Passively mode-locked picosecond lasers with up to 59 GHz repetition rate

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We present very compact Nd:YVO_4 lasers which are passively mode-locked with a semiconductor saturable absorber mirror at very high repetition rates between 39 and 59 GHz. We achieved between 30 and 80 mW of average output power and pulse durations of 4.8–5.5 ps. As the pulse-to-pulse spacing is only 17 ps at 59 GHz, we are approaching the limit in repetition rate which is set by the pulse duration. © *2000 American Institute of Physics.* [S0003-6951(00)04240-6]

Pulse trains with ultrahigh repetition rates are in most cases generated either with mode-locked semiconductor lasers or with actively mode-locked fiber lasers. More than 1 THz repetition rate was achieved with semiconductor lasers,[1] which can generate only very small average output powers, and thus pulse energies well below 1 pJ. Fiber lasers have been developed with higher average powers and repetition rates of up to 200 GHz.[2] But for the harmonic mode locking to be sufficiently stable, fairly sophisticated setups are required. Therefore, as an alternative approach for some applications, we recently proposed and demonstrated passively mode-locked solid-state lasers with repetition rates of 12.6 GHz[3] and even 29 GHz.[4] Previously, passively mode-locked lasers were limited to repetition rates of typically <1 GHz because of Q-switching instabilities. The recent improvements became possible through a comprehensive study of Q-switching instabilities[5] which lead us to optimized laser designs. We use compact Nd:YVO_4 lasers for fundamental (i.e., not harmonic) mode locking. In this letter we demonstrate further increases in repetition rates up to 59 GHz, so that we are now approaching the limit which is set by the pulse duration of about 5 ps.

The laser setup is shown in Fig. 1. Each experiment is done with one of three Nd:YVO_4 crystals with 3% Nd doping and different lengths L of 1.15, 1.38, and 1.73 mm, respectively, which determine the repetition rates. One side is curved (10 mm radius) and coated for 99.8% reflectivity at the laser wavelength (1064 nm) and high transmission ($>98\%$) at the pump wavelength (809 nm). The other side is flat polished and antireflection coated for the laser wavelength. To the flat side of the crystal we attached a semiconductor saturable absorber mirror (SESAM),[6] which was described in Ref. 4. The measured SESAM parameters are: modulation depth$=0.24\%$, recovery time$=100\,\mathrm{ps}$, nonsaturable losses$<0.1\%$, saturation fluence$=100\,\mu\mathrm{J/cm}^2$.

The pump light from a Ti:sapphire laser at 809 nm is launched into the crystal through the curved side. The pump absorption length is 90 μm. 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 diameter on the SESAM and in the gain medium between 24 and 29 μm (depending on the crystal length L)

Figure 2 shows the noncollinear autocorrelation (AC) and optical spectrum of the crystal with the largest length of 1.73 mm, corresponding to a repetition rate of 39.2 GHz, for an incident pump power of 505 mW (at the crystal) and an average output power of 60 mW. The AC trace is consistent with a 5.5 ps pulse train and a superimposed constant background of 4% of the peak power. This background, which was not observed at lower repetition rates,[4] becomes stronger for the higher repetition rates of 48.9 GHz (Fig. 3) and 59.3 GHz (Fig. 4). The AC trace of the 48.9 GHz laser fits best to a 5.3 ps train with 5% background, while for the 59.3 GHz laser we obtain 4.8 ps pulses with 19% background. The likely reason for this increasing background is that the pulse-to-pulse spacing (e.g., 17 ps for 59.3 GHz) gets much shorter than the recovery time of the SESAM (≈ 100 ps), so that the SESAM can no longer fully recover between the pulses and thus the effective modulation depth is reduced. SESAMs with faster recovery time can be fabricated with low- tem-

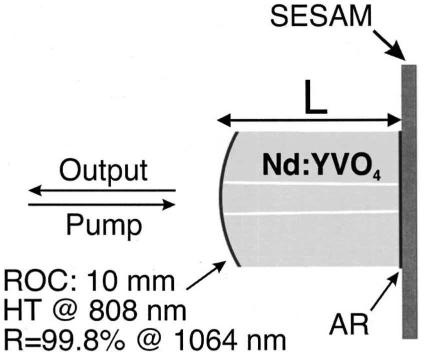

FIG. 1. Laser setup. Three different crystals were used with $L=1.15$ mm, 1.38 mm, and 1.73 mm, respectively, ROC=radius of curvature, HT=high transmission, AR=antireflection coating.

