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1 kW, 200 mJ picosecond thin-disk laser system

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We report on a laser system based on thin-disk technology and chirped pulse amplification, providing output pulse energies of 200 mJ at a 5 kHz repetition rate. The amplifier contains a ring-type cavity and two thin Yb:YAG disks, each pumped by diode laser systems providing up to 3.5 kW power at a 969 nm wavelength. The average output power of more than 1 kW is delivered in an excellent output beam characterized by $M^2 = 1.1$. The output pulses are compressed to 1.1 ps at full power with a pair of dielectric gratings.

OCIS codes: (140.3460) Lasers; (140.3480) Lasers, diode-pumped; (140.3615) Lasers, ytterbium; (140.3580) Lasers, solid-state; (140.7090) Ultrafast lasers.

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The emergence of sources of few-cycle laser pulses based on optical parametric chirped pulse amplification (OPCPA) [1–3] has increased the demand for high-power pump lasers. Scaling OPCPA systems to terawatt peak powers at kilohertz repetition rates [4] calls for picosecond pump pulses with an energy of hundreds of mJ. At a multi-kilohertz repetition rate, this implies an average power of the order of 1 kW. Slab lasers have yielded sub-ps pulses with more than 1 kW of average power at a 20 MHz repetition rate [5] and pulse energies of 20 mJ at 12.5 kHz [6]. A strong asymmetric thermal lens tends to compromise the output beam quality for increasing power levels. Fiber lasers offer a very good beam quality ($M^2 < 1.2$) at output energies in the mJ range at a 100 kHz repetition rate [7]. A coherent combination of several amplifier channels [8] allowed scaling of this technology, by use of eight channels, meanwhile up to 1 kW of output power at a 1 MHz repetition rate [9]. Cryogenic cooling offered yet another option for achieving multi-10 mJ pulse energies at kilohertz repetition rates at the expense of strongly reduced gain bandwidth [10].

Laser systems based on the thin-disk gain geometry [11] offer high-energy/high-average-power performance without these complications (cryogenic cooling and coherent multiplexing). This capability comes without compromising the temporal and spatial quality of the output beam, both being critical preconditions for driving a broadband OPA chain efficiently. Yb:YAG thin-disk picosecond pulse amplifiers have achieved average powers of more than 1 kW [12,13], as well as pulse energies of several hundreds of millihoules [14–16], but the combination of these performances has not been demonstrated so far.

Here we report on the development of a pump laser for OPCPA applications with an average output power of more than 1 kW at both 5 and 10 kHz repetition rates. The system is based on chirped pulse amplification (CPA) [17] and a Kerr-lens mode-locked (KLM) thin-disk oscillator as a front-end [18] with pulse energies of 1.3 μJ and a pulse length of ~350 fs. A grating stretcher extends the seed pulse to a chirped pulse with a duration of 1.5 ns and a frequency sweep of 500 ps/nm. After stretching, the 1 μJ seed pulses are pre-amplified in a small thin-disk-based regenerative amplifier to 1–2 mJ pulse energy. The main amplifier is built around two diode-pumped Yb:YAG disks, which are used as gain media in a ring-type resonator. The whole setup of the main amplifier is built into a monolithic aluminum housing for high thermal and mechanical stability. A compressor based on multilayer dielectric (MLD) gratings recompresses the output pulses to ~1.1 ps duration. The block diagram of the complete system is shown in Fig. 1.

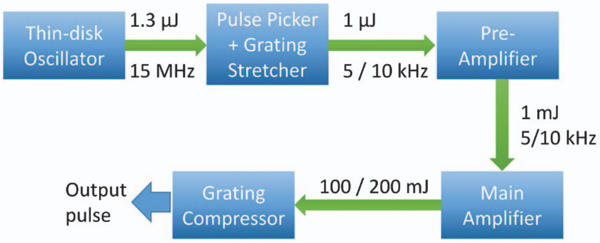

Fig. 1. Block diagram of the amplification chain.

