1.1-J, 120-fs laser system based on Nd:glass-pumped Ti:sapphire

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We have developed an ultrashort-pulse laser system in which the final Ti:sapphire amplifier stage is pumped by the frequency-doubled output of a Nd:glass laser. The laser produces pulses with an energy in excess of 1 J on target and an estimated peak focused irradiance of 5×10^{19} W/cm^2. © 1996 Optical Society of America

By using chirped pulse amplification (CPA), laser designers have succeeded in building laser systems that can produce extremely short pulses[1] with high peak powers.[2] Early femtosecond laser systems, based on fluorescent dyes, were limited in energy to several millijoules because of their low saturation fluences. CPA has made possible the construction of high-intensity femtosecond laser systems based on solid-state gain media (e.g., Nd:glass,[2,3] Ti:sapphire,[1,4,5] and Cr:LISAF[6,7]), which have much higher energy-storage capacities and higher saturation fluences than dyes. CPA is achieved by stretching, or chirping, the pulse before amplification in a dispersive delay line[8] consisting of a diffraction grating and an imaging optic (e.g., a lens or a spherical or parabolic mirror). The stretched pulse has a significantly lower intensity, permitting amplification to a higher energy before nonlinear interactions with the optical components of the laser system become a cause for concern. After amplification the stretched pulse is recompressed in a second dispersive delay line that has the opposite sign of dispersion,[9] yielding a short, high-energy pulse.

In this Letter we report the development of a CPA Ti:sapphire laser system in which the final amplifier stage is pumped by the frequency-doubled output of a multistage Nd:glass laser system. The ultrashort-pulse laser has demonstrated an energy of 1.1 J in 120-fs pulses with a peak power of 9.8 TW. The laser has been focused by an off-axis parabolic mirror to produce a power that we conservatively estimated to be 5×10^{19} W/cm^2. Although this energy and power do not represent a significant improvement over those in previous research, the peak power is the highest ever published, to our knowledge. In addition, in contrast to that for our other research in flash-lamp[10] and laser-pumped[5] amplifiers, the architecture of this system can be easily and economically scaled to much higher output energies.

Solid-state amplifiers for ultrashort pulses currently take two forms: flash-lamp pumped and laser pumped. Flash-lamp-pumped amplifiers provide gain over the entire volume, which can be fairly uniform provided that the doping level of the rod is carefully chosen. However, not all materials can be flash-lamp pumped; if the upper-state lifetime of a gain medium is less than the flash-lamp emission duration, as is true for Ti:sapphire,[10] only a small fraction of the pump energy will be available for gain. Also, because the inversion density is generally low (limited by the ability to concentrate the flash-lamp energy) large volumes of the gain medium are necessary to produce high-energy laser pulses. With amorphous materials, such as Nd:glass, this is not a great limitation, as amplifiers can easily be scaled to large sizes. However, with crystalline materials, such as Cr:LISAF, large volumes are much larger to obtain. This is especially true because the doping level must decrease with increasing rod diameter to maintain a uniform gain profile across the amplifier. There is then a concurrent requirement that the rod length correspondingly increase for a fixed total gain. Because there is a practical limit to the length that crystals can be grown, there is a maximum energy that a system composed of flash-lamp-pumped crystalline amplifier rods can reach. Additionally, a large fraction of the energy emitted by the flash lamps falls into spectral ranges that do not contribute to the electronic excitation of the gain medium. Most of this energy ultimately ends up as heat in the amplifier that must be removed, limiting the repetition rate of the laser. The heating of the amplifier can also result in significant distortion of the beam profile and polarization because of thermal-induced refractive-index changes and birefringence.

In order to scale to higher energy the gain medium must be figured into disks, which is the current design of the final amplifiers of large Nd:glass lasers. By figuring the gain medium into disks, the level of doping is made independent of diameter. Currently large disks of Cr:LISAF are unavailable; however, disks of Ti:sapphire with apertures up to 100 mm can be made with current growth techniques. Higher gain volumes require higher flash-lamp energy so that the length of the flash lamps in the amplifier is required to grow. This means that, in general, several amplifier disks distributed along the length of the flash lamps are necessary for efficient use of the flash-lamp energy. Unlike for glass disks, the cost of Ti:sapphire disks can be quite high, making a multidisk flash-lamp-pumped amplifier prohibitively expensive.

