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Rapid communication

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Compact high-energy picosecond laser for micromachining applications

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ABSTRACT Picosecond pulse generation by active mode locking and subsequent regenerative amplification in a Nd : vanadate laser crystal has been realized in one and the same cavity using the all-in-one laser concept. An active prelasing stabilization loop has been implemented acting on the mode locker, allowing stable operation up to repetition rates as high as 3 kHz. Sub-30-ps pulses with an energy of 800 μJ have been achieved, constituting the highest peak power and the highest average output power ever demonstrated by means of the all-in-one approach. The combination of compact design, high peak and average power along with a near-diffraction-limited beam profile makes this source a promising tool for precision micromachining applications.

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1 Introduction

Recently, there has been considerable interest in laser sources suitable for high precision micromachining applications in metals [1], e.g. for surface structuring of tribologic strained surfaces [2] or for drilling microholes in injection nozzles used in car engines. Simulations show that for optimizing the combustion process (which is crucial for reducing the overall gasoline consumption) it would be advantageous to build nozzles with hole diameters well below 100 μm, preferably with a well-defined conical shape. However, the current standard method for this task, electrical discharge machining (EDM), cannot meet these demands. Therefore laser micromachining seems to be the method of choice. Conventional laser sources, operating in continuous-wave (cw) or Q-switched mode, act as a pure thermal heat source, resulting in melting and vaporization of the machined material. This leads to many unwanted side effects, like the generation of crater-like structures around the diameter of the hole, limiting the precision of the machining process. If ultrashort laser pulses are used, however, material is removed from the illuminated volume before heat could penetrate into the surrounding regions, resulting in precisely controlled machined structures. The time constants involved in the interaction of the laser pulse with conventional metals, like stainless steel, are in the order of several tens of picoseconds, implying that lasers with pulse durations in this range are ideally suited for 'cold' ablation [3]. Shorter pulses come not only at the expense of added complexity; they also give rise to plasma generation in air [4].

As the pulse energies needed for industrial machining applications are in the several-hundred-microjoule range, ultra-short pulses have to be amplified. The most widespread technique for producing such pulses is regenerative amplification. However, such systems consisting of a seed oscillator and a power amplifier are inherently complex and expensive, limiting their use to laboratory experiments.

Implementing these two functions in one and the same laser cavity holds promise for a simplified, more compact, robust and user-friendly system. In this 'all-in-one' approach a picosecond laser pulse is first generated by mode locking inside a cavity with a very low Q (high intracavity losses) and with a corresponding high saturated gain inside the laser crystal. This phase is commonly referred to as 'prelasing'. After a steady-state laser pulse has evolved, the losses are electronically switched to (almost) zero, resulting in strong amplification of the pulse. After the gain has been depleted (typically upon a few tens of round trips) and the pulse reaches its maximum energy, it is finally dumped out of the cavity. As the system accomplishes all functions of a seed-oscillator/regenerative-amplifier chain in a single laser cavity, the underlying concept has been dubbed the all-in-one principle.

Several different schemes have already been demonstrated for implementing the all-in-one concept. The standard setup contains an acousto-optic mode locker, an acousto-optic Q-switch for controlling the cavity losses and a Pockels cell for switching the pulses out of the cavity [5, 6] in addition to the basic components of a laser cavity. At the beginning of prelasing, however, strong relaxation oscillations tend to set in in solid-state lasers with a long (sub-millisecond) laser relaxation time, resulting in high losses and limiting the highest possible repetition rate to less than 1 kHz. The implementation of a feedback loop, acting on the Q-switch, greatly reduces the relax-

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ation oscillations and opens the way to higher repetition rates [7]. In a much more compact setup, however, the Pockels cell is not only used for switching the amplified pulses out of the cavity, but it is also acting as the Q-switch [8, 9]. This measure resulted in a much simpler and more compact setup. However, this improvement came at the expense of the feedback-control loop demonstrated by Dymott et al. [7], which could not be employed in this compact arrangement.

2 Setup

In this paper we report a compact, diode-pumped all-in-one laser, which is not only simple but is also able to control relaxation oscillations. Nd : YVO_4 has been chosen as a laser material because of its several favorable characteristics including a relatively large bandwidth and a short upper-state lifetime of $\tau_2 = 100\,\mu s$. A schematic of the laser is shown in Fig. 1.

