High-contrast 1.16 PW Ti:sapphire laser system combined with a doubled chirped-pulse amplification scheme and a femtosecond optical-parametric amplifier

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Based on a combined scheme of doubled chirped-pulse amplification and a femtosecond noncollinear optical-parametric amplifier, a high-contrast femtosecond laser pulse with energy of up to 32.3 J has been generated by improving the gain efficiency and boosting the pump energy to 120 J in the final amplifier. Our measurements show that the contrast ratio of the main laser pulse is around 10^{10} within the time scale of –400 ps and the duration of compressed pulse is 27.9 fs, corresponding to a peak power of 1.16 PW.

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The progress of chirped-pulse amplification (CPA) technology [1] provides great opportunities to study laser–matter interactions with on-target intensity exceeding 10^{22} W/cm^2 in the relativistic regimes [2]. The first petawatt (PW) laser was based on a hybrid Ti:sapphire–Nd:glass laser system [3]. Since then, significant efforts have been made to pursue even higher peak power. To date, several PW-class laser systems have been developed, with Ti:sapphire as the gain medium, to offer the benefits of compact size, short pulse, and high repetition rate [4–6]. With the rising interest of researchers for high-intensity lasers, the Extreme Light Infrastructure, one of Europe's most ambitious scientific projects, is planning to deliver 200 PW peak power based on a Ti:sapphire laser system [7]. To perform the laser–matter interaction experiments at such an intense level, the contrast is required to be as high as 10^{10} to prevent preplasma dynamics. Several pulse-cleaning techniques have been developed. For example, contrasts as high as 10^{10} to 10^{11} have been achieved with cross-polarized wave generation [8], nonlinear polarization rotation, doubled CPA (DCPA) [9], and optical-parametric CPA [10–13]. Although those techniques are being continuously improved, they are still achieved mainly in a limited power level.

In this Letter, the recent progress on high-contrast PW laser pulse generation from our XL-III laser facility with a DCPA scheme is presented. By replacing the previous regenerative amplifier with a new CPA system and a femtosecond noncollinear optical-parametric amplifier (NOPA), the pulse contrast ratio is as high as 10^{10} between the main pulse, and amplified spontaneous emission is obtained in the time scales of 400 ps. The output energy from the final amplifier is boosted to 46.8 J under a pump energy of 120 J at 527 nm before the compressor by using a thicker Ti: sapphire crystal surrounded with special liquid material to decrease the parasitic lasing. Enlarging the amplified laser to diameter of 150 mm and then recompressing the pulse duration by a grating based compressor, the pulse duration as short as 27.9 fs was obtained and measured with a commercial frequency-resolved optical gating (FROG) device. Compressed pulse energy up to 32.3 J was observed with a transmission efficiency of 69%, corresponding to a peak power of 1.16 PW.

The schematic diagram of the system is shown in Fig. 1. A homemade mode-locked Ti:sapphire oscillator was used as the seeding source and stable sub-10-fs laser pulses with a broad spectrum were generated at repetition rate of 80 MHz, corresponding to a pulse energy of 4 nJ. A splitter with a bandwidth of about 200 nm was used to divide the laser beam into two parts with energies of 70% (~3 nJ) and 30% (~1 nJ). The 70% was used as the seed for the first CPA stage (CPA I), and the other 30% was used as the signal of the NOPA. In CPA I, the expanded pulse was amplified to 5 mJ by two multipass amplifiers, AMP-I1 and AMP-I2, with a pulse duration of ~50 fs. After CPA I, the amplified laser pulse was frequency doubled by two pieces of Type I β-BaB_2O_4 (BBO-I) crystals to generate second-harmonic pulses with energy of up to 500 μJ in each beam for pumping the two-stage NOPA [12]. The delay between the signal pulse and the pumping pulse of the NOPA was accurately controlled by a Herriott telescope, which consisted of a plane mirror and a concave mirror with a radius of curvature of 16 m. The distance between two mirrors was 1.2 m. The signal pulse traveled 12 round trips inside the telescope and the total optical path length was about 30 m. Because of the reflection loss, the energy of the signal pulse arriving at the first NOPA crystal was reduced to 750 pJ. Based on phase match calculation, a piece of

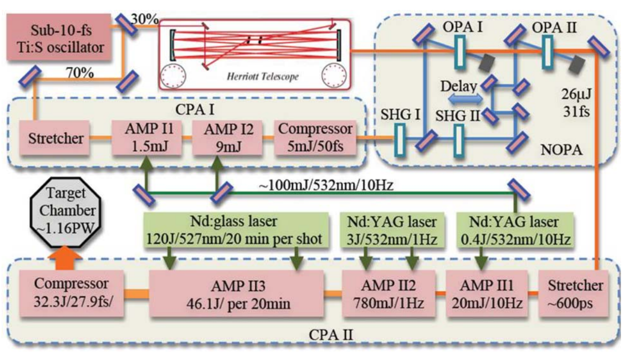

Fig. 1. (Color online) Schematic experimental setup of the DCPA.

