29GHz modelocked miniature Nd:YVO$_4$ laser

L. Krainer, R. Paschotta, G.J. Spühler, M. Moser and U. Keller

A miniature Nd:vanadate (Nd:YVO$_4$) laser is presented which was passively modelocked at the very high repetition rate of 29GHz using a semiconductor saturable absorber mirror (SESAM). An 81mW average output power was achieved, which corresponds to 2.8pJ pulse energy, and a pulse duration of 6.8ps.

Introduction: Lasers with multi-gigahertz repetition rates will find applications in the fields of microwave/millimetre-wave communications, photonic switching, telecommunications and particle accelerators. Semiconductor lasers have been demonstrated with repetition rates of hundreds of gigahertz or even > 1THz [1], but with pulse energies well below 1pJ, which are not sufficient for many applications. Much higher pulse energies and average powers in a diffraction-limited beam can be obtained from diode-pumped solid-state lasers. Actively modelocked solid-state lasers have been demonstrated with 40GHz repetition rate and 0.5pJ pulse energy [2]. The passive harmonic modelocking of Cr^{4+}:YAG lasers has resulted in up to 2.7GHz with 30.4pJ pulse energy [3], while with fundamental (i.e. not harmonic) modelocking of solid-state lasers the maximum repetition rate was ~1GHz with 200pJ pulse energy [4]. Another way of generating high repetition rate optical pulse trains is to multiply the repetition frequency using an extracavity dispersive medium ([5, 6]) or by intracavity spectral filtering [7], but these techniques add additional complexity and losses to the setup, and they tend to increase intensity fluctuations and pulse duration.

Our approach to obtaining high repetition rates is to passively modelock miniature Nd:YVO$_4$ lasers which are operated at their fundamental repetition rate (i.e. with only one pulse circulating in the cavity), avoiding instabilities as observed in harmonically modelocked lasers. As a passive modelocker we use a semiconductor saturable absorber mirror (SESAM) [8, 9], which is not only compact and simple to use but also provides sufficient design freedom for operation in extreme parameter regimes.

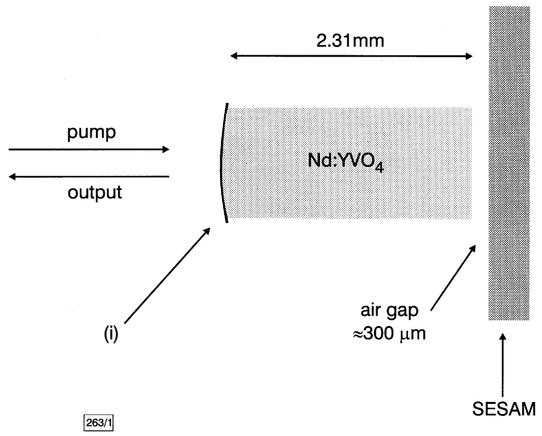

Fig. 1 *Setup of Nd:YVO$_4$ laser*

(i) radius = 10mm, high transmission at 808nm
radius = 99.8% at 1064nm

Criterion for stable modelocking: For fundamental modelocking at high repetition rates, very short laser cavities (< 1cm length) are required. The main challenge for the modelocking of such cavities is that the saturable absorber induces a strong tendency for Q-switched modelocking (QML) [10]. From the results of [10] we derived the criterion

$$I_L > I_{L,crit} = f_{rep} F_{L,sat} \frac{\Delta R}{S} \qquad (1)$$

for stable modelocked operation in the picosecond regime (i.e. not for soliton lasers). Here I_L is the average laser intensity in the gain medium which must exceed the critical value $I_{L,CRIT}$. f_{REP} is the repetition rate of the laser. $F_{L,SAT} = h\nu_L/(2\sigma_L)$ is the saturation fluence of the gain medium where σ_L is the emission cross-section at the laser wavelength and the factor 2 accounts for the double-pass in a standing-wave cavity. ΔR is the modulation depth of the saturable absorber, and the saturation parameter S is the ratio of pulse fluence on the absorber and its saturation fluence. For the whole analysis we assumed that the laser is operated far above threshold ($S \geq 3$), that the absorber is fully saturated, and that the absorber fully recovers between two pulses.

