Fiber-amplifier pumped high average power few-cycle pulse non-collinear OPCPA

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Abstract: We report on the performance of a 60 kHz repetition rate sub-10 fs, optical parametric chirped pulse amplifier system with 2 W average power and 3 GW peak power. This is to our knowledge the highest average power sub-10 fs kHz-amplifier system reported to date. The amplifier is conceived for applications at free electron laser facilities and is designed such to be scalable in energy and repetition rate.

OCIS codes: (140.4480) Optical Amplifiers;(190.4970) Parametric Oscillators and Amplifiers; (190.4410) Nonlinear Optics and Parametric Processes

References and links

1. A. Dubietis, G. Jonusauskas and A. Piskarskas, "Powerful femtosecond pulse generation by chirped and stretched pulse parametric amplification in BBO crystal," Opt. Commun. **88**, 437-440, (1992).
2. J. Piel, M. Beutter, and E. Riedle, "20 50-fs pulses tunable across the near infrared from a blue-pumped noncollinear parametric amplifier," Opt. Lett. **25**, 180-182 (2000).
3. C. Schriever, S. Lochbrunner, P. Krok and E. Riedle, "Tunable pulses from below 300 to 970 nm with durations down to 14 fs based on a 2 MHz ytterbium-doped fiber system," Opt. Lett. **33**, 192-194 (2008).
4. S. Adachi, H. Ishii, T. Kanai, N. Ishii, A. Kosuge and S. Watanabe "1.5 mJ, 6.4 fs parametric chirped-pulse amplification system at 1 kHz," Opt. Lett. **32**, 2487-2489 (2007).
5. N. Ishii, L. Turi, V. S. Yakovlev, T. Fuji, F. Krausz, A. Baltuska, R. Butkus, G. Veitas, V. Smilgevicius, R. Danielius and A. Piskarskas, "Multimillijoule chirped parametric amplification of few-cycle pulses," Opt. Lett. **30**, 567-569 (2005).
6. S. Witte, R.Th. Zinkstok, A.L. Wolf, W. Hogervorst, W. Ubachs and K.S.E. Eikema, "A source of 2 terawatt, 2.7 cycle laser pulses based on noncollinear optical parametric chirped pulse amplification," Opt. Express **14**, 8168-8177 (2006).
7. F. Tavella, Y. Nomura, L. Veisz, V. Pervak, A. Marcinkevicius and F. Krausz, "Dispersion management of a noncollinear optical parametric chirped pulse amplifier," Opt. Lett. **32**, 2227-2229 (2007).

