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Spectral shaping of an OPCPA preamplifier for a sub-20-fs multi-PW laser

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Abstract: We developed an OPCPA preamplifier with an actively shaped output spectrum to obtain a sub-20-fs-duration pulse for a 4-PW laser. The active spectral shaping was facilitated by controlling the temporal profile of a pump pulse in the OPCPA preamplifier. By optimizing the output spectrum of the OPCPA to compensate for the gain-depletion effect in the 4-PW laser, a final laser pulse with a broad spectrum of 101-nm in width (FWHM), resulting in a short pulse duration of 17 fs, was achieved.

1. Introduction

Ultra-high power lasers, based on the chirped-pulse amplification (CPA) technique [1], have been developed for the exploration of high-field science. Recently, femtosecond PW-level CPA lasers have been demonstrated [2–7] and applied to laser-driven acceleration of ions and electrons and to the generation of X-ray lasers [8–10]. At the Center for Relativistic Laser Science (CoReLS), a 20-fs, 4-PW Ti:sapphire laser was developed in 2017 for exploring relativistic laser-matter interactions. Currently, multi-PW lasers are being developed at several institutions around the world. At the Shanghai Institute of Optics and Fine Mechanics, development of a 5.4-PW laser with a pulse energy of 202.8 J and a pulse duration of 24 fs was reported, and a 10-PW laser facility is scheduled to be constructed [11]. The European Union has launched the Extreme Light Infrastructure program for the development of lasers with powers in the range 2–10 PW in Czech Republic, Hungary, and Romania [12]. The Apollon laser with a peak power of 10 PW has been under development in France [13]. When developing these multi-PW lasers, a short pulse duration is favorable for maximizing the peak power, and therefore spectral broadening, which is a prerequisite for reduction of the pulse duration, is being strongly pursued [7].

In general, spectral narrowing is induced by gain-narrowing and gain-depletion effects during the amplification process. Specifically, the strong gain-narrowing effect due to strong gain amplification in a multi-pass preamplifier induces strong spectral narrowing. However, the gain-narrowing effect can be suppressed in an optical parametric chirped-pulse amplification (OPCPA) amplifier, which supports a broadband gain through an optical parametric amplification process [14–18]. Thus, an OPCPA amplifier can be utilized as a high-gain preamplifier in multi-PW lasers to obtain a broad output spectrum [19].

In addition to the gain-narrowing effect, the gain-depletion effect should also be suppressed in multi-PW lasers to obtain a broad spectrum. By limiting the longer-wavelength components of the output spectrum of a front-end system, the gain-depletion effect in subsequent multi-pass amplifiers can be compensated. In practice, in the 4-PW laser at CoReLS, the output spectrum of the OPCPA preamplifier had been shaped by modulating the seed-pulse spectrum with an acousto-optic programmable dispersive filter (AOPDF) [7].

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However, the seed pulse suffered significant energy loss after passing through the AOPDF, resulting in an output energy decrease in the OPCPA preamplifier. Considering that a high-energy seed pulse in the OPCPA amplifier has the advantages of high temporal contrast and a high-energy output pulse [20], it is necessary to shape the output spectrum without energy loss of the seed pulse.

The spectral gain profile and conversion efficiency of an OPCPA amplifier depend on the temporal profile of the pump laser [21]. Pump pulses with Gaussian temporal profiles induce a higher amplification gain in the central wavelength range, resulting in a narrow spectral gain and low conversion efficiency for the OPCPA amplifier [22]. By contrast, a super-Gaussian pump laser is advantageous both for broad spectral gain and high conversion efficiency [23–25]. If the pump pulse can be shaped, an optimized spectral gain profile as well as a high conversion efficiency can be achieved in an OPCPA amplifier [26].

In this paper, we suggest an OPCPA preamplifier with active spectral shaping for sub-20-fs-duration pulses in multi-PW lasers. Active spectral shaping without seed-energy loss was implemented by controlling the temporal profile of the pump pulse rather than by shaping the spectrum of the seed with an AOPDF. After optimizing the spectral shape in the OPCPA preamplifier, we realized a broad spectrum of 101 nm in width (FWHM) and a short pulse duration of 17 fs.

2. OPCPA design

The 0.1-Hz, 4-PW laser at CoReLS was developed using the CPA technique in 2017 [7]. As shown in Fig. 1, the laser consists of a Ti:sapphire oscillator, a front-end multi-pass amplifier, a cross-polarized wave generation (XPW) stage [27–29], a grating stretcher, an OPCPA preamplifier, two power amplifiers, two booster amplifiers, and a grating compressor; the OPCPA preamplifier was installed after the grating stretcher to maintain the broad spectrum from the XPW stage and to enhance the temporal contrast. The final spectral width was maximized by shaping the output spectrum of the OPCPA preamplifier.