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The regenerative amplifier consists of two Yb:YAG disk modules (manufactured by *TRUMPF Laser GmbH*) equipped with disks of a thickness of ~0.2 mm and of 14 mm diameter and pumped by diode laser stacks yielding a power of up to 3.5 kW per disk. They are integrated into a ring-type resonator of 15 m optical path length, which accommodates two telescopes and a double-crystal BBO Pockels cell (crystal size is 12 × 12 × 20 mm), inducing the $\lambda/2$ phase shift required by pulse picking. The cw pump diodes operate at a wavelength of 969 nm and are stabilized by volume Bragg gratings. This wavelength matches the zero-phonon line (ZPL) transition of the gain material and lowers the heat load on the disks by about 30% due to the reduced quantum defect, as compared to the usual 940 nm pump wavelength. It has been shown that, by using ZPL pumping, the output power of a thin-disk laser system can be significantly improved [19,20]. The pump spot on both disks has a size of 6.8 mm, implying a pump intensity of $5.5\mathrm{kW/cm^2}$ at a pump power level of 2 kW.

In Fig. 2, the optical setup of the resonator can be seen. The ring resonator configuration has been chosen to be able to extract the high average output power of more than 1 kW without having to pass a Faraday isolator. In regular amplifiers, based on a linear resonator, the amplified output beam overlaps with the seed pulse and has to be separated from it by using an optical isolator. By contrast, the seed and output pulses are intrinsically separated in a ring amplifier. Thus, one can elegantly avoid introducing nonlinear effects to the output pulse and distortions caused by the thermal lens in the isolator crystal. In order to fit the whole amplifier setup into a compact (80 × 120 cm), water-cooled aluminum housing, the beam path has to be folded many times. The resonator mirrors are mounted with flexure bearings to ensure a high mechanical rigidity and stability. Water-cooled apertures and metal shieldings protect the components from being heated by stray light or fluorescence radiation emitted by the pump cavities.

The resonator mode (see Fig. 3) was calculated by using ABCD matrix formalism and is designed to fulfill two requirements to reduce the peak power on the optics: it keeps the minimum mode diameter above 2.5 mm and, furthermore, ensures a mode size of ~5.5 mm on both disks. The resonator mode is symmetric with respect to the position of the two laser disks, ensuring an almost identical mode size on both of them. A separate pre-amplifier enables the system to run with fewer resonator passes, allowing stable operation up to repetition rates of 10 kHz. At repetition rates above 1 kHz, pulse energy bifurcation effects can occur on pulse energy dynamics in regenerative amplifiers, as described in earlier works [21–23]. These effects are caused by the lifetime of the upper laser level in Yb:YAG resulting in gain dynamics which lead to chaotic behavior of the output pulse energy. For a stable operation of the main amplifier, this chaotic regime has to be avoided which can be achieved by either applying more pump power to the gain medium or by increasing the seed pulse energy.

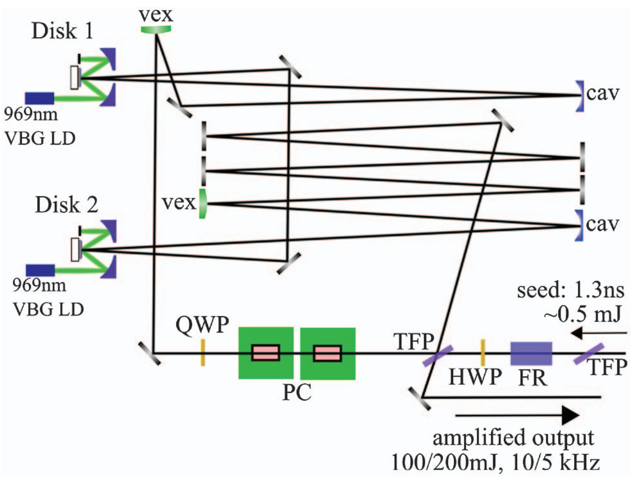

Fig. 2. Optical setup of the regenerative amplifier. QWP, quarter-wave plate; HWP, half-wave plate; FR, Faraday rotator; PC, Pockels cell; TFP, thin-film polarizer. VEX denotes a 10 m RoC convex mirror, and CAV denotes a 15 m ROC concave mirror. All other mirrors are plane.

