High-efficiency, single-stage 7-kHz high-average-power ultrafast laser system

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We demonstrate a simple and practical single-stage ultrafast laser amplifier system that operates at a repetition frequency from 1 to 10 kHz, with millijoule pulse energy and as much as 13 W of average power. The repetition rate can be adjusted continuously from 1 to 10 kHz by new all-solid-state pump laser technology. This is to our knowledge the highest average power ever obtained from a single-stage ultrafast laser amplifier system. This laser will significantly increase the average power and the repetition rate that is easily accessible for high-field experiments such as coherent x-ray generation or for laser-synchrotron studies.

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The development of compact, high-intensity, ultrafast lasers has facilitated many new experiments in high field science. Many applications of these sources, including laser-synchrotron experiments, coherent x-ray generation, time-resolved holography, ultrafast surface science, and metrology for extreme-ultraviolet (EUV) optical systems, are limited by the average flux available for experiments rather than by the available peak power or pulse energy. High-harmonic generation (HHG), for example, can be successfully driven by $\approx 200\text{-}\mu\text{J}$ pulse energies, provided that the laser pulse width is sufficiently short (≈ 20 fs). The recent development of techniques for phase-matched HHG by use of hollow waveguides,[1–4] demonstrating the use of temporally shaped pulses for optimizing the conversion efficiency to a single harmonic order,[5] has significantly advanced the utility of this source. Phase-matched frequency conversion in a hollow-core waveguide also makes it practical to develop coherent EUV sources with extremely high repetition rates. The waveguide geometry eliminates the need for pulsed-valve gas sources to implement HHG, which were limited at an $\sim$1-kHz repetition rate. The hollow waveguide can be maintained at a relatively high gas pressure, where the hollow waveguide limits the gas flow into the vacuum system by serving as a differential pumping aperture of diameter ≈ 150 μm. Laser-synchrotron experiments can also take advantage of the extremely high repetition rates of synchrotrons (>500 kHz) only if the laser repetition rate is increased. These and other considerations have motivated the development of simple, high-repetition-rate ($\geq$1-kHz) laser systems capable of generating $>$1-mJ pulse energies with good ($M^2 < 2$) beam quality. The ability to vary the repetition rate of the laser continuously, such that initial alignment of an experiment can be performed at modest average powers, is also desirable.

Past research has demonstrated ultrafast laser systems that operate at terawatt peak powers for 1-kHz repetition-rate systems and at average powers of as much as 25 W for 5–10-kHz repetition-rate systems.[6–14] However, high-average-power systems that have been demonstrated to date have been large (requiring two or more optical tables), complex, and expensive, typically requiring several stages of amplification and $>$100 W of 532-nm pump light from multiple pump lasers. In this Letter we describe a compact, single-stage, diode-pumped ultrafast laser system with which millijoule pulse energies with 24-fs-duration pulses can be delivered at a repetition rate that can be varied from 1 to 10 kHz. This system builds both on previous research on high-average-power ultrafast lasers based on simple multipass ring amplifier designs[15,16] and on the use of cryogenically cooled Ti:sapphire amplifiers.[17] This research also benefits from recently developed high-average-power diode-pumped frequency-doubled YAG lasers, resulting in a compact laser ($\sim$1.5 m^2 of table space) based on a simple optical design.

This laser system employs well-established Ti:sapphire oscillator designs[18] that routinely generate 11-fs pulses as well as chirped-pulse amplification technologies and a liquid-nitrogen-cooled 12-pass single-stage amplifier, as shown in Fig. 1. Cooling the crystal to 77 K essentially eliminated thermal lensing effects, even when the crystal was pumped continuously at a repetition rate of 10 kHz at 75 W of average power. The elimination of the thermal lens has two benefits. It allows us to use a simple 12-pass ring amplifier design and also to obtain an extremely high conversion efficiency (26%) for pump light to ultrafast pulses from the amplifier. Previous high-average-power systems relied on compensating for the thermal lens with a static optical element, one example of which is the thermal eigenmode amplifier.[19] This approach can partially eliminate the effect of the lens but does not allow for moderate

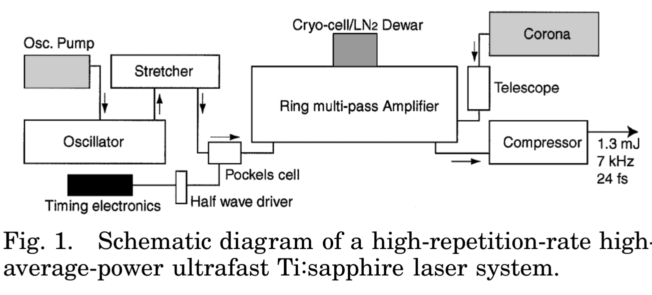

Fig. 1. Schematic diagram of a high-repetition-rate high-average-power ultrafast Ti:sapphire laser system.

changes in the average power of the pump laser that occur as the repetition rate is changed and does not compensate for higher-order aberrations in beam focusing resulting from the thermal lens. Thus, in the case of the thermal eigenmode design, the system must be designed for a specific repetition rate. Furthermore, for the very high (>100-W) pump powers needed for multikilohertz amplification, the induced thermal lens is simply too strong to be compensated for. Therefore the complexity of a system that might compensate for the thermal lens increases considerably, because an intermediate-power regenerative amplifier and a subsequent low-gain power amplifier are required.

