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Generation of synchronized signal and pump pulses for an optical parametric chirped pulse amplification based multi-terawatt Nd:glass laser system

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Abstract. Synchronized signal (650 ps) and pump (1.3 ns) pulses were generated using 4-pass geometry in a grating pair based pulse stretcher unit. The pump pulse has been further amplified in a high gain regenerative amplifier. This amplified pulse was used as the pump in an optical parametric chirped pulse amplification based Nd:glass laser system. As the chirped signal pulse and the pump pulse originated from the same oscillator, the time jitter between the pump pulse and the signal pulse can be <50 ps.

Keywords. Ultrafast pulses; pulse stretcher; regenerative amplifier; optical parametric amplifiers.

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1. Introduction

The discovery of chirped pulse amplification (CPA) technology [1] has provided an unprecedented opportunity to a number of laboratories world-wide to build Ti:sapphire and Nd:glass terawatt power laser systems to study extreme field science including acceleration of charged particles, laser driven fast ignitor based fusion, plasma physics etc. The CPA technology allows scaling of the peak powers up to ∼1 petawatt (PW) and focussed intensity to $\sim 10^{21}$ W/cm^2. But, some of the problems encountered with the CPA scheme are: (1) gain narrowing, occurring mainly in the regenerative amplifiers, limiting the ultimate pulse duration that can be achieved after pulse compression and (2) the limited pre-pulse contrast leading to the formation of a pre-plasma on the target before the arrival of the main laser pulse. Recently, optical parametric chirped pulse amplification (OPCPA) concept [2] has emerged as a promising alternative to address these problems. Laser Plasma Division, RRCAT, India, had earlier built a CPA based Nd:glass table top terawatt laser system [3] delivering 1 J in 1 ps. Work has now started on an OPCPA based 50 TW Nd:glass laser system for which a prototype pre-amplifier has been set up and characterized. Considering the stringent temporal synchronization requirements there, a scheme to derive the pump pulse and the signal pulse out of the femtosecond oscillator, to take care of the synchronization issue, has been investigated. In this paper, the synchronized generation and development of a sufficiently long pump pulse in a grating pair based stretcher in 4-pass configuration, its regenerative amplification and characterization for various parameters, is presented.

In general, the OPCPA scheme involves amplification of a temporally stretched signal laser pulse in a phase-matched non-linear crystal, that is pumped by another synchronized laser, a strong pump pulse (at doubled frequency: in degenerate case). In early experiments, this involved two independent laser sources, one a chirped laser pulse (signal), which was to be amplified and the other, a strong laser beam (pump), which were then synchronized and mixed in the crystal. As optical parametric amplification (OPA) utilizes instantaneous non-linear interaction of the signal and the pump beams, the performance of OPCPA system is expected to be highly sensitive to the temporal synchronization errors between them (required to be less than ∼100 ps). One way to eliminate this problem is to derive the signal and the pump beams out of the same oscillator, in which case the synchronization becomes easier. In addition, the pumping pulse width is also important as the OPA offers broad amplification bandwidth over a temporal window governed by the pump pulse. This means that the pump pulse can neither be very long nor very short in comparison to the signal pulse. If the pump is too long in comparison to the signal pulse, then coupling of the signal will be low and hence extraction efficiency will be low. If the pump is shorter, it is likely to result in spectral narrowing because (1) only those spectral components which fit within the pump temporal window will be amplified and (2) the gain will vary according to pump variation with time (depending on its shape). Hence for optimum performance, we have generated two equal intense pulses from a pulse stretcher unit, a shorter stretched signal pulse, and a sufficiently longer chirped pump pulse. As reported by Limpert *et al* [4], a chirped pump beam is more useful in ultra bandwidth enhancement, at degeneracy (i.e. when 2ω pump is used to amplify the signal at ω).

Martinez scheme of pulse stretcher was used to generate the chirped signal pulse, in double pass configuration, that will be amplified in various OPA stages. A part of this doubly stretched pulse was further stretched in the same stretcher unit so that it is sufficiently longer than the signal pulse to act as a pump pulse. But, this pulse, being very low in energy, has to be amplified in a regenerative amplifier to mJ level. This can be further amplified to the required energy level in a laser chain containing double pass/single pass amplifiers to act as a pump beam for pumping the OPA stages. In this scheme, the pulse duration of both the pulses can also be varied by simply varying the parameters of the stretcher, keeping the ratio between them fixed.

