Third-generation femtosecond technology: supplementary material

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We briefly recapitulate the evolution of femtosecond optical pulse generation directly from laser oscillators (at multi-MHz repetition rates) and the boosting of their peak and average power at kHz-to-MHz repetition rates in subsequent laser (1FST, 2FST) and parametric amplifiers, with the latter serving as the basis for 3FST. (see the primary article, <http://dx.doi.org/10.1364/optica.1.000045>). A detailed discussion of the thin-disk technology, OPCPA and HHG simulation is presented in sections 2, 3 and 4. © 2014 Optical Society of America

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1. Femtosecond Technology – Brief Historical Overview

1.A. First Generation: Femtosecond Dye Lasers

The femtosecond era was heralded by the advent of the dye laser in 1970 [1]. Phase locking the longitudinal modes (briefly: modelocking, [2-4]) of cw dye lasers by a “slow” saturable absorber yielded near-1-ps pulses [5-7] and dispersion compensation allowed their gradual shortening to 200 fs [8, 9]. The implementation of colliding-pulse modelocking (CPM) allowed the 100-fs barrier to be broken [10, 11]. Improvement of

the control of the intracavity group-delay dispersion (GDD) [12-14] led to the generation of pulses as short as 27 fs [15]. Extracavity pulse compression based on self-phase modulation in a single-mode fiber followed by chirp compensation in a grating-pair-based dispersive delay line [16] gave rise to a further decrease in pulse duration to reach the long-standing record of 6 fs by 1987 [17].

The above results were achieved at pulse energies of the order of 1 nanojoule, corresponding to peak powers of a fraction of 1 megawatt in the red/near-infrared spectral range. Dye amplifiers pumped by kHz-rate lasers boosted the energy and peak power of femtosecond pulses to microjoules and tens of megawatts,

respectively [18, 19]. The peak and average power achieved with the best-performing system is depicted in Fig. 1 of the paper. Detailed discussions of ultrashort-pulse dye lasers can be found in [20-22].

1.B. Second Generation: Femtosecond CPA Solid-State Lasers

A variety of broadband transition-metal-doped laser crystals and their performance had been demonstrated by the end of the 1980's [23-25]. Thanks to its excellent optical, mechanical and thermal properties, titanium-doped sapphire ($\text{Ti}^{3+}\text{Al}_2\text{O}_3$ or Ti:Sa, gain band: 650-1050 nm) stood out and became the first choice of laser material for femtosecond lasers. Shortly after the demonstration of the first Kerr-lens mode-locked (KLM) Ti:Sa laser oscillator in 1991 by Sibbett and coworkers [26] and subsequent pioneering experimental [27, 28] as well as theoretical [29-32] work, chirped mirrors [33, 34] allowed GDD control over the entire bandwidth of the laser oscillator and – for the first time – the routine generation of few-cycle pulses (with a carrier wavelength of $\sim 750\text{-}800\text{ nm}$) directly from a laser oscillator [35, 36]. Femtosecond KLM Ti:Sa lasers rapidly became the workhorse in ultrafast laser laboratories all over the world (for comprehensive reviews, see [22, 37]).

The technique of chirped-pulse amplification (CPA) invented by Mourou and coworkers [38-40] permitted boosting the nanojoule pulse energies by many orders of magnitude in external amplifiers. When coupled to external broadening, fiber-based CPA amplifier systems represent a compact and easy-to-handle source of femtosecond pulses in the range of MHz repetition rates (e.g. [41]). Generation of sub-30-fs pulses with average powers as high as 135 W have been achieved in such systems with the incorporation of coherent combination of pulses [42].

KLM Ti:Sa systems have also largely benefited from the CPA technology. Here, we briefly review these advances at kHz repetition rates. Careful control of pulse dispersion [43] and spectral shaping to combat gain narrowing [44] allowed for the generation of 30-fs-scale several-millijoule-energy pulses at kHz repetition rates [45-52]. The average power of the resultant pulses with terawatt-scale peak powers could be increased up to 40 W by cryogenic cooling of the gain medium [53]. Thermally-induced beam degradation prevented the scaling of Ti:Sa-based femtosecond amplifiers beyond this record so far (for a summary of some of the most powerful kHz Ti:Sa systems, see Fig. 1).

For exploiting extreme nonlinearities of matter and pushing the frontiers of ultrafast science into the attosecond regime, powerful femtosecond pulses had to be shortened to the ultimate limit of femtosecond technology, to laser pulses carrying a dominant fraction of their energy in a single oscillation cycle of the electromagnetic field [37]. For the first time, this goal could be achieved via self-phase modulation of energetic sub-30-fs-duration pulses from Ti:Sa systems in gas-filled hollow-core fibers [54] and by their subsequent temporal compression in a series of dispersive chirped multilayer mirrors (henceforth briefly: chirped-mirror compressor) [33, 55, 56]. Advances in chirped mirrors meanwhile allowed the generation of 3.3-fs pulses (full-width at intensity half maximum) at a carrier wavelength of 720 nm (oscillation cycle: 2.4 fs) [57]. This technique is routinely applicable – and is being used in dozens of laboratories – up to pulse energies of the order of 1 mJ [58]. Excessive ionization and thermal instabilities limit the achievable peak and average power from these few-cycle pulse generators to approximately 1 TW and 10 W, respectively [59, 60]. These limits of few-cycle pulse generation may be overcome by broadband OPA, addressed in Sec. 3.

