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A 10-Hz TERAWATT CLASS Ti: SAPPHIRE LASER SYSTEM: DEVELOPMENT AND APPLICATIONS*

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A 10-Hz terawatt class Ti:Sapphire laser system: Development and applications

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Abstract

We developed a two-stage Ti:Sapphire laser system to generate 16 mJ/80fs laser pulses at the pulse repetition rate of 10 Hz. The key deriver for the present design is implementing a highly efficient symmetric confocal pre-amplifier and employing a simple, inexpensive synchronization scheme relying only on a commercial digital delay-generator. We characterized the amplified pulses in spatial-, spectral-, and temporal-domains. The laser system was used to investigate various nonlinear optical processes, and to modify the optical properties of metal- and semiconductor-surfaces. We are currently building a third amplifier to boost the laser power to the multi-terawatt range.

1. Introduction

Since the invention of chirped-pulse amplification (CPA) technique [1], terawatt to petawatt class CPA laser systems using different gain media have been realized. In particular, Ti:sapphire CPA laser systems [1-3] have become standard tabletop source of powerful femtosecond laser pulses. Such energetic pulses are being employed in various scientific and industrial applications, and to explore new horizons in almost every scientific field such as material processing, production of ultrafast source of particles and radiation, high-order harmonic generation, and particle acceleration, for example.

In this paper, we report the design, development and use of a tabletop Ti:sapphire amplifier system that generates 0.2TW/80fs pulses at a repetition rate of 10 Hz. It starts with a sub-25fs Ti:sapphire oscillator, an all-reflective double-pass pulse stretcher, an acousto-optic programmable dispersive filter (AOPDF), a pulse picker, a highly efficient symmetric confocal 12-pass pre-amplifier followed by a 4-pass power amplifier, and finally a double-pass pulse compressor. We employ a simple, inexpensive synchronization scheme using only a commercial digital delay-generator. We characterized the amplified laser pulses in the spatial-, spectral-, and temporal-domains. Finally, we present the interesting findings from some experiments conducted using this laser system.

2. Description of the laser system

Fig.1 depicts the schematic diagram of the laser system. The oscillator consists of a 5 mm optically thick Ti:sapphire crystal (Red Optronics), two curved mirrors of 5 cm focal length (one TNM2 series negative chirp mirror, and another SWP series dichroic mirror from CVI), a 12% output coupler (10B20OC.20 from Newport Inc), along with a high reflecting end-mirror (LGVD series mirror from CVI), arranged in a standard bow-tie cavity configuration. We explored several combinations of output couplers, cavity-

and high-reflectors of the oscillator to obtain the maximum spectral bandwidth and maximum output power. The Spectra Physics Millennia laser (maximum power of 6 Watt) pumped the gain medium using a 10 cm focal length lens (PLCX series lens from CVI). The lengths of the non-dispersive and dispersive arms of the resonator are ~68 cm and ~88 cm respectively. Dispersion compensation is achieved by a pair of fused silica prisms separated by 61.5 cm. The oscillator delivers horizontally polarized laser pulses with a FWHM spectral bandwidth of ~50 nm, supporting ~20 fs laser pulse, at a repetition rate of ~89 MHz. The average power is 400 mW at a pump power of 4.5W. Stable mode-locking is initiated by tapping on the stage holding one of the prisms.

The oscillator pulses are injected into an all-reflective Lemoff and Barty pulse stretcher [4], consisting of two anti-parallel gratings with a groove density of 1200 l/mm (Spectrogon), two gold-coated concave mirrors (f = 61cm), and a gold coated plane mirror that facilitates a double-pass arrangement by a vertical tilt of ~3.5mrad. The gratings SG1 and SG2 (Fig.1) are separated from their respective concave mirrors by a distance of ~22 cm and ~32 cm. The stretching factor and the spectral pass-bandwidth of the stretcher are ~5.6 ps/ nm and ~95 nm, respectively, at an incident angle of 45^0. The throughput of the stretcher is ~25%, limited by the low diffraction-efficiency of the gratings that operate at an incidence angle that is different from the Littrow angle due to geometrical constraints. The pulse duration after stretcher is ~150 ps, measured using 40GHz detector (New Focus 1001) and analog oscilloscope (Tektronix 7104) with modules 7S11 and 7T11 as sampling and time base respectively.

