Appl Phys B (2011) 103: 5–8
DOI 10.1007/s00340-011-4509-0

Applied Physics B
Lasers and Optics

RAPID COMMUNICATION

High-energy picosecond $Nd:YVO_4$ slab amplifier for OPCPA pumping

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Received: 18 March 2011 / Published online: 7 April 2011

Abstract We demonstrate 12-ps pulses with up to 0.6-mJ pulse energy at repetition rates of 50 kHz and 100 kHz from a $Nd:YVO_4$ slab amplifier built in a simple four-pass configuration. Excellent noise performance with pulse energy fluctuations below 0.8% rms has been achieved by using 10-µJ seed pulses from a highly stable industrial laser system and moderate gain (30–46) in the slab amplifier.

1 Introduction

Reliable picosecond lasers with high peak power and hundreds of microjoules of pulse energy enable numerous industrial and scientific applications. One important example are modern ultra-broadband optical parametric chirped-pulse amplifiers (OPCPAs) [1, 2]. Such systems are used to explore high-field phenomena in previously uncovered wavelength regimes [3]. A pump pulse duration of approximately 10 ps is ideal for this type of OPCPA [4]. The reason for this is the required stretching of the seed pulses, because significant temporal overlap is required for efficient energy transfer. On one hand, stretching to less than several picoseconds would cause unacceptably high peak powers in the gain medium or severely limit the maximum achievable output fluence. On the other hand, stretching few-cycle pulses beyond several picoseconds renders recompression challenging.

To date, not many diode-pumped solid-state laser systems have been reported that deliver picosecond pulses with peak powers in the MW regime. Most of them are limited to repetition rates below 10 kHz [5–8]. For example, Yb:YAG thin-disk amplifiers produced pulse energies up to 4.5 mJ at a pulse duration of 4.5 ps. Our system as described here reduces the complexity compared to these implementations. We focus on stability and ease of operation while obtaining as much pulse energy as possible.

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2 Description of the amplifier

We adopt the InnoSlab concept [9, 10] for amplifying energetic picosecond pulses at 50–100 kHz repetition rates from a picosecond seed laser. This concept has been proven for the amplification of low-peak-power lasers without deteriorating beam quality and noise performance [9]. Up to now, slab amplifiers have only been used for picosecond pulses in a side-pumped geometry yielding <20 MW peak power [6, 7]. Successful power scaling of a 615-fs system at 20-MHz repetition rate has recently been demonstrated with two Yb:YAG slabs in a 7 + 1 pass configuration yielding kW-level output power [11].

Here, we present a picosecond $Nd:YVO_4$ InnoSlab amplifier with a record high pulse energy of 600 µJ and 12-ps pulse duration. It exhibits excellent noise performance with pulse fluctuations below 0.8% rms over a measurement interval of 30 min.

Our amplifier is built in a four-pass configuration based on a 0.4% doped $Nd:YVO_4$ crystal with a dimension of $1 \times 10 \times 10\ mm^3$. The InnoSlab concept consists of a thin crystal that can be conduction cooled homogeneously and efficiently through the large sides of the slab. This results in a one-dimensional heat flow transversely to the laser beam propagation. The resulting thermal lens is cylindrical with low aberrations and avoids depolarization losses. A hybrid resonator-like multi-pass configuration with one stable and one unstable axis enables high-energy pulses with excellent beam quality [9].

Our seed source is the industrial laser 'Duetto' from Time-Bandwidth Products Inc., delivering 12-ps pulses at repetition rates of 30 kHz to 8 MHz and an average output power of up to 12 W. Highest pulse energies are achieved at low repetition rates; therefore, we operate the laser at 50 and 100 kHz. Only 1 W of the laser output power is used to seed the slab amplifier while the remaining power pumps the first stage of a mid-IR few-cycle OPCPA [1]. Seeding with less power reduces the output energy stability of the slab amplifier. The output of the slab amplifier described here is then used for pumping an additional high-energy stage of this OPCPA.

