

Parasitic lasing suppression in high gain femtosecond petawatt Ti:sapphire amplifier

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Abstract: New parasitic lasing suppression techniques are developed and high gain amplification is demonstrated in a petawatt level Ti:sapphire amplifier based on the chirped pulse amplification (CPA) scheme. Cladding the large aperture Ti:sapphire with refractive-index matched liquid doped with absorber suppresses the transverse lasing. The acousto-optic programmable dispersive filter (AOPDF) is used to realize side-lobe suppression in the temporal profile of the compressed pulse. The 800 nm laser output with peak power of 0.89 PW and pulse width of 29.0 fs is demonstrated.

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References and links

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1. Introduction

The invention of chirped pulse amplification (CPA) technique [1] opened a new avenue for the generation of ultrashort laser pulses with extremely high intensity. The powerful CPA lasers give rise to the birth and breakthrough of new science and technologies, such as the fast ignition approach of laser fusion, bright X-ray generation, relativistic particle acceleration, laboratory astrophysics and experimental quantum electrodynamics [2,3]. Intense ultrashort pulse Ti:sapphire lasers with peak power of higher than 100 TW [4-8] have been developed in many laboratories. The first petawatt (PW) level CPA laser system using Nd:glass amplifiers was demonstrated at Lawrence Livermore National Laboratory in 1990s [9] with sub-picosecond pulse width. More recently Japan Atomic Energy Research Institute reported the output of 0.85 PW based on Ti:sapphire amplifiers with the pulse width down to 33 fs [10]. The multi-table-top femtosecond petawatt Ti:sapphire laser facility is strongly desired for many applications in university laboratories and potentially in industries. However, the difficulties in ensuring high efficiency amplification and clean temporal profile of laser pulses remain to be overcome.

For large aperture amplifiers in a petawatt level laser system, the laser gain is usually limited by the transverse parasitic lasing in the amplifiers. Some methods for parasitic lasing suppression in Ti:sapphire amplifiers have been successfully demonstrated [11]. The cladding fading is one of the main obstacles limiting the long term performance of the high gain amplification and the refreshment of cladding remains difficult technically. On the other hand, the manipulation of high order dispersion in the pulse stretching, amplification and compression processes is very important for reducing the pulse width, suppressing the side-lobes in the temporal profile [12,13] and therefore improving the signal noise ratio of the compressed laser pulses. For example, the fourth-order dispersion has to be minimized in order to obtain laser pulses shorter than 30 fs.

In this paper we report an ultrafast intense Ti:sapphire CPA laser system with the output peak power of 0.89 PW and the pulse duration of 29.0 fs. New parasitic lasing suppression techniques are developed and high gain amplification is demonstrated. Two different methods are explored to suppress the parasitic lasing in the large aperture Ti:sapphire amplifier. One is the cladding with refractive index-matched liquid and another is the direct absorber coating on side surfaces. The experimental results show that these two methods are both effective and high gain amplification is consequently achieved.

To obtain a shorter than 30 fs pulse duration, the combination of an acousto-optic programmable dispersive filter (AOPDF) [14] and the mixed grating stretcher-compressor [12] are used to compensate the material dispersion in the laser system. The high-order dispersion is partially compensated by the AOPDF and side-lobe suppression in the temporal profile of the compressed pulse is demonstrated in this petawatt level laser system.

2. Experiments and Results

This PW level laser system is a typical CPA laser facility based on Ti:sapphire amplifiers. It consists of a self-mode-locked 10 fs Ti:sapphire oscillator, an AOPDF, pulse stretcher using 1200-gr/mm gratings, regenerative amplifier, three stages of multipass amplifiers and a

four-grating compressor using 1480-gr/mm gratings, as shown in Fig. 1. The signal pulse is stretched to ~ 1.6 ns with the bandwidth of 90 nm.