2. Power and Energy Scaling of Thin-Disk Amplifiers

The scaling of power and energy have already been demonstrated separately beyond 1 kW [61] and several hundreds of mJ [62, 63], respectively. Reaching these parameters simultaneously has not yet been achieved, due to the challenges presented by the difference in laser parameters optimal for high peak power and high average power. At average powers below $\sim 100\text{ W}$, amplified spontaneous emission (ASE) provides the ultimate limitation for the achievable energy, but at higher average powers the inevitable increase in the temperature of the laser medium plays an important role. Minimization of these two effects places opposing constraints on the thin-disk parameters such as doping concentration, diameter and thickness of the thin-disk. The accumulated nonlinear phase distortions in the pulse during the amplification also restrict the energy scalability, which can be mitigated by CPA [38], i.e. by first stretching the low-energy seed pulse to hundreds ps or more, followed by amplification in the thin-disk regenerative and/or multipass amplifier, and finally recompressing the pulse.

ASE: Amplified spontaneous emission inevitably arises in any laser amplifier. ASE depends strongly on the gain and therefore on both the thickness of the thin-disk and the diameter of the pumped region. In the presence of feedback due to reflecting surfaces, strong ASE can cause parasitic lasing, strictly limiting the achievable population inversion.

The total ASE cannot be directly measured and its detailed treatment is out of scope of this article, but several theoretical calculations have been done for thin-disk media, including volumetric integration over the amplified volume [64], numerical calculation of time-dependent evolution with amplified linewidth and gain narrowing included [65, 66]. The ASE can be controlled by optimizing the gain and the size of the laser medium, by minimizing feedback at the edges of the amplification volume, using beveled disks [64, 67-69] including treatment to the side of the disk [70] or utilizing an undoped anti-ASE cap [71]. In the model used for our numerical study, the effective decay rate approximation was employed, following [64], giving an effective reduction in the upper state lifetime associated with transverse ASE, expressed by

$$\tau_{eff} = \frac{\tau_0}{1 + e^{2g\xi}/2\xi}, \quad (1)$$

where τ_0 is the fluorescence lifetime, g is the gain; ξ is the geometric factor; defined as $\xi = D/2d$, D is the diameter of the pump spot and d is the thickness of the disk. It follows from Eq. (1) that increased gain and disk diameter will increase the ASE, while increased disk thickness d will keep the ASE level fixed at constant gain, while increasing the energy storage capacity of the medium. However, increasing the thickness will have a deleterious effect on thermal management.

Temperature: In the thin-disk geometry, the absorbed pump energy not removed via stimulated emission dissipates following the one-dimensional temperature gradient from the disk to the cooler in the form of heat. Although thin-disk lasers with YAG as the host material show robust behavior against thermo-mechanical distortions [72], the achievable population inversion is inversely proportional to the temperature [64, 67, 68]. The average temperature inside the disk can be expressed as:

$$\bar{T} = \frac{\eta_H d}{3k_T(T)} I_p + T_0 \quad (2)$$

where k_T (T) is the thermal conductivity of the disk, I_p is the absorbed pump power and T_0 is the temperature of the cooler. $\eta_H = (1_L - 1_P)/1_L$ is the fractional heat parameter, where 1_P and 1_L

are the pump and laser wavelengths, respectively. Under typical experimental conditions, η_H tends to have a higher value due to additional relaxation and heat recapture effects. Therefore its expected value should be measured experimentally, for example by using a thermal imaging camera. In our simulation we used the measured values of $\eta_H=0.15$ for $\lambda_p=940$ nm and $\eta_H=0.07$ for $\lambda_p=969$ nm. Eq.(2) indicates that for high average power amplification, thinner disks are favorable.

B-integral: The total accumulated non-linear phase distortions can be estimated by B-integral, expressed here as a summation of the consecutive passes through the amplifier:

$$B = \frac{8}{\lambda \tau} \sum \left[E_k \int \frac{n_2(z)}{D^2(z)} dz \right] \quad (3)$$

where λ is the wavelength, τ is the pulse duration, E_k is the pulse energy at the k -th pass and $D(z)$ is the effective beam diameter of the laser beam. $n_2(z)$ shows the nonlinear refractive index of the optical components through which the laser passes. In a thin-disk regenerative amplifier, the Pockels cell crystal is the major source of B-integral, as it is the thickest transmission optical element in a typical cavity. It is essential to keep the cavity mode as large as possible, in particular through the Pockels cell, but this is limited in practice by the available crystal aperture and the required half-wave voltage.

The direct contribution of the disk thickness to the B-integral compared to the air and Pockels cell is small. However, the number of required passes for saturation should be as low as possible and consequently the gain should be as high as possible for minimizing the required amount of stretching and size and cost of the compressor gratings. In a thin-disk multipass amplifier, air has the main contribution to the the B-integral, making operation in vacuum necessary for extremely high pulse energies.

