Ti:sapphire amplifier producing millijoule-level, 21-fs pulses at 1 kHz

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We have developed a Ti:sapphire amplifier system capable of producing pulses of 1 mJ, with 20−22-fs pulse duration, at a 1-kHz repetition rate. The amplifier has a unique design consisting of a three-mirror multipass ring configuration with a highly doped Ti:sapphire crystal as the gain medium. Pulses of 15-fs duration from a Ti:sapphire oscillator are temporally stretched and injected into the amplifier, which is an eight-pass system with a total gain of 10^6. The amplifier is more than 10% efficient, and the shot-to-shot energy fluctuation of the output is less than 2%. The output beam focuses to 1.8 times the diffraction limit. © 1995 Optical Society of America

Ti:sapphire laser systems that use the technique of chirped-pulse amplification can attain terawatt peak powers with femtosecond pulse durations.[1,2] These systems are used in many applications such as high-harmonic generation,[3,4] high-density plasmas, and ultrafast x-ray production.[5] Lasers capable of tera-watt power levels typically occupy two or more optical tables and have repetition rates of 10 Hz or less. However, for some studies a higher repetition rate can be an advantage, even at some expense of the peak power. We report a laser system that produces 0.05 TW of power at a repetition rate of 1 kHz. The entire system including pump lasers can easily fit on one optical table, and the short-pulse oscillator[6] and amplifier occupy a 0.5 m × 2.75 m section of table. The output pulses have a typical energy of 1.0 mJ with a duration of 21 fs. Our multipass configuration mini-mizes astigmatism and reduces material dispersion compared with regenerative amplifier designs that employ intracavity Pockels cells.

Our research extends past work on high-repetition-rate chirped-pulse amplification systems reported by Rudd *et al.*[7] (350 μJ at 55 fs) and Wynne *et al.*[8] (60 μJ at 30 fs) and in typical commercial systems. These Ti:sapphire laser systems also operate at high repeti-tion rates of 1 and 5 kHz, respectively, but use regenerative amplifier configurations and suffer from longer pulse durations. Recently Lenzer *et al.* pro-duced 18-fs pulses with 100-μJ energy at a kilohertz repetition rate, using a four-pass amplifier.[9] Within the high-repetition-rate class of femtosecond laser sys-tems, our design represents a significant increase in available peak powers because it combines both high pulse energy and short pulse duration.

The seed pulses used in our system originate from a self-mode-locked Ti:sapphire oscillator, which has been described in detail elsewhere.[6] The oscillator is pumped with 5 W of power from an Ar-ion laser (Spectra-Physics). The 4-nJ 15-fs pulses from the oscillator are stretched to ~45 ps by an all-reflective pulse stretcher, also described elsewhere.[2,10] The stretcher consists of a grating and a telescope with a magnification factor of 1, in a double-pass configura-tion. The pulse then travels through a KD*P Pockels

cell (Quantum Technology) between crossed calcite polarizers. This permits transmission of a single pulse during a 7-ns window that is timed to the laser oscillator through a frequency divider. The extinction of the polarizers and the Pockels cell in the off state is $>10^4$. The divider receives the 91-MHz signal from the output pulses of the oscillator and divides this rate to 1 kHz.

After the Pockels cell, the pulse is injected by a care-fully positioned mirror into a three-mirror ring multi-pass amplifier. Figure 1 shows a schematic of the entire laser system. The amplifier consists of a flat 10.6-cm gold mirror and two dielectric-coated focusing mirrors of 100-cm radius. The two curved mirrors are separated by the sum of their focal lengths, at 100 cm. The flat mirror is situated perpendicular to the other mirrors and approximately 15 cm away from the line intersecting the two curved mirrors. With this configuration it is possible for a laser beam to make 1 to 30 passes around the triangular loop, while on each pass reflecting from different points on the mirrors. Two additional mirrors inject and extract the beam af-ter the desired number of round trips in the amplifier. This alleviates the need for the Pockels cell or polar-izers used in the regenerative amplifier designs.

