser. The configuration of the nonlinear optical loop mirror (NOLM) is similar to that in Refs. [12,13] with some difference. In our fiber laser, the combination of coupler 2 (coupling ratio is 50:50) and coupler 3 (coupling ratio is 97:3) acts as the asymmetric couple. Power of 97% after the coupler 3 goes into the cavity. The length of the single-mode fiber (SMF) is 40 m. The operation of the mode-locked figure-eight fiber laser relies on the different phase shifts between counter-propagating pulses in the loop. A single input is split into two counter-propagating pulses with different intensities. When the two pulses propagate in the loop, they have different phase shifts induced by SPM. Finally, they recombine at the coupler 2 synchronously. The NOLM acts as a fast saturable absorber. The buildup of pulses

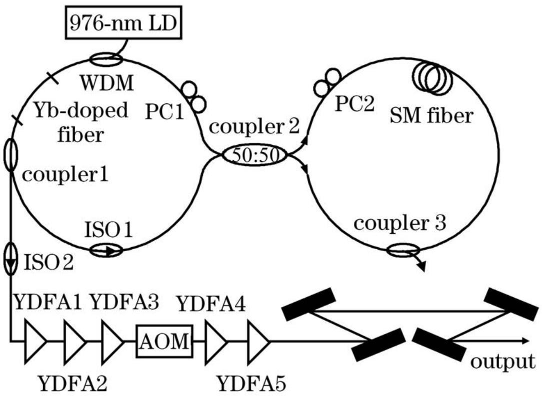

Fig. 1. Experimental setup of the fiber-based CPA system.

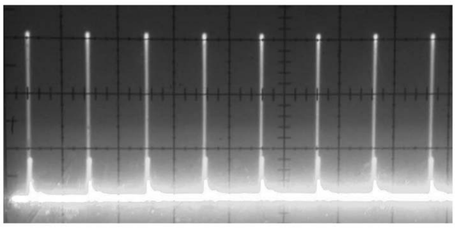

Fig. 2. Output pulse train signal in the time domain.

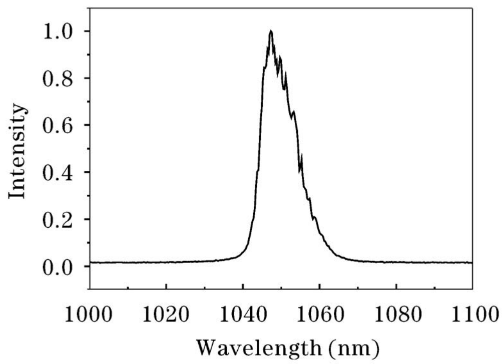

Fig. 3. Spectrum of the fiber laser.

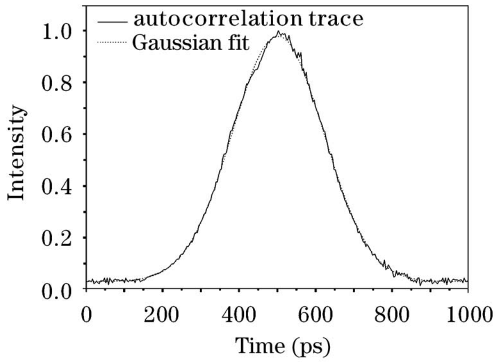

Fig. 4. Autocorrelation trace of seed pulses.

comes from noise. The phenomena of self-pulse appear when the pump power is 250 mW. If we select a most suitable coupling ratio of coupler 3 and the positions of polarization controllers (PC1 and PC2), the laser will be much easy self-starting. When the pump power exceeded 280 mW, the fiber laser operated with a stable mode-locked state. The output pulse train signals are shown in Fig. 2. The multiple pulse and Q-switching are observed when adjusting the PC1 and PC2. The laser generates an average power of 2 mW, 205-ps pulse with a repetition rate of 3.9 MHz, and a center wavelength of 1.05 μm. The spectrum of the fiber laser is shown in Fig. 3. And Fig. 4 shows the autocorrelation trace of the seed pulse. The spectrum bandwidth is about 10 nm and the pulse width is 205 ps. So the pulses are non-Fourier transform limited and have strong chirp come from the passively mode-locked figure-eight fiber laser. Because all of the fibers in the fiber laser are positive dispersion at 1.05 μm. Therefore, there is no stretcher in our system.

After the isolator (ISO2), about 0.25-nJ pulse energy is coupled into the preamplifiers. The first and second preamplifiers are constructed with single mode ytterbium-doped fibers of 3.5- and 4-m lengths. The absorption coefficient of the fiber is 35.8 dB/m at 976 nm. The core diameter is 3.8 μm with NA of 0.18, and the cut-off wavelength is 900 nm. The third preamplifier is constructed with single mode ytterbium-doped fiber of 1.5-m length and an absorption coefficient of 208 dB/m at 976 nm. The core diameter is 4.2 μm with NA of 0.16, and the cut-off wavelength is 900 nm. All of the preamplifiers are pumped by fiber-coupled single-mode of 250 mW diode lasers operating at the wavelength of 976 nm. The pump beams are injected into the ytterbium-doped fiber through 976 nm/1050 nm WDM. After the third preamplifier, the pulse energy is increased to 41 nJ, corresponding to a gain of 22 dB.