In contrast, by removing the thermal lens by cooling the amplifier crystal, our laser system is capable of running at widely varying repetition rates and average powers. Figure 2(a) plots the power of the thermal lens as a function of average pump power for the case of a pump pulse focused to a 600-μm spot that corresponds to a single-pass gain of 9 and for temperatures of 77 and 300 K. It is clear from this simulation that, at temperatures of 300 K, thermal lensing can be extremely severe, varying from 11 cm at 10 W to 1 cm at 100 W. However, at temperatures of 77 K, the power of the lens varies from 5000 cm at 10 W to 500 cm at 100 W. Therefore there is a 500-fold decrease in the strength of the thermal lens when the crystal is cooled from 300 to 77 K.[20] This decrease is the result of both the large increase in thermal conductivity and the large decrease in $\mathrm{d}n/\mathrm{d}T$ of sapphire. At 300 K, the thermal conductivity is 0.26 W/cm K^{-1}, whereas at 77 K it increases to 9.8 W/cm K^{-1}. The corresponding values of $\mathrm{d}n/\mathrm{d}T$ are 1.3×10^{-5}/K at 300 K and 1.8×10^{-6}/K at 77 K.[21]

The cryogenically cooled cell consists of a 2-L insulated stainless-steel can connected to a vacuum cell enclosing the Ti:sapphire crystal. A stainless-steel pipe brings the liquid nitrogen (LN_2) into the vacuum cell and is connected to a copper mount that holds the Ti:sapphire crystal. The vacuum cell has Brewster-angle windows for the entry and exit beams, with a total vacuum beam path of 20 cm. Care must be taken to ensure good heat conduction from the LN_2 to the Ti:sapphire crystal; a hole was bored directly into the crystal mount to ensure a large area for heat conduction. The temperature of the crystal was monitored with a thermocouple that was sandwiched between the Ti:sapphire and the copper mount. We observed little deviation from 77 K, even at the highest pump average power. At this pumping level the LN_2 is consumed at ~1 L/h. In the future we intend to use a closed-loop LN_2 system to cool the crystal. Typical closed-loop cryo-cooled systems that do not cool to LN_2 temperatures would not be capable of removing the high heat loads at higher repetition rates.

In our amplifier system, the 11-fs pulses from the oscillator are stretched to 206 ps by the pulse stretcher. Spectral reshaping as a result of gain narrowing in the amplifier reduces this pulse width to 126 ps. Pulses of the desired repetition rate are then injected into the LN_2-cooled, 12-pass, single-stage amplifier. The B integral calculated for this system is 0.33 rad, which takes into account the dynamically changing pulse width in the amplifier. The amplifier is pumped by a diode-pumped frequency-doubled Nd:YAG laser (Coherent Inc. Corona). Because the output beam from this laser is highly multimode, a beam expander and an imager are needed. The pump beam is focused with a 3.8-cm lens placed 14 cm from the output of the laser. This focal point is then imaged onto the crystal by two 1-m radius-of-curvature mirrors. The beam passes through one of the curved mirrors of the ring amplifier and is focused into the crystal (50 cm away) with a spot size of ~600 μm. The crystal itself is a 1-cm-diameter Brewster-cut, 0.25% doped Ti:sapphire rod (Bicron, Inc.). The high-angle-of-incidence flat ($1'' \times 4''$; $1'' = 2.54$ cm) mirror (Alpine Research Optics, Inc.) in the multipass amplifier was specially designed for maximum bandwidth, low spectral phase aberration, and a high damage threshold at a high angle of incidence. The polarization of the amplifier beam is S (perpendicular to the plane of the table) to produce maximum bandwidth of the dielectric mirrors and for ease of cooling of the amplifier crystal. The performance of the amplifier is shown in Fig. 2(b). The top curve shows that, for approximately 8–8.6 mJ of pump energy at repetition rates varying from 1 to 5 kHz, we obtain 1.4 mJ of compressed output. At 6 and 7 kHz, the output drops to ~1.3 mJ, and for 8, 9, and 10 kHz the output drops to 1.0 mJ, 700 μJ, and 600 μJ, respectively. Much of this energy drop is due to decreasing pump pulse energy (from 8.6 to 6.34 mJ) because of both expansion of the pump beam and roll-off in pump energy at higher repetition rates. The maximum average power from the amplifier system is 13 W at 7 kHz. This is to our knowledge the highest average power obtained from a single-stage ultrafast laser amplifier system.

