Laser system generating 250-mJ bunches of 5-GHz repetition rate, 12-ps pulses

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Abstract: We report on a high-energy solid-state laser based on a master-oscillator power-amplifier system seeded by a 5-GHz repetition-rate mode-locked oscillator, aimed at the excitation of the dynamic Casimir effect by optically modulating a microwave resonator. Solid-state amplifiers provide up to 250 mJ at 1064 nm in a 500-ns (macro-)pulse envelope containing 12-ps (micro-)pulses, with a macro/micropulse format and energy resembling that of near-infrared free-electron lasers. Efficient second-harmonic conversion allowed synchronous pumping of an optical parametric oscillator, obtaining up to 40 mJ in the range 750-850 nm.

OCIS codes: (140.4050) Mode-locked lasers; (140.3280) Laser amplifiers; (190.2620) Harmonic generation and mixing; (190.4970) Parametric oscillators and amplifiers.

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1. Introduction

Hundred or thousand nanosecond-long macro-pulses containing trains of picosecond pulses are most usually produced only in Free Electron Laser (FEL) facilities. The extraordinary wide wavelength tuning range, the peculiarly flexible pulse structure, and the remarkable energy levels and peak powers achieved by FELs repay for these huge, complex and expensive systems, substantially irreplaceable in many scientific, industrial and medical applications [1]. Typically, existing FELs in the near infrared wavelength region generate trains of few picosecond micro-pulses within a few µs-envelope of macro-pulses and produce few hundreds of mJ energy per macro-pulse at few Hertz repetition frequency.

In this work we describe a different solution based on a master-oscillator power-amplifier (MOPA) all-solid-state laser system, developed at request for the investigation of the dynamical Casimir effect [2], that shows pulse format and energy substantially comparable to near-infrared FELs. The final goal for the laser system was to provide tens of mJ at 780-820 nm in an approximately rectangular-shape envelope containing a few thousands of picosecond pulses at nearly 5-GHz repetition rate, in order to modulate the length of a suitable microwave resonant cavity through plasma generation in a semiconductor mirror, inducing photon production from the quantum vacuum provided a certain energy threshold is exceeded (see Ref. [2] for a detailed description of the experiment and further references on the dynamical Casimir effect).

Compact, reliable and cost-effective state-of-the-art solutions such as semiconductor saturable-absorber-mirror (SAM) passively mode-locked oscillator can produce the picosecond pulses needed to seed the system [3]. The MOPA approach reported in this Letter takes advantage of recent developments of very high gain, laterally diode-pumped, grazing incidence Nd:YVO$_4$ amplification modules [4-7], that can be employed as preamplifier stages.

Owing to the good gain bandwidth overlap, standard and well tested Nd:YAG flash-lamp pumped modules can be conveniently chosen as boost amplifiers, providing the final energy up-scaling to hundreds of mJ, still maintaining the excellent beam quality produced in the diode-pumped setup. Finally, a flexible and efficient output wavelength management can be achieved thanks to the high energy, high brightness generated pulses. Either the second harmonic or even the fundamental at 1064 nm can be used to reach the desired near- or medium-infrared operating wavelength through optical parametric oscillation or other non-linear processes.

2. Experiments and discussion

A conceptual scheme of the laser system is shown in Fig. 1. The master oscillator was passively mode-locked by an 0.7% reflectivity modulation commercial SAM (Batop GmbH). The ≈ 3-cm long, V-folded cavity, was pumped by a commercial 1-W continuous wave (cw) laser diode emitting at 808 nm. The Fresnel loss of the Brewster-cut face of the 1% doped, *a*-cut, Nd:YVO$_4$ active medium provided the useful output coupling. As already proved for a similar Nd:GdVO$_4$ multi-GHz oscillator [8], the reduced amount of output coupling, measured to be ≈ 0.2%, allowed to overcome the Q-switching instabilities even at such high repetition rates. Such a small output coupling reduced the available output power (and pulse energy) to a fraction of the optimum that can be achieved in pure cw operation. Under these operating conditions, we obtained stable cw-mode-locking pulse trains with an average power of about 15 mW at ≈ 5-GHz repetition rate, and 6-ps time duration (fwhm).

From the continuous pulse train, an acousto-optic modulator selected a train of picosecond pulses (macro-pulse), whose number and exact envelope profile could be readily

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controlled by acting on the radio-frequency signal driving the acousto-optic device. The repetition rate of the macro-pulse was not an issue: for convenience, we operated at 1 Hz in order to limit the thermal load in the cryogenically cooled, microwave Casimir resonator [2]. In principle, flash-lamp high-energy amplifiers could be operated at repetition rates as high as ≈ 100 Hz using quartz rotators for managing thermally-induced depolarization. For our specific purposes we had to manage trains containing from 1000 to 2500 pulses (200-500 ns long pulse envelopes). In principle, wider envelopes could be generated, also with different micro-pulse repetition rates.