In order to increase the pulse energy, the repetition rate of the amplified pulses needs to be reduced. Here, we adjust the repetition rate to 30 kHz by using a fiber-coupled acousto-optic modulator (AOM). The AOM efficiency is about 19%, therefore, the pre-amplified pulses energy is reduced to 7.7 nJ. Then the pulses are coupled into the power amplifiers. The power amplifiers utilize a two-stage architecture. Each amplifier stage uses an efficient ytterbium-doped double-clad fiber pumped by the light of a broad stripe laser diode. Efficient laser to fiber coupling is achieved via V-groove side pumping technology. The pump powers of the two-stage amplifier are 1 and 5 W, respectively. 0.4-m-long ytterbium-doped double-clad fiber is used in the first stage and 1-m-long fiber is used in the second stage. The core diameter is 20 μm with NA of 0.14 and the clad diameter is 250 μm with NA of 0.4. Figure 5 shows the output power as a function of the pump current of the second power amplifier.

After the power amplifiers, the pulse energy has been amplified to 12 μJ corresponding to a gain of 31 dB with a pulse width of 211 ps. The output signal is close to a circular polarized light. The amplified pulses spectrum is shown in Fig. 6. The broadened spectrum of the amplified pulses should be come from the self-phase modulation.

The amplified pulses are compressed by a paired diffraction grating compressor whose structure is shown in Fig. 1. Four 1800-line/mm gratings are used in a quasi-littrow configuration. Best compression is found at a grating separation of 13 cm and the compressed pulses are characterized by using non-collinear autocorrelation function curve. Figure 7 shows the autocorrelation trace

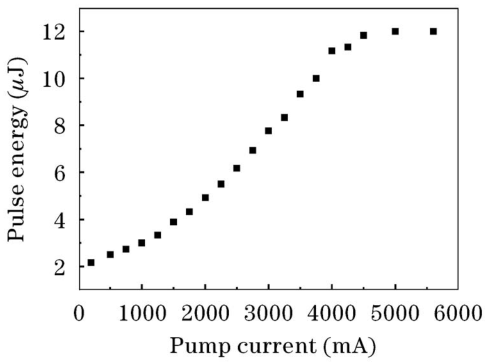

Fig. 5. Output pulse energy versus pump current of the second power amplifier.

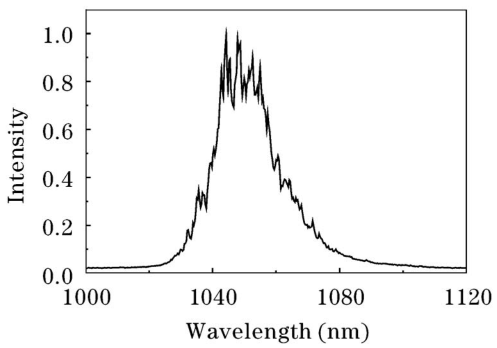

Fig. 6. Spectrum of the amplified pulses.

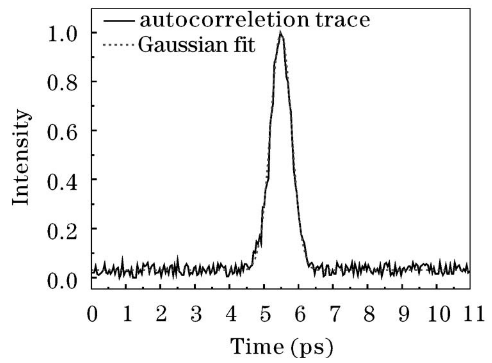

Fig. 7. Autocorrelation trace of compressed pulses.

of the compressed pulses. The full-width at half maximum (FWHM) of the pulse is 525 fs with assumption of a Gaussian shape. The efficiency of the compressor is about 40.8 %. And the compressed pulse energy is 4.9 μJ. The pulse width is limited due to third order dispersion effects of the fiber laser and fiber amplifiers which can not be compensated by a grating compressor, because the third order dispersions of both grating compressor and fiber are positive.

In conclusion, we have demonstrated a stable picosecond pulsed ytterbium-doped passively mode-locked figure-eight fiber laser and fiber-based CPA system without stretcher. The amplified pulse energy is as high as 12 μJ at repetition rate of 30 kHz. The pulses are compressed to 525 fs with the peak power about 9.3 MW by using a paired diffraction grating compressor. Compressed pulse width is limited by third-order dispersion effects of the fiber and grating compressor.

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