T.3 High energy short pulse laser systems and ultrashort pulse diagnostics

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Introduction

Since the invention of laser in 1960, there has been an unending quest for achieving higher and higher laser power for different applications. Presently, there are laser systems which can deliver laser peak power in excess of 10^{15} W in ultrashort pulse duration regime (sub-50 fs) as well as short pulse duration regime (sub-ps). Such laser systems are essentially based either on concept of chirped pulse amplification (CPA) or its variant optical parametric chirped pulse amplification (OPCPA). Development of such ultrahigh power laser systems has opened up new regimes of ultrahigh field physics, development of compact x-ray sources, particle accelerators, fusion neutron sources, inertial confinement fusion, nuclear medicine, nuclear waste disposal etc. While ultrashort pulse ultrahigh power laser systems generally use Ti:Sapphire as active medium and operate in the pulse energy below few tens of joules, the short pulse ultrahigh power lasers essentially use Nd:glass (because of its high energy storage capacity) and can operate in pulse energy of few kJ. Although, the low-energy Ti:Sapphire based sub-PW class CPA laser systems are now commercially available, high-energy high-power short pulse laser systems are built exclusively in-house. Next, the development of such lasers and their applications, both require reliable ultrafast measurement techniques to determine the various pulse parameters like pulse duration, pulse shape, pulse chirp, pulse-front tilt etc. Since the response of electronic photo-detection systems is limited to a few tens of ps for fast photo-detectors and to a few hundred fs for fastest streak cameras (which may cost more than Rs 100 lakhs and may not be available for use due to export embargo), ultrashort laser pulses are characterized by indirect one-dimensional (1-D) time-domain correlation methods or 2-D time-frequency correlation methods. Laser Plasma Division of RRCAT is actively involved in the above research arenas and has built a CPA based Nd:glass table top terawatt (T^3) laser system [1-3] delivering pulses of energy in excess of 1 J over duration of ~1 ps at repetition rate of one pulse in ~3 minutes; variety of simple, innovative, low-cost ultrashort laser pulse diagnostics [4-11]; and presently working towards setting up a high-contrast high energy OPCPA based 50 TW laser system [2,12]. The present article aims to provide an overview of work done in this field.

The concept of CPA technique is illustrated in Fig.T.3.1. In this technique, an ultrashort laser pulse is first temporally stretched, and then amplified in laser amplifiers in "master oscillator and power amplifiers" (MOPA) scheme. Finally the amplified stretched pulse is compressed back to an ultrashort pulse resulting in very high peak power output.

The CPA technique is an advantageous and efficient route to amplify ultrashort pulses as it avoids any non-linear optical effects and subsequent lasing medium damage expected in direct amplification of ultrashort laser pulses. Moreover, in comparison to conventional long pulse MOPA based high power lasers, a CPA based laser system can be set up at a much lower cost and smaller size. The CPA technique has resulted in generation of laser pulses of very high intensities even at kHz repetition rate.

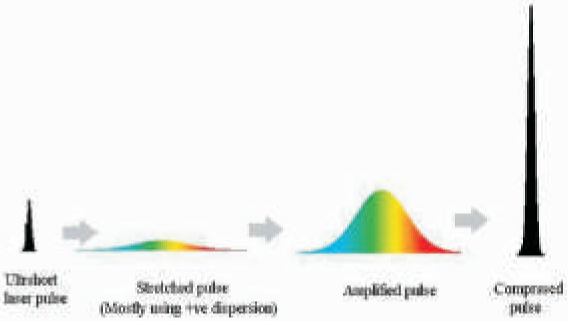

Fig.T.3.1 : Scheme of Chirped Pulse Amplification

Development of Laser Systems

The CPA based Nd:glass T^3 laser system designed and developed [1,2] at Laser Plasma Division of RRCAT is shown in Fig T.3.2. It has a cw mode locked master oscillator (delivering pulses of duration ~200 fs at 100 MHz repetition rate), a double pass grating based pulse stretcher (providing stretching factor in excess of 10^3), an electro-optic single pulse selector, pulse injector and ejector units, a highly-stable high-gain (>10^7) Nd:glass regenerative amplifier (regen) [3], an electro-optic pulse cleaner unit, beam expanders, a double pass amplifier, a single pass amplifier, a vacuum spatial filter cum image relay system, and a double pass grating based pulse compressor. A safety interlock unit has also been incorporated to avoid damage to optical components due to any accidental injection of un-stretched laser pulses.

