High-repetition-rate picosecond pump laser based on a Yb:YAG disk amplifier for optical parametric amplification

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We report an optically synchronized picosecond pump laser for optical parametric amplifiers based on an Yb:YAG thin-disk amplifier. At 3 kHz repetition rate, pulse energies of 25 mJ with 1.6 ps pulse duration were achieved with an rms fluctuation in pulse energy of $<0.7\%$ by utilizing a broadly intermittent single-energy regime in the deterministic chaos of a continuously pumped regenerative amplifier. © 2009 Optical Society of America

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Producing isolated attosecond extreme-UV pulses via high harmonic generation requires high-energy few-cycle pulses preferably with kilohertz repetition rates for exploring hyperfast electronic phenomena [1]. Ultrashort pulses in the range of a few femtoseconds at approximately kilohertz repetition rates have been demonstrated using a complex design consisting of an oscillator, a multipass chirped pulse amplifier, and an additional nonlinear compression stage [2,3]. However, it has been difficult to extend these systems to the multimillijoule level [4]. Optical parametric chirped pulse amplifiers (OPCPAs) have emerged as a powerful alternative for creating broadband few-cycle pulses and are the only method by which high-energy multimillijoule few-cycle coherent light pulses have been generated [5,6]. However, current OPCPA designs suffer from complex stretcher and compressor elements. Stretching the seed pulse to a significant fraction of the pump pulse duration is required for efficient energy extraction, but extensive stretching to tens of picoseconds requires highly dispersive prisms or grating components and subsequently intricate adaptive dispersion management schemes for proper recompression [7,8]. The use of shorter pump pulses in the range of a few picoseconds would eliminate the need for such a large stretching and compression ratio and allow stretching of the seed pulses by passing through a few-centimeters-long dispersive optical material and recompression by a highly efficient compressor made up of a few chirped multilayer mirrors [9]. Furthermore, the threshold intensity for optical damage of transparent materials increases even faster than the $1/\tau^{1/2}$ for laser pulse durations decreasing below 20 ps [10]. As a consequence, exposing the nonlinear crystal to higher intensities allows the same optical parametric amplification (OPA) gain to be attained with a shorter crystal and hence over a broader bandwidth [11]. Recent experiments in the area of IR multikilohertz few picosecond amplifiers without chirped pulse amplification (CPA) [12] showed temporal pulse broadening owing to self-phase-modulation (SPM) for energies below 1 mJ [13]. Fortunately, in the near-IR spectral range, CPA can be implemented with low loss owing to the availability of gratings with diffraction efficiencies of ~99% [14].

In this Letter, we present an Yb:YAG picosecond pump laser operated within a broadly intermittent stable single-energy regime in the deterministic chaos of a continuously diode-laser-pumped regenerative amplifier that produces 1.6 ps, 25 mJ pulses at a repetition rate of 3 kHz. Chaotic behavior and bifurcations in a regenerative amplifier were first theoretically described and partially experimentally analyzed in [15]. But only in [16] was it theoretically discovered that intermittent stable regimes could be used for creating a stable multikilohertz regenerative amplifier with small energy fluctuations. In this work the laser has been designed to especially use intermittent stable regimes for creating high-energy pulses for use in pumping an efficient, high gain, high contrast, IR OPCPA with a simplified stretcher–compressor system. The repetition rate of the regenerative amplifier was matched to that of our 3 kHz Ti:sapphire-based OPA seed source but can be tuned up to $f_r=20$ kHz. The experimental apparatus, schematically shown in Fig. 1, consists of a seed laser, a stretcher, a fiber preamplifier, a pulse picker, an amplifier resonator, and a compressor. The seed pulses are delivered by an ultrabroadband chirped-mirror Ti:sapphire oscillator (Rainbow, Femtolasers Produktions GmbH) covering the spectral range of 650–1100 nm [17]. This approach allows for nearly jitter-free optical synchronization between pump and signal pulses in the OPCPA, as they are both derived from the same source [8]. The resultant seed energy in the

