1-kHz high efficiency Ti:sapphire laser amplifier

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We describe a Ti:sapphire multi-pass amplifier with high efficiency at the repetition rate of 1 kHz. In the amplifier, the incident pulse is 0.66 mJ with the pulse duration about 90 ps. The incident pulse is amplified to 7.2 mJ when the pump energy is 23 mJ. The energy efficiency in the amplifier is nearly 30% with extracting efficiency larger than 40% when considering about 25% static reflecting loss in the amplifier. After compressed in the compressor, 5.4-mJ, 36-fs pulses with peak power larger than 0.1 TW are obtained.

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In the past decade, high intensity ultrashort laser generation witnessed great development due to many applications in X-ray laser, plasma physics and attosecond pulse generation[1,2]. By using chirped pulse amplification technology[3], pulses with peak power of 0.85 PW and 10-Hz repetition frequency have been obtained in the laboratory[4]. In many research regions, such as high harmonic generation, ultrashort surface physics, femtosecond laser micro-machining, the laser pulse with high repetition frequency and high average power is more important. By using liquid-nitrogen-cooled Ti:sapphire crystal, Backus *et al.*[5] obtained 6.7-mJ amplified pulses at 1 kHz repetition frequency with 0.7-W inject pulses and 26.5-W pump pulses. Very recently, Seres *et al.*[6] got 3.8-mJ amplified pulses with 0.5-mJ inject pulses and 25-W pump pulses at 1-kHz repetition frequency. In the system, the Ti:sapphire crystal was cooled by using a closed-loop cryostat and the pulse was compressed to 10 fs. We design an amplification system with a high extractive efficiency through optimizing the optical structure and cooling the crystal through a cryostat. In the amplifier, the energy of the incident pulse is 0.66 mJ. The energy of the incident pulse is amplified to 7.2 mJ when the pump energy is 23 mJ. The energy efficiency in the amplifier is nearly 30%, and the extractive efficiency exceeds 40% when considering about 30% static reflecting loss in the amplifier.

The laser system setup is shown in Fig. 1. The front part of the laser system is a commercial laser system (Spitefire50fs, Spectra_Physics Company). The seed pulse with 35-fs pulse duration and about 35-nm spectral bandwidth is generated from a Ti:sapphire oscillator. The seed pulse is expanded to about 90 ps after passing through an acousto-optic programmable dispersive filter (AOPDF) and a stretcher. After amplified in the regenerative amplifier, the laser pulse earns energy about 1mJ at the repetition frequency of 1 kHz. The laser beam is injected to the four passes amplifier after beam diameter is demagnified. And then the output amplified pulse is compressed through a grating based compressor to obtain a femtosecond pulse.

The pump laser used in the multi-pass amplifier is a commerical double frequency Nd:YLF laser pumped by lamp (Falcon-527-40-M, Quantronix). The wavelength of the pump pulse is 527 nm with the repetition frequency of 1 kHz. The maxium pulse energy of the pump laser is 25 mJ with the energy stability about 2%. The pump beam is focused onto a Brewster-cut Ti:sapphire crystal with a composed lens pair. The crystal is $\Phi 10\times 12$ (mm) with about 90% single pass absorption. The residual pump laser is refocused onto the crystal by a concave reflect mirror. The diameter of the pump beam in the crystal is about 1.3 mm. The Ti:sapphire crystal is fixed in a red copper frame. There is a 0.1-mm-thick indium slice between the crystal and the frame to improve the thermo conductivity. A low temperature sensor is attached to the crystal to monitor its temperature. The red copper frame is fixed on the cooling head of a closed-loop cryostat (IGC Polycold Systems Inc, Cryotiger-PT30). The crystal is cooled to about 142 K with temperature offset less than 0.2 K, which dramatically improves thermal conductivity and decreases the temperature coefficient of the refractive index of the sapphire crystal[5−8]. To avoid vapor condensing on the surface of the crystal, the crystal is located in a vacuum cell which is pumped by a vacuum pumping system (Varian Inc.). The vacuum cell has Brewster-angle windows for the entry and exit beam.

