

Video Article

20 mJ, 1 ps Yb:YAG Thin-disk Regenerative Amplifier

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Abstract

This is a report on a 100 W, 20 mJ, 1 ps Yb:YAG thin-disk regenerative amplifier. A homemade Yb:YAG thin-disk, Kerr-lens mode-locked oscillator with turn-key performance and microjoule-level pulse energy is used to seed the regenerative chirped-pulse amplifier. The amplifier is placed in airtight housing. It operates at room temperature and exhibits stable operation at a 5 kHz repetition rate, with a pulse-to-pulse stability less than 1%. By employing a 1.5 mm-thick beta barium borate crystal, the frequency of the laser output is doubled to 515 nm, with an average power of 70 W, which corresponds to an optical-to-optical efficiency of 70%. This superior performance makes the system an attractive pump source for optical parametric chirped-pulse amplifiers in the near-infrared and mid-infrared spectral range. Combining the turn-key performance and the superior stability of the regenerative amplifier, the system facilitates the generation of a broadband, CEP-stable seed. Providing the seed and pump of the optical parametric chirped-pulse amplification (OPCPA) from one laser source eliminates the demand of active temporal synchronization between these pulses. This work presents a detailed guide to set up and operate a Yb:YAG thin-disk regenerative amplifier, based on chirped-pulse amplification (CPA), as a pump source for an optical parametric chirped-pulse amplifier.

Video Link

The video component of this article can be found at <https://www.jove.com/video/55717/>

Introduction

The generation of high-energy, few-cycle laser pulses at a high repetition rate is of great interest to applied fields, such as attosecond science^{1,2,3,4} and high-field physics^{5,6}, which stand to directly benefit from the availability of such sources. OPCPA represents the most promising route to achieving high pulse energies and large amplification bandwidths that simultaneously support few-cycle pulses¹. To date, OPCPA allows for ultra-broadband amplification, which generates few-cycle pulses^{7,8,9,10}. However, a modified implementation of the OPCPA scheme, which uses short pump pulses on the picosecond scale, holds promise for making this approach scalable for even higher pulse energies and average powers in the few-cycle regime^{1,11,12}. Due to the high pump intensity in short-pulse pumped OPCPA, the high single-pass gain allows for the use of very thin crystals to support large amplification bandwidths. Although the short-pulse pumped OPCPA has many advantages, the realizability of this approach is subject to the availability of lasers that are specially tailored for this purpose. Such pump lasers are required to deliver high-energy picosecond pulses with near-diffraction limited beam quality at repetition rates in the kHz to MHz range^{13,14,15}.

The introduction of ytterbium-doped lasers at different geometries, capable of delivering picosecond laser pulses with high energy and high average power, are about to change the current state of the field^{1,13,14,15,16,17,18}. Yb:YAG has good thermal conductivity and a long upper-state lifetime, and it can be pumped by cost-effective diode lasers. Its performance when used in thin-disk geometry is outstanding due to the efficient cooling of the gain medium to simultaneously scale the peak and average power. Moreover, the occurrence of self-focusing inside the gain medium during the amplification process is suppressed due to the slenderness of the thin-disk in comparison to other gain medium geometries, resulting in excellent temporal and spatial profiles of the amplified pulses. Combining this concept with CPA holds promise for generating picosecond pulses with hundreds of millijoules of energy and hundreds of watts of average power^{19,20}.

The aim of this work is to demonstrate a turn-key Yb:YAG thin-disk regenerative amplifier with outstanding daily performance as a suitable source for pumping OPCPAs²¹. To achieve this goal, this study employs a Yb:YAG thin-disk oscillator²² with several microjoules of pulse energy to seed the amplifier to minimize the accumulated nonlinear phase during the amplification process. This protocol provides the recipe for building and operating the laser system, which is described elsewhere²¹. Details about component implementation and control software are presented, and the alignment process of the system is described.

Protocol

Caution: Please be aware of all safety regulations that are relevant to lasers before using this equipment. Avoid exposure of the eyes or skin to direct or scattered laser beams. Please wear appropriate laser safety goggles throughout the process.

