Generation of few-cycle terawatt light pulses using optical parametric chirped pulse amplification

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Abstract: We demonstrate the generation of 9.8 ± 0.3 fs laser pulses with a peak power exceeding one terawatt at 30 Hz repetition rate, using optical parametric chirped pulse amplification. The amplifier is pumped by 140 mJ, 60 ps pulses at 532 nm, and amplifies seed pulses from a Ti:Sapphire oscillator to 23 mJ/pulse, resulting in 10.5 mJ/pulse after compression while amplified fluorescence is kept below 1%. We employ grating-based stretching and compression in combination with an LCD phase-shaper, allowing compression close to the Fourier limit of 9.3 fs.

OCIS codes: (140.3280) Laser amplifiers; (190.4970) Parametric oscillators and amplifiers; (320.7090) Ultrafast lasers; (320.7160) Ultrafast technology

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1. Introduction

The study of strong-field laser-matter interactions is a rapidly advancing branch of physics [1]. Progress in topics such as high-harmonic generation and quantum coherent control have led, for example, to the rise of attosecond science [2], laser-based particle acceleration, and laser-assisted nuclear fusion [3]. Since some of these applications require extreme peak power delivered in as short a time span as possible, considerable effort is spent to push the limits in attainable pulse duration and peak intensity.

The current state-of-the-art in peak power consists of huge Nd:Glass-based facilities capable of generating petawatt pulses of ~ 400 fs duration [4, 5, 6], and Ti:Sapphire systems which have been demonstrated to produce 0.85 PW in 33 fs pulses [7]. The shortest pulses to date have been generated using noncollinear optical parametric amplifiers (NOPA’s) pumped by frequency-doubled Ti:Sapphire amplifiers [8], and through self-phase-modulation of amplified Ti:Sapphire pulses in gas-filled hollow fibers [9]. Both techniques have produced 4 fs pulses at a peak intensity of $\sim$1 GW for NOPA’s, and up to $\sim$100 GW for hollow fibers. However, scaling to higher power is very complicated with such systems.

Present-day high power table-top laser systems mostly rely on Ti:Sapphire as an amplifier medium, and several terawatt-class laser systems have been demonstrated [10, 11, 12, 13]. However, these systems become increasingly complex when aiming for shorter and more intense pulses, as the thermal load on the amplifiers causes wavefront distortions and thermal lensing. Compensation of such effects is only possible with carefully designed optical systems, or cryogenic cooling of the Ti:Sapphire crystals. Also, powerful Ti:Sapphire systems usually require multiple amplification stages (typically a regenerative amplifier and one or more multi-pass amplifiers), as many passes through the amplification medium are necessary.

In addition, the production of few-cycle pulses is very difficult with Ti:Sapphire amplifiers due to spectral gain narrowing. Elaborate techniques are required to maintain a large bandwidth after amplification, such as spectral broadening in gas-filled hollow fibers between consecutive stages of a Ti:Sapphire amplifier chain [14].

2. Optical parametric chirped pulse amplification

An alternative to Ti:Sapphire amplification that is very promising for the production of high power few-cycle laser pulses is optical parametric chirped pulse amplification (OPCPA) [15]. Multi-TW OPCPA systems producing pulses much longer than 100 fs have been demonstrated using Nd:Glass pump lasers [16, 17], and progress towards petawatt powers and beyond is already quite far [18, 19]. At the same time, noncollinear OPCPA (NOPCPA) can have this large gain over a bandwidth supporting sub-10-fs laser pulses [18, 20]. Combined with the absence of significant thermal aberrations, this paves the way for few-cycle pulses with multi-TW peak power.

In a previous paper, we showed the feasibility of this concept by demonstrating phase-controlled amplification of 11.8 fs pulses to 0.1 mJ energy at a repetition rate of 1 kHz, using a Ti:Sapphire seed laser and a frequency-doubled Nd:YAG pump laser [21]. Ishii et al. [22] performed parametric amplification of 10 fs pulses to 5 mJ at 20 Hz rep. rate. In this paper we report on the amplification of pulses to 23 mJ at 30 Hz, resulting in 9.8 fs pulses with a peak power exceeding 1.0 TW after compression. These pulses contain very little amplified superfluorescence, and have been compressed to within 6% of the Fourier limit using adaptive spectral phase shaping.

