A simple highly stable and temporally synchronizable Nd:glass laser oscillator delivering laser pulses of variable pulse duration from sub-nanosecond to few nanoseconds

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Abstract

A simple flash lamp pumped Nd:phosphate glass laser oscillator has been designed and set up delivering laser pulses of variable duration from ~800 ps to 6 ns. It is based on Q-switching and full-wavelength cavity dumping and provides single laser pulse energy of 5 mJ and 11 mJ corresponding to pulse duration of ~800 ps and 6 ns respectively at an electrical pump energy of 50 J. While the maximum pulse duration is governed by the cavity round trip time, the lower limit is decided by the switching speed of the high voltage pulse to the Pockels cell of the cavity dumper. Output laser pulses have shown enhanced pulse energy stability by dumping the cavity four round trips after the peak buildup. The laser pulses were synchronized with 250 ps positively chirped laser pulse train derived from an independent commercial cw mode locked Nd:fluorophosphate glass laser oscillator. The temporal jitter between these two pulses was measured to be ~200 ps, limited by the speed of the electronics used.

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1. Introduction

Laser pulses of duration in the range of few hundred picoseconds to few nanoseconds, find wide ranging applications in many scientific and industrial research areas such as laser plasma interaction studies [1,2], optical parametric chirped pulse amplification (OPCPA) [3–12]; non linear optics [13], and fiber optic sensors [14,15] etc. Among these, OPCPA is particularly required for setting up of compact, prepulse-free ultrashort ultrahigh power laser systems. In the OPCPA scheme, parametric amplification of a temporally stretched seed laser pulse (typically of duration in the range of 200 ps to 1 ns) is achieved in phase-matched non-linear crystals used in an optical parametric amplifier (OPA). This requires a good spatial and temporal overlap between the pump laser pulse and the stretched seed laser pulse. In several cases the OPCPA scheme has been realized using commercial pump lasers delivering laser pulses of much larger duration (in range 6–10 ns), resulting in a poor conversion efficiency due to small temporal overlap with the seed laser pulse [6,7,10]. Further, energy conversion efficiency and gain bandwidth of an OPA not only depend on pulse duration but also affected by the temporal pulse shape and beam profiles [4,5,9,10]. Next, any fluctuation in the pump pulse energy or in the temporal overlap (temporal jitter) causes fluctuation in the OPA gain and bandwidth and thereby in the compressed laser pulse parameters in the OPCPA based laser systems. Highly stable pump lasers, delivering temporally synchronizable spatio-temporally shaped laser pulses [9,10] of duration comparable to that of the seed pulse, are desirable.
While the duration of laser pulses from a Q-switching (QS) and cavity dumping (CD) based conventional solid-state laser oscillators is few ns or larger, a laser oscillator based on mode locking (ML) technique provides laser pulses of duration smaller than few hundred picoseconds. Laser pulses of duration in the range of sub-ns to few ns, have been generated through intra-cavity injection in Q-switched and cavity dumped lasers [16], and Q-switched diode pumped microchip solid-state lasers [17]. The pulses in the above temporal range can also be generated indirectly using pulse-slicing techniques [18], post-pulse compression techniques based on stimulated Brillouin scattering (SBS) [19], by stacking a sequence of short duration laser pulses in mismatched regenerative amplifier cavity [20], or using intra-cavity dispersion/etalon effects [21]. However, these methods have their own advantages and disadvantages in terms of complexity and performance characteristics. For instance, while the cavity-dumped lasers with intra-cavity injection require well defined temporally correlated high amplitude step voltage pulse, the pulse-slicing technique reduces the output pulse energy. Recently high-energy pump laser using sophisticated pulse shaping technique was developed which delivered spatial-temporal shaped (super-Gaussian shape both in space and time domains) laser pulses of duration around 1 ns for enhanced energy extraction efficiency and gain bandwidth. Using such laser pulses, the conversion efficiency of OPA approached the maximum achievable value for 1 ns stretched seed laser pulse. However, this requires a precise synchronization.