A regenerative amplifier (RA) and a multipass amplifier (MP), each consisting of two optimized thin-disk modules pumped at 969 nm, were designed for energy amplification up to 200 mJ and 2 J, respectively. Detailed parameters of these two systems are summarized in Table S1.

Table S1: Designed parameters of thin-disk amplifiers

energy (J)	type	pump diameter (mm)	pump power (kW)	stretched-pulse duration (ns)
0.2	RA/air	7	2	1.8
2	MP/vac.	15	12	0.2

3. OPCPA Simulations

We performed numerical simulations of the tunable OPCPA system and the multi-channel synthesizer, using the SISYFOS code. SISYFOS uses a Fourier-space method to simulate second-order nonlinear interactions. In this method each beam is decomposed into plane-wave eigenmodes and the coupled differential equations are solved for the slowly varying eigenmode amplitudes [73, 74]. The code is capable of handling wide bandwidths, linear and two-photon absorption, thermal effects, nonlinear refraction, parasitic processes and non-collinear beams with possibly tilted pulse fronts.

In the following study, thermal effects are not included and the Sellmeier coefficients are taken from [75-77]. The multi-channel OPCPA synthesizer is designed for maximum spectral bandwidth and conversion efficiency. The latter has been improved by using the residual pump energy after the penultimate amplifier stage for

pumping the final stage [78]. In the crystal of the last stage, the phase-matching angle, non-collinear pump-signal angle, spatial walk-off and the spatial overlap of the interacting beams are slightly readjusted for maximum efficiency. The pulse front of the pump and seed beams are assumed to be perpendicular to the their propagation direction. A linearly-chirped super-Gaussian spectrum of order four is used for the seed pulses and we have assumed a Gaussian beam profile for both pump and seed and a Gaussian temporal profile of the pump pulses. The pump- and seed-pulse duration in each channel is set to 1.6 ps full width at intensity half maximum (FWHM). After setting the pump beam diameter such that the desired on-axis peak intensity (or energy fluence) is realized, the size of the seed beam is optimized for best efficiency and amplified beam profile. In the experimental spectrum shown in Fig. 8, different spectral regions, 1600 nm to 2800 nm (MIR channel), 700 nm to 1400 nm (NIR channel) and 450 nm to 650 nm (VIS channel), contain 40 %, 40 %, and 3.5 % of the total energy of the super-continuum, respectively. In our study, we have assumed the same spectral energy distribution for the input seed containing a total energy of 6.5 μ J.

We have considered two types of phase-matching schemes for the MIR channel: (i) Near-collinear, degenerate OPA using a type-I, LiNbO₃ crystal with a signal-optical axis phase-matching angle (θ) of 45°. (ii) Non-collinear type-I geometry in a BBO crystal with an internal pump-signal angle (α) of 2.2° and $\theta = 20^\circ$.

Although amplification in a BBO crystal with a length of 2 mm supports pulses as short as 19 fs, the linear absorption coefficient of the crystal at 2.55 μ m reaches 0.5 cm⁻¹ and the accumulated heat in this process may impede the OPCPA conversion efficiency [79]. For $\alpha = 3^\circ$ the center of the amplified spectrum moves to a higher frequency, but the amplified spectral bandwidth only supports 43 fs pulses. Therefore, LiNbO₃ is chosen as the gain medium for a 4-stage MIR OPCPA chain pumped with the total pulse energy of 86 mJ. The residual pump energy surviving the third stage is reused to pump the fourth stage. The pump intensity in all stages is kept at 70 GW/cm² to avoid photorefraction [80]. The d_{eff} is assumed to be 3.3 pm/V. The details of the MIR OPCPA chain are summarized in Table S2 and Table S3.

Table S2. The detailed parameters of the MIR OPCPA chain

stage	Pump energy (mJ)	Crystal thickness (mm)	Amplified energy (mJ)
1	1	2.5	0.146
2	7	1.7	1.3
3	78	1.4	12
4	--	1.1	19.2

Table S3. Beam diameters of the MIR OPCPA chain

stage	1 st	2 nd	3 rd	4 th
Pump _{FWHM} (mm)	0.9	2.4	7.6	6.1
Seed _{FWHM} (mm)	0.9	D _{amp} ×3	D _{amp} ×3.5	D _{amp} ×1.2

*D_{amp}: diameter of the amplified signal beam

In the second-harmonic-pumped NIR channel, utilizing a BBO crystal with $\alpha = 2.2^\circ$ and $\theta = 22^\circ$, or an LBO crystal with $\alpha = 1.1^\circ$, $\theta = 90^\circ$ and $\varphi = 15.5^\circ$ in the non-collinear type-I geometry leads to a broad phase-matching bandwidth. Our crystal of choice is LBO as the gain medium because it supports somewhat shorter amplified pulses. The NIR OPCPA chain also consists of 4 crystals being pumped with a total energy of 74 mJ and the peak pump intensity of 110 GW/cm² resulting in 22.7-mJ amplified pulse energy for the d_{eff} value of 0.82 pm/V. The detailed parameters of the NIR chain are summarized in Table S4 and Table S5.

