56-ps passively Q-switched diode-pumped microchip laser

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We passively Q switched a diode-pumped Nd:YVO_4 microchip crystal with an antiresonant Fabry–Perot saturable absorber and achieved single-frequency pulses as short as 56 ps. We can vary the pulse width from 56 ps to 30 ns and the repetition rate from 27 kHz up to 7 MHz by changing the design parameters of the saturable absorber and the pump power.

Motivated by the compactness and simplicity of Q-switched microchip lasers, many research efforts are directed toward shorter pulses and higher pulse energies. Previously, passive Q switching with Cr^{4+}:YAG saturable absorbers has generated pulses as short as 218 ps,[1] and with a semiconductor antiresonant Fabry–Perot saturable absorber[2–4] (A-FPSA) pulses as short as 180 ps (Ref. 5) have been obtained. In addition, active Q switching with an electro-optic modulator resulted in pulses as short as 115 ps.[6] Further optimization of the design parameters of the A-FPSA with respect to saturable and nonsaturable losses led to a significant improvement of our earlier results. In this Letter we demonstrate passively Q-switched single-frequency pulses as short as 56 ps (Fig. 1) with a diode-pumped Nd:YVO_4 microchip laser. To our knowledge these are the shortest Q-switched pulses ever reported from a solid-state laser. The compact and simple microchip laser can provide high peak power with a diffraction-limited output beam, which makes it interesting for a variety of scientific and industrial applications, such as in medicine or lidar.

The use of a semiconductor saturable absorber mirror to passively Q switch microchip lasers has several advantages. First, there is no significant increase in the cavity length. Thus, short pulses can be achieved because the pulse width is directly proportional to the cavity round-trip time. Second, the bandgap of the absorber layer can be adapted to laser crystals at different lasing wavelengths. Finally, there is enough design freedom to adjust the saturation intensity and the maximum modulation depth independently. These are the absorber parameters that determine pulse width and repetition rate. Thus the pulse width as well as the repetition rate can be designed in a deterministic way over several orders of magnitude.

A schematic of the experimental setup is shown in Fig. 2 (for further details see Ref. 5). The pump source is a linearly polarized 200-μm-wide, 2-W diode array focused to radii of 20 and 50 μm inside the Nd:YVO_4 crystal for the fast and the slow axes, respectively. The pump wavelength is 808 nm. The microchip crystal is a 3%-doped Nd:YVO_4 crystal with a thickness of 200 μm, a nominal absorption length of 100 μm, and an emitting wavelength of 1064 nm. The crystal is sandwiched between an A-FPSA and a 10% output coupler.

The A-FPSA has a high-reflection coating for the pump wavelength and a designed reflection for the laser wavelength. For the experiments described here a SiO_2/HfO_2 dielectric top reflector with a reflectivity of 25, 50, or 75% is used. The absorber is grown either by metal-organic chemical-vapor deposition (MOCVD) at normal growth temperature or by molecular beam epitaxy (MBE) at a below-normal growth temperature of 480 °C. Both types of A-FPSA consist of an InGaAs/GaAs multiple-quantum-well absorber layer grown on top of a highly reflecting AlAs/GaAs Bragg mirror. The thickness of the absorber layer is adjusted to the antiresonance condition of the Fabry–Perot saturable absorber, which is formed by the lower Bragg mirror and a dielectric top reflector. The MBE-grown A-FPSA has 35 quantum wells and only one specific top reflector of 50%, which provides a maximum modulation depth of 13%. The MOCVD-grown absorber consists of either 9 or 18 quantum wells with different dielectric top reflectors of 25, 50, or 75%. Because InGaAs with a band gap at ≈ 1 μm is not lattice matched to GaAs, there is a critical thickness for the absorber layer, above which crosshatches that are due to strain appear and significantly degrade the surface quality.[7] This critical thickness is generally larger for MBE growth at low to intermediate temperatures, but at the expense of a smaller modulation depth and higher nonsaturable losses.[8] We had to reduce the absorber thickness for the normally grown MOCVD sample to prevent degradation of the surface quality and introduce less nonsaturable loss. We typically obtained a 5:1 or better ratio between modulation depth and nonsaturable losses.

