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2 MHz repetition rate, 200 ps pulse duration from a monolithic, passively Q-switched microchip laser

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Abstract We present a monolithic passively Q-switched microchip laser generating 200 ps pulses at a wavelength of 1064 nm with a repetition rate of up to 2 MHz. While maintaining transversal and longitudinal single-mode operation, the pulse energy can be changed from 130 nJ to 400 nJ by varying the pump conditions of the laser. To the best of our knowledge, the repetition rate of 2 MHz is by far the highest ever reported from such lasers operating in the sub-ns regime.

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1 Introduction

The application area for short-pulse laser sources in the near infrared region is comprehensive and covers a wide range in scientific and commercial fields [1]. These applications include frequency conversion [2], micromachining, microsurgery, lidar and precision measurements [3, 4]. In many cases, there is a demand for simple, reliable and affordable laser sources delivering high peak power with single longitudinal- and transverse-mode operation. Diode-pumped passively Q-switched microchip lasers based on different laser crystals and semiconductor saturable absorber mirrors (SESAMs) have been demonstrated in the past to be a promising concept for the generation of short and ultra-short pulses. Nanosecond to sub-100 ps pulses with repetition rates from several tens kHz to few MHz were demonstrated [5, 6]. However, the etalon effects of the air gap between the resonator components inhibit a stable and reliable operation of the microchip laser. To avoid this, monolithic passively Q-switched microchip lasers with resonator components bonded by spin-on-glass glue were recently reported, achieving 1 μJ, 50 ps pulses and repetition rates of 166 kHz [7]. Nonetheless, high peak powers and pulse energies can be easily achieved by additional amplification, while the pulse width and repetition rate only depend on the seed source. Hence, a passively Q-switched microchip laser with picosecond pulses and a repetition rate in the Megahertz regime is a very interesting seed source since it delivers much higher pulse energies at useful repetition rates compared to mode-locked picosecond lasers.

In this paper, we report on a diode-pumped passively Q-switched microchip laser based on Nd:YVO_4 as the gain medium and a SESAM as the passive Q-switch, monolithically bonded with spin-on-glass (SOG) as the adhesive. By varying the pump intensity in the laser crystal, we can change the repetition rate in the range from 100 kHz to 2 MHz and achieve pulse energies from 400 nJ to 130 nJ, while still maintaining singe transversal- and longitudinal-mode operation.

2 Experimental setup and results

The passively Q-switched monolithic microchip laser discussed in this contribution (Fig. 1) consists of a 250 μm long a-cut YVO_4 crystal doped with 3% neodymium-ions and a semiconductor saturable absorber mirror (SESAM).

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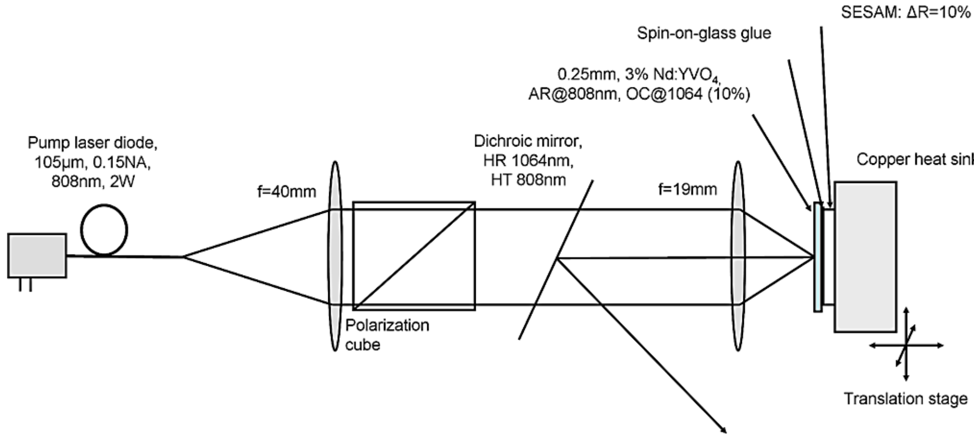

Fig. 1 The layout of the experimental setup of the monolithic passive Q-switched microchip laser. The polarization cube polarizes pump light parallel to the c-axis of the $Nd:YVO_4$ in order to reduce the thermal load on the SESAM due to the absorption of the residual pump light

