Tailored pulse sequences from an 880 nm pumped $Nd:YVO_4$ bounce amplifier

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Received October 11, 2011; revised November 16, 2011; accepted November 25, 2011; posted November 28, 2011 (Doc. ID 154416); published January 12, 2012

We report on an 880 nm quasi-continuously pumped $Nd:YVO_4$ grazing-incidence “bounce” amplifier, operating at a 300 Hz repetition rate. More than 70 dB small signal gain is achieved with a single crystal. Combined with fast programmable modulators, high-contrast and near-diffraction-limited pulse sequences at the 100 μJ level are produced and can be tailored in terms of pulse duration, amplitude, and a temporal spacing well into the microsecond range. This system could significantly improve extreme-UV comb generation based on parametric amplification and harmonic upconversion of two near-IR comb laser pulses.

OCIS codes: 140.3530, 140.3280.

An increasing number of research groups have developed terawatt intensity, ultrafast optical parametric chirped-pulse amplifier systems because their considerable potential in fields such as attoscience and high-energy physics (see, for example, [1–3]). Recently we showed that such a system is also well suited to perform frequency comb metrology in the extreme-UV by amplifying and upconverting two consecutive pulses from a near-IR frequency comb laser [4]. This approach requires a carefully synchronized pump pulse for each frequency comb pulse that is amplified in the parametric amplifier. Up to now, these have been generated by applying beam splitters and a fixed delay line in the pump laser. Here we present a more versatile and general approach, using an ultrahigh-gain amplifier combined with fast modulators. The system employs a grazing-incidence “bounce” amplifier, based on Nd^{3+}-doped gain material ($Nd:YVO_4$), which benefits in particular from high-peak-power quasi-continuous-wave (QCW) diode pumping [5]. Hundreds of microjoules of amplified pulse energies have been reported for picosecond pulses with small signal gains of around 40 and 60 dB for single and double slab modules, respectively [6]. To the best of our knowledge, all reported Nd^{3+}-doped bounce amplifiers so far (see, for example, [5–9]) have been pumped by 808 nm light. Despite a slightly lower absorption coefficient, direct pumping in the upper-band laser level at 880 nm is a promising alternative thanks to the higher quantum efficiency and lower thermal distortion [10].

In this Letter we present, to the best of our knowledge, the first $Nd:YVO_4$ bounce amplifier pumped at 880 nm. Together with spectral clipping and the combination of fast electro-optical and high-contrast acousto-optical modulators, the system produces near-diffraction-limited pulse sequences with widely tunable timings, intensities, and pulse lengths.

Figure 1 shows a simplified sketch of the experimental setup. The master oscillator is a home-built high-power $Nd:YVO_4$ laser, mode locked with a semiconductor saturable absorber mirror and pumped with 24 W at 880 nm. It provides 0.25 nm spectral bandwidth in a 126 MHz pulse train with 5 W average output power; the repetition rate is locked via a piezo-mounted mirror.

A slit on a translation stage close to the Fourier plane of a $4f$-grating-system was used for spectral selection. Because of the high-power master oscillator and overall efficiency of 60% of the grating-system, more than 90% of the spectral power can be clipped, while still obtaining sufficient seeding energy ($\lesssim$10 pJ) for the amplifier. Hence, a great flexibility in terms of amplified bandwidth and center wavelength is achieved, and the system supports Gaussian-shaped pulses as short as 12 ps (full bandwidth) to about 100 ps (10 pJ seeding energy). For the presented measurements, the spectral clipping was set to transmit $\Delta\lambda \lesssim 0.05$ nm (resolution limited by the optical spectrum analyzer) at the peak of the amplifier emission spectrum, resulting in a 59 ps Gaussian-shaped pulse, which is equal to the typical pump pulse length employed in our parametric amplifier system [4]. The returning beam was extracted via the rejection port of the optical isolator and coupled into a single-mode fiber.

