Conclusion

Femtosecond oscillators serve as important instruments in many experiments and are essential elements for amplifier and enhancement cavity systems. The development of such oscillators is of crucial interest. The results presented in Chaps. 2–7 demonstrate reasonable progress in the development of femtosecond high-power lasers. Kerr-lens mode-locked thin-disk Yb:YAG oscillators can lead to many interesting applications in science and technology. Some of which are highlighted in the thesis.

In Chap. 4 an Yb:YAG thin-disk oscillator mode-locked via a SESAM is presented. Many different SESAMs were investigated experimentally, among which only a few samples could be used and all others were damaged due to self-Q-switching. These efforts culminated in the development of an oscillator with 100 W output power, 800 fs pulse duration and 2.5 μJ pulse energy. At this energy level the appearance of CW components in the spectrum was observed. To overcome this limitation an experiment on mode-locking this oscillator in the regime of positive dispersion was carried out, but due to damage to the SESAM no mode-locking could be obtained. The aforementioned experimental efforts lead to the conclusion that SESAMs are limited regarding damage due to the self-Q-switching, surface quality, TPA, heating and the corresponding thermal effects. Simultaneous operation of the oscillator with high power ($>$1 kW intracavity), high energy ($>$20 μJ) and short pulses ($<$300 fs) is limited due to the above-listed shortcomings. Major technological improvements are needed to overcome these obstacles.

Chapter 5 describes the experimental steps in the first realization of KLM in the thin-disk oscillators, motivated by the limitations of SESAM mode- locking. The experimental results of the oscillator operating with 0.5-, 1-, 3-, 6-mm-thick fused silica as Kerr medium are presented. The best performance was reached with the 1-mm-thick Kerr plate and total GDD of $-22000\,\mathrm{fs}^2$. The oscillator was successfully operated with two different output couplers of 5.5 and 14 % transmission. With 5.5 % transmission 200 fs pulse duration and 0.4 μJ pulse energy with 17 W of average power at 15 % optical-to-optical efficiency was achieved. With higher output coupling the parameters were 250 fs, 1.1 μJ, 45 W and 25 % efficiency. These results were obtained with a weak SESAM having a negligible modulation depth $\triangle R < 0.1\,\%$ and

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thermal effects. The chip was developed in the frame of this work. Pure hard-aperture KLM was also realized with similar parameters and a somewhat shorter pulse duration of 190 fs. Peak-to-peak intensity fluctuations of the oscillator are below 0.8 % and are defined by the fluctuations of the pump diodes. The laser shows excellent beam pointing stability with $<10\,\mu$rad and is insensitive to back reflections. This oscillator configuration was also operated in the positive dispersion regime with the weak SESAM as starter. The average power of 17 W and pulse duration of 1.7 ps with a full spectral width of over 20 nm could be reached at an output-coupling transmission of 5.5 %. The pulses were externally compressed down to 190 fs. These parameters were obtained at nearly an order of magnitude lower GDD in comparison with the negative dispersion regime. It was found in experiment that the oscillator could not be started at the positive GDD exceeding 10000 fs^2.

The Yb:YAG thin-disk oscillator was mode-locked via SESAM and pure KLM in the negative and positive dispersion regimes with practically the same resonator configuration. This allows one to make an adequate comparison of those regimes with each other and with the theoretical model presented in Chap. 2.

In Chap. 6 spectral fibre-broadening and compression of 250-fs, 1.1-μJ pulses from the TD oscillator is presented. The sub-40-fs pulses obtained were limited by the bandwidth of the available chirped compressor mirrors. Spectral broadening with a corresponding Fourier limit of 19 fs was achieved at the full power throughput of 40 W. The compressed output was used to detect the f_{CEO} beat signal, which was stable in amplitude for hours and exhibited fluctuations within a 2 MHz range. Preliminary experiments on the stabilization of f_{CEO} via feedback control of the pump diodes show that eliminating noise from the pump diodes as well as acoustic noise from the active TD cooling should enable CE phase-locking with at least sub-radian stability, making high-field experiments possible.

In Chap. 7 a novel method of coupling XUV light out of the cavity and separating it from the driving field is realized. It consists of a glass substrate having a low-loss anti-reflection coating for the wavelength 1030 nm at grazing incidence of 75° and simultaneously serving as a high reflector for radiation in the range of 1–100 nm with reflectivity >60 %. The device can be used for both extra- and intra-cavity XUV generation experiments.

The power scalability of KLM thin-disk oscillators is supported by the energy scaling laws in the regime of positive or negative dispersion, by the power scalability of the thin-disk concept and the absence of absorption or parasitic intensity-dependent effects in a Kerr medium. The combination of the thin-disk concept and Kerr-lens mode-locking has proved its potential in this work and will very likely be a basis for the next generation of all solid-state diode-pumped thin-disk oscillators.