Table S4. Detailed parameters of the NIR channel

stage	Pump energy (mJ)	Crystal thickness (mm)	Amplified energy (mJ)
1	1	2.5	0.189
2	7	1.5	1.6
3	66	1.5	14
4	--	1.2	22.5

Table S5. Beam diameters of the NIR OPCPA chain

stage	1 st	2 nd	3 rd	4 th
Pump _{FWHM} (mm)	0.7	1.8	5.6	4.5
Seed _{FWHM} (mm)	0.7	*D _{amp} ×2.5	D _{amp} ×3.2	D _{amp} ×1.2

Finally the VIS channel pumped with 40-mJ, 343-nm pulses has been modeled by using type-I BBO crystals with $\theta = 32.7^\circ$ and $\alpha = 4.5^\circ$ in 3 amplifier stages. The pump intensity in all stages is kept to 70 GW/cm² to avoid BBO degradation over time [81]. With pump energies of 3 mJ and 37 mJ for the first two OPCPA stages and reusing the residual pump energy of the second stage in the third stage, 7.1 mJ, 5.1 fs pulses could be generated where the d_{eff} is 1.56 pm/V. The detailed parameters of the chain are summarized in Table S6 and Table S7.

Table S6. Detailed parameters of the VIS channel

stage	Pump energy (mJ)	Crystal thickness (mm)	Amplified energy (mJ)
1	3	1.2	0.474
2	37	0.7	4.8
3	--	0.5	7.1

Table S7. Beam diameters of the VIS channel

stage	1 st	2 nd	3 rd	4 th
Pump _{FWHM} (mm)	0.7	1.8	5.6	4.5
Seed _{FWHM} (mm)	0.7	D _{amp} ×2.5	D _{amp} ×3.2	D _{amp} ×1.2

For the numerical study of the tunable OPCPA system, we have assumed a Gaussian beam profile for both pump and seed and a Gaussian temporal profile of the pump pulses. By using different harmonics of a 10 kHz, Yb:YAG regenerative amplifier an different crystals, mJ, sub-40-fs pulses, tunable from 445 nm to 2750 nm could be generated (Table S8). The amplification chain consists of two cascaded OPCPA stages, where the residual pump energy after the first stage is used to pump the second stage. The tunability of the system is achieved by changing the temporal delay between pump and seed pulses and fine tuning of the phase-matching angle of the crystals at OPCPA stages. The length of the OPCPA crystals is kept constant for each chain, pumped by different harmonics. As the amplification gain is different for different frequencies, the gain saturation of all the frequencies in one set of crystal lengths is ensured by shaping and scaling the amplitude of the input signal to the cascaded OPCPA stages. Utilizing a prism compressor, these sub-40-fs pulses could be compressed close to their Fourier transform limit.

Table S8. Detailed parameters of the tunable OPCPA system.

pump harmonic	pump energy (mJ)	crystal	tunable bandwidth (nm)
fundamental	12	LiNbO ₃	1500-2750
second harmonic	10	LBO	670-1420
third harmonic	8	BBO	445-660

4. HHG simulations

The optimization of the Fourier transformed waveform of the multi-terawatt synthesizer is done both by solving numerically the time-dependent Schrödinger equation for a single atom as well as

using the classical approach based on the simple man's model [82, 83]. The goal is to reach the highest cut-off energy in the HHG process. The optimization is performed in terms of the global phase and the spectral chirp of the waveform, the highest cut-off energy is achieved for the global phase = $\pi/4$ and a group delay dispersion of 4 fs². There will be a larger number of free parameters in the multichannel synthesizer, but a full spectral phase and amplitude optimization of all channels is beyond the scope of this study.

Fig. 13(e) of the main manuscript shows the harmonic flux generated by a cylindrically symmetric laser beam in an infinitesimally thin layer of helium atoms. The single-atom dipole response is evaluated within the strong-field approximation [84] using a model that accounts for the depletion of the atomic ground state, but neglects the contribution from ions to high-harmonic generation [85]. We have neglected the magnetic drift as the electron in this parameter regime is not yet relativistic (see e.g. [86, 87]). The energy of the waveform is set to 49 mJ and the beam waist was adjusted in such a way to have the peak intensity of $I \sim 9 \times 10^{15}$ W/cm², corresponding to a peak electric field $E_0 \sim 0.5$ atomic units, in the laser focus. From the comparison between the HHG spectra obtained by using a Gaussian pulse and the one generated by the pre-optimized waveform (see Fig. 13(e)) it can be seen, while the strong ground-state depletion makes the cut-off practically invisible in the case of Gaussian pulse, and optimized waveform leaves a sufficient number of neutral atoms by the time when electron trajectories with the highest recollision energy get launched. This leads to an extension on the harmonic cut-off and an increase in the harmonic flux in the keV energy region. This would pave the way to the generation of high energy coherent radiation by using pre-optimized waveforms.