There are two confocal concave reflecting mirrors M1, M2 and a large plan reflecting mirror M3 in the multi-amplifier. The angle at the concave is about 12°, which can compensate the astigmatism of the Brewster-cut crystal[9]. In the amplifier, the radii of curvature of M1 and M2 are 1400 and 1200 mm, respectively. The beam

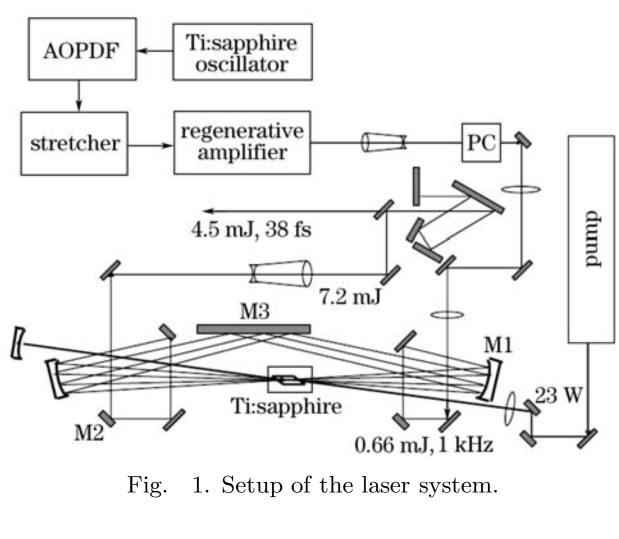

Fig. 1. Setup of the laser system.

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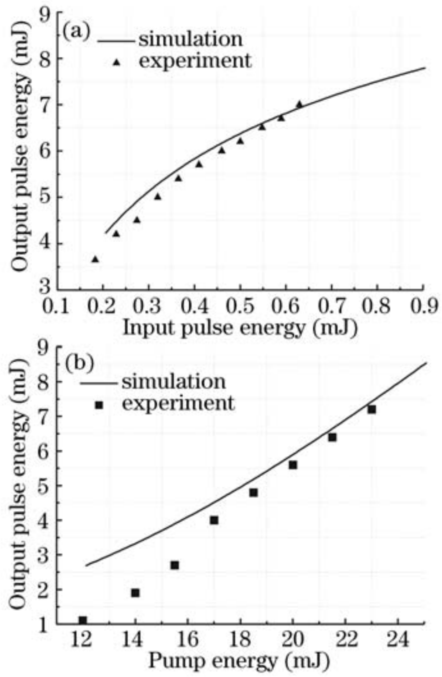

Fig. 2. Energy of the amplified pulse increases with the energy of the (a) seed pulse and (b) pump pulse.

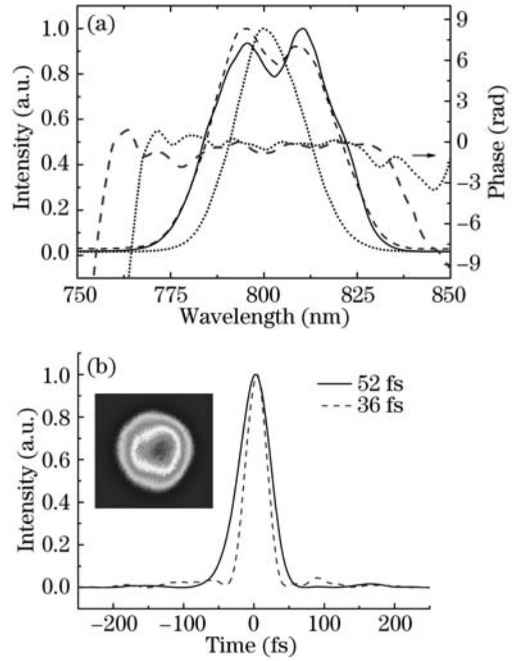

Fig. 3. (a) Spectra and spectral phase of the amplified pulse; (b) spatial and temporal profiles of the amplified pulse.