The alternative to expensive multidisk flash-lamp-pumped Ti:sapphire amplifiers is to use a large Nd:glass laser to laser pump a single Ti:sapphire disk. The cost of a Nd:glass laser that can produce >10 J of energy at the second harmonic is comparable with the cost of a 10-Hz Nd:YAG laser. An important concern in the design of laser-pumped disk amplifiers is the prevention of gain dumping by amplified spontaneous emission perpendicular to the axis of the disk. Be-

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cause the pump fluence falls along the length of gain medium as a result of exponential absorption, there is a corresponding exponential dependence in the population inversion. Therefore the highest inversion is found at the entrance face of the disk, and it is likely for the gain perpendicular to the disk axis to be greater than the gain along the axis. If the gain is high enough, amplified spontaneous emission across the amplifier face can significantly reduce the efficiency of the amplifier. To prevent this problem the doping of the amplifier must be adjusted to reduce the gain across the disk face and distribute the pump energy along the axis of the disk.

We have designed and built a final amplifier stage for our existing ultrashort-pulse Ti:sapphire laser system in which the ability to scale flash-lamp-pumped Nd:glass lasers to higher energy easily has allowed us to increase the output energy significantly. Our laser uses a small Nd:glass laser system to produce 15 J of energy at 532 nm. This energy is used to pump a large Ti:sapphire disk, producing compressed pulses with an energy of 1.1 J on target and a duration of 120 fs.

The laser system that we have constructed is diagrammed in Fig. 1. It uses a Ti:sapphire oscillator operating with a center wavelength of 800 nm and generating 100-fs pulses. The oscillator output is stretched to approximately 250 ps in a diffractive pulse stretcher that uses 1800-line/mm gratings. The stretched pulses are then amplified to an energy of 10 mJ in a regenerative amplifier pumped by a fraction of the 532-nm radiation from a Q-switched Nd:YAG laser. After the regenerative amplifier, the pulse is amplified in a five-pass bow tie arrangement in a second Ti:sapphire crystal. The amplifier is longitudinally pumped from the one end with remaining frequency-doubled output from the first Q-switched Nd:YAG laser and from the other end by the entire output of a second doubled YAG. The total pump energy in the second amplifier is 1.2 J. Although energies as high as 400 mJ have been obtained from this amplifier, the typical output energy is 280 mJ.

The final Ti:sapphire amplifier is an 80-mm diameter $\times$ 25-mm thick Ti:sapphire disk, which is pumped by the doubled output from a Nd:glass (LG-670 silicate) laser chain. The Nd:glass laser chain starts with a Q-switched Nd:YAG oscillator, which produces 400-mJ pulses of 1.064-μm radiation at 10 Hz. After passing through a Faraday isolator and a vacuum expansion telescope, the laser beam is apodized by a circular sawtooth aperture. The aperture transmits 100% of the incident radiation out to a radius of 9.5 mm; then the transmission falls linearly to zero at a diameter of 15.9 mm. This produces a super-Gaussian laser beam with a profile needed to balance the increased gain at the outside of the flash-lamp-pumped Nd:glass amplifiers. The beam is then amplified in three Nd:glass amplifier stages with diameters of 15.9, 19.1, and 31.8 mm. The amplifiers are separated by beam-expanding spatial filters to clean up the spatial profile of the beam as well as to match the beam diameter to the size of the next amplifier. Faraday isolators are used between successive stages of amplification to prevent reflections from traveling backward through the chain and causing optical damage. After the final amplifier the energy at 1.064 μm is approximately 30 J and can be frequency doubled to 15 J at 532 nm. The laser can be fired once every 4 min and produces an excellent flat-top pump beam with a 28-mm diameter. The entire system, including the Nd:glass laser, fits on three standard optical tables.