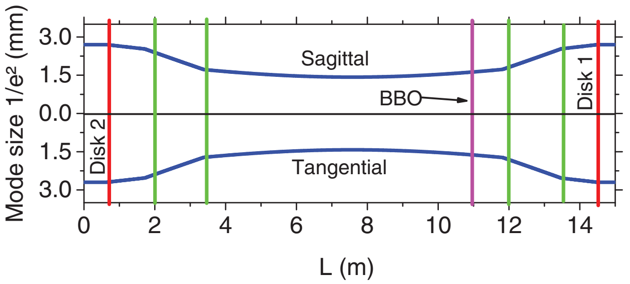

Fig. 3. Calculated eigenmode of the resonator configuration. The vertical lines denote positions of curved mirrors and transmissive elements.

At 5 kHz operation, 1.9 kW per disk has been found to be sufficient for stable operation when seeding the main amplifier with the stretched 1 μJ pulses from the oscillator directly without the usage of a pre-amplifier. However, at a repetition rate of 10 kHz a low-energy seed pulse would require around 3 kW of pump power for each disk, which would lead to a high thermal load and an optical intensity close to the damage threshold of the disks. The use of a separate pre-amplifier for the stretched pulses resolves these issues and significantly improves the power and energy stability of the system. This pre-amplifier runs with an average power of ~10 W at the same repetition rate as the main amplifier. The system setup and the resonator configuration are similar to those described in [24], although running at a pump power of only ~70 W. The output power fluctuations have been measured to be 0.5% RMS over a period of several hours, while the pulse energy fluctuations were determined to be 0.8% RMS. The pre-amplifier system delivers a good beam quality and excellent long-term power stability, allowing for reliable and flexible seeding of the main amplifier with hundreds of μJ of pulse energy.

As shown in Fig. 4(a), we are able to extract 1 kW of output power from the main amplifier over more than 5 h with power fluctuations of 0.3% RMS. This power level was achieved at both 5 and 10 kHz repetition rates, corresponding to pulse energies of 200 and 100 mJ, respectively. Running the amplifier at a 10 kHz repetition rate, we were able to achieve more than 1.4 kW of output power [Fig. 4(b)] for several minutes whereas, at 5 kHz, a maximum output power of 1.1 kW was reached on similar timescales. The damage threshold of the optics in the resonator was found to be the main limitation for even higher output power levels and longer operation times.

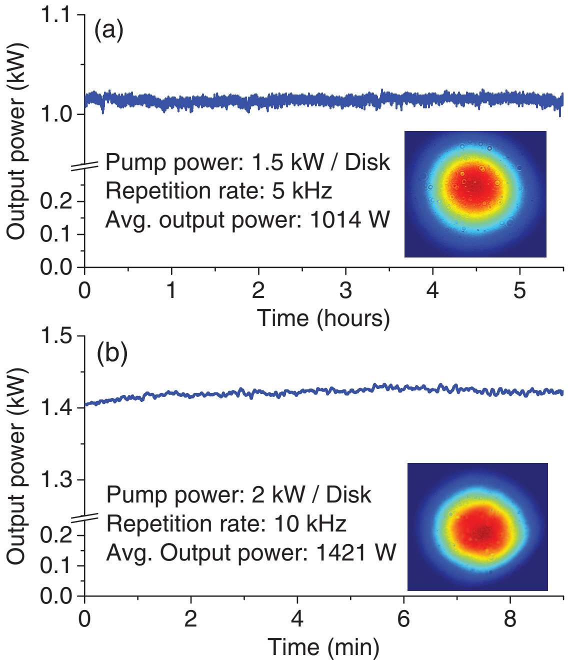

Fig. 4. Output power of the regenerative amplifier at (a) a 5 kHz repetition rate over a period of several hours. The pump power applied for the measurement is 1.5 kW, and the seed pulse energy is 600 μJ, provided by a thin-disk-based regenerative pre-amplifier. At a 10 kHz repetition rate, a maximum output power of 1.42 kW was achieved for several minutes (b). The power traces were acquired by measuring the uncompressed beam directly after the amplifier. The insets show the measured output beam profiles for each repetition rate.