Except the seed femtosecond laser oscillator, all the subsystems of the above laser system are designed and set up in-house. Next, theoretical modeling has been done and issues related to parametric criticality of CPA based laser systems have also been extensively studied [2] in order to optimize the performance of the laser system. The laser system provides laser pulses of peak power > 1 TW over duration of ~1 ps at pulse-to-pulse time interval of ~3 minutes. A brief description of the sub-systems of the above laser system is given below.

Martinez pulse stretcher has been chosen for our CPA system because of its simplicity and capability to support few hundred fs duration laser pulses. It consists of a pair of identical holographic gratings, a telescope of unit magnification, and a retro-reflector for making a double-pass configuration. The two gratings (groove density 1740 l/mm) are placed symmetrically outside of two identical achromatic lenses (focal length of 500 mm) at a distance of 250 mm. For an incidence angle of 75° at the first grating and $d=0.5747 \mu m$, the stretcher provides a linear chirp of ~ -44 ps/nm at a central wavelength of 1054 nm.

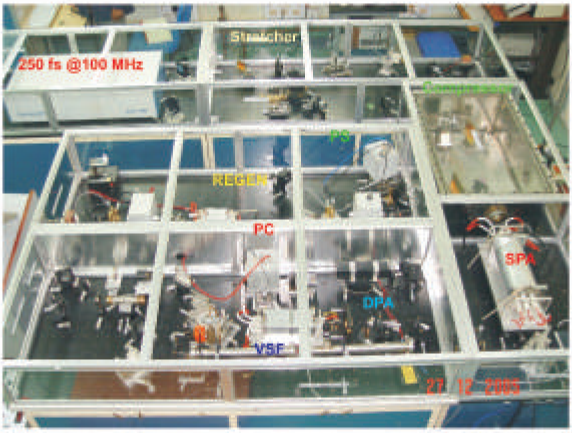

Fig.T.3.2: Photograph of the T^3 laser system

As per typical behavior of mode-locked laser oscillators, the seed oscillator GLX200 also sometimes goes into Q-switched mode of operation, resulting in a very narrow spectral bandwidth (~1 nm) seed laser pulse of few ps duration. Such pulses cannot be stretched to the desired temporal pulse duration (~300 ps), and hence their amplification may result in damage of the optics of the laser system. An interlock system has been developed for safety against any such accidental injection of an un-stretched laser pulse into an amplifier cavity. For this purpose a photodiode is placed at one end of the diffracted (and line focussed) pattern of the laser beam such that in case there is a reduction in the spectral width of the seed laser pulses, the output signal of this photodiode drops to lower value. The difference is used in discriminating between the two operating regimes of the oscillator and generating a safety interlock [2]. The photodiode output signal is compared in a logic circuit with a fixed reference, which in turn generates a control signal. The latter is gated (AND) with the trigger signals to the inputs of the various Pockels cells of the regenerative amplifier. Thus the injection is aborted if the spectral width of the seed pulse is found to be small.

A single stretched laser pulse is selected from the 100 MHz pulse train by using a double Pockels cell kept between two crossed polarizers and powered by synchronized 3.4 kV, 5 ns duration electrical pulse. The single stretched pulse is then injected into regenerative amplifier. The regenerative amplifier has three main parts: 1) pulse injector, 2) resonator cavity with amplifying medium (Nd:phosphate glass rod of 5 mm diameter, 100 mm length) and 3) pulse ejector. The glass rod is pumped by the two air cooled xenon gas filled flash lamps. The flash lamps are energized through two capacitors each of 100 µF connected in parallel. The active medium is cooled by circulating a mixture of ethylene glycol and distilled water (in equal proportion by volume) at room temperature. The injection of seed pulse in regen cavity is accomplished with the help of two 100% reflectivity beam steering mirrors and pin-holes kept in the regenerative amplifier cavity. The injector consists of a plate polarizer, a DKDP crystal based single Pockels cell (SPC), and a quarter wave plate. The ejector consists of a DKDP based SPC and a plate polarizer. The pulse amplification in regenerative amplifier has been simulated using a simple model considering various amplifier parameters and distributed losses. Simulation showed [3] that highly stable pulse energy can be obtained via interplay of gain and loss of amplifier, if the amplified laser pulse is ejected from the amplifier cavity a few round trips after the peak fluence build up time. Such stable amplification was experimentally demonstrated and found to be consistent with the theoretical model and a pulse energy stability of ~2.5% (rms) was measured over 30 shots with shot-to-shot time interval of ~2 minutes. The effect of gain narrowing was studied experimentally with varying number of passes and with varying input seed pulse energy. Pulse energy of ~10 mJ and spectrum of ~ 2 nm was measured at the output of regen amplifier at electrical pulse energy of ~50 J. To avoid electromagnetic interference noise arising from high-voltage switching of the various Pockels cells, special metallic enclosures [13] housing both the Pockels cell and electronic circuitry were designed, and fabricated for each electro-optic unit.

