Journal of the Optical Society of Korea, Vol. 7, No. 3, September 2003, pp. 135-138

High-power Femtosecond Ti:sapphire Laser at 1 kHz with a Long-cavity Femtosecond Oscillator

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(Received 27 June, 2003)

A chirped-pulse amplification femtosecond Ti:sapphire laser operating at 1 kHz has been developed. The laser system consisted of a long-cavity femtosecond oscillator, a four-pass grating pulse stretcher, two multi-pass amplifiers and a double-pass grating pulse compressor. Thermal lensing at the amplifiers was reduced by cooling Ti:sapphire crystals using Peltier coolers. Gain narrowing and residual phase errors were compensated for by the use of an acousto-optic pulse shaper. The final laser output had an energy per pulse of 2.0 mJ and a pulse duration of 19.5 fs, reaching 0.1 TW at 1 kHz.

OCIS codes : 140.3590, 140.4480, 140.7090, 320.0320, 320.7090.

I. INTRODUCTION

Ti:sapphire laser systems combined with chirped-pulse amplification (CPA) can produce pulses with terawatt peak powers and femtosecond pulse durations. These high-power laser systems have been used in many high-field applications such as high-harmonic generation, optical-field ionization and plasma physics. Since some femtosecond laser applications require laser pulses with high average flux as well as high peak power and energy, a laser system with a high repetition rate of higher than 1 kHz can have an advantage over lasers with repetition rate of 10 Hz or less. In recent years there has been rapid progress in the development of high-average power femtosecond laser systems [1-3]. In this paper, we present the system configuration of a 1-kHz CPA Ti:sapphire laser that delivers pulse energy of 2.0 mJ with pulse duration of 19.5 fs.

In a kHz CPA Ti:sapphire laser system, there are several problems to be addressed. Thermal effect induced by the strong average pump power in the amplifier crystal leads to unwanted thermal lensing and thermal distortion. As a result, the wavefront of the amplified pulse becomes distorted and the amplification efficiency decreases. Two limiting factors in producing sub-20-fs laser pulses are gain narrowing and residual phase errors. The high amplification in the pre-amplifier accompanies a narrowing of the laser spectrum because of a high gain over 10^6. This gain narrowing is a main source for pulse lengthening. On the other hand, phase distortion arises from an imperfect dispersion compensation in a compressor due to additional material dispersion in the amplifier chain. In our laser setup, the thermal focusing and distortion were suppressed by cooling the crystal in a vacuum chamber. And, the spectral narrowing and phase distortion were compensated for using an acousto-optic pulse shaper (AOPS).

II. LASER SETUP

The kHz, high-power, femtosecond Ti:sapphire laser consisted of a laser oscillator, a stretcher, two multi-pass amplifiers and a compressor. The seed pulses for the amplifier were generated from a prism-dispersion-controlled femtosecond Ti:sapphire laser oscillator in a long-cavity configuration, as shown in Fig. 1 [4]. The oscillator was pumped by a frequency-doubled, diode-pumped Nd:YVO_4 laser(Spectra Physics). The gain medium was a 3-mm-long Brewster-cut Ti:sapphire crystal with an absorption coefficient of 6.8 cm^{-1} at 532 nm and two focusing mirrors with a 10-cm radius of curvature were used in the X-folded cavity. The cavity length was extended by applying the image relay method [5] in the nondispersive arm of the oscillator,

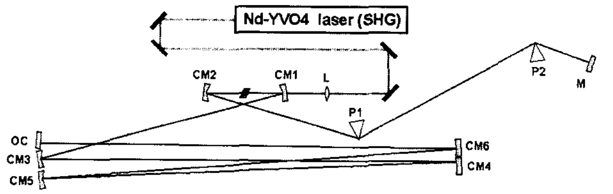
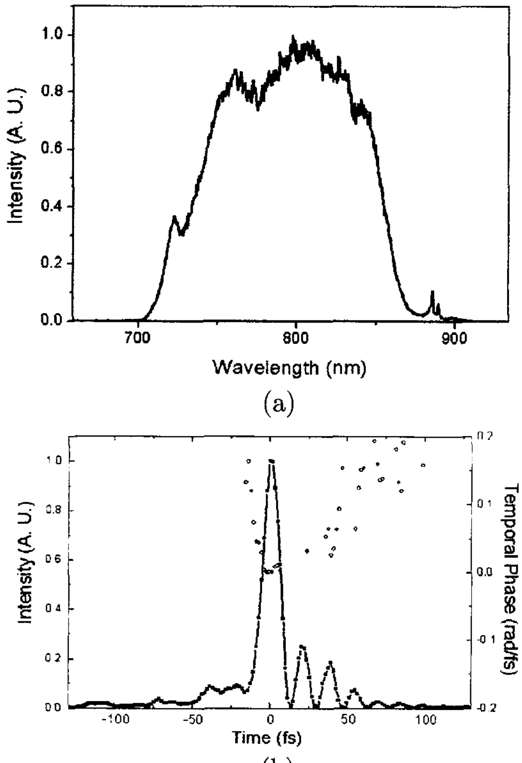


