Phase-stable single-pass cryogenic amplifier for high repetition rate few-cycle laser pulses

Akira Ozawa¹, Waldemar Schneider, Theodor W Hänsch, Thomas Udem and Peter Hommelhoff¹
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D 85748 Garching, Germany
E-mail: akira.ozawa@mpq.mpg.de and peter.hommelhoff@mpq.mpg.de

New Journal of Physics 11 (2009) 083029 (11pp)
Received 14 May 2009
Published 24 August 2009
Online at http://www.njp.org/
doi:10.1088/1367-2630/11/8/083029

Abstract. We demonstrate cryogenic Ti:sapphire single-pass amplification of sub-7 fs laser pulses with 80 MHz repetition rate. We amplify the output of a broadband Ti:sapphire oscillator by more than a factor of two, re-compress the pulses down to sub-7 fs, and show that the rms carrier-envelope phase jitter stays below 70 as after amplification. The amplified output exceeds 2 MW of peak power and 1 W of average power. In addition, we demonstrate amplification of ~200 fs, 75 MHz oscillator pulses up to 1.6 W with a gain of four. This work opens a new way to explore phase sensitive and highly nonlinear phenomena at the full oscillator repetition rate. As a first example, we demonstrate white light generation in a bulk crystal at the full oscillator repetition rate.

¹ Author to whom any correspondence should be addressed.
1. Introduction

Few-cycle titanium:sapphire laser oscillators are employed in diverse fields such as optical clocks [1], direct frequency comb spectroscopy [2, 3] and ophthalmology [4, 5]. Other important applications such as high-harmonic generation (HHG) [6] require peak powers that are out of reach even for state-of-the-art oscillators.

Many highly nonlinear processes have an associated effective threshold intensity that has to be reached in order to make the process observable. For example, HHG [6] requires laser intensities exceeding $10^{13}$ W cm$^{-2}$. Efficient HHG is of prime interest for spectroscopy of, e.g. extreme ultraviolet atomic shell transitions like the 1s–2s transition in He$^+$ [7, 8] and for the investigation of processes taking place on attosecond timescales [9]. In direct femtosecond frequency comb spectroscopy [10], the repetition rate of the driving laser should lie above the atomic linewidth so that comb lines of the HHG spectrum can be individually resolved. Thus far, HHG at multi-MHz repetition rates has only been achieved with sophisticated tools like optical enhancement cavities [11, 12] or micro-fabricated nanoantennas [13].

To reach high peak intensities it is advantageous to use very short, i.e. few-cycle light pulses. In addition, for few-cycle oscillators, simple carrier-envelope phase (CEP)-locking schemes exist [14], which are indispensable for frequency comb generation. Also, few-cycle phase-controlled lasers are necessary for the investigation of phase-sensitive processes in the time-domain such as electron emission in the resolved tunneling regime [15].

Nowadays most femtosecond laser oscillators are of the passively Kerr-lens mode-locked type. Although tremendous efforts have been put into extending the parameter range of these oscillators, success has been limited as the need for a delicate balancing of intracavity parameters to start and maintain mode-locked operation sets stringent limits on output parameters. Pulse energies from few-cycle oscillators have thus been limited to $\sim$10 nJ [16]. Focusing more tightly to reach a desired peak intensity is unfavorable as this reduces the interaction volume drastically. For example, HHG scales with the confocal parameter cubed [17], so that an increase in intensity by a factor of two due to tighter focusing would reduce the harmonic output by almost an order of magnitude. Even if very tight focusing is an option, it is challenging to focus more tightly than we do here, maintain sub-7 fs pulse duration
Figure 1. Setup of the experiment. The LN2-cooled Ti:sapphire crystal is mounted in a small vacuum chamber (an exploded view is shown in figure 2). The 18 W pump beam (green) traverses a telescope that enables adjustment of the pump beam focal spot size. The seed beam (red) is overlapped with the pump beam on a dichroic focusing mirror with an incidence angle chosen for astigmatic compensation of the crystal’s Brewster cut and re-collimating focusing mirror. LPF, low pass filter; APD, avalanche photo diode; AOM, acousto-optic modulator.

and reach $10^{13}$ W cm$^{-2}$. Thus, increasing the peak power is mandatory. For oscillators optimized for high peak power an amplifier gain of 2 will already enable us to drastically increase the rate for highly nonlinear processes. In addition, carrier-envelope offset frequency stabilization as well as auxiliary monitoring devices often require a fixed amount of laser power, so that a doubling of the oscillator output power can easily translate into an order of magnitude more power available for the experiment.

