Passively Q-switched 1.34-μm Nd:YVO$_4$ microchip laser with semiconductor saturable-absorber mirrors

R. Fluck, B. Braun, E. Gini, H. Melchior, and U. Keller

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

Received February 27, 1997

We demonstrate a passively Q-switched diode-pumped 1.34-μm Nd:YVO$_4$ microchip laser. We achieved single-frequency, 230-ps pulses by using an InGaAsP semiconductor saturable-absorber mirror. We can vary the pulse width and the repetition rate from 230 ps to 12 ns and from 30 kHz to 4 MHz, respectively, by changing the design parameters of the saturable absorber, the thickness of the crystal, and the pump power. © 1997 Optical Society of America

There is considerable interest in microchip lasers because they are compact and simple to fabricate, are insensitive to pump beam alignment, and can lase in a single longitudinal mode. These characteristics make them suitable for scientific and industrial applications such as in fiber optics, light detection and ranging, material processing, and medicine. Most microchip lasers operate at 1 μm. But there is a widespread need for a source operating near 1.3 μm to coincide with the transmission window of silica optical fibers. Simple and compact Q-switched oscillators at 1.3 μm can be realized by ternary and quaternary semiconductor diodes. The advantage of these devices is that they can be excited by carrier injection. The disadvantages are low pulse energies, spectral and spatial mode impurity, and broad linewidth. In contrast, Q-switched diode-pumped solid-state microchip lasers have the potential to provide good beam quality and high peak output powers at single frequency.

In this Letter we demonstrate a passively Q-switched, diode-pumped 1.34-μm Nd:YVO$_4$ microchip laser that uses InGaAsP semiconductor saturable-absorber mirrors (SESAM's).[1-3] We achieved pulses as short as 230 ps with a repetition rate of 53 kHz and a peak power of 450 W (Fig. 1). This is to our knowledge the first demonstration of a passively Q-switched microchip laser at 1.3 μm. Both actively[4] and passively[5] Q-switched Nd:YVO$_4$ microchip lasers have been demonstrated at 1 μm with pulses as short as 56 ps.[5] At the emission wavelength of 1.3 μm, only cw and actively Q-switched microchip lasers have been reported.[6-10]

Our goal is realization of a diode-pumped passively Q-switched microchip laser that provides short pulses and high peak output power in a single longitudinal mode. For short-pulse generation the laser cavity has to be short, because the pulse width increases linearly with the cavity length. For single-frequency operation the cavity has to be sufficiently short that the axial mode spacing exceeds the gain bandwidth. In addition, a short absorption length is needed for efficient lasing with a short cavity length. Furthermore, for a low lasing threshold the $\sigma_g \tau_g$ product has to be high, where σ_g is the gain cross section and τ_g is the upper-state lifetime of the laser material. Among the most common microchip laser materials at 1 μm, 3%-doped Nd:YVO$_4$ shows the highest $\sigma_g \tau_g$ and the shortest nominal absorption length at 1.3 μm (Table 1). The broad absorption spectrum and the short absorption length at 808 nm make Nd:YVO$_4$ attractive for diode pumping; therefore we chose it as an active laser material at $\approx$1.3 μm.

As a passive Q-switching element we use a SESAM.[1-3] Because the penetration depth into the SESAM is less than 1 μm, there is no significant increase in the cavity length compared with those of other saturable absorbers such as Cr:YAG, which typically would result in an additional cavity length of a few hundred micrometers. Even with a fixed mode area, there is enough design freedom with a SESAM to control the important Q-switching parameters, i.e., the maximum modulation depth and the saturation intensity, for a specific laser crystal. These parameters are the absorber parameters that determine pulse width and the repetition rate.[5] In contrast to ion-doped crystal absorbers, SESAM's can be adapted to many wavelengths when different semiconductor materials are used.

A schematic of the experimental setup is shown in Fig. 2. The laser crystal is a 3%-doped Nd:YVO$_4$ crystal 200 μm thick. The crystal is sandwiched between an output coupler and a SESAM. The pump source is a 1-W, 100-μm stripe-width diode array emitting at 808 nm. It is focused into the crystal through a dichroic beam splitter that transmits the pump light and reflects the output beam at 1.34 μm. The pump