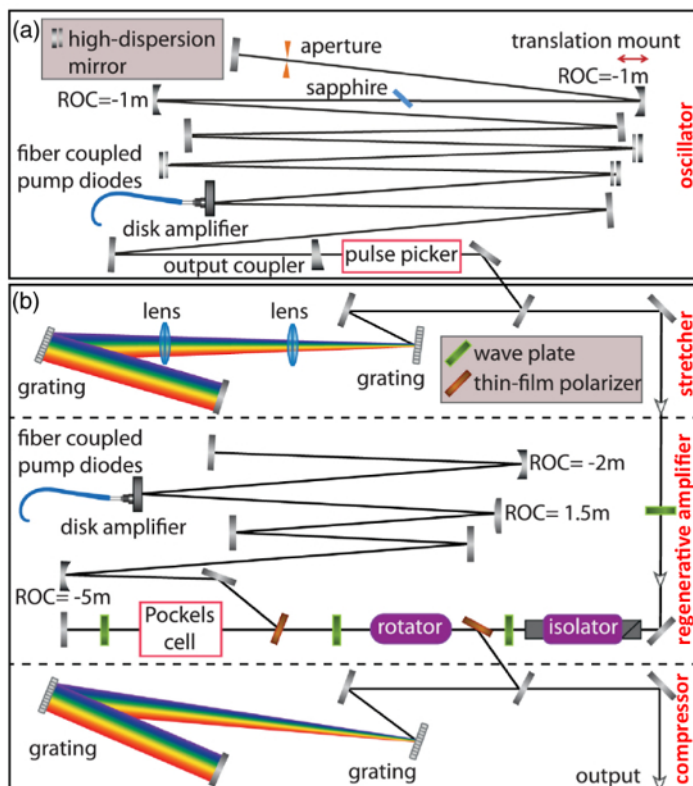


Figure 1: Schematic layout of the Yb:YAG thin-disk regenerative amplifier. (a) Yb:YAG thin-disk Kerr-lens mode-locked oscillator. The 13 m linear cavity of the oscillator consists of a 13% transmission output coupler, three high-dispersion mirrors with GDD of $-3,000 \text{ fs}^2$, 1 mm sapphire Kerr medium, and a copper hard aperture. A pulse picker, containing a 25 mm-thick BBO crystal, is used to reduce the repetition rate to 5 kHz. (b) CPA. First block: the pulse stretcher setup containing two antiparallel gold gratings (1,740 lines/mm), where the seed pulses are temporally stretched to approximately 2 ns. Second block: the regenerative amplifier, where the seed pulse is confined in the amplifier cavity for amplification when the high voltage of the Pockels cell, which contains a BBO crystal with a thickness of 20 mm, is applied. Third block: the pulse compressor containing two parallel dielectric gratings (1,740 lines/mm), where the amplified pulses are temporally compressed down to 1 ps. This figure has been modified from Fattahi *et al.*, with permission from reference²¹. Please click here to view a larger version of this figure.

Component	ROC	Distance
	(mm)	(mm)
OC	∞	0
TD	-17000	600
M ₁	-1000	5000
BP	∞	510
M ₂	-1000	510
EM	∞	800

Table 1: Cavity design of the oscillator. ROC: radius of curvature, OC: output coupler, TD: thin-disk, M: mirror, BP: Brewster plate, EM: end mirror.

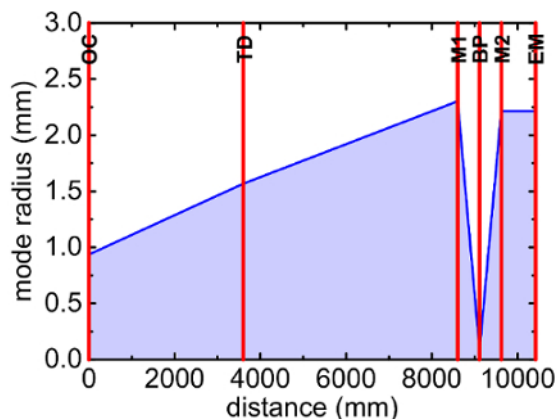


Figure 2: Oscillator cavity design. Calculated mode radius on the cavity components. OC: output coupler, TD: thin-disk, M: mirror, BP: Brewster plate, EM: end mirror. [Please click here to view a larger version of this figure.](#)

Component	ROC	Distance
	(mm)	(mm)
EM ₁	∞	0
PC	∞	200
M ₁	-5000	525
M ₂	1500	1500
TD	-2000	1050
EM ₂	-2000	2350

Table 2: Cavity design of the regenerative amplifier. ROC: radius of curvature, EM: end mirror, PC: Pockels cell, M: mirror, TD: thin-disk.

