

High-power, 1-ps, all Yb:YAG thin-disk regenerative amplifier

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We report a 100 W, 20 mJ, 1-ps, all Yb:YAG thin-disk regenerative amplifier seeded by a μ J-level Yb:YAG thin-disk Kerr-lens mode-locked oscillator. The regenerative amplifier is implemented in a chirped pulse amplification system and operates at ambient temperature in air, delivering ultrastable output pulses at 5 kHz repetition rate and with a root mean square (rms) power noise value of less than 0.5%. Second harmonic generation of the amplifier's output in a 1.5 mm-thick BBO crystal, results in more than 70 W at 515 nm, making the system an attractive source for pumping optical parametric chirped pulse amplifiers in the visible and near-infrared spectral range. © 2016 Optical Society of America

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Attosecond technology has provided direct time-domain access to the motion of electrons on the atomic time scale [1]. However, there are many exciting phenomena with significant technological and scientific implications waiting to be observed and controlled once attosecond pulses with higher flux and energy become available. Few-cycle pulses of Ti:Sa based chirped pulse amplification (CPA) systems have been the workhorse for the generation of attosecond pulses for more than a decade [2] but their peak- and average-power for few-cycle pulses are limited. As the cutoff frequency in high harmonic generation (HHG) is proportional to the energy and square of the wavelength of the driving pulses [3, 4], the state of the art of HHG can be dramatically changed if short pulses at higher energy and longer wavelength are available. Unlike CPA lasers, optical parametric chirped pulse amplifiers (OPCPA) are scalable in average- and peak-power and flexible in terms of the central frequency of the

amplified spectrum [5, 6] but their realization demands high peak-power pump lasers.

Among the currently available laser media, Yb-doped materials are most promising for scaling the average- or/and peak-power of few-ps pulses [7–11] and therefore unrivaled pump sources for OPCPA. The medium can be pumped with cost-effective diode lasers and because of the absence of excited-state absorption, good thermal conductivity, and cubic crystal structure, they show superior performance in thin-disk geometry. Here, efficient heat transfer takes place through a heat sink attached to the laser gain medium. Due to this cooling concept, the crystal size in thin-disk amplifiers can be scaled easily, which holds promise to reach pulses at J-level energy and kW-scale average power [12, 13]. However the amplified energy is limited by amplified spontaneous emission [14].

Combining the Yb:YAG gain medium in thin-disk geometry with CPA allows scaling of the energy of near-1-ps pulses, while keeping the B-integral in the amplifier low. This results in pulses with excellent temporal and spatial profiles, which are important to achieve high efficiency and good beam and pulse-quality in an OPCPA.

In this work we show an all Yb:YAG thin-disk regenerative amplifier, seeded with an Yb:YAG thin-disk Kerr-lens mode-locked (KLM) oscillator, delivering 26 mJ, 1-ps pulses, at 130 W of average power with an excellent short- and long-term stability. Figure 1 outlines the scheme of the system. As described in [15], higher seed energy results in less accumulated nonlinear phase in regenerative amplifiers. Therefore an Yb:YAG thin-disk KLM oscillator was developed to provide a high input seed energy for the regenerative amplifier.

The front-end oscillator was designed to meet certain parameters that are critical in reaching optimum day-to-day performance of the attached amplifier system. Among them are μ J-level pulse energy, sub-picosecond pulse duration, low beam-pointing fluctuations as well as good thermal and mechanical stability. Today the highest pulse energy directly from mode-locked oscillators is generated with the thin-disk technology,

mainly employing Yb:YAG as gain material [16–18]. Ultrashort pulse formation via solitonic mode-locking can be achieved by balancing intra-cavity dispersion and the nonlinear phase-shift. An additional self-amplitude modulation is required to start and stabilize the pulse formation which is commonly implemented by SESAMs, or KLM [19, 20]. We have opted for KLM, which yields shorter pulses and is more robust against optical damage, the realization of which is described below.