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8. K. Schmid, L. Veisz, F. Tavella, S. Benavides, R. Tautz, D. Herrmann, A. Buck, B. Hidding, A. Marcinkevicius, U. Schramm, M. Geissler, J. Meyer-ter-Vehn, D. Habs and F. Krausz, "Few-Cycle Laser-Driven Electron Acceleration," Phys. Rev. Lett. **102**, 124801 (2009).
9. A. Dubietis, R. Butkus, A. Piskarskas,"Trends in chirped pulse optical parametric amplifiers," IEEE J. Sel. Top. Quantum. Electron. **12**, 163-172 (2006).
10. F. Röser, T. Eidam, J. Rothhardt, O. Schmidt, D. N. Schimpf, J. Limpert, and A. Tünnermann, "Millijoule pulse energy high repetition rate femtosecond fiber chirped-pulse amplification system," Opt. Lett. **32**, 3495-3497, (2007).
11. T. Eidam, S. Hädrich, F. Röser, E. Seise, T. Gottschall, J. Rothhardt, T. Schreiber, J. Limpert, and A. Tünnermann, "325W Average Power Fiber CPA System delivering sub-400fs pulses," IEEE J. Sel. Top. Quantum. Electron. **15**, 187-190, (2009).
12. T. Eidam, S. Hanf, E. Seise, T. Andersen, T. Gabler, C. Wirth, T. Schreiber, J. Limpert, and A. Tünnermann, "Femtosecond fiber CPA system emitting 830 W average output power," Opt. Lett. **35**, 94-96, (2010).
13. S. Hädrich, J. Rothhardt, F. Röser, T. Gottschall, J. Limpert, and A. Tünnermann, "Degenerate optical parametric amplifier delivering sub 30 fs pulses with 2GW peak power," Opt. Express **16**, 19812-19820, (2008).
14. J. Rothhardt, S. Hädrich, F. Röser, J. Limpert, and A. Tünnermann, "500 MW peak power degenerated optical parametric amplifier delivering 52 fs pulses at 97 kHz repetition rate," Opt. Express **16**, 8981-8988, (2008).
15. A.E. Robinson and B. Plummer eds., "Science and technology of future light sources: A white paper," Stanford (2008).
16. W. Ackermann *et. al.*, "Operation of a free electron laser from the extreme ultraviolett to the water window," Nature Photonics **1**, 336-342 (2007).
17. D. Garzella, T. Hara, B. Carre, P. Salieres, T. Shintake, H. Kitamura, M. E. Couprie, "Using VUV high-order harmonics generated in gas as a seed for single pass FEL," Nuclear Instruments and Methods in Physics Research A **528**, 502-505 (2004).
18. G. Lambert, T. Hara, D. Garzella, T. Tanikawa, M. Labat, B. Carre, H. Kitamura, T. Shintake, M. Bougeard, S. Inoue, Y. Tanaka, P. Salieres, H. Merdji, O. Chubar, O. Gobert, K. Tahara and M. E. Couprie, "Injection of harmonics generated in gas in a free-electron laser providing intense and coherent extreme-ultraviolet light," Nature Physics **4**, 296-300 (2008).
19. C. Y. Teisset, N. Ishii, T. Fuji, T. Metzger, S. Köhler, R. Holzwarth, A. Baltuska, A. M. Zheltikov and F. Krausz, "Soliton-based pumpseed synchronization for few-cycle OPCPA," Opt. Express **13**, 6550-6557 (2005).
20. T. Binhammer, E. Rittweger, R. Ell, F. X. Kärtner and U. Morgner, "Prism-based pulse shaper for octave spanning spectra," IEEE J. Sel. Top. Quantum. Electron. **41**, 1552-1557 (2005).
21. F. Tavella, A. Marcinkevicius and F. Krausz, "Inverstigation of the superfluorescence generation in a multiterawatt OPCPA," New J. Phys. **8**, 219 (2006).
22. P. H. Russbüldt, T. Mans, G. Rotarius, D. Hoffmann, R. Poprawe, T. Eidam, J. Limpert, and A. Tünnermann, "Hybrid 400W Fiber-Innoslab fs-Amplifier," in Advanced Solid-State Photonics (2009).

1. Introduction

Ultra-short few-cycle-pulse laser amplifier systems have revolutionized many fields of research in physics. Ultra-short pulse generation based on optical parametric amplification [1] has found wide application in spectroscopy, where tunable sources are needed [2, 3]. It was shown that multi-millijoule few-cycle pulses can be attained at high repetition rate [4] or with high peak power [5, 6, 7]. A multi-TW peak power amplifier system based on the OPCPA technique has already been used for experiments in plasma physics [8]. A substantial overview on existing OPA and OPCPA systems is given in reference [9].

Parametric amplification combined with the chirped pulse amplification technique is to date the only way possible for amplification of sub-10 fs pulses at highest average power. A further increase in average power in OPCPA systems requires high average power pump lasers. Recently, fiber laser systems have reached the millijoule pulse energy range with femtosecond pulse durations [10] and average power as high as 830 W with femtosecond pulses [11, 12]. This generation of amplifier systems is well suited as OPCPA pump laser [13, 14]. Certainly, the tendency in OPCPA amplifier development will in future shift towards higher flux which is required for precision pump-probe experiments and coincidence measurements. Also the latest generation of storage ring-based synchrotron radiation sources and linear accelerator-based free-electron laser (FEL) sources [15] require this kind of laser amplifiers especially for pump probe experiments.

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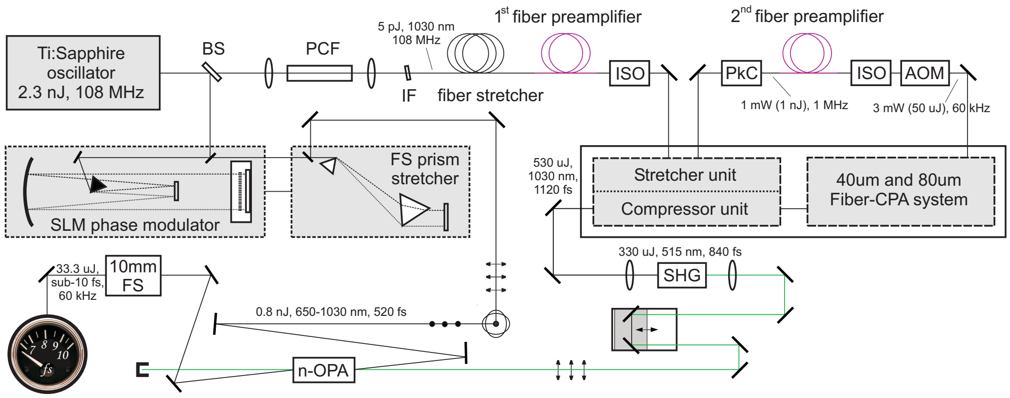

Fig. 1. Optical schematic of the high repetition rate non-collinear optical parametric chirped amplifier system. BS...beam splitter, PCF...photonic crystal fibre, IF...interference filter, ISO...optical isolator, PkC...Pockels cell, AOM...acousto-optical modulator, SLM...spatial light modulator, FS...fused silica, SHG...second harmonic generation, n-OPA...non-collinear optical parametric amplifier.