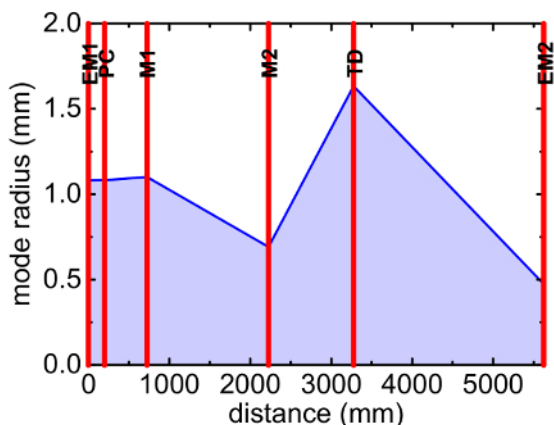


Figure 3: Regenerative amplifier cavity design. Calculated mode radius on the cavity components. EM: end mirror, PC: Pockels cell, M: mirror, TD: thin-disk. [Please click here to view a larger version of this figure.](#)

1. Oscillator

1. Turn on the cooling water for the oscillator (**Figure 1a**).
2. Switch on the cooling chillers to cool down the pump diodes, the thin-disk head, and the breadboard. Set the temperature on both chillers to 20 °C.
3. Switch on the power supply for the pump diode unit (see the **Table of Materials**, No. 1) and click the "OUTPUT ON/OFF" button.
NOTE: A laser cavity simulation software (see the **Table of Materials**, No. 113) was used to simulate and design the oscillator and regenerative amplifier cavity (Table 1 and Table 2; **Figure 2** and **Figure 3**)²³.
4. Pump the thin-disk (see the **Table of Materials**, No. 14) via the coupled fiber at a wavelength of 940 nm by setting the "current" knob on the power supply to 26.2 A, corresponding to the 210-W output, to start the lasing in the oscillator in the continuous wave (CW) mode.
5. **To observe the output spectrum of the CW mode, connect a fiber to the spectrometer and place it before the pulse picker after using an appropriate attenuation.**
 1. In spectrometer software, select the "Spectrometer" tab and then click "Rescan Devices."
 2. Right-click on the spectrometer name and select "Spectrum Graph."

3. Click the "Accept" button on the "Choose Target" window.
4. After blocking the laser beam, click the "Store Dark Spectrum" button on the tool bar and click the "Scope Minus Dark" button to subtract the background spectrum.
5. Unblock the laser beam to observe the spectrum.
6. Observe the output power of the CW mode on the power meter before the pulse picker.
7. To operate the oscillator in pulsed mode and to initiate mode-locking, perturb the high-reflectivity mirror inside the laser cavity (on a translation stage) by mechanically pushing the stage from the back **Figure 1a**.
NOTE: High-reflectivity mirrors with a high damage threshold were used in the oscillator and regenerative amplifier cavity (see the **Table of Materials**, No. 24 and 28).
8. Observe the spectrum and the output power of the pulsed mode before the pulse picker using a spectrometer and a power meter, respectively.
NOTE: The oscillator output has 25 W of average power at a wavelength of 1,030 nm, an 11-MHz repetition rate, and a 4-nm spectral bandwidth (FWHM). If oscillator optimization is not required, skip steps 1.9-1.14.
9. Slightly increase the current on the power supply until a CW spike appears in the spectrum measured by the spectrometer.
10. Align the hard aperture in the oscillator (see **Figure 1a**) by tuning its micrometer screws vertically and horizontally to maximize the CW spike.
11. **Observe the depletion of the pump beam profile on the thin-disk.**
 1. Run disk camera program and select "Monochrome" from the "choose mode" window.
 2. Click the "Open camera" button on the tool bar to observe the beam spot on the thin-disk.
12. Tune the piezo linear actuators of the end mirror (motorized knobs) by pushing the "+" or "-" button on the vertical or horizontal motor from the hand-control pad in order to align this depletion to the center of the pump beam profile.
13. Slightly reduce the current on the power supply until the CW spike vanishes in the spectrum.
14. Repeat steps in 1.9-1.13 until a spectrum and an output power similar to the obtained reference levels are achieved (see the measured spectrum in **Figure 4a** (red curve) at 25 W of average power).
15. **To observe the output pulse train and to determine the pulse-to-pulse stability, connect a fast photodiode to an oscilloscope and place it before the pulse picker (after using an appropriate attenuation).**
 1. Select an appropriate trigger level by tuning the "trigger level" knob on the oscilloscope to stabilize the repeating waveforms and observe the output pulse train on the oscilloscope screen.
 2. From the "Measure" menu, select "Peak to Peak Amplitude" to determine the pulse-to-pulse stability.
16. **Observe the output beam profile before the pulse picker and determine the beam-pointing fluctuations.**
 1. Run the beam profiler software and click the "Go, start capture" button from the tool bar to observe the beam profile.
 2. From the tool bar, open the "beam wander" dialog and then click the "clear" button to start new beam-pointing stability measurement.
NOTE: Fluctuations in the beam or a distorted beam profile (caused by optical damage, beam clipping, etc.) can deteriorate system stability.
17. Measure the pulse duration using frequency-resolved optical gating based on second harmonic generation (SHG-FROG)^{21,24}.

