Eyesafe pulsed microchip laser using semiconductor saturable absorber mirrors

R. Fluck,[a] R. Häring,[b] R. Paschotta, E. Gini, H. Melchior, and U. Keller
Institute of Quantum Electronics, Swiss Federal Institute of Technology, ETH Hönggerberg-HPT, CH-8093 Zürich, Switzerland

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We passively Q-switched a diode-pumped Er/Yb:glass microchip laser at a 1.535 μm wavelength using semiconductor saturable absorber mirrors and demonstrated pulses as short as 1.2 ns. By varying the design parameters of the saturable absorber, the pump power, and the pump spot size, we achieved repetition rates from 300 Hz to 100 kHz with pulse energies up to 4 μJ. © *1998 American Institute of Physics.* [S0003-6951(98)03725-5]

There is considerable interest in compact pulsed high peak power laser sources emitting at wavelengths near 1.55 μm. Range finders and other applications with free-space propagation could strongly benefit from such a device. The wavelength of around 1.55 μm is in the eyesafe regime where significantly higher pulse energies can be used without damaging the human eyes.

A pulsed microchip laser is compact and simple to realize and can provide high peak power in a diffraction-limited beam. We developed a diode-pumped, passively Q-switched Er/Yb:glass microchip laser at 1.535 μm (Fig. 1). We achieved 5.6 ns pulses with 4 μJ pulse energy at a repetition rate of 320 Hz, resulting in a peak power of 725 W. The average output power was 1.3 mW. As a passive Q-switching device, we used a metal-organic chemical vapor deposition (MOCVD) grown InGaAsP/InP semiconductor saturable absorber mirror (SESAM).[1,2]

In earlier work, we already demonstrated passive Q-switching of microchip lasers at ≈ 1 μm (Refs. 3 and 4) and ≈ 1.3 μm (Ref. 5) using SESAMs. Previously, cw operation of Er/Yb:glass microchip lasers at ≈ 1.5 μm has been reported.[6,7] So far, to the best of our knowledge, no passively Q-switched microchip laser at 1.5 μm has been demonstrated, even though several solid-state saturable absorbers such as Co:YSGG, Er:CaF, U:SrF, and Co:ZnSe, are available at 1.5 μm.[8–12] These passive Q-switches have been used in Er/Yb:glass lasers with a typical resonator length of a few centimeters, and therefore, produce pulses longer than 10 ns. In our microchip lasers, the SESAM is directly attached to the gain material. The penetration depth into the SESAM is only a few microns.[13] Thus, the cavity length is just defined by the length of the gain material. This approach has lead to pulses as short as 1.2 ns, so far.

A schematic of the experimental setup is shown in Fig. 1. The 1 mm thick Er/Yb:glass (Kigre, QX/Er) is sandwiched between the output coupler and the SESAM. The ytterbium codoping of the glass makes possible the efficient absorption of the pump light within the short length of glass which is required for short pulse generation.[14] A 500 mW, 30 μm stripe-width diode emitting at 975 nm (Uniphase Laser Enterprise) is focused into the glass through a dichroic beamsplitter that transmits the pump light and reflects the output beam at 1.5 μm. The SESAM is mounted on a copper block which acts as a heat sink. No active cooling was required.

The parameters of the SESAMs we used in this work are listed in Table I. All SESAMs consist of an absorber layer embedded between a highly reflecting bottom Bragg mirror and a top reflector. These two mirrors form a Fabry-Perot. The thickness of the absorber is designed to be in antiresonance in order to minimize the insertion losses, and to be less sensitive to thermal shifts of the Fabry-Perot structure. This specific design of the SESAM is also referred to as an antiresonant Fabry-Perot saturable absorber.[1,2] We used an InGaAsP/InP SESAM to obtain a higher modulation depth than for an InGaAs/GaAs SESAM.[15] The InGaAsP/InP SESAM is MOCVD grown and lattice matched to an InP substrate. The bottom Bragg mirror consists of 40 pairs of $In_{0.65}Ga_{0.35}As_{0.73}P_{0.27}/InP$ ($\lambda_{gap} \approx 1.4$ μm) quarter-wave layers. We use absorbers of different thicknesses which consist of $In_{0.58}Ga_{0.42}As_{0.9}P_{0.1}$ ($\lambda_{gap} \approx 1.55$ μm). The SiO_2/HfO_2 top coatings have 50% and 70% reflectivities with respect to InP at the laser wavelength of 1.53 μm and are highly reflecting at the pump wavelength of 975 nm. This allows for a double pass of the pump and leads to an increase in the absorption efficiency.