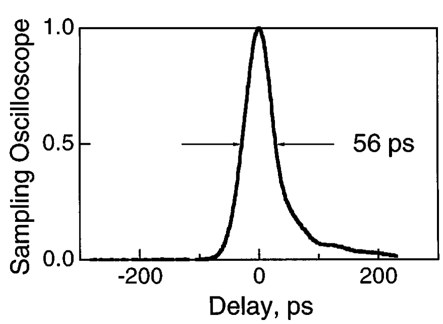

Fig. 1. Oscilloscope trace of the single-frequency, 56-ps-long, Q-switched pulse with a peak power of 1.1 kW and a repetition rate of 85 kHz.

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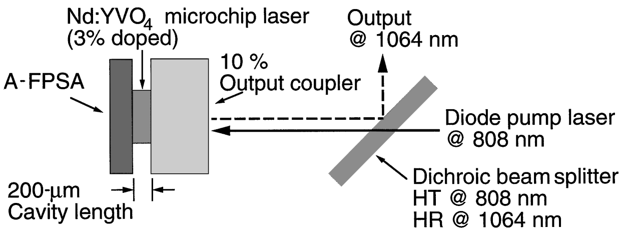

Fig. 2. Layout of the Q-switched $Nd:YVO_4$ laser with an A-FPSA in direct contact with the crystal.

As expected, we achieved the shortest pulses with the MBE-grown A-FPSA, which provided the largest modulation depth of 13%. With a 10% output coupler and an incident pump power of 460 mW, we obtained single-frequency Q-switched pulses of 56 ps FWHM and a peak power of 1.1 kW (Fig. 1). The average output power was 5.3 mW, the repetition rate 85 kHz, and the pulse energy 62 nJ. With the MOCVD-grown A-FPSA with 18 InGaAs/GaAs quantum wells, a 25% top reflector, and a maximum modulation depth of 11%, we achieved slightly longer single-frequency pulses of 68 ps FWHM but with a significantly larger average output power of 58 mW and a peak power of 5.4 kW with 940 mW of pump power. The repetition rate was 160 kHz, and the pulse energy was 0.37 μJ. For both results, the same 10% output coupler and the same 200-μm-thick $Nd:YVO_4$ crystal were used. The pulse widths were measured with a 50-GHz sampling oscilloscope and a 40-GHz photodetector with a time resolution better than 20 ps.

Numerical simulations of the Q-switching dynamics show that we obtain the largest extracted pulse energy under given pumping conditions if the modulation depth of the absorber is as large as the output coupling and the absorber is fully bleached by the pulse energy. For this case we find that the center portion of the pulse is proportional to a $\mathrm{sech}^2(t/\tau)$ with a FWHM pulse width of

$$\tau_p = 1.76\tau = 1.76\,\frac{2T_R}{\Delta R}\,, \qquad (1)$$

where T_R is the cavity round-trip time and ΔR the maximum modulation depth with respect to the intensity. Therefore, for a fully saturated absorber, the pulse duration will be constant with increased pump power. This equation is identical with the expression derived by Zayhowski and Dill.[9]

As long as the pulse repetition rate f_{rep} is much greater than the inverse of the upper-state lifetime τ_L of the laser (i.e., $f_{\mathrm{rep}} \geq 2/\tau_L$), it can be shown that

$$f_{\mathrm{rep}} \cong \frac{g_0}{2\Delta R \tau_L}\,, \qquad (2)$$

where g_0 is the small-signal gain coefficient with $g_0 = r l_{\mathrm{tot}}$, with r being the pump parameter and l_{tot} the total intensity loss coefficient including ΔR. Since f_{rep} is a linear function of g_0, the pulse repetition rate is proportional to the pump power, and the pulse energy is expected to be constant as a function of the pump power.

