Passively Q-switched 180-ps Nd:LaSc$_3$(BO$_3$)$_4$ microchip laser

B. Braun, F. X. Kärtner, and U. Keller

Ultrafast Laser Physics, Institute of Quantum Electronics, Swiss Federal Institute of Technology, ETH Hönggerberg–HPT, CH-8093 Zürich, Switzerland

J.-P. Meyn* and G. Huber

Institute of Laser-Physics, University of Hamburg, Jungiusstrasse 9–11, D-20355 Hamburg, Germany

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We passively Q switched a Nd:LaSc$_3$(BO$_3$)$_4$ microchip laser with an antiresonant Fabry–Perot saturable absorber (A-FPSA) and achieved single-frequency, 180-ps pulses with 0.1 μJ of pulse energy at a repetition rate of 110 kHz. Because of the compactness and scaling possibilities offered by the A-FPSA, the pulse width can be varied from 180 ps to 30 ns and the repetition rate from 50 kHz to 7 MHz.

Q-switched microchip lasers are compact and simple solid-state lasers that can provide high peak powers with a diffraction-limited output beam. An extremely short cavity length, typically less than 1 mm, allows for single-frequency Q-switched operation with pulse widths well below 1 ns. Previously, pulse durations of 337 ps and more recently 218 ps were demonstrated with a passively Q-switched microchip laser consisting of a Nd:YAG crystal bonded to a thin piece of Cr^{4+}:YAG.[1,2] With a monolithic Cr^{4+}-codoped Nd:YAG laser, pulses of 290 ps have been obtained.[3] We used an antiresonant Fabry–Perot saturable absorber[4,5] (A-FPSA) to passively Q-switch a monolithic Nd:YAG ring laser, producing ≅100-ns pulses.[6] In this Letter we demonstrate an extension of this approach to microchip lasers that uses an A-FPSA and a Nd:LaSc$_3$(BO$_3$)$_4$ (Nd:LSB) laser crystal. We obtained pulses as short as 180 ps (Fig. 1), which are to our knowledge the shortest pulses reported from a passively Q-switched solid-state laser. With diode pumping we achieved similar performance with pulses as short as 200 ps. Depending on the A-FPSA design and the pump power, the pulse width can be varied from 180 ps to 30 ns.

Figure 2 shows the experimental setup. A 220-μm-thick Nd:LSB laser crystal[7–9] is sandwiched between a 10% output coupler and an A-FPSA. The top reflector of the A-FPSA is a high reflector for the pump wavelength, and a partial reflector for the 1.062-μm lasing wavelength varied from 80% to 90%. The Nd:LSB crystal is pumped by either a Ti:sapphire laser or a 2-W diode array (200 μm long) at 808 nm through a dichroic beam splitter that transmits the pump light and reflects the output beam at 1.062 μm. The Ti:sapphire pump radius was measured to be 40 μm, and the diode pump radii were 20 μm × 55 μm. A diode-pumped cw Nd:LSB microchip laser was demonstrated previously.[8]

To obtain short Q-switched pulses, one has to make the cavity as short as possible. A highly doped laser crystal with a short absorption length supports a short and efficient laser cavity. Nd:LSB permits stoichiometric doping with Nd^{3+} ions in contrast to standard Nd^{3+}-doped material such as Nd:YAG. However, the higher doping results in larger temperature gradients, which ultimately limit the laser efficiency.[10] We used a doping level of 25% (Nd atoms on La sites), which allowed us to pump with powers up to ≅1.5 W before we saw detrimental thermal effects.