2. Experimental set-up

The experimental lay-out is shown in figure 1. The laser pulses were derived from a Kerr lens mode-locked Ti:sapphire oscillator (Model: Chameleon Ultra II, M/s Coherent Inc., USA). This laser delivers an average power of ∼520 mW at

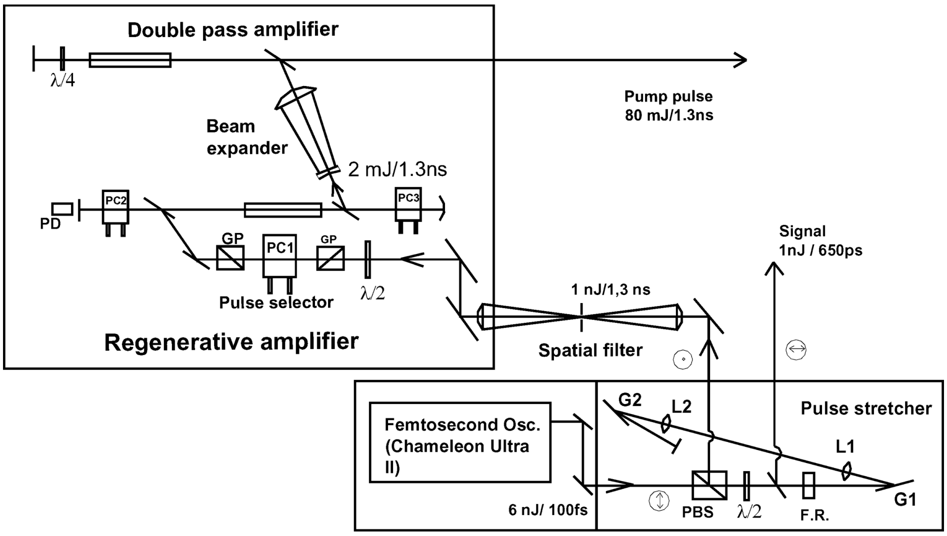

Figure 1. Experimental scheme for the generation of pump and signal laser pulses.

1054 nm wavelength at 80 MHz repetition rate with a spectral bandwidth ($\Delta\lambda$) of ≈13 nm (FWHM). Assuming sech^2 pulse shape, the corresponding transform limited pulse duration of the laser pulses is ∼90 fs. The duration of the pulse was found to be ∼100 fs, measured with an in-house built single-shot auto-correlator, and is comparable to the theoretically estimated value. These laser pulses were used to derive both the signal and the pump pulses, after chirping, in a pulse stretcher unit. The additional optics that we used for the 4-pass scheme are a polarizing beam splitter (PBS), a $\lambda/2$ plate and a Faraday rotator. The p-polarized pulses from the oscillator are passed through the PBS, which allows horizontally polarized pulses. After this, a half-wave ($\lambda/2$) plate with optic axis kept at 22.5° with respect to the input polarization (in a plane above the horizontal axis) rotates the plane of polarization to 45° (in the plane above the horizontal axis) with respect to the input beam. Following this, a Faraday rotator (12 mm ϕ) allows 45° rotation in the Faraday glass such that it retains its original horizontal polarization. After this, the laser pulses were expanded in time in a pulse stretcher unit.

The pulse stretcher unit is shown in figure 1. It consists of a pair of identical holographic gratings (groove density 1740 l/mm), a telescope of unit magnification and a retro-reflector for making a double-pass configuration. The laser beam, after the Faraday rotator with horizontal polarization, is incident on first grating G_1, at an angle (α) of 75°, and the second grating G_2 is placed parallel to the image of the first grating G_1, made by the telescope. The distance between the second grating and the image of the first grating, referred to as effective chirping length (l), is 580 mm. A retromirror is used, in vertical geometry, to make double pass through the grating pair–lens pair. The stretching factor (chirp parameter) per each pass of this pulse stretcher for $n = 1$ (n being order of diffraction) is given by

$$\frac{\mathrm{d}\tau}{\mathrm{d}\lambda} = \frac{-\lambda l}{cd^2 \cos^2 \beta}$$

where c is the velocity of light and β is the angle of diffraction at the central wavelength. At a central wavelength of $\lambda = 1054$ nm, chirping length $l = 580$ mm, $\beta = 60.23°$ and $d = 0.57$ μm, the imparted linear chirp, using the above equation, is 25 ps/nm per pass. Thus, these pulses with $\Delta\lambda$ of $\approx$13 nm were stretched, in double pass configuration, to 650 ps.

The output beam, from the double pass in the stretcher, comes out from G_1 and is spatially displaced downwards with respect to the input beam, due to the vertical retromirror. At this stage, as the laser beam retraces its path backwards, it is intercepted by a mirror with 70%R (see figure 1) at normal incidence, such that a part of the beam is reflected back into the pulse stretcher unit. The remaining 30%T beam, with an average power of 80 mW, with pulse duration of 650 ps, is reflected by a pickup mirror. This signal beam with 1 nJ energy will be amplified in various OPA stages for making the multi-terawatt laser system.