2. Experimental realization with few-cycle pulses

Single- or double-pass titanium-doped sapphire (Ti:sapphire) amplifiers have been demonstrated before [18]–[20]. However, they did not reach high peak powers at high repetition rates, and it was not shown that it is possible to amplify few-cycle pulses, nor was the phase stability of the amplifier proven. Also, it has been demonstrated that with Ti:sapphire as gain medium it is highly advantageous to cool the gain crystal to liquid nitrogen (LN2) temperatures [20]–[22]. This is due to the more than one order of magnitude larger heat conductivity and the smaller dependence of the refractive index on temperature variations as compared to room temperature, which enable fast heat removal from the focus region and mitigate thermal lens effects.

2.1. Setup

Figure 1 shows the setup of our experiment. A highly doped Ti:sapphire crystal is mounted in an LN2-cooled copper block, which is placed in a home-built plexiglass vacuum chamber
The Ti:sapphire crystal is 2.6 mm long, Brewster cut, and highly doped ($\alpha \sim 7 \text{ cm}^{-1}$ at 514 nm). Astigmatic compensation needs careful alignment, which we ensured by imaging with a long-working distance microscope objective the focal plane inside a sapphire crystal whose input side was Brewster cut and whose output side was perpendicular to the beam propagation direction. The different indices of refraction of the crystal for pump and seed beam lead to a less than $1^\circ$ difference in incident beam angles on the crystal. After compensation, the laser crystal was put back into place. The vacuum chamber windows are 1 mm thick and carry a broad-band anti-reflective coating. They are mounted 16 mm away from the focal plane in order to prevent damage due to high laser intensity. The LN2 reservoir with a volume of 0.8 liter is a home-built stainless steel dewar that sits on top of the crystal mount and serves as the lid of the vacuum vessel. The chamber is connected to a small turbo-molecular pump with 50 liters s$^{-1}$ pumping speed. The vacuum vessel with the crystal mount is attached to a two-dimensional translation stage that is mounted on the optical table for precise tuning of crystal position against laser beams. The pump beam is generated by a low-noise frequency-doubled Nd:YVO$_4$ laser with up to 18.5 W of output power (Coherent Verdi-18). The first seed beam is generated in a double-chirped mirror dispersion controlled Kerr-lens mode-locked Ti:sapphire oscillator (Nanolayers Venteon, high power version) that is pumped with 6.3 W from another frequency-doubled Nd:YVO$_4$ laser.

Amplifier pump and seed beams are initially aligned to overlap in the crystal with the help of a dichroic mirror that also serves as a focusing mirror for the seed beam ($f = 37.5 \text{ mm}$). The pump beam is focused with an achromatic doublet with $f = 100 \text{ mm}$. The spot size ($1/e^2$ intensity radius) of the pump and seed are measured as 10.2 and 9.1 $\mu$m in the crystal. Too tight focusing of pump and seed reduces the interaction volume within the gain medium. On the other hand, for too weak focusing the small field intensity in the gain medium limits amplification. Optimum focusing can be found by a numerical simulation of the amplification based on rate equations that include focusing [23]. The infrared beam is re-collimated with another curved dichroic mirror, dispersion is compensated with several bounces off chirped mirror pairs, and the
amplified beam is sent to a dispersion balanced interferometric autocorrelator, a spectrometer and/or a power meter.

2.2. Amplification results

Figure 3 displays the output power of the amplifier after filtering out the remaining pump light. It can be seen that the output power monotonically increases with pump power up to 1.1 W, i.e. a gain of 2.1. After careful optimization of the amplification by aligning the pump and seed beams the amplifier runs stably over more than 20 h without any adjustments. At full pump power the crystal mount is at 96 K.

