High-power parametric amplification of 11.8-fs laser pulses with carrier-envelope phase control

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Received July 26, 2004

Phase-stable parametric chirped-pulse amplification of ultrashort pulses from a carrier-envelope phase-stabilized mode-locked Ti:sapphire oscillator (11.0 fs) to 0.25 mJ/pulse at 1 kHz is demonstrated. Compression with a grating compressor and a LCD shaper yields near-Fourier-limited 11.8-fs pulses with an energy of 0.12 mJ. The amplifier is pumped by 532-nm pulses from a synchronized mode-locked laser, Nd:YAG amplifier system. This approach is shown to be promising for the next generation of ultrafast amplifiers aimed at producing terawatt-level phase-controlled few-cycle laser pulses.

OCIS codes: 190.4970, 320.7090, 320.7160, 350.5030.

Generation of high-power ultrashort laser pulses has become a routine matter in recent years,[1] but for many applications stabilization and control of the phase φ_{CE} between the carrier wave and the field envelope are required as well. This control was demonstrated several years ago in the field of frequency metrology with low-power oscillator pulses,[2,3] and recent experiments using multipass Ti:sapphire (Ti:Sa) amplifiers have shown that it is possible to produce φ_{CE}-stabilized few-cycle pulses at the millijoule level.[4,5] However, increasing the power to the terawatt (TW) level using Ti:Sa-based amplifiers is challenging already without control of φ_{CE},[4,6,7] let alone when φ_{CE} control is required.

A promising alternative for obtaining powerful ultrashort laser pulses with φ_{CE} control is offered by noncollinear optical parametric chirped-pulse amplification (NOPCPA) based on lithium triborate or β-barium borate (BBO) crystals pumped at 532 nm. With this technique multi-TW peak powers have been demonstrated with Nd:glass laser systems, albeit with pulse lengths of approximately 155 (Ref. 8) and 300 fs (Ref. 9) and without phase control. Recently, Hauri *et al.*[10] reported phase-preserving NOPCPA with the pump derived from the seed beam by regenerative amplification. They obtained 85-μJ, 17.3-fs pulses and demonstrated phase stability qualitatively. Here we report, to the best of our knowledge, the first realization of 532-nm pumped parametric amplification of ultrashort laser pulses from a Ti:Sa laser, quantitatively demonstrating φ_{CE} phase-stable ultrabroadband parametric amplification to the microjoule level. The pump laser for this approach is based on a Nd:YAG amplified mode-locked laser system, which can be easily scaled up with standard Nd:YAG technology so that parametric amplification of few-cycle pulses to a TW peak power becomes feasible with a relatively simple system. Moreover, it is demonstrated that grating-based stretching and compression of pulses can maintain carrier-envelope phase stability, in contrast with what is often assumed.[11,12]

Several design studies have been published about systems that in principle should be able to generate TW- and possibly even petawatt-peak-power few-cycle laser pulses.[13,14] The main advantages of parametric compared with Ti:Sa amplification are the much broader gain bandwidth, the insignificant power dissipation in the amplifier medium, and the low stretching and compression factor required.

A schematic of our setup is shown in Fig. 1. The seed pulses stem from a Kerr-lens mode-locked Ti:Sa oscillator laser (FemtoLaser Scientific Pro), which delivers ~8-nJ, 11.0-fs pulses at a repetition rate of 75 MHz. The carrier-envelope phase slip is locked with a precision of rms ~ 1/40th of an optical cycle (150 mrad) to 1/5th of a cycle per pulse by use of the standard $f - 2f$ technique.[15] The repetition rate of the Ti:Sa laser is stabilized with a dual-locking scheme at 75 MHz for coarse adjustment and at the 140th harmonic to a 10.4-GHz reference oscillator for fine adjustments and tight synchronization with the picosecond pump laser system. All frequencies are referenced to a global positioning system–disciplined rubidium clock.

The Ti:Sa laser pulses are stretched to approximately 10 ps in a combined LCD shaper–grating stretcher setup. It consists of two gold-coated cylindrical mirrors (radius of curvature of 0.5 m), two 600-line/mm gold-coated gratings, and a 640-pixel LCD phase-only shaper (Jenoptik SLM-S 640/12).

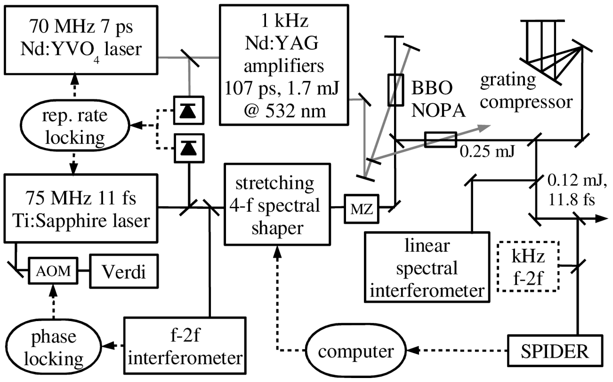

Fig. 1. Setup used for parametric amplification of phase-controlled few-cycle laser pulses: MZ, small Mach–Zehnder pulse-replica generator; AOM, acousto-optic modulator; NOPA, noncollinear optical parametric amplifier.

