High-pulse-energy passively Q-switched quasi-monolithic microchip lasers operating in the sub-100-ps pulse regime

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Received April 24, 2007; revised June 13, 2007; accepted June 13, 2007;
posted June 18, 2007 (Doc. ID 82396); published July 20, 2007

We present passively Q-switched microchip lasers with items bonded by spin-on-glass glue. Passive Q-switching is obtained by a semiconductor saturable absorber mirror. The laser medium is a $Nd:YVO_4$ crystal. These lasers generate pulse peak powers up to 20 kW at a pulse duration as short as 50 ps and pulse repetition rates of 166 kHz. At 1064 nm, a linear polarized transversal and longitudinal single-mode beam is emitted. To the best of our knowledge, these are the shortest pulses in the 1 μJ energy range ever obtained with passively Q-switched microchip lasers. The quasi-monolithic setup ensures stable and reliable performance. © 2007 Optical Society of America

OCIS codes: 140.3070, 140.3380, 140.3480, 140.3530, 140.3540, 140.3570.

Passively Q-switched microchip lasers have found various applications in the industrial and scientific market, since they are reliable, simple, and nearly maintenance free owing to their monolithic concept. Many applications, such as lidar, range finding, and micromachining, require robust and simple lasers delivering high peak powers in a simple setup [1,2]. The most common combination of laser material and passive Q-switch for monolithic passively Q-switched microchip laser concepts has been Nd:YAG and Cr:YAG, respectively. However, with this concept it is not possible to reach pulse durations below 200 ps, since the passive Q-switch works in transmission and requires a certain length to ensure sufficient modulation contrast. On the other hand, the minimum pulse duration is proportional to the resonator length of the laser [3]. In previous work, very short pulse durations well below 60 ps have been obtained with a combination of $Nd:YVO_4$ as the laser material and a semiconductor saturable absorber mirror (SESAM) as the Q-switch element [4]. Since the SESAM acts as a mirror and, unlike Cr:YAG, not as a bulk absorber with a limited minimum absorption length, the SESAM does not significantly contribute to the resonator length. In this case, the minimum resonator length is limited only by the pump absorption length of the laser material. The use of SESAMs as a passive Q-switch also provides access to wavelengths between 1030 and 1540 nm for microchip lasers [5–7]. The saturable absorption wavelength of the SESAM can be easily tailored by adapting the bandgap of the SESAM's absorber layer to the desired wavelength. In the above-mentioned lasers, a resonator is formed by pressing a thin slice of a laser material between an outcoupling mirror and a SESAM with air gaps remaining between the components. The air gap depends on the mechanical pressure on the components. The gap heavily influences the Q-switching performance by etalon effects in the resonator [8]. Hence, reproducible and long-term stable laser performance was difficult to obtain, and this promising concept of ultrashort pulse microchip lasers fell into oblivion.

In this Letter, we present a new optical bonding approach to overcome the problem of the above-mentioned air gap. We use a spin-on-glass glue to bond the components. Spin-on-glass glues are commonly used to interconnect and overcoat passivation of integrated circuits. They have a high dielectric strength of more than 5 MV/cm and hence can withstand strong electric fields [9]. As optically transparent spin-on-glass glue is available, it is an attractive approach to use it for optical bonding of laser components. For our microchip laser, we decided to use $Nd:YVO_4$ as the laser material because of its very short absorption length and its uniquely low saturation fluence. This allows for a short crystal length and for a low pulse energy's being generated in the resonator during the Q-switch pulse evolution, since the pulse energy is proportional to the saturation fluence of the laser material with [8]

$$E_P = F_{sat,L} A \Delta R \frac{T}{T+L}. \tag{1}$$

$F_{sat,L}$ denotes the saturation fluence of the laser material, A is the mode area in the resonator, T equals the transmission of the resonator, L is the sum of intrinsic losses, and ΔR denotes the modulation contrast of the SESAM. The pulse duration can be estimated to be

$$t_p \geqslant 7nl/c\Delta R, \tag{2}$$

where n is the refractive index of the laser material and l is the resonator length [8]. One should note that this approximation is most precise if the transmission of the output coupler equals the modulation contrast of the SESAM at negligible intrinsic losses