Two cw-operated laser diode bars, each producing approximately 25 W of average power, are used for pumping the laser crystal. The pump light is delivered by fibers having a numerical aperture of 0.22 and a core diameter of 0.8 mm and focused down by standard spherical optics. An acousto-optic mode locker (IntraAction ML-404C1) is placed near one of the cavity end mirrors and driven at a frequency of 70 MHz with a power of 5 W of radio-frequency (RF) power. The mode locker driver frequency was matched to the effective resonator length of 937 mm, resulting in a round-trip frequency of 140 MHz. A low-voltage $LiNbO_3$ Pockels cell, acting as a Q-switch and a cavity dumper, is inserted in close proximity of the other end mirror. To avoid damage to the $LiNbO_3$ crystal the laser beam is expanded by a telescope in front of the crystal. A quarter-wave plate is used to bias the Pockels cell, so that cavity dumping can be realized by switching the high voltage down to zero. The Pockels cell combined with a polarizer acts as an output coupler with an electronically controllable transmission from virtually 0 to 100% by adjusting the applied voltage from the quarter-wave voltage (around 2 kV in our case) to 0 V. Simultaneously, the combination also acts as a Q-switch as well as a cavity dumper.

3 Operation

One of the most critical parameters for optimum operation of the all-in-one laser is the level of prelasing. After a single pulse has been dumped out of the cavity, the gain can be assumed to be fully depleted. Because of the cw pumping, the gain will start to increase again, but as the cavity losses are high now (for the prelasing phase), there will be no laser action. By introducing high enough losses to suppress laser oscillation into the cavity, the inversion inside the laser crystal, assuming an ideal four-level system, will build up exponentially to a maximum value of

$$N_{2,0} = N W_P \tau_2 \,, \tag{1}$$

where N is the total number of active atoms and W_P is the pump rate, resulting in a maximum single-pass gain of

$$g_0 = N_{2,0} \sigma L \,, \tag{2}$$

where L is the length of the laser crystal and σ its emission cross section.

Because of spontaneous emission, however, an increasing amount of the pump energy cannot be stored inside the crystal any more, which results in an energy loss E_L proportional to the difference of the two graphs depicted in Fig. 2 [10]. If the cavity losses are lower than g_0, however, the laser will start to oscillate once the inversion reaches the corresponding value. A low prelasing level results in a low gain available in the amplification phase and a reduced maximum energy of the output pulses. A high prelasing level, on the other hand, results in higher losses caused by the spontaneous emission and in a longer time needed for the laser to start oscillation. We found that as a rule of thumb the prelasing level has to be optimally set to a value allowing the laser action to start after a time equal to the upper lifetime of the laser crystal. In the case of Nd : YVO_4 this is $100\,\mu s$. A good trade-off between high single-pass gain and low gain buildup time was achieved at a single-pass gain equal to 63% of its maximum possible value. Figure 2 illustrates this relationship. As expected, however, without any prelasing compensation the relaxation oscillations do not permit stable operation of the laser in the relevant frequency range above 1 kHz, as it takes a time of almost 1 ms until a stable pulse train is generated. At the moment when the first relaxation oscillations occur, however, there is no short pulse circulating in the cavity, as it takes around $200\,\mu s$ for the acousto-optic mode locker to shorten the pulse [11]. During this time, the periodic loss modulation of this device introduces high losses into the cavity. Therefore, the applied RF frequency can be directly used to control the cavity losses and consequently to actively control the relaxation oscillations. Figure 3 schematically shows the corresponding control loop. The intracavity intensity is monitored by a photodiode, the rise time of which is set in such a way that the relaxation oscillations can easily be resolved (≈ 1 MHz),

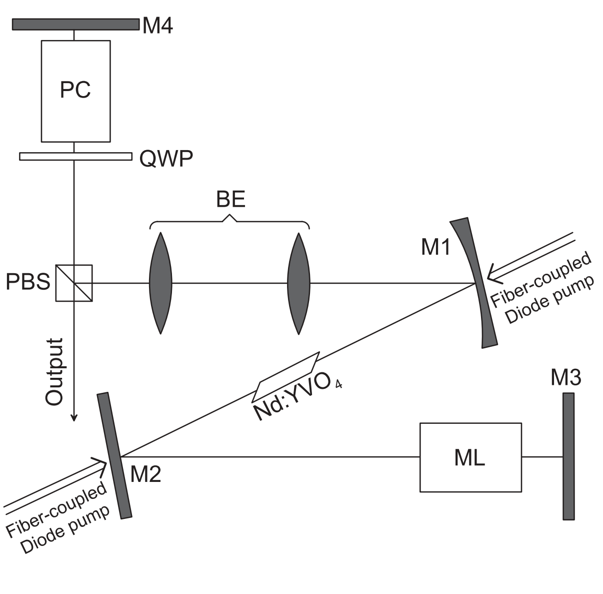

FIGURE 1 Schematic of the all-in-one laser: PC, Pockels cell; ML, acousto-optic mode locker; QWP, quarter-wave plate; PBS, polarizing beam splitter; BE, 2:1 beam expander; M1, $R = 800$ mm radius of curvature mirror; M2, M3, M4, flat mirrors

