Development of a compact efficient 10 Hz 20 TW Ti:sapphire laser system with a 1 kHz regenerative amplifier

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We have constructed a compact efficient Ti:sapphire laser system that generates 30 fs, 630 mJ pulses at a repetition rate of 10 Hz. A new geometry for a single-stage multipass power amplifier is proposed that greatly weakens and even makes use of thermal lensing. Such geometry can realize high output in a single-stage power amplifier; otherwise at least two-stage power amplifiers are required. The new configuration simplifies the laser system and reduces the cost. The key point in this design is that the beam spot size evolution is considered in combination with the pulse amplification. © 2007 Optical Society of America

OCIS codes: 140.3280, 140.3460, 140.7240, 190.2620.

Since the invention of chirped pulse amplification[1] (CPA), the Ti:sapphire laser has attracted more and more interest and has been extensively applied to various domains of research. Of special importance in recent years are studies of tabletop x-ray lasers,[2–4] high-order harmonics,[5–7] etc., which have been under rapid development with distinct breakthroughs. With the advancement of CPA laser systems, amplified pulses with higher energy and shorter duration are generated, and therefore effects such as spectral narrowing, phase distortion, high-order dispersion, and thermal lensing have to be dealt with. These effects lead to the reduction of the spectral bandwidth and phase modulation, which consequently limits the output energy and increases the pulse duration.

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Received 18 September 2006; revised 15 January 2007; accepted 16 January 2007; posted 29 January 2007 (Doc. ID 75162); published 9 April 2007.

0003-6935/07/132498-05$15.00/0

In a CPA laser system, amplifiers usually use a cylindrically symmetric gain medium that is longitudinally pumped. Since the temperature at the center of the medium is higher and the refractive index increases with increasing temperature, the refractive index has a gradient distribution along the radius, which resembles a focusing lens. Thermal lensing has been extensively discussed, and a variety of approaches have been proposed to exploit, compensate for, or remove the effect. Thermal lensing resulting from the pump power within the amplifier was exploited to create an equivalent lens waveguide for the production of diffraction-limited beams.[8,9] This method was able to properly control the thermal lensing effect but has been applied only to high-average-power-pumped kilohertz laser systems that have a particularly strong thermal lensing effect. Thermal lensing was also successfully controlled by a stable quasi-cavity with two concave mirrors.[10,11] In addition, most of the approaches used a method to cool the gain medium to temperatures sufficiently low to remove the thermal lensing.[12–15] The main drawbacks of such amplifiers based on a cryogenically cooled crystal are increased complexity and higher running costs due to high consumption of liquid nitrogen.

The above approaches are aimed mainly at high-repetition-rate laser systems with serious thermal lensing. However, thermal lensing cannot be neglected in high-peak-power CPA laser systems either, because its effects are similarly large and detrimental. Beam propagation can also be severely influenced by thermal lensing.[16,17] In the multipass amplifier of a high-peak-power laser system, the output beam spot size will be notably reduced due to thermal lensing. The higher the pump energy and the more times the beam passes through the gain medium, the smaller the output beam spot size will be. A seriously reduced beam spot size is harmful to high power amplification, resulting in unwanted consequences such as early gain saturation before efficient energy extraction or damage of optical components. Thus, in order to construct a compact and efficient high-peak-power laser system, thermal lensing also needs to be well managed, in addition to spectral narrowing and high-order dispersion compensation.

Here we show how to solve such related problems for building a compact and efficient 10 Hz Ti:sapphire laser system with peak power of 20 TW. We performed a simple calculation of multipass amplification and also measurements of the evolution of the spot size of the seed beam during amplification. Based on these results, we proposed a new idea to greatly reduce and even exploit the beam spot size reduction, instead of trying to compensate for thermal lensing. Then we designed a new strategy for a single-stage multipass power amplifier, where a midway expansion system was added between the fourth and the fifth passes in a single-stage six-pass power amplifier. Without this method, at least two-stage multipass power amplifiers have to be used for obtaining the same output energy. Such a user-friendly approach played an important role in guaranteeing durable and robust operation of the laser system.