The shaper is traversed twice, and the gratings are displaced from the 4*f* configuration to generate a group-velocity dispersion of $4 \times 10^4\ \mathrm{fs}^2$. Because of the high damage threshold of BBO, only a small stretching and compression factor (~1000×) is required for the seed pulses. Ray-tracing calculations show that this results in negligible φ_{CE} noise (less than 20 mrad) from the stretcher and compressor, which was verified by a measurement of the phase noise from these devices by use of a Fourier-transform spectral interferometer.

A home-built cw diode-pumped Nd:YAG amplifier system produces the pump pulses for the optical parametric amplifier (OPA). It is seeded by a Nd:$\mathrm{YVO_4}$ mode-locked laser (High Q Laser) whose 70-MHz repetition rate is asynchronously locked to the same 10.4-GHz oscillator that is used for locking the Ti:Sa oscillator laser. To prevent optical damage during amplification, the spectrum of the picosecond laser is clipped in a 4*f* system to ensure a pulse length of approximately 100 ps. A combination of a regenerative amplifier and two postamplifiers boosts the power to 2.8 mJ at 1 kHz. After frequency-doubling in a KTP crystal, 1.7-mJ pulses at 532 nm with a duration of 107 ps (measured with a streak camera) are available to pump the OPA.

The stretched pulses from the oscillator laser and the pump beam are both loosely focused into a 10-mm-long BBO crystal ($\theta = 22.5°$, $\phi = 0°$, type I phase matching) and overlapped in time for parametric amplification. The timing jitter between the pump and the seed pulses is less than 100 fs. The pump beam has a power density of approximately $10\ \mathrm{GW/cm^2}$ in the first crystal and produces only a weak superfluorescence cone without the seed beam present. At an internal angle of the seed beam to the pump beam of 2.38°, phase matching is possible between 740 and 1000 nm.[16] The seed pulses make two passes through the first crystal and one more pass in a second, identical crystal, yielding 3–4 μJ, 0.15 mJ, and 0.25 mJ/pulse, respectively, after each pass, with a pulse-to-pulse power fluctuation of approximately 5%. The unusually high ratio of approximately 1:10 for the seed-to-pump pulse duration facilitates an ultrabroad bandwidth. A high energy conversion efficiency of more than 20% (signal + idler) is still obtained by saturation of the gain and the possibility of shifting the pump and seed pulses in time relative to each other in the second and third passes. In this way the frequencies at the edges of the chirped seed pulse can also profit from the full gain at the center of the pump pulse.

The output pulses are compressed by a grating compressor (1200 lines/mm, separation of ~40 mm), after which an output power of 0.12 mJ/pulse is obtained. Dispersion compensation to the third order is achieved by choosing different angles and grating constants for the stretcher and compressor. Fine tuning of higher-order dispersion is performed with the LCD shaper in the stretcher.

For pulse characterization we use a home-built spectral phase interferometer for direct electric field reconstruction (SPIDER).[17] Figure 2 shows the fundamental and amplified spectra, together with the spectral phase retrieved from a SPIDER measurement. The inset in this figure contains the reconstructed pulse in the time domain, which has a FWHM duration of 11.8 ± 0.3 fs that is within 5% of the Fourier limit of 11.4 fs. The amplified spectrum is different in shape from the input seed spectrum, mainly because of phase-matching effects (preventing the amplification of light below 740 nm) and OPA gain saturation. Nevertheless, the pulse lengths of the seed and the amplified pulses are almost equal. The strong amplitude variations near 900 nm are the result of the dispersion characteristics of the chirped mirrors employed in the seed oscillator. These have little influence on the SPIDER measurements, since this modulation is filtered out in the course of the phase-retrieval algorithm.

The stability of φ_{CE} has been measured in two ways: by use of a kilohertz $f - 2f$ interferometer[18] and by Fourier-transform spectral interferometry.[19,20] The $f - 2f$ technique requires single filament continuum generation, which itself introduced ~0.8-rad spurious phase noise in our case owing to the 5% OPA output power fluctuations.