Even before the pulse ejector unit is fired, ASE from the regen amplifier and the amplifying laser pulse can leak out from polarizer of the pulse ejector stage due to limited extinction ratio of the polarizer. The ASE or pre-pulses can build up substantially in the subsequent amplifier stages and may create long scale-length plasma at the target. Therefore, it is necessary to temporally clean the amplified laser pulse from regen amplifier. This is accomplished using a pulse cleaner unit, which is identical to the single pulse selector stage and consists of a DKDP based DPC and a polarizer. A main pulse to pre-pulse contrast of 10^3 has been measured and it is found to be limited by the polarizing optics.

The laser beam from regenerative amplifier is then magnified using suitable expander and amplified further using one double pass amplifier (DPA), kept after the pulse cleaner unit, followed by vacuum spatial filter cum image relay system and one single pass amplifier (SPA). The DPA comprises of a water-cooled Nd:phosphate glass rod (15 mm diameter, 200 mm length), pumped by four air-cooled xenon-gas filled flash lamps (energized by two capacitor each of 100 μF and two lamps in series configuration), a quarter wave plate and a ~100% reflectivity plane dielectric mirror to make double pass optical geometry. The DPA provided a small-signal gain of ~100 at capacitor bank energy of 1.8 kJ. The SPA stage consists of a water-cooled Nd:phosphate glass rod (25 mm dia. 300 mm length), pumped by six air-cooled xenon-gas filled flash lamps (three capacitors each of 100 μF and two lamps in series configuration). The circular geometry of the reflector was chosen for this amplifier as number of flash lamps is large, in contrast to clover leaf reflector geometry for regen amplifier and DPA. The SPA provided a small-signal gain of ~3 at capacitor bank energy of 7.2 kJ. Presently, we are testing double pass configuration of this amplifier in order to improve its performance.

After SPA, laser beam enters the vacuum compressor for pulse compression, providing a negative frequency chirp. It consists of two identical holographic gratings (groove density of 1740 lines per mm, same as that for gratings used in pulse stretcher) of size 80mm x 110 mm and a dielectric mirror based retro reflector (two mirrors, each of size 70 mm x 50 mm, kept at 90° to each other). A dielectric pick-up mirror sends the compressed pulse to the plasma chamber for laser matter interaction experiments. The chamber housing of pulse compressor unit was evacuated to ~10^{-3} Torr. A single laser pulse of energy ~1J and duration ~1ps (at every 3 min. interval) has been obtained after compressor. The pre-pulse contrast ratio was measured in excess of 10^3 and was found to be limited by the polarizing optics. The spatial beam profile has been recorded in near and far field regime [2] and a M^2 parameter of ~1.7 was estimated at the compressor output.

It may be noted that pulse spectrum of amplified pulse is drastically reduced and pre-pulse contrast is also poor (which may be improved by good quality optics) at the output of regenerative amplifier. Both these limitations can be overcome by replacing regenerative amplifier by an optical parametric amplifier (OPA). Since in OPA, the amplification gain is available to very small spatial interaction lengths (governed by length of non-linear crystal) and temporal duration (decided by the duration of pump laser pulse), it eliminates the problems of pre-pulses, spectral gain narrowing, accumulated non-linear spatial and temporal phase, dispersion effects of amplifiers commonly encountered in CPA scheme. However, this new approach called OPCPA, for obtaining ultrashort high-contrast ultrahigh-intense laser pulses necessarily requires high-energy synchronized pump laser, with respect to stretched seed laser pulse, delivering spatio-temporal shaped laser pulses of duration typically around 1 ns.