2. Pulse Picker and Pulse Stretcher

NOTE: Caution, be aware of all relevant electrical safety regulations before applying the high voltage on the pulse picker. Use appropriate high-voltage isolation. Remove the diagnostics from the beam path before proceeding with this section. If aligning the pulse picker and its setting is not required, skip steps 2.1, 2.3-2.6, 2.8-2.9, and 2.11.

1. Use two mirrors before the pulse picker setup to align the output beam from the oscillator through the pulse picker unit (see the **Table of Materials**, No. 5 and 7) and its 25 mm-thick beta barium borate (BBO) crystal (see the **Table of Materials**, No. 12) with the aid of the infrared viewer and the laser viewing card (**Figure 1a**).
2. Run the pulse picker program on the oscillator computer.
3. Observe the switching signal of the pulse picker and the pulse train of the oscillator on the oscilloscope (see step 1.15) with the assistance of a fast photodiode.
4. In the pulse picker program, set the delay time (delay A) from the "define delay parameters" dialog to synchronize the switching signal and the pulse train at the pulse picker crystal.
5. Set the switching time window (delay B) from the "define delay parameters" dialog box to select one pulse from the pulse train.
6. Set the internal trigger time (inhibit) from the "define delay parameters" dialog box to 200 μ s to pick one pulse every 5 kHz.
7. Reduce the repetition rate of the oscillator from 11 MHz to 5 kHz by switching the power supply of the pulse picker driver to "on" to apply high voltage to the crystal.
8. Select the picked pulses from the pulse train by using a thin-film polarizer (TFP) (see the **Table of Materials**, No. 31) after the pulse picker and dump the remaining pulses into a beam dump.
9. Improve the contrast of the picked pulses by adjusting the half-wave plate (see the **Table of Materials**, No. 32) before the pulse picker.
10. Reduce the peak power of the laser pulse by passing the picked pulses through the stretcher setup to stretch the pulses to a duration of 2 ns (see **Figure 1a-b**).
11. Use two mirrors after the pulse picker setup to align the picked pulses through the stretcher setup, if required.
NOTE: The stretcher contains two antiparallel gold gratings (see the **Table of Materials**, No. 20 and 21) with a line density of 1,740 lines/mm to stretch the pulses to a duration of 2 ns to avoid damaging the optics during the amplification process in the regenerative amplifier due to a high peak intensity. These pulses are used to seed the regenerative amplifier, as described in the next section (**Figure 1b**, top).

3. Regenerative Amplifier

Caution; Be aware of all relevant electrical safety regulations before applying the high voltage to the Pockels cell. Use appropriate high-voltage isolation. Remove the diagnostics from the beam path before proceeding with this section. Seed pulses are delivered from the Yb:YAG thin-disk Kerr-lens mode-locked oscillator. Other seed strategies can be used to seed the amplifier, such as fiber amplifiers.