Due to the high average power, the system needs to thermalize before stable output parameters are reached. The thermalization time was determined to be approximately 1 h. After an initial optimization phase of the resonator by using a motorized mirror in the cavity and the seed incoupling optics, the system does not need any further realignment and reproducibly reaches the same power level on every cycle of operation.

Reliable kilowatt-level operation requires the optimization of seed pulse energy, amplification time in the resonator, and pump power per each disk. For the measured data, as shown in Fig. 4(a), a seed pulse energy of 600 μJ and 38 resonator round-trips has been used. These parameters, as well as the required pump power of 1.5 kW per disk, have been determined experimentally and proved to be the most suitable values for stable kilowatt-scale operation of the system. While the fluctuations of the average output power amount to 0.3% the pulse-to-pulse (PTP) energy fluctuations have been measured to be 0.7% RMS, provided that the system is fully thermalized and the resonator has been aligned to the highest output power. At 10 kHz, the PTP stability is approximately 1%.

Figure 5 shows the pulse spectra at different locations in the amplification chain. The stretched pulse seeding the pre-amplifier has a spectral bandwidth of 3.5 nm, which is subsequently reduced by gain narrowing effects in the two amplifier stages to 1.5 nm. Apart from the bandwidth reduction, the output spectrum retains its Gaussian shape, even at a 200 mJ pulse energy before compression.

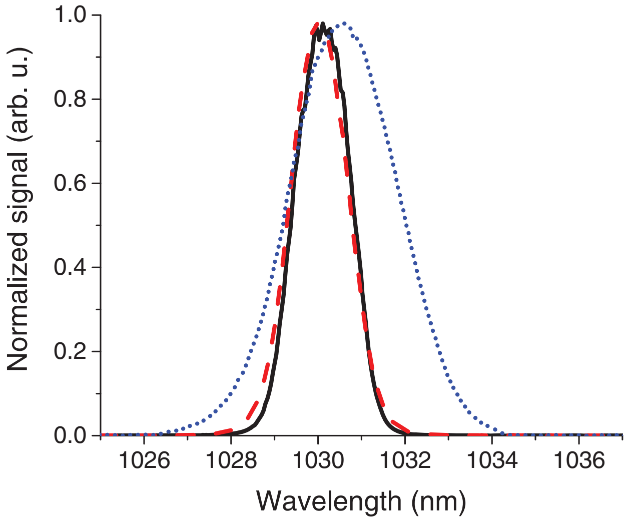

Fig. 5. Output spectrum of the stretched seed pulse (blue dotted line), the pre-amplified seed pulse (1 mJ pulse energy, red dashed line), and the output pulse of the main amplifier (black solid line) running at 5 kHz and 1 kW power.

Measurement of the output beam profile (insets in Fig. 4) shows a symmetric, Gaussian-shaped profile at a 1 kW power level. The beam caustic measurement (Fig. 6) was performed with an $M^2 - 200\ sM^2$ measuring system (*Ophir-Spiricon*). We determined the M^2 to be ~1.1 on both the *x*- and *y*-axes, which indicates an excellent, almost diffraction-limited output beam. Its profile does not change significantly over the power range of 200 W to 1 kW. The beam shape and the caustic at 10 kHz operation with a 100 mJ pulse energy are almost identical to the values at a 5 kHz repetition rate.