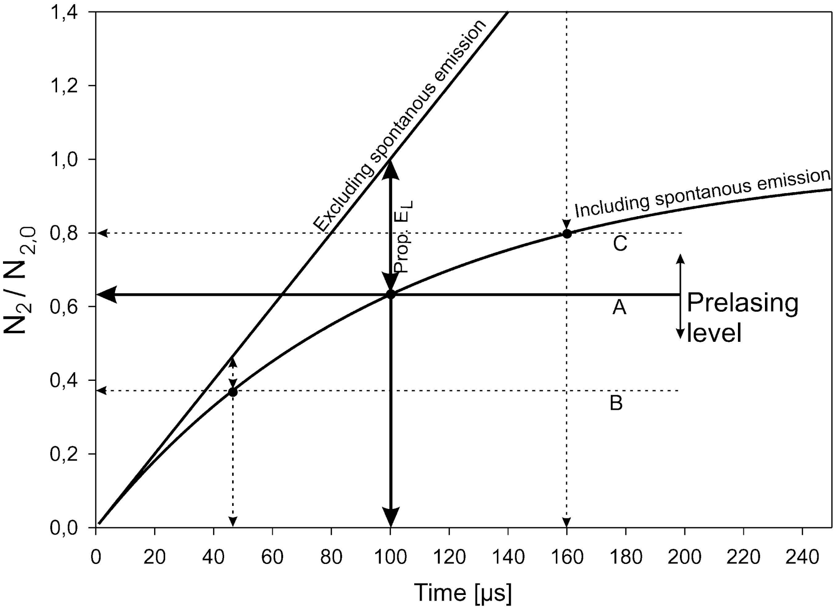

FIGURE 2 Population inversion inside the $Nd:YVO_4$ crystal vs. time. A properly adjusted prelasing level ensures that a reasonably high inversion can build up in a relatively short time with low losses due to spontaneous emission (curve A). If the prelasing level is too low, only a limited pulse energy can be achieved at the same pump power (curve B). A too high prelasing level results in excessive losses and a long buildup time, limiting the maximum repetition rate (curve C)

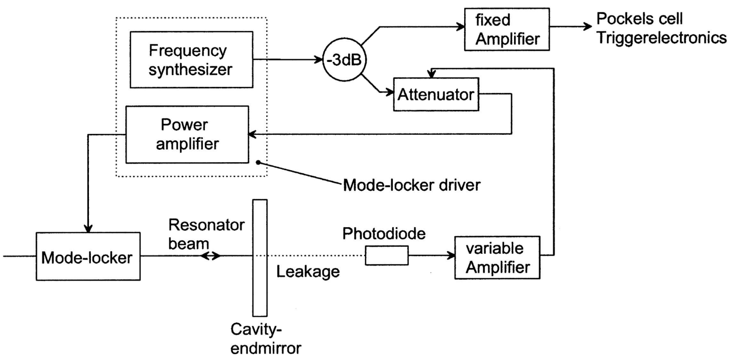

FIGURE 3 Schematic of the feedback loop for suppression of the relaxation oscillations. The RF-power level applied to the acousto-optic mode locker is modulated proportional to the intensity of the relaxation oscillations

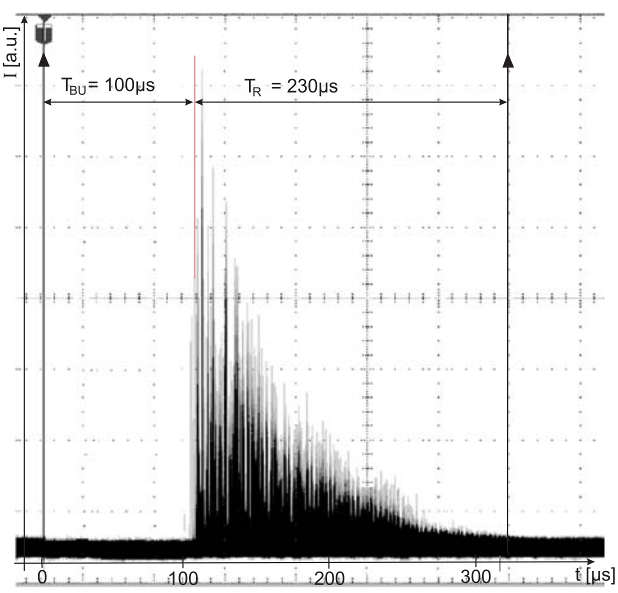

FIGURE 4 Output of the all-in-one laser. The output pulses at $t = 0$ and at $t = 330\,\mu s$ are many orders of magnitude larger than the relaxation oscillations and the prelasing

but the evolving pulses are averaged out (140 MHz). As the sensitivity of the diode is high enough, it is sufficient to use the leakage through a standard high-reflecting mirror as a monitor signal. If a single relaxation oscillation is emerging, the RF power applied to the mode locker is increased to its maximum, resulting in slightly higher intracavity losses than the average level. At the falling edge of the oscillation, the RF power is lowered, resulting in a loss modulation damping the relaxation oscillations.