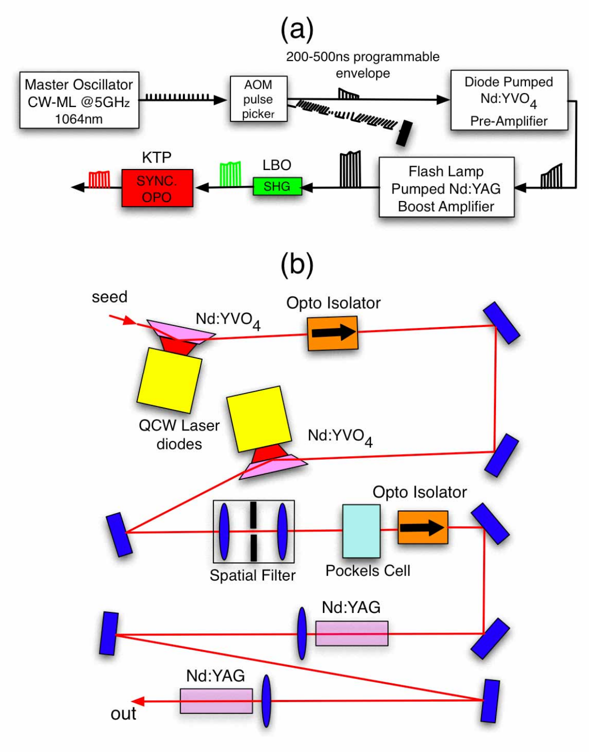

Fig. 1. (a) Conceptual setup of the laser system. (b) Detail of the 1064-nm amplifiers section.

It is well known that under high gain saturation there is severe envelope distortion during pulse-burst amplification [9]. To eliminate this effect we shaped the input drive signal of the acousto-optic device to get the appropriate output envelope that compensates for amplification distortions, as numerically predicted by the Frantz-Nodvik model [9]. A custom electronic command and control interface, able to provide both the programmable temporal shapes for deflection and the synchronization signals for the following amplifying stages, has thus been developed. An experimental comparison between a rectangular shaped deflected pulse envelope and a compensated one, passed through the whole amplification chain, is shown in Fig. 2.

Thanks to its high small-signal single-pass gain, its relatively simple optical arrangement, and its good performance in terms of beam quality and pulse duration preservation [5,6], we opted for a pre-amplifier stage comprised of a couple of Nd:YVO$_4$ 14x4x2 mm^3, *a*-cut, 1% doped slabs, each side-pumped by a pulsed 150-W peak power laser diode array in a grazing incidence, total internal reflection configuration (Fig. 1). The pump radiation was coupled to the active medium through a cylindrical fast-axis collimation lens that produced a ≈ 0.9x10

mm^2 beam cross section. The deflected laser beam emerging from the acousto-optic modulator was carefully collimated to a vertical dimension well contained in the pumped layer, while the path between the two amplification heads was intentionally kept longer than necessary in order to reduce the amount of amplified spontaneous emission (ASE) generated in the first and injected into the second slab. Furthermore, a Faraday opto-isolator was inserted between the two slabs in order to extinguish laser action back into the direction of the master oscillator. All these optimizations contributed to achieve a single-pass gain higher than 60 dB with a well preserved beam quality ($M^2 \approx 1.2$) and an only slightly increased pulse duration ≈ 8.9 ps after the first amplification stage, as in Fig. 3.

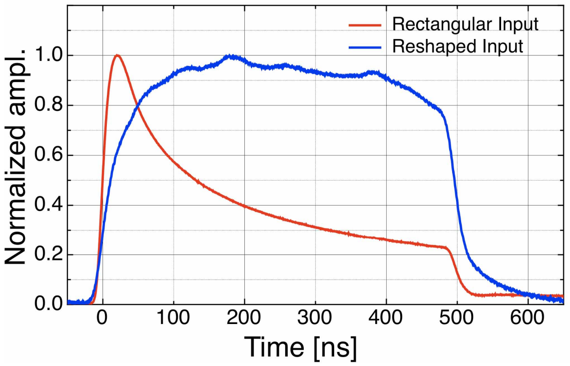

Fig. 2. Experimental comparison of output pulse train envelopes in case of no compensation (red curve) and of programmed deflection for gain saturation compensation (blue curve).