In a typical operating regime, the crystal is far from saturation near the input facet and strongly saturated at the output so that a significant fraction of the gain medium is unsaturated. We thus expect an exponential growth as a function of pump power. Conversion efficiency defined by the ratio between transferred power from pump beam to amplified beam versus total pump power is found to be 3.1%. For the above-mentioned reasons of (partial) saturation, we characterize saturation phenomena in terms of conversion efficiency as opposed to gain. Numerically, we can show that 50% of the maximum conversion efficiency of about 22% (∼4 W output power at 18.5 W pump power) can be extracted at a seed power of about 2 W. This implies that laser beams with such a high input power can also be amplified efficiently. Detailed calculations of the amplification process are complicated and will be discussed in a forthcoming publication [23].
2.3. Beam profiles

The spatial profile of the amplified beam is shown in figure 4. LN2 cooling is necessary to maintain good beam quality and to make use of the full 18.5 W of pump power available. When the amplifier is operated without cooling (crystal mount temperature at $\sim$314 K) the output power starts to decrease with increasing pump power ($>8$ W, figure 3). This is because of the reduced overlap between the pump and the seed beam due to thermal lensing. When the crystal was cooled with double-stacked Peltier elements ($\sim$260 K at crystal mount), strong distortions of the beams were still observed. The monotonic increase of output power as a function of pump power as shown in figure 3 is only possible with LN2 cooling.

2.4. Spectrum and pulse duration

Figure 5(a) shows the spectrum and autocorrelation trace of the laser before and after the amplifier. The beam is more efficiently amplified at the center of the spectrum compared to both spectral wings. Dividing these two curves gives the spectrally dependent gain, also shown in the figure. This gain curve is narrower than the room temperature Ti:sapphire gain spectrum because of reduced thermal excitation of vibrationally excited states at LN2 temperatures. In figures 5(b) and (c), autocorrelation traces measured before and after the amplifier are shown. From the spectrum and initial autocorrelation trace we infer that the laser pulses are less than 6.1 fs long assuming a Gaussian pulse shape; after amplification the pulse duration can be compressed to less than 6.5 fs. The Fourier-limited pulse durations inferred from the spectra are 5.8 and 6.3 fs for un-amplified and amplified pulses, respectively. The amplified spectrum is more evenly distributed and less structured. This is reflected in the reduced side-lobe structure of the amplified autocorrelation trace.
Figure 5. Spectrum and autocorrelation traces. (a) Spectrum of the laser pulses before (1) and after (2) amplification with 18.5 W pump power. The ratio gives the gain spectrum of our amplifier (3). The Ti:sapphire gain curve at room temperature [24] is also shown (4); its peak is scaled so that it matches the peak of curve (3). Curve (5) shows the spectrum of the 200 fs laser. (b) Autocorrelation traces of the ∼6 fs laser pulses before and (c) after amplification with 18.5 W pump power. The full red line shows measured data, the blue line shows a calculated curve obtained from a Fourier transformation of the spectral data in (a) assuming a flat phase. We have checked that no satellite pulses are visible in the autocorrelation traces out to ∼±100 fs.

2.5. White light generation in a bulk crystal

To pursue the possibility of investigating nonlinear processes at high repetition rates it is helpful to focus the amplified beam tightly to obtain high peak intensities. An achromatic triplet objective ($f = 5.8$ mm) is installed in the amplified beam after pre-compensating the positive chirp introduced by the objective. The pulse width at the focus is confirmed to be less than 6.5 fs long by measuring the autocorrelation trace with a 10 μm thick second-harmonic crystal placed in the focus of the objective. The focal radius is measured to be 3.4 μm by imaging with an achromatic microscope objective. With this setup the cycle-averaged peak intensity at the focus is estimated to be $1.0 \times 10^{13}$ W cm$^{-2}$. By placing a 4 mm thick bulk potassium gadolinium tungstate (KGDl[WO$_4$]) or KGW) crystal into the focus [25] we observe white light generation.
including self-trapping, which we infer from the more divergent beam profile (figure 6). This confirms the high peak power. As opposed to self-phase modulation, white light generation scales with power \[26\] whereas the former scales with intensity.