The temporal jitter between the output laser pulse and Q-switch trigger in a Q-switched laser oscillator may be some fraction of a round trip time due to inherent shot-to-shot difference in the pulse buildup time. The effect of large inherent jitter in QS pulse buildup time can be avoided in QS & CD laser systems, if the trigger signals to Q-switch unit and cavity dumper are synchronized. Further, laser pulses of duration much shorter than the cavity round trip time can be generated from such QS & CD laser systems by operating the cavity dumper in a full wavelength switching mode. Next the pulse energy stability in a QS laser is limited by fluctuation of the pump source. However, this can also be overcome in a QS & CD laser oscillator, which is essentially similar to a regenerative amplifier, except that no external injection of laser pulse is required. This can be accomplished by exploiting passive stabilization mechanism through interplay of gain and loss of laser cavity demonstrated for regenerative amplifier of a CPA based laser systems [22,23] to obtain highly stable energy output.

In this paper, we present a simple flash lamp pumped Nd:phosphate glass based QS & CD laser oscillator, which combines the techniques of full-wavelength switching and passive stabilization, to generate stable laser pulses of variable pulse duration in the range of ~800 ps to 6 ns. The output laser pulses could be synchronized with positively chirped laser pulse train (100 MHz pulse repetition rate) of 250 ps duration pulses derived from an independent commercial cw mode locked Nd:fluorophosphate glass laser oscillator. The temporal jitter between two pulses was measured to be ~200 ps, which is limited by the speed of the electronics circuitry. The output pulses of energy of ~5 mJ in 800 ps and ~11 mJ in 6 ns pulse duration have been measured at electrical pump energy of 50 J.

2. Generation of stable laser pulse of duration tunable in the range of sub-ns to few ns

The simplest approach to generate laser pulses in the above mentioned region is to have a pulse slicing unit kept outside the laser oscillator. The conventional pulse slicer unit (shown in Fig. 1a) operates in λ/2 switching mode (λ/2-pulse slicer) and requires high voltage (HV) square pulse applied to a Pockels cell. The duration of the sliced laser pulse in such a case is governed by the duration of the HV square pulse, which is limited to 4–5 ns in the case of fast HV switches [24]. Although shorter duration HV pulses can be generated using a photoconductive switch [25,26], but the experimental setup and design involved become rather complicated. In contrast to the above, laser pulses of duration in the range of sub-ns to few ns can be obtained using a simple technique of λ-switching in the pulse slicer [11,18]. In λ-switching mode of pulse slicer (i.e. λ-pulse slicer), the pass temporal window (either in transmission or reflection optical geometry) is governed by the rise time (t_r) or fall time (t_f) of the HV step pulse as depicted in Fig. 1b. In such a case the duration of pass
temporal window is 0.6$t$, or 0.6$t$ considering $\sin^2(\pi V(t)/V_2)$ transmission function in polarizer–analyser combination. The $V(t)$ is the voltage applied to Pockels cell at time $t$ and $V_2$ is the full wavelength voltage corresponding to material of electro-optic switch.

The rise or fall time of a HV step pulse may be changed by choosing different RC value of HV pulse driver circuit. For instance simply adding capacitors across the PC increases the rise or fall time of HV pulse. Therefore duration of the sliced laser pulse can be changed by varying the rise or fall time of the HV step pulse. Since HV step pulse with rise or fall time of $\sim$1 ns can be achieved, the sliced pulse duration of $\sim$500 ps may be obtained quite easily. For instance, 200 ps rise time 4 kV pulses have been generated in avalanche transistor stacks [27]. The generation of single HV step pulse is easy compared to short duration square HV pulse. Next, the rise time of a HV step pulse can be changed more easily compared to the duration of a HV square pulse. Therefore, the use of a $\lambda$-pulse slicer may be advantages over conventional $\lambda/2$-pulse slicer, as the former require use of single HV step pulse. A pulse slicer may use single or double Pockels cell (DPC). In order to minimize the voltage requirement for $\lambda$-switching, one may prefer a DPC in double pass optical geometry. For DKDP based DPC, the voltage required for $\lambda$-switching is 3.4 kV in the double pass optical geometry.