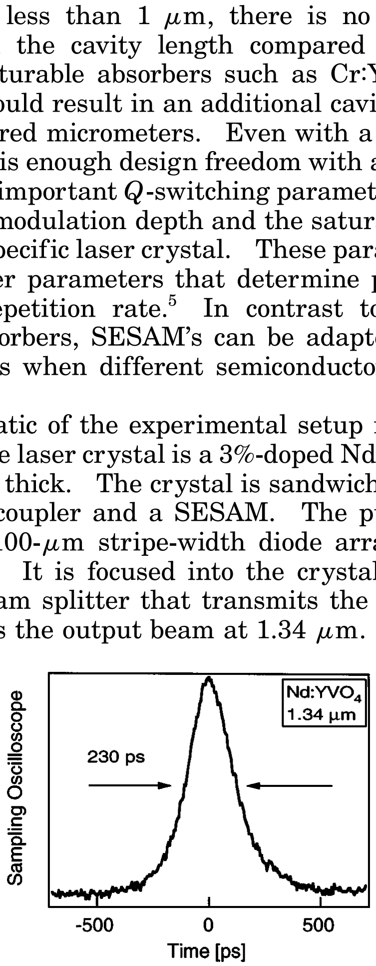

Fig. 1. Sampling oscilloscope trace of the single-frequency 230-ps-long Q-switched pulse at 1.34 μm.

Table 1. Material Properties of Common Microchip Laser Materials[a]

Laser Material	σ_g (10^{-19} cm^2) 1-μm Absorption	σ_g (10^{-19} cm^2) 1.3-μm Absorption	τ_g (μs)	$1/\alpha$ (μm)
3% Nd:YVO$_4$	25 (11)	~6 (12)	50 (11)	90 (11)
25% Nd:LSB	1.3 (13), (14)	0.1 (14)	87 (13), (14)	110 (13)
1.1% Nd:YAG	~5 (12)	≈0.5	240 (12)	1200 (13)

[a] Numbers in parentheses are reference numbers.

radii were 50 μm × 30 μm at the focus, with a confocal parameter of 760 μm at a pump power of 400 mW. The maximum available pump power incident at the microchip was 550 mW.

The SESAM that we used consisted of an absorbed layer embedded between a highly reflecting Bragg mirror and a top reflector. These two mirrors form a Fabry–Perot absorber, and the thickness of the absorber is designed to be at antiresonance. This SESAM is called an antiresonant Fabry–Perot saturable absorber.[1,2,3,15] In earlier research with mode-locked lasers at 1.3 μm (Ref. 16) we used molecular beam epitaxy–grown InGaAs absorber structures upon an AlAs/GaAs Bragg mirror. However, for saturable absorption at 1.34 μm, the indium concentration in the InGaAs absorber material must be increased to approximately 40%, which results in a significant lattice mismatch to the GaAs substrate. This lattice mismatch reduces the surface quality and results in higher insertion losses. Furthermore, the thickness of the absorber is limited because of strain effects. Low-temperature growth partially relieves the lattice mismatch, but the absorber lifetime would drop into the few-picosecond regime. In contrast with fast saturable-absorber mode locking, for which a fast recovery time of the absorber is needed, passive Q-switching requires a small saturation intensity, i.e., a long absorber lifetime. To overcome this problem we chose lattice-matched InGaAsP quaternary structures grown upon InP substrates by metal organic chemical-vapor deposition at normal growth temperature. The band gap can be adjusted by alteration of the composition of the quaternary. But the difference in the refractive indices of the two materials, InP and InGaAsP, is less than that for AlAs and GaAs (Fig. 3). Therefore, for a reflectivity of ≈99%, 40 pairs of 104-nm InP and 96-nm $In_{0.73}Ga_{0.27}As_{0.57}P_{0.43}$ ($\lambda_{gap} \approx 1.27$ μm) layers must be grown, compared with 25 pairs of AlAs and GaAs layers upon a GaAs substrate. The saturable-absorber layer is 0.65-μm-thick bulk $In_{0.65}Ga_{0.35}As_{0.73}P_{0.27}$ ($\lambda_{gap} \approx 1.4$ μm) grown on top of the InGaAsP/InP Bragg mirror. The absorber has a dielectric SiO_2/HfO_2 top reflector, which is a high reflector for the pump and has a reflectivity of 50% at the lasing wavelength.

The solid curve in Fig. 3 shows the reflectivity of the final SESAM as described in the previous paragraph. The dotted curve shows the absorber with an antireflection coating instead of the SiO_2/HfO_2 reflector. We used the antireflection-coated absorber for the pump–probe and saturation fluence measurements and then scaled the results to the 50% top reflector according to Ref. 15. With a standard degenerate pump–probe measurement using 150-fs pulses from a synchronously pumped optical parametric oscillator at 1.32 μm we obtained an absorber recovery time of >300 ps [Fig. 4(a)]. Using the same laser, we measured the saturation of the absorber as a function of incident pulse energy density [Fig. 4(b)]. Note that we scaled the axes in Figs. 4(a) and Fig. 4(b) to the