Fourier-transform spectral interferometry, on the other hand, is a linear technique without amplitude-to-phase coupling effects of its own. Given the power fluctuation of the OPA output, this method is better suited for measuring the phase noise added by the process of parametric amplification. For this measurement the seed pulse for the OPA was split into two replicas by a slightly misaligned Mach–Zehnder interferometer. The misalignment caused the pulses to be separated by a few millimeters in space and slightly more than 100 ps in time. One of these pulses is used as the OPA seed, whereas the other remains unamplified because of the difference in timing and spatial separation. The fact that the pulses stay relatively close ensures that effects of slow thermal drift and acoustic noise are minimized. After the compressor both pulses are recombined up to a small delay (~1 ps) in a second, identical interferometer. The pulse pair

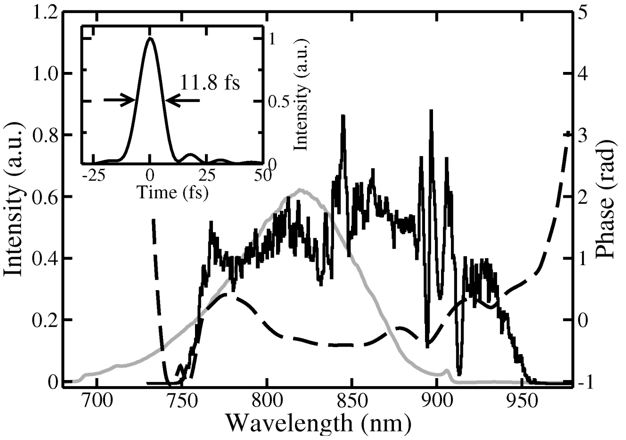

Fig. 2. Measured spectrum of the amplified pulses (darker solid curve), input seed spectrum (lighter solid curve), and measured spectral phase (dashed curve). Inset, reconstructed pulse shape in the time domain.

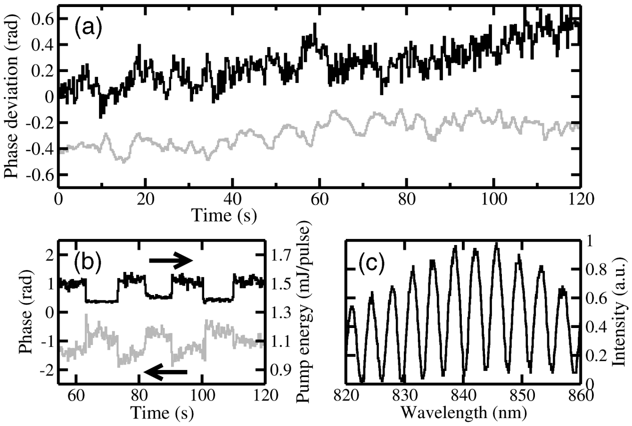

Fig. 3. Phase deviations measured with a linear Fourier-transform spectral interferometer. (a) Phase measurement with (darker trace) and without (lighter trace) amplification. (b) Effect of pump intensity variations (darker trace) on φ_{CE} (lighter trace). (c) Typical interferogram from the Fourier-transform spectral interferometer setup with an ~95% contrast.

is then sent into a spectrometer, generating bright spectral fringes from which the phase jitter between the two pulses can be deduced. The results of these measurements are shown in Fig. 3. The interferograms, averaged over 30 pulses (~30 ms), have a contrast exceeding 90%, and no significant deterioration is seen when the amplifier is turned on. From this we can conclude that, on time scales shorter than 30 ms, the phase jitter added by the OPA is less than 0.1 rad. Tracking the interferogram over a time scale of approximately 2 min results in traces such as the one shown in Fig. 3(a). The slow variations and drift of the signals are attributed to mechanical vibrations and environmental instabilities. From a comparison of the phase stability with and without amplification the phase noise added by the OPA process on a time scale of minutes was found to be ~0.1 rad, or ~1/60th of an optical cycle. This phase jitter can most likely be attributed to amplitude-to-phase coupling in the OPA process. Evidence for this is given by Fig. 3(b), showing the dependence of the phase on the pump laser intensity. It can be seen that a pump pulse energy modulation of 0.2 mJ induces a phase shift of approximately 0.7 rad. This indicates that the B integral of our amplifier is relatively high, i.e., of the order of π. A NOPCPA design with a lower B integral will therefore exhibit even better phase stability. Ross *et al.*[13] suggest that the spectral phase, and hence φ_{CE}, is gain dependent, which could also induce phase shifts. Calculations show that this effect is orders of magnitude smaller than the amplitude-to-phase coupling in our case.

In conclusion, we have demonstrated phase-stable amplification of ultrashort laser pulses up to 0.25 mJ/pulse by using a NOPCPA laser system with a Nd:YAG pump source. The amplified spectrum spans more than 174 nm FWHM, yielding an output pulse after compression of 11.8 fs and an energy of 0.12 mJ at a 1-kHz repetition rate.

The combination of a Nd:YAG-based pump laser for the NOPCPA and grating-based stretching and compression shows great potential for replacing traditional Ti:Sa-based systems to yield phase-stable TW-peak-power pulses with a duration of 10 fs or less.

This project was financially supported by the Foundation for Fundamental Research on Matter, the Netherlands Organization for Scientific Research, and the EU Integrated Initiative FP6 program. These contributions are gratefully acknowledged. R. Zinkstok's e-mail address is rzinkstk@nat.vu.nl.

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