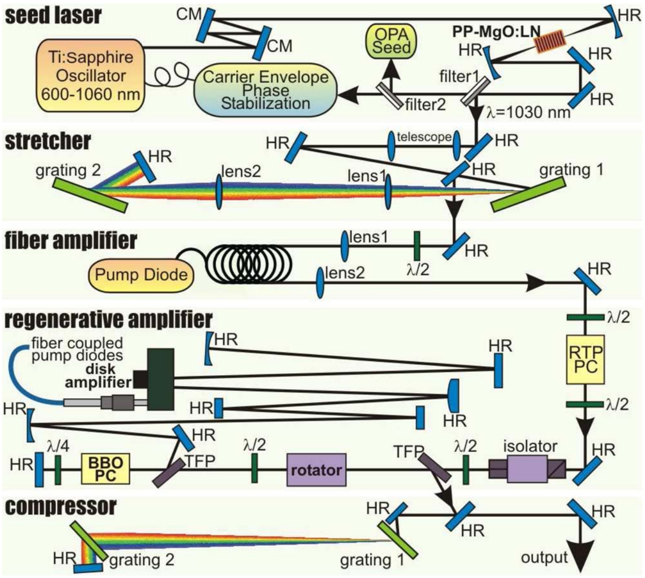

Fig. 1. (Color online) Schematical laser setup. HR, high reflecting mirror; CM, chirped mirror; RTP, rubidium titanyl phosphate; PC, Pockels cell; TFP, thin-film polarizer; $\lambda/2$, half-wave-plate; $\lambda/4$, quarter-wave-plate; PP-MgO:LN, MgO-doped periodically poled $\mathrm{LiNbO_3}$ crystal.

spectral region of the ~5.3 nm broad gain bandwidth of Yb:YAG, centered at 1030 nm, is ~2 pJ. Before amplification, the seed pulse is temporally dispersed in a $4f$ stretcher consisting of a pair of reflection gratings with 1740 lines/mm, inserted at an angle of incidence of 59°, and two lenses ($f=1000$ mm) [18]. In a double pass the stretcher introduces a group delay dispersion of $1.19\times10^8\ \mathrm{fs}^2$ and has 70% throughput efficiency. The stretcher supports a 4 nm broad spectrum centered at 1030 nm and cuts off all other spectral components owing to the limited size of the used optical components. The calculated Fourier-limited pulse duration of the 4 nm broad seed spectrum supported by the stretcher is ~0.77 ps (FWHM). After stretching to ~430 ps, a 40 dB homebuilt double-stage fiber amplifier from Friedrich-Schiller-University Jena increases the total seed energy to ~1.2 nJ, and a rubidium titanyl phosphate (RTP) Pockels cell is used to slice pulses from the ~70 MHz oscillator pulse train at a frequency of 6 kHz. An isolator protects the Pockels cell against feedback from the amplifier. To avoid nonlinear effects, a Pockels cell using a relatively short (20 mm) β-barium borate (BBO) crystal (quarter-wave voltage of 16 kV) has been chosen for switching the selected pulses in and out of the amplifier cavity. The $1/e^2$ beam diameter in this element is 2.8 mm, leading to a calculated B integral of 1.67. Inside the cavity, pulses are amplified in an arrangement similar to that described in [19]. The amplifier head from TRUMPF Laser contains a ~1/10 mm thin, 12.5% doped, Yb:YAG disk mounted on a heat sink, and is pumped in a 20 pass cavity with up to 500 W at 940 nm by laser diodes (LDM 500, Laserline GmbH) in a region of 2.8 mm in diameter. Following amplification, recompression is performed using two transmission gratings with 1400 lines/mm arranged in a double-pass Littrow configuration ($\mathrm{GDD}=-1.19\times10^8\ \mathrm{fs}^2$), with overall transmission of ~77%.

Operating in an intermittent stable regime in the deterministic chaos of the continuously pumped regenerative amplifier, we reproducibly achieve an average output power of 75 W at $f_r=3$ kHz with pulse energies exceeding 25 mJ, a pulse-to-pulse stability of <0.7% (rms), a pulse duration of 1.6 ps and a bandwidth of 1 nm (FWHM) at a center wavelength of 1030.2 nm. Figure 2 shows the measured autocorrelation (AC) trace and the optical spectrum of the laser output at a pulse energy of 25 mJ. The resulting time-bandwidth product of 0.46 is within 5% of the transform limit of 0.441 for Gaussian pulses. Gain narrowing reduces the bandwidth to 1 nm and shortens the pulse duration inside the amplifier cavity to 200 ps before compression.