The pulse slicing can be done using laser pulses from a Q-switched or a Q-switched and cavity dumped laser oscillator. While the fluctuations in the pulse energy in case of QS laser oscillator shall be governed by the fluctuation of the pump source, the former in a conventional QS & CD laser oscillator can be reduced to a level much below the fluctuations of pump source using interplay of gain and loss of laser cavity [22] as mentioned earlier. The latter requires cavity dumping at a stable point of the pulse buildup, which occurs few round trips after the peak buildup. Next, the duration of output laser pulse from conventional QS & CD laser oscillator is around the round trip time of the laser cavity. Much shorter duration laser pulses of duration in the range of sub-ns to few ns can be obtained by operated the cavity dumper in $\lambda$-switching mode, which will require $\lambda/2$ switching voltage due to double pass in the case of a linear cavity. In this configuration of a QS & CD laser oscillator, the cavity dumper will also do the job of pulse slicer, thus avoiding the use of an external $\lambda$-pulse slicer, which in turn requires additional Pockels cell and other optical and electrical components. Next, the duration of output laser pulse can also be varied electronically simply changing the rise time of HV step pulse. Therefore, by operating cavity dumper in $\lambda$-switching mode at stable point of pulse buildup, highly stable laser pulses of duration tunable in the range of sub-ns to few ns can be generated directly from laser oscillator. The present laser oscillator can also avoid several limitations [19] of SBS based laser oscillator such as fluctuations in its pulse duration and energy, non-uniform compression over full beam cross-section, asymmetric temporal pulse shape etc.

3. Experimental demonstration

The experimental setup of our cavity dumped laser oscillator is shown in Fig. 2. It consists of three main parts: (a) Q switch unit, (b) Nd:phosphate glass rod (5 mm dia., 100 mm long) and (c) cavity dumper. While Q switch unit uses a DKDP crystal based single Pockels cell (SPC), the cavity dumper consisted of a DKDP based DPC in combination with a thin film polarizer kept near the DPC. The resonator cavity is formed by two $\sim$100% reflectivity dielectric coated multi-layer mirrors of 25 mm diameter kept $\sim$0.9 m apart (round trip time of 6 ns). While one mirror has a radius of curvature of 6 m, the other one is a plane mirror. Both the electro-optics units (i.e. Q-switch, cavity dumper) were kept inside an aluminum enclosure [28] in order to avoid electromagnetic interference noise. The near field beam profile has been recorded at the output of the laser oscillator using a CCD camera (11.8 $\mu$m x 8.3 $\mu$m pixel size) – frame grabber – computer combination. A smooth profile close to TEM mode has been obtained. Typical spatial profile of laser pulses is also shown in Fig. 2. The beam diameter (1/e$^2$ points) was estimated to be $\sim$2 mm from the observed beam profile.

When the cavity dumper is operated in $\lambda/2$ switching mode (i.e. by applying $\lambda/4$ switching voltage to the cavity dumper), the oscillator provides stable laser pulses of 6 ns (FWHM) duration as shown in Fig. 3a. The generation of variable pulse duration laser pulses in the range of sub-ns to few ns has been demonstrated by operating cavity dumper in $\lambda$-switching mode. This is achieved by applying 3.4 kV HV step pulse to cavity dumper with $t_1 \sim$1.5 ns (measured using 400 MHz HV Lecroy probe and 500 MHz Lecroy LA 354 analog oscilloscope) to the DPC of the cavity dumper and the output laser pulse was detected using a avalanche photodiode (APD) with a response time of $\sim$1.2 ns. A faster response APD or an optical streak camera will be required for exact measurements of the laser pulse shape. However, a gross estimate of the pulse duration ($\Delta t_{ac}$) could be obtained using the relation $\Delta t_{ac} = \Delta t_{meas}^{\frac{1}{2}} - \Delta t_{res}^{\frac{1}{2}}$, where the parameters $\Delta t_{meas}$ and $\Delta t_{res}$ are the measured pulse duration and overall response of the detection system respectively. A typical laser pulse recorded with 500 MHz, 5 Giga samples/s digital storage oscilloscope (Tektronix DPO TDS 3054B) is shown in Fig. 3b. The full width at half maxima (FWHM) duration of the waveform is measured to be 1.4 ns, which
shall correspond to a laser pulse duration of ~800 ps. This estimated value of laser pulse duration is consistent with a measured rise time of HV step pulse. The fluctuations in pulse duration was measured to be <10% and the same may be attributed either to sampling limitations or due to the difference in shot–shot pulse buildup as the rise time of the HV pulse was observed to be almost same for each shot.