2.6. Phase noise of the carrier-envelope offset frequency after amplification

The CEP stability of few-cycle laser pulses is an important issue especially in nonlinear processes governed by the optical electric field shape. To investigate possible effects of the amplifier on the CEP stability, two carrier-envelope offset frequency detectors are installed to measure possible additional CEP noise from the amplifier (figure 1); \(~60\%\) of the Ti:sapphire oscillator output power is picked up from the main beam, pre-chirp compensated by a pair of chirped mirrors and sent into a highly nonlinear periodically poled magnesium-oxide-doped lithium niobate (PP-MgO:LN) crystal with 13.86 \(\mu\)m period for CEP locking of the laser. After spectral broadening and frequency doubling in the PP-MgO:LN crystal, the green part of the spectrum is detected with an Si avalanche photodiode (Hamamatsu S5343). This way, we routinely obtain the carrier-envelope beat note with more than 45 dB of signal to noise (S/N) ratio in 300 kHz resolution bandwidth. After the amplification, we focus the beam with an achromatic triplet lens into another PP-MgO:LN crystal with 11.21 \(\mu\)m poling period. Dispersion is pre-compensated with chirped mirrors, and 90 mW of laser power is sufficient to generate a 40 dB S/N signal in 300 kHz resolution bandwidth. We mix a part of the output of the in-loop carrier-envelope offset frequency, locked to 20.4 MHz, with the output of the out-of-loop signal, record a 0.5 s long real-time trace of this signal with 200 MS s\(^{-1}\) on a digital oscilloscope (LeCroy WavePro 735Zi) and perform an efficient FFT analysis \[27\] to obtain the two-sided phase noise spectral density as shown in figure 7. The root-mean-square (rms) phase noise is obtained to be 171 mrad, integrated from 40 MHz to 2 Hz, corresponding to 68 as of rms timing jitter. It shows detectable phase noise at frequencies lower than 1 kHz, which can be assigned to mechanical vibrations of the amplifier setup. Above 10 kHz the noise contribution from the amplifier is very small and below the noise floor of our detection system. The integrated rms noise described above is obtained including the noise floor and thus gives a strict upper limit to the amplifier phase noise.
3. Amplification of 200 fs pulses

We have also amplified the output from a 75 MHz repetition rate $\sim$200 fs Ti:sapphire oscillator running at 805 nm center wavelength (Coherent Mira) with the same setup. With 18.5 W of pump power and 400 mW of input power (5.3 nJ) we obtain 1.6 W of output power (21.3 nJ), i.e. a single-pass gain of 4.0 and a power conversion efficiency of 6.5%. The gain is higher in this case because of better spectral overlap with the gain profile of Ti:sapphire as in the few-cycle laser case. To the best of our knowledge this is the most efficient cryogenic single-pass amplification demonstrated so far. The inset of figure 3 shows the output power as function of seed power. From the almost straight curve we infer that amplification is mainly in the small signal gain regime. With these long pulses, a perfect double-pass geometry can be realized with an optical isolator [19, 20] and so double- and multi-passing should enable the even more efficient fully saturated regime to be reached. Also, we infer from figure 5 that the single-pass gain should reach a factor of 5 with a laser running at 780 nm.

4. Summary

We have achieved efficient single-pass amplification of sub-7 fs and $\sim$200 fs near-infrared oscillator pulses in the 75 MHz range by factors of 2.1 and 4.0 with good beam quality. The rms phase noise from the amplifier is characterized to be less than 171 mrad, integrated from 2 Hz to 40 MHz. Ti:sapphire oscillators are being used in many diverse fields spanning from precision spectroscopy of atomic transitions [2] via multi-photon microscopy of (living) tissue [28] to laser surgery [29]. This, together with the empirical notion that for a given pulse duration the
oscillator pulse energy is limited, makes single-pass cryogenic amplifiers a tool of great interest for a large variety of users.

Acknowledgments

We acknowledge Faraz Najafi for help in the initial stage of the experiment, Maximilian Bradler and Eberhard Riedle for the joint white-light generation experiment, Vladimir Pervak for dispersion compensation mirrors, Adrian Cavalieri, Peter Fierlinger and Jens Rauschenberger for loan of equipment. PH welcomes support from MPG, EU and the Munich Center for Advanced Photonics.

