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13-W picosecond Nd:GdVO4 regenerative amplifier with 200-kHz repetition rate

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ABSTRACT We report a diode-pumped picosecond Nd:GdVO4 regenerative amplifier system designed for micro-machining applications. Nd:GdVO4 was chosen as gain material because it offers – in comparison to the commonly used Nd:YVO4 – improved thermal properties and a larger gain bandwidth. At the maximum repetition rate of 200 kHz, the system generated 6.8-ps-long pulses with a pulse energy of 65 µJ, which corresponds to an average output power of 13 W. At 100 kHz, the pulse energy increased to 123 µJ, whereas the average power of 12.3 W remained almost identical. The broadening of the pulses due to gain narrowing was investigated in dependence on the number of cavity round trips and on the repetition rate. At 200 kHz, the injected 5.3-ps-long pulses broadened slightly to about 6.8 ps.

PACS 42.55.Xi; 42.60.Da; 42.65.Re

High-energy ultra-short laser pulses are a powerful tool for precise micro-machining of various metallic and non-metallic materials. The application of this tool in an industrial environment is still hampered by the systems' complexity, the low average output power and the limited repetition rate, which result in long processing times. Recently, a new generation of fast electro-optical switches (based on BBO (β-barium borate) and RTP (rubidium titanyl phosphate)) in combination with improved high-voltage driver electronics became available. These components allow the operation of high-energy ultra-short-pulse laser sources with repetition rates of several hundred kilohertz.

A femtosecond system based on ytterbium-doped KYW [KY(WO$_4$)$_2$] has recently been reported [1]. Operated at a repetition rate of 200 kHz, it generates 280-fs-long pulses with an energy of 9 µJ, which corresponds to an average output power of 1.8 W. Other gain materials such as Nd:YVO4 and Nd:GdVO4 are well suited for powerful, compact picosecond laser sources. These systems are very attractive since they do not require any pulse stretching and compression [2–4]. Such pulse shaping not only adds to the complexity of the laser systems, but it also reduces their overall efficiency. On the other hand, high-energy picosecond pulses are of strong interest, since detailed investigations have proven that the high-energy picosecond pulses are well suited for machining metals with high precision [5].

In this paper, we report a Nd:GdVO4 regenerative amplifier system which generates 7-ps-long pulses with a pulse energy of 65 µJ at a repetition rate of up to 200 kHz. The average power of the pulsed output is up to 13 W. Neodymium-doped GdVO4 [6] was chosen as gain material since it provides many of the advantageous properties of the more commonly used Nd:YVO4, but in addition offers a significantly higher thermal conductivity along the crystal's c and a axes (11.4 W/m K and 10.1 W/m K, respectively) [7, 8]. The material also shows a somewhat larger gain bandwidth of 330 GHz, which allows for the generation and amplification of shorter pulses [6].

The experimental scheme of the realized system is shown in Fig. 1. It consists of a continuous-wave (cw) mode-locked diode-pumped Nd:GdVO4 oscillator, a RTP pulse picker and a regenerative amplifier. The concept of the oscillator is described in detail for Nd:YVO4 in Ref. [9]. In the present system, a 0.7 at.% doped Nd:GdVO4 crystal is pumped by a single fiber-coupled diode laser. When passively mode locked with a semiconductor saturable absorber mirror [10], the laser generates 5.3-ps-long pulses with an average output power of 2.9 W at a repetition rate of 70 MHz.

The pulse picker comprises a RTP Pockels cell (provided by FastPulse Technology, Inc.) with a clear aperture of 4 mm and a thin-film polarizer (TFP). The Pockels cell is connected to high-speed driver electronics, which allow switching of the polarization of the transmitted light with a repetition rate of up to 1 MHz and an optically measured rise time of less than 5 ns. The pulses pass an additional thin-film polarizer, a Faraday rotator (FR) and a half-wave plate (HWP). These components separate the pulse amplified in the regenerative amplifier from the injected pulse generated by the mode-locked oscillator. A lens with a focal length of $f = 750$ mm is used to match the divergence and the waist location of the injected beam to the resonator mode of the regenerative amplifier.