FIG. 1. Optical layout of a long-cavity Ti:sapphire oscillator. CM1, CM2, concave mirror with 10-cm radius of curvature; CM3-CM6, concave mirror with 1-m radius of curvature; OC, 15% output coupler; P1, P2, fused-silica prisms; M, full mirror; L, f = 10 cm lens

lowering the repetition rate of the oscillator from 100 to 27 MHz. The laser generated 13-fs pulses with an energy of 13 nJ and a spectral width of 120 nm with 3.7-W pumping, resulting in the peak power of 1 MW. Fig. 2 shows the laser spectrum and temporal profile of the long-cavity Ti:sapphire laser. The temporal intensity and phase of the pulse were reconstructed using the spectral phase interferometry for direct electric-field reconstruction technique. The adoption of the long-cavity oscillator as the front-end of the CPA laser system could reduce the amplified spontaneous emission (ASE) because one could decrease the number of passes in the amplifier [4]. Moreover, a long interval between pulses helped achieve high-contrast pulse selection in the CPA Ti:sapphire laser.



(a)

(b)

FIG. 2. (a) Spectrum and (b) temporal intensity (square-solid line) and phase (circle) of the long-cavity Ti:sapphire laser.

Laser pulses from the oscillator were stretched to about 220 ps by an aberration-free all-reflective Öffner-triplet-type stretcher [6], in which a grating with 1400 grooves/mm was used. Pulses then passed through an AOPS, which can control the spectral amplitude and phase of the laser pulses simultaneously, and through a Faraday isolator to block the backward ASE from the amplifiers. The pulse was then injected into an 8-pass pre-amplifier, as shown in Fig. 3. The amplifier consisted of three dielectric-coated flat mirrors and two dielectric-coated focusing mirrors with 90-cm radius curvature. The two curved mirrors were placed in a confocal geometry. The pre-amplifier was pumped by 9-mJ green laser pulses from a Q-switched intracavity-frequency-doubled Nd:YLF laser (Merlin, Positive Light). The seed beam is focused into the crystal by the first curved mirror, recollimated by the second curved mirror, and then directed toward the flat mirrors. After the first four passes, the preamplified pulse train is extracted from the amplifier, and pulses are selected using a Pockels cell with 1-kHz repetition rate. The selected pulses are reinjected into the amplifier and their energy is boosted up to 1.5 mJ in the four passes. In this configuration, the Pockels cell not only acts as pulse selector but also suppresses ASE emerging from the preamplification process. And, a mask consisting of a series of small holes, through which the beam passes at each pass, was placed in the amplifier to reduce the ASE. The amplified pulse from the pre-amplifier was injected into a 4-pass amplifier. The second amplifier has the same configuration as the pre-amplifier. When pumped by 11-mJ green laser pulses, the amplified pulse reached an energy of 2.7 mJ. In the two amplifiers, the laser pulses have S-polarization because mirrors with broader bandwidth are available for this polarization.

When high average pump power is used, one of major problems is thermal lensing induced by local heating in the amplifier crystal. The thermal lensing can lead not only to a mismatch between the pump beam and amplified beam modes in subsequent passes but also to optical damage. Moreover, nonquadratic characteristics of the thermal lensing outside the pumped

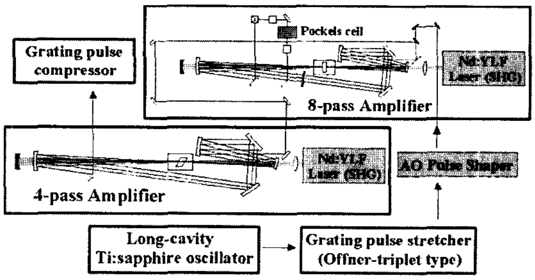


FIG. 3. Schematics of the 1 kHz high-power Ti:sapphire laser.

area in the crystal can induce strong thermal aberrations that reduce the focusability of the beam. Thus, in order to obtain good beam quality and sufficient amplification efficiency, either reducing or compensating for the thermal lensing and corresponding distortion is required [7,8]. Cooling the Ti:sapphire crystal increases the thermal conductivity and reduces the change of refractive index per unit temperature($\frac{dn}{dT}$), resulting in the reduction of the thermal lensing and distortion [9]. For this reason, we lowered the temperature of the crystal to - 40 °C by contacting with a copper block cooled with Peltier cooler, installed in a small vacuum chamber.