The schematic of the laser system is shown in Fig. 1. To realize such a laser system,[18] we made a compact self-mode-locked femtosecond Ti:sapphire oscillator with a size of 600 mm × 200 mm × 150 mm. It adopted a multifold X-type configuration with standard and commercial mirrors and prisms, including a 4 mm long crystal and a fused silica prism pair. Although it could deliver pulses as short as 20 fs, it routinely operated at about 25 fs. The center of the spectrum could be modified between 760 and 850 nm at an average output of over 500 mW at a repetition rate of 82 MHz when pumped by a 6.5 W diode-pumped frequency-doubled Nd:YVO_4 laser (Verdi-8, Coherent).

The stretcher was a double-pass, on-axis Öffner configuration. It consisted of a concave mirror (R = 1000 mm), a convex mirror (R = 500 mm), a grating (1200 lines/mm), and a pair of roof flat mirrors. Two mirrors were arranged in a concentric configuration. The grating was placed between the convex mirror and the curvature center. The incident angle of the stretcher was adjusted to be less than the Littrow angle so that the angle of the compressor was near the Littrow angle. This played an important role in assuring high diffraction efficiency and third-order dispersion compensation. After passing through a Farady isolator, pulses from the oscillator were incident on the stretcher, to be stretched to more than 300 ps.

The stretched pulse passed through an acousto-optic programmable dispersive filter (AOPDF) (Dazzler800/1.0a, Fastlite). Then the beam was injected into a 1 kHz regenerative amplifier. Because

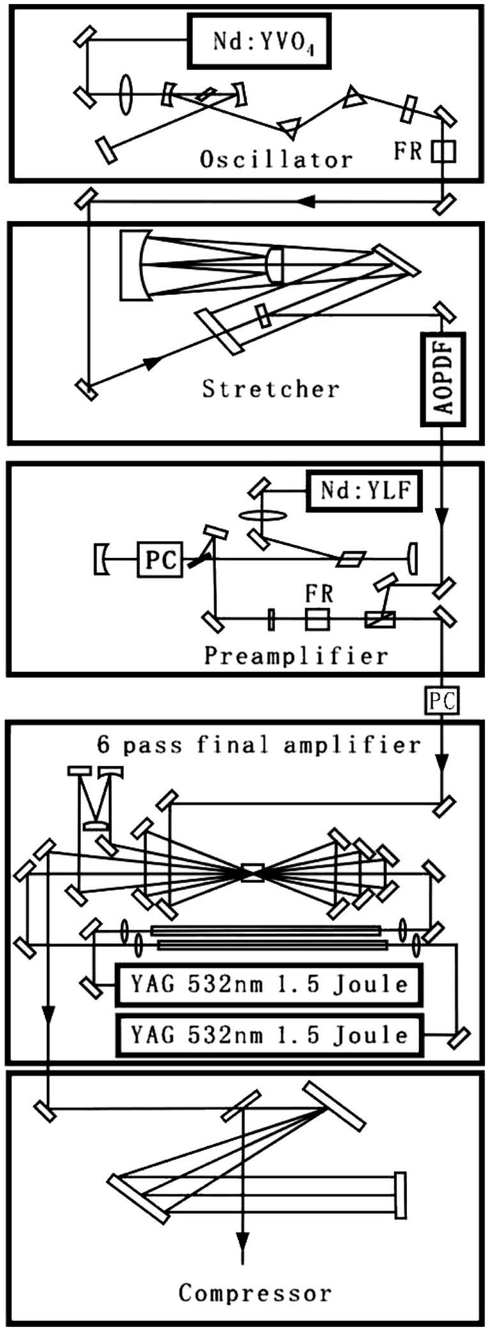

Fig. 1. Schematic diagram of the laser system. FR, Faraday rotator; PC, Pockels cell.

