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J. KLEINBAUER✉
R. KNAPPE
R. WALLENSTEIN

A powerful diode-pumped laser source for micro-machining with ps pulses in the infrared, the visible and the ultraviolet

Fachbereich Physik, Technische Universität Kaiserslautern, Erwin-Schrödinger-Straße 46, 67663 Kaiserslautern, Germany

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ABSTRACT We report a ps diode-pumped Nd:YVO_4 laser system for micro-machining applications. The system consists of a passively mode-locked oscillator followed by a regenerative amplifier. It provides laser pulses at 1064 nm with a pulse duration of 10.2 ps, a repetition rate of 20 kHz and an average output power of 10.8 W. This average power corresponds to a pulse energy of 0.54 mJ. Second-harmonic generation in LBO and fourth-harmonic generation in BBO provide visible (532-nm) and ultraviolet (266-nm) radiation with pulse energies of 270 μJ and 75 μJ, respectively. Amplification in a diode-pumped single-pass Nd:YVO_4 amplifier increases the pulse energy of the fundamental 1064-nm laser pulses to 1 mJ.

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1 Introduction

Micro-machining of metals with high precision is an important application for ultra-short high-energy laser pulses. Due to the short interaction time between the radiation and the material, thermal and mechanical damage of the workpiece is strongly reduced or completely avoided [1–5]. In the past, the successful demonstration of Kerr-lens mode locking (KLM) in solid-state lasers (like titanium-doped sapphire, Ti:Sa) [6–10] and chirped pulse amplification (CPA) [11–14] were important milestones towards the development of powerful ultra-short pulse laser sources. Today, most lasers used for micro-machining are based on this concept and Ti:Sa has become the standard material for the generation and the amplification of femtosecond pulses. Ti:Sa, however, has to be pumped with visible laser radiation, usually provided by frequency-doubled diode-pumped solid-state lasers. CPA adds further to the complexity of the system. As a result, systems based on Ti:Sa are expensive and rather inefficient sources of short laser pulses with limited average output power.

To overcome the disadvantageous properties of Ti:Sa there is a strong interest in finding alternative laser materials for high-power ultra-short pulse systems. In contrast to Ti:Sa, ytterbium-doped materials such as Yb:YAG and Yb:KGW offer the advantage of direct diode pumping. Using these materials, femtosecond pulses with high energy have been generated with a variety of systems based on the technique of regenerative amplification [15–20].

In the past, machining results with Ti:Sa seemed to indicate that pulse durations of several hundred femtoseconds or less provide best results in high-precision micro-machining. Recent investigations demonstrated, however, that pulses with durations in the range of several picoseconds are well suited for the precise machining of metals [21, 22]. Compared to femtosecond sources, picosecond laser systems are much simpler and more cost effective. The laser materials used in these sources are based on neodymium-doped crystals (such as Nd:YAG or Nd:YVO_4), which allow for direct diode pumping. Moreover, since the pulse durations are in the picosecond regime, CPA is not required.

The amplification of short laser pulses with kHz repetition rates has been investigated in detail by using regenerative amplification in Nd:YAG. However, the narrow line width of the laser transition restricts the pulse duration to about 20–50 ps [23–26]. In this paper, we report a diode-pumped Nd:YVO_4 regenerative amplifier system that generates 10-ps pulses with a repetition rate of 20 kHz and an average output power of 10.8 W, which corresponds to a pulse energy of 0.54 mJ. The amplifier is seeded by the pulses of a diode-pumped Nd:YVO_4 oscillator, passively mode locked with a semiconductor saturable absorber mirror (SESAM). This oscillator provides pulses with a duration of 6.6 ps and an energy of 50 nJ at a repetition rate of 82 MHz, which corresponds to an average output power of 4.2 W.

Since the processing of materials such as copper or ceramics requires high-energy picosecond laser pulses at wavelengths in the visible or the ultraviolet, the amplified infrared laser pulses have been frequency converted by second- and fourth-harmonic generation. Using LBO, frequency-doubled 532-nm radiation provided pulses with an energy of 270 μJ. The 266-nm fourth-harmonic generated in a BBO crystal consisted of pulses with an energy of 75 μJ.

Even higher pulse energies are expected at these wavelengths, since the amplification of the 1064-nm radiation in a subsequent diode-pumped single-pass Nd:YVO_4 amplifier increased the energy of the infrared laser pulses to 1 mJ.