The amplified pulses were double-passed through two parallel gratings that have 1480 grooves/mm. For the elimination of thermal distortion and optical damage on the gratings, the beam diameter was expanded to 10 mm by using a convex/concave mirror pair. After compression, the output energy of 2.0 mJ was obtained with a compressor throughput efficiency of 70%. The optical schematics of the laser system are shown in Fig. 3.

III. OPTIMIZATION OF THE LASER PULSE WITH AN AOPS

To compensate for gain narrowing and residual phase error that put a limit on the pulse duration in high-power femtosecond laser systems, AOPS was introduced between the stretcher and the pre-amplifier, as shown in Fig. 3. The AOPS is based on a collinear acousto-optic interaction and makes it possible to simultaneously control the spectral amplitude and phase of the pulse [10,11]. By interacting with a longitudinally traveling acoustic wave in the acousto-optic crystal, the incident laser beam is diffracted into the extraordinary axis with the polarization rotated by 90 degree. The spectral phase of the diffracted laser pulse is controlled by adjusting the longitudinal position in the crystal at which the diffraction occurs for each spectral component. Simultaneously, the spectral amplitude is controlled by adjusting the diffraction efficiency for each spectral component. As a result, the spectral amplitude and phase of the optical pulse are driven by the acoustic wave amplitude and frequency. Fig. 4 shows the spectral intensity of amplified pulse when the spectral amplitude was modulated for the compensation for gain narrowing. After the application of AOPS, the spectrum of the output pulse was broadened from the full width of half maximum (FWHM) of 40 nm to 65 nm. The spectrum, however, contains a double-peaked structure, resulting in pronounced wings shown in the compressed pulse, which should be improved for a single-peaked structure. The output pulses were characterized by the frequency-resolved optical gating (FROG) based on noncollinear second-harmonic generation. By applying phase correction through the AOPS, the phase distortion was reduced to less than 1 radian for the bandwidth over 100 nm, as shown in Fig. 4. Thus, the output-pulse duration decreased to 19.5 fs (FWHM) from 30 fs, as shown in Fig. 5. This AOPS allows us to shape arbitrarily the pulses in time and frequency domain. By performing adaptive control of both spectral phase and amplitude of pulses with the AOPS, accurate pulse shaping could be achieved for optimization of a certain physical or chemical process [12,13].

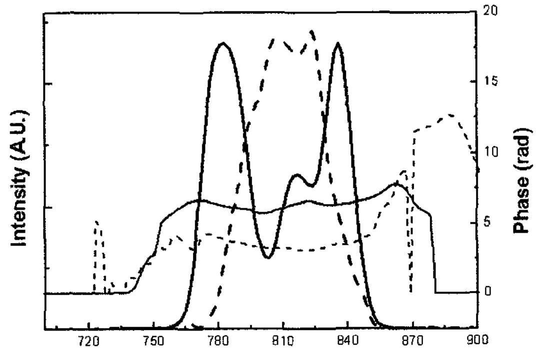


FIG. 4. The spectral intensity and phase of amplified pulses before (dashed line) and after (solid line) using an acousto-optic pulse shaper.

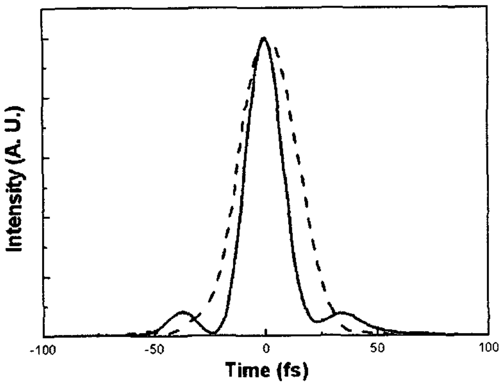


FIG. 5. The temporal intensity profiles of a initial 30 fs pulse (dashed line) and of a corrected 19.5 fs pulse(solid line), retrieved from FROG.

IV. CONCLUSION

We demonstrated a high-power femtosecond Ti:sapphire laser at 1 kHz with energy of 2.0 mJ and pulse duration of 19.5 fs, yielding a peak power of 0.1 TW. Due to broad spectrum, low ASE and long interval between pulses, the long-cavity oscillator was used as the front-end oscillator of the CPA laser system. To reduce the thermal lensing in the amplifier, the Ti:sapphire amplifier crystals were cooled by Peltier coolers in a vacuum chamber. By implementing an AOPS to control spectral amplitude and phase, we could compensate for gain narrowing and residual phase. In this way, the output pulse duration was reduced from 30 fs to 19.5 fs. This laser will be useful for applications requiring high-average-power femtosecond laser pulses, such as high harmonic generation, ultrafast spectroscopy and micro-machining.

ACKNOWLEDGEMENTS

This research was supported by the Ministry of Science and Technology of Korea through the Creative Research Initiative Program.

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