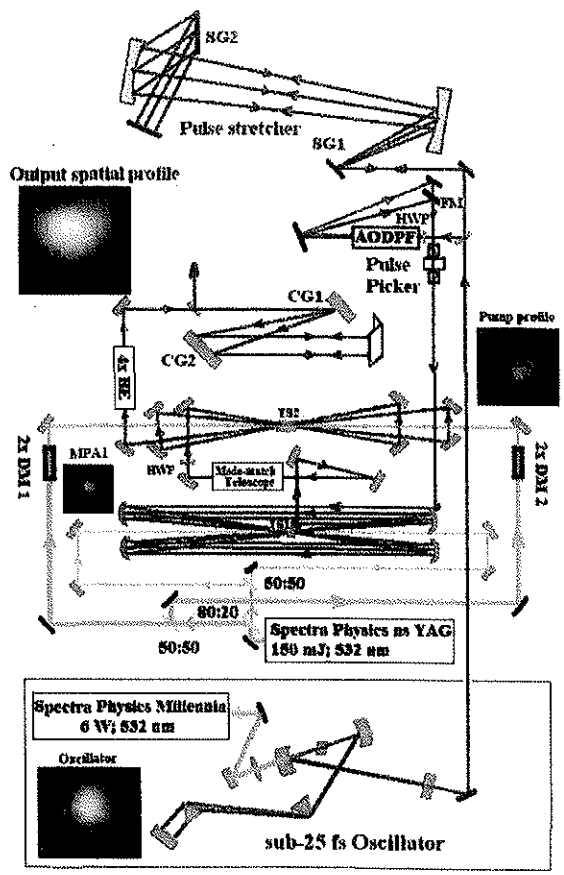

Fig. 1: Layout of the laser system

The stretched laser pulses then pass through half wave-plate to preserve the horizontal polarization needed for the downstream optics and an acousto-optic programmable dispersive filter (AOPDF), which is externally triggered at 10Hz. The AOPDF actively controls the laser pulses' spectral shape, and adjusts their spectral phase to pre-compensate for the narrowing of the spectral gain, spectral shifting, and changes in the spectral phase during amplification and propagation. The diffracted pulses then are propagated through a pulse picker (from KM Laboratory) to lower the pulse repetition rate to 10 Hz. A flip mount, marked FM in Fig.1 allows bypassing the AOPDF, if needed.

The stretched laser pulses then are sent to a 12-pass pre-amplifier. Instead of using a conventional regenerative amplifier, we employed a multiple pass amplifier (MPA) that reduces the accumulated material dispersion and minimizes the effect of spectral-gain narrowing. This preamplifier consists of a Ti:sapphire crystal (10mm dia., 10 mm long; Red-Optronics) placed slightly asymmetrically (45 cm from pulse injecting concave mirror) inside the confocal configuration formed by four concave mirrors (f=0.5m). A 0.5 inch diameter mirror is used to extract the amplified pulse. The pre-amplifier is pumped by two beams of equal energy from a frequency doubled Q-switched Nd:YAG laser (spectra physics). In order to match the pump spatial profile with that of seed, a 1 meter focal length lens, positioned at ~85 cm away from Ti:Sapphire crystal, is used to focus the pump beam. The absorption of the pump laser pulse is ~90%. The output pulse energy after 12 passes is ~3 mJ at a pump energy of ~25 mJ; thus an overall gain and extraction efficiency of $5x10^6$ and ~12%, respectively at pump energy fluence of ~2.5 J/cm^2 on each arm. This extraction efficiency is much larger than 0.1-3% reported for a symmetric- [2] and an asymmetric- confocal amplifier [3]. Our results are also comparable to those from a well- optimized double confocal amplifier (~19%) [5]. Improved extraction efficiency is attributed to the better spatial and temporal overlap between the pump- and seed-beam. This can be improved further by using a tighter focusing geometry.