The main material properties of Nd:LSB are summarized in Table 1, together with the material parameters of Nd:YAG for comparison.[8–10] The broad absorption bandwidth of 3.0 nm, centered around 808 nm, together with the short absorption length makes Nd:LSB attractive for diode pumping. The large gain bandwidth, however, is a disadvantage for achieving a single-frequency Q-switched microchip laser. Because of spatial hole burning several modes can reach threshold.[11] Therefore the crystal thickness has to be chosen sufficiently small to eliminate all neighboring modes within the gain bandwidth. The 220-μm-thick crystal used in our experiments shows single-frequency output up to an incident pump power of approximately 550 mW, i.e., approximately 5 times above threshold, whereas the 430-μm-thick crystal shows multimode output when pumped more than 1.5 times above threshold. The flat–flat resonator is stabilized by the thermal lens induced from the absorbed pump power.[8]

The parameters of the A-FPSA important for Q switching can be engineered. The band gap of the

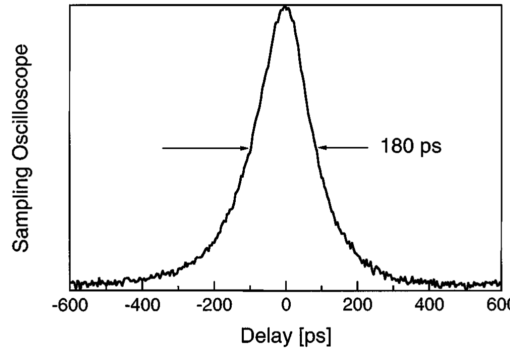

Fig. 1. Oscilloscope trace of the single-frequency 180-ps-long Q-switched pulse with a pulse energy of 0.1 μJ and a repetition rate of 110 kHz.

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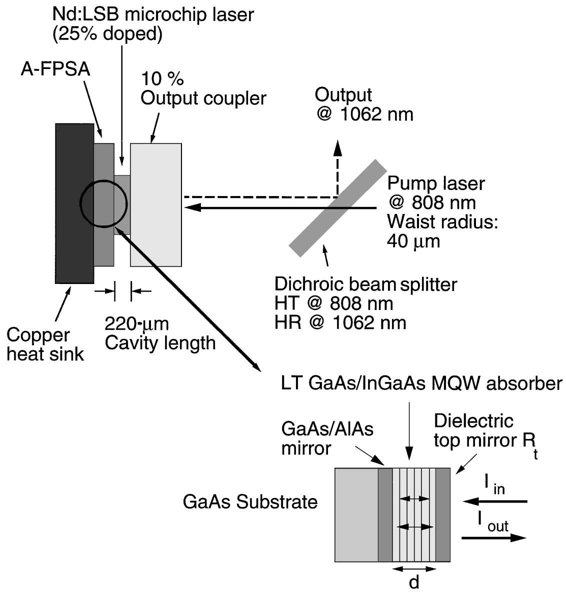

Fig. 2. Layout of the Q-switched Nd:LSB laser with an A-FPSA directly contacted to the crystal. LT, low-temperature; MQW, multiple quantum well.

semiconductor can be adapted to the laser wavelength. Therefore this technique can be extended to other laser crystals at different wavelengths, in contrast to Cr^{4+}:YAG as an absorber medium, which is limited to specific spectral regions. The important material parameters of the absorber are the cross section σ and the carrier recombination time τ_A. They determine the saturation fluence $E_{\mathrm{sat}} = h\nu/2\sigma$ and the saturation intensity I_{sat}, with $I_{\mathrm{sat}} = E_{\mathrm{sat}}/\tau_A$ of the material (the factor of 2 takes into account the standing wave in the linear cavity). The carrier recombination time can be adjusted from a subpicosecond to a nanosecond by the molecular-beam-epitaxy growth temperature. The thickness of the absorber and the reflectivity of the top reflector determine the amount of saturable loss, i.e., the nonlinear reflectivity change ΔR and the effective saturation fluence $E_{\mathrm{sat}}^{\mathrm{eff}}$ of the A-FPSA.[12] Therefore, even if the mode size A is fixed, as is the case in most monolithic lasers, there are enough free parameters to independently optimize the saturable losses ΔR and the effective saturation intensity $I_{\mathrm{sat}}^{\mathrm{eff}}$, with $I_{\mathrm{sat}}^{\mathrm{eff}} = E_{\mathrm{sat}}^{\mathrm{eff}}/\tau_A$. In addition, because the A-FPSA is used as an end mirror and has an effective penetration depth of less than 1 μm, we can add a saturable absorber to the microchip laser with only a negligible increase in the cavity length. This allows us to maintain a shorter cavity length and therefore a shorter Q-switched pulse width compared with those from other approaches, which require larger bulk modulation elements. The A-FPSA's used in our experiments consist of a low-temperature-grown InGaAs/GaAs multiple quantum well (growth temperature $T = 350\,^{\circ}\mathrm{C}$) placed between an AlAs/GaAs buried-bottom mirror and a dichroic top reflector. The carrier recombination time was measured to be $\tau_A = 24$ ps with a standard degenerate pump–probe technique at 1057 nm. Because of the antiresonance condition, the saturation fluence of 50 $\mu\mathrm{J/cm^2}$ for the antireflection-coated sample is increased by the top reflector.[12] For a top reflector R_t of 80%, 85%, and 90%, used in our experiments, effective saturation fluences of 0.61, 0.84, and 1.3 $\mathrm{mJ/cm^2}$ and saturable power losses ΔR of 3.1%, 2.3%, and 1.5%, respectively, are obtained. For the results discussed in this Letter we did not observe any damage to the A-FPSA.