✉ Fax: +49-631-205-3906, E-mail: kleinbau@physik.uni-kl.de

2 Nd:YVO_4 oscillator amplifier system

The scheme of the Nd:YVO_4 oscillator amplifier system is shown in Fig. 1. It consists of a mode-locked picosecond Nd:YVO_4 oscillator, a pulse picker and a Nd:YVO_4 regenerative amplifier.

The picosecond oscillator is a diode-pumped Nd:YVO_4 laser, passively mode locked with a semiconductor saturable absorber mirror. Pumped with an average power of about 10 W from a fiber-coupled diode laser, the oscillator generates pulses with a duration of 6.6 ps at a repetition rate of 82 MHz. The average output power is 4.2 W, emitted in a TEM_{00} beam with a M^2 value below 1.1. Figure 2 shows the intensity autocorrelation signal and the optical spectrum of the generated laser pulses. Assuming a $sech^2$ temporal shape, the pulse duration, as stated above, is 6.6 ps. The optical spectrum, measured with a scanning Fabry–Pérot interferometer, has a width of about 89 GHz. Both the large time–bandwidth product of 0.58 and the shape of the spectrum indicate that the frequency chirp of the pulses should be moderate. In fact, the temporal and the spectral pulse shapes are typical for lasers with a 'gain-at-the-end' configuration, commonly used for enhancing the spatial hole burning. This allows us to generate shorter pulses due to an inhomogeneous broadening of the gain [27, 28].

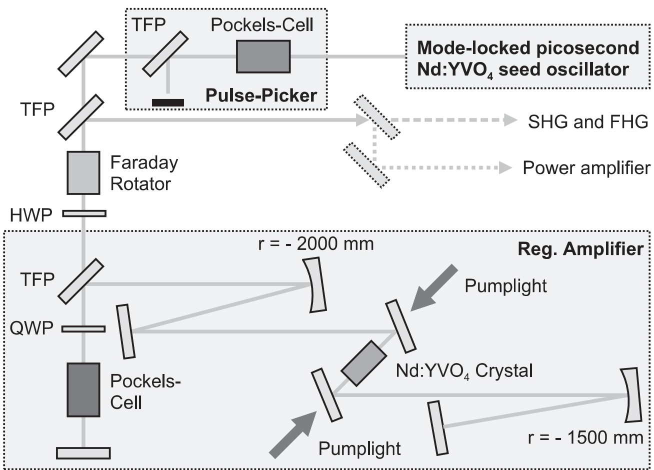

FIGURE 1 Experimental setup of the picosecond Nd:YVO_4 oscillator amplifier system

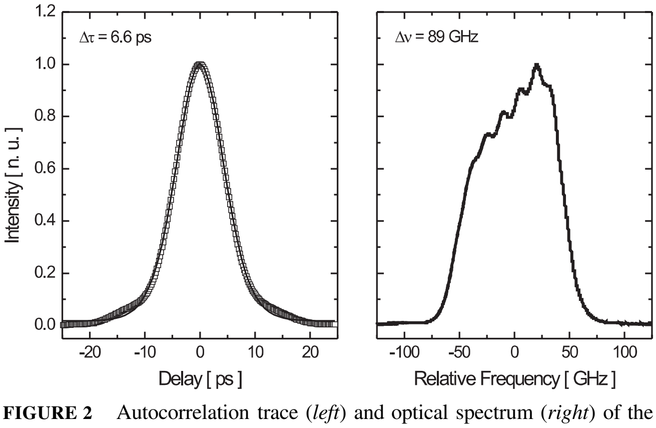

FIGURE 2 Autocorrelation trace (*left*) and optical spectrum (*right*) of the seed pulses

From the train of picosecond laser pulses, single pulses are selected by the pulse picker, which consists of a polarizer and a BBO Pockels cell (Quantum Technology, Inc.) with a clear aperture of 3 mm and a half-wave voltage of about 5.4 kV. The selected pulses are then injected into the regenerative amplifier through a combination of a Faraday rotator and a half-wave plate (HWP).

The main components of the regenerative amplifier are the optical resonator (formed by seven high-reflective mirrors), a diode-pumped Nd:YVO_4 laser crystal and an electro-optical modulator (Pockels cell). In combination with a thin-film polarizer (TFP) and a quarter-wave plate (QWP), the Pockels cell allows for injecting the laser pulses selected by the pulse picker into the cavity of the amplifier. After several round trips, the amplified pulses can be ejected from the resonator by the same optical elements.