A simple explanation for the expression of the pulse width and the repetition rate can be given with the numerical results shown in Fig. 3. Figure 3 shows the Q-switched pulse power $P(t)$, the power-gain coefficient $g(t)$, the power-loss coefficient of the saturable absorber $q(t)$, and the constant total unsaturated power-loss coefficient l (including the output coupling) per round trip as a function of time. The maximum modulation depth ΔR is given by $\Delta R = 1 - \exp(-\Delta q) \approx \Delta q$. Here we assume that the saturable absorber is fully saturated and ΔR is smaller than the total unsaturated loss of the cavity. During the pulse build-up time, we can assume in the zeroth-order approximation that $g - l - q \approx \Delta R$ is constant. For this approximation we obtain an initial exponential power growth rate of $\Delta R/T_R$. For the pulse decay we can assume again in the zeroth-order approximation that $g - l - q \approx -\Delta R$. The decay is not dominated by the cavity decay rate for $\Delta q < l$, because the pulse reaches maximum power for $g = l$ and then continues to saturate the gain further by roughly the same amount (assuming symmetric pulses). The initial growth and final decay rate would give an estimated pulse duration of $2T_R/\Delta R$. The additional factor of ≈ 2 in Eq. (1) takes into account the decrease in growth and decay of the pulse during saturation of the gain, as was similarly noted by Zayhowski and Kelley for the case of a rapidly Q-switched laser.[10] The growth rate of the gain between the Q-switched pulses is given by g_0/τ_L. Given $T_{\mathrm{rep}} < \tau_L$, the gain grows approximately linear during the build-up time. Because the gain has to recover by approximately $2\Delta R$, the pulse repetition rate is then given by Eq. (2).

The amount of modulation depth allows us to adjust the pulse width, whereas the increase of the pump power linearly increases the repetition rate. For short pulses, ΔR has to be as large as possible. In addition, simulations show that, in contrast to mode locking, use of a fast saturable absorber with a short recovery time does not help to achieve shorter pulses. The absorber switches faster from a high loss value to a low loss value with a long recovery time τ_A of the absorber and thus with a small saturation intensity ($I_{\mathrm{sat}} = h\nu/2\sigma_A\tau_A$, where $h\nu$ is the photon energy and σ_A the absorber cross section). Therefore the saturation intensity has to be small but still large enough to satisfy the Q-switching condition, i.e., large enough that the absorber is not bleached in cw operation.[11,12] Increasing the MBE- or MOCVD-growth temperature results in a larger absorber recovery time

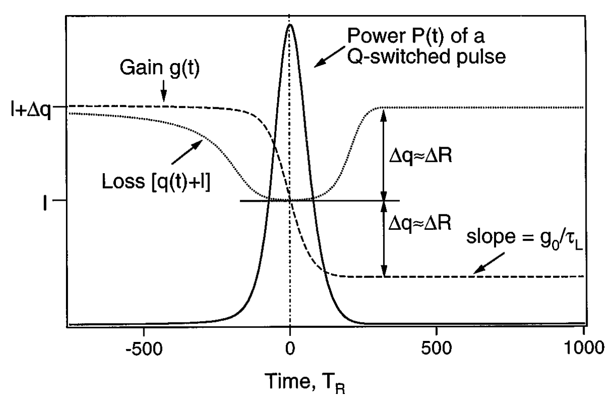

Fig. 3. Numerical simulation of the Q-switching dynamics of a passively Q-switched laser.