In the present oscillator design, simply by applying 3.4 kV and 1.7 kV single step pulse to the DPC of cavity dumper, one obtains laser pulses of minimum (governed by rise time of HV step pulse) and maximum duration (decided by the cavity round trip time). Pulse duration in the above-specified range has been achieved by adding suitable ceramic capacitors across the DPC of the cavity dumper. The single laser pulse energy has been measured to be 5 mJ for 800 ps pulses and 11 mJ for 6 ns duration laser pulses at electrical pump energy of 50 J by simply applying 3.4 kV and 1.7 kV to the cavity dumper. In contrast to this, pulse slicing outside a Q-switched laser oscillator will result in a large reduction of pulse energy because of very small ratio (r) of duration of temporal pass window to duration of incident laser pulse and passive losses of λ-pulse slicer in double pass optical geometry. For instance, the energy for sliced laser pulse of duration ~800 ps was measured to be less than 1 mJ in case of λ-pulse slicer (passive losses of ~70%) kept outside a Q-switch laser delivering laser pulses of duration of 20–25 ns. Next, one may compare the output laser pulse energy in the case of intra-cavity λ-switching and intra cavity λ/2-switching. The reason for relatively higher energy of 5 mJ (in 800 ps laser pulse) in λ-switching is not fully clear, as one does not expect an increase in the laser intensity during intra-cavity slicing. This may be partly due to the contribution of leakage through the polarizer to the energy measured using a pyroelectric detector.

The laser cavity was dumped at a stable point of pulse buildup to minimize the fluctuation in energy of output pulse. In our case, the stable point was obtained ~4 round trips after the peak pulse buildup [23]. Shot-to-shot pulse root mean square (rms) fluctuation of 2.5% over 30 shots with shot-to-shot time interval of ~2 min, has been observed by dumping the laser cavity at a stable point. While the measured rms fluctuation in the pulse energy is larger than reported earlier (0.4% rms [22]) using this passive energy stabilization technique [22], the former can be reduced further by minimizing the fluctuations of the flash lamp output and increasing the pump energy (which requires use of high damage threshold optics) or optimizing the loss level of the cavity. Next, the peak to background intensity contrast of the pulses is limited by the extinction of the polarizer and DPC combination and in the present study it was measured to be ~50. The later is limited by the extinction ratio of the thin film polarizer. Using high contrast polarizers (a simple calcite wedge may also work) or using suitable saturable absorber one can further enhance peak to background contrast ratio of the laser pulse.