1. Turn on the cooling water for the regenerative amplifier (**Figure 1b**, middle).
2. Switch on the cooling chillers to cool down the pump diodes, the thin-disk, the laser head, and the Pockels cell. Set the temperature of the chillers to 28 °C, 17 °C, and 18 °C and then activate the interlock system.
NOTE: Misaligned seed beam can deteriorate the amplifier stability. If aligning the regenerative amplifier is not required, skip steps 3.3-3.13 and 3.25.
3. Switch on the power supply of the pump diode unit (see the **Table of Materials**, No. 2) and then click the "OUTPUT ON/OFF" button.
4. Pump the thin-disk via the coupled fiber at a wavelength of 940 nm by setting the "current" knob on the power supply to the threshold.
5. Observe the pump beam profile on the disk by using the disk camera (see step 1.11) and select "Circle Geometry" on the "Draw" menu on the disk camera program to mark the position of the beam in the camera program.
6. Reduce the power supply current to zero and then click the "OUTPUT ON/OFF" button. Switch off the power supply of the pump diode unit.
7. Use two mirrors before the regenerative amplifier to align the output beam from the stretcher (seed pulses) through the incoupling optics in the regenerative amplifier to reach the first-end mirror (behind the Pockels cell). Use the beam profiler, the infrared viewer, and the laser viewing card to help with this.
8. Close the amplifier cavity by turning the quarter-wave plate (see the **Table of Materials**, No. 33), behind the Pockels cell, eliminating the laser beam inside the cavity.
9. Tune the motorized knobs of the first-end mirror by pushing the "+" or "-" button on the vertical or horizontal motor (driver 1) from the hand-control pad to align the outcoupling beam.
10. Open the amplifier cavity by turning the quarter-wave plate (behind the Pockels cell) until maximum laser beam intensity is attained inside the cavity. Block the back-reflected beam from the second end mirror.
11. Observe the beam profile of the seed pulses on the disk camera program and overlap the beam with the marked position by tuning the knobs of one of the cavity mirrors before the thin-disk.
12. Unblock the back-reflected beam and observe its spot on the disk camera program.
13. Tune the motorized knobs of the second end mirror by pushing the "+" or "-" button for the vertical or horizontal motor (driver 2) on the hand-control pad to overlap the back reflection with the marked position.
14. From Pockels cell computer, run the Pockels cell program.
NOTE: If the setting of the Pockels cell is not required, skip steps 3.15-3.18.
15. Observe the switching signal of the Pockels cell (see the **Table of Materials**, No. 6 and 8) and the seed pulses on the oscilloscope (see step 1.15) with the aid of a fast photodiode (**Figure 1b**, middle).
16. In the Pockels cell program, set the delay time (delay A) from the "define delay parameters" dialog box to synchronize the switching of the Pockels cell and the seed pulses at the Pockels cell crystal.
17. Set the switching time window (delay B) from the "define delay parameters" dialog box to confine one pulse inside the cavity of the regenerative amplifier to 4 μ s, corresponding to 87 round trips of the pulse.
18. Set the internal trigger time (inhibit) from the "define delay parameters" dialog to "200 μ s" to confine the rate to one pulse every 5 kHz.
19. Switch on the power supply of the Pockels cell driver to apply the high voltage on the crystal.
20. Switch on the power supply of the pump diode unit and click the "OUTPUT ON/OFF" button.
21. To amplify the seed pulses in the regenerative amplifier, pump the thin-disk by setting the "current" knob on the power supply to 57.7 A, corresponding to 280 W.
NOTE: The amplified beam is separated from the seed beam by the combination of a Faraday rotator (see the **Table of Materials**, No. 19) and a TFP. The Yb:YAG oscillator is protected from the back reflection of the amplified beam by an isolator (see the **Table of Materials**, No. 18).
NOTE: Keep the operation of the Pockels cell and the pump diode unit in the order mentioned above to avoid damaging the optics by Q-switching.
22. Observe the spectrum and the output power (see steps 1.5 and 1.6) before the compressor.
NOTE: The amplifier output has 125 W of average power at a wavelength of 1,030 nm, a 5-kHz repetition rate, and a 1-nm spectral bandwidth (FWHM).
23. Observe the output pulse train before the compressor on the oscilloscope screen and determine the pulse-to-pulse stability with the aid of a fast photodiode (see step 1.15).
24. Observe the output beam profile before the compressor and determine the beam-pointing fluctuations (see step 1.16).
25. Finely tune the motorized knobs of the second end mirror by pushing the "+" or "-" button on the vertical or horizontal motor (driver 2) from the hand-control pad to improve the operation of the regenerative amplifier, if required.
26. **Characterize the gain-narrowing effect.**
 1. Consider the amplification for different seed energy levels by adjusting the seed energy with neutral-density filters.
 2. Change the number of round trips to obtain the highest output power for a fixed pump power of 300 W.
 3. Observe the output spectrum for each case.