3. NOPCPA setup

A schematic of our amplifier system is shown in Fig. 1. The seed source is a Kerr-lens mode-locked Ti:Sapphire oscillator (Femtosource Scientific Pro), delivering 11 fs, 8 nJ pulses at 75 MHz repetition rate. These pulses are stretched to 10 ps full width at half-maximum (FWHM) in a grating-based pulse stretcher (600 l/mm gold coated gratings), in which an 640-element LCD phase-only spectral shaper (Jenoptik) is incorporated for high-resolution spectral phase control.

As a pump laser source for the NOPCPA, we have constructed a Nd:YAG laser system capable of producing 220 mJ, 60 ps pulses at 1064 nm, with a repetition rate of 30 Hz. It is seeded by a SESAM mode-locked 7 ps Nd:YVO_4 laser (High-Q Laser), synchronized to the Ti:Sapphire laser with a timing jitter of $<$100 fs. The delay between pump and seed pulses can be adjusted roughly using an electronic phase shifter in the feedback loop of the Ti:Sapphire laser, and fine-tuned with a translation stage in the seed beam [21].

This Nd:YVO_4 laser emits 50 nJ pulses, which are first stretched in time by clipping the spectrum in a zero-dispersion $4f$ setup to ensure a pulse duration larger than 60 ps. These pulses are amplified to 1.5 mJ in a diode-pumped Nd:YAG regenerative amplifier (regen). The regen output beam is expanded to 11 mm, and is further amplified to 220 mJ/pulse in a double-pass post-amplifier, based on two flashlamp-pumped 12 mm diameter Nd:YAG rods (EKSPLA Ltd.). These rods are relay imaged onto each other, and the polarization state is rotated between the rods by a 90° quartz rotator to compensate for thermally induced birefringence. The relay image telescope contains a vacuum spatial filter to preserve beam quality. The seed pulses are

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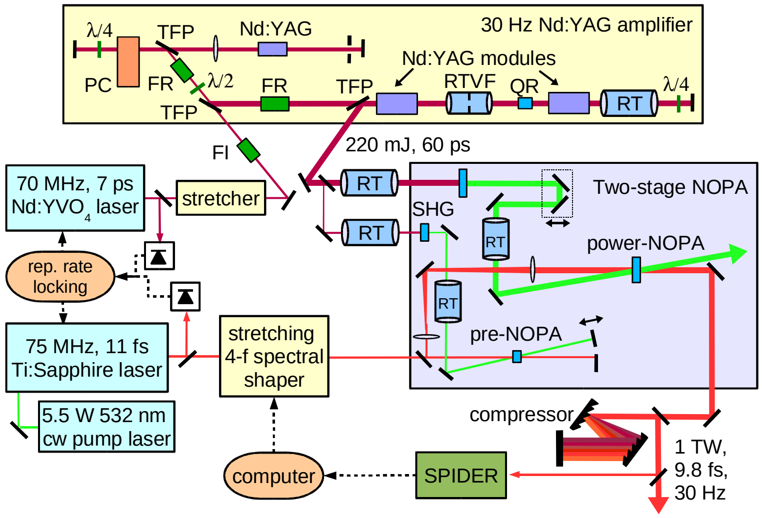

Fig. 1. The terawatt 10 fs NOPCPA setup. Relay imaging is employed from the Nd:YAG amplifier to the SHG crystals, and from there to the OPA-stages (RT, relay imaging telescope; RTVF, relay imaging telescope with vacuum spatial filter). The various parts of the setup are explained in detail in the text. NOPA, noncollinear optical parametric amplifier; FI, Faraday isolator; TFP, thin-film polarizer; QR, quartz rotator; PC, Pockels cell; FR, Faraday rotator. In the two-stage NOPA setup, only reflective optics are used; the lenses drawn represent mirrors.

stretched to only 1/6th of the pump pulse duration, to ensure that the low intensity outer edges of the spectrum still experience a high gain. Gain saturation is then expected to result in a 30 ps flat-top temporal profile, thereby increasing the energy extraction efficiency.