As mentioned in Section 1, synchronization with sub-ns accuracy is necessary for pump and stretched seed laser pulses of duration below ~1 ns to realize the OPCPA scheme. To achieve synchronization between these two pulses, the QS and CD trigger signals of cavity-dumped oscillator were derived using in-house developed fast synchronization electronic circuitry [29] and commercial digital delay generator (Model 9650 A from Signal Recovery, USA). The present oscillator is identical with our regenerative amplifier [23] except that no injection of external chirped pulse is done and cavity dumper is operated in λ-switching mode. The synchronization electronic circuitry generates a synchronized trigger w.r. to 100 MHz radio-frequency signal derived from the cw mode-locked Nd:glass laser oscillator (GLX 200 from Time Bandwidth Products) for a user controlled external trigger. This synchronized signal was fed to a digital delay generator to generate various synchronized triggers for cavity dumped laser oscillator and other control units. The power conditioning of cavity-dumped oscillator was achieved using in-house developed personal computer based electronic control [30]. The synchronization between pulse train from cw mode-locked laser oscillator and laser output pulse from cavity-dumped oscillator is demonstrated by recording the laser pulse from cavity dumped laser oscillator and 250 ps duration laser pulse train derived from cw mode-locked Nd:glass laser oscillator using fast APDs and using digital storage oscilloscope (Tektronix DPO TDS 3054 B) with sampling time interval of 200 ps and accuracy of 20 ps in the cursor placements. The recorded laser pulses from cavity dumped laser oscillator and pulse train is shown in Fig. 4. It may be seen from this figure that ultra-short laser pulse train is well synchronized with laser pulse from cavity-dumped laser oscillator. A temporal jitter of
Fig. 4. The laser pulses of sub-ns duration from the cavity dumped oscillator and 250 ps duration laser pulse train derived from independent femtosecond laser oscillator (signals were integrated over several shots). The temporal jitter of ~200 ps (peak-to-peak) has been measured.

~200 ps (peak-to-peak) over several laser shots was observed between the pulse train and single laser pulses from cavity dumped oscillator. In a QS & CD configuration, the temporal jitter in the output pulse is governed by the temporal jitter between the trigger signals to the Pockels cells of Q-switch and the cavity dumper. Thus shot-to-shot difference in the pulse buildup does not affect the temporal synchronization, but it can result in fluctuation of the output pulse energy. However, as described in the manuscript, the output energy stability is achieved through passive stabilization. Therefore, the observed temporal jitter of 200 ps is mainly attributed to the temporal jitter due to homemade synchronization electronic circuitry and temporal jitter in high voltage switches.

While the laser pulses from above described cavity dumped laser oscillator can be used in different applications, we discuss its suitability to realize an OCPA scheme. The temporal jitter of 200 ps in present case may put some limitation on the suitability for OCPA application for the short duration pump pulse, as the pulse shape may not be sufficiently flat profile over the interaction time. This may result in shifting the peak wavelength or loss of the spectral bandwidth of amplified seed laser pulses. However, for the pump pulses of duration of 1–2 ns, one may get a sufficiently broad plateau region required for OCPA application using 250 ps stretched seed pulses. In such a case the effect of temporal jitter may also not be significant. Next, the desired temporal pulse shape and beam profile of laser can be obtained as discussed below. The spatial beam profile can be tailored to be super-Gaussian by using suitable passive or active apodizer [31,32] preferably kept inside the laser cavity. Similarly output temporal pulse shape can also be tailored by applying appropriately shaped HV pulse [33] to the cavity dumper to control its time resolved transmission. Next, the laser pulse shape may change during amplification in the saturated amplifiers. Laser pulses of complimentary pulse shape may be generated from the QS & CD laser oscillator to compensate for the above change. Further, for smooth temporal pulse, the present laser oscillator can be easily upgraded to operate in single longitudinal mode using suitable frequency selective optical element and lasing material with narrow lasing bandwidth such as Nd:YLF or Nd:YAG.

In conclusion, a simple flash lamp pumped Nd:phosphate glass laser oscillator, based on technique of Q-switching and full-wavelength cavity-dumping, has been presented to obtain temporally synchronizable laser pulses of duration variable electronically in the range of ~800 ps to 6 ns with enhanced output pulse stability. Single laser pulse energy of 5 mJ and 11 mJ has been measured for pulses of duration ~800 ps and 6 ns respectively at electrical pump energy of 50 J. While the maximum and minimum pulse duration have been obtained by applying quarter and half wave voltage to double Pockels cell of the cavity dumper, the pulses of duration in intermediate region were obtained by changing the rise time of the high voltage step pulse. The laser pulses are synchronizable with laser pulses from an independent oscillator with an accuracy of ~200 ps, limited by the speed of electronics used. Such energetic laser pulses may find wide-ranging applications in many scientific and industrial research applications.

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References