0146-9592/07/152115-3/$15.00

[8]. The Nd:YVO_4 crystal used in our setup has a thickness of 200 μm, an area of 3 mm$\times$3 mm, and a Nd^{3+} doping concentration of 3%. At this doping concentration, Nd:YVO_4 allows a crystal thickness of less than 200 μm for sufficient pump light absorption. One side of the crystal is coated to be antireflective for the pump wavelength at 808 nm and partially transmitting at the laser wavelength with a transmission of 10% at 1064 nm. The glued side is uncoated. During the gluing process, a weight is used to press the items together, making the glue layer as thin as possible. When pressure is applied, visible Newton fringes disappear after a short time, indicating that the glue layer reaches a thickness of less than a few hundred nanometers. The glued chip is bonded with thermally conductive glue onto an aluminium cylinder as a heat sink. The resonator length of 200 μm at a given refractive index for Nd:YVO_4 of $n=1.9$ results in a longitudinal mode spacing of 1.49 nm. Given the spectral amplification bandwidth of Nd:YVO_4 of 0.8 nm at a 1064 nm center wavelength, the resonator is hence forced to oscillate in a single longitudinal mode. This effectively prevents mode-hopping effects and ensures a high peak-to-peak stability of the pulse train [8]. The SESAM is grown by molecular beam epitaxy on an n-GaAs substrate. The absorber region of the SESAM consists of InGaAs–GaAs quantum wells with a photoluminescence emission peaked at 1080 nm. The semiconductor mirror comprises 24 quarter-wavelength AlAs/GaAs layers, ensuring a reflectivity >99%. The nonlinear reflectivity of the SESAM has been characterized with picosecond laser pulses at 1060 nm. The saturation fluence of the SESAMs is $F_{\text{sat}} \sim 500\ \mu\text{J/cm}^2$; the recovery time of both SESAMs has been measured to be 320 ps. In this experiment, two SESAMs with different modulation contrasts have been used. The modulation contrast is $\Delta R \sim 20.5\%$ for SESAM-1 and $\Delta R \sim 11\%$ for SESAM-2. According to Eq. (2), one would expect a pulse duration of at least $t_p \geqslant 44$ ps for SESAM-1 and $t_p \geqslant 80$ ps for SESAM-2, since the output coupling is equal to or smaller than the modulation depth of the SESAM. The quasi-monolithic microchip formed by the SESAM and the coated crystal was pumped by a fiber coupled diode laser with pump power of 500 mW coming out of a 100 μm, 0.22 NA fiber. The employed focusing optic produces a spot size at the crystal of about 70 μm. The laser light was separated from the pump light by a dichroic mirror, as shown in Fig. 1. To measure the pulse shape, we used a digital sampling oscilloscope and a fast photodiode with a frequency resolution limit of 25 GHz. Since passively Q-switched lasers have an inherently high pulse-to-pulse jitter, we used a fiber optical delay line to provide a trigger signal arriving earlier at the oscilloscope than the laser pulse.

With SESAM-1, we obtained a pulse duration of 50 ps FWHM at a repetition rate of 40 kHz and a pulse energy of 1 μJ in a linear polarized transversal and longitudinal single-mode beam. The pulse peak power is 20 kW, and the peak-to-peak fluctuations of the pulses were below the resolution limit of the employed oscilloscope. The measured diode signal is shown in Fig. 2. The intracavity intensity exceeds 20 GW/cm^2. To the best of our knowledge, a peak power of 20 kW in a 50 ps pulse at a repetition rate of 40 kHz was never obtained before with monolithic microchip lasers. The laser was driven slightly below the damage threshold of the glue layer, but we found spots on the microchips where stable operation was observed for many hours. Since the microchip laser employing SESAM-2 was working a lot more reliably, we focused on this one for further measurements.

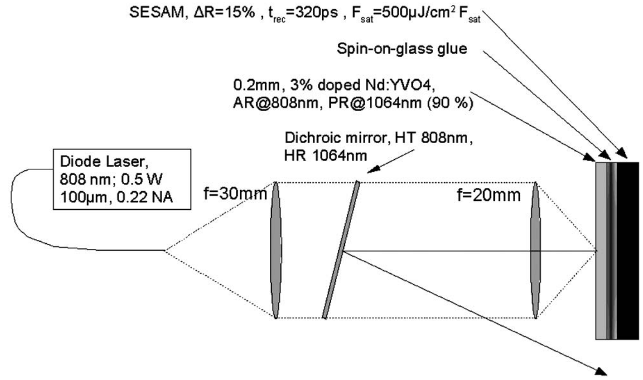

Fig. 1. Setup of the microchip laser.