In the current configuration the final Ti:sapphire amplifier is pumped by 12 J of 532-nm radiation, and the stretched 800-nm pulse makes two passes to reach an energy of 2.2 J. This beam has been compressed to a duration of 120 fs and an energy of 1.1 J. The corresponding peak power is 9.2 TW. A single-shot third-order autocorrelation of the full-energy compressed beam is shown in Fig. 2. Included in Fig. 2 is a computed pulse that yields a third-order autocorrelation, which is the same as the measurement. The FWHM of the computed pulse is 120 fs. This is consistent with the duration of the measurement if the pulse is assumed to be Gaussian. A fraction of the full-energy beam has been focused by an $f/3.2$ off-axis parabolic mirror to a 3.8 μm $\times$ 3.1 μm spot. A conservative estimate indicates that the main spot contains at least 80% of the focused energy, with the remaining 20% distributed in a broad pedestal around the central spot. From the measured pulse duration and focused spot size the peak irradiance, assuming Gaussian temporal and spatial profiles, is estimated to be 5×10^{19} W/cm^2, which we believe to be the highest irradiance ever reported.

It should be pointed out that this laser system is capable of considerably greater energy with minimum modification. The final energy of the laser system is determined primarily by the pulse compressor gratings

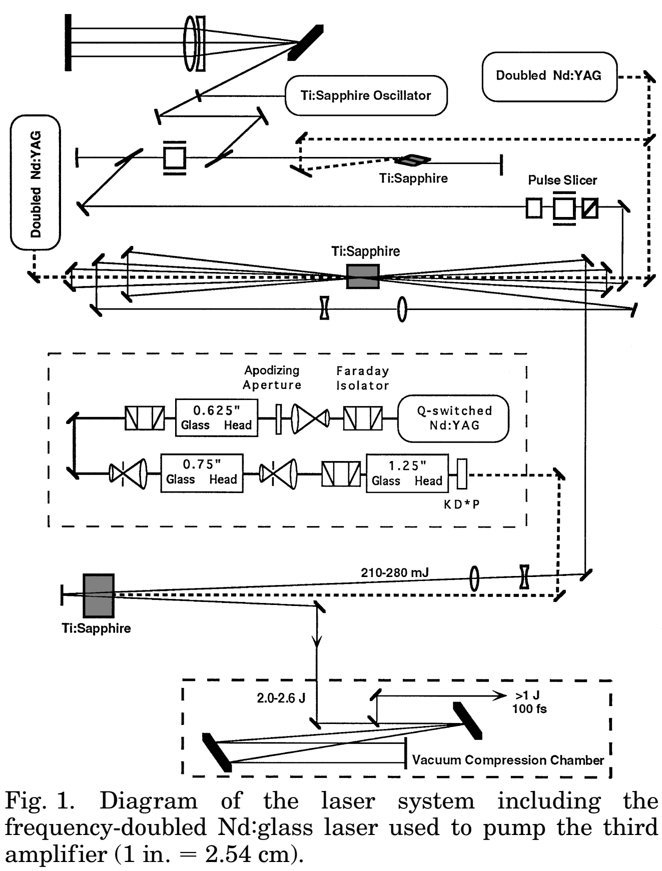

Fig. 1. Diagram of the laser system including the frequency-doubled Nd:glass laser used to pump the third amplifier (1 in. = 2.54 cm).