As shown in Fig. 1, two of the seven cavity mirrors are spherical to compensate for the thermal lensing in the laser crystal. The gain medium is a $4 \times 4 \times 12\ mm^3$ *a*-cut Nd:YVO_4 crystal with a doping concentration of 0.3 at. %. The facets are AR coated for both the 1064-nm laser and the 808-nm pumping wavelengths. The crystal is end pumped from both sides by fiber-coupled diode lasers, which provide an output power of 21 W each. Suitable optics focus the two pump beams to a spot size of about 800 μm.

The BBO Pockels cell (Quantum Technology, Inc.) with a clear aperture of 4 mm and the quarter-wave plate are placed at one end of the cavity. The quarter-wave voltage of the cell is about 6.4 kV. The high-voltage driver used (Quantum Technology, Inc.) restricted the maximum repetition rate to 20 kHz. The optically measured rise and fall times of the Pockels cell were in the range of 12–16 ns. These response times required a cavity with a total length of 3.3 m in order to avoid the simultaneous amplification of several laser pulses. The optical length of the resonator corresponds to a round-trip time of about 22 ns.

In the experiment, the resonator was first aligned for cw operation, with the Pockels cell and the quarter-wave plate removed. Also, one of the flat end mirrors was replaced by an output coupler with a transmission of 12%. In this configuration, the amplifier operated as a laser and emitted a maximum average output power of 20 W in a diffraction-limited beam with a M^2 value below 1.1. When the Pockels cell was inserted back into the resonator, the cw output power dropped to about 16 W due to additional losses at the surfaces of the BBO crystal and the cell windows.

Figure 3 shows the average output power and the pulse energy of the regenerative amplifier in dependence on the repetition rate. At a repetition rate of 20 kHz, the system generated a maximum average power of 10.8 W. This power corresponds to a pulse energy of 0.54 mJ and an amplification factor of about 10^4. By reducing the repetition rate to 13.3 kHz, the average output power of the system dropped to 8.8 W, whereas the corresponding pulse energy increased to a maximum of 0.66 mJ.

The trace of the output pulses, measured with a fast photodiode and monitored by an oscilloscope, shows a clean signal without noticeable pre- or post-pulses (left-hand part of Fig. 4). The center part of this figure shows the power of the amplified pulse inside the amplifier after each round trip. The

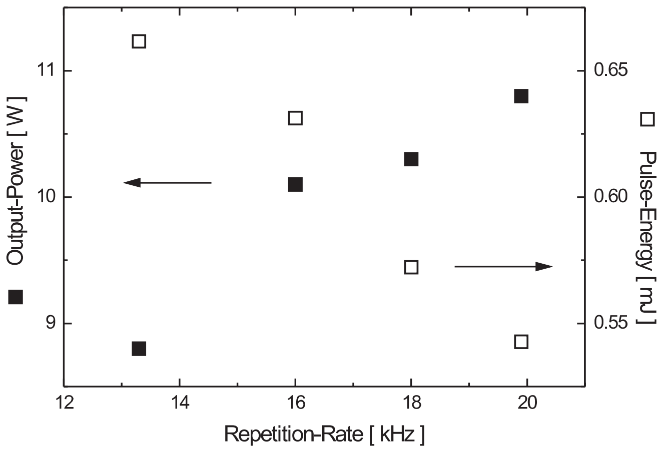

FIGURE 3 Average output power (*filled squares*) and pulse energy (*open squares*) at different repetition rates

measured pulses are temporally spaced by the cavity round-trip time of 22 ns. After only seven round trips, that is 14 passes through the gain medium, the power of the amplified pulse is saturated and the pulse is ejected from the cavity. The small post-pulses seen after each round trip are due to an echo in the diagnostic electronics and are not part of the generated laser output. In the right-hand part of Fig. 4, the amplitude variation of 50 subsequent output pulses is shown. The monitored signal demonstrates that the amplifier provides a pulse-to-pulse amplitude stability with a standard deviation of below 1%.

An important parameter limiting the precision obtainable in micro-machining applications is the spatial quality of the laser beam. This can be a problem for systems using chirped pulse amplification (CPA), where the transversal profile of the output beam depends sensitively on the precise alignment of the optical grating pair used for pulse compression. Small misalignments can cause changes in the spatial distribution of the laser power and result in a poor quality of the laser beam. The concept of the Nd:YVO_4 amplifier system presented here does not imply such restrictions. Figure 5 shows the transverse beam profile of the output beam, measured with a CCD camera. The picture indicates a small ellipticity of the beam with an almost Gaussian profile. The spatial beam quality is in fact close to the diffraction limit with a value of M^2 below 1.2.