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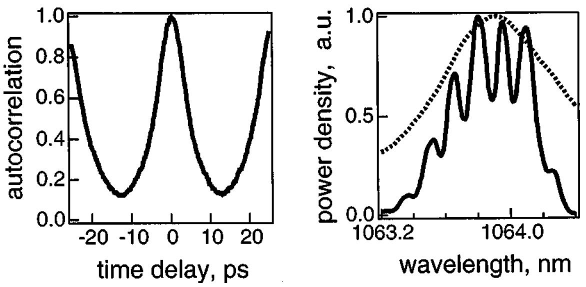

FIG. 2. Autocorrelation and spectrum of the 39.2 GHz mode-locked pulse train, corresponding to 26 ps pulse-to-pulse spacing. The dotted curve shows the gain spectrum of Nd:YVO$_4$.

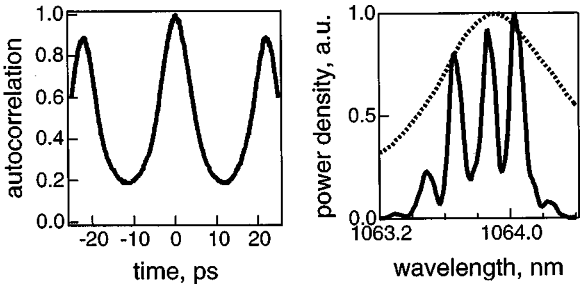

FIG. 3. Left-hand side: autocorrelation of the 48.9 GHz pulse train. Increased losses of our spinning-wheel autocorrelator, which was used in this particular experiment, decreased the height of the cross-correlation peaks. Right-hand side: optical spectrum, compared with the gain spectrum of Nd:YVO$_4$ (dotted curve).

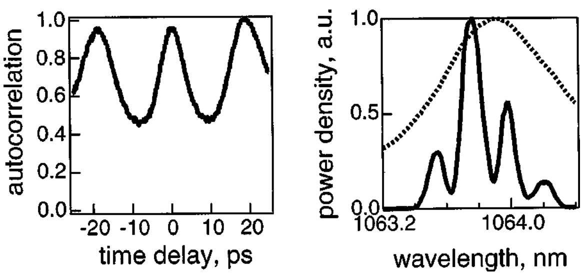

FIG. 4. Autocorrelation and optical spectrum of the 59.3 GHz pulse train. The dotted curve shows the gain spectrum of Nd:YVO$_4$.

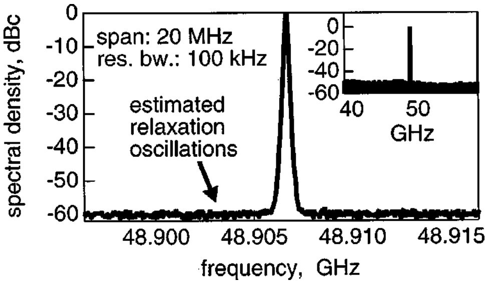

FIG. 5. rf spectrum of the 48.9 GHz pulse train. The absence of satellite peaks shows that Q-switching instabilities are firmly suppressed.

perature (LT) growth, but this typically increases the nonsaturable losses which are critical in this case. It has recently been demonstrated that post-growth annealing[7] or Be doping[8] of LT GaAs can resolve these problems in LT GaAs. We would expect that similar results can be obtained also with LT InGaAs saturable absorbers. However, this needs further investigation.

In the optical spectra (Figs. 2–4), the longitudinal modes of the cavity are clearly resolved. For the highest repetition rate (59.3 GHz), only four longitudinal modes are lasing, and these already fill a large fraction of the gain bandwidth.

Figure 5 shows a rf spectrum, recorded with a fast photodiode (45 GHz bandwidth), an HP 11974A mixer and an HP 8563E rf spectrum analyzer, for the 48.9 GHz laser. The absence of any peaks around the first harmonic at 48.9 GHz shows that Q-switching instabilities are fully suppressed. Similar spectra have been recorded for the other two lasers, except that the noise background increased to ≈ -30 dBc for 59.3 GHz due to the limited performance of the detection system at these high frequencies.

The average output powers of 60, 80, and 30 mW for 39.2, 48.9, and 59.3 GHz, respectively, were limited by lasing of higher-order transverse modes which occurred for higher pump powers. This results from the very small mode radii (24–29 μm) which are necessary to suppress Q-switching instabilities. We see that a laser diode as a replacement of the Ti:sapphire pump laser should deliver $\approx$0.5 W in a nearly diffraction-limited beam. Given the fast progress on the development of diode lasers, such pump lasers should soon become available.

In conclusion, we have demonstrated passive mode locking of compact Nd:YVO$_4$ lasers at very high repetition rates of 39–59 GHz without the onset of Q-switching instabilities. Up to 80 mW of average output power and pulse durations of 4.8–5.5 ps were achieved. We are approaching the limit to the repetition rate which is given by the pulse duration.

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