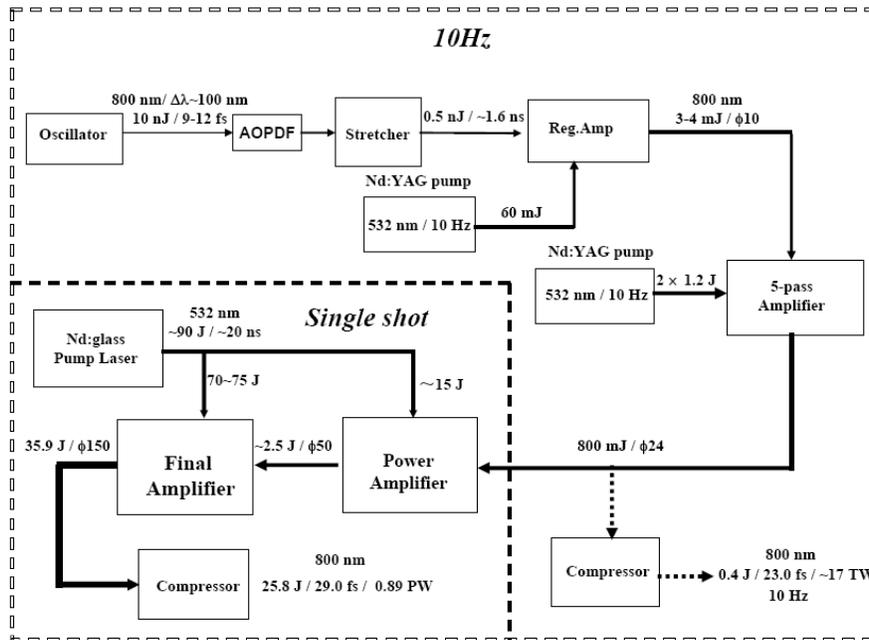


Fig. 1. Schematic layout of the femtosecond PW Ti:sapphire CPA laser system

As we know, the gain narrowing in regenerative amplifier is very serious because of high gain. According to the calculations, the output bandwidth is only 47 nm even with a white light seeding when the gain is as high as 10^7 [13]. To relieve the gain narrowing, the quartz birefringence filter with a thickness of 0.761 mm is used in the regenerative amplifier to induce the spectrally dependent losses [15] (specially reduce the gain at 800 nm). The spectral narrowing in this regenerative amplifier is controlled effectively and a broad bandwidth output is therefore achieved. As shown in Fig. 2, the output bandwidth from the regenerative amplifier is improved to 65 nm from 28 nm by using the birefringence filter. In order to compensate the redshift in the following cascade amplifiers, the laser spectrum is pre-blueshifted. The output spectral profile could be tuned by adjusting the angle between the birefringence filter and the optical axis of the regenerative cavity. On the other hand, the large mode volume in the regenerative amplifier is necessary to support a higher energy output. So a convex-concave structure cavity containing a 10 mm long normal incidence Ti:sapphire rod is employed. With the pump energy of 50-60 mJ, the amplified laser energy is 3~4 mJ.

The pump fluence and spatial mode matching between the pump and signal laser beams are optimized for the high efficiency conversion in the following multi-pass amplifiers. For the pre-amplifier pumped from both sides with an intensity of ~ 2.7 J/cm² at 10 Hz repetition rate, the thermal lensing in Ti:sapphire is one of major problems. Here we use a passive method to compensate the thermal lens effect. A proper beam divergence is introduced by adjusting the lenses separation in the Galilean telescope beam expander for the laser beam from the regenerative amplifier, which is matched with the pump intensity of the pre-amplifier to counteract the thermal lens effect in the crystal. For the first pass, the laser beam size is larger than the pump beam diameter of 10 mm and is then automatically restricted by it. After

five-pass amplification, the output laser energy is 800 mJ with the pump energy of 2.1 J at a repetition rate of 10 Hz (using two frequency doubled Q-switched Nd:YAG laser, Quanta-Ray Pro 230, Spectra Physics Co. Ltd.). The output laser beam diameter of the pre-amplifier is ~9 mm. This beam is then expanded to 32 mm by using a Galilean telescope and only the center uniform part with a diameter of 24 mm is injected to the next 4-pass power amplifier. Alternatively, the output from the pre-amplifier can be compressed to 23.2 fs with a peak power of 17 TW. The beam quality at this stage is almost diffraction-limited with M^2 of ~1.2.