The front surface of the $Nd:YVO_4$ crystal contained a dielectric coating of 10% output coupler at 1064 nm and being high transparent for the pump wavelength. The bonded laser crystal side was uncoated. The monolithic approach is accomplished by applying a spin-on-glass glue [7], typically used for planarization in the wafer technology, between the microchip components. During the annealing process a special tool was used to maintain a constant pressure on the assembly in order to keep the glue layer homogeneous and avoid mechanically induced stress. The utilized SESAM is grown by molecular beam epitaxy on an n-GaAs substrate with InGaAs–GaAs quantum wells with a nominal modulation depth of $\Delta R = 10\%$ at a wavelength of 1064 nm and a saturation fluence of approximately 500 µJ/cm^2. For heat dissipation, the microchip assembly was glued to a copper heat sink with a thermally conductive adhesive and mounted on a precision translation stage for further characterization. This approach allowed receiving a reliable cartography of the entire microchip laser, exact re-localization of any spots and fine positioning in the pump focus. As a pump source, a fiber-coupled, wavelength stabilized laser diode was used with central wavelength of 808 nm, an FWHM bandwidth of 3 nm and 2 watts of output power in a 105/125 µm DC fiber with an NA of 0.15. Since the absorption cross section at 808 nm in a $Nd:YVO_4$ differs for π- and σ-polarization, the pump light was additionally linear polarized in order to achieve shortest absorption length. At 3% Nd-doping concentration the absorption coefficient for pump light polarized parallel to the crystal c-axis is around 75 cm^{-1} and more than twice as large as for the perpendicular one. Using the polarization cube we obtain polarized pump light parallel to the c-axis of the crystal. This reduces the thermal load on the SESAM and the glue layer due to the absorption of residual pump light compared to the case using unpolarized pump light. Using a collimating lens with focal length of $f = 40$ mm and an aspherical focusing lens of $f = 19$ mm, the pump light was delivered from the fiber with $\mathrm{NA} = 0.15$ into the microchip laser. By an M^2 of 30 of the delivery fiber, the focused pump light is assumed to be top-hat in the near-field. The laser light was separated from the pump light by a dichroic mirror. A near-field imaging apparatus was used to localize precisely the pump spot in the crystal.

According to the well established and experimentally confirmed formalisms of passive Q-switched microchip laser [6] the pulse energy can be estimated as follows:

$$E_p \approx F_{\mathrm{sat},L} \cdot A \cdot \Delta R \cdot \frac{T}{T+L}, \tag{1}$$

where $F_{\mathrm{sat},L}$ is the saturation fluence of the laser material, A is the pump spot area in the resonator, ΔR denotes the modulation contrast of the SESAM, T equals to the out coupler transmission and L summarizes the intrinsic losses. The repetition rate is calculated dividing the average output power by the pulse energy. The average output power itself is proportional to the pump power; therefore the repetition rate shows linear behavior by changing the pump power at constant spot area:

$$f_{\mathrm{rep}} = \frac{P_{\mathrm{av}}}{E_p} = \frac{\eta_s \cdot (P_p - P_{p,\mathrm{th}})}{E_p}, \tag{2}$$

η_s denotes the slope efficiency, P_p the pump power and the $P_{p,\mathrm{th}}$ the pump threshold of the laser. The pulse duration in passive Q-switched lasers can be estimated as:

$$t_p \approx \frac{3.52 \cdot T_R}{\Delta R}, \tag{3}$$

where T_R is the resonator round trip time.

In our experimental work, we made two approaches for the characterization of the microchip laser. First the repetition rate, output power and beam quality were measured simultaneously for different pump powers with a fixed pump spot size (Figs. 2, 3, 4, and 5, solid line). The repetition rate changed almost linearly from 330 kHz to 2 MHz by varying the pump power from 0.2 to 0.8 watts, while the pulse energy stayed mostly constant at ~130 nJ, the beam quality has been characterized to M_X^2, $M_Y^2 < 1.3$ (by the

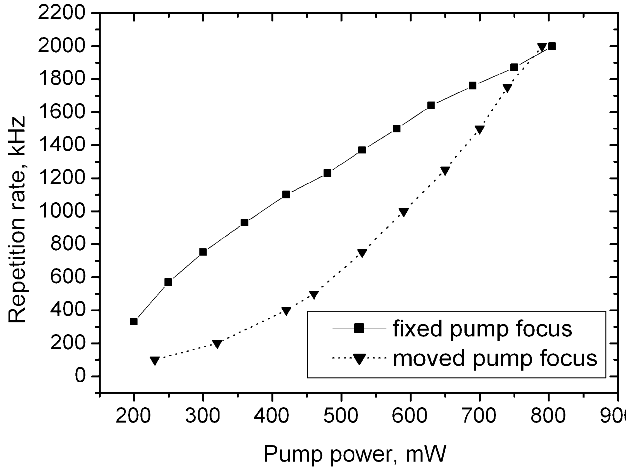

Fig. 2 Repetition rate of the passively Q-switched microchip as a function of the pump power: The *solid line* (fixed pump focus) shows almost linear trend, while the *dashed line* (moved pump focus) has a non-linear trend due additional change of the pump spot area