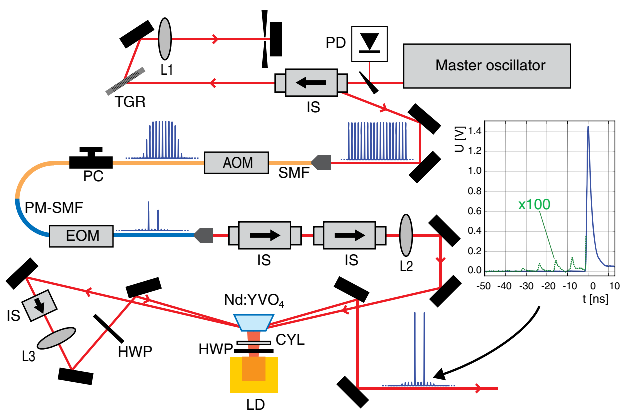

Fig. 1. (Color online) Schematic of the experimental setup. PD, photodiode; IS, optical isolator; TGR, transmission grating (1680 lines/mm); SMF, single-mode fiber; AOM, acousto-optical modulator; PC, polarization controller; PM-SMF, polarization-maintaining single-mode fiber; EOM, electro-optical modulator; L1, L2, and L3, spherical lenses with $f1 = 30$ cm, $f2 = 75$ cm and $f3 = 60$ cm; HWP, half-wave plate; CYL, cylindrical lens with $f = 25$ mm; LD, laser diode. The inset shows an oscilloscope trace illustrating the amplified pulse contrast.

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To select individual pulses from the 126 MHz oscillator pulse train, a fast electro-optical switch is needed. Suitable bulk Pockels cells require electrical pulses of a few kilovolts and are limited to repetition rates at the kilohertz level. For the implemented fiber-coupled electro-optical modulator (EOM, AM 1060 HF, Jenoptik), less than 3 V is needed. Hence, it can be controlled by combining different output channels from a commercial delay generator (DG645, Stanford Research Systems), providing full and programmable control over the picked pulse sequences in terms of amplitude and timing. To improve the extinction ratio of 33 dB of the fast EOM, it was augmented with a slower, 30 ns rise time fiber-coupled acousto-optical modulator (AOM, T-M150-0.4, Gooch and Housego). This combination provided an extinction ratio of more than 90 dB for pulses outside of both picking gates and introduced losses of 10 dB.

The amplifier consists of a single 5° wedged, 1 at. %-doped 2 mm × 4 mm × 20 mm $Nd:YVO_4$ crystal. It is antireflection coated for 880 nm at the pump surface, and for 1064 nm at the entrance and exit sides. The crystal is pumped at a repetition rate of 300 Hz by 130-μs-long pulses (limited by the duty cycle of the available diode driver) from a fast-axis collimated 170 W peak-power QCW 880 nm linear diode array. A half-wave plate rotates the polarization of the pump diode to be parallel to the c axis of the $Nd:YVO_4$ crystal, and a 25 mm focal length cylindrical lens was used to obtain a gain region height of 0.6 mm. The seed beam diameter and internal grazing angle of 0.34 mm and 2.8° were increased to 0.41 mm and 3.4° from the first to the second pass, respectively.

In Fig. 2(a), the extracted pulse energy for a single seed pulse is shown for single- and double-pass operation (including the losses of the isolator after the first pass). At 62 pJ seed energy, a maximum of 182 μJ could be extracted, corresponding to a saturated gain of 65 dB. For low seed energy, the unsaturated small signal gain exceeded 70 dB. The unseeded average power of the amplified spontaneous emission (ASE) was less than 4% of the seeded output power.