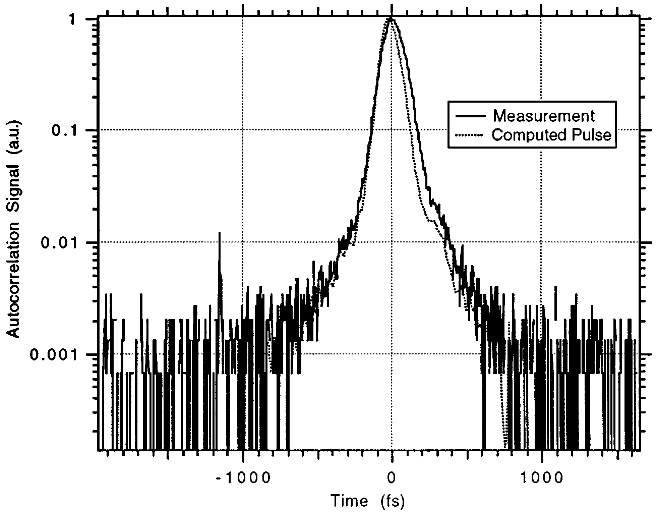

Fig. 2. Single-shot third-order autocorrelation of the full-energy laser beam. Also shown is a computed pulse shape based on the pulse measurement. This pulse duration is 120 fs FWHM. This value is in excellent agreement with that obtained when a Gaussian pulse shape is assumed.

and must be traded off against spectral clipping. For a fixed grating size, a smaller laser beam will experience less spectral clipping but will have a higher fluence and may damage the compressor gratings. Because current grating-damage thresholds are fixed at approximately 400 mJ/cm^2, we must use larger gratings and a larger beam to be able to increase the output energy of the system. We are in the process of obtaining larger diffraction gratings, which should allow us to increase the pump energy of the final Ti:sapphire amplifier stage to the maximum of 15 J and also to increase the number of passes of the 800-nm radiation in the final amplifier. Because 25% extraction efficiency is common in laser-pumped Ti:sapphire amplifiers, we expect the uncompressed output energy to reach 3.7 J. The new diffraction gratings are expected to have diffraction efficiencies of 92%, allowing us to obtain a compressed output energy of 2.7 J with a corresponding increase in the focused irradiance to in excess of 10^{20} W/cm^2.

At this point it is worthwhile to compare this laser system with those previously reported by us.[5,10] In Ref. 5, the pump laser used in the final stage was a flash-lamp-pumped dye laser. Although designed to operate at 5 Hz, it could not do so without failure of the power supply. Additionally, the beam quality was poor and the dye could produce the peak energy only when new. The output energy dropped to half its peak value in approximately 5000 shots. Also, with a pulse length of 3 μs only one third of the pump energy was available for extraction from the amplifier. Finally, the mirrors and windows of the laser cavity had a very short lifetime because of the high intracavity energy density. For Ref. 10 we used a flash-lamp-pumped Ti:sapphire rod as the final amplifier in the system. Because of the short lifetime of the upper state of Ti:sapphire compared with the flash-lamp pulse width, it was necessary to double pass the amplifier to get significant gain. The long amplifier length caused a significant problem with the B integral. Also, the long crystal was of relatively poor optical quality compared with the short pieces used in our laser-pumped amplifiers. Finally, the poor crystal quality and large B integral led to amplifier damage on two occasions, requiring replacement of the expensive Ti:sapphire rod. By comparison, the laser used to pump our final amplifier has excellent beam quality and energy reproducibility and has never damaged a component. Also, the amplifier material length is kept short by the high pump fluence that is available.

In conclusion, we have demonstrated a laser system in which the final amplifier is pumped by the frequency-doubled output of a Nd:glass laser. This laser system produces pulses with an energy of 1.1 J and a duration of 120 fs, giving a peak power of 9.2 TW. This laser has been focused by an $f/3.2$ off-axis parabolic mirror to an estimated peak irradiance of 5×10^{19} W/cm^2. The technique used in design of this system is such that future Ti:sapphire laser systems can be scaled to considerably higher energies. We are currently in the process of constructing another system in which the third and fourth amplifier stages are to be pumped by the frequency-doubled output of the existing Janus laser facility. The Janus laser is a two-beam Nd:glass laser that can produce 100 J of 532-nm radiation per beam. Our current plan is to use one of the two beams to pump the Ti:sapphire amplifiers, with the goal of producing 15-J pulses at 800 nm with a duration of 100 fs. We expect a peak power of 150 TW and a peak focused irradiance approaching 10^{21} W/cm^2.

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