The pre-amplified beam is sent to a beam-expanding telescope (f=125 mm, & f=-75 mm), and then to the 4-pass power amplifier (MPA2), pumped by additional two beams, each having pulse energy of ~50 mJ, derived from the same frequency-doubled Q-switched Nd:YAG laser. Two independent 0.5x beam expanders, DM1 (f=100mm & f=-50mm) and DM2 (f=150mm & f=-75mm), assure reaching a pump-beam diameter of ~3 mm on the amplifier crystal, to attain a pump fluence of ~1.5 J/cm^2. Fig. 2 shows the pulse spectra recorded after the oscillator, after the pre-amplifier (MPA1) with and without AOPDF, after the MPA2 with AODPF, and the ASE. The amplified spectrum after MPA2 has a spectral bandwidth of 30 nm and 20 nm (FWHM), with and without AOPDF, respectively.

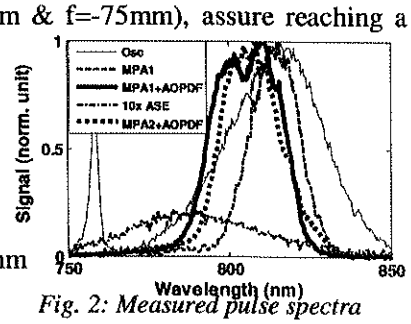

Fig. 2: Measured pulse spectra

The final amplified energy reaches ~25 mJ per pulse with ±15% fluctuations (peak-to-peak) throughout 4 hours of continuous operation. Without any ASE suppression controls, it has an estimated ASE background ratio of 1:20, assessed from the measured pulse energy with and without seeding the amplifiers. To minimize the variation in the pulse energy and ASE due to beam misalignment caused by variation in laboratory's temperature and humidity conditions, we installed low-cost video cameras to monitor the input and amplified output beams at different locations and to correct their spatial position. Normally, it takes 10-20 minutes to refine the alignment after stabilizing the pump laser beam.

The amplified beam diameter was increased 4 times using an expander (f=-100 mm, & f=400 mm) and then sent to the pulse compressor. The latter consists of two 1200 lines/mm diffraction gratings, kept parallel to each other, and a retro-reflecting mirror for making a double-pass arrangement. The incidence angle on the compressor's identical gratings should be close to that of stretcher for perfect dispersion compensation. However, to increase the energy throughput of the compressor up to 70%, we chose an angle of incidence of 35^0 with a grating separation of ~62 cm. We achieved pulse compression down to 80 fs, as shown in Fig.3. The compressed pulse was characterized via conventional intensity autocorrelation and SHG FROG. Bypassing the AOPDF yielded a compressed pulse of ~100fs. The estimated pulse-width for measured bandwidth of 30 nm is ~25fs; we attributed this difference to the mismatch between the stretcher and the compressor.

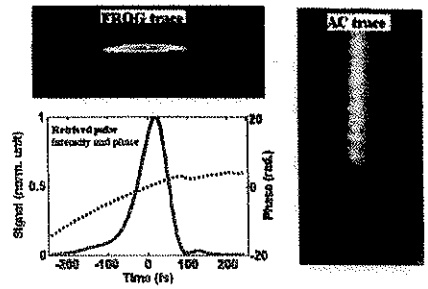

Fig.3: Measured FROG and AC trace, and retrieved pulse using FROG. Horizontal-vertical axes are, respectively, the time-wavelength in FROG trace, and the time-space in the AC trace.

In the present laser synchronization, we did not use the conventional electronic frequency divider scheme [6] to generate trigger pulses; rather, we employed a simple, low-cost alternative synchronization scheme using only a Stanford DG535 digital delay-generator. The latter is triggered directly by the amplified 89MHz signal derived from laser oscillator using a fast silicon detector (rise time < 300 ps) and Stanford 300 MHz amplifier (SR440). The low-frequency trigger signals are generated by setting the delay to one of its output channel (D) slightly smaller than the time period ($1/f_{tr}$) of the desired trigger rate (f_{tr}). Thus, for 10 Hz signals, this delay is set at 99.9 ms. The minimum and maximum trigger rate can be 1 mHz, and 1 MHz, as dictated by the longest allowed delay and minimum cycling time of the delay generator, respectively. Once digital delay-generator is triggered by one of pulse of the train, it ignores rest of trigger pulses till the D delay is over and then re-triggers again, thus effectively generating low frequency synchronized trigger signals. The delay outputs namely T_o, A, B, and C from the delay-generator are used to trigger the AOPDF, firing the flash lamps, Q-switch, and activating the pulse picker respectively.