This work was focused on the development of two main prerequisites for creating a compact XUV source: an oscillator with high intracavity intensity and average power as well as a device able to efficiently couple out the generated XUV radiation. This combination justifies the title of this thesis and should allow compact thin-disk-based XUV sources in the near future.

Appendix A
Summary of Different TD Oscillators

Table A.1 Summary of different thin-disk oscillators with output power above 10 W

Gain medium	Mode locker	Pulse duration (fs)	Average power (W)	Pulse energy (μJ)	Repetition rate (MHz)	Reference
Yb:YAG	SESAM	1120	145	0.941	3.5	[1]
	SESAM	1040	108	30.7	3.5	[2]
	SESAM	928	76	25.9	2.93	[3]
	SESAM	810	60	1.7	34.3	[4]
	SESAM	796	63	5.1	12.3	[5]
	SESAM	791	45	11.3	4	[6]
	SESAM	730	16.2	0.5	34.6	[7]
	SESAM	705	80	1.4	57	[8]
	KLM	270	45	1.1	40	[9]
	KLM	200	17	0.4	40	[9]
Yb:Lu_2O_3	SESAM	738	141	2.4	60	[10]
	SESAM	535	63	0.8	81	[11]
	SESAM	523	24	0.4	65	[12]
	SESAM	370	20.5	0.3	65	[12]
	SESAM	329	40	0.5	81	[11]
Yb:$LuScO_3$	SESAM	235	23	0.3	70	[13]
Yb:$KLu(WO_4)_2$	SESAM	440	21.3	0.6	34.7	[14]
Yb:$KY(WO_4)_2$	SESAM; spectral filtering	240	22	0.9	25	[15]

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Appendix B
Laser Housing

The complete oscillator housing can be assembled from components available from Bosch-Rexroth GmbH. It consists of 4 monolithic profiles serving as walls and one 8-mm-thick plexiglass cover (Fig. B.1a). The walls were machined in a workshop to give them 45° edges (Fig. B.1b). The whole construction is very rigid, prevents air turbulence induced by the above situated flow box and has good acoustic insulation.

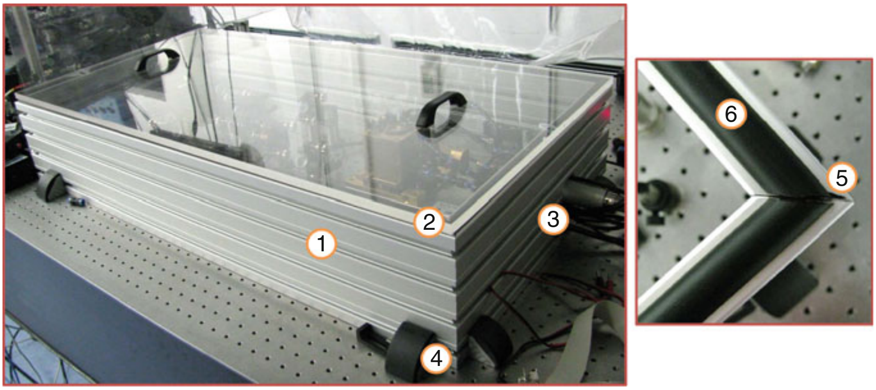

Fig. B.1 Oscillator housing. **a** Photo of the box, assembled from 4 pieces of monolithic Bosch-Rexroth profile; **b** 45°-joint between two walls and a sealing rubber profile

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Appendix C
Data Archiving

The experimental raw data used in this thesis, the evaluation files, as well as the LaTeX source code of the thesis can be found on the data archive server of the Max Planck Institute of Quantum Optics, Laboratory for Attosecond Physics, in the following directories:

Oscillator	Master directory, containing the LaTeX code and other important directories:
Chap. 1 Figs, Chap. 2 Figs, Chap. 3 Figs etc.	Directories containing the figures ordered according to their appearance in the thesis
Publications	The journal papers co-authored by O. Pronin, in .pdf format

In the following, a complete list of the directories Chap. 1 Figs, Chap. 2 Figs etc. containing figures, measurement and/or simulation data is given.