cross-section get smaller after M1 and get larger in the Ti:sapphire as the amplifier pass increases. This structure solves the problem of gain saturation in the design that M1 and M2 have equal curvature radii as the amplifier pass increases. Then the energy extractive efficiency in the amplifier is improved with this unsymmetrical structure. In the amplifier, the incident pulse is 0.66 mJ with the pulse duration about 90 ps. The incident pulse is amplified to 7.2 mJ when the pump energy is 23 mJ. The energy efficiency in the amplifier is nearly 25% and the extractive efficiency is larger than 40% when the about 30% static reflection loss in the amplifier is considered. The diameter of the amplified laser is expanded to about 12 mm then the pulse is the grating based compressor. At first, we used a grating with 1500 ln/mm in the compressor and obtained compressed pulses with 4.5 mJ, 38 fs[10]. Recently, we replace the 1500 ln/mm grating with a 1480 ln/mm grating (Jobin Yvon). The mismatch grating[11] groove between stretcher and compressor can compensate the second and third order dispersion very well. In the system, we also use the AOPDF to compensate the high order dispersion at the beginning.

We numerically simulate the energy changes of the amplified pulse with the energy of the pump and seed pulse. Figure 2(a) shows the energy of the amplified pulse evolves with the input pulse energy. The gain saturation is retarded due to the asymmetric concave design. Figure 2(b) shows the energy changes of the output pulse with the increase of the pump energy when the input pulse energy is 0.66 mJ. The experimental result is far lower than the simulation because the pulses time delay between the pump pulse and the seed pulse is not the best when the pump energy is low. As can be seen from Fig. 2 that we can boost the energy of the amplified pulse to larger than 8 mJ with larger pump and input pulse energy. After the compressor, we obtain an about 5.4 mJ compressed femtosecond pulse with 75% efficiency in compressor.

In the regenerative amplifier, the spectrum of the pulse is dramatically narrowed due to repetitious passing through the crystal[12]. In our system, we use an AOPDF before the stretcher to modulate the spectrum of the seed pulse. The spectrum of the seed pulse after the AOPDF has a saddle shape which can precompensate the gain narrowing effect. The spectral width of the pulse after the regenerative amplifier is narrowed from 35 to 22 nm, as shown in Fig. 3(a) with dot line. And the pulse duration after multi-amplifier and compressor is 52 fs (Fig. 3(b) solid line). When we add modulation on the seed pulse by using AOPDF, the spectral width of the amplified pulse is about 36 nm which is shown in Fig. 3(a) with short dash line. After compressed in the compressor, a 38-fs compressed femtosecond pulse is obtained (Fig. 3(b) dash line). In the experiment, the pulse duration and spectral phase are measured by using spectral phase interferometry for direct electric-field reconstruction (SPIDER). The spectrum of the pulse is measured by using a fiber spectrometer of Ocean-Optics Inc. And we also measure the spatial model of the laser beam by using a CCD (LBA-300PC). Figure 3(b) shows the beam has great spatial quality. By using a 1.5-m lens, we obtained the Guassian profile beam diameter at the focus as about 170 μm.

In conclusion, we successfully set up a high efficiency multi-pass Ti:sapphire amplifier at the repetition of 1 kHz. By optimizing the optical design, we obtain a 7.2 mJ amplified pulse at 23 mJ pump and 0.66 mJ input. The energy efficiency in the amplifier is nearly 30% with extractive efficiency larger than 40% when the about 25% static reflecting loss in the amplifier is considered. After compression, we obtained a femtosecond intense laser pulse at 1 kHz, 36 fs, and 5.4 mJ with peak power higher than 0.1 TW. After compressed by using hole-fiber or filamentation in Argon filled cell, we expected to obtain laser pulse with pulse duration shorter than 10 fs and pulse energy larger than 1 mJ. With the use of the carrier-envelope phase stable oscillator, we expect to obtain carrier-envelope phase stablized amplified pulse in the near future. The laser system offers an efficient tool for high order harmonic generation and other ultrashort intense laser physics.

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