References

[1] Takamoto M, Hong F L, Higashi R and Katori H 2005 An optical lattice clock Nature 435 321–4
[2] Udem Th, Holzwarth R and Hänsch T W 2002 Optical frequency metrology Nature 416 233–7
[3] Cundiff S T and Ye J 2003 Colloquium: femtosecond optical frequency combs Rev. Mod. Phys. 75 325–42
[4] Fujimoto J G 2003 Optical coherence tomography for ultrahigh resolution in vivo imaging Nat. Biotechnol. 21 1361–7
[5] Hermann B, Fernandez E J, Unterhuber A, Sattmann H, Fercher A F, Drexler W, Prieto P M and Artal P 2004 Adaptive-optics ultrahigh-resolution optical coherence tomography Opt. Lett. 29 2142–4
[6] Corkum P B and Fender H 2007 Attosecond science Nat. Phys. 3 381–7
[7] Eyler E E, Chieda D E, Stowe M C, Thorpe M J, Schibli T R and Ye J 2008 Prospects for precision measurements of atomic helium using direct frequency comb spectroscopy Eur. Phys. J. D 48 43–55
[8] Herrmann M et al 2009 The 1s–2s transition in singly ionized helium: feasibility of high-precision spectroscopy in the XUV Phys. Rev. A 79 052505
[9] Bucksbaum P H 2007 The future of attosecond spectroscopy Science 317 766–9
[10] Fendel P, Bergeson S D, Udem Th and Hänsch T W 2007 Two-photon frequency comb spectroscopy of the 6s–8s transition in cesium Opt. Lett. 32 701–3
[11] Gohle C, Udem Th, Herrmann M, Rauschenberger J, Holzwarth R, Schuessler H A, Krausz F and Hänsch T W 2005 A frequency comb in the extreme ultraviolet Nature 436 234–7
[12] Jones R J, Moll K D, Thorpe M J and Ye J 2005 Phase-coherent frequency combs in the vacuum ultraviolet via high-harmonic generation inside a femtosecond enhancement cavity Phys. Rev. Lett. 94 193001
[13] Kim S, Jin J H, Kim Y J, Park I Y, Kim Y and Kim S W 2008 High-harmonic generation by resonant plasmon field enhancement Nature 453 757–60
[14] Fuji T, Rauschenberger J, Gohle C, Apolonski A, Udem Th, Yakovlev V S, Tempea G, Hansch T W and Krausz F 2005 Attosecond control of optical waveforms New J. Phys. 7 116
[15] Hommelhoff P, Kealhofer C and Kasevich M A 2006 Ultrafast electron pulses from a tungsten tip triggered by low-power femtosecond laser pulses Phys. Rev. Lett. 97 247402
[16] Xu L, Tempea G, Spielmann C, Krausz F, Stingl A, Ferencz K and Takano S 1998 Continuous-wave mode-locked Ti:sapphire laser focussable to 5 × 10^{15} W/cm^2 Opt. Lett. 23 789–91
[17] Balco P, Cornaggie C, Gomes A S L, Lompre A L and L’Huillier A 1992 Optimizing high-order harmonic-generation in strong fields J. Phys. B: At. Mol. Opt. Phys. 25 4467–85
[18] Liu Z, Murakami H, Kozeki T, Ohtake H and Sarukura N 2000 High-gain, reflection-double pass, Ti:sapphire continuous-wave amplifier delivering 5.77 W average power, 82 MHz repetition rate, femtosecond pulses Appl. Phys. Lett. 76 3182
[19] Huber R, Adler F, Leitenstorfer A, Beutter M, Baum P and Riedle E 2003 12-fs pulses from a continuous-wave-pumped 200-nJ Ti:sapphire amplifier at a variable repetition rate as high as 4 MHz Opt. Lett. 28 2118

New Journal of Physics 11 (2009) 083029 (http://www.njp.org/)
[20] Dantan A, Laurat J, Ourjoumtsev A, Tualle-Brouri R and Grangier P 2007 Femtosecond Ti:sapphire cryogenic amplifier with high gain and MHz repetition rate Opt. Express 15 8864
[21] Backus S, Durfee C G, Mourou G, Kapteyn H C and Murnane M M 1997 0.2-TW laser system at 1 kHz Opt. Lett. 22 1256–8
[22] Zavelani-Rossi M, Lindner F, Le Blanc C, Cheriaux G and Chambaret J P 2000 Control of thermal effects for high-intensity Ti:sapphire laser chains Appl. Phys. B 70 S193–6
[23] Ozawa A, Hommelhoff P, Hänsch T W and Udem Th to be published
[24] Moulton P F 1986 Spectroscopic and laser characteristics of Ti-Al$_2$O$_3$ J. Opt. Soc. Am. B 3 125–33
[25] Bradler M, Baum P and Riedle E 2009 Femtosecond continuum generation in laser host materials Appl. Phys. B to appear
[26] Boyd R W 2003 Nonlinear Optics 2nd edn (London: Academic)
[27] http://fftw.org/
[28] Helmchen F and Denk W 2005 Deep tissue two-photon microscopy Nat. Methods 2 932–40
[29] Yanik M F, Cinar H, Cinar H N, Chisholm A D, Jin Y S and Ben-Yakar A 2004 Neurosurgery—functional regeneration after laser axotomy Nature 432 822

New Journal of Physics 11 (2009) 083029 (http://www.njp.org/)