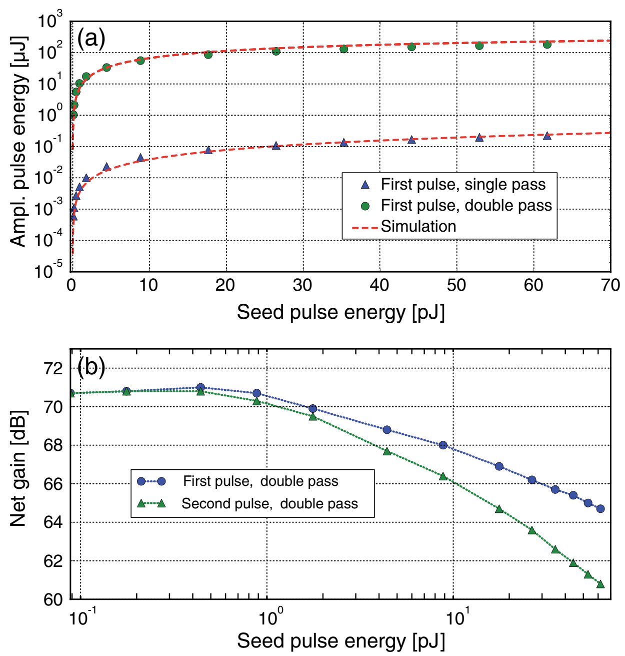

Fig. 2. (Color online) Extracted pulse energy from the amplifier versus seed energy. (a) Single pulse in single- and double-pass configuration. (b) Achieved double-pass gain factors for a pulse pair (32 ns spacing).

We adapted the theoretical model developed by Agnesi *et al.* [11], which approximates the pump and signal-beam geometry and calculates the gain according to the Franz–Nodvik amplifier theory [12]. As an extension, we incorporated the depletion of the gain of the individual amplifier stages due to ASE. According to [13], ASE reduces the small signal gain coefficient g_0 to

$$g(L) = \frac{g_0}{L} \int_0^L \frac{F_p/F_{\mathrm{ASE}}(0) - \exp[g(z)]}{F_p/F_{\mathrm{ASE}}(0) + \exp[g(z)]} \mathrm{d}z, \qquad (1)$$

where L is length of the pumped region in the crystal and F_p is the pump fluence. The fluence of ASE at $L = 0$ is estimated as

$$F_{\mathrm{ASE}}(0) = \frac{\eta_F \Delta\Omega \hbar \omega_{\mathrm{ASE}}}{4\sigma_{\mathrm{ASE}} T}, \qquad (2)$$

and depends on the fluorescence quantum yield η_F, the solid angle $\Delta\Omega$ from exit to entrance area of the gain sheet, and on the fluorescence lifetime and cross section, T and σ_{ASE}, respectively. The ratio $F_p/F_{\mathrm{ASE}}(0)$ (≈39 dB in the present setup) represents the ultimate limit of small signal gain for a single pass due to ASE depletion.

Apart from the assumed pump saturation intensity of the crystal of $I_{p,\mathrm{sat}} = 5.2$ kW, which was derived based on the absorption measurements at 880 nm in [14] and scaled by the emission bandwidth of the pump diode, the biggest uncertainty in the simulation results stems from the limited accuracy of the stimulated emission cross section of $Nd:YVO_4$ at 1064 nm. Recently published values of σ_e range from 1.14×10^{-18} cm^2 [15] to 1.44×10^{-18} cm^2 [16]. A good agreement between our experimental data and the theoretical model was achieved for an emission cross section of $\sigma_e = 1.10 \times 10^{-18}$ cm^2. A slight underestimation of σ_e can be due to intrinsic model approximations and imperfect beam matching of pump and seed light. Excluding the ASE depletion of the gain in the model results in an underestimation of σ_e of about 10% or an overestimation of the small signal gain by a factor 10.

While Fig. 2(a) describes single-pulse operation, Fig. 2(b) visualizes how the gain decreases for a second, slightly delayed pulse, due to gain depletion of the first pulse. The pulse pair was created by combining two individual output channels from the delay generator as the input signal for the EOM. Hence the amplitude ratio of the two pulses can be freely adjusted and, for seed energies of the first and second pulse of about 30 and 60 pJ, respectively, two equally energetic pulses of about 100 μJ were obtained. The spacing between the two pulses can be changed by multiples of the pulse separation of the master oscillator as shown in Figs. 3(a)–(c) for different pulse delays. The energy of both pulses fluctuated by less than 1% rms, due to saturation in the amplifier.