The reflected laser pulses (180 mW power) that are redirected into the pulse stretcher are allowed to undergo another double pass for further stretching. Thus these laser pulses make four passes through the grating pair before they emerge from the grating G1. It should be noted that these pulses, after making four passes, will now be compensated for the vertical displacement occurred in the 2-pass geometry. Hence they are at the same height as the input beam. As they emerge from G_1, they pass through the Faraday rotator in the backward direction, and undergo a further 45° rotation in the same direction as the input beam. Now these laser pulses are plane polarized at 45° (in the plane below the horizontal axis) with respect to the input beam. After this, as they pass through the half-wave plate in the backward direction, their plane of polarization changes and becomes vertically polarized at 90° with respect to the input beam. With vertical polarization, as they enter the polarization beam splitter, they get reflected. Thus, temporal duration of these chirped laser pulses, as calculated from the chirp parameter equation, should be 1.3 ns.

3. Results

The temporal profile of these pulses (double pass and 4-pass) was recorded with a 1 GHz photoreceiver (Model:1611-FC-AC M/s New Focus) connected to a 1 GHz scope (Le Croy make, 10 Gs/s). The double pass pulse (to be used as the signal pulse) had an FWHM value of 680 ps, which is in agreement with the theoretically calculated value of 650 ps. The optical throughput of the stretcher was experimentally measured to be ~52%. The output of double pass stretcher was ~270 mW. The measured pulse duration of the 4-pass chirped pulse (to be used as the seed for pump beam) was ~1.35 ns (FWHM) which is also in very good agreement with the theoretical value of 1.3 ns. But, the throughput of the stretcher unit being ~52% in two passes and due to additional losses, they had an average power of ~85 mW. But, as the energy of these pulses is ~1 nJ, they needed high gain to act as pump source.

The spectra from the oscillator, doubly stretched and quadruply stretched pulses were recorded. The limited bandwidth of the finite-sized optics resulted in fractional hard clipping of the spectrum. For the available sized optics, the distances between the gratings and the lenses were optimized to keep the spectral loss minimal. The input pulse spectrum had a bandwidth of 13 nm and the spectral bandwidths of the pulse after 2-passes and 4-passes were 11 nm and 9.5 nm respectively.

4. Amplification of the stretched pulses

The chirped and stretched 1.3 ns pulses of 1 nJ were propagated through an image relay cum spatial filter system using two lenses of $f = 2.5$ m (75 ϕ), up to the Nd:glass regenerative amplifier. From this 80 MHz train of stretched pulses, a single pulse was selected using an electro-optic switch (HTS-50-08UF, Behlke, Germany), a Pockels cell PC1, and two Glan polarizers. The selected single laser pulse, acting as a seed, was injected into the regenerative amplifier by another Pockels cell PC2, and a polarizer combination. This amplifier was a cavity dumped, seeded Q-switched oscillator formed by two 100% R dielectric coated mirrors, one of which was a curved mirror with 8 m radius of curvature and the other, a plane mirror. Once the pulse was trapped inside the cavity, it was allowed to make several transits through the gain medium gaining on each transit, and it was ejected out of the cavity after ∼52 round trips (i.e. pulse build-up time ∼520 ns) using another Pockels cell PC3, and a polarizer combination. With an input seed fluence of 1.4×10^{-8} J/cm^2, the pulse was amplified to an energy of 2 mJ, i.e. a net gain of $\sim 2 \times 10^6$, from which it was estimated that the small signal gain coefficient was 1.15 in each pass. More details of the regenerative amplifier can be obtained from ref. [5]. This was further amplified to 80 mJ in a double-pass Nd:glass amplifier (200 mm length, 15 ϕ). This beam will be further amplified in a traditional chain of Nd:glass amplifiers and converted into its second harmonic at 527 nm to be used as a synchronized pump beam for the proposed multi-terawatt laser.

5. Conclusion

In conclusion, a simple means for obtaining a strong pumping pulse for the optical parametric chirped pulse amplification-based Nd:glass laser system is presented. This is especially suitable for OPCPA laser systems in providing an accurate temporal synchronization between the pump pulse and the signal pulse by deriving them from the same femtosecond oscillator. After suitably stretching them in the same stretcher unit, the pump pulse was amplified in a regenerative amplifier providing a net gain of 2×10^6. This set-up will be used for setting up an OPCPA-based 50 TW Nd:glass laser system.

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