With an 85% top reflector of the A-FPSA, a 10% output coupler, and an incident pump power of 300 mW, we obtained single-frequency TEM_{00} Q-switched pulses of 180 ps FWHM with a pulse energy of 0.1 μJ, a peak power of approximately 500 W, and an average output power of 11 mW at a repetition rate of 110 kHz (Fig. 1). The pulse-to-pulse timing jitter was $\approx$5% (i.e., $\approx$0.5 μs) of the pulse repetition period of $\approx$9 ms. To measure the 180-ps pulse duration, we used a 50-GHz sampling oscilloscope (Tektronix CSA 803) with a 40-GHz p-i–n photodetector. The time resolution is better than 20 ps, confirmed with a 200-fs pulse from a cw mode-locked Nd:glass laser. Because of the microsecond pulse-to-pulse timing jitter, the measured Q-switched pulse has to be triggered on itself to preserve the time resolution. This was done with a 10-m optical delay line for the signal.

The pulse width was varied from 180 ps to 30 ns and the repetition rate from 50 kHz to 7 MHz (Fig. 3), depending on the effective saturation fluence, the pump power, and the amount of saturable losses. The crystal thickness and the output coupler were fixed at 220 μm and 10%, respectively. As expected the pulse width and the repetition rate decrease with higher saturable losses, i.e., a lower top reflector. We expect shorter pulses with increasing pump power resulting from the larger modulation depth ΔR that is due to stronger absorption bleaching. Figure 3(a) shows this tendency for the 90% top reflector.

We achieved our highest Q-switched average output power of 230 mW for a pump power of 1 W with a 430-μm-thick Nd:LSB crystal, a 90% top reflector on

Table 1. Material Properties of Nd:LSB and Nd:YAG

Parameter	Nd:LSB	Nd:YAG
Doping D	$\leq$100%	1.1% (typically)
Absorption length	110 μm ($D = 25\%$)	1.2 mm
Absorption bandwidth	3.0 nm	0.8 nm
Gain bandwidth	4.0 nm	0.5 nm
Upper-state lifetime	87 μs ($D = 25\%$)	250 μs
Gain cross section	$1.3 \times 10^{-19}\ \mathrm{cm^2}$ ($D = 25\%$)	$3.3 \times 10^{-19}\ \mathrm{cm^2}$
Thermal conductivity (300 K)	0.028 W/(cm K) ($D = 10\%$)	0.13 W/(cm K)
$\mathrm{d}n/\mathrm{d}T$	$4.4 \times 10^{-6}\ \mathrm{K^{-1}}$ ($D = 10\%$)	$7.3 \times 10^{-6}\ \mathrm{K^{-1}}$