The temporal and the spectral properties of the amplified laser pulses were characterized by recording an intensity au-

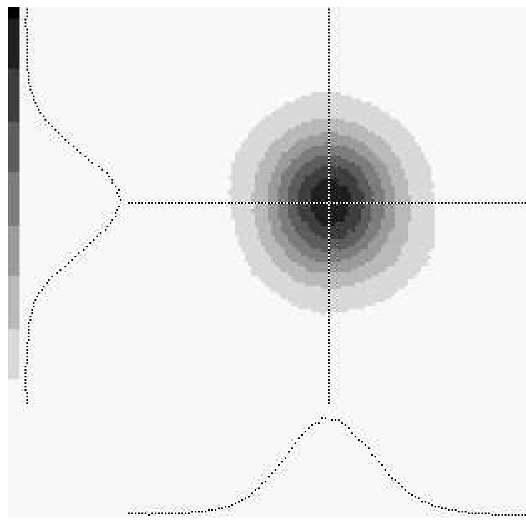

FIGURE 5 Spatial profile of the amplified beam, showing TEM_{00}-mode operation

tocorrelation signal and the optical spectrum. In a regenerative amplifier, the limited bandwidth of the gain material typically causes a spectral narrowing and thus a temporal broadening of the pulses. This effect is called gain narrowing and can be seen by comparing the pulse duration of the seed and the output pulses, as well as their optical spectra. Figure 6 shows the autocorrelation trace and the optical spectrum of the amplified beam. Assuming a $sech^2$ pulse shape, the measured pulse duration of the amplified pulses is 10.2 ps, indicating gain narrowing in the amplifier, which causes a temporal broadening of the pulses during amplification from 6.6 ps (see Fig. 2) to 10.2 ps.

Simultaneously, the spectrum of the amplified pulses is modulated and broadened from about 90 GHz to 150 GHz. This is due to self-phase modulation, caused by the large peak intensities involved in the laser crystal and in the crystal of the Pockels cell. Figure 7 illustrates this effect by showing the measured spectral width of the amplified pulses after each round trip in the amplifier. At the beginning, the spectral width is reduced compared to the seed pulses due to gain narrowing. As the power of the amplified pulses increases during each round trip, self-phase modulation becomes a dominating effect and the spectrum broadens.

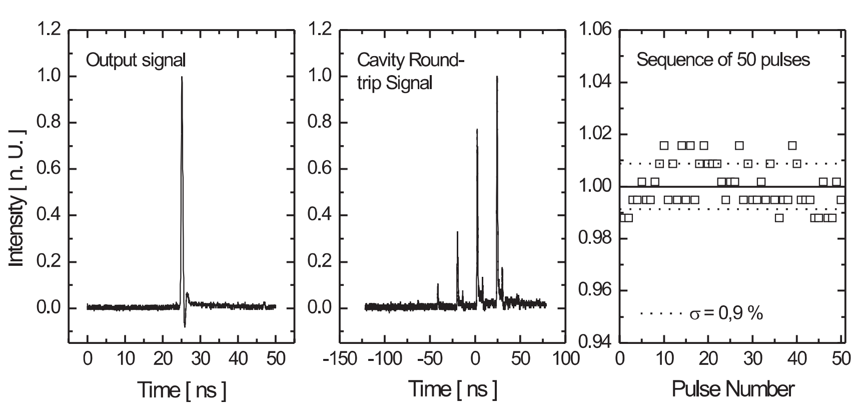

FIGURE 4 Oscilloscope trace of the amplifier output pulse (*left*), of the amplified pulse after each cavity round trip (*middle*) and of the amplitude variation of a sequence of 50 output pulses (*right*), all measured with a fast photodiode