The output pulses are compressed with a pair of MLD gratings. They resist the above pulse energies and average powers, and exhibit a high diffraction efficiency above 98%, yielding a compression efficiency of more than 92%. While running the

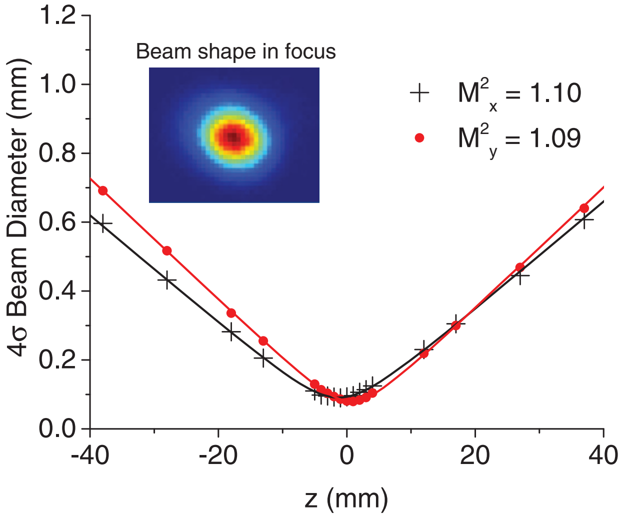

Fig. 6. M^2 of the output beam measured at 1.01 kW power and a repetition rate of 5 kHz. The inset shows the beam shape at the waist. The measured values are $M_x^2 = 1.1$ and $M_y^2 = 1.09$.

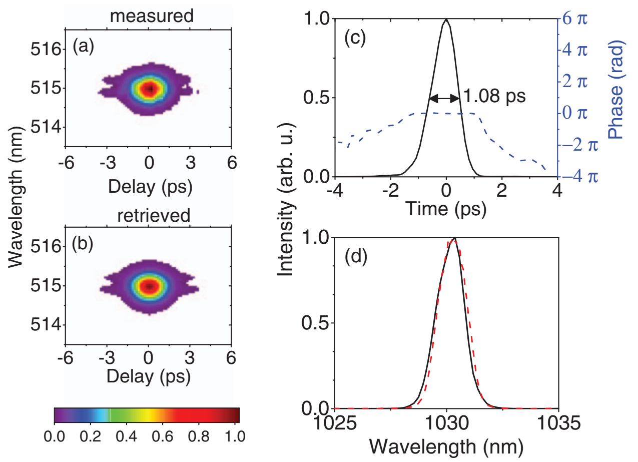

Fig. 7. SH-FROG measurement of the compressed pulse at an output power of 1.03 kW and at a 5 kHz repetition rate. (a) Measured trace. (b) Reconstructed trace. (c) Temporal shape and phase. (d) Reconstructed (black, solid) and measured (red, dashed) spectrum after compression. The pulse duration at FWHM is 1.08 ps (Fourier transform limit, 1.03 ps; FROG error, $3.6 \cdot 10^{-3}$).

main amplifier at 5 kHz and 1.1 kW output power, the pulses have been compressed to 1.08 ps (see Fig. 7); the output power after the compressor was measured to be 1.03 kW which corresponds to a pulse energy of 206 mJ. To the best of our knowledge, these are the highest-energy ultrashort pulses that have been achieved at repetition rates above 1 kHz so far.

In conclusion, we demonstrated a regenerative thin-disk laser amplifier with more than 1 kW of output power at 5 and 10 kHz repetition rates. The system is able to deliver this power level over at least several hours, while still maintaining an excellent beam shape and $M^2 = 1.1$. To achieve this high average power, a ring-cavity-type resonator is used for the amplifier which is seeded by a thin-disk-based KLM oscillator and a subsequent thin-disk-based pre-amplifier providing a seed pulse energy of up to 2 mJ. The amplified pulses have been compressed to ∼1.1 ps by using a pair of dielectric gratings, and a pulse energy of more than 200 mJ has been reached after compression. The system has proven to be an excellent and highly reliable pump source suitable for high-power OPA stages and will form the basis for further power and energy scaling of ultrafast thin-disk laser systems.

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