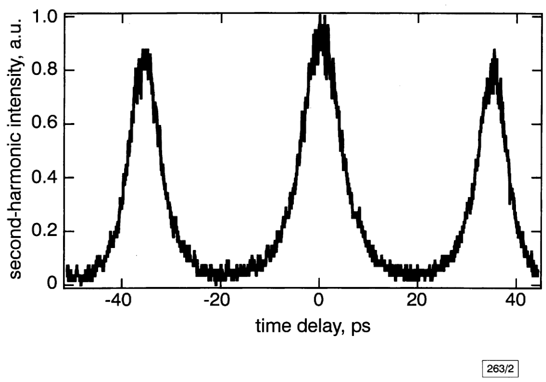

Fig. 2 *Auto-correlation of 6.8ps short pulses at 29GHz repetition rate*

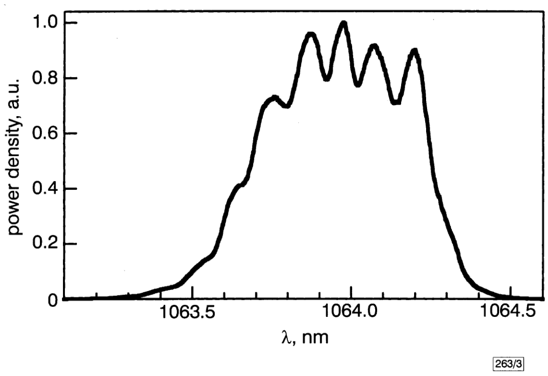

Fig. 3 *Optical spectrum of output with longitudinal cavity modes resolved*

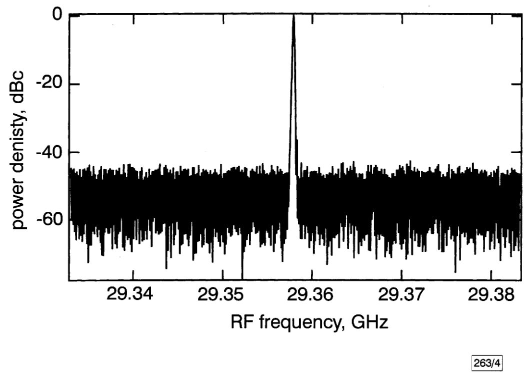

Fig. 4 *RF spectrum of output at full output power (81mW)*

The lack of side peaks indicates the absence of Q-switching instabilities

It is apparent that eqn. 1 for stable passive modelocking becomes harder to satisfy for large values of f_{REP}; the other factors on the right side of eqn. 1 must therefore be kept as small as possible. Nd:YVO$_4$ is a good choice of laser medium as it has a high emission cross-section and also a large amplification bandwidth, thus allowing for short pulses. (Note that the pulsewidth should be significantly shorter than the inverse repetition rate.) Furthermore the modulation depth ΔR should be only as large as necessary for starting and stabilising the modelocking process with sufficiently short pulses. A larger value of the saturation parameter S (indicating how strongly the SESAM is saturated) would help; however, this could lead to a fast degradation of the absorber, particularly at high repetition rates. Therefore we have chosen to operate our laser with a very low value of $S \simeq 0.5$. The SESAM is still sufficiently saturated because the pulse repetition period is shorter than the recovery time. (Eqn. 1 is actually no more valid in this regime but can still be used as a guideline.) Finally, the design of a laser cavity with small round-trip losses (including an output coupler with small transmission) and a small mode size in the gain medium help to maintain a large value of the intracavity intensity I_L.

Experiment: Our miniature laser setup is shown in Fig. 1. The 2.31 mm long $Nd:YVO_4$ crystal with 3% neodymium doping has a curved side (10 mm radius of curvature) which is coated for 99.8% reflection at the laser wavelength (1064 nm) and high transmission (> 98%) at the pump wavelength (808 nm). The other side is flat polished and anti-reflection coated for the laser wavelength. The SESAM is located ~0.3 mm from the flat side of the crystal; it was grown using MOCVD and has parameters $F_{A,SAT} \simeq 100 \mu J/cm^2$ and $\Delta R \simeq 0.24\%$. It also has a dielectric top mirror with 70% reflectiviy to reduce internal losses. The recovery time of ~100 ps is longer than the round-trip time of ~34 ps, which somewhat violates the assumptions made in the discussion above but still allows for stable mode-locking. The pump power of up to ~1 W from a Ti:sapphire laser is launched into the crystal through the coating, which acts as the output coupler. The output beam is separated from the pump beam with a dichroic mirror (not shown in Fig. 1). This compact setup provides for a small mode radius of ~30 μm on the SESAM and in the gain medium.