4. Pulse Compressor, Beam Alignment, and Stabilization System

NOTE: Remove the diagnostics from the beam path before proceeding with this section. If aligning the compressor and the beam stabilizer unit is not required, skip steps 4.3 and 4.6.

1. Turn the motorized rotation mount of the half-wave plate (in the output path) by pushing the "+" or "-" button on motor A (driver 5) from the hand-control pad to send a few watts of the amplifier output to the compressor (**Figure 1b**, bottom).

2. Compress the laser pulse down to 1 ps by passing the amplified beam through the compressor setup.
3. Use two mirrors after the regenerative amplifier setup to align the amplified pulses through the compressor setup, if required.
NOTE: The compressor contains two parallel dielectric gratings (see the **Table of Materials**, No. 22 and 23), with a line density of 1,740 lines/mm.
4. Switch on the power supply of the beam stabilizer unit (see the **Table of Materials**, No. 98). Run the beam stabilizer program on the beam stabilizer computer.
5. Use two mirrors before the detector setup of the beam stabilizer to align the zero-order diffraction from the first grating in the compressor to the beam stabilizer detectors.
6. Push the "regulation" button on the beam stabilizer program to lock the laser beam to avoid beam-drift after the compressor. Turn the motorized half-wave plate again to pass the full output power of the amplifier through the compressor. Adjust the gain of the beam stabilizer detectors with the aid of a neutral-density filter.
7. Characterize the time duration of the compressed pulses using SHG-FROG^{21,24}.

5. Pump Source of the OPCPA System

NOTE: Remove the diagnostics from the beam path before proceeding with this section.

1. From the OPCPA computer, run the program of the beam profiler.
2. Collimate and adjust the laser beam size after the compressor, using an appropriate telescope to reach the peak intensity of 80 GW/cm². Use the beam profiler, infrared viewer, and laser viewing card.
NOTE: A 1.5 mm-thick BBO crystal was selected for SHG based on the results of the simulation done on the Simulation System for Optical Science (SISYFOS) code²⁵.
3. Guide the fundamental beam (1,030 nm) through a nonlinear crystal (1.5 mm-thick BBO; see the **Table of Materials**, No. 54) to generate the second harmonic (SH) at 515 nm.
4. Separate the SH beam from the unconverted fundamental beam by placing a harmonic separator at 45° (see the **Table of Materials**, No. 56) after the crystal.
NOTE: The SH beam is reflected from the harmonic separator, while the unconverted fundamental beam is transmitted through.
5. Precisely optimize the phase-matching angle of the SH by tuning the knob of the crystal mount to reach the highest conversion efficiency of the SH (70%, corresponding to 70 W).
6. Observe the power of the SH and the unconverted fundamental beams on the power meters (see step 1.6).
7. Observe the Gaussian beam profile of the SH and the unconverted fundamental beams (see step 1.16).
8. Characterize the temporal shape of the SH pulses using cross-correlation frequency resolved optical gating (XFROG)^{21,24}.

Representative Results

The oscillator delivers 350 fs, 2 μJ, 25-W pulses at 11 MHz repetition rate, with a pulse-to-pulse stability of 1% (rms) and beam-pointing fluctuations of less than 0.6% over 1 h of measurement (**Figure 4**).

