77 GHz soliton modelocked Nd:YVO_4 laser

L. Krainer, R. Paschotta, M. Moser and U. Keller

An Nd:YVO_4 laser which was passively modelocked at the very high repetition rate of ~77GHz, using a semiconductor saturable absorber mirror (SESAM), is demonstrated. The soliton-like pulses are well separated in time and their duration is 2.7ps. The required negative dispersion is introduced by a GTI-like structure, which is formed by the gain medium and the SESAM.

Introduction: Recently we have demonstrated that solid-state lasers can be passively modelocked at very high repetition rates of 29GHz [1] and later even up to 59GHz [2]. Our concept is based on an Nd:YVO_4 laser with a very compact, quasi-monolithic setup, which is modelocked with a semiconductor saturable absorber mirror [3]. Such lasers are interesting sources for optical clocking or electro-optic sampling for example. Compared to modelocked semiconductor lasers [4], much higher pulse energies can be obtained, while our setup is still very simple and compact compared to a harmonically modelocked fibre laser [5]. With a repetition rate of 59GHz [2], we reached the limit which is given by the pulse duration, of ~ 5ps; and the pulses begin to overlap temporally. For further increases of repetition rate, shorter pulses are required, and the suppression of Q-switching instabilities [6] would also be a challenging task. In this Letter we describe an extension of our concept, which helps to overcome the two limitations mentioned above and demonstrate a modelocked laser with a repetition rate as high as 77GHz with clearly separated pulses. We achieved this by employing soliton modelocking [7], with negative dispersion generated in a GTI-like structure. Repetition rates > 100GHz should be feasible with this approach.

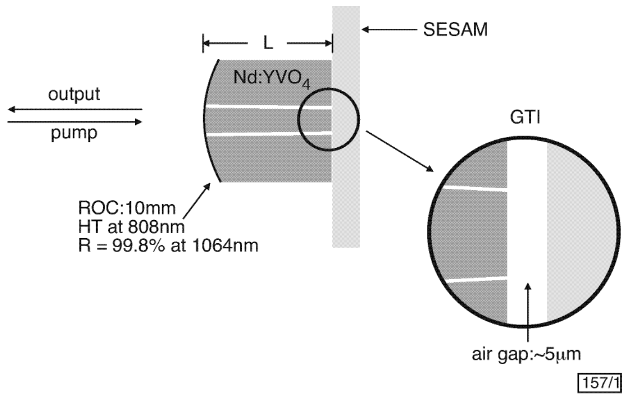

Fig. 1 *Cavity setup with GTI structure*
L = 0.9mm for 77GHz

Advantages of soliton modelocking: The obvious advantage is that shorter pulse durations become possible if the pulse shaping is done mainly by soliton effects rather than by a slow saturable absorber. (The recovery time of the used SESAM is ~100ps, much longer than the pulse duration.) One might first expect that the small modulation depth of our SESAM (~0.24%), which cannot be substantially increased because of Q-switching instabilities, would not allow modelocking of a large fraction of the gain bandwidth. However, this is not so, as the low cavity losses (0.2% from the output coupler and < 0.1% from the SESAM) lead to only weak gain filtering in each cavity roundtrip. The relevant quantity is not the absolute value of the modulation depth, but the ratio of the modulation depth and the total cavity losses. This ratio is rather favourable in our case, and for this reason we obtain rather short pulses of only 2.7ps duration. To our knowledge, these are also the shortest pulses demonstrated directly from a modelocked Nd:YVO_4 laser.

The second and less obvious advantage of soliton modelocking is that it provides increased stability against Q-switching tendencies [6]. Any rise in pulse energy of a soliton is accompanied by an increase of spectral width, so that the effective gain is reduced. This mechanism provides a negative feedback, stabilising the pulse energy. It has been shown [6] that the criterion for stable CW soliton modelocking is

$$E_{sat,L} g K^2 E_p^3 + E_p^2 = E_{p,crit}^2 > E_{sat,L} E_{sat,A} \Delta R \qquad (1)$$

Here, E_p is the intracavity pulse energy. $E_{sat,L} = h\nu_L/(2\sigma L)A_L$ is the saturation energy of the gain medium where σ_L is the emission cross-section at the laser wavelength, the factor 2 accounts for the double pass in a standing-wave cavity and A_L is the laser mode area in the gain medium. ΔR is the modulation depth and $E_{sat,A}$ the saturation energy of the (slow) saturable absorber. K is the ratio of pulse bandwidth and gain bandwidth, divided by the pulse energy E_p, and g is the gain. Typically, the soliton effects reduce $E_{p,crit}$ by a factor of ~3 to 5. This means that soliton effects should allow us to scale up the repetition rate much further without Q-switching instabilities. Other measures for stable CW modelocking are the choice of Nd:YVO_4 (because of its high emission cross-section), the use of a cavity setup with low losses and a rather small mode radius in the gain medium, and optimised SESAM parameters.