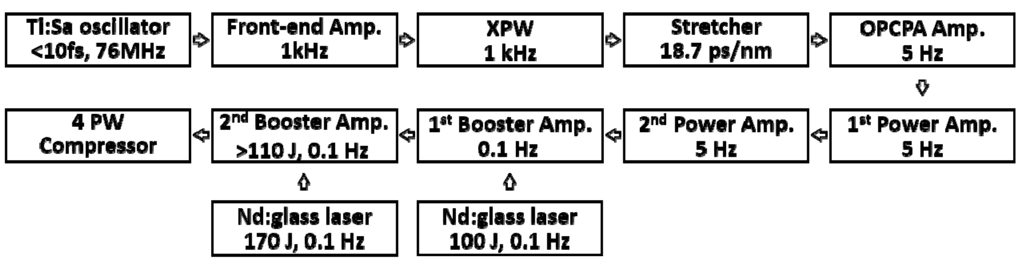

Fig. 1. Schematic diagram of the 4-PW laser at CoReLS.

A two-stage OPCPA preamplifier was designed for broad spectral gain via a non-collinear geometry. As shown in Fig. 2, high-contrast broadband laser pulses from the XPW stage were stretched by an Öffner-triplet-type pulse stretcher with a 1400-grooves/mm grating and then selected at 5 Hz using a Pockels cell (Lasermetrics 5046ER) before the OPCPA preamplifier. The selected laser pulses were guided to two Type-I BBO crystals sequentially, and then the OPCPA output pulse passed through a serrated aperture and a spatial filter before the first power amplifier to obtain a Gaussian beam profile. The thicknesses of the first and second BBO crystals were 15 mm and 4 mm, respectively; the rear surfaces of the crystals were cut at 2° to suppress superfluorescence. For broad spectral gain, the non-collinear and phase-matching angles were determined, via simulation, to be 2.39° and 23.84°, respectively.

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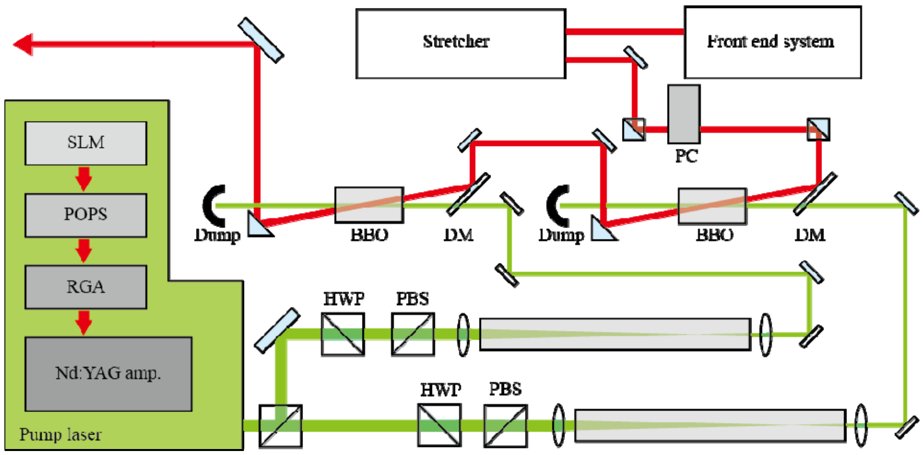

Fig. 2. Configuration of the two-stage OPCPA preamplifier (HWP: half wave plate, PBS: polarizing beam splitter, DM: dichroic mirror, PC: Pockels cell, SLM: single-longitudinal mode laser, POPS: programmable optical pulse shaper, RGA: regenerative amplifier).

A Q-switched frequency-doubled Nd:YAG laser (Continuum) was used as a pump source in the OPCPA preamplifier. As shown in Fig. 2, a single-longitudinal-mode beam was temporally manipulated with a programmable optical pulse shaper (POPS) to obtain an arbitrary waveform and then was amplified in two amplification stages to obtain an energy of 7 J. Here, the POPS consists of a fiber-optic Mach-Zehnder modulator, bias control circuitry and a programmable arbitrary impulse synthesizer, allowing the arbitrary shape impulse in a 100-ns-duration and the sampling space is 125 ps with output waveform rise/fall time of 200 ps. Finally, 4-J green single-longitudinal-mode laser pulses were delivered at a repetition rate of 5 Hz. The green pulses with 3-ns durations were well-synchronized with the 2.5-ns seed pulses just with a timing jitter of ± 120 ps to prevent temporal-contrast degradation due to amplified parametric fluorescence [30]. The green pump laser was image-relayed with lenses to obtain a 4.9-mm-diameter spot on each BBO crystal.