References

1. O. G. Peterson, S. A. Tuccio, and B. B. Snively, "CW operation of an organic dye solution laser," Appl. Phys. Lett. **17**, 245-247 (1970).
2. M. DiDomenico, "Small-signal analysis of internal (coupling-type) modulation of lasers," J. Appl. Phys. **35**, 2870-2876 (1964).
3. L. E. Hargrove, R. L. Fork, and M. A. Pollack, "Locking of He-Ne laser modes induced by synchronous intracavity modulation," Appl. Phys. Lett. **5**, 4-5 (1964).
4. A. Yariv, "Internal modulation in multimode laser oscillators," J. Appl. Phys. **36**, 388-391 (1965).
5. C. V. Shank and E. P. Ippen, "Subpicosecond kilowatt pulses from a mode-locked cw dye laser," Appl. Phys. Lett. **24**, 373-375 (1974).
6. E. P. Ippen, C. V. Shank, and A. Dienes, "Passive mode locking of the cw dye laser," Appl. Phys. Lett. **21**, 348-350 (1972).
7. H. Uchiki, M. Yoshizawa, and T. Kobayashi, "Pulse shortening in dye laser side-pumped by TEA N<inf>2</inf>laser," Quantum Electronics, IEEE Journal of **19**, 551-557 (1983).
8. E. P. Ippen and C. V. Shank, "Dynamic spectroscopy and subpicosecond pulse compression," Appl. Phys. Lett. **27**, 488-490 (1975).
9. J. C. Diels, E. Vanstryland, and G. Benedict, "Generation and measurement of 200 femtosecond optical pulses," Opt. Commun. **25**, 93-96 (1978).
10. R. L. Fork, B. I. Greene, and C. V. Shank, "Generation of optical pulses shorter than 0.1 psec by colliding pulse mode-locking," Appl. Phys. Lett. **38**, 671-672 (1981).