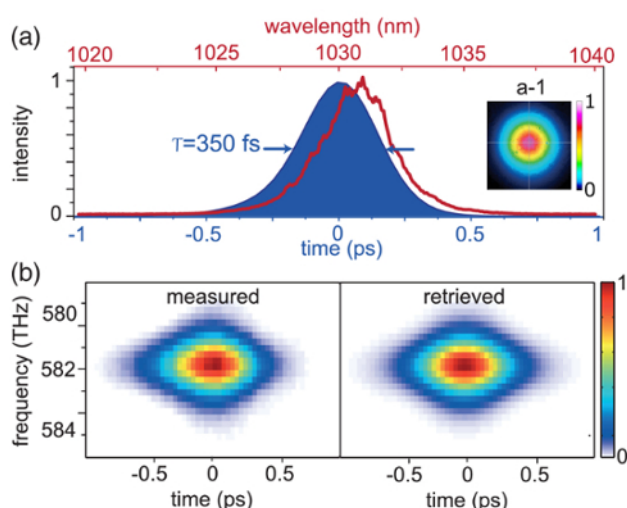


Figure 4: Yb:YAG thin-disk, Kerr-lens mode-locked oscillator. (a) The spectrum (red), the retrieved temporal intensity profile (blue), and the spatial profile (inset) of the oscillator pulses. (b) Measured and retrieved SHG-FROG spectrograph of the oscillator. This figure has been modified from Fattahi *et al.*, with permission from reference²¹. [Please click here to view a larger version of this figure.](#)

The seed pulses are amplified in the regenerative amplifier to 125 W while being pumped with a CW fiber-coupled diode at a wavelength of 940 nm at 280 W, corresponding to an optical-to optical efficiency of 47%. The pulse-to-pulse stability of the amplifier is less than 1%, and the amplifier exhibits excellent long-term stability after 10 h of continuous operation. The amplified beam has an excellent spatial profile, with a M^2 of 1 ($M^2_x = 1.08$ and $M^2_y = 1.07$) and an excellent temporal profile after compression to 1 ps (at FWHM) (**Figure 5**).

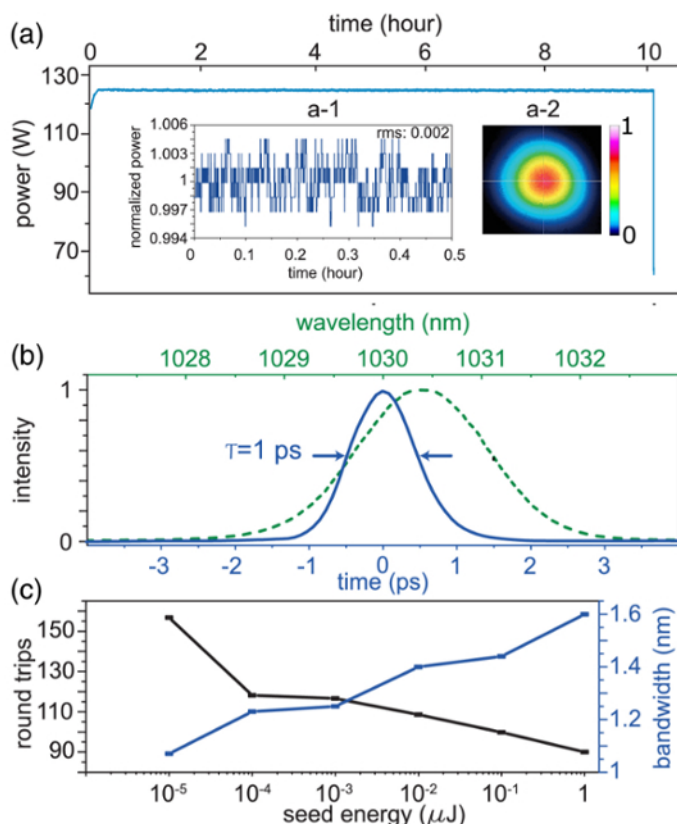


Figure 5: Characterization of the regenerative amplifier output and the gain-narrowing effect. (a) The stability of the regenerative amplifier average power after 10 h of continuous operation. Inset: (a-1) Normalized power to its mean value in a time window of 0.5 h; (a-2) Output beam profile of the regenerative amplifier. (b) Amplifier output spectrum (green) and the retrieved temporal intensity (blue) of the laser pulses at 100 W average power after the grating compressor. (c) Seed energy versus spectral bandwidth (FWHM) of the amplifier output and the required round trips for the same output average power at 300 W of pump power. This figure has been modified from Fattahi *et al.*, with permission from reference²¹. [Please click here to view a larger version of this figure.](#)

The SHG was analyzed using the SISYFOS code²⁵. Two different crystals with the following parameters were considered: 1) a type-I, 6 mm-thick lithium triborate (LBO), with a phase-matching angle of 13.7° and a nonlinear coefficient of 0.819 pm/V , and 2) a type-I, 3 mm-thick BBO with a phase-matching angle of 23.4° and a nonlinear coefficient of 2 pm/V ^{26,27}. 1-ps, 20-mJ pulses at 1,030 nm and a peak intensity of 100 GW/cm^2 were considered as the input of the simulation. The simulation results showed that the BBO performance was superior to that of the LBO for SHG (Figure 6).