The amplifier's resonator consists of the mirrors M1–M5, all highly
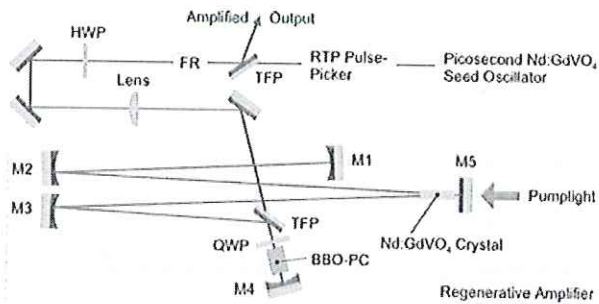
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FIGURE 1 Scheme of the Nd:GdVO$_4$ regenerative amplifier. M1–M4: curved high-reflectivity mirrors; M5: plane pump window; TFP: thin-film polarizer; FR: Faraday rotator; HWP: half-wave plate; QWP: quarter-wave plate

reflective for the laser wavelength of 1064 nm. Mirror M5 is highly transmissive with an additional antireflection-coated back surface for the 808-nm diode laser pump radiation. The mirrors M1–M4 are spherical with a radius of curvature of $r = -2000$ mm (M1 and M4) and $r = -750$ mm (M2 and M3), respectively. The total length of the resonator is about 1.8 m, corresponding to a cavity round-trip time of 12 ns. The gain medium is a $4 \times 4 \times 12$ mm^3 a-cut Nd:GdVO$_4$ crystal with a doping concentration of 0.3 at.%. The crystal is positioned close to mirror M5, which provides four passes of the pulse through the crystal for each cavity round trip. The crystal is pumped by a fiber-coupled diode laser with a power of 34.5 W. In order to avoid thermally induced damage of the laser crystal, the pump beam is magnified to a spot size of 1.3 mm. Additionally, the pump radiation is spectrally shifted slightly away from the absorption peak at 808.5 nm. A combination of a thin-film polarizer, a quarter-wave plate and a β-barium borate (BBO) Pockels cell (provided by LINOS Photonics GmbH) with an aperture of 4 mm is used for the injection of the laser pulses into the cavity of the regenerative amplifier. The maximum switching frequency of the Pockels cell was 200 kHz, limited by the driver electronics.

In the experiments, the cavity was first aligned in cw operation with mirror M1 replaced by a 15% output coupler. In this configuration, the system generated an output power of almost 16 W in a diffraction-limited beam with $M^2 < 1.1$.

Pulses with an energy of about 35 nJ were then injected into the amplifier and the number of round trips was increased until the output pulse energy saturated. The left-hand part of Fig. 2 shows the average output power of the amplifier for two different repetition rates in dependence on the number of round trips. At 100-kHz repetition rate, a maximum output of 12.3 W is achieved after 19 round trips of the pulse in the amplifier. At a repetition rate of 200 kHz, the output power increased by about 6% to almost 13 W, which is achieved after 26 round trips. The average output powers correspond to pulse energies of 123 µJ at 100 kHz and 65 µJ at 200 kHz, respectively, as shown in the

right-hand part of Fig. 2. The comparison of the absorbed pump power with the extracted power yields an overall efficiency of the amplifier of 40%. In order to prevent laser-induced damage due to the high energy of the generated picosecond pulses, the amplifier's resonator was designed to ensure large beam sizes on all critical components such as the laser crystal and the Pockels cell. In fact, no optical damage of the system has been observed so far during the course of our investigations.