In addition to pump-probe experiments, a special application at free electron lasers with superconducting accelerator technology [16] is seeding with laser-driven higher order harmonics in gas-target [17, 18] which requires highest repetition rate and multi-millijoule single pulse energy. The optical parametric chirped pulse amplifier we describe here is the front-end of the first high repetition rate few-cycle pulse amplifier systems that will be used at fourth generation EUV and X-ray sources (FEL) at DESY (Hamburg).

2. The amplifier

A detailed schematic of the amplifier system is shown in Fig. 1. A broadband few-cycle Ti:Sapphire oscillator (rainbow, FEMTOLASERS GmBH) is used to seed both the optical parametric amplifier and the fiber chirped pulse amplification (Fiber-CPA) system. The oscillator delivers 2.3 nJ pulses with a 10 dB bandwidth of $\sim$300 nm at 108 MHz repetition rate. The repetition rate is chosen to be a sub-harmonic of the master-clock repetition rate (1.3 GHz) of the FLASH free electron laser to serve for synchronization to the FEL.

Part of the oscillator output (60%) is used to optically seed an Ytterbium-doped fiber amplifier system via solitonic self-frequency shifting [19]. A soliton at 1030 nm with an energy content of about 4 pJ in 5 nm bandwidth is created in a 20 cm long highly nonlinear photonic crystal fiber (NL-PM750, Crystal Fibre) through enhanced nonlinear effects. This radiation is first coupled in a $\sim$100 m long fiber stretcher and subsequently amplified in the first Yb-doped fiber pre-amplifier up to 250 mW average power at 108 MHz. The pulses are then further stretched in a grating stretcher to 1.5 ns. A repetition rate of 1 MHz is picked by a fast Pockels cell with an extinction ratio of 1:500. This train of pulses is then fed into a second Yb-doped fiber preamplifier followed by an acousto-optical modulator (AOM) designed to pick pulses at a lower repetition rate of between 50-200 kHz. The output power after the AOM is up to 2-8 mW, depending on the repetition rate. In the current setup, a rate of 60 kHz is used for a first test of the entire amplifier system. Optimization of the amplifier at higher repetition rates will be investigated in future. The 60 kHz pulse train is fed into a photonic crystal fiber amplifier which is described in detail elsewhere [10]. The design goal of $>500\mu$J compressed pulse energy (530 μJ) was reached at 60 kHz repetition rate attaining 32 W of average power. The pulse

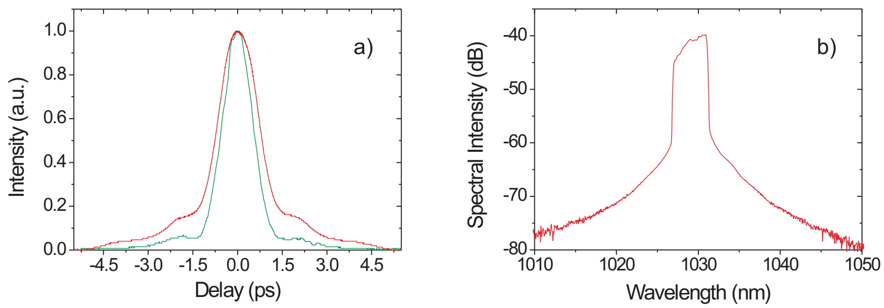

Fig. 2. (a) Autocorrelation measurement of the fundamental pump amplifier pulses (red) and autocorrelation measurement of the second harmonic (green); (b) Spectrum of the amplified 1030 nm pulses.

spectrum and the autocorrelation measurement (τ_{AC}=1.6 ps, thus τ_{FWHM} $\sim$1.1 ps assuming a gaussian pulse shape) are shown in Fig. 2(a) and (b). This radiation is frequency doubled in a 1 mm type I BBO crystal with an efficiency of 60% and used to pump the OPA stage (330 μJ, 20 W, 515 nm). The pulse duration of the second harmonic is also measured Fig. 2(a) and amounts to τ_{FWHM}=840 fs.