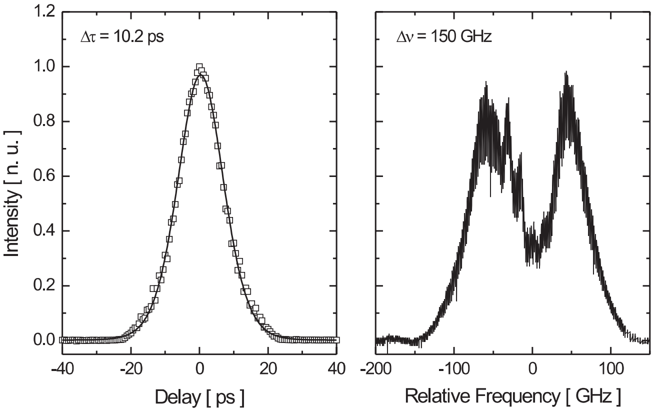

FIGURE 6 Autocorrelation trace (*left*) and optical spectrum (*right*) of the amplified laser pulses

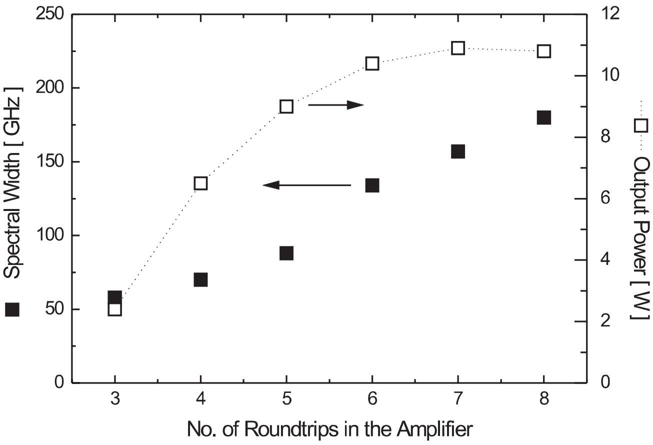

FIGURE 7 Spectral width (*filled squares*) and average output power (*open squares*) of the amplified pulses in dependence on the number of round trips in the amplifier

The high quality of the generated laser pulses was demonstrated with a simple experimental setup by drilling holes in a plate of industrial steel with a thickness of 1 mm. For this application, the output beam of the regenerative amplifier was focussed on to the plate by a lens with a focal length of 50 mm. As an example, Fig. 8 shows a picture of such a workpiece, indicating a hole diameter of about 100 μm. Structures like this were routinely processed in a time of the order of a few seconds.

Thorough investigations regarding drilling and surface structuring by ultra-short laser pulses have been performed with this laser source in Stuttgart, Germany, at the Institut für Strahlwerkzeuge (IFSW). These experiments confirm that excellent results can be achieved with pulses of several picoseconds in duration [29]. More importantly, no significant differences were observed between the quality of the features generated with picosecond laser pulses and those obtained with femtosecond laser pulses. The picosecond laser system, however, offers the advantage of shorter processing times and lower system costs, since it provides comparable pulse energies at a significantly higher repetition rate and it requires neither CPA nor a complex and inefficient pump source.

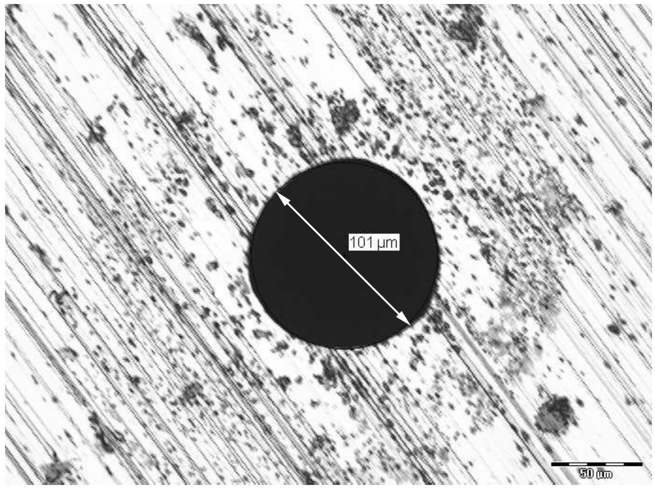

FIGURE 8 Application of the laser pulses from the Nd:YVO_4 regenerative amplifier for drilling a hole in a plate of industrial steel with a thickness of 1 mm

3 Generation of high-energy pulses in the visible and the UV

Recent investigations with a laser system similar to the one described in this work indicate that certain applications and materials can benefit from the processing at shorter wavelengths and exhibit an improved quality of the produced structures [30]. Moreover, wavelengths in the green and in the UV spectral range can be utilized for the fabrication of very small feature sizes and the processing of materials with low absorption in the IR [31].