11. M. Yoshizawa and T. Kobayashi, "Experimental and theoretical studies on colliding pulse mode locking," *Quantum Electronics, IEEE Journal of* **20**, 797-803 (1984).
12. W. Dietel, E. Doppel, D. Kuhlke, and B. Wilhelmi, "Pulses in the femtosecond range from a cw dye ring laser in the colliding pulse mode-locking (CPM) regime with down-chirp," *Opt. Commun.* **43**, 433-436 (1982).
13. W. Dietel, J. J. Fontaine, and J. C. Diels, "Intracavity pulse-compression with glass - a new method of generating pulses shorter than 60 fsec," *Opt. Lett.* **8**, 4-6 (1983).
14. R. L. Fork, O. E. Martinez, and J. P. Gordon, "Negative dispersion using pairs of prisms," *Opt. Lett.* **9**, 150-152 (1984).
15. J. A. Valdmanis, R. L. Fork, and J. P. Gordon, "Generation of optical pulses as short as 27 femtoseconds directly from a laser balancing self-phase modulation, group-velocity dispersion, saturable absorption, and saturable gain," *Opt. Lett.* **10**, 131-133 (1985).
16. E. B. Treacy, "Measurement of picosecond pulse substructure using compression techniques," *Appl. Phys. Lett.* **14**, 112 (1969).
17. R. L. Fork, C. H. B. Cruz, P. C. Becker, and C. V. Shank, "Compression of optical pulses to 6 femtoseconds by using cubic phase compensation," *Opt. Lett.* **12**, 483-485 (1987).
18. W. H. Knox, M. C. Downer, R. L. Fork, and C. V. Shank, "Amplified femtosecond optical pulses and continuum generation at 5-kHz repetition rate," *Opt. Lett.* **9**, 552-554 (1984).
19. C. Rolland and P. B. Corkum, "Amplification of 70-fs-pulses in a high repetition rate XeCl pumped dye-laser amplifier," *Opt. Commun.* **59**, 64-68 (1986).
20. C. V. Shank, "Generation of ultrashort optical pulses," *Topics in Applied Physics* **60**, 5-34 (1988).
21. J. C. Diels, "Chapter 3 - Femtosecond dye lasers," in *Dye Laser Principles*, F. J. Duarte and L. W. Hillman, eds. (Academic Press, San Diego, 1990), pp. 41-132.
22. P. M. W. French, "The generation of ultrashort laser-pulses," *Rep. Prog. Phys.* **58**, 169-262 (1995).
23. P. F. Moulton, "Spectroscopic and laser characteristics of Ti-Al₂O₃," *Journal of the Optical Society of America B-Optical Physics* **3**, 125-133 (1986).
24. V. Petričević, S. K. Gayen, R. R. Alfano, K. Yamagishi, H. Anzai, and Y. Yamaguchi, "Laser action in chromium-doped forsterite," *Appl. Phys. Lett.* **52**, 1040-1042 (1988).
25. E. Sorokin, S. Naumov, and I. T. Sorokina, "Ultrabroadband infrared solid-state lasers," *IEEE J. Select. Top. Quantum Electron.* **11**, 690-712 (2005).
26. D. E. Spence, P. N. Kean, and W. Sibbett, "60-fsec pulse generation from a self-mode-locked Ti-sapphire laser," *Opt. Lett.* **16**, 42-44 (1991).
27. U. Keller, G. W. Thooft, W. H. Knox, and J. E. Cunningham, "Femtosecond pulses from a continuously self-starting passively mode-locked Ti-sapphire laser," *Opt. Lett.* **16**, 1022-1024 (1991).
28. L. Spinelli, B. Couillaud, N. Goldblatt, and D. K. Negus, "Starting and generation of sub-100 fs pulses in Ti:Al₂O₃ by self-focusing," in *Conference on Lasers and Electro-Optics*, O. T. D. Series, ed. (Optical Society of America, Washington, D.C., 1991), p. CPDP7.
29. M. Piche, "Beam reshaping and self-mode-locking in nonlinear laser resonators," *Opt. Commun.* **86**, 156-160 (1991).
30. T. Brabec, C. Spielmann, P. F. Curley, and F. Krausz, "Kerr lens mode-locking," *Opt. Lett.* **17**, 1292-1294 (1992).
31. H. A. Haus, J. G. Fujimoto, and E. P. Ippen, "Analytic theory of additive pulse and Kerr lens mode-locking," *IEEE J. Quantum Electron.* **28**, 2086-2096 (1992).
32. V. P. Kalosha, M. Muller, J. Herrmann, and S. Gatz, "Spatiotemporal model of femtosecond pulse generation in Kerr-lens mode-locked solid-state lasers," *Journal of the Optical Society of America B-Optical Physics* **15**, 535-550 (1998).
33. R. Szipöcs, K. Ferencz, C. Spielmann, and F. Krausz, "Chirped multilayer coatings for broad-band dispersion control in femtosecond lasers," *Opt. Lett.* **19**, 201-203 (1994).
34. R. Szipöcs, A. Stingl, C. Spielmann, and F. Krausz, "Chirped dielectric mirrors for dispersion control in femtosecond laser systems," *Generation, Amplification, and Measurement of Ultrashort Laser Pulses II* **2377**, 11-22 (1995).
35. A. Stingl, M. Lenzner, C. Spielmann, F. Krausz, and R. Szipöcs, "Sub-10-fs mirror-dispersion-controlled Ti-sapphire laser," *Opt. Lett.* **20**, 602-604 (1995).
36. A. Kasper and K. J. Witte, "10-fs pulse generation from a unidirectional Kerr-lens mode-locked Ti:sapphire ring laser," *Opt. Lett.* **21**, 360-362 (1996).
37. T. Brabec and F. Krausz, "Intense few-cycle laser fields: Frontiers of nonlinear optics," *Rev. Mod. Phys.* **72**, 545-591 (2000).
38. D. Strickland and G. Mourou, "Compression of amplified chirped optical pulses," *Opt. Commun.* **56**, 219-221 (1985).
39. P. Maine, D. Strickland, P. Bado, M. Pessot, and G. Mourou, "Generation of ultrahigh peak power pulses by chirped pulse amplification," *IEEE J. Quantum Electron.* **24**, 398-403 (1988).
40. J. V. Rudd, G. Korn, S. Kane, J. Squier, G. Mourou, and P. Bado, "Chirped-pulse amplification of 55-fs pulses at a 1-kHz repetition rate in a Ti-Al₂O₃ regenerative amplifier," *Opt. Lett.* **18**, 2044-2046 (1993).
41. J. Rothhardt, S. Hädrich, H. Carstens, N. Herrick, S. Demmler, J. Limpert, and A. Tünnermann, "1 MHz repetition rate hollow fiber pulse compression to sub-100-fs duration at 100 W average power," *Opt. Lett.* **36**, 4605-4607 (2011).
42. S. Hädrich, A. Klenke, A. Hoffmann, T. Eidam, T. Gottschall, J. Rothhardt, J. Limpert, and A. Tünnermann, "Nonlinear compression to sub-30-fs, 0.5 mJ pulses at 135 W of average power," *Opt. Lett.* **38**, 3866-3869 (2013).
43. O. E. Martinez, "Design of high-power ultrashort pulse amplifiers by expansion and recompression," *IEEE J. Quantum Electron.* **23**, 1385-1387 (1987).
44. C. P. J. Barty, G. Korn, F. Raksi, A. C. Tien, K. R. Wilson, V. V. Yakovlev, C. Rose-Petruck, J. Squier, and K. Yamakawa, "Regenerative pulse shaping and amplification of ultrabroadband optical pulses," *Opt. Lett.* **21**, 219-221 (1996).
45. S. Backus, C. G. Durfee, G. Mourou, H. C. Kapteyn, and M. M. Murnane, "0.2-TW laser system at 1 kHz," *Opt. Lett.* **22**, 1256-1258 (1997).
46. Y. Nabekawa, Y. Kuramoto, T. Togashi, T. Sekikawa, and S. Watanabe, "Generation of 0.66-TW pulses at 1 kHz by a Ti : sapphire laser," *Opt. Lett.* **23**, 1384-1386 (1998).
47. M. Hentschel, Z. Cheng, F. Krausz, and C. Spielmann, "Generation of 0.1-TW optical pulses with a single-