For Q-switching, it is desirable to have a long recovery

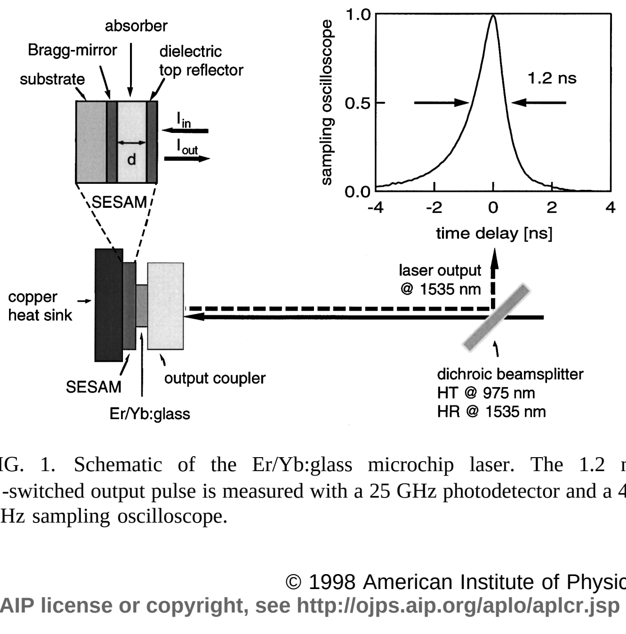

FIG. 1. Schematic of the Er/Yb:glass microchip laser. The 1.2 ns Q-switched output pulse is measured with a 25 GHz photodetector and a 40 GHz sampling oscilloscope.

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[a] Electronic mail: rfluck@iqe.phys.ethz.ch

[b] Electronic mail: haring@iqe.phys.ethz.ch

TABLE I. Design parameters of the different SESAMs used in this work: d is the thickness of the absorber layer, τ_{absorber} is the measured recovery time of the absorber, R_{top} is the reflectivity of the top reflector, ΔR is the maximum modulation depth of the SESAM, and τ_{pulse} is the measured full width at half maximum pulse width out of the microchip laser using a 40 GHz sampling scope with a 25 GHz photodetector.

SESAM No.	d (nm)	InP cap	τ_{absorber} (ns)	R_{top} (%)	ΔR (%)	τ_{pulse} (ns)
1	108	No	0.139	50	5	1.2
2	324	No	0.474	⋯	⋯	⋯
3	757	No	1.1	⋯	⋯	⋯
4	40	Yes	6.8	70	1.1	5.6
5	310	Yes	5.0	70	3.0	2.7

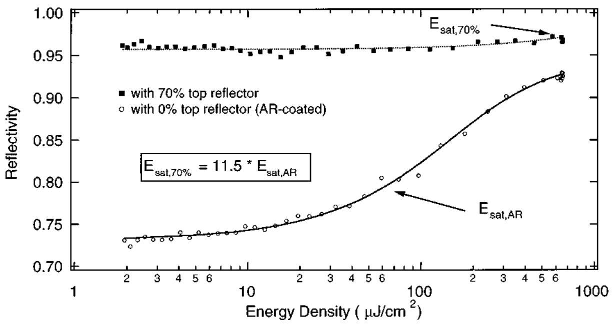

FIG. 3. Measured and fitted reflectivity of the SESAMs as a function of incident pulse energy.

time which leads to a lower saturation intensity and a better efficiency. Therefore, we measured the recovery times of various saturable absorbers in a standard degenerate pump-probe setup, using 150 fs pulses from a synchronously pumped optical parametric oscillator (OPO) at 1.52 μm. The recovery times of the absorbers were between 100 ps and 10 ns (Fig. 2). For a SESAM with a pure bulk InGaAsP absorber, the recovery time increased with the absorber thickness. This indicates surface trapping and recombination and could be ascribed to nonlocalized states at the surface of the quarternary InGaAsP. With an InP cap layer (20–30 nm) on top of the InGaAsP absorber layer, we achieved longer absorber lifetimes (>1 ns) independent of the absorber thickness. We believe this effect happens due to confinement of the carriers below the surface.

Figure 3 shows the reflectivity of the SESAM (No. 5) as a function of the incident pulse energy density. This kind of saturation measurement provides the amount of nonsaturable and saturable losses. The saturable losses determine the maximum modulation depth, a key parameter for the laser performance. Pulse width and repetition rate are inversely proportional to the modulation depth.[4] Because the pulse energy density of the used OPO is not high enough to fully saturate the SESAMs (Fig. 3, squares), we usually use the absorbers with an antireflection (AR) coating (Fig. 3, circles) to perform the pump-probe and saturation fluence measurements. Afterwards, we scale the results according to the top reflector as described in Ref. 16. The modulation depths ΔR of the SESAMs are between 1% and 5% with residual insertion losses of 0.5% and 3%, respectively.