The output signal of the regenerative amplifier was recorded with a fast photodiode. As seen in the left-hand part of Fig. 3, the amplifier generates a clean output pulse without any noticeable pre- or post-pulses. The measured contrast ratio was better than 100:1. The center part of the figure shows the amplitude of the pulse during amplification inside the amplifier for consecutive round trips. The recorded pulses are temporally spaced by the cavity round-trip time of 12 ns. After 26 round trips (only 14 of these are shown in the figure), the energy of the circulating pulse is saturated and the pulse is ejected from the amplifier. In the right-hand part of Fig. 3, the amplitude variation of 100 consecutive output pulses of the amplifier is shown. The monitored signal demonstrates that the amplifier provides a pulse-to-pulse amplitude stability with a standard deviation of less than 1%. The spatial quality of the output beam, measured using an M^2-200 beam-propagation analyzer from Spiricon, Inc., was almost diffraction limited with an M^2 value of 1.15 on both axes. It should be noted that a beam quality close to the diffraction limit is essential for applications in high-quality micro-machining of small structures.
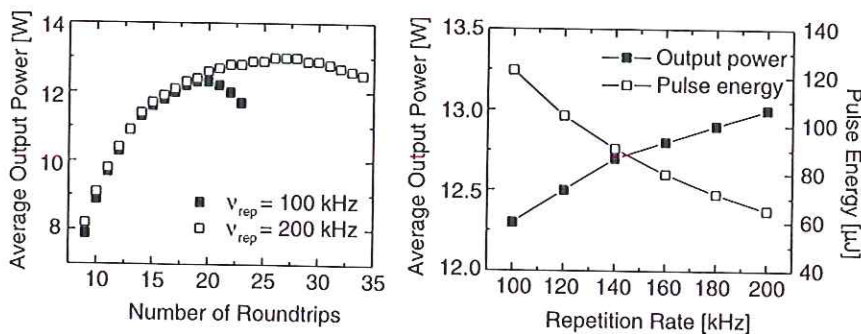

FIGURE 2 Output power and pulse energy of the regenerative amplifier in dependence on the number of round trips (*left*) and the repetition rate (*right*)
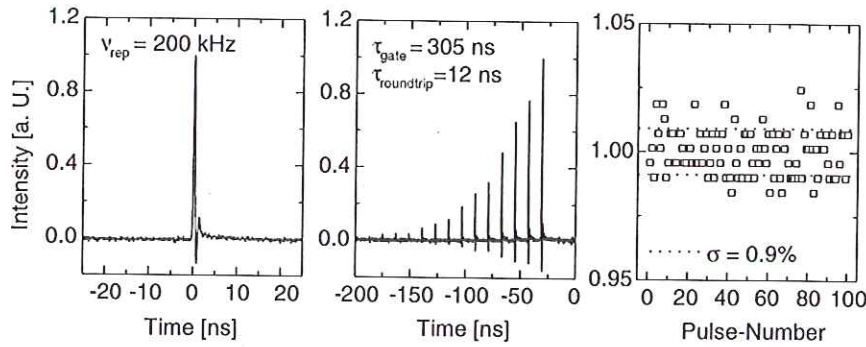
FIGURE 3 Fast oscilloscope trace of the amplified output pulses (*left*), of the pulses during amplification (*center*) and of the amplitude variation of 100 consecutive pulses (*right*)