The pulse train shown in Fig. 3(d) was realized by picking five pulses of equal seeding energy of 23 pJ.

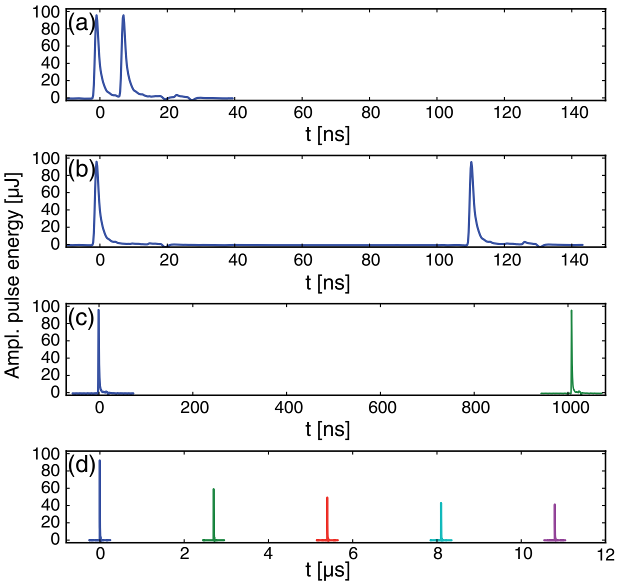

Fig. 3. (Color online) Oscilloscope traces of precompensated pulse pairs with spacing of (a) 8, (b) 111, and (c) 1009 ns; (d) shows an uncompensated pulse train with 2.7 μs spacing.

By combining more individual outputs from the delay generator (or external modulation of the voltage pulse), one can straightforwardly tailor such sequences of megawatt peak-power pulses in terms of spacing and amplitude.

Thanks to the low average thermal load on the amplifier crystal (owing to QCW pumping at 880 nm), the beam hardly deteriorates through the amplification process, as can be seen in Fig. 4. The beam waist measurement after focusing the amplified pulses with a 25 mm focal length lens indicates an $M^2 < 1.2$ on both axis. The slight ellipticity of the beam is due to the noncircular gain sheet, which is imprinted on the amplified beam.

In conclusion, we have demonstrated an 880 nm QCW pumped single-slab $Nd:YVO_4$ bounce amplifier system with more than 70 dB small signal gain, which produces near-diffraction-limited pulse sequences with an energy of up to 100 μJ per pulse and an intensity stability better than 1%. It provides an excellent front end for postamplification based on $Nd:YVO_4$ or Nd:YAG, and is capable of generating double-pulse sequences over a time scale of microseconds without a physical delay line. This is particularly interesting as a driver for parametric amplification and harmonic upconversion of frequency comb laser pulses, which could improve the accuracy of extreme-UV frequency combs based on this principle [4] by several orders of magnitude.

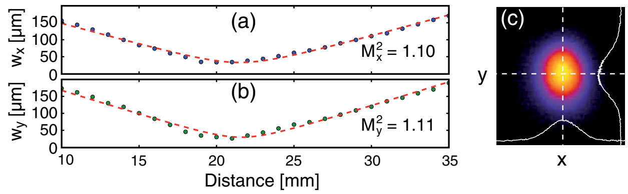

Fig. 4. (Color online) Beam waist measurements and fits of (a) horizontal and (b) vertical axes of the amplified beam; (c) shows a CCD image of the unfocused amplified beam 20 cm from the $Nd:YVO_4$ crystal.

This work was supported by the Foundation for Fundamental Research on Matter (FOM) through its program “Broken Mirrors and Drifting Constants”, the Netherlands Organisation for Scientific Research (NWO) by a VICI grant, and the European Union (EU) Integrated Initiative FP7 program JRA ALADIN 2.

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