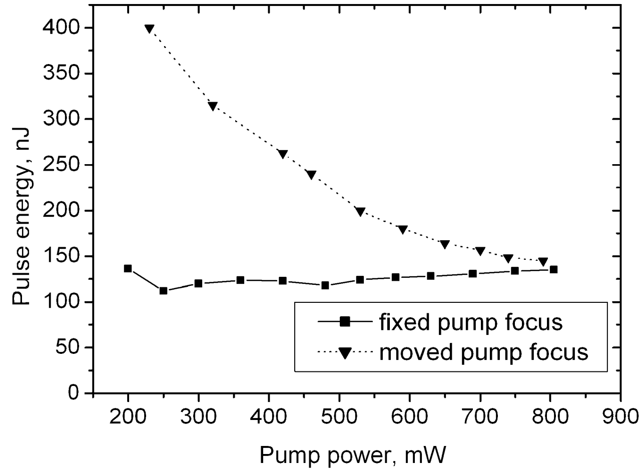

Fig. 4 Pulse energy as a function of pump power. In order to avoid transverse-mode instabilities, the pump spot area for higher pump powers (*dashed line*) needed to be reduced and lead to convergence of the pulse energy to the one of fixed pump spot

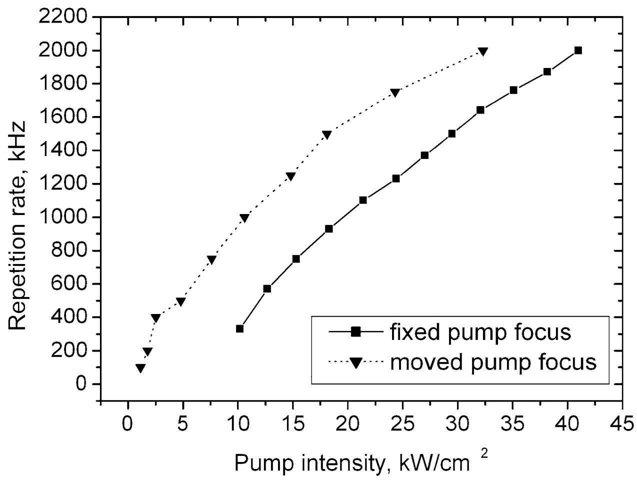

Fig. 3 Repetition rate as a function of pump intensity: the graphs show a similar trend. The *dashed line* (moved pump focus) reaches a defined repetition rate already at lower pump intensity. This decreases the thermal lens effect and provides higher pulse energies

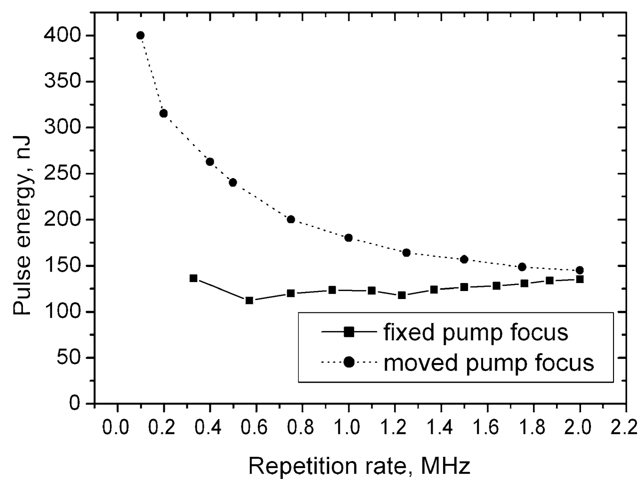

Fig. 5 Pulse energy versus repetition rate. The *solid line* shows a small change of pulse energy due to the changes in the modulation depth over the repetition rate, although the theoretically predicted pulse energy should be constant

SPIRICON $M^2 - 200$ using 4σ method). Secondly, we varied the pump power and the pump spot size in terms of maximizing the output power for a desired repetition rate while ensuring single transverse-mode operation. We obtained an even wider bandwidth of 100 kHz to 2 MHz of the repetition rate with pulse energies of 400 nJ for lower and reciprocally converging to 145 nJ for higher values (Figs. 2, 3, 4, and 5, dashed line). A further decrease of the pump spot size in order to achieve lower repetition rates was limited by the transverse-mode instabilities and very high timing jitter. The pump power was varied from 0.23 to 0.79 watts, and the beam quality maintained to be M_X^2, $M_Y^2 < 1.25$ (by the SPIRICON $M^2 - 200$ using 4σ method). Using a 25 GHz digital sampling oscilloscope and a fast photodiode with 12 ps of rise time, the pulse width was measured to be 200–222 ps for higher and lower pump powers, respectively (Fig. 6). The timing jitter, which is statistically caused by the evolution of the pulse due to onset of the spontaneous emission in the laser cavity, was shorter than 40 ns for low and 2.5 ns for high repetition rates resulting in a relative timing jitter smaller than 1% (Fig. 7). The slight change of the pulse duration might be attributed to the fact that the saturable absorber is not completely bleached for lower output power levels. Further, the difference between the measured pulse width and the theoretically predictable pulse width of 130 ps (3) is attributed to the change of the nominal modulation depth ΔR of the SESAM. This change of ΔR can be explained by influenced coupling into the SESAM due to mis-