The temporal and the spectral properties of the injected and amplified laser pulses were characterized by measuring their intensity autocorrelation signal and optical spectrum. The left-hand part of Fig. 4 shows the autocorrelation trace of the injected and amplified pulses at a repetition rate of 200 kHz after 26 cavity round trips. In the right-hand part of this figure the corresponding optical spectra are shown, measured using a scanning Fabry–Pérot interferometer with a free spectral range of 300 GHz and 750 GHz, respectively. Assuming a sech² pulse shape, the measured duration was 5.3 ps for the injected pulses and 6.8 ps for the amplified output. This broadening can be attributed to gain narrowing in the amplifier [11]. Simultaneously, the spectra of the pulses are broadened from 78 GHz to about 134 GHz after the amplification process. The spectral shape of the amplified pulses shows a pronounced modulation, which becomes even stronger with an increasing number of round trips. This is considered to be a consequence of self-phase modulation (SPM), accumulated in each pass through both the laser crystal and the Pockels cell. It is caused by a nonlinear change in the refractive index due to the high peak intensity of the amplified beam ($\approx 1\,\mathrm{GW/cm^2}$ in the last round trip).
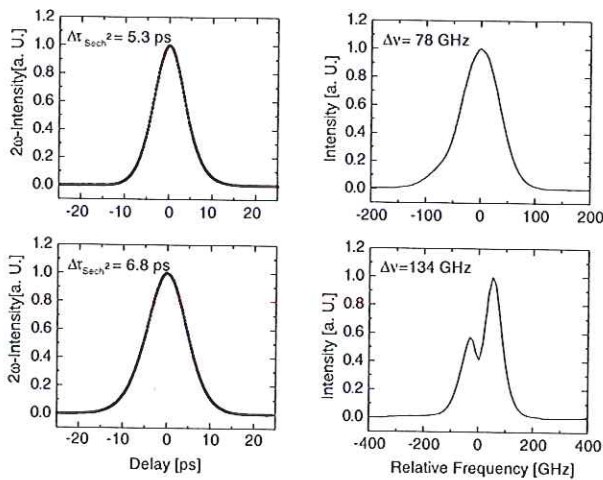
The broadening of the amplified pulses due to gain narrowing is shown in the left-hand part of Fig. 5 for an increasing number of round trips. At a repetition rate of 200 kHz, the pulse duration increases from about 6.4 ps after nine round trips to about 7.2 ps after the maximum of 34 round trips. At the same time, the spectral width of the amplified pulses is increased by SPM from 70 GHz to about 170 GHz. The right-hand part of this figure shows the pulse duration of the amplified pulses as a function of the repetition rate. For each repetition rate, the number of round trips was adjusted for maximum output pulse energy. The results show that with increasing repetition rate the pulse width is reduced from about 7.3 ps at 100 kHz to 6.8 ps at 200 kHz. This behavior is caused by the lower gain at higher repetition rates. The initial gain is reduced, since the recovery time between consecutive injected pulses is reduced from 10 μs to 5 μs when the repetition rate is increased from 100 kHz to 200 kHz. The lower gain results in less gain narrowing and thus in a reduction of pulse broadening.

In conclusion, we have reported a fast and powerful diode-pumped regenerative amplifier operating in the picosecond regime. The system is based

FIGURE 4 Intensity autocorrelation trace (*left*) and optical spectrum (*right*) of the injected (*top*) and the amplified (*bottom*) laser pulses
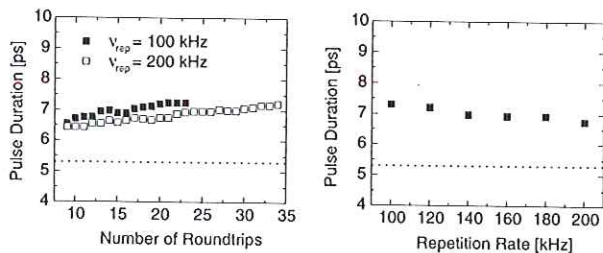

FIGURE 5 Pulse duration of the regenerative amplifier depending on the number of round trips (*left*) and the repetition rate (*right*). The *dotted line* indicates the duration of the injected pulses

on diode-pumped Nd:GdVO$_4$ as the gain material and provides pulses with up to 13 W of average output power when operated at a repetition rate of 200 kHz. Due to moderate gain narrowing, the injected laser pulses are broadened from 5.3 ps to about 6.8 ps during amplification. To the best of our knowledge, this is the highest output power generated so far from an ultra-fast regenerative amplifier operating at such high repetition rates. As demonstrated in previous experiments, a further increase of the output power and the pulse energy can be achieved in a straightforward way by adding a single- or double-pass amplification stage behind the regenerative amplifier [4]. In this way, output powers exceeding 20 W at repetition rates of 200 kHz are soon to be expected.

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