One method for the generation of high-energy picosecond radiation in the visible and in the UV is harmonic generation in nonlinear crystals. Figure 9 shows a straightforward setup for frequency conversion of the output of the Nd:YVO_4 regenerative amplifier system into the visible and into the UV by second- and fourth-harmonic generation.

To generate the second harmonic, an LBO (lithium borate) crystal with a length of 5 mm and an aperture of $3 \times 3\ mm^2$ was placed into the unfocussed output beam of the Nd:YVO_4 regenerative amplifier system. The diameter of the laser beam at this position was approximately 1 mm. The LBO crystal was AR coated for both the fundamental wavelength at 1064 nm and the second harmonic at 532 nm and critically phase matched at room temperature ($\varphi = 11.3°$, $\theta = 90°$). The second harmonic was subsequently separated from the remaining fundamental power using a dichroic mirror.

In a similar way, the fourth harmonic was generated by frequency doubling the second harmonic in a BBO (barium borate) crystal with a length of 3 mm and an aperture of 3 ×

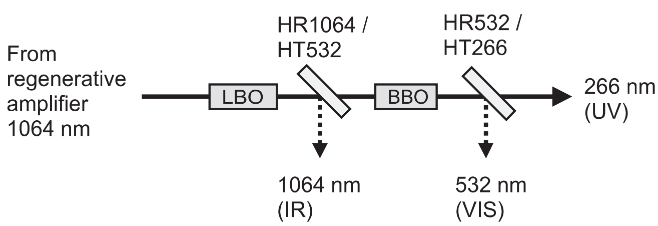

FIGURE 9 Scheme for the generation of the second and the fourth harmonics of the 1064-nm laser pulses

3 mm^2. This crystal was also AR coated and critically phase matched at room temperature ($\theta = 47°$). The fourth harmonic at 266 nm was separated from the remaining green radiation using an additional dichroic beam splitter.

Figure 10 shows the pulse energy of the generated second harmonic in dependence on the energy of the fundamental laser pulses. The maximum output pulse energy obtained at a repetition rate of 20 kHz was 270 μJ, which corresponds to an average output power of 5.4 W and a conversion efficiency of about 50%. This efficiency is close to the value of 60%, estimated by the Boyd–Kleinman model. The high conversion efficiency is a clear indication for the excellent spatial and temporal quality of the pulses generated by the regenerative amplifier.

The 532-nm second-harmonic radiation was converted into the UV by frequency doubling in a BBO crystal. In this way, a maximum output pulse energy of 75 μJ was generated at 266 nm. This pulse energy corresponds to an average output power of 1.5 W and a conversion efficiency of 28%.

4 Power scaling of the generated 1064-nm laser pulses

The output power of the system described so far is limited by the damage threshold of the intracavity optical elements, like the laser crystal and, in particular, the Pockels cell. A possible solution to overcome this limitation and to generate higher pulse energies is to further amplify the laser pulses in a linear amplifier.

For this purpose, a single-pass amplifier was positioned behind the $Nd:YVO_4$ regenerative amplifier. The amplifier consisted of a $4 \times 4 \times 12$ mm^3 $Nd:YVO_4$ crystal (with a doping concentration of 0.3 at. %) end pumped from both sides by fiber-coupled diode lasers. The pump power of up to 50 W was focussed into the crystal to a spot size of 800 μm. Using a lens with a focal length of 1 m, the output of the regenerative amplifier was focussed into the laser crystal to match the spot size of the laser diodes. The input power could be varied by using a combination of a half-wave plate and a thin-film polarizer.

At a repetition rate of 20 kHz and an input power of 10.4 W, the power of the amplified pulses was as high as 20.3 W. This average power corresponds to a pulse energy of approximately 1 mJ. Figure 11 shows the output power of the amplifier in dependence on the power of the input pulses provided by the regenerative amplifier.

5 Conclusion

This paper reports the generation of high-energy picosecond laser pulses for micro-machining applications in the infrared, the visible and the UV. The system consists of a mode-locked seed oscillator and a $Nd:YVO_4$ regenerative amplifier, both pumped by high-power fiber-coupled diode lasers.