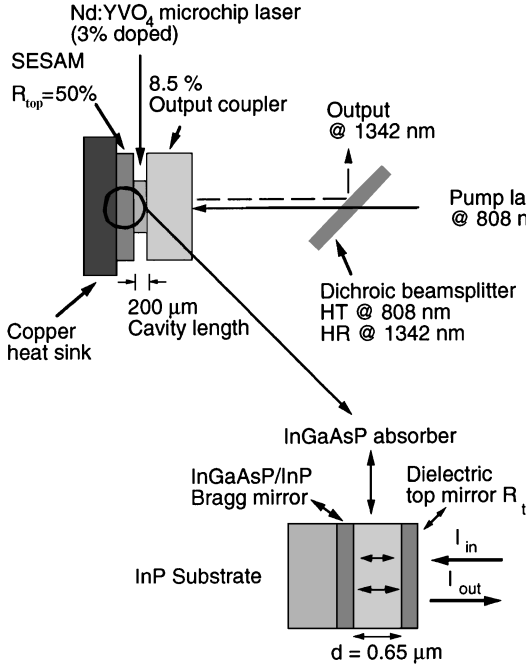

Fig. 2. Schematic of the Q-switched Nd:YVO$_4$ laser system with a SESAM in direct contact with the crystal. HT, highly transmitting; HR, highly reflecting.

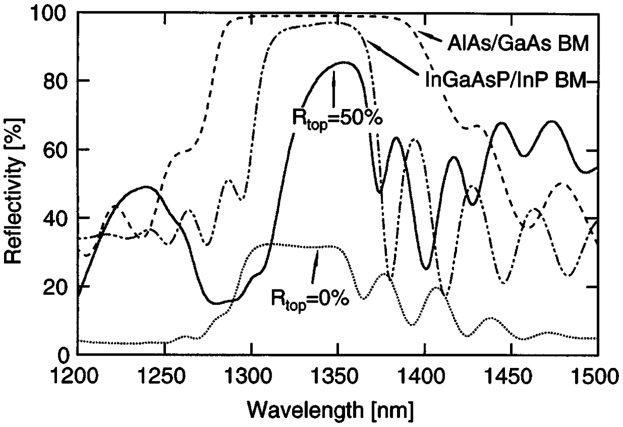

Fig. 3. Low-intensity reflectivity measurement of the AlAs/GaAs and InGaAsP/InP Bragg mirrors (BM's) and the InGaAsP SESAM with a 50% top reflector and with an antireflection coating.

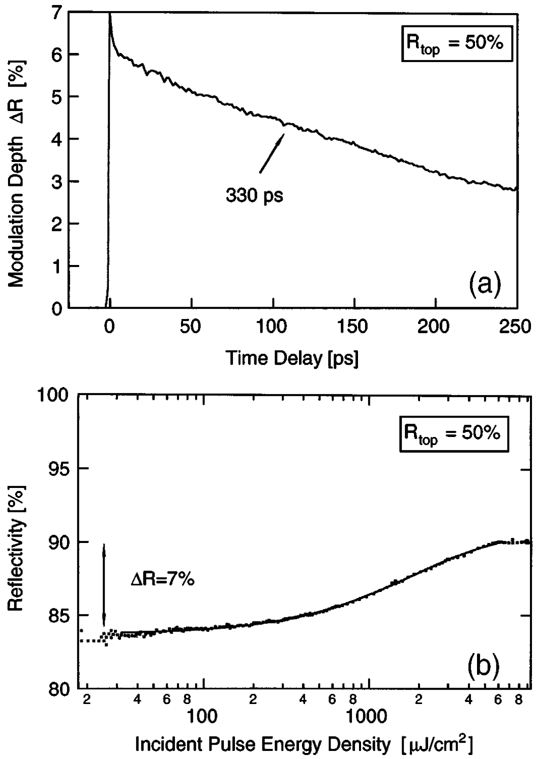

Fig. 4. (a) Lifetime measurement of the SESAM with 150-fs pulses and a pulse energy density in the saturated regime. (b) Reflectivity of the SESAM as a function of incident pulse energy density.

final absorber with the 50% top reflector.[11] The saturation fluence of the final SESAM is 670 μJ/cm^2. The saturation measurement also provides the amounts of nonsaturable and saturable loss, which are key parameters for laser performance. The maximum saturable-intensity loss, also referred to as modulation depth, was 7%, with a residual nonsaturable insertion loss of 10% [Fig. 4(b)]. A better ratio of saturable to nonsaturable absorption should be attainable with improved growth parameters.