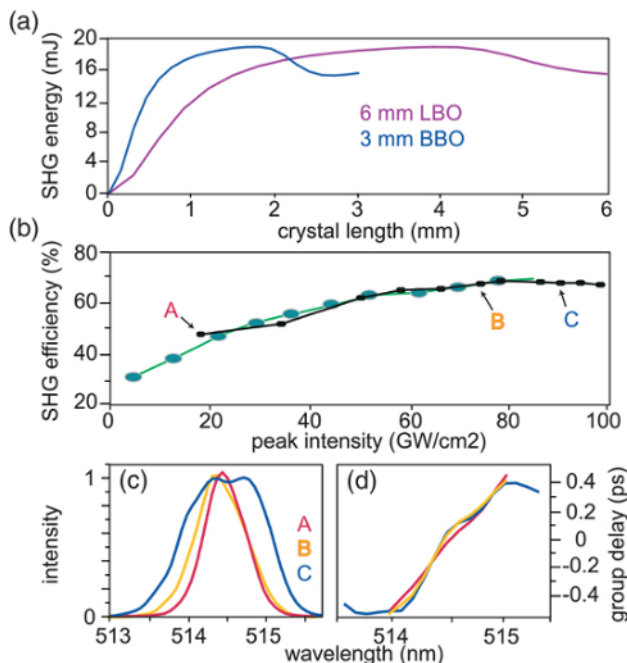


Figure 6: Second harmonic generation. (a) Simulated SHG energy for a 6 mm-thick LBO crystal and a 3 mm-thick BBO crystal. (b) Experimental SHG efficiency versus input pump peak intensity in a 1.5 mm-thick BBO crystal using 0.5 mJ (black) and 20 mJ (green) of the amplifier output. (c) The retrieved spectral intensity and (d) the group delay of XFROG measurements for different SHG efficiencies corresponding to points A, B, and C in (b). This figure has been modified from Fattahi *et al.*, with permission from reference²¹. [Please click here to view a larger version of this figure.](#)

Discussion

The turn-key operation of the oscillator is achieved by the optimum heat management of the different components of the laser. The output of the oscillator is reproducible on a daily basis, with no need for extra alignment or optimization. In addition, the pulse-to-pulse energy stability and spatial pointing stability of the seed laser fulfills the preconditions to achieving the stable operation of the regenerative amplifier.

Other low-energy seed sources, such as fiber amplifiers, can be used to seed the amplifier. In this study, a 2 μ J Yb:YAG thin-disk KLM oscillator was used to assist the amplification of the regenerative amplifier by reducing the growth of the accumulated nonlinear phases, since the required number of round trips is reduced for higher-input seed energy. Additionally, the higher seed energy influences the amplification process and reduces the gain narrowing. The measured spectral bandwidth of the amplified pulses for different seed energies at a fixed pump power is shown in **Figure 5c**. Amplified spectral bandwidth decreases for lower seed energies because of gain narrowing. For 10 pJ seed energy, the laser operates in the period doubling, and it is not possible to reach stable operation, even by increasing the number of round trips. In addition to the careful optimization of the cooling systems and the power supply of the diodes, the operation of the regenerative amplifier at saturation plays a major role in the achieved stability of the amplifier.

The fundamental or second harmonic of the laser can be used to pump an OPCPA system. For SHG, the performances of an LBO and a BBO crystal were compared, as they offer a high nonlinear coefficient and damage threshold, in spite of the larger spatial walk-off and the limited available aperture in the case of BBO. As the nonlinear coefficient of BBO is almost twice that of the LBO, a shorter crystal is sufficient to reach the saturation limit for SHG (**Figure 6a**). Therefore, BBO is the more suitable choice, as the accumulated nonlinear phase is smaller²⁸.

The pulse durations of the SH pulses are characterized experimentally at different conversion efficiencies. It was observed that at high conversion efficiencies, the SHG spectrum is broadened and a higher-order spectral phase appears (**Figure 6**). Therefore, case B, with the conversion efficiency of 70%, is chosen where the SH and the unconverted fundamental beams maintain excellent quality.

Disclosures

The authors have nothing to disclose.

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