Figure 3 shows the energy distribution in a bifurcation diagram acquired by incrementing the pump power in steps of 2 W over the range of $P_p=100-300$ W with the number of round trips in the amplifier being kept constant at $N_{\mathrm{rt}}=150$. Owing to low thermal lensing in the disk, the amplifier cavity and the output beam profile were stable and did not change over this entire pump power range. For each set value of the pump power, 200 amplified pulses extracted with the Pockels cell from the cavity were recorded by a fast, energy-calibrated, photodiode (rise time <175 ps). Figure 3 plots the range of pulse energies attained this way for each individual pump power. For $P_p<140$ W normal amplification at the full 6 kHz repetition rate of the Pockels cell is observed. For $P_p>140$ W the first bifurcation occurs, leading to completely chaotic behavior above 170 W. A stable regime of period doubling commences for $P_p>240$ W, resulting in a repetition rate of 3 kHz of the amplified pulses.

The energy of the intermediate pulses extracted from the cavity amounts to ~0.2% of that of the main amplified pulses. For pumping an OPCPA this is negligible owing to the exponential scaling of nonsaturated OPA gain with the pump intensity [11]. At 3 kHz repetition rate the maximum output power of 75 W after the compression is reached at a pump power of 284 W. The total optical efficiency was cal-

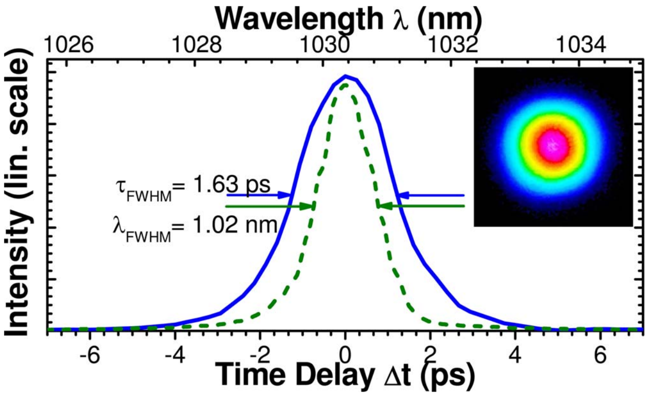

Fig. 2. (Color online) AC trace, optical spectrum, and beam profile (measured $M^2<1.1$) of the laser output. The AC trace corresponds to a FWHM pulse duration of 1.6 ps, assuming a Gaussian pulse shape.

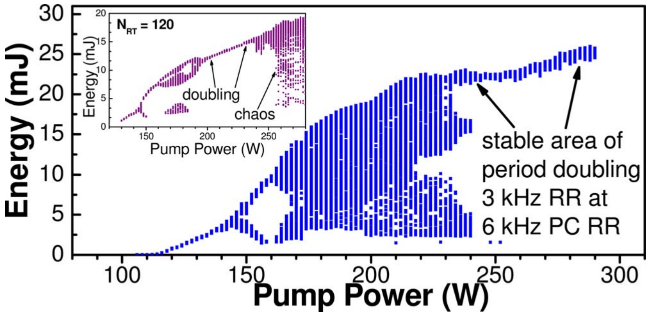

Fig. 3. (Color online) Measured bifurcation diagram for 150 round trips in dependence of the pump power at a repetition rate of 6 kHz. The inset shows the result of the same measurement with 120 round trips.

culated to be 26%, including compression losses. Complete saturation of the gain medium in every second amplification cycle ensures highly stable operation, with pulse-to-pulse energy fluctuations lower than 0.7% rms. By varying parameters such as the number of round trips and the pump power, which affect the laser's bifurcation characteristics [15,16], the intermittent stable pulse regime of period doubling can be shifted to different pulse-energy regimes, allowing output energies at a repetition rate of 3 kHz between 2 and 25 mJ. For example, by lowering the number of round trips in the amplifier, the intermittent stable regime is followed by a further chaotic interval and stable output energy occurs between a lower and upper pump power limit for period doubling; see the inset of Fig. 3. The disk amplifier also exhibits an excellent beam quality, which is also critical for parametric amplification. The amplifier cavity supports only the TEM_{00} fundamental laser mode, resulting in a near-diffraction-limited beam with $M^2 < 1.1$ measured at the maximum pulse energy. The measured beam profile is shown as an inset in Fig. 2.

In conclusion, we have reported the generation of 25 mJ, 1.6 ps pulses delivered in a near-diffraction-limited beam at a wavelength of 1030.2 nm with a rms pulse-to-pulse stability of smaller than 0.7% and a repetition rate of 3 kHz from a regenerative chirped pulse amplifier based on a thin-disk Yb:YAG gain medium. The peak power exceeds 15 GW. To the best of our knowledge, this is the most powerful multikilohertz regenerative amplifier reported to date.

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