The lower curve of Fig. 2(b) shows the optical-to-optical efficiency of the amplifier as a function of repetition rate. From 1 to 7 kHz we observe efficiencies of 26–22%. These efficiencies are comparable with the best reported efficiencies (~25%) obtained from Ti:sapphire with regenerative amplifiers.[22] At 8–10 kHz the efficiency decreases because of reduced gain. However, even at the highest repetition

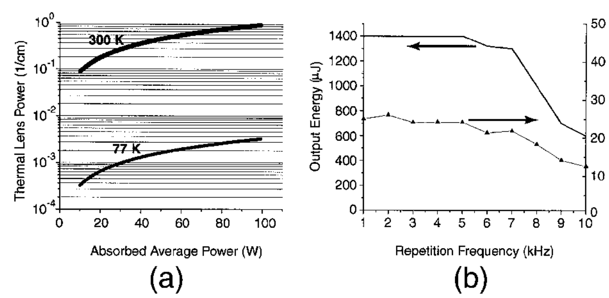

Fig. 2. (a) Thermal lens power as a function of pump power for a pump spot diameter of 600 μm and a single-pass gain of ~9. This setup amplifies nanojoule-level seed pulses to millijoule energies. (b) Output performance of the cryogenically cooled Ti:sapphire amplifier system. Left axis, upper curve, total output power; right axis, lower curve, the total pump-to-output conversion efficiency.

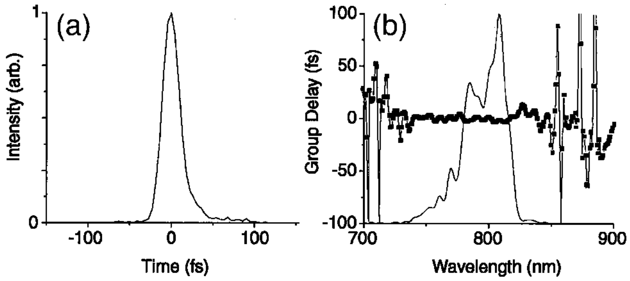

Fig. 3. Second-harmonic frequency-resolved optical gating trace of the laser output, demonstrating a pulse duration of 24 fs.

rates the laser output remains stable, with an ~2% shot-to-shot variation in output energy that originates from similar fluctuations in the pump pulse energy. The pulses are compressed with a 1200-g/mm grating pair compressor and are characterized by use of second-harmonic-generation frequency-resolved optical gating.[23] The measured width was 24 fs in a near-transform-limited pulse, as shown in Fig. 3. We made no effort as yet to broaden the bandwidth by using an etalon to obtain ultrahigh-bandwidth operation, because high-damage-threshold narrow-band optics are currently used in the amplifier.[16,24,25] However, these will soon be replaced by broader-bandwidth optics that will permit operation at 15-fs pulse widths. At that time a new design for a piezo-driven, deformable mirror pulse shaper also will be incorporated into the pulse stretcher to compensate for higher-order dispersion and to allow for feedback control of coherent x-ray generation.

The output beam quality from the amplifier is good, with measured values for M^2 of 1.20 and 1.36 in the X and Y directions, respectively. The deviation in M^2 from the diffraction limit is likely the result of thermal loading of the diffraction gratings. The gratings use a Zerodur substrate, with an epoxy grating replica layer containing the rulings. This expoxy layer is overcoated with gold, resulting in a diffraction efficiency of 91%. For incident powers of 13 W in a beam diameter of 2.5 cm, the absorbed power heats the epoxy layer, deforming it and leading to a beam distortion that varies with incident spot size. The availability of higher-diffraction-efficiency gratings upon a thermally managed substrate would be of great benefit for these high-average-power systems. Finally, to demonstrate the utility of this laser for its intended purpose, we used the laser to generate EUV light at a high repetition rate. We injected a 600-μJ 7-kHz, 24-fs pulse train into a 175-μm-diameter argon-filled hollow fiber. After rejection of the laser light by a 0.2-μm aluminum filter, the HHG beam was observed by use of an image intensifier at intensities consistent with those at lower repetition rates previously used. The EUV generation cell operated over a period of hours with no adverse effects.

In conclusion, we have demonstrated a simple and practical single-stage high-average-power all-solid-state ultrafast laser system. The laser is continuously tunable from 1 to 10 kHz without change in amplifier characteristics. We observed average output powers of as much as 13 W maximum from the laser, which is to our knowledge the highest average power demonstrated from a single-stage amplifier system to date. This laser will have many applications for high-repetition data acquisition, and duplicating it should be easily practical.

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