When a collimated beam is injected into the multi-pass system, the beam is repeatedly focused at the midpoint between the two curved mirrors. The opti-cal system can be aligned so that the beam paths on each round trip cross each other in the region of this focus, which is where the amplifying medium is po-sitioned. The width of this crossing region grows as the number of passes is increased. The most compact crossing of the beam paths occurs when all beam paths lie in a single plane. To accommodate more passes it is possible to stagger the reflection points on the mir-rors in two vertically displaced rows, but the size of the crossing region grows and takes on a helical pattern instead of a circular one. We chose to configure our system with eight passes lying in one plane. At the crossing region the center of each beam pass is within 150 μm of any other, and as the beams emerge from the region the divergence between the first pass and the last pass is ~5 deg. We found that when mirrors
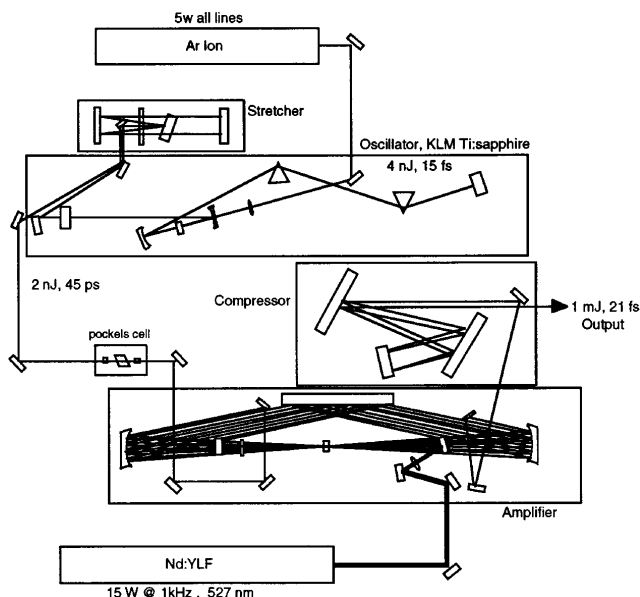
Fig. 1. Schematic of a laser system based on high-repetition-rate multipass amplification.

of unequal focal lengths were used it was not possible for the beams to cross in a small focal region. Day-to-day alignment of the entire amplifier system takes ~10 min, and warm-up time is ~30 min. The alignment consists of minor adjustments to a mirror pair that is injecting the beam into the multipass amplifier.

The amplifier is pumped by a Quantronix Model 527 DP-H frequency-doubled multimode Nd:YLF laser (Excel/Quantronix), which produces up to 20 W of 527-nm light at 1 kHz. The pump beam is focused into an antireflection-coated normal-incidence 0.5-cm Ti:sapphire crystal (Union Carbide) with 0.2% doping. The pump spot size on the amplifier crystal is ~800 μm ($1/e^2$ diameter), whereas the 2-mm-diameter injected seed pulse is focused to ~300 μm. On the first pass through the Ti:sapphire crystal, 74% of the pump light is absorbed. The residual energy is refocused back into the crystal from the opposite side. To remove the excess heat from the crystal, we cool the amplifier crystal to ≈10 °C.

A mask with a series of separate 1-mm holes through which the beam passes on each successive pass was inserted into the amplifier cavity 22 cm before the Ti:sapphire crystal. This mask reduces amplified spontaneous emission (ASE) as well as compensating for thermal lensing owing to high average pump power (typically 15 W). If the beam in the amplifier ring is not restricted by the mask, the spot size on the curved mirrors grows on each successive pass. Simultaneously, the beam is focused to a smaller spot size in the amplifier crystal. If it is unchecked, this thermal lensing not only causes a smaller spot in the crystal that extracts pump energy less efficiently but can also result in damage to the crystal from the amplified femtosecond beam. A secondary problem is that, if the beam grows in diameter to the point where successive passes overlap, the beam can no longer be extracted cleanly from the amplifier.

For a pump pulse energy of 15.3 mJ (13.8 mJ absorbed by the crystal) the output energy from the amplifier is typically 1.6 mJ. This gives a conversion of the pump energy to the output pulse energy of just over 10%. After amplification, the pulses are temporally compressed by a double pass on a grating pair. Both the stretcher and the compressor gratings have 600 grooves/mm (Milton Roy), and the compressor has a throughput efficiency of ~60%. The output energy fluctuation is typically less than 2% both in shot-to-shot fluctuations and long term over an 8-h period.