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	Directory **Chap. 1 Figs**	
Fig. 2.6	Oscilloscope screenshot	QML.pptx
	Directory **Chap. 2 Figs**	
Fig. 3.3b	Calculated data	CavitySimple.opj Calculated by Jonathan Brons. Standard ABCD matrix formalism
Fig. 3.4	Measurement data	OutputPowerSimple.opj
Fig. 3.5b	Calculated data	CavitySimple.opj Calculated by Jonathan Brons. Standard ABCD matrix formalism
	Directory **Chap. 3 Figs**	
Figs. 4.2, 4.3	Measurement data	SESAMs.opj Measured by Farina Schättiger and Dominik Bauer
Fig. 4.4	Measurement data	absR.opj
Fig. 4.6	Measurement data	Embedded in: surfaceSAM.pptx Measured by Mikhail Larionov
Fig. 4.7	Measurement data	Embedded in: surfaceBatop.pptx Measured by Dominik Bauer
Fig. 4.8	Measurement data	Embedded in: temperatureHD.pptx
Fig. 4.9	Calculated data	cavitySAM.opj Calculated in Winlase software
Fig. 4.12	Measurement data	specsM4838.opj
Fig. 4.13	Measurement data	outputPowerSAM.opj
Fig. 4.14	Measurement data	specsBatop2.opj
Fig. 4.15	Simulation data	EvsGddBatop2.opj Simulated by Vladimir Kalashnikov. Described in text
Fig. 4.16a	Measurement data	chaoticQswitch1.opj
Fig. 4.16b	Simulation data	chaoticQswitch2.opj Simulated by Vladimir Kalashnikov. Described in text
	Directory **Chap. 4 Figs**	
Fig. 5.3	Calculated data	ModeVsd.opj Calculated by Jonathan Brons. Standard ABCD matrix formalism
Fig. 5.5	Measurement data	SpecsSF57.opj
Figs. 5.6, 5.7	Measurement data	specsThickGlass.opj
Fig. 5.8	Measurement data	specs1mm5_5OC.opj
Fig. 5.9	Measurement data	specs1mm14OC.opj
Fig. 5.10	Measurement data	specs1mmHardaperture.opj
Fig. 5.12	Measurement data	noiseKLM.opj
Fig. 5.13	Measurement data	rfKLMSESAM.opj
Fig. 5.16	Measurement data	buildupPDR.opj
Fig. 5.17	Measurement data	spectraPDR.opj
Fig. 5.18	Measurement data	acPDR.opj
Fig. 5.19, Fig. 5.20	Measurement data	Embedded in: NomarskiAndThermo.pptx
Fig. 5.21	Measurement data	specs1mmYbLuO.opj

	Directory **Chap. 5 Figs**	
Fig. 6.2a	Measurement data	LMA2535.opj
Fig. 6.4	Measurement data	LMA35compressed.opj
Fig. 6.6	Optical spectrum analyzer screenshot	octavePCForig.jpg
Fig. 6.7	Measurement data	octaveBulk.opj
Fig. 6.9	RF spectrum analyzer screenshot	Embedded in: CEphase.pptx
	Directory **Chap. 6 Figs**	
Fig. 7.2	Calculated data	SapphFS.opj Calculated in Optilayer software
Fig. 7.4	Calculated data	RvsNm85.opj Calculated in Optilayer software
Fig. 7.5	Calculated data	RvsNm85.opj Calculated in Optilayer software by V. Pervak
Fig. 7.7, Fig. 7.8	Measurement data	ARmeasured.opj Measured at PTB Bessy

Curriculum Vitae

Contact information
Name: Oleg Pronin
Address: Ludwig-Maximilians-Universität
München (LMU),
Am Coulombwall 1, 85748 Garching
Phone: +49 (0) 89 289 14187
E-mail: oleg.pronin@mpq.mpg.de
http://www.attoworld.de/

Personal data
Date of birth: April 4th, 1985
Place of birth: Ertil, Voronezh District, Russia
Nationality: Russian

Education
2008–2012:
Ph.D. student at Max Planck Institute of Quantum Optics.
Laboratory of Attosecond and High-Field Physics. Group of Prof. Dr. Krausz.
Ph.D. thesis : Towards a compact thin-disk-based femtosecond XUV source.
2002–2008:
Moscow Engineering and Physics Institute (MEPhI, Technical university), Department of Laser physics
Diploma thesis: Optical diagnostics of the plasma lens for a heavy-ion beam focusing system. Supervisor: Dr. Andrey Kuznetsov.
1992–2002:
Elementary and high school

Summer school
08.2006–09.2006:

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GSI (Gesellschaft für Schwerionenforschung) summer school. Data analysis in Matlab.

Working experience
2012–present:
Postdoc at Ludwig-Maximilians-Universität München.
Laboratory of Attosecond and High-Field Physics. Group of Prof. Dr. Krausz.
2005–2008:
Engineer (part-time) at the Institute of Theoretical and Experimental Physics (ITEP), Moscow.

Scholarships
2008–present:
Scholarship of the International Max Planck Research School (IMPRS) on Advanced Photon Science.
2005–2008:
Honorary scholarship at the Institute of Theoretical and Experimental Physics (reviewed periodically every year)

Language skills
Russian mother-tongue, English, German (basic knowledge)

Sport Tennis, cycling, hiking

Publications

Journal Publications

- O. Pronin, J. Brons, C. Grasse, V. Pervak, G. Boehm, M.-C. Amann, A. Apolonski, V. Kalashnikov, and F. Krausz, "High-power Kerr-lens mode-locked Yb:YAG thin-disk oscillator in the positive dispersion regime," *Opt. Lett.*, vol. 37, no. 17, pp. 3543?3545, 2012.
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