Compact 10-GHz Nd:GdVO$_4$ laser with 0.5-W average output power and low timing jitter

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We demonstrate a compact, diode-pumped Nd:GdVO$_4$ laser with a repetition rate of 9.66 GHz and 0.5-W average output power. The laser is passively mode locked with a semiconductor saturable absorber mirror (SESAM), yielding 12-ps-long sech^2-shaped pulses. For synchronization of the pulse train to an external reference clock, the SESAM is mounted on a piezoelectric transducer. With an electronic feedback loop of only a few kilohertz loop bandwidth we achieved a rms timing jitter of 146 fs (integrated from 10 Hz to 10 MHz). This is an upper limit because it is mostly limited by the measurement system. The laser setup with a simple linear cavity has a footprint of only 130 mm × 30 mm.