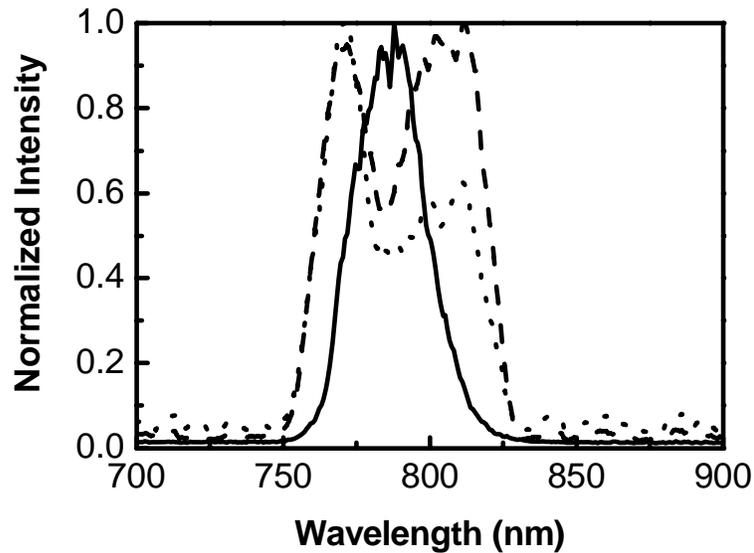


Fig. 2. Laser spectral profiles from the regenerative amplifier with (dotted line) and without (solid line) the birefringence plate, and from the pre-amplifier (dashed line).

The laser energy of this system is boosted in the power amplifier and the final amplifier operating in a single shot basis limited by the pump laser (4 shots per hour). The pump laser is a Nd:glass laser system with the maximum output energy of 150 J at 527 nm. Its seed pulse is a diode pumped single frequency oscillator at 1053 nm with a repetition rate of 1 Hz and pulse width of ~40 ns. The beam is then clipped temporally to be flat top with a width of 20 ns. The final output from the Nd:glass amplifier chain with the diameter up to 70 mm is 300 J. Between every two amplifiers, spatial filters and optical isolators are used to improve the beam uniformity and to isolate the feeding back. A KD*P frequency doubler with a thickness of 30 mm is used and about 50 % conversion efficiency is achieved. The pump laser normally delivers ~100 J in the experiments. The pump laser is split into two beams for pumping the power and final amplifiers. Both beams are spatially filtered and image replayed to the Ti:sapphire disks. The effective pump laser energies for the two amplifiers are ~16 J and 72 J, respectively. The parasitic lasing suppression is mainly implemented in the two amplifiers.

The power amplifier is a 4-pass configuration with a Ti:sapphire disk. In order to check the effect of the new parasitic lasing suppression technique the rectangular Ti:sapphire disk with the size of 42×50×23 (mm³) is used. The parasitic lasing due to the Fresnel reflection of flat side surface is more significant than the circular Ti:sapphire disk. At first we explored a simple coating method using black ink. The gain of this amplifier is only ~3 with the output energy of ~1 J at the pump energy of 15 J when the side surface is not coated. There is only little increase in the output with the increase in the pump intensity. Meanwhile, the temporal

synchronization between the pump and the laser pulse had to be very accurate with the pump pulse arriving 5~8 ns ahead of the chirped laser pulse. It indicates that the parasitic lasing can deplete the population conversion quickly. When the side surfaces are coated with black pen ink (ink from ZEBRA, Japan, catalog number MO-120-MC-BK), the output is improved by 5 times to 5 J. Additionally, the gain is less sensitive to the synchronization between the pump and the laser pulses, and the pump pulse arriving ahead of the laser pulse within a range of ~30 ns can sustain a stable amplification. We should point out that the absorption coating using black pen ink can be bleached after several shots but it is easy to clean and recoat the crystal. This coating technique is a simple and effective scheme for parasitic lasing suppression.