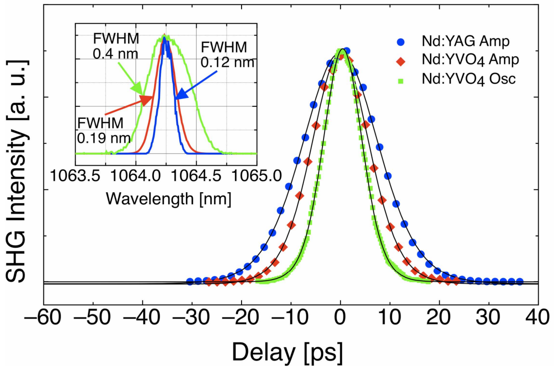

Fig. 3. Background-free noncollinear autocorrelation of the mode-locking pulses generated by the master oscillator (green, fwhm = 6 ps) after the diode-pumped Nd:YVO_4 pre-amplifier (red, fwhm = 8.9 ps) and lamp-pumped Nd:YAG boost amplifier stages (blue, fwhm = 11.7 ps). $Sech^2$ intensity shape was assumed for best fit. Inset: pulse optical spectrum of the oscillator, after Nd:YVO_4 and Nd:YAG amplifiers, same legend.

Owing to the good overlap between Nd:YAG and Nd:YVO_4 gain bandwidths, we could take advantage of the good thermo-mechanical properties and higher saturation fluence of Nd:YAG for the final power amplification stage. Two 12-cm long, 6-mm diameter, flash-lamp pumped, 1% doped Nd:YAG rods were employed. At the maximum pump level, we obtained energies as high as 250 mJ within the 500-ns macro-pulse, with a net gain of ≈ 33 dB from the Nd:YAG amplifiers. By autocorrelation of the amplified bursts, we checked the generation of background-free, 12-ps pulses (see Fig. 3). At the low repetition rate of 1 Hz, no appreciable thermally-induced depolarization effects were experienced, leaving the seed beam quality substantially unaltered after amplification. The narrowing of the pulse optical spectrum contributed to reduce the time-bandwidth product to 0.38, approaching the limit set by transform limited, $sech^2$-shaped pulses.

The principal factor that limited the available gain, and hence output pulse energy, was ASE. Moreover, with such a high single pass gain (> 90 dB) the system was prone to self-lasing into parasitic whispering gallery modes. We tested several solutions to limit ASE, prevent self-lasing, and protect the master oscillator from back-injected noise. Back-injection was limited by placing a second Faraday opto-isolator before the Nd:YAG amplifiers. In order to decrease the solid view angle between the amplifiers, and hence reduce spontaneous emission amplification, a spatial filter was designed [10] and inserted in the focal plane of the expanding telescope between the diode and flash-lamp pumped amplifier stages. Furthermore, an electro-optic Pockels cell switch synchronized with the acousto-optic deflection was inserted between the two stages as a means for opening the path between the amplifiers only when the seed was injected into the chain. All these arrangements contributed for about 3 dB loss of the signal.

A Galilean beam collimator was used to reduce the transverse dimensions of the 6-mm super-Gaussian beam emerging from the Nd:YAG amplifiers to a diameter of ≈ 1.8 mm. The good beam quality ($M^2 \approx 1.5$) of the collimated beam and high peak power of the single pulses in the amplified burst (≈ 10 MW) allowed very efficient nonlinear frequency conversion. Second-harmonic generation (SHG) efficiency as high as 60% at 532 nm was achieved in a 16-mm long type-I LiB_3O_5 (LBO) crystal.

The second harmonic output beam was used to synchronously pump an optical parametric oscillator (OPO) plane-plane cavity. The nonlinear crystal was a 12-mm long AR coated $KTiOPO_4$ (KTP) crystal cut for type II phase-matching in the *xy*-plane. Both the OPO mirrors and the crystal coatings were designed to obtain a singly-resonant oscillator operating around 800 nm, as required by the experiment.

At the maximum green pump energy we operated up to seven times above threshold with a 20% transmitting output coupler, obtaining 40-mJ, 500-ns long, rectangular-shaped macro-pulses. Similar performance at the maximum pump rate were obtained testing a 40% transmitting output coupler. Thanks to the high above-threshold operation, OPO performance was relatively unaffected by slight cavity length variations up to ≈ ±1 mm.

In conclusion, a multi-GHz all solid-state MOPA laser system has been developed. The system is able to provide up to 250 mJ at 1064 nm in a rectangular-shaped 500-ns long macro-pulse containing from 1000 to 2500 picosecond pulses at 5-GHz repetition rate. Both macro-pulse duration and micro-pulse repetition rate were dictated by laser system final application, but in principle they could be widely varied. Owing to high peak-power and brightness of the micropulses, efficient non-linear wavelength conversion stages can be set up in order to tune across the final output wavelength. Our particular application required laser output around 800 nm. SHG of the fundamental was used to synchronously pump an OPO cavity, eventually yielding macro-pulse energy as high as 40 mJ at the requested final wavelength, tunable in the range 750-850 nm. However, the same technology might be employed to expand the tuning range from ultraviolet to medium- or far-infrared. In addition, it is worth noting that solid-state laser sources based on the proposed architecture may also be of some interest as photocathode injection of RF guns in electrostatic accelerators [11].

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