- stage Ti : sapphire amplifier at a 1-kHz repetition rate," *Appl. Phys. B* **70**, S161-S164 (2000).
48. J. Z. H. Yang and B. C. Walker, "0.09-terawatt pulses with a 31% efficient, kilohertz repetition-rate Ti : sapphire regenerative amplifier," *Opt. Lett.* **26**, 453-455 (2001).
49. S. Backus, R. Bartels, S. Thompson, R. Dollinger, M. Murnane, and H. Kapteyn, "High efficiency, single-stage, 7 kHz, high average power ultrafast laser system," in *Conference on Lasers and Electro-Optics* (2001),
50. D. M. Gaudiosi, A. L. Lytle, P. Kohl, M. M. Murnane, H. C. Kapteyn, and S. Backus, "11-W average power Ti:sapphire amplifier system using downchirped pulse amplification," *Opt. Lett.* **29**, 2665-2667 (2004).
51. T. Imahoko, N. Inoue, K. Takasago, T. Sumiyoshi, H. Sekita, and M. Obara, "Development of a 50 kHz, 13 W Ti:sapphire femtosecond regenerative amplifier," 2007 Pacific Rim Conference on Lasers and Electro-Optics, Vols 1-4, 774-775 (2007).
52. S. Chen, M. Chini, H. Wang, C. Yun, H. Mashiko, Y. Wu, and Z. Chang, "Carrier-envelope phase stabilization and control of 1 kHz, 6 mJ, 30 fs laser pulses from a Ti:sapphire regenerative amplifier," *Appl. Opt.* **48**, 5692-5695 (2009).
53. I. Matsushima, H. Yashiro, and T. Tomie, "10 kHz 40 W Ti:sapphire regenerative ring amplifier," *Opt. Lett.* **31**, 2066-2068 (2006).
54. M. Nisoli, S. DeSilvestri, and O. Svelto, "Generation of high energy 10 fs pulses by a new pulse compression technique," *Appl. Phys. Lett.* **68**, 2793-2795 (1996).
55. M. Nisoli, S. DeSilvestri, O. Svelto, R. Szipöcs, K. Ferencz, C. Spielmann, S. Sartania, and F. Krausz, "Compression of high-energy laser pulses below 5 fs," *Opt. Lett.* **22**, 522-524 (1997).
56. S. Sartania, Z. Cheng, M. Lenzner, G. Tempea, C. Spielmann, F. Krausz, and K. Ferencz, "Generation of 0.1-TW 5-fs optical pulses at a 1-kHz repetition rate," *Opt. Lett.* **22**, 1562-1564 (1997).
57. E. Goulielmakis, M. Schultze, M. Hofstetter, V. S. Yakovlev, J. Gagnon, M. Uiberacker, A. L. Aquila, E. M. Gullikson, D. T. Attwood, R. Kienberger, F. Krausz, and U. Kleineberg, "Single-cycle nonlinear optics," *Science* **320**, 1614-1617 (2008).
58. A. L. Cavalieri, E. Goulielmakis, B. Horvath, W. Helml, M. Schultze, M. Fieß, V. Pervak, L. Veisz, V. S. Yakovlev, M. Uiberacker, A. Apolonski, F. Krausz, and R. Kienberger, "Intense 1.5-cycle near infrared laser waveforms and their use for the generation of ultra-broadband soft-x-ray harmonic continua," *New Journal of Physics* **9**, 242 (2007).
59. S. Bohman, A. Suda, T. Kanai, S. Yamaguchi, and K. Midorikawa, "Generation of 5.0 fs, 5.0 mJ pulses at 1 kHz using hollow-fiber pulse compression," *Opt. Lett.* **35**, 1887-1889 (2010).
60. W. Schweinberger, A. Sommer, E. Bothschafter, J. Li, F. Krausz, R. Kienberger, and M. Schultze, "Waveform-controlled near-single-cycle milli-joule laser pulses generate sub-10 nm extreme ultraviolet continua," *Opt. Lett.* **37**, 3573-3575 (2012).
61. Y. H. Peng, Y. X. Lim, J. Cheng, Y. Guo, Y. Y. Cheah, and K. S. Lai, "Near fundamental mode 1.1 kW Yb:YAG thin-disk laser," *Opt. Lett.* **38**, 1709-1711 (2013).
62. W. P. Latham, A. Lobad, T. C. Newell, and D. Stalnaker, "6.5 kW, Yb:YAG Ceramic Thin Disk Laser," *AIP Conf. Proc.* **1278**, 758-764 (2010).
63. J. Tümmler, R. Jung, H. Stiel, P. V. Nickles, and W. Sandner, "High-repetition-rate chirped-pulse-amplification thin-disk laser system with joule-level pulse energy," *Opt. Lett.* **34**, 1378-1380 (2009).
64. J. Speiser, "Scaling of thin-disk lasers - influence of amplified spontaneous emission," *J. Opt. Soc. Am. B* **26**, 26-35 (2009).
65. P. Peterson, A. Gavrielides, T. C. Newell, N. Vretnar, and W. P. Latham, "ASE in thin disk lasers: theory and experiment," *Opt. Exp.* **19**, 25672-25684 (2011).
66. D. A. Copeland, "Amplified spontaneous emission (ASE) models and approximations for thin-disk laser modeling," in (2013), 85991P-85991P-85924.
67. D. Kouznetsov, J.-F. Bisson, J. Dong, and K.-i. Ueda, "Surface loss limit of the power scaling of a thin-disk laser," *J. Opt. Soc. Am. B* **23**, 1074-1082 (2006).
68. D. Kouznetsov, J.-F. Bisson, and K. Ueda, "Scaling laws of disk lasers," *Optical Materials* **31**, 754-759 (2009).
69. H. Su and X.-J. Wang, "Amplified spontaneous emission in thin-disk lasers," in (2012), 82351Q-82351Q-82358.
70. Y. Zhang, H. Ye, M. Li, J. Zheng, X. Wei, S. Gao, Q. Deng, X. Jiang, X. Yan, and Z. Wang, "ASE suppression in high-gain solid-state amplifiers by a leak method," *Laser Phys.* **23**, 075802 (2013).
71. H. Furuse, H. Chosrowjan, J. Kawanaka, N. Miyanaga, M. Fujita, and Y. Izawa, "ASE and parasitic lasing in thin disk laser with anti-ASE cap," *Opt. Exp.* **21**, 13118-13124 (2013).
72. A. Giesen and J. Speiser, "Fifteen years of work on thin-disk lasers: results and scaling laws," *IEEE J. Select. Top. Quantum Electron.* **13**, 598-609 (2007).
73. G. Arisholm, "General numerical methods for simulating second-order nonlinear interactions in birefringent media," *J. Opt. Soc. Am. B* **14**, 2543-2549 (1997).
74. G. Arisholm, "Quantum noise initiation and macroscopic fluctuations in optical parametric oscillators," *J. Opt. Soc. Am. B* **16**, 117-127 (1999).
75. K. Kato, "Temperature-tuned 90° phase-matching properties of LiB₃O₅," *IEEE J. Quantum Electron.* **30**, 2950-2952 (1994).
76. D. E. Zelmon, D. L. Small, and D. Jundt, "Infrared corrected Sellmeier coefficients for congruently grown lithium niobate and 5 mol.% magnesium oxide doped lithium niobate," *J. Opt. Soc. Am. B* **14**, 3319-3322 (1997).
77. D. Zhang, Y. Kong, and J.-y. Zhang, "Optical parametric properties of 532-nm-pumped beta-barium-borate near the infrared absorption edge," *Opt. Commun.* **184**(2000).
78. H. Fattahi, C. Skrobol, M. Ueffing, Y. Deng, A. Schwarz, Y. Kida, V. Pervak, T. Metzger, Z. Major, and F. Krausz, "High efficiency, multi-mJ, sub 10 fs, optical parametric amplifier at 3 kHz," in *Conference on Lasers and Electro-Optics 2012*, OSA Technical Digest (online) (Optical Society of America, 2012), CTh1N.6.
79. E. Riedle, M. Beutter, S. Lochbrunner, J. Piel, S. Schenkl, S. Sporlein, and W. Zinth, "Generation of 10 to 50 fs pulses tunable through all of the visible and the NIR," *Applied Physics B-Lasers and Optics* **71**, 457-465 (2000).
80. M. Aillerie, P. Bourson, M. Mostefa, F. Abdi, and M. D. Fontana, "Photorefractive damage in congruent LiNbO₃. Part II. Magnesium doped lithium niobate crystals," *Journal of Physics: Conference Series* **416**, 012002 (2013).