We achieved the shortest pulses with the metal organic chemical-vapor deposition–grown SESAM described above. With an 8.5% output coupler and an incident pump power of 400 mW, we obtained single-frequency Q-switched pulses with durations of 230 ps FWHM (Fig. 1) at a repetition rate of 53 kHz. We measured an average power of 6.5 mW, resulting in a pulse energy of 120 nJ and a peak power of $\sim$450 mW. The pump threshold was 250 mW. The pulse widths were measured with a Tektronix sampling oscilloscope with a 20-GHz sampling head and a 25-GHz photodetector. Simple analytical expressions for the pulse width and the repetition rate are given in Ref. 5. They predict a pulse width $\tau_{\text{theory}} = 150$ ps and a repetition rate $f_{\text{theory}} = 73$ kHz for a fully bleached absorber with $\Delta R = 7\%$, total nonsaturable losses of 18.5% (including the 8.5% output coupler), and a pump parameter of 2.8, which results in a small-signal gain coefficient $g_0 = 0.52$. Thus these simple theoretical predictions provide the correct order of magnitude for the pulse width and the repetition rate.

Variations in pump power, crystal length, and design of the SESAM resulted in pulse widths of 230 ps to 12 ns and repetition rates of 30 kHz to 4 MHz, similar to those of the passively Q-switched Nd:YVO$_4$ microchip at 1 μm.[5] For all pump powers the microchip laser oscillated in a single longitudinal mode. We achieved the highest peak power of 800 W by using the 200-μm-thick crystal. The average output power was 16 mW at a pump power of 450 mW and a repetition rate of 50 kHz, resulting in a pulse energy of 0.32 μJ. The timing jitter at a pulse width near 300 ps and a repetition rate of 60 kHz was $\sim$2 μs, i.e., 12% of the pulse repetition period. For longer pulses, $\approx$1 ns, and repetition rates of $\approx$75 kHz, the maximum pulse-to-pulse timing jitter decreased to $\sim$290 ns, i.e., 2% of the pulse repetition period. We measured the polarization of the output beam to be better than 1:100. For typical pulse widths of 300–400 ps and a pump power of 400 mW the transverse beam mode was close to an ideal Gaussian, with a beam radius of 36 μm and an M^2 of 1.1 and 1.2 with respect to the fast and the slow axes, respectively, of the pump diode.

This research was supported by the Swiss Priority Program in Optics.

References

1. U. Keller, D. A. B. Miller, G. D. Boyd, T. H. Chiu, J. F. Ferguson, and M. T. Asom, Opt. Lett. **17,** 505 (1992).
2. U. Keller, Appl. Phys. B **58,** 347 (1994).
3. U. Keller, K. J. Weingarten, F. X. Kärtner, D. Kopf, B. Baum, I. D. Jung, R. Fluck, C. Hönninger, N. Matuschek, and J. Aus der Au, IEEE J. Sel. Topics Quantum Electron. **2,** 435 (1996).
4. J. J. Zayhowski and C. Dill III, Opt. Lett. **20,** 716 (1995).
5. B. Braun, F. X. Kärtner, M. Moser, G. Zhang, and U. Keller, Opt. Lett. **22,** 381 (1997).
6. J. J. Zayhowski and A. Mooradian, Opt. Lett. **14,** 24 (1989).
7. F. Zhou and A. I. Ferguson, Electron. Lett. **26,** 490 (1990).
8. G. C. Bowkett, G. W. Baxter, D. J. Booth, T. Taira, H. Tarenishi, and T. Kobayashi, Opt. Lett. **19,** 957 (1994).
9. F. Zhou and A. I. Ferguson, Opt. Lett. **16,** 79 (1991).
10. J. A. Keszenheimer, E. J. Balboni, and J. J. Zayhowski, Opt. Lett. **17,** 648 (1992).
11. CASIX, Inc., *Crystals & Materials* (Fuzhou, China, 1995).
12. A. W. Tucker, M. Birnbaum, C. L. Fincher, and J. W. Erler, J. Appl. Phys. **48,** 4907 (1977).
13. J.-P. Meyn, T. Jensen, and G. Huber, IEEE J. Quantum Electron. **30,** 913 (1994).
14. J.-P. Meyn, "Neodym-Lanthan-Scandium-Borat: Ein neues Material für miniaturisierte Feskörperlaser," Ph.D. dissertation (Universität Hamburg, Hamburg, Germany, 1994).
15. L. R. Brovelli, U. Keller, and T. H. Chiu, J. Opt. Soc. Am. B **12,** 311 (1995).
16. R. Fluck, G. Zhang, U. Keller, K. J. Weingarten, and M. Moser, Opt. Lett. **21,** 1378 (1996).