The other 40% of the Ti:Sapphire pulse energy is used to seed a non-collinear optical parametric amplifier stage. A spatial light modulator (SLM) in 4-f geometry is used for adaptive control of the spectral phase [20]. This prism based SLM setup is used in combination with a prism stretcher to maximize the transmission through the shaping and stretcher setup ($\eta_{stretcher+SLM}$ $\sim$50%). The prism separation is chosen such to obtain a net negative dispersion of second, third and fourth order, to be used in combination with a glass compressor. The pulses from the Ti:Saphire oscillator are stretched to 520 fs FWHM to match the temporal pump pulse gain window. The negatively chirped pulses sustain already compression in the 4 mm BBO crystal (OPA stage) down to 300 fs FWHM. The remaining dispersion is compensated in a 10 mm fused silica alignment-free compressor ($\eta_{compressor}$ =95%) and by the phase modulator (SLM) up to the sixth order. The CPA setup is configured such to have a compensated second order dispersion. The calculated residual spectral phase coefficients $\frac{\partial^i \phi}{\partial \omega^i}$ of order $i > 2^{nd}$ to 6^{th} at a central wavelength of 760 nm are -1.58E3 fs^3, -1.18E4 fs^4, 1.10E4 fs^5 and -5.26E4 fs^6. These dispersion orders are compensated with the spatial light modulator.

The OPA stage is currently working in the tangential phase matching scheme at a non-collinear angle of 2.22° and the phase matching angle at 24.15°. Angular detuning allows to amplify a larger bandwidth in a 4 mm long type I BBO crystal (see Fig. 3a, dotted line) compared to the ideal phase-matched case. The pump and seed beam diameter used are 0.9 mm and 0.75 mm (FWHM), respectively. The pump intensity is 25 GW/cm^2 and the resulting gain is on the order of $>10^4$.

3. Amplifier performance

The 0.5 nJ seed beam is amplified to 35 μJ of single pulse energy. The average power from seed pulses which are not amplified in the OPA stage is already taken into account. The amplified signal power versus the pump pulse power is shown in Fig. 3(b). The maximum average power extraction is reached at the saturation point of this stage. The level of amplified optical parametric fluorescence is 30 mW as determined by blocking the seed beam and measuring the

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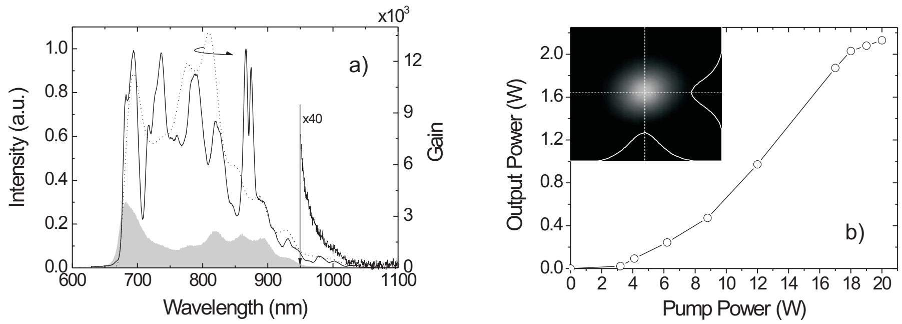

Fig. 3. (a) Spectrum of the 35 uJ, 60 kHz amplified signal pulses (solid line) compared to simulation of gain (dotted line) and oscillator spectrum (shaded grey and solid black line 40x magnification from 950-1100nm); (b) Measured energetics of the optical parametric amplifier stage and of the (inset) amplified beam profile.

OPF content after a ∼3 mm aperture at 1 meter distance from the OPA stage. The effective optical parametric fluorescence (OPF) present in an area which equals the FWHM of the seed beam is smaller by more than one order of magnitude, which is a consequence of the different divergence of the signal beam compared to OPF. Additionally, an OPF quenching effect is expected if the signal beam is present and amplified. An estimate is given by numerical simulation [21] which gives a quenching factor of 3. This results in a value of OPF smaller than 1 mW in presence of the seed beam and taking into account the different divergence of the signal and OPF beam. In this case, the temporal contrast ratio after compression is better than 5 orders of magnitude.