of higher pulse-to-pulse stability and better beam quality resulting from the cavity structure, a 1 kHz regenerative amplifier was chosen as the preamplifier. As an additional advantage, the pulse from the 1 kHz regenerative amplifier could be directly fed into the compressor to obtain a compressed 1 kHz pulse. The cavity of the regenerative amplifier had a compact structure consisting of a concave mirror and a convex mirror. A Brewster-cut, 18 mm long, 6 mm diameter Ti:sapphire crystal was used as the gain medium. A Pockels cell (Lasermetrics 5046, Fastpulse Technology, Inc.) was used to capture the seed pulse

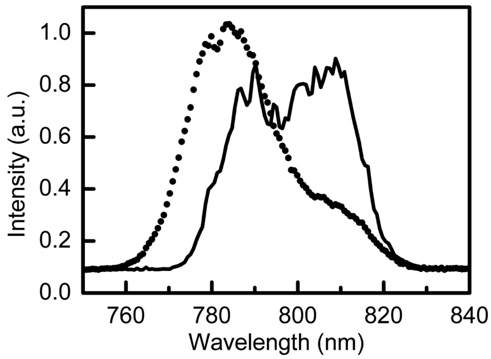

Fig. 2. Seed pulse spectrum after the AOPDF (dotted curve) and output spectrum of the regenerative amplifier (solid curve).

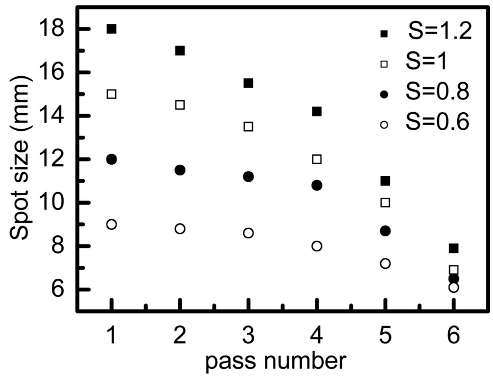

Fig. 3. Variation of the seed beam spot size versus pass number for different ratios between the initial seed and the pump beam spot sizes ($S = w_s/w_p$, where w_s is the spot diameter of the seed beam and w_p is that of the pump beam). The pump beam has a fluence of 1 J cm^{-2}.

within the cavity and to dump the amplified pulse. The pump beam, with a central wavelength of 527 nm from a 1 kHz frequency-doubled *Q*-switched Nd:YLF laser (Jade, THALES Laser) was focused onto the Ti:sapphire crystal by a 300 mm focal length lens. The output from the regenerative amplifier was 2.2 W with a pump power of 19.5 W. Without the pulse shaping by the AOPDF, the output spectral bandwidth was reduced to 18 nm, mainly by gain narrowing. In addition, because the regenerative amplifier was saturated so that the leading edge of the amplified chirped pulse underwent higher gain than the trailing edge, a strong spectral redshift was induced. This phenomenon also contributed to spectral narrowing. For our laser system, the spectrum of the seed pulse was finely adjusted with the AOPDF to be asymmetrical, and its peak position was shifted to the short-wavelength side compared with that of the amplified spectrum without the seed pulse. Figure 2 shows the spectra of the reshaped seed pulse and the amplified pulse. It can be seen that the output spectrum is nearly flat topped with a bandwidth of about 37 nm (FWHM). The spectral narrowing is strongly attenuated. The AOPDF has also demonstrated its flexibility in reshaping the seed pulse spectrum to control spectral narrowing caused by both gain narrowing and spectral redshift.

The 1 kHz output pulses from the regenerative amplifier were selected to be 10 Hz by using a Pockels cell (Lasermetrics 5046, Fastpulse Technology, Inc.) before being sent into a 10 Hz six-pass power amplifier. The power amplifier has a 20 mm long, 20 mm diameter Ti:sapphire crystal. The pump laser beam at 532 nm from two frequency-doubled *Q*-switched Nd:YAG lasers (1.5 J per output) was image relayed onto the Ti:sapphire crystal by using a 1:1 imaging system to ensure good beam quality.