Presently, a high contrast OPCPA based 50 TW laser system [2] is being set up. A new, simple laser oscillator [12], based on Q-switching and full-wavelength cavity dumping, has been designed and developed to generate highly stable laser pulses of duration tunable in sub-ns to few ns range (typically ~800 ps to 6 ns). These laser pulses were synchronized with stretched laser pulses of ~300 ps duration with an accuracy of 200 ps (limited by speed of electronics used). The present oscillator design offers several distinct advantages over the stimulated Brillouin scattering compression based laser oscillators, which deliver laser pulses in the same temporal range. This oscillator will be modified to operate in single longitudinal mode and to deliver super-Gaussian space and temporal profiles. Presently, this oscillator is being used as seed oscillator in our prototype study on MOPA based compact Nd:glass laser system to pump OPA.

Ultrafast Laser Diagnostics

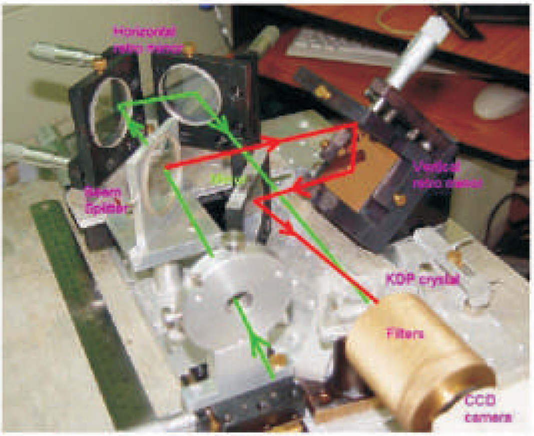

Fig.T.3.3: Photograph of the TPFAC

It is clear from above discussion that a CPA laser involves laser pulses of duration in range from few 100 fs to few 100 ps, with pulse-to-pulse repetition rate of 100 MHz or 1 pulse at 3 minutes interval. To measure various pulse parameters of such laser pulses, variety of simple autocorrelators have been designed and developed in-house.

These includes conventional non-linear optical crystal based single-shot autocorrelator and its extension to tilted pulse-front autocorrelator [4-5] (TPFAC) (Fig.T.3.3) for simultaneous measurement of pulse duration and pulse-front tilt (PFT) in ultrashort pulse laser beams. TPFAC is basically a variant of conventional single-shot autocorrelator, which uses inverted pulse fronts of two replica of a laser beam. It is demonstrated that TPFAC can measure and detect sign of the PFT without ambiguity of its sign (see Fig.T.3.4) and is an order magnitude more sensitive compared to other techniques [5]. The effects of propagation distance on the PFT have also been studied experimentally. A theoretical model has been developed which predicts quite accurately the observed experimental results [5]. A high-dynamic range high order autocorrelator, based on non-linear crystals, has also been designed and presented [2] for pulse contrast measurement and is being tested for its performance.

Semiconductor optoelectronic devices with non-linear photocurrent (e.g. quadratic) can simply replace the NLO crystal and a linear photo-detector combination used in recording of autocorrelation (AC) signals in above discussed autocorrelators. They also offer several distinct advantages over the NLO crystals such as non-requirement of phase matching condition, non-hygroscopic etc. Prior to use of LEDs in AC measurement, it is essential to characterize the photo-response of the LED. The photo-response has been measured for its intensity dynamic range [6], effect of reverse bias voltage [14], incident laser polarization [15], and aging [6] etc. It has been observed that, the quadratic response can be enhanced substantially if one uses these devices in the reverse biased mode just below their breakdown voltage. Further, the quadratic photocurrent in such devices is understood due to the two-photon absorption and second harmonic generation in the device material over very small interaction lengths. To know the physical mechanism responsible for quadratic photo- response and to study the polarization dependence of quadratic photocurrent, the cross-polarized autocorrelation signals were recorded using a simple modified Michelson interferometer. The cross-polarized AC signals were analyzed and compared with the theoretically calculated AC signals [15]. It is found that the quadratic photocurrent is primarily dominated by the two photon absorption in the commercial LED samples used in our study.