At this saturation level of the OPA stage, also conversion in the second harmonic has been observed. 10% of the signal output was converted, leaving a total amplified signal average output power of 2 W taking into account the compressor efficiency or ∼33.3 μJ compressed pulse energy. The spectrum of the amplified signal is shown in Fig. 3(a) and it's corresponding beam profile in the inset of Fig. 3(b). The pulse duration measurement in this regime of amplification turned out to be challenging due to the large amount of second harmonic light present. A second order autocorrelation measurement is performed with a commercial autocorrelator (Femtometer, Femtolasers GmbH). The correlation trace in Fig. 4(a) shows a deconvoluted compressed pulse duration of 7.8 fs at FWHM (assuming a gaussian pulse shape) attaining a pulse peak power of 3 GW by estimating the energy content at FWHM.

The gain was reduced by a factor of ∼2 to reduce generation of the second harmonic of the signal beam (1.2 W output power) to be able to perform more accurate pulse duration measurements. The compressed pulse duration for these parameters is measured via autocorrelation and is 7 fs. A SPIDER measurement was performed to confirm this result and gives a pulse duration measurement of 6.9 fs. There is still some room of improvement, the Fourier limited pulse duration amounts to ∼6 fs. In this regime of amplification, the amount of amplified optical parametric fluorescence is substantially lower and the average power stability of the OPCPA is 1.3% rms. The pulse stability was measured in unit of power, with an acquisition rate of 4 kHz. The compression results for the 33.3 μJ pulses are shown in Fig. 4(a) while the compression results for the 20 μJ pulses are shown in Fig. 4(b)-(d).

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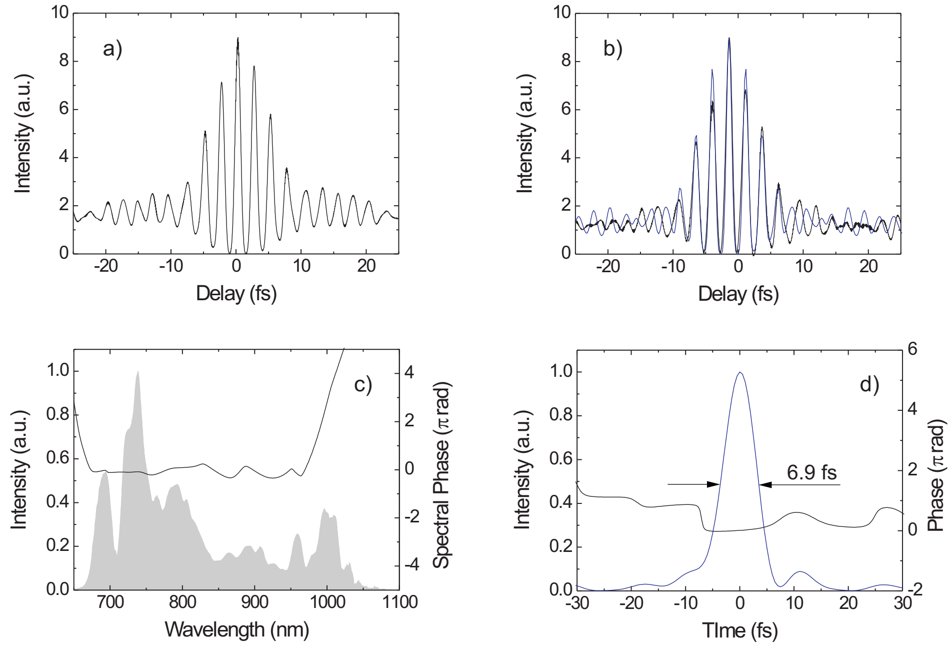

Fig. 4. (a) Interferometric autocorrelation trace of 33.3 μJ pulses b) interferometric autocorrelation trace of 20 μJ signal pulses (black) compared to the calculated autocorrelation trace from a SPIDER measurement (blue). (c and d) SPIDER measurement of the same 20 μJ signal pulses: (c) spectral phase and amplified spectrum; (d) temporal phase and reconstructed temporal pulse shape.

4. Conclusions

We have reported on the generation of 6.9 fs pulses with 20 μJl and 7.8 fs pulses with 33.3 μJ single pulse energy, at 60 kHz repetition rate from an ultrabroadband optical parametric chirped pulse amplifier system. The pulses are stable within 1.3% rms and the calculated maximal pulse peak power amounts to 2.03 and 3 GW, respectively. This optical parametric chirped pulse amplifier represents the first step towards the development of a new generation of ultrashort-pulse high repetition rate amplifiers to be deployed at linear accelerator-based free electron laser EUV and X-ray sources. The pump amplifier technology is scalable in energy and repetition rate[12, 22]. The final objective is to reach MHz repetition rate and several millijoule output pulse energy. Moreover, the output of the optical parametric amplifier has the potential to be shortened in pulse duration. Carrier envelope offset stabilization of the amplified pulses is as well possible and can be implemented in future upgrades of the amplifier.

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