13-mJ, Single Frequency, Sub-nanosecond Nd:YAG Laser at kHz Repetition Rate with Near Diffraction Limited Beam Quality

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Abstract: Near diffraction limited, single frequency, passively Q-switched Nd:YAG laser (240-µJ, 830-ps at 0.5-kHz) is amplified up to 13-mJ in a three-stage diode pumped amplifier whilst preserving pulse duration, beam quality and linear polarization.

OCIS codes: (140.4480) Optical amplifiers; (140.3480) Lasers, diode-pumped; (140.3580) Lasers, solid-state

Compact and reliable laser systems providing both high-energy (in the tens of mJ range) and high-peak power (>10MW) pulses at kHz repetition rates with diffraction-limited beams are desirable for a number of applications, e.g. LIDAR [1], materials processing [2], high efficient nonlinear optical conversion [3] and optical parametric processes [4]. Passively Q-switched microchip lasers are simple, miniature and robust sources that can provide single-frequency, high-repetition-rate, and sub-nanosecond pulses with diffraction-limited output around 1 micron wavelength [5]. However, the small gain volume limits the amount of energy that can be stored in the active medium, thus microchip lasers can reach only very modest output energies, typically up to hundreds of micro joules. In order to overcome this deficiency, complicated amplification geometries have been developed and up to 5.7-W (0.2-mJ) and 0.4-MW at 500-ps were achieved [6]. Recently, a Nd:YVO$_4$ bounce geometry was used for amplification of a passively Q-switched laser with energy up to 0.54-mJ and 577-ps pulse duration [7]. Even though these approaches have some advantages in terms of extraction efficiency they have limitations in energy scaling either due to small volume of the active medium or the unsuitability of the amplification scheme itself. For a 1.064-nm Nd:YAG Q-switched microchip laser both Nd:YAG and Nd:YVO$_4$ [8] can be used as active media for the amplifier. The choice of the active material and its geometry is dictated by the targeted and the initial pulse energy. For example, Nd:YVO$_4$ exhibits a larger emission cross section and a lower saturation fluence. Hence it is a better choice for up-scaling the output from oscillators with pulse energies ranging from a few to several tens of micro joules. On the other hand, Nd:YAG has a lower amplification gain than Nd:YVO$_4$ but shows favorable mechanical and thermal properties, in addition to a longer excited state lifetime. Consequently, Nd:YAG is the preferred gain medium for high-energy (1 to10-mJ at ~1kHz repetition rates) sub-nanosecond laser systems. However, in the vast variety of the existing kHz laser systems the output pulse energy is substantially smaller than 10-mJ while, on the other hand, the repetition rate of the 10-100 mJ systems does not exceed 100-Hz. In this work we report on the amplification of pulses from a near- diffraction limited, single frequency, passively Q-switched Nd:YAG laser (240 µJ, 830 ps at 0.5 kHz) up to 13-mJ in a three-stage diode pumped amplifier, whilst preserving pulse duration, beam quality and linear polarization.

As a master oscillator, we use a passively Q-switched chip laser with mirror coatings deposited directly on the Cr:YAG/Nd:YAG active element. It is longitudinally pumped by a fiber-coupled 70-W quasi-cw diode laser array (Jenoptik Laser GmbH, JOLD70-QPXF-1L) driven with 80-µs, 70-A current pulses at 0.5-kHz repetition rate. The pump beam is delivered through a 400-µm core optical fiber and imaged in the active element through an aspheric-lens objective with 1:1 magnification ratio. The single frequency operation of the oscillator is achieved through the short resonator length (7-mm) and the maximum energy of the polarized output is 240-µJ at 0.5-kHz repetition rate. The duration of pulses from the oscillator and from the output of the MOPA system are measured by a 1.5-GHz oscilloscope and an InGaAs p-i-n photodiode and the overall response time of the detection system is 350 ps. Beam quality at each amplification stage is measured with a commercial CCD-based beam analyzer. The signal from the oscillator is pre-amplified with only one passing through an 9-mm long Nd:YVO$_4$ crystal, with 0.5 at. % doping, longitudinally pumped by 808-nm laser pulses with 120-µs duration and 6.2-mJ total energy, delivered from a second fiber-coupled laser diode array (Jenoptik Laser GmbH, JOLD70-QPXF-1L). Further amplification is done by utilizing two double-pass stages with transversely diode-pumped modules. Each module employs a 0.6 at % doped Nd:YAG rod crystal, that is 3-mm in diameter and 90-mm long, of which 50-mm are pumped by three linear arrays of laser diode bars, placed at 120° from each other in a three-fold geometry; each array is composed by five 40-W laser diode bars. Optimal beam sizes in each amplification stage are achieved by using two lens objectives that ensure diameters of 0.7-mm, 1.3-mm and 2-mm (at $1/e^2$ level) in the preamplifier, first and second amplification stages, respectively. Double-pass amplification in the final two stages is realized by a polarizer and a quarter-wave plate. In this setup, the incident linear P-polarized pulse makes one pass through the polarizer, the amplification module and the quarter-wave plate. After the reflection at the rear mirror the pulse makes a second pass through the quarter-wave plate, thus changing its polarization to S-state and after traversing the active crystal is then reflected by the polarizer.