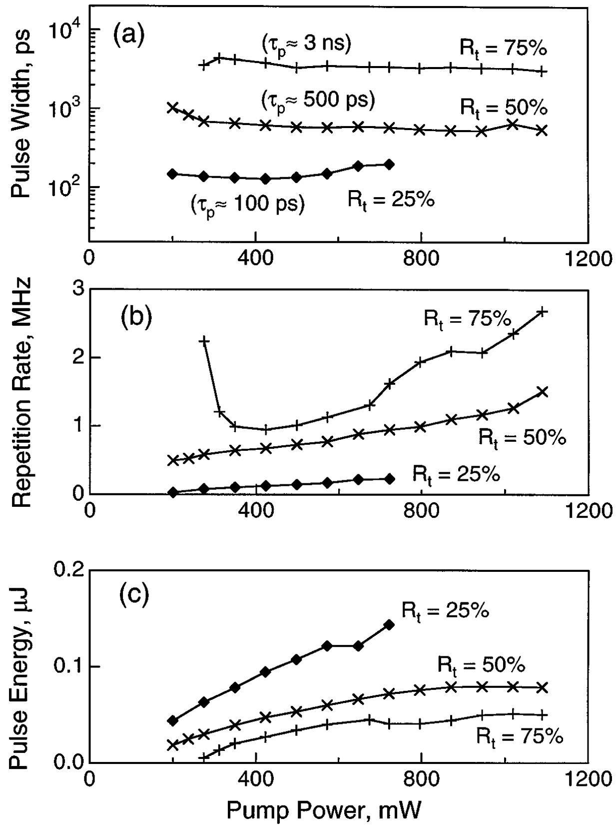

Fig. 4. (a) Pulse width, (b) repetition rate, and (c) pulse energy of the Q-switched Nd:YVO_4 laser as a function of the pump power for different top reflectors on the A-FPSA.

and therefore a lower saturation intensity as well as a better optical quality of the absorber. By using absorbers grown at higher temperature, we could significantly reduce the nonsaturable losses.[8] For the experiments discussed here we did not observe damage to the A-FPSA.

In Fig. 4, we changed the saturation intensity and the modulation depth of the A-FPSA by choosing different top reflectors of one specific MOCVD-grown saturable absorber with nine InGaAs quantum wells. We obtained ΔR values of $\sim$10, 3, and 1%, corresponding to top reflectors of 25, 50, and 75%, respectively. We measured the modulation depth as a function of the incident pulse-energy density with a passively mode-locked Nd:glass laser at 1.061 μm. Using these A-FPSA's, we could vary the pulse width from $\tau_p \approx$ 100 ps for $R_t = 25\%$ ($\tau_{\text{theory}} = 100$ ps) and $\tau_p \approx$ 500 ps ($\tau_{\text{theory}} = 350$ ps) for $R_t = 50\%$ up to $\tau_p \approx 4$ ns for $R_t = 75\%$ ($\tau_{\text{theory}} = 1$ ns) [Fig. 4(a)]. The theoretical predictions made with Eq. (1) are given in parentheses and show the correct order of magnitude. Because the A-FPSA's are fully bleached for higher pump-power levels, we obtained an approximately constant pulse duration as predicted by Eq. (1) and shown in Fig. 4(a). The repetition rate varies from 30 kHz up to 3 MHz [Fig. 4(b)] and increases approximately linearly with increased pump power as expected from Eq. (2), assuming a fully saturated absorber. The initial decrease in the repetition rate of the $R_t = 75\%$ sample indicates that it is not fully saturated at low pump-power levels. The corresponding pulse energies are plotted in Fig. 4(c). For all results shown the output was single frequency. The pulse-to-pulse timing jitter is typically less than 1%. The output beam of the cw-running laser is circular and TEM_{00} up to a pump power of $\sim$400 mW. At higher pump powers the output beam becomes slightly elliptical, with an M^2 value that is always less than 1.2 for the y axis (fast axis of the pump diode) and an M^2 value rising to 2.9 for the x axis at a pump power of 1 W. The waist radius of the output beam is 35 μm at low pump-power levels. The waist decreases to 30 μm for the y axis and increases to 45 μm for the x axis at higher pumping levels. This has to be expected, since the pump is elliptical with a spot size of (20 μm $\times$ 50 μm $\times$ π). Thus, at higher pumping levels higher-order transverse modes can lase.

In conclusion, we have demonstrated single-frequency Q-switched pulses as short as 56 ps. The use of an A-FPSA as a saturable absorber does not significantly increase the cavity length and thus can lead to extremely short pulses when combined with microchip lasers. The important absorber parameters to optimize the Q-switching dynamics can be adjusted for many different pulse widths, repetition rates, and pulse energies. In addition, this technique can be easily adapted to other laser wavelengths.

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