The cavity setup of the oscillator is shown in Fig. 1(a). The linear cavity is bounded by a wedged output-coupler with 13% transmission and a plane highly reflective end-mirror and has a total length of about 13 m. Light amplification is performed by a flat Yb:YAG thin-disk that works in reflection and is pumped by fiber coupled laser-diodes at 940 nm wavelength. Solitonic pulse-shaping is supported by a net intra-cavity group-delay-dispersion (GDD) of -18000 fs^2 per roundtrip, introduced by three high-dispersion mirrors. The necessary loss modulation for stable pulse generation is provided by a 1-mm-thin sapphire Kerr-medium placed between two concave focusing mirrors (-1 m radius of curvature), in combination with a copper aperture and the soft aperture of the gain. Mode locking is initiated by perturbing a concave mirror on a translation stage.

Frequency-resolved optical gating based on second-harmonic generation (SHG-FROG) employing a $100 \mu\text{m}$ BBO crystal is used to characterize the oscillator pulses. The output pulses are transform-limited with a duration of 350 fs at full width at half maximum (FWHM), each carrying about $2 \mu\text{J}$ energy (Fig. 2). During the course of a work day the average output power is 25 W while the root mean square (rms) intensity noise on a photodiode is less than 1% in a 1 Hz - 13 MHz spectral window. The rms of the beam pointing fluctuations of the oscillator is less than 0.6% of the beam size over a measurement time window of one hour. The thermal stability of the system is sufficient for near turn-key operation such that alignment of the oscillator is not required on consecutive work-days. The most important parameters of the oscillator, such as spectral intensity, transverse spatial intensity, and temporal intensity profile are shown in Fig. 2.

The repetition rate of the pulse train delivered by the oscillator is reduced to 5 kHz before seeding the regenerative amplifier, using a pulse picker containing a 25 mm-thick BBO crystal. A pair of gold gratings is used to stretch the high-energy seed pulses. The grating setup provides the GDD of -500 ps/nm . After the stretcher the seed pulses have $1 \mu\text{J}$ of energy and 2.92 nm spectral bandwidth (FWHM). The stretched pulses are sent to the cavity of the regenerative amplifier, which contains a Faraday rotator to separate incoming and outgoing pulses and a Pockels cell with a 20-mm-thick BBO crystal and a clear aperture of $10 \times 10 \text{ mm}^2$ to couple out pulses from the amplifier.

An approximately $100\text{-}\mu\text{m}$ -thick Yb:YAG thin-disk provided by TRUMPF Laser GmbH is used as gain medium. The 9-mm-diameter disk has a radius of curvature of -2 m and doped about 7%. The disk module is thermally back-contacted to a water-cooled diamond heat sink which is connected to a chiller and is pumped with continuous-wave (cw) fiber-coupled diodes at a wavelength of 940 nm with a near-flat-top beam profile of diameter of 3.5 mm.

At 280 W of cw pumping and 87 round trips, 130 W of average power is achieved corresponding to an optical-to-optical efficiency of 47%. The M^2 measurement indicates $M_x^2=1.08$ and $M_y^2=1.07$ for the amplified beam. The beam profile and the spectrum of the amplified pulses are shown in Fig. 3(a) and (b). The amplifier is operated in saturation and delivers pulses