A small part of the 1064 nm light is split off to a SHG crystal (KTP, type II), where 10 mJ of 532 nm light is generated to pump the first stage of the NOPCPA. It consists of a 5 mm long BBO crystal ($\theta = 22.5^\circ$, $\phi = 0^\circ$, type I phase matching). Both pump and seed beam have a diameter of 1.5 mm inside the crystal, with an internal noncollinear angle between them of around 2.38°. The beams are reflected back through the crystal for a second amplification pass. As the gain is highest in this pre-amplifier (10^3 - 10^4 small-signal gain per pass), any residual phase mismatch may lead to narrowing of the spectral gain bandwidth. Therefore, the second pass is aligned at a slightly different angle to broaden the amplified spectrum. This pre-amplifier stage increases the pulse energy from 1.5 nJ to a few tenths of a mJ.

The main part of the 1064 nm pump light is passed to another SHG crystal (BBO type I, 3 mm long, 14 mm diameter), where 140 mJ per pulse at 532 nm is generated. The output of the pre-amplifier is expanded to match the 10 mm diameter pump beam and overlapped with it in a second BBO crystal (5 mm long, 14 mm diameter, same angles as the first NOPCPA crystal). This power-amplifier stage boosts the pulse energy to typically 23 mJ per pulse at 140 mJ pump energy, with less than 1% amplified superfluorescence. A maximum energy of 30 mJ per pulse has been generated with this system, but only with increased amounts of superfluorescence (estimated 6% at 30 mJ), and reduced stability.

After the post-amplifier, the transverse beam profile resembles a top-hat distribution. Relay-imaging has therefore been applied from the post-amplifier to the respective SHG stages, and from there to the OPA crystals. CCD camera images of the pump and amplified signal beam profiles at the power amplifier stage are shown in Fig. 2. Due to gain saturation, the beam profile of the amplified signal resembles that of the pump beam. A check for the presence of

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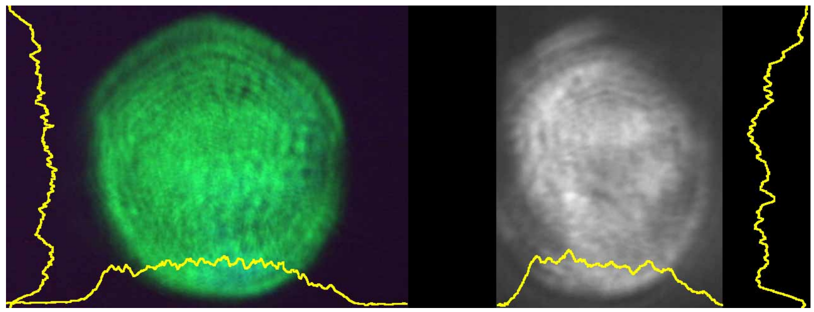

Fig. 2. Beam profile images of the relay-imaged 140 mJ pump beam at the power amplifier (left) and the 10.5 mJ OPA output beam (right). The latter is slightly cut off on the left due to spatial constraints in setting up the relay imaging, without excluding any important features.

angular chirp has been performed by scanning a fiber-coupled optical spectrum analyzer across the far-field beam profile, and no position-dependent spectral distribution was detected.

The amount of amplified superfluorescence has been determined by monitoring the fluorescence power in a spectral region around 1000 nm, where the seed pulse has zero spectral intensity. At this wavelength the fluorescence intensity is seen to decrease when seed light is added, as the pump power density is lowered due to gain depletion by the amplified seed pulses. In combination with a measurement of the NOPCPA output power with and without seeding, the remaining amount of superfluorescence in the presence of seed light can be estimated to be less than ~1% of the total output power.

After amplification the beam is expanded to 13 mm diameter and the pulses are compressed by a grating compressor (1200 lines/mm, 18 mm grating separation). The angles and grating constants of the stretcher and compressor are chosen such that dispersion compensation is achieved up to third order. The compressor has an efficiency of 46%, resulting in recompressed pulses with an energy of 10.5 mJ. To characterize the compressed output pulse, we employ