3. Results and discussion

In a multi-PW laser system, the broad spectral range from the XPW stage should be maintained after the high-gain preamplifier to obtain a final broad spectrum that can support sub-20-fs pulse durations. Figure 3 shows the output spectra of the OPCPA preamplifier without the AOPDF and a 4-pass Ti:sapphire preamplifier with the AOPDF. When the broadband laser pulse was amplified in the 4-pass Ti:sapphire amplifier using a pump energy of 130 mJ, the output spectrum became extremely narrow due to the strong gain-narrowing effect, resulting in a spectral width (FWHM) of 32 nm. To partially compensate for this gain-narrowing effect, the spectrum of the seed pulse was shaped with an AOPDF incurring the seed energy loss of ~75% and a broader spectral width of 47 nm was achieved; however, the spectral range of the output pulse was still considerably narrowed, as shown in Fig. 3. Instead, when the broadband seed pulse was amplified in the OPCPA preamplifier, pumped by a temporally shaped green laser with a pulse energy of 800 mJ, a broad output spectrum was produced without the spectral modulation of the seed pulse using AOPDF, with only a slight reduction of the spectral range.

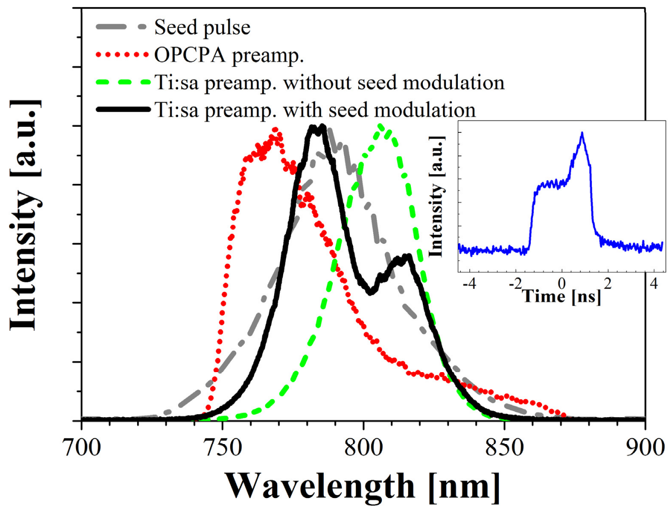

Fig. 3. Spectra of the seed (dash-dotted gray line), the output of the OPCPA preamplifier pumped by a temporally shaped laser (dotted red line), and the output of the 4-pass Ti:sapphire preamplifier without (dashed green line) and with (solid black line) seed-spectrum modulation. The inset showed a temporal profile of the pump pulse for the OPCPA preamplifier.

The output spectrum of the OPCPA preamplifier was shaped by manipulating the temporal profile of the pump laser pulses. Longer wavelength components of the OPCPA output spectrum should be suppressed to compensate for the gain-depletion effect. At the first stage of the OPCPA preamplifier, the phase-matching condition was adjusted to maximize the entire output spectral width. At the second stage, the phase-matching condition was adjusted to obtain a higher gain over a shorter wavelength range. By using a top-hat pump pulse, the longer-wavelength components were reduced, as shown in Fig. 4(a). However, the center- and long-wavelength components were not suppressed efficiently enough to provide adequate compensation for the gain-depletion effect. Considering that the pump pulse is temporally overlapped with a positively-chirped seed-laser pulse in the BBO crystals, the center- and long-wavelength components of the amplified spectrum can be suppressed more strongly by weakening the preceding part of the pump pulse. Figure 4(b) shows the results obtained by using the actively shaped pump pulse: a rear-peaked pump pulse induced a lower amplification gain in the preceding part of the seed-laser pulse, resulting in stronger suppression of the center- and longer-wavelength components. Consequently, this temporal-profile shaping of the pump pulse facilitates optimization of the OPCPA-output-spectrum profile for near-perfect compensation of the gain-depletion effect.

We measured the temporal contrast of the output pulse of the OPCPA amplifier with the temporally shaped pump pulse. The ASE level was measured to be ~10^{-12}. The temporal contrast degradation incurred by the OPCPA superfluorescence was negligible, considering the seed pulse ASE level of 10^{-12}; the ASE level after the front-end was 10^{-8}, and it was enhanced to 10^{-12} due to the XPW.