The laser beam from the power amplifier is expanded to 65-70 mm and again the ~50 mm center part with a uniform profile and energy of 2.5~3 J is injected to the final booster amplifier. The Ti:sapphire crystal used in the final booster amplifier is a commercially available disk (Crystal System, Inc.) with 80 mm in diameter and 32 mm in thickness. It is antireflection coated at pump and signal wavelengths on two main surfaces, but not polished for the cylindrical surface. In order to maintain the uniformity of the amplified beam, the laser beam is relay imaged on the disk for every pass. Based on the calculations, three passes are enough to realize the maximum amplification. To achieve high gain amplification, the parasitic lasing resulted from the Fresnel reflection of the cylinder surface should be suppressed. A layer of index-matched thermoplastic polymer as absorption cladding [10] was previously used for successful parasitic lasing suppression. Here we explore the cladding method using the refractive index-matched (1.726) liquid doped with ink powder and we find it is easy to bond with the crystal surface. The gain of the final amplifier without cladding as a function of the pump fluence is shown in Fig. 3. A threshold of serious parasitic lasing is clearly shown in this figure.

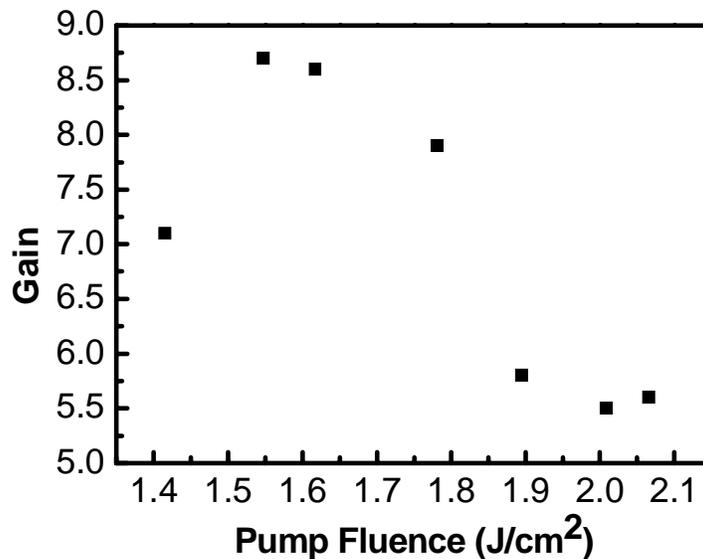


Fig. 3. The gain of the final amplifier without cladding as a function of the pump fluence

The thickness of the liquid cladding layer is 1.2 cm with 40 ml liquid. The effect of different doped concentration of ink powder was investigated and a high and stable gain was obtained for more than 0.6 g dopant in the 40 ml liquid. The output of the final amplifier with cladding as a function of the pump energy is shown in Fig. 4. The result indicates that this method can effectively remove the air on the interfaces and extremely reduce the reflection on the side surface. We find that the bleaching of doped absorber is not pronounced even after tens of shots. This is much better than the direct absorption coating with black pen ink. With the pump energy of ~ 72.0 J, the output energy of 35.9 J is achieved with a conversion efficiency of higher than 50 %. The thermal lens effect in the disk amplifier is not significant and the crystal is not actively cooled because of the low repetition rate.