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$10\,\mathrm{mm} \times 10\,\mathrm{mm} \times 3\,\mathrm{mm}$ BBO crystal cut for Type I phase matching ($\theta = 28.9°$, $\varphi = 0°$) was used to parametrically amplify the signal pulse in each NOPA stage. The spot sizes of signal and pump pulses were matched to 3 mm in the NOPA crystals and the internal noncollinear angle was 3.7°. After careful alignment, amplified signal energy of 26 μJ was obtained, corresponding to the total gain of 3.4×10^4 in the two-stage NOPA. Since the nonlinear process between the signal and the pump pulse occurs on a time scale of tens of femtoseconds in the NOPA system, the background noise beyond this time range cannot be amplified. Consequently, the improvement factor of the signal contrast is approximately equal to the gain.

In the second CPA stage (CPA II), the clean high-energy signal pulse was expanded by an Öffner-triplet stretcher to a width of about 600 ps. Our stretcher consisted of a single 1480 grooves/mm gold-coated grating, one concave spherical mirror ($R = 1000\,\mathrm{mm}$), and one convex spherical mirror ($R = -500\,\mathrm{mm}$). The incident angle on the grating was about 22.5° and the distance between the grating and the concave mirror was about 790 mm. Following the stretcher, the chirped pulses were boosted to energy of about 20 mJ after multipass amplifier AMP-II1, which was pumped by 150 mJ pulses of 532 nm at a 10 Hz repetition rate (Quantry PRO-170). Then the beam was enlarged to 12 mm for further amplification in the second stage amplifier, AMP-II2, which was pumped by a frequency-doubled Nd:YAG laser (Beamtech Inc.) at a 1 Hz repetition rate, with single pulse energy of 2.6 J at 532 nm. For better beam quality, two diffractive homogenizers (Silios Tech.) were installed into the beam lines of the pump laser. The transmission efficiency of the homogenizers was about 85%, and the beam size on the Ti:sapphire crystal was about 10 mm in diameter. Under the optimized alignment, amplified laser pulse with energy of about 780 mJ was obtained.

To increase the laser power to the PW class, we further boosted the energy by a multipass final amplifier, AMP-II3, which was pumped by a custom-designed frequency-doubled Nd:glass laser (Beamtech Inc.). The Nd:glass laser was designed with a dual-beam output of 65 mm in diameter, running at a repetition rate of 20 min per shot. Two homogenizers were used to improve the uniform of beam pattern in each laser path. The maximum second-harmonic generation energies were 50 and 70 J at 527 nm for each beam. The total available energy of 120 J supports a pump flux of $3.6\,\mathrm{J/cm^2}$. Before injecting the amplified chirped laser pulse into AMP-II3, the beam size was expanded to 65 mm to mode match the pump beam by a telescope system set in a vacuum chamber as an image delay. The Ti:sapphire disk used in the final amplifier had a size of $\Phi 80\,\mathrm{mm} \times 40\,\mathrm{mm}$ with antireflection coating on both surfaces. To eliminate parasitic lasing, the crystal was wrapped with an absorptive polymer thermoplastic (Cargille Laboratories, Inc.). Pumping the disk crystal with energy of 105 J, the output energy after five-pass amplification was around 46.8 J. In seven single-shot measurements, the maximum energy was 48.1 J and the minimum energy was 44.8 J, as shown in Fig. 2. This implies that the energy fluctuation shot to shot is about 1.5%. After optimized amplification, the output beam was enlarged to 150 mm by a vacuum image transferred

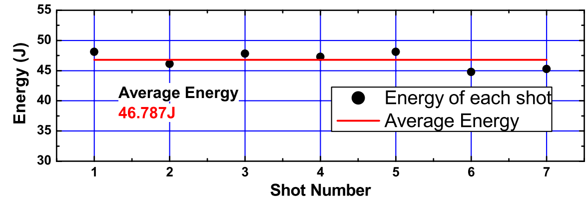

Fig. 2. (Color online) Measured output energies for 105 J pump energy in the booster amplifier. For the seven-shot measurements, the maximum energy was 48.1 J and the minimum energy was 44.8 J. The rms was about 1.5%.

tube and then sent into the compressor, which is consisted of four gold-coated holographic gratings (Jobin-Yvon Inc.) with grooves of 1480 lines/mm and a video FROG instrument (Femtosoft Tech. Model: GRENOUILLE USB-8-20) to diagnose the characteristics of the compressed pulse. According to the simulated results based on ray tracing analysis for compressor design [14], the amplified laser pulse was injected into the compressor at an incident angle of 20.5° onto the first grating. The distance between two gratings was set to about 390 mm. With fine adjustment for dispersion compensation, pulse duration as short as 27.9 fs was obtained after optimized compression. Figure 3(a) shows the spectrum of each stage amplifier. From the OPA amplifier, the spectral bandwidth is about 120 nm. After the 10 and 1 Hz amplifiers, the spectral bandwidth is decreased to about 60 nm because of the gain narrowing and the spectral bandwidth limitation of the stretcher. Figure 3 shows the typical FROG trace and the corresponding curves of pulse duration and spectrum. The measured transmission efficiency of the compressor was about 69%, indicating an average energy of 32.3 J for a compressed pulse, corresponding to a peak power of 1.16 PW. The contrast ratio was further measured by a third-order scanning cross correlator (Sequoia, Amplitude Technologies). Figure 4 shows that the contrast ratio is around 10^{10} within the time scale of −400 ps. The beam profile was measured with a commercial beam analyzer (Model M^2-200s-FW, Ophir-Spiricon Inc.). The beam size after the compressor was collimated to 20 mm and injected into the analyzer. Figure 5 shows the far-field beam