With SESAM-2, we obtained a pulse duration of 110 ps FWHM at a peak power of 6 kW and a repetition rate of 166 kHz, corresponding to ~100 mW average output power, as illustrated in Fig. 3. We have observed no internal damage so far, even after many days of operation. The threshold of this laser was at 0.2 W of pump power, and the slope efficiency was about 14%. We did not observe any roll off in output power between 0.2 and 1 W of pump power. The beam quality was measured with a beam diagnostics system to be $M^2=1.5$. The maximum peak-to-peak amplitude fluctuation was ~6%. Assuming, e.g., a Poisson distribution of the fluctuations in the time domain, the average peak-to-peak amplitude fluctuation is ~3%. The jitter of the microchip laser employing SESAM-2 was measured in the time domain, since the neighbor pulses compared with the triggered pulse occurred in a time window with a certain width. To measure this width, we set the oscilloscope

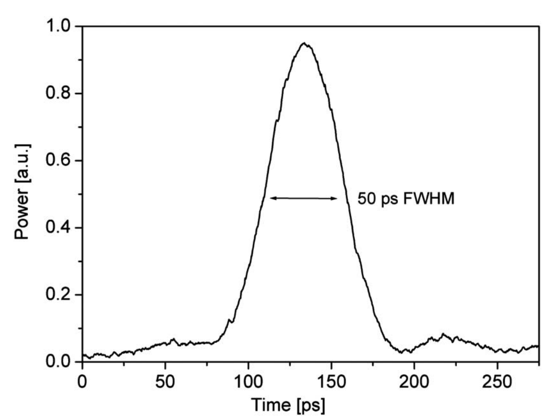

Fig. 2. Measured photodiode signal of the microchip laser employing SESAM-1.

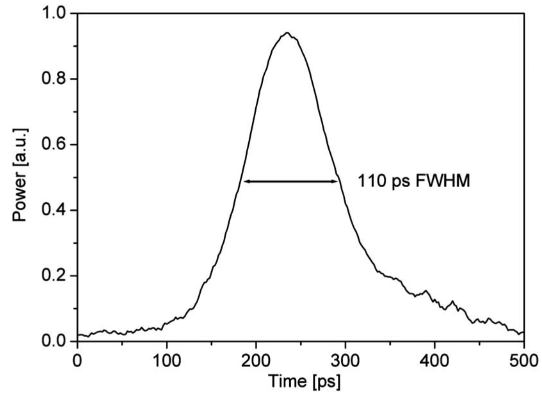

Fig. 3. Measured photodiode signal of the microchip laser employing SESAM-2.

to infinite line afterglow. The frozen pictures of the pulses finally formed a sharply defined time window. The dependence of the width of this time window on the repetition rate is shown in Fig. 4. It can be seen that the jitter is very high when the laser is driven only slightly above threshold. This can be explained by the need for one initial spontaneous emission to start pulse evolution. Since this is a statistical event, it becomes more and more likely if the pump rate is being increased. Because of this, the jitter diminishes steadily when the repetition rate is increasing. These considerations are particularly important for applications where triggering techniques are required. In this case, it is unavoidable to work with delay lines to generate a sufficient time interval between the trigger event and the pulse itself. As stated in Eqs. (1) and (2), the pulse energy and the pulse duration can be tailored to many different regimes by simply changing the modulation depth of the SESAM. Since the pulse energy is nearly independent of the pump power, the repetition rate can be easily adjusted by simply changing the pump power incident on the crystal [8].

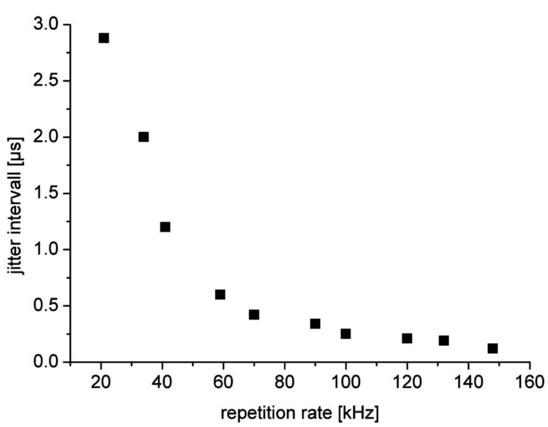

Fig. 4. Jitter width depending on the repetition rate.

In conclusion, we have developed a quasi-monolithic, ultrashort pulse microchip laser concept capable of generating 50 ps pulses at repetition rates of 40 kHz and peak powers of 20 kW. We have also generated 110 ps pulses with a repetition rate of 166 kHz and a peak power of 6 kW with a different SESAM. We have investigated the jitter properties of the microchip lasers and found the jitter width in the time domain to diminish steadily when the repetition rate is increased. The gluing technique withstands peak intensities of more than 20 GW/cm^2, making it an attractive technique for easy and inexpensive bonding of intracavity laser components. We are convinced that the gluing technique can be advanced to withstand even higher intensities. In future investigations we will focus on fiber amplification of quasi-monolithic, ultrashort pulse microchip lasers. This approach has the potential to compete with bulky and expensive regeneratively amplified mode-locked picosecond lasers. Since the laser oscillates on a single longitudinal mode, it can be used for many applications requiring high peak powers, short pulses, and high spectral brightness at the same time.

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