Considering the compactness and cost, we planned to use a single-stage six-pass power amplifier. However, we observed that the output beam spot size was seriously reduced because of thermal lensing. The initial 18 mm diameter seed beam was reduced to about 10 mm in diameter after six passes, for an output energy of 750 mJ. Under this circumstance, higher energy was difficult to obtain because of gain saturation and the damage threshold for optical components. Therefore we needed to solve this problem to achieve higher output. First, we measured the variation of the seed beam spot size versus the pass number for different ratios between the initial seed and the pump beam spot sizes in a single-stage six-pass power amplifier. The results are shown in Fig. 3. It can be seen that the reduction in the beam spot size is closely related to ratio S and pass number; i.e., it becomes large when the seed beam spot size is the same or even bigger than the pump beam, and the variation evidently becomes stronger for the last two or three passes.

The simple saturation model of Frantz and Nodvik has generally been used to describe ultrashort pulse amplification in Ti:sapphire.[19,20] Under the assumption of uniform transverse beam profiles, through solution of a recursion function, the relation between the input fluence and the output fluence can be expressed as follows:

$$J_{n+1} = TJ_{\mathrm{sat}} \ln\{G_0{}^n[\exp(J_n/J_{\mathrm{sat}}) - 1] + 1\}, \qquad (1)$$

where J_{sat} is the saturation fluence, n is the pass number, and J_n and J_{n+1} are the input and the output fluence, respectively. T represents the loss for a single-pass transmission. $G_0{}^n$ is the total small-signal gain through the amplifier active medium of length L, which is given by

$$G_0{}^n = \exp(J_{\mathrm{sto}}{}^n/J_{\mathrm{sat}}). \qquad (2)$$

Here $J_{\mathrm{sto}}{}^n$ is the fluence stored in the amplifying medium that is available for extraction through amplification.

We calculated the normalized output fluence versus pass number by using the above function. Figure 4 shows that varying the input fluence leads to the same output saturation, but in a different number of passes, and that the energy cannot be transferred from the pump pulses to the seed pulses after it enters the saturation regime.

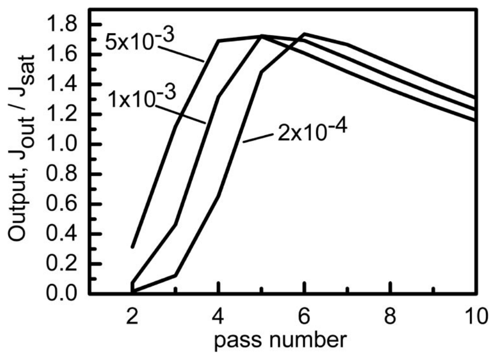

Fig. 4. Normalized output fluence, J_{out}/J_{sat}, versus pass number. The normalized input fluence, J_{in}/J_{sat}, is varied from 2×10^{-4} and 1×10^{-3} to 5×10^{-3}.

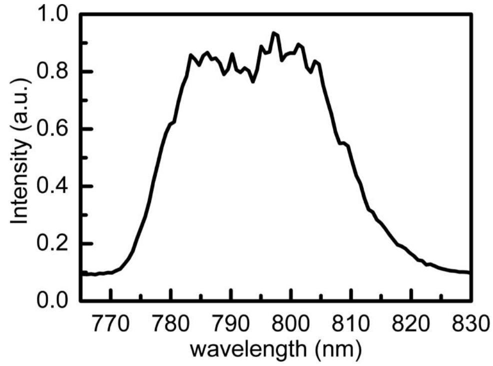

Fig. 5. Spectrum of the compressed pulse.

Based on the above calculation and measurement, a new idea for a single-stage multipass power amplifier can be conceived. In contrast with most of the literature, the spot size of the seed beam from the regenerative amplifier is initially enlarged but is smaller than that of the pump beam. Thus the spot size of the seed beam is gradually reduced during initial passes, and the higher input fluence guarantees high gain for each pass. Then the seed beam is again expanded to be larger than the pump beam for further high-energy extraction during the final passes of this single-stage power amplifier. In such a single-stage multipass power amplifier the gradual beam spot size reduction can even play a positive role, which can contribute to high input fluence during initial passes. Although it is still inevitable during the final passes, the beam spot size reduction is greatly minimized because there are fewer total passes.