Experiment: Our miniature laser setup is shown in Fig. 1. The 0.9mm-long Nd:YVO_4 crystal with 3% neodymium doping is pumped with up to 0.5W at 808nm from a Ti:sapphire laser. The crystal has a curved side (10mm radius of curvature) which is coated for 99.8% reflection at the laser wavelength (1064nm) and high transmission (> 98%) at the pump wavelength (808nm). The other side is flat polished. The SESAM is located in ~5μm distance from the flat side of the crystal; it was grown with MOCVD. It has a saturation fluence of ~100μJ/cm^2 and a modulation depth of $\Delta R \simeq 0.24\%$. It also has a dielectric top mirror with 70% reflectivity to reduce the losses. The recovery time is ~100ps. The output beam is separated from the pump beam with a dichroic mirror (not shown in Fig. 1). The laser mode radius is only ~22μm on the SESAM and in the gain medium.

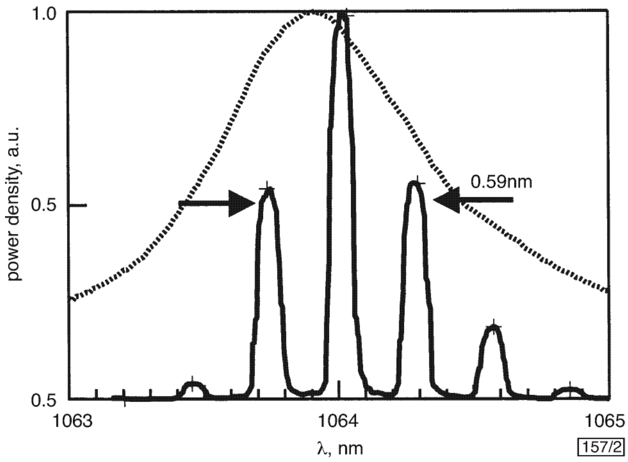

Fig. 2 *Optical spectrum*
Each longitudinal mode is resolved
··········· gain spectrum of Nd:YVO_4

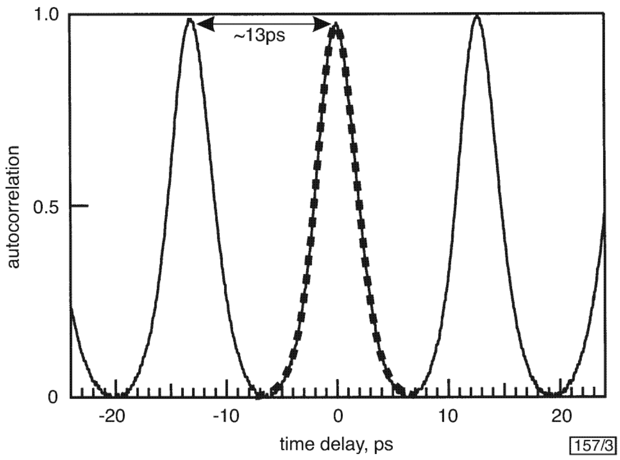

Fig. 3 *Second harmonic autocorrelation*
–■–■–■– sech^2 fit, resulting in 2.7ps pulses separated by ~13ps, corresponding to 77GHz repetition rate

A small air gap, ~5μm-thin, remains between the uncoated face of the crystal and the SESAM, and leads to a GTI-like effect [8], generating negative dispersion. Because the dispersion depends very sensitively on the width of the air gap, this width was adjusted by applying some mechanical pressure to the SESAM which was in direct contact with the crystal, but possibly with a slight tilt angle. This configuration formed a stable GTI structure with a thin air gap between. We observed that stable soliton modelocking was obtained for hours, but only when the air gap was appropriately adjusted. Otherwise we obtained ~5ps-long pulses (with significant overlap of consecutive pulses). For better long-term stability, one could, for example, replace the air gap with a suitable dielectric coating on the SESAM.

The maximum output power of 65mW is generated for a pump power of 450mW. The laser threshold is very low (~2mW). The optical spectrum is shown in Fig. 2. The FWHM bandwidth of 0.59nm is roughly half the amplification bandwidth of $Nd:YVO_4$. Each longitudinal mode could be clearly resolved. Fig. 3 shows the autocorrelation of the pulses, indicating a pulse width of 2.7ps (assuming a $sech^2$ pulse shape). The time-bandwidth product is 0.42. The side peaks result from the correlation with adjacent pulses. The autocorrelation shows that the pulses are separated by ~13ps, corresponding to a repetition rate of 77GHz. Because of this extreme repetition rate, we were not able to measure the microwave frequency spectrum. However, *Q*-switching instabilities can still be excluded because the pulse energy, detected with a fast photodiode, was found to fluctuate by less than 1% within 1s.

Summary: We have demonstrated that the limit for the repetition rate of passively modelocked lasers can be substantially increased by employing soliton modelocking. Negative dispersion was obtained with a GTI formed by a small air gap between SESAM and laser crystal. An alternative would be to use a specially designed SESAM with negative dispersion [9, 10]. Our first experiment resulted in a repetition rate as high as ~77GHz with pulses as short as 2.7ps. Despite this high repetition rate, the overlap of consecutive pulses is very small. This approach should also greatly increase the repetition rates which can be obtained at other wavelengths, such as 1.5μm with Cr:YAG [11] or 1.3μm with $Nd:YVO_4$ [12].

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L. Krainer, R. Paschotta 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*)

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