The maximum output power of 81 mW is generated for a pump power of 950 mW. The laser threshold is very low (~4 mW), but Q-switched modelocked operation is observed below ~570 mW pump power or ~50 mW output power. For higher output powers, we obtained stable self-starting CW modelocking at 29.3 GHz. Fig. 2 shows the auto-correlation of the pulses, indicating a pulsewidth of 6.8 ps (assuming a $sech^2$ pulse shape). The side peaks result from the correlation with adjacent pulses and appear somewhat lower only because of the increased loss of the autocorrelator for large delays. The optical spectrum is shown in Fig. 3; the resolution of ~0.1 nm was sufficient to resolve the longitudinal cavity modes. The FWHM bandwidth of 0.57 nm is roughly half the amplification bandwidth of $Nd:YVO_4$. The RF spectrum (Fig. 4) shows the first harmonic at 29 GHz with a frequency span of 50 MHz and no side peaks which would indicate Q-switching instabilities.

Summary: We have demonstrated passive fundamental modelocking of an $Nd:YVO_4$ laser with a repetition rate as high as 29 GHz and a maximum output power of ~81 mW which corresponds to 2.8 pJ pulse energy. Q-switching instabilities were avoided by using a carefully optimised compact laser cavity with small mode sizes and an SESAM as a modelocker.

21 May 1999
Electronics Letters Online No: 19990801
DOI: 10.1049/el:19990801

L. Krainer, R. Paschotta, G.J. Spühler and U. Keller (*Ultrafast Laser Physics, Institute of Quantum Electronics, Swiss Federal Institute of Technology, ETH Hönggerberg HPT, CH-8093 Zürich, Switzerland*)

E-mail: krainer@iqe.phys.ethz.ch

M. Moser (*CSEM Zürich, Badenerstrasse 569, CH-8048 Zürich, Switzerland*)

References

1 ARAHIRA, S., MATSUI, Y., and OGAWA, Y.: 'Mode-locking at very high repetition rates more than terahertz in passively mode-locked distributed-Bragg-reflector laser diodes', *IEEE J. Quantum Electron.*, 1996, **32**, (7), pp. 1211–1224

2 VIEIRA, A.J.C., HERCZFELD, P.R., and CONTARINO, V.M.: 'Microchip laser for microwave and millimeter-wave generation'. Proc. SBMO/IEEE MTT-S Int. Microwave and Optoelectronics Conf., 1997, (IEEE), Vol. 2, pp. 333–337

3 COLLINGS, B.C., BERGMAN, K., and KNOX, W.H.: 'True fundamental solitons in a passively mode-locked short-cavity Cr^{4+}/:YAG laser', *Opt. Lett.*, 1997, **22**, (10), pp. 336–339

4 KELLER, U., NELSON, L.E., and CHIU, T.H.: 'Diode-pumped, high repetition rate, resonant passive mode-locked Nd:YLF laser'. OSA Proc. Advanced Solid-State Lasers, 1992, (OSA), Vol. 13, pp. 94–97

5 SHAKE, I., TAKARA, H., KAWANISHI, S., and SARUWATARI, M.: 'High-repetition-rate optical pulse generation by using chirped optical pulses', *Electron. Lett.*, 1998, **34**, (8), pp. 792–793

6 ARAHIRA, S., KUTSUZAWA, S., MATSUI, Y., KUNIMATSU, D., and OGAWA, Y.: 'Repetition-frequency multiplication of mode-locked pulses using fiber dispersion', *J. Lightwave Technol.*, 1998, **16**, (3), pp. 405–410

7 SERKLAND, D.K., BARTOLINI, G.D., KATH, W.L., KUMAR, P., and SAHAKIAN, A.V.: 'Rate multiplication of a 59-GHz soliton source at 1550 nm', *J. Lightwave Technol.*, 1998, **16**, (4), pp. 670–677

8 KELLER, U., WEINGARTEN, K.J., KÄRTNER, F.X., KOPF, D., BRAUN, B., JUNG, I.D., FLUCK, R., HÖNNINGER, C., MATUSCHEK, N., and AUS DER AU, J.: 'Semiconductor saturable absorber mirrors (SESAM's) for femtosecond to nanosecond pulse generation in solid-state lasers', *IEEE J. Sel. Topics Quantum Electron.*, 1996, **2**, (2), pp. 435–453

9 KELLER, U., MILLER, D.A.B., BOYD, G.D., CHIU, T.H., FERGUSON, J.F., and ASOM, M.T.: 'Solid-state low-loss intracavity saturable absorber for Nd:YLF lasers: an antiresonant semiconductor Fabry-Perot saturable absorber', *Opt. Lett.*, 1992, **17**, pp. 505–507

10 HÖNNINGER, C., PASCHOTTA, R., and KELLER, U., NORIER-GENOUD, F., and MOSER, N.: 'Q-switching stability limits of continuous-wave passive mode locking', *J. Opt. Soc. Am. B*, 1999, **16**, (1), pp. 46–56