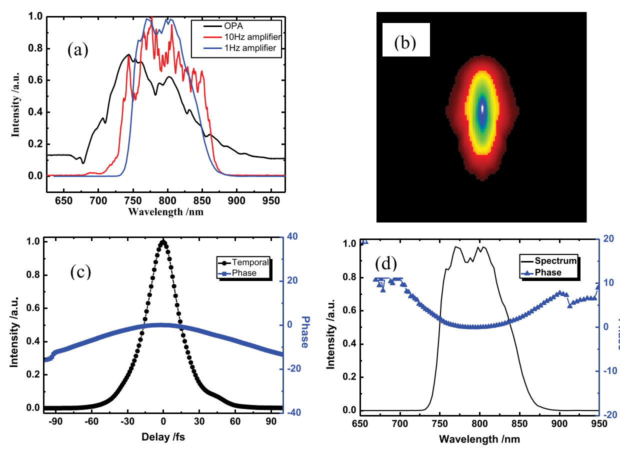

Fig. 3. (Color online) (a) Spectrum of each stage, (b) the trace of the FROG measurement, (c) the measured pulse duration, and (d) the spectrum of compressed pulse using the video FROG instrument.

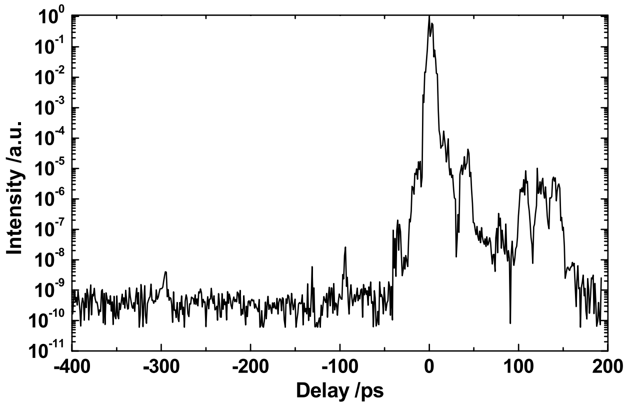

Fig. 4. Contrast ratio of the compressed pulse within the time scale from −400 to 200 ps.

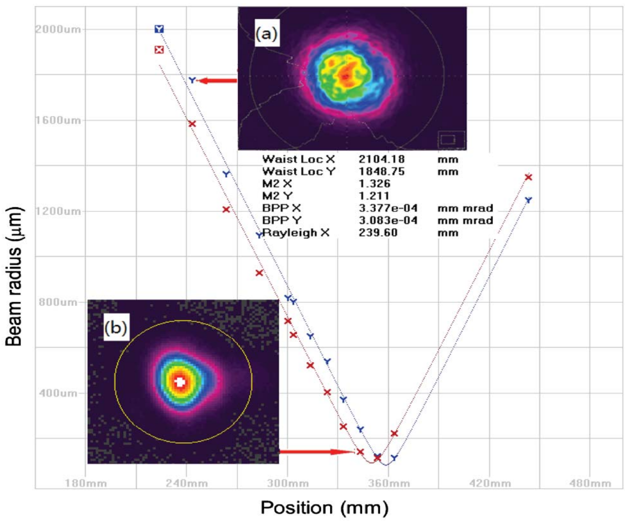

Fig. 5. (Color online) (a) Near-field and (b) far-field beam profiles and M^2 factor of the compressed pulse in the second CPA stage.

profile and M^2 factor of the compressed pulse in the second CPA stage. The calculated M^2 factors are $M_x^2 = 1.326$, $M_y^2 = 1.211$.

It is worth mentioning that this laser system has been used to perform an initial experiment of interaction with matter, and its effectiveness was proved by the brightness enhancement of $K\alpha$ x rays comparing to the conventional high-power Ti:sapphire laser, which will be reported in a separate paper on laser–matter interaction.

In conclusion, we have successfully demonstrated a DCPA scheme by using a contrast enhancement technique based on a femtosecond NOPA. Peak power of up to 1.16 PW and contrast ratio enhancement to 10^{10} are achieved, which represents the highest peak power and the best contrast ratio from a Ti:sapphire-based amplifier to date, to the best of our knowledge. Such a contrast ratio is sufficient for high-field experiments of plasma physics at an intensity level of 10^{22} W/cm^2. In addition, this NOPA scheme well overcomes the gain narrowing effect, and a broad bandwidth of up to 60 nm (FWHM) is obtained with recompressed pulse duration shorter than 30 fs. We believe that a DCPA with our NOPA design can be employed as a high-energy and high-contrast design for high-intensity Ti:sapphire- or Nd:glass-based CPA systems.

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