In general, to achieve efficient energy extraction from a pulse amplifier, the energy density of the input signal must be close to the saturation density of the used laser material. Taken into account, that the Nd:YAG media has a saturation density of 0.66 J/cm^2 and the diameter of the used rods is 3 mm, there is a need to reach an energy of ~1 mJ for the 0.8-ns input pulses in order to efficiently saturate the amplification in the active media. In our setup, this condition is met by implementing a pre-amplifier with Nd:YVO$_4$, due to its low saturation density – more than five times lower (0.12 J/cm^2) compared to Nd:YAG, allowing high amplification for a single pass. At maximal pumping the preamplifier is operated in a saturated regime (fig. 1), allowing the extraction of pulses with 0.84-mJ energy at 0.5-kHz repetition rate, with 10% extraction efficiency and near-diffraction-limited beam quality. To further boost the pulse energy over ~10-mJ, we applied 120-mJ optical pump energy in 200-µs pulses in each of the amplifier modules. We were able to achieve average output power of the entire system of 6.5 W, corresponding to 13 mJ energy in a single pulse and 15.7-MW peak power. Fig. 2 shows that saturation of the amplification is achieved on the second pass in the final amplifier module but this however did not lead to substantial pulse shortening on the output of the MOPA and the pulse duration was the same as the one of the microchip oscillator, i.e. 830-ps. The observed beam profiles after: the master oscillator (M_x^2 x M_y^2=1.38 x 1.31), the first stage (M_x^2 x M_y^2=1.39 x 1.33) and at the output of the second stage (M_x^2 x M_y^2=1.4 x 1.35) are shown on fig. 3. The results show minor beam quality deterioration after the first as well as the second stages of the amplifier.

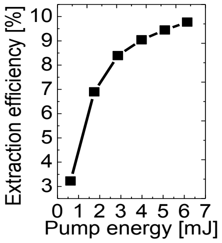

Fig. 1. Saturation of the amplification in the single pass through the Nd:YVO$_4$ pre-amplifier (solid line is for eye guidance);

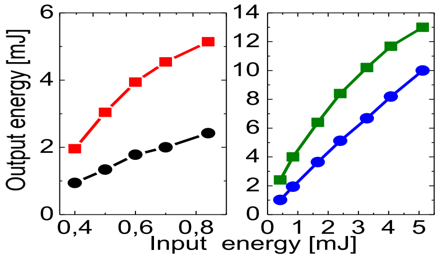

Fig. 2. Output energy vs. input energy for single and double pass amplification in the first amplification stage (black and red curves, respectively) and in the second stage (blue and green curves, respectively). Solid lines are for eye guidance.

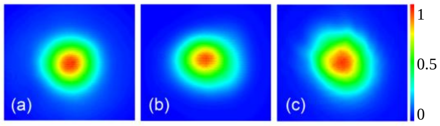

Fig.3. Laser beam profile from the oscillator (a), after the first amplification stage (b) and after the second amplification stage (c).

In conclusion, we have demonstrated a sub-nanosecond single frequency MOPA laser system generating an intense (15.7-MW) single-mode 830-ps pulses with energy up to 13-mJ at 0.5-kHz repetition rate and near diffraction limited beam quality. The proposed approach is easily scalable towards higher pulse energies. The currently achieved intensity level and beam characteristics make the MOPA system an attractive pump source for optical parametric devices.

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