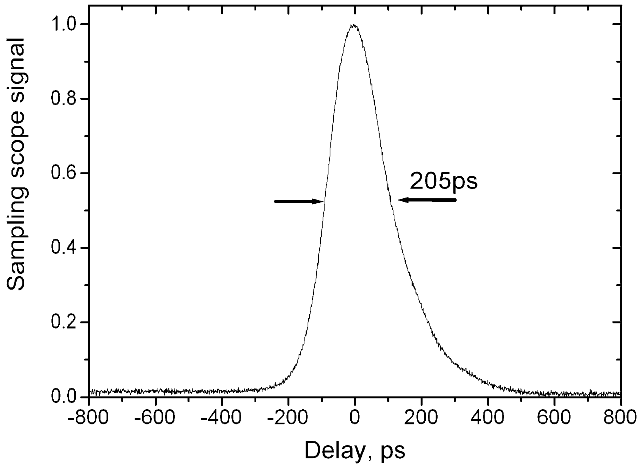

Fig. 6 Trace of the 205 ps pulse with 134 nJ pulse energy and a repetition rate of 500 kHz, measured with a 25 GHz sampling oscilloscope

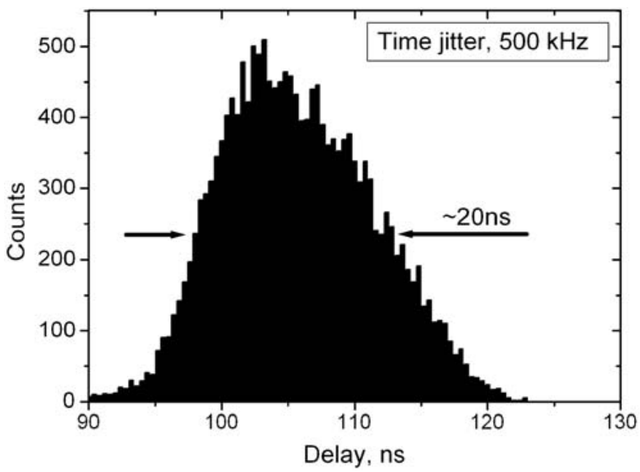

Fig. 7 Histogram of the timing jitter of the pulse and was taken using the 25 GHz sampling oscilloscope. The total counts number was over 20,000

match in the index of refraction between the SESAM and the spin-on-glass glue. From the obtained pulse width, the effective modulation contrast can be computed using (3) and is $\Delta R_{\mathrm{eff}} = 6.3\%$ and $\Delta R_{\mathrm{eff}} = 5.76\%$ for high and low repetition rate correspondingly in our case. To verify the change in the modulation contrast between low and high pump powers, we set the experimentally obtained pulse energies measured at a constant pump spot into relation to each other using (1) and obtain a change of approximately 10%. This correlates to the relative change in the modulation depth from 5.76% to 6.3% calculated with (3) and verifies the accuracy of the interpretation.

Despite the fact that the pump power is increased slightly to operate at 100 kHz, we also received much higher pulse energies for increased spot size of the pump area than for fixed one. This effect can be explained by thermal lensing in the microchip laser. The enlargement of the pump volume decreases the refraction power of the thermal lens. The laser mode area becomes bigger and can deplete more of the stored energy inside the laser crystal. In the second approach we operated the microchip cavity at its stability limit for single transverse mode. Whenever the pump power was increased the pump spot needed to be adapted to this particular value so that for high repetition rates the pulse energy converged to the one of fixed pump focus.

3 Conclusion

We have demonstrated a passively Q-switched microchip laser operating in a single longitudinal and transverse mode. We were able to continuously tune the repetition rate with more than one order of magnitude and achieved stable and reliable pulses with 2 MHz, 140 nJ and 200 ps. To the best of our knowledge these are by far the highest repetition rate and widest range of 100 kHz to 2 MHz obtained from a single monolithic passively Q-switched microchip laser. Further fiber based amplification of this laser source will find many applications, e.g. micromachining like micromilling and microdrilling [8, 9].

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