As expected from theory,[4] we obtained the shortest pulses of 1.2 ns using the SESAM (No. 1) with the largest modulation depth of 5%. The pulse width was measured using a 40 GHz Tektronix sampling oscilloscope and a 25 GHz photodetector with a time resolution of 14 ps. The pump spot radii were 45 and 20 μm. With a 1% output coupler and an incident pump power of 200 mW, we obtained pulses of 1.2 ns at a repetition rate of 47 kHz. We measured an average output power of 2.1 mW, resulting in a pulse energy of 45 nJ and a peak power of 37 W. In this regime, however, we often observed damage of the SESAM. In order to obtain reliable operation, we used a SESAM (No. 4) with higher top mirror reflectivity (70% instead of 50%). This reduced the tendency for damage by reducing the pulse fluence in the cavity and even more in the absorber. We could, nevertheless, increase the externally measured pulse energy and peak power to 4 μJ and 730 W, respectively, by using larger pump spot radii of 135 and 70 μm (which also increased the laser mode size) and an output coupler with higher transmission of 5%, thus improving the output coupling efficiency. However, the average power was then only 1.3 mW and the repetition rate 320 Hz at 300 mW pump power because of the increased threshold power. The pulse width was 5.6 ns, longer than before due to the reduced modulation depth of 1.1%. The transverse beam mode was close to an ideal Gaussian, with an M^2 value of about 1.2 and 1.3 with respect to the fast and the slow axes of the pump diode, respectively. The laser output was linearly polarized due to the anisotropy induced by the nonuniform pump distribution of the diode laser. However, for pumping with the circular spot of a Ti:sapphire laser we obtained an unpolarized laser output.

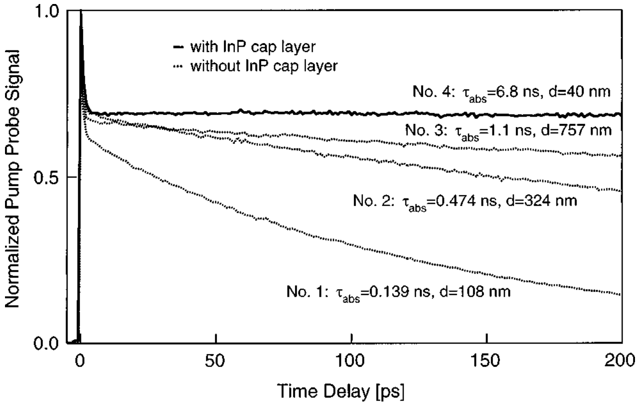

FIG. 2. Recovery time measurements of AR-coated SESAMs according to Table I with and without an InP cap layer.

For a comparison of experimental data with the theoretical model of Ref. 4, we used a Ti:sapphire pump laser because of its well-defined mode and spectrum. As expected from the theory, the pulse width, pulse energy and peak power remain independent of the pump power whereas the repetition rate increases linearly with increasing pump power (Fig. 4). A simple analytical expression for the pulse width, given in Ref. 4, predicts a pulse width of $\tau_{\mathrm{theory}} = 1.2$ ns for a fully bleached absorber with $\Delta R = 3\%$ (No. 5), to be compared with a measured pulse width of 2.7 ns. We explain this discrepancy with an effective reduction of the modulation depth, caused by an interference effect at the air gap between the SESAM and the (uncoated) gain material. Assuming the reduced modulation depth which explains the 2.7 ns pulse width, we estimated a pulse energy of 6 μJ, which is in reasonable agreement with the measured 3.8 μJ, given the fact that the model assumes a top-hat beam profile. The mea-

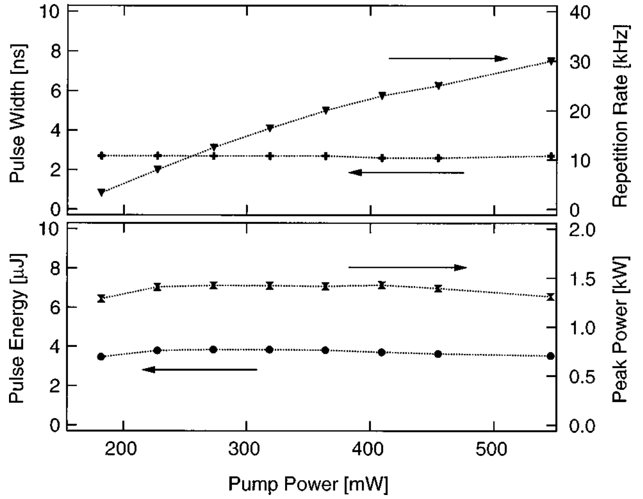

FIG. 4. Pulse width, repetition rate, pulse energy and peak power of the Q-switched Er/Yb:glass laser as a function of the pump power.

sured slope efficiency of 39% is in good agreement with an estimate based on the pump absorption efficiency, the quantum defect and the output coupling efficiency (5% output coupling and 1.5% nonsaturable losses). The intracavity pulse fluence of roughly 150 mJ/cm^2 is approaching the damage threshold of the SESAM.

Single-frequency operation of the Er/Yb:glass microchip laser is difficult to achieve because of the broad gain spectrum which covers many longitudinal modes of the resonator. The mode spacing of 0.75 nm cannot be increased much further because an even shorter gain medium could not efficiently absorb the pump power and provide sufficient gain.

Note added in proof: In the meantime, we have achieved Q-switched operation on a single longitudinal mode by incorporating a 0.5 nm thick piece of $LiNbO_3$ in the cavity, which introduces spectral filtering by a Fabry-Perot effect.

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