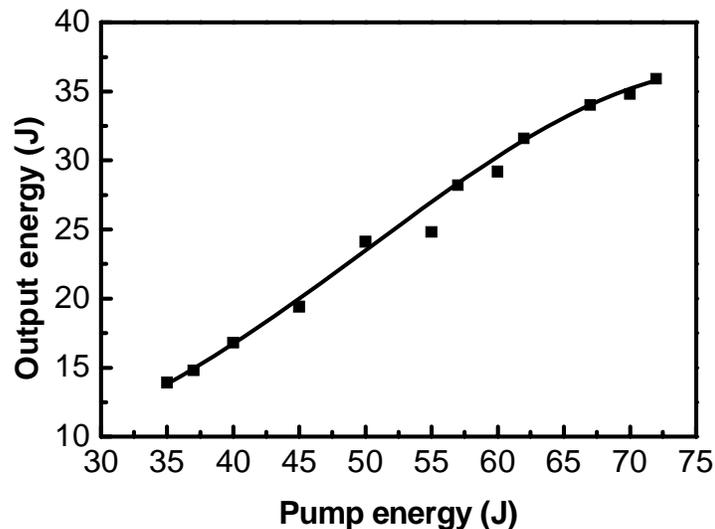


Fig. 4. Output energy of the final amplifier as a function of the pump energy

The output laser beam from the final amplifier is expanded to 150 mm through an achromatic spatial filter and relay imaged to the pulse compressor using four 1480-gr/mm gratings. The optimized incident angle and separation between the gratings are 24.1° and 513 mm, and the transmission efficiency is 72 %. The mixed grating scheme can compensate for as high as fourth-order dispersion [10]. However, considerable side-lobes resulted from residual dispersion appear in the autocorrelation trace (as shown in the inset of Fig. 5). Active amplitude and phase control can be realized by using an AOPDF [14]. Here an AOPDF (Dazzler WB-800, Fastlite, France) is used and the higher-order dispersion and residual lower order dispersion is partially compensated. The side-lobes suppression in the temporal profile of the compressed pulse is realized. The measured autocorrelation traces of the compressed laser pulse with and without using the AOPDF are shown in Fig. 5. The shortest pulse duration is 29.0 fs (FWHM) with output energy of 25.8 J, corresponding to a peak power of 0.89 PW.

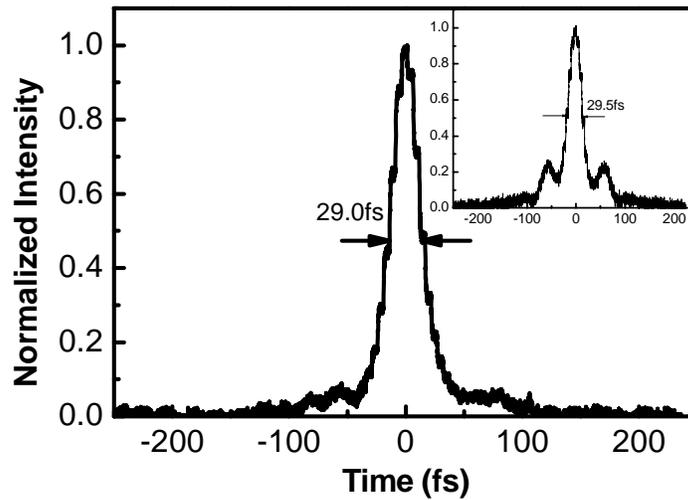


Fig. 5. Measured autocorrelation trace of the compressed laser pulse with AOPDF. The inset shows the result without AOPDF.

The beam quality is retained by controlling the optical quality of components such as mirrors, gratings and crystals, and the use of relaying image technique and soft-apertures. The M^2 of compressed laser beam is measured to be 2.5 in X and 1.9 in Y axis, respectively.

3. Conclusions

In conclusion, we developed new parasitic lasing suppression techniques and demonstrated high gain amplification in a petawatt level Ti:sapphire amplifier based on the chirped pulse amplification (CPA) scheme. Cladding the large aperture Ti:sapphire with the refractive-index matched liquid doped with absorber suppressed the transverse lasing. This cladding technique overcomes the technical difficulty of the long term performance of the high gain amplification and the cladding refreshment of large aperture Ti:sapphire crystal. The acousto-optic programmable dispersive filter (AOPDF) was used to realize the side-lobes suppression in the temporal profile of the compressed pulse. The 800 nm laser output with peak power of 0.89 PW and pulse width of 29.0 fs was demonstrated. The relay imaging of laser beams and optical quality control of the components ensure the good beam quality for the final output of the petawatt level femtosecond laser facility.

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