With this method, we were able to achieve stable mode-locked, cavity-dumped operation up to repetition frequencies as high as 3 kHz (Fig. 4). An important detail of our electronics is that the RF signal is also sent to the trigger electronics of our Pockels cell. Because of the finite switching time of the high-voltage switches inside the Pockels cell, it is very important that the cavity dumping is initiated right after the pulse has left this device, making almost the full round-trip time (7 ns) available for completing the switching of the voltage down to zero. This phase information can be obtained from the mode-locker RF signal, as the pulse is always passing this device at the zero point of the applied voltage.

Another option for implementing a feedback loop would be to control the losses via the Pockels cell. As the relaxation oscillations have a frequency of around 1 MHz, however, the control variable has to be modulated in a MHz range. As it is easier to modulate the amplitude of the RF power, applied to the mode locker, at these high frequencies, we opted for this latter approach. The cut-off frequency of our control loop was measured to be 10 MHz, which turned out to be sufficient for achieving a very efficient damping of the relaxation oscillations. In Fig. 4, the timing of the subsequent operation modes of the laser is outlined. After the last pulse has been dumped out, there is a buildup time of $T_{BU} = 100\,\mu s$, until the first relaxation oscillation is observed. Due to the control loop, after around $230\,\mu s$ a stable prelasing level is reached and the Pockels cell can be switched to the quarter-wave voltage, tantamount to an output coupling of 0% or zero losses in the cavity. 250 ns later, the pulse, circulating inside the closed cavity, has reached its maximum energy and is dumped out of the cavity.

4 Results

The undesirable laser output, leaking out of the cavity during the prelasing action, can be simply quantified by omitting to dump the main pulse out of the cavity. The average power of this leakage is found to be approximately 0.4 W. Although the intensity of this quasi-cw radiation is several orders of magnitude lower than that of the actual output pulse, this could lead, depending on the specific application and the material to be processed, to heating of the sample and, thus, to unwanted side effects. One approach to overcome this limitation is to frequency double the output of the all-in-one laser. As the conversion efficiency is proportional to the fundamental intensity, the disturbing background can easily be removed by that means, if necessary. We will address this issue below.

The energy of the output pulses at a wavelength of 1064 nm is 800 μJ, when the laser is operated at a repetition rate of 3 kHz. The average output power is 2.8 W, some 14% of which is delivered in MHz-rate nanojoule-energy pulses. The pulse duration has been determined with a standard non-collinear autocorrelator. Assuming a Gaussian intensity envelope, which is typical for actively mode-locked lasers [11], a pulse duration of 29 ps (full width at intensity half-maximum) has been deduced from the measured autocorrelation trace. These parameters yield a peak power in excess of 27 MW. An M^2 measurement has revealed values of $M^2 = 1.1$ in the horizontal direction and $M^2 = 1.05$ in the vertical direction. The high-peak-power pulses delivered in a near-diffraction-limited beam make this source ideal for micromachining applications.

We have also frequency doubled the laser output by focusing it down with a $f = 100$ mm lens onto a 10-mm-long LBO crystal. Conversion efficiencies up to 60% could be achieved, resulting in 532-nm picosecond pulses with energies as high as 0.5 mJ at 3 kHz. As the prelasing background is of very low intensity, only the main pulses are frequency doubled, resulting in a clean 3-kHz high-energy pulse train free from a low-energy background at 532 nm. In the absence of an autocorrelator for these frequency-doubled laser pulses, we estimated the pulse duration as significantly less than 30 ps, because the phase-matching bandwidth of the crystal is orders of magnitude larger than the Fourier-limited spectral width of the infrared laser pulses. Theoretically, the frequency-doubled pulses are expected to be shorter by a factor of $\sqrt{2}$ than the pulses at the near-infrared fundamental frequency.

5 Conclusions

We have demonstrated a compact mode-locked, cavity-dumped all-solid-state laser capable of producing sub-30-ps pulses at a 3-kHz repetition rate with energies of 800 μJ in the infrared (1064 nm) and 500 μJ in the green (532 nm) spectral regions. This is, to our knowledge, the highest peak power and the highest average power ever achieved with the all-in-one approach. As no separate Q-switch is necessary in our setup, the laser is compact, reliable and user-friendly. We have shown that careful adjustment of the prelasing level and the implementation of a feedback loop for active control of the relaxation oscillations are crucial for efficient operation at high repetition rates. The demonstrated source constitutes a cost-effective, robust tool for a wide range of precision micromachining applications.

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