81. K. Takachiho, M. Yoshimura, Y. Takahashi, M. Imade, T. Sasaki, and Y. Mori, "Ultraviolet laser-induced degradation of CsLiB₆O₁₀ and β -BaB₂O₄," *Optical Materials Express* **4**, 559-567 (2014).
82. P. B. Corkum, "Plasma perspective on strong field multiphoton ionization," *Phys. Rev. Lett.* **71**, 1994-1997 (1993).
83. L. E. Chipperfield, J. S. Robinson, J. W. G. Tisch, and J. P. Marangos, "Ideal Waveform to Generate the Maximum Possible Electron Recollision Energy for Any Given Oscillation Period," *Phys. Rev. Lett.* **102**, 063003 (2009).
84. M. Lewenstein, P. Balcou, M. Y. Ivanov, A. L'Huillier, and P. B. Corkum, "Theory of high-harmonic generation by low-frequency laser fields," *Phys. Rev. A* **49**, 2117-2132 (1994).
85. V. S. Yakovlev, M. Ivanov, and F. Krausz, "Enhanced phase-matching for generation of soft X-ray harmonics and attosecond pulses in atomic gases," *Opt. Exp.* **15**, 15351-15364 (2007).
86. S. Palaniyappan, I. Ghebregziabher, A. DiChiara, J. MacDonald, and B. C. Walker, "Emergence from nonrelativistic strong-field rescattering to ultrastrong-field laser-atom physics: a semiclassical analysis," *Phys. Rev. A* **74**, 033403 (2006).
87. H. R. Reiss, "The tunneling model of laser-induced ionization and its failure at low frequencies," *arXiv.org*, arXiv:1403.0568v1401 [physics.atom-ph] (2014).