3. Applications of the laser system

To demonstrate the applicability of the laser system, we conducted two set of experiments. First, we generated efficient third-harmonic radiation in air using tight focusing conditions and then generated white light in the fused silica. To obtain the third harmonic generation (THG) signal, and white light, the amplified compressed beam was focused in ambient conditions using a 10 cm focal-length lens, and then

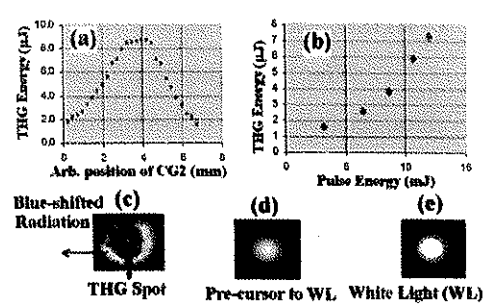

Fig. 4: (a) THG w.r.t. grating separation; (b) Energy scaling of THG ; (c) Spatial image of THG; (d) Precursor to white-light generation (WLG); and, (e) WHG in fused silica.

re-collimating the beam using another quartz lens of 12.5-cm focal length. The third harmonic radiation, filtered spectrally with a quartz prism, was monitored by a pyroelectric joule-meter. We explored the effect of pulse chirp on THG by changing the separation between the compressors' gratings (Fig.4a). Having maximized the THG signal at the optimum grating separation, power scaling with the input laser's pulse energy (Fig.4b) was obtained. The spatial profile of THG signal recorded using a digital camera also is shown in Fig.4c. The overall efficiency of the THG was 0.07% in accordance with that reported in the literature [7]. The THG was also accompanied by a blue-shifted radiation (>300nm), that occurred in a preferential cone of ~6^0 from the laser propagation. After placing a piece of 15 mm thick fused silica (FS) before the focus of the first lens, a white-light was produced, as depicted, respectively, in Figs.4d and 4e for the FS plate sited ~5 cm and ~8 cm from the first lens.

In the second set of experiments, we used only the pre-amplifier output to study the formation of sub-wavelength gratings [8] on metal (eg. Cu, Mo etc) mirrors, and on Si surface in the ambient. Grating formation over large sample area was achieved by raster scanning the sample at a fixed beam. Figure 5 illustrates the typical SEM images of gratings generated on a molybdenum mirror recorded with and without ultrasonic cleaning (~1hr) using 100 fs duration pulses with ~40μm spot, and ~3μJ pulse energy. The periodic structure is perpendicular to the polarization of the laser beam. Details of the experiments will be presented.

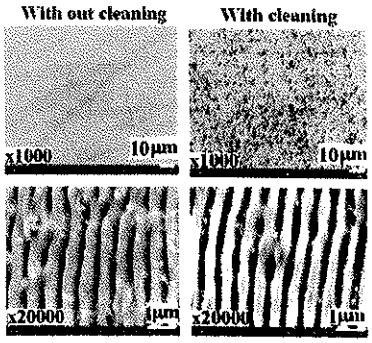

Fig.5: SEM images demonstrating imprinting of sub-wavelength grating

4. Conclusion and Future outlook

In conclusion, we developed a terawatt-class laser system delivering 0.2TW/80fs laser pulses at a pulse repetition rate of 10Hz. The laser system is designed to have a highly efficient confocal pre-amplifier and uses a simple and low-cost synchronization scheme. The compressed laser pulses were used in nonlinear optics experiments and in modifying the surfaces of Si- and molybdenum-mirrors. We are building a third-stage amplifier to increase peak power to the multi-terawatt range by an additional 1.5J frequency-doubled Nd:YAG laser as a pump source. An ASE suppression scheme will be employed. Furthermore, we will implement a matched stretcher and compressor to work at near Littrow angle.

5. References

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