When the seed pulses are amplified, their spectral width reduces from 53 nm to ~40 nm. The laser spectrum from the oscillator was tuned so that it matches the gain profile of the multipass amplifier as much as possible (i.e., produces the broadest possible output spectrum from the amplifier). A comparison between the input and output spectra is shown in Fig. 2. The oscillator can operate with a wider spectrum and hence shorter pulses than those shown in Fig. 2, but then its spectral peak then shifts to the blue, away from the output spectrum of the amplifier. This results in a narrower output spectrum from the amplifier, with a lower energy and a longer duration. Spectral shaping and limiting in the amplifier is a result of gain narrowing and finite grating reflectance bandwidth.[2,10] The Fourier transform of the amplified output spectrum corresponds to a 19-fs FWHM pulse, which agrees well with our experimental measurements of 20 ± 1 fs, assuming a sech^2 shape, and 22 ± 1 fs, assuming a Gaussian shape. A single-shot autocorrelator geometry was used to measure the amplified pulse duration, with the data averaged over many pulses. Our autocorrelator consisted of a beam splitter, a delay line, and an appropriate compensating plate. The two beams are crossed in a 279-μm-thick KDP crystal at an angle of ~2°. The second-harmonic emission from the KDP is then imaged onto a CCD camera. We calibrated the setup by moving the delay line and correlating the position of the micrometer with the peak position of the autocorrelation trace. The data are then read into a computer. An autocorrelation trace corresponding to a 21 ± 1 fs pulse train is shown in Fig. 3. To determine the pulse duration, we fitted the autocorrelation of a sech^2 function to the data and extracted the full width at half-maximum of the laser pulse.
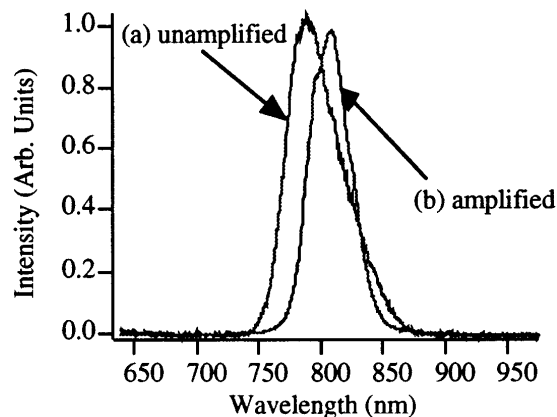

Fig. 2. Unamplified input and amplified output spectra of the multipass amplifier.
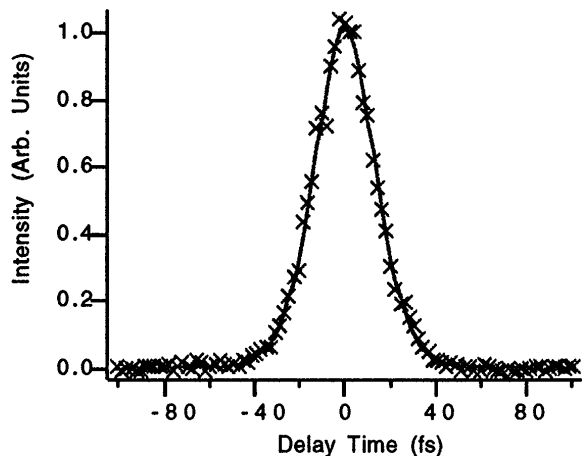
Fig. 3.   Autocorrelation trace and best fit to a sech^2 pulse shape of a 1.0-mJ pulse train. The trace corresponds to a pulse with a full width at half-maximum pulse width of 21 fs.

With the output pulse energy at 800 μJ the seed pulse was blocked, and the output energy decreased only to 200 μJ. This would indicate that a quarter of our pulse energy is due to ASE, which tends to peak after the normal output pulse and has a duration of $\sim$30 ns. However, we found that when the seed pulse was present the ASE was dramatically reduced ($>$95%), because the amplified pulse depletes the gain medium. To observe the ASE while the seed pulse was present, we focused the output pulse into a piece of glass, so that a large fraction of the seeded pulse was converted into broadly diverging white light. On the other hand, because the ASE is much less intense (incompressible), it could pass through the glass undisturbed. A prism was used to separate a large portion of the white light from the ASE, which passed through a pinhole. In this way we could observe that when the seed pulse was injected into the amplifier the ASE pulse virtually disappeared compared with that in the case when there was no seed pulse present. We estimate that when the seed pulse is injected the ASE carries at most 3% (rather than 25%) of pulse energy, and possibly much less. We determined focusability by

focusing the output beam with f/220 optics into a CCD camera. The best focus had a diameter of 235 μm, with a Gaussian-like profile, and was slightly elliptical (0.75 ratio). This indicates that the beam is within 1.8 times the diffraction limit.

In summary, we have developed a simple, compact laser source capable of generating pulses of 1-mJ energy, with 21-fs pulse duration, and at a repetition rate of 1 kHz. The amplifier has a unique three-mirror multipass design, with low ASE and good stability. When the beam is focused with f/5 optics, the obtainable peak intensity from this system should be 10^{17} W/cm^2, at a repetition rate of 1 kHz. This laser system is therefore ideal for high-repetition-rate x-ray sources and harmonic generation.

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