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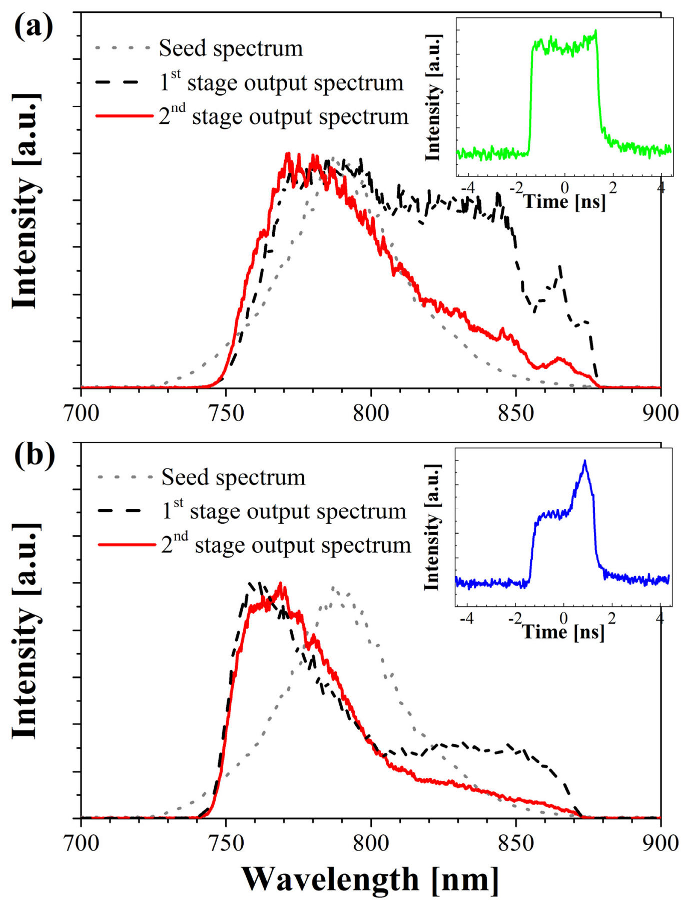

Fig. 4. The input and output spectra of the OPCPA preamplifier, obtained using a pump laser with a top-hat temporal profile (a), and with a rear-peaked temporal profile (b); the insets show the temporal profiles of the pump lasers in each case.

The output energy of the OPCPA preamplifier was measured as a function of pump energy, as shown in Fig. 5. When the pump laser has a top-hat temporal profile, the output energy at the first stage increased exponentially with the pump energy because of the high amplification gain and low seed energy. By contrast, the output energy at the second stage increased almost linearly with the pump energy because the seed pulse energy was not much lower than the pump energy [31]. The maximum output energy for this pump-laser profile was 140 mJ when the total pump energy was 800 mJ, giving a total conversion efficiency of 17%. When the pump laser had a rear-peaked temporal profile, the trend of increasing output energy was similar to that of the top-hat temporal profile at each stage. However, the maximum output energy increased to 240 mJ for 800 mJ of total pump energy, resulting in a higher conversion efficiency of 30%.