Michelson interferometer based real-time scanning autocorrelator [6] has been designed, and set up using commercial LED (costing less than Re 1) as a quadratic detector and commercial audio speakers (costing < Rs 100) for optical delay line. The temporal scan range of this autocorrelator is enhanced using twin audio speakers [7], one each in the two arms of the interferometer. For pulse measurements, time calibration for the AC signal is a necessary requirement. Various time calibration schemes have been studied and compared for this application. A simple method for time calibration based on counting the number of interference fringes in interferometric autocorrelation (IAC) signal has been worked out [6].

New techniques, namely unbalanced Interferometric Correlation Envelope (ICE) and its extension ICE signals together with pulse spectrum (ICES) [8], have been proposed and used for real-time simultaneous visual detection and measurement of pulse chirp and pulse shape with enhanced sensitivity. These methods involve recording and modification of second order unbalanced interferometric correlation (IC) signals and measurement of pulse spectrum (or field AC signal). The above techniques are more improved and advanced methods than the earlier reported methods : Unbalanced MOdified Spectrum Auto Interferometric Correlation (UMOSAIC) technique [9] proposed by us, and MOdified Spectrum Auto Interferometric Correlation (MOSAIC) technique worked out by us for chirp estimation [10].

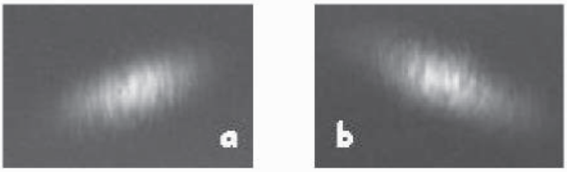

Fig.T.3.4 : Typical AC traces for the case of (a) a single prism; (b) a pair of prisms; (While angle of AC trace provides sign and magnitude of PFT, vertical scan gives the duration of pulse).

While in ICE technique, modified signals are generated by taking difference of normalized envelope functions of unbalanced IC signals, the modified signal in MOSAIC technique is generated by suitable weighted addition of two terms of balanced IAC signal using signal-processing tools. The MOSAIC signals do not provide any information about the pulse asymmetry, as they remain symmetric even for unbalanced IAC signals. On the other hand, it is found that unbalanced ICE difference (ICED) signals are even more sensitive than third-order unbalanced intensity autocorrelation for detection of pulse asymmetry [9]. Moreover, the ICED signal is found to be twice more sensitive towards the chirp [6] and much less affected by various errors and detector noises compared to the MOSAIC signals [11].

The capability of ICE and ICES techniques for real-time sensitive detection and measurement of pulse parameters has been demonstrated by recording unbalanced IAC signals using ~200 fs laser pulses [8]. The IAC signals are displayed on a digital storage oscilloscope interfaced with personal computer (PC) via GPIB interface on either USB port of PC or on dedicated GPIB card attached to PC. LabVIEW based computer program retrieves the signals from the oscilloscope and generates ICE, ICED signals in real time using suitable signal processing tools. Finally, the IAC, ICE and ICED signals are displayed on the monitor of the PC. This program also counts the interference fringes in an IAC signal over a user defined temporal position and estimate the duration of the laser pulse automatically. The MOSAIC signal is also generated and displayed on the PC monitor for comparison. Different features of the laser pulse have been observed under different operating conditions of the laser oscillator, which otherwise were not observed in the direct unbalanced IAC signals.

Experimentally recorded first and second order IAC signals and retrieved ICE signals are shown in upper and middle row of Fig.T.3.5. It is seen clearly from middle row of this figure that laser pulse is chirped and asymmetric. Such features of laser pulses are not visually seen in corresponding IAC signals. The retrieved pulse spectrum from 1st order IAC signals and retrieved laser pulse shape and temporal phase corresponding to stable operation of laser oscillator is also shown in bottom row of Fig.T.3.5.