Other InnoSlab amplifiers use a confocal, cylindrical cavity in the unstable axis to increase the beam diameter within the amplifier and, therefore, to limit the intensity with increasing power [9]. We however implemented a simpler plane–plane mirror configuration (Fig. 1), using the adapted inherent divergence of the Gaussian seed beam for the same purpose [12]. The beam divergence of the seed beam is adapted to generate a fast and a slow diverging beam with a simple and robust telescope, consisting of only one spherical and one cylindrical lens. The plane mirrors have to be tilted with respect to each other to avoid parasitic oscillations within the multi-pass resonator. These tilt angles together with the slow-axis beam divergence are designed to obtain a large fill factor inside the gain crystal, a small overlap of the individual beams and low diffraction losses at the gain crystal edges. The seed beam is adjusted such that the divergence is set to about 9.7 mrad in the fast (stable) axis and 5.5 mrad in the slow (unstable) axis, resulting in a beam diameter of 600 µm and 300 µm, respectively, at the entrance of our hybrid resonator. In the fast axis, the Gaussian-shaped gain profile of the slab fits to the resonator's TEM_{00} mode and the cylindrical thermal lens reproduces the mode at the cavity mirrors. The thermal lens changes with pump power; it is therefore favorable to operate the amplifier at a fixed working point. We optimized our setup for an absorbed pump power of 180 W (200-W incident pump power). Due to the larger divergence of the seed, a part of the seed clips at the crystal mount for all other pump powers, resulting in a distorted beam profile.

The output of the amplifier is transformed back into a round beam profile with a three-lens telescope. We obtained an M^2 of 1.15 in the stable and 1.38 in the unstable direction. A spherical lens is used to set the collimated beam diameter and a cylindrical lens telescope ensures a circular beam shape. A typical reshaped output beam profile at full pump power is shown in Fig. 1. For all output energies the intensity autocorrelation has been measured, which shows no deviation from the Gaussian-shaped seed trace (see insets in Fig. 3).

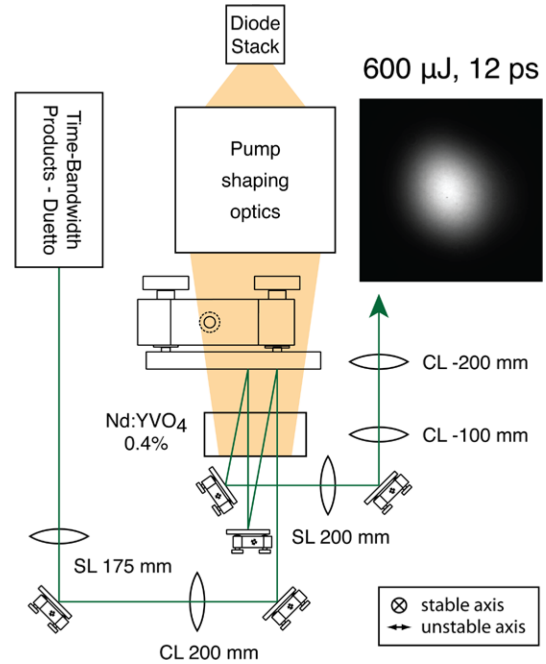

Fig. 1 Amplifier setup with typical beam profile. A cylindrical lens (CL) and a spherical lens (SL) are used to set the divergence for the hybrid resonator. A telescope of cylindrical lenses ensures a circular beam profile

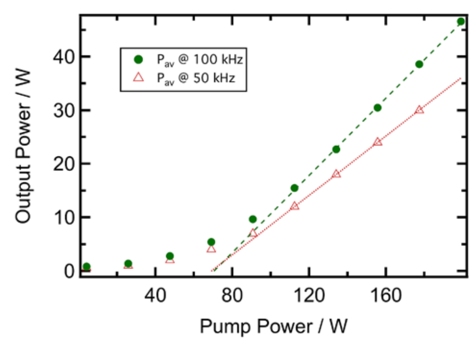

Fig. 2 Output of the slab amplifier versus pump power. The slope efficiency is 36% at 100 kHz (*solid circles*) and 27% at 50 kHz (*open triangles*) repetition rates

Our design goal was to generate the largest possible beam diameter for the last pass through the slab amplifier to minimize the optical power density and to maximize the overlap with the pumped gain area. With the relatively short seed pulse duration of 12 ps, power scaling is not limited by thermal effects but by the B-integral determined by the peak power of the amplified pulse. To avoid any damage to the vanadate crystal, we limit the output peak powers to a range where the spectral broadening through self-phase modulation (SPM) does not exceed a factor of two (Fig. 3). The maximum achievable output energy could be increased by chirped pulse operation, reducing the B-integral, as implemented in [13]. This would, however, come at the expense