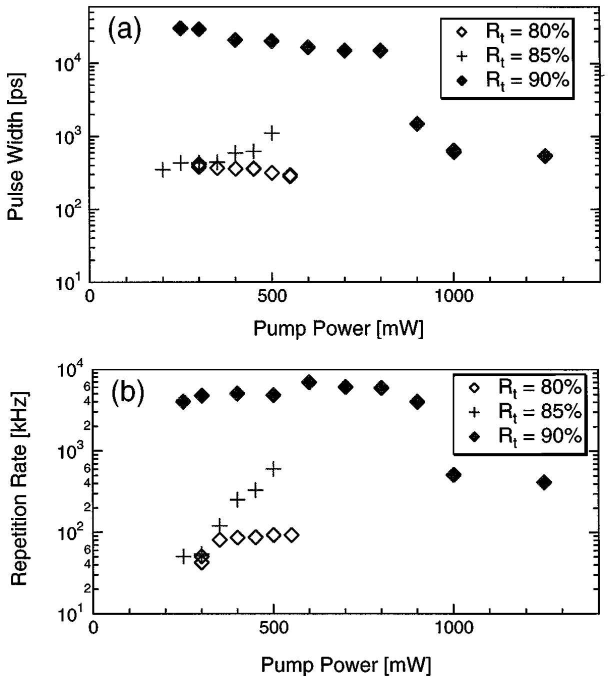

Fig. 3. (a) Pulse width and (b) repetition rate of the Q-switched Nd:LSB laser as a function of the pump power for different top reflectors on the A-FPSA.

the A-FPSA, and a 4% output coupler. The pulse width was 4 ns at a repetition rate of 1.4 MHz, with several longitudinal modes running because of the longer crystal. As soon as the laser starts lasing in several longitudinal modes the timing jitter significantly increases, from approximately 5% to 20%.

We achieved our highest peak power of 1.6 kW with an 80% top reflector on the A-FPSA, a 220-μm-thick crystal, and a 10% output coupler at an incident pump power of 450 mW. In this case the single-frequency pulse width was 360 ps at 86 kHz with an average output power of 51 mW, resulting in a 0.6-μJ pulse energy.

A threshold condition for Q switching can be derived from the rate equations for the laser transition and the absorber, assuming a fast saturable absorber, small changes in laser intensity, and small gain per round trip.[13,14] For $\chi \gg (r-1)$, we have[6]

$$\frac{T_L \Delta R}{\chi}\,\frac{(r-1)}{r} > 1\,, \tag{1}$$

where r is the pump parameter (i.e., how many times above threshold the laser is operated), $T_L = \tau_L/T_{\mathrm{R}} \approx 3.8 \times 10^7$ is the laser upper-state lifetime normalized to the round-trip time, and $\chi = I_{\mathrm{sat}}^{\mathrm{eff}}/I_L$ with I_L the saturation intensity of the gain medium. With $I_L = 8.3\ \mathrm{kW/cm^2}$ for Nd:LSB (Table 1), a value of $\chi \cong 5 \times 10^3 \gg 1$ results, depending on the top reflector of the A-FPSA used in our experiments. We obtain for the critical product $T_L \Delta R/\chi$ on the left-hand side of relation (1) values of 8×10^2, 4.5×10^2, and 1.9×10^2 for the 80%, 85%, and 90% top reflectors, respectively. Thus the threshold for Q switching is reached even for very small pump parameters r. We estimate that the rise and fall times of the Q-switched pulses are of the order of $T_R/\Delta R$, so that the achievable pulse width is of the order of $\tau_p = 2T_R/\Delta R = 160-320$ ps. This agrees well with the observed pulse durations and the general tendency for shorter pulses at a larger saturable loss [Fig. 3(a)]. The repetition rate of the Q-switched pulses depends on the strength of the gain depletion, i.e., the pulse energy, and on the small-signal gain, i.e., the pump parameter r. Therefore a larger saturable loss ΔR, obtained with a lower top reflector at a constant absorber thickness, leads to smaller repetition rates and higher pulse energies [Fig. 3(b)].

In conclusion, we have demonstrated single-frequency pulses as short as 180 ps from a passively Q-switched Nd:LSB laser. By varying the top reflector of the A-FPSA and the pump power, we have achieved pulse widths from 180 ps to 30 ns and repetition rates from 50 kHz to 7 MHz. Further optimization of the absorber parameters will lead to shorter pulses, lower repetition rates, and therefore higher peak powers. Peak powers above 1 kW from such a simple, potentially low-cost microchip laser would allow for a variety of interesting applications, such as in lidar systems, medicine, frequency conversion, and micromachining.

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*Present address, Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305.

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