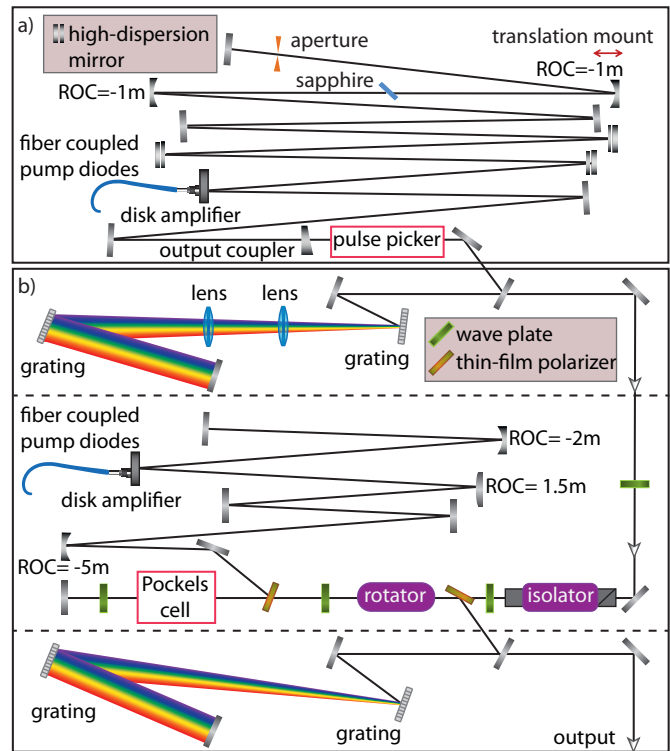


Fig. 1. Schematic layout of the Yb:YAG thin-disk regenerative amplifier. (a) The fiber-coupled diode-pumped KLM thin-disk Yb:YAG oscillator delivers 350 fs pulse at 11 MHz repetition rate and $2 \mu\text{J}$ of energy. A pulse picker is used to reduce the repetition rate to 5 kHz at the input of the amplifier. (b) The input seed pulses are temporally stretched before entering the regenerative amplifier. The amplifier cavity contains a fiber-coupled, diode-pumped, Yb:YAG thin-disk gain medium. The amplified pulses are coupled out using a Pockels cell and subsequently compressed in a reflective dielectric grating compressor. ROC: Radius Of Curvature.

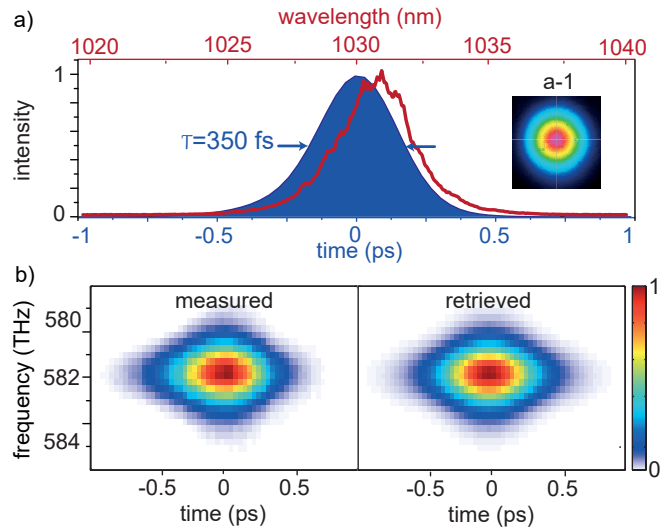


Fig. 2. (a) Oscillator's output spectrum at 25 W of average power (red) along with the retrieved temporal intensity (blue). Inset: transverse intensity profile of the oscillator. (b) Measured and retrieved SHG-FROG spectrograph of the oscillator. $G_{\text{error}}: 6.8 \times 10^{-3}$.

with high stability: the rms of peak-to-peak energy fluctuations, is measured to be less than 1% over a period of 2 s while the amplifier shows outstanding average power stability over 10 hours uninterrupted operation (Fig. 3(a)). Keys to this performance include aggressive gain saturation and optimization of the power supply of the laser diodes and the cooling system for most stable operation.