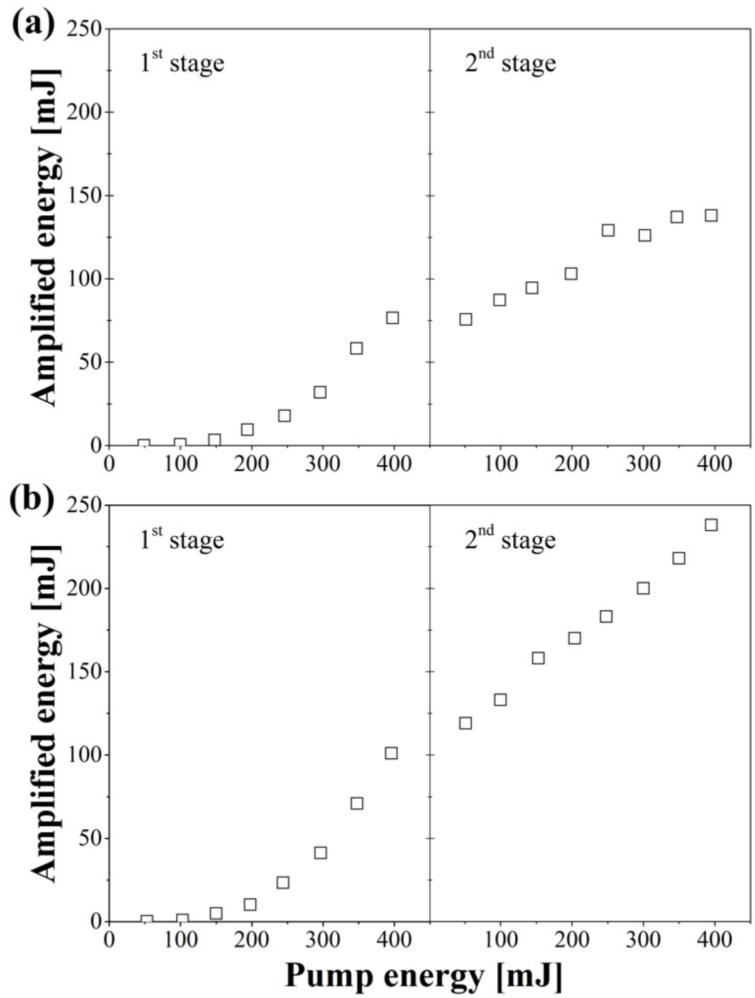

Fig. 5. Measured output energies of the OPCPA preamplifier as a function of the energy of the pump laser with a top-hat temporal profile (a) and with a rear-peaked temporal profile (b).

The conversion efficiency of the OPCPA preamplifier depends on the temporal profile of the pump laser. At the first stage of the OPCPA preamplifier, spectral gain was manipulated to maximize the output spectral bandwidth by adjusting the phase-matching condition. However, at the second stage, the spectral gain was modulated in order to have a higher amplification gain over a shorter wavelength range. This adjustment of the phase-matching condition resulted in a total conversion efficiency of 17% with the top-hat pump laser. In contrast, when the pump laser had the rear-peaked temporal profile, the conversion efficiency of the second stage was greatly increased to 30% because of the stronger pump intensity and the optimized phase matching condition over a shorter wavelength range, leading a higher gain over this range. Consequently, the rear-peaked pump laser resulted in a high total conversion efficiency.

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The final spectral width of the 4-PW laser was maximized by compensating for the gain-depletion effect. For this compensation, longer-wavelength components of the OPCPA output spectrum were suppressed using the rear-peaked OPCPA pump laser. After optimizing the OPCPA output spectrum via precise control of the temporal profile of the pump pulse, the final amplified laser pulse had a very broad spectrum with a bandwidth of 101 nm (FWHM), supporting a Fourier-transform-limited pulse duration of 17 fs, as shown in Fig. 6(a). After passing through the pulse compressor, the amplified laser pulse was recompressed to obtain a duration of 17 fs, measured by a spectral interferometry for direct electric field reconstruction (SPIDER; APE) as shown in Fig. 6(b).

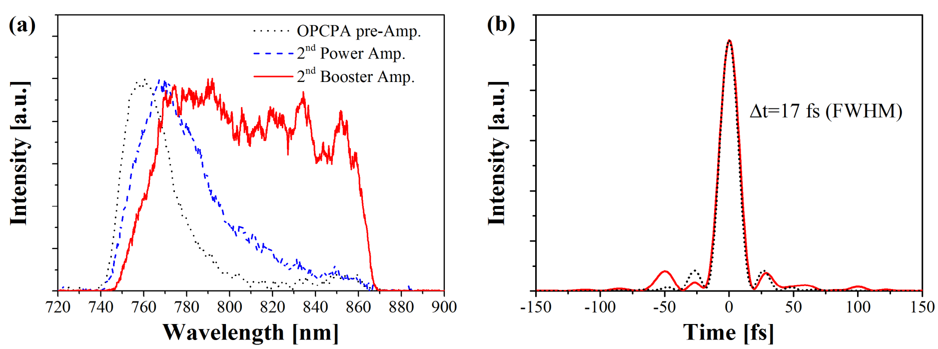

Fig. 6. Amplified spectra measured after each of the amplification stages: OPCPA preamplifier, second power amplifier, and second Booster amplifier (a), and reconstructed temporal profile of the 4-PW laser pulse (solid red line) and temporal profile of the Fourier-transform-limited pulse (dotted black line) (b).

4. Conclusion

In conclusion, we developed a two-stage OPCPA preamplifier with active spectral shaping to obtain a broad spectrum supporting a sub-20-fs pulse duration in a 4-PW laser. The output spectral amplitude of the OPCPA amplifier was shaped by manipulating the temporal profile of the pump laser. After optimizing the OPCPA output spectrum to compensate for the gain-depletion effect, the final amplified spectrum of the 4-PW laser had a broad width (101 nm, FWHM). Further, we demonstrated a high conversion efficiency of 30% for the OPCPA amplifier. After compression, the final laser pulse had a duration of 17 fs, which is the shortest reported duration of any multi-PW laser, to the best of our knowledge. Our broadband OPCPA amplifier with active spectral control can be a reliable tool to obtain sub-20-fs pulse durations in multi-PW Ti:sapphire lasers.

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