In our laser system we used a single-stage six-pass power amplifier. The diameter of the pump beam was 15 mm. The beam from the regenerative amplifier was enlarged to be 10 mm in diameter before entering the power amplifier. After four initial passes, the pulse was amplified to be close to saturation. From the fifth pass, the beam was expanded again to an 18 mm diameter with an expansion system composed of a concave ($R = 5$ m) and a convex ($R = -2$ m) mirror. Then the pulse went through the last two passes. The final output beam was about 14 mm in diameter, while an output of 1.1 J was obtained, which corresponds to an extraction efficiency of 40%. Without a midway expansion system, two-stage (at least eight passes total) power amplifiers are usually required for such a high output. This method not only effectively minimizes the thermal lensing but also simplifies the power amplifier and reduces the cost. Furthermore, such an expansion system can be flexibly placed at the proper position in a single-stage multipass amplifier process according to the variation of the beam spot size during amplification.

After the power amplifier, the laser beam was enlarged to 40 mm in diameter with an off-axis reflective telescope and then sent into the compressor. The pulse was compressed with a pair of gratings (1800 lines/mm). The output of the compressor was 630 mJ. The spectrum of the pulse from the compressor is shown in Fig. 5. The spectral bandwidth is 33 nm (FWHM). The pulse duration was measured with (FROG, frequency-resolved optical gating Video FROG, Mesa Photonics) as shown in Fig. 6. Because the spectrum of the output pulse was approximately a rectanglar shape, we calculated the temporal trace of the output pulse by Fourier transformation of the spectrum as shown in Fig. 5. Figure 6 indicates that the calculated temporal trace agrees well with that measured with FROG. The pulse duration was about 30 fs (FWHM).

In conclusion, we have constructed a compact efficient 20 TW, 10 Hz Ti:sapphire laser system. The compact oscillator provides a widely wavelength-tunable and robust source for the seed pulse. The Öffner stretcher allows sufficient pulse stretching for high-fluence amplification. The AOPDF plays a key role in reducing spectral narrowing and high-order dispersion compensation. The 1 kHz regenerative amplifier, which is used as a preamplifier, produces pulses with higher stability and better quality for the power amplifier. As a feasible extensional application, the 1 kHz pulse from the regenerative amplifier can also be directly introduced into the compressor to obtain a compressed 1 kHz fs pulse. A newly designed scheme for a single-stage six-pass power amplifier is adopted, which is effective in extracting the energy

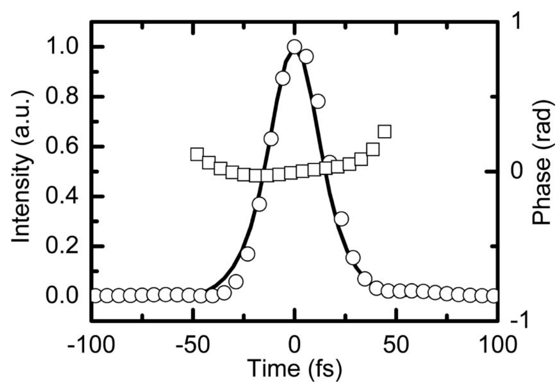

Fig. 6. Measured FROG trace of the intensity profiles (open circles) and phases (open squares) of a compressed pulse and the calculated intensity profiles (solid curve) from the Fourier transform of the spectrum shown in Fig. 5.

and greatly lowering the beam spot size reduction resulting from thermal lensing. The amplified pulse is compressed to a nearly transform-limited duration of 30 fs. The whole system is placed on a 1.3 m $\times$ 3.8 m optical table. It is very compact for a laser system that provides 10 Hz high-peak-power output and 1 kHz high-average-power output. The 10 Hz pulses are now used for research on tabletop x-ray lasers and high-order harmonic generation, while the 1 kHz pulses are used for research on material micro-processing.

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