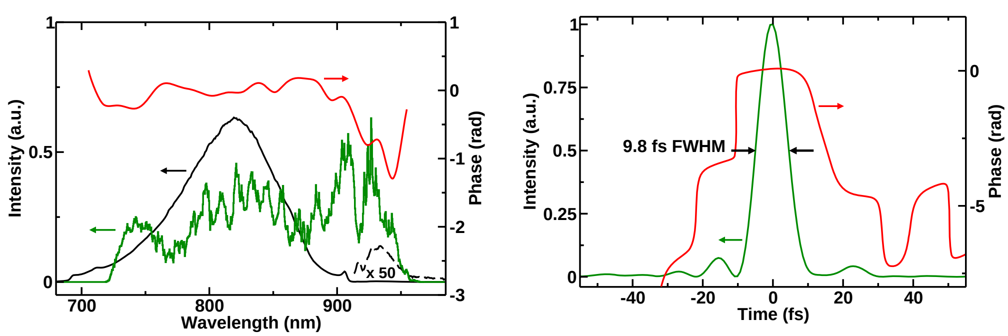

Fig. 3. Left: Spectra of the input seed pulses (black curve), and the OPCPA output pulses after compression (green curve). The slow modulation results from phase-matching effects in the power-amplifier, while the faster modulation is presumably caused by a synchronization artefact of the scanning spectrum analyzer used for this measurement. Dashed black curve: seed spectrum 50 times enlarged for clarity. Red curve: spectral phase of the compressed output pulses measured using SPIDER. The deviation from zero at wavelengths longer than 900 nm is caused by limitations of the shaper, see text. Right: Temporal profile of the compressed output pulse (green curve) and temporal phase (red curve).

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spectral phase interferometry for direct electric field reconstruction (SPIDER) [23]. The measured spectral phase is used as a feedback signal in an optimization loop with the LCD shaper, yielding pulses with a FWHM duration of 9.8 ± 0.3 fs, which is within 6% of the Fourier limit of 9.3 fs. The peak power of the pulses then exceeds 1 TW. The spectra of the input seed and amplified output and the compensated spectral phase, as well as the temporal pulse structure and phase are shown in Fig. 3. Considerable reshaping of the spectrum in the amplifier is immediately apparent. Phase mismatching suppresses amplification below 720 nm, while the high gain towards longer wavelengths amplifies even the very weak edge of the spectrum to a sizeable intensity. The spectral phase shows the effects of residual higher order dispersion at the long wavelength side of the spectrum, which could not be completely compensated due to an insufficient shaper resolution (Nyquist limitation). The measured pulse-to-pulse output power fluctuations are about 5% for the NOPCPA, and 3% for the pump laser. An upper limit for possible beam pointing variations is determined to be 50 μrad half-angle.

4. Discussion and outlook

The NOPCPA system described here displays several interesting features. For example, the setup is remarkably compact: the total path length from the Ti:Sapphire seed oscillator to the compressor output can be kept well below 10 metres, and the pulses only pass through 2 cm of material in total. This is mostly due to the high single-pass gain of the NOPCPA stages. Also, the modest stretching ratio employed ($\sim 10^3$) allows the stretcher and compressor to be very compact, especially considering that the shaper is integrated in the stretcher. Hence, the seed beam is minimally disturbed (the B-integral of the entire NOPCPA system is calculated to be less than 1), which is beneficial for applications where carrier-envelope phase stability of the amplified pulses is required [24]. The parametric amplification process has already been demonstrated to preserve the phase of the seed pulses [21, 25], and the grating-based stretching and compression is known to be phase-stable as well [21, 26]. Furthermore, the broad gain bandwidth facilitates amplification of sub-10-fs pulses without the need for spectral broadening through self-phase-modulation in gas-filled hollow fibers, making the system more robust, less sensitive to alignment, and better scalable to higher power.

The system described here can be upgraded to deliver >2 TW just by employing negative dispersion stretching and high-throughput bulk glass compression [22, 27]. When using a seed oscillator with a broader spectral bandwidth, pulses shorter than 7 fs should be feasible [18, 20]. Therefore, although the pump laser requires more effort compared to Ti:Sapphire amplifiers due to the high peak power and the need for careful synchronization, a NOPCPA system like the one presented in this paper is very well suited for the amplification of few-cycle laser pulses with a stabilized carrier-envelope phase to the terawatt level and beyond.

5. Conclusion

In conclusion, we have demonstrated the production of sub-10 fs pulses with a peak power exceeding one terawatt. The system is remarkably compact due to the high parametric gain and the small stretching-ratio, and produces only low levels of amplified superfluorescence. The pulses are compressed to within 6% of the Fourier limit with good spatial quality. Thermal effects in the amplifier medium are negligible, and do not limit the achievable peak power and repetition rate. With a suitable pump laser, the amplification of few-cycle pulses to multi-terawatt or even petawatt peak powers using NOPCPA seems feasible.

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