The oscillator is a passively mode-locked diode-pumped $Nd:YVO_4$ laser, operated at a repetition rate of 82 MHz, and provides 6.6-ps-long pulses with an energy of 50 nJ. In a $Nd:YVO_4$ crystal pumped with a total power of 2×21 W, the pulses were regeneratively amplified by a factor of 10^4 to a pulse energy of 0.54 mJ at a repetition rate of 20 kHz. The repetition rate was limited by the electro-optical modulators and the high-voltage drivers available at the time of the experiment. The pulse duration of the amplified pulses, measured by intensity autocorrelation, is approximately 10.2 ps. Pulse duration and energy correspond to a peak power of about 52 MW. The spatial quality of the output beam was close to the diffraction limit, with a value of M^2 below 1.2.

First applications of the system for drilling and surface structuring of metal confirmed the potential of high-energy picosecond laser pulses for this purpose. The quality of the produced structures is fully equivalent to that obtained with pulses from conventional femtosecond laser systems. However, the higher repetition rate of the picosecond laser system at concurrently high pulse energies allows faster processing of the workpieces, which is an important advantage in respect of commercial applications.

For applications requiring high-energy pulses at wavelengths shorter than 1 μm, the infrared output pulses of the regenerative amplifier were frequency converted into the visible

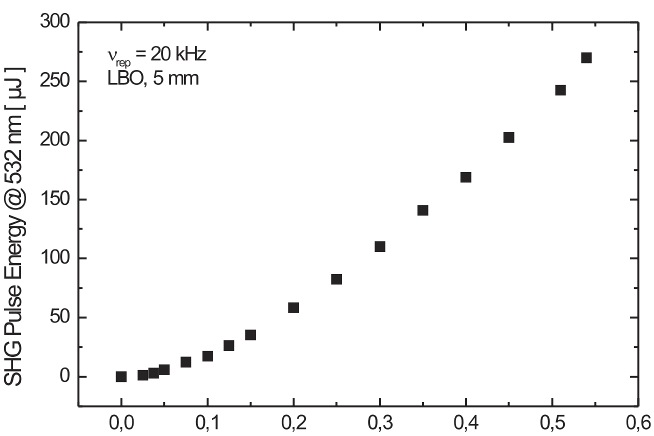

FIGURE 10 Pulse energy of the second-harmonic 532-nm radiation in dependence on the energy of the 1064-nm laser pulses. At a repetition rate of 20 kHz, the generated maximum pulse energy was 270 μJ

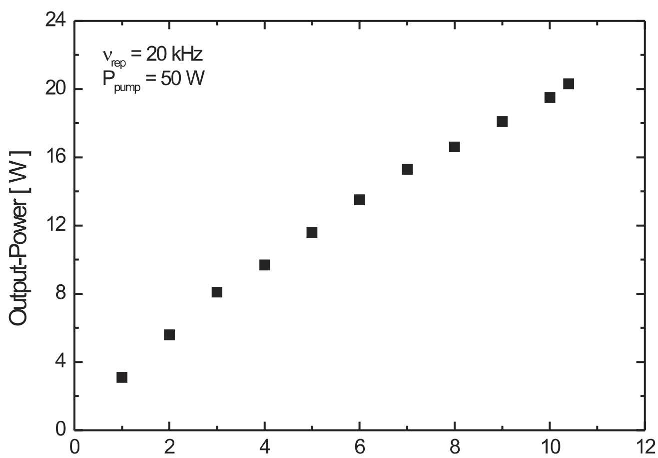

FIGURE 11 Average output power of the single-pass amplifier in dependence on the input power provided by the regenerative amplifier. At a repetition rate of 20 kHz, a maximum output power of 20.3 W was obtained, which corresponds to a pulse energy of about 1 mJ

and into the UV. The second harmonic at 532 nm was generated by frequency doubling of the 1064-nm pulses in an LBO crystal with a length of 5 mm, critically phase matched at room temperature. At 532 nm, a maximum pulse energy of 270 μJ was obtained at a repetition rate of 20 kHz. This output corresponds to a conversion efficiency of 50%.

The fourth harmonic at 266 nm was generated in a 3-mm-long BBO crystal with a conversion efficiency of about 28%. The maximum pulse energy obtained in the UV was 75 μJ.

Power scaling was demonstrated by amplifying the 1064-nm infrared pulses in a single-pass amplifier. With a total pump power of 2×25 W, the input pulses were amplified to an average output power of 20.3 W, which corresponds to a pulse energy of about 1 mJ at a repetition rate of 20 kHz.

These results clearly indicate that, by adding single-pass amplifier stages, ultra-short picosecond laser pulses with even higher pulse energies could be generated.

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