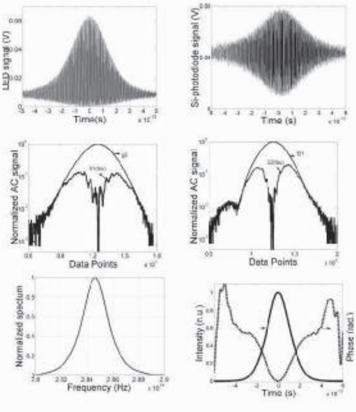

Fig.T.3.5 : Typical second order (top-left) and first order (top-right) interferometric AC; Retrieved ICED signals for pulse chirp (middle-left) and pulse asymmetry (middle-right); Retrieved pulse spectrum from experimental first order IAC signal (bottom-left) and retrieved pulse intensity and phase (bottom-right) using ICES technique.

In conclusion, a chirped pulse amplification based Nd:glass table top terawatt laser systems has been developed. It delivers laser pulses of power > 1TW over a temporal duration of ~ 1ps at pulse-to-pulse time interval of 3 minutes. A novel oscillator has been proposed and demonstrated to provide highly stable synchronizable laser pulses of duration tunable in range from 800 ps to 6 ns. It is being used to setting up a high contrast 50TW optical parametric chirped pulse amplification based laser system. New technique called ICES has been proposed and demonstrated for simultaneous real time visual detection of pulse chirp and asymmetry without direction-of-time ambiguity in ultrashort laser pulses. Several low cost diagnostics namely two photon absorption based real time autocorrelator, second harmonic generation based single shot autocorrelator and tilted pulse front autocorrelators have been developed for measurement of pulse duration, chirp, pulse-front tilt in ultrashort laser beams. A general model has been worked out to account for pulse front tilt, angular dispersion and duration of ultrashort pulse laser beams while traversing through a dispersive optical system. The quadratic photo-response of light emitting diodes has been extensively studied to optimize or improve the performance of the two photon absorption based real time autocorrelator.

References

1. "Development of chirped pulse amplification based T^3 Nd:glass laser system", P. A. Naik, P. D. Gupta, C. P. Navathe, A. K. Sharma, M. S. Ansari, M. Raghuramaiah, S. R. Kumbhare, J. Upadhayay, H. R. Bundel, K. K. Mishra, R. P. Kushwaha, and R. A. Joshi, CAT Internal Report CAT-28, (2003).
2. Ph.D. thesis of Avnish Kumar Sharma, Devi Ahilya Vishwa Vidyalaya, Indore (2007); Research work was carried out at RRCAT, Indore.
3. A. K. Sharma, M. Raghuramaiah, K. K. Mishra, P. A. Naik, S. R. Kumbhare, and P. D. Gupta, *Optics Communication* 252, 369-380 (2005).
4. M. Raghuramaiah, A. K. Sharma, P. A. Naik, and P. D. Gupta, *Optics Communication* 223, 163-168 (2003).
5. A. K. Sharma, R. K. Patidar, M. Raghuramaiah, P. A. Naik, and P. D. Gupta, *Optics Express* 14, 26, 13131-13141 (2006); ibid 15, 12, 7537 (2007). [also linked in Virtual J. Ultrafast Science 6, 2007]
6. A. K. Sharma, M. Raghuramaiah, P. A. Naik, and P. D. Gupta, *Optics Communication* 246, 195-204 (2005).
7. A. K. Sharma, P. A. Naik, and P. D. Gupta, *Optics and Laser Technology* 39, 465-469, (2007).
8. A. K. Sharma, P. A. Naik, P. D. Gupta, *Applied Physics B: Laser & Optics* 87, 655-663 (2007).
9. A. K. Sharma, P. A. Naik, and P. D. Gupta, *Optics Express* 12, 7, 1389-1396 (2004).
10. A. K. Sharma, P. A. Naik, and P. D. Gupta, *Optics Communication* 233,431-437 (2004).
11. A. K. Sharma, P. A. Naik, and P. D. Gupta, *Optics Communication* 259, 350-359 (2006).
12. A. K. Sharma, R. A. Joshi, R. K. Patidar, P. A. Naik, P. D. Gupta, *Optics Communications* 272, 455-460 (2007).
13. A. K. Sharma, K. K. Mishra, M. Raghuramaiah, P. A. Naik, and P. D. Gupta, Sadhana 32, 3, 235-242 (2007).
14. A. K. Sharma, P. A. Naik, and P. D. Gupta, *Applied Physics B: Laser and Optics* 82, 407-411 (2006).
15. A. K. Sharma, P. A. Naik, P. D. Gupta, *Applied Physics B: Laser & Optics* 88, 67-73 (2007).