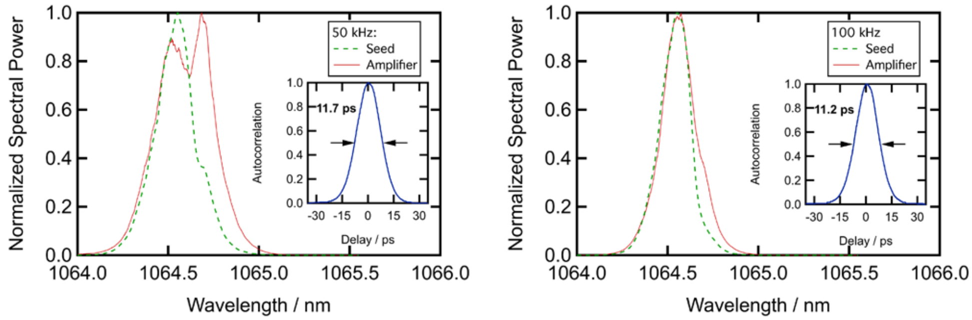

Fig. 3 Optical spectra of seed and amplified seed at 50 and 100 kHz, respectively. Only small spectral broadening is observed at 100 kHz, 38 MW (*left*). Broadening by a factor of two occurs at 50 kHz, 50 MW (*right*). At 50 kHz repetition rate the pump power is limited to 177 W in order to avoid damage at the Nd:YVO_4 crystal. The *insets* show intensity autocorrelation traces for maximum output power. No sign of temporal distortion has been observed over the whole range of operation

of a higher complexity of the system, which we wanted to keep low. Simplicity was one of our main design objectives.

We optimized the system for good noise performance. A 1-W seed was used for reducing the gain to below 20 dB, considerably suppressing noise caused by amplified spontaneous emission (ASE). Furthermore, a stable laser-diode driver, isolation from air currents and a small footprint resulted in as little as 0.8% rms pulse energy fluctuations over a measurement interval of 30 min. The rms fluctuations have been quantified with a photodiode (10-ns rise time). We ensure operation of the photodiode in a linear regime ($I < 0.7$ mA) and eliminate sensitivity towards pointing instabilities by recording the stray light of a large-area power meter.

The amplifier is used in our laboratory on a daily basis and realignment was not needed over a period of several months, which further confirms its excellent long-term stability. The system provides a reliable pump for our OPCPA. The peak power of the output pulses is verified with the power scaling of second-harmonic generation (SHG) in LBO. A quadratic dependence of the second harmonic with respect to the incident fundamental power validates a vanishing noise background. Our OPCPA experiments represent an independent confirmation of this observation.

3 Summary

In conclusion, we have demonstrated a high peak and average power slab amplifier at 50–100 kHz pulse repetition rates delivering hundreds of microjoules of pulse energy. Our setup maintains the excellent beam profile and low noise of our industry-grade seed laser. We chose not to operate the system beyond spectral broadening by a factor of two compared to the initial seed bandwidth. This is a somewhat arbitrary but conservative choice and limits the maximum peak power in this experiment. The maximum output pulse energy we achieve is 600 μJ ($P_{av} = 30$ W, $P_{peak} = 50$ MW) at 50 kHz and 466 μJ ($P_{av} = 46$ W, $P_{peak} = 38$ MW) at a repetition rate of 100 kHz (Fig. 2). The scaling of output power with pump power shows no sign of thermal rollover. This indicates the potential of scaling to higher average powers at higher repetition rates. Our seed source is capable of tuning its repetition rate from 30 kHz to 8 MHz with only minimal output beam parameter changes. Since the target repetition rate for our OPCPA is 100 kHz and below, other regimes were not explored [1]. We observe no indications for being close to the damage threshold when operating the system at its maximum peak power and limiting the SPM-induced spectral broadening.

Acknowledgements This research was supported by the NCCR Quantum Photonics (NCCR QP), a research instrument of the Swiss National Science Foundation (SNSF).

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