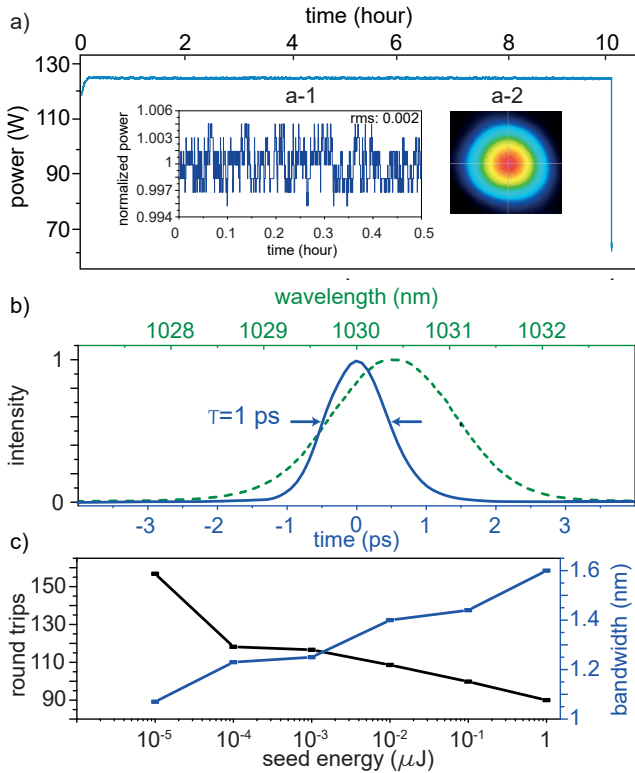


Fig. 3. (a) Average power of the Yb:YAG thin-disk laser over 10 hours continuous operation, measured with an OPHIR powermeter head (L1500W-BB-50-V2). Inset: (a-1): power normalized to its mean value in a half an hour time window. (a-2): Beam profile of the amplified pulses. (b) Output spectrum (green) and the retrieved temporal profile (blue) of the laser pulses at 100 W average power after the grating compressor. (c) Spectral bandwidth (FWHM) of the amplified pulses, and the required round trips at 300 W of pump energy versus seed energy.

The amplified pulses are sent to a reflective multilayer dielectric grating pair (line density of 17401/mm) for temporal compression with overall throughput efficiency of 80%. Figure 3(b) shows the retrieved temporal intensity profile of amplifier pulses, measured by using a SHG-FROG and yielding a pulse duration of 1 ps at FWHM, which is near the 0.98 ps transform limit.

We also measured the spectral bandwidth of the amplified pulses versus seed energy while the pump energy was fixed and the number of round trips in the amplifier was adjusted to obtain the highest output energy for each seed energy. The seed energy was reduced by neutral density filters. 3(c) shows spectral bandwidth of the amplified pulse (FWHM) and the required number of round trips versus seed energy. It is clearly seen that gain narrowing reduces the bandwidth of the amplified pulses when the seed energy is reduced. For seed energy below 10 pJ,

the amplifier was unstable and it was not possible to overcome period doubling by increasing the round trip time in the cavity.

The performance reported above renders this system an ideal candidate for pumping OPCPA systems in the near-infrared and (after frequency upconversion) visible spectral range. Fulfilling conservation of energy in the visible OPCPA requires the generation of low-order harmonics of the amplifier. Among the numerous available materials for SHG, critically-phase-matched LBO and BBO are the best candidates due to their fairly high nonlinear coefficients and damage thresholds. BBO has a higher nonlinearity than LBO but a larger spatial walk-off and is limited in the available aperture.

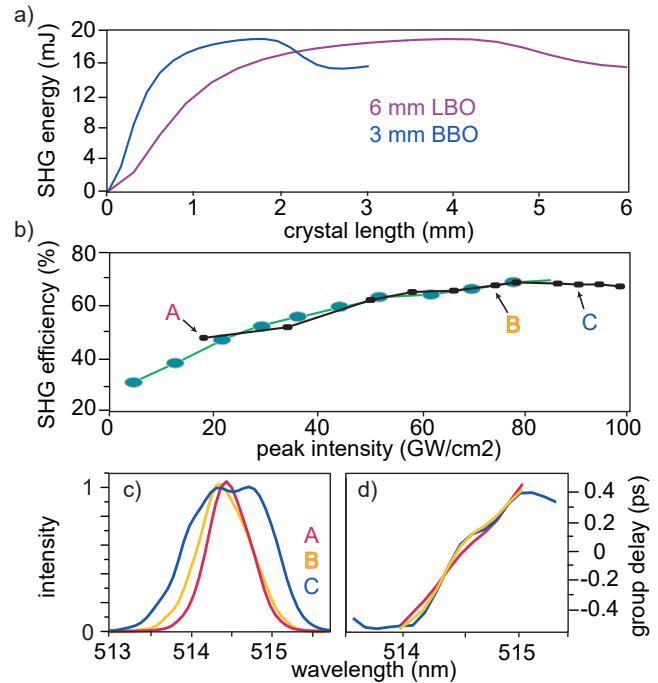


Fig. 4. (a) Simulated second harmonic generation (SHG) efficiency versus crystal length in a 3-mm-thick BBO and 6-mm-thick LBO crystal. (b) Experimental SHG energy versus input pump energy in 1.5 mm BBO crystal using 0.5 mJ (black curve), and 20 mJ (green curve) of the amplifier's energy. Retrieved (c) spectral intensity and (d) group delay of XFROG measurements of SHG at different efficiency. Red, orange and blue curves correspond to point A, B, and C in SHG efficiency curve (black curve in part b).

The SHG stage was designed by simulating SHG in BBO and LBO using the SISYFOS code [21]. As the measured pump pulses in space and time have a near Gaussian profile, we assumed a Gaussian spatiotemporal structure for the pump pulses. In LBO the phase-matching angle (θ) was 13.7° and d_{eff} was 0.819 pm/V , and in BBO they were $\theta = 23.4^\circ$ and 2 pm/V , respectively. The Sellmeier coefficients were taken from [22, 23].

Figure 4(a) shows the simulated energy of SHG versus crystal length for 1-ps pulses (FWHM) centered at 1030 nm with a pulse energy of 20 mJ and a peak intensity of 100 GW/cm^2 in type-I BBO and LBO crystals. In the case of the BBO crystal, SHG reaches saturation in a 1.5 mm-thick crystal. For a longer crystal back conversion from the second harmonic to the fundamental pulse takes place. It can be seen that because of the lower nonlinearity of LBO as compared to BBO, the saturation of SHG in

LBO occurs at twice the thickness of BBO. However, due to the smaller spatial walk-off between the second harmonic beam and the fundamental beam in LBO, a conversion efficiency similar to BBO can be achieved [24].

To find the optimum operation regime, SHG-XFROG measurements of pulses at 515 nm and different efficiencies were performed, where the 1-ps pulses of the amplifier were used as the gate pulse. For simplicity, this measurement was conducted in a test SHG stage, containing a 1.5-mm-thick BBO crystal, but with using only 0.5-mJ pulse energy from the amplifier. The peak intensity on the crystal was adjusted to operate the SHG stage in saturation (Fig. 4(b), black curve).

Figure 4(c) compares the retrieved spectral intensity of experimental second harmonic pulses at different efficiency points indicated on the black efficiency curve of Fig. 4(b) as A, B, and C. For 50% conversion efficiency the second harmonic pulses have a pulse duration of 0.89 ps, due to pulse shortening based on the χ^2 effect. At higher efficiencies, higher order spectral phase and spectral broadening is observed. As it is shown in Fig. 4(c), at point C the spectrum is modulated and a dip appears, owing to the back conversion of energy from second harmonic pulses to fundamental pulses. Nevertheless, these chirped second harmonic pulses still maintain a good spatial and temporal quality.

Equipped with this information the accumulation of the nonlinear phase in the experimental SHG stage was minimized by using a 1.5 mm-thick BBO crystal for the frequency doubling of the full output of the amplifier. The pump beam size was adjusted to reach the peak intensity of 80 GW/cm² which resulted in SHG efficiency of 70% maintaining an excellent beam quality in both space and time (Fig. 4(b), green curve). The second harmonic pulses have 70 W of average power and no phase-mismatch due to thermal effect or degradation of the crystal is observed.

In conclusion, we have demonstrated an all-Yb:YAG-thin-disk laser system. By using a μ J-scale, sub-400-fs KLM oscillator as the front end of the Yb:YAG thin-disk regenerative amplifier, the required number of round trips in the amplifier, and hence spectral narrowing of the amplified pulses, is greatly reduced as compared to previous experiments [25]. This allows amplification of each pulse seeded into the amplifier (as opposed to reported period doubling [26]) and substantially improves the stability of the output pulses. As our previous study showed, higher seed energy also reduces the accumulated nonlinear phase and therefore improves the temporal phase of the amplified pulses [15].

The system delivers 1 ps pulses (FWHM) with 20 mJ energy at 5 kHz repetition rate after the grating compressor. Frequency doubling of the amplified pulses in a simple SHG stage, consisting of a 1.5 mm-thick BBO crystal results in more than 70 W of average power at 515 nm with the optical-to-optical efficiency of 70%. The turn-key performance of the amplifier combined with the demonstrated outstanding stability enables the generation of a stable, broadband supercontinuum from the same laser that pumps an OPCPA. This eliminates the need for temporal synchronization of seed and pump pulses, and together with passive carrier-envelope phase stability [26–28] it can lead to a new generation of high-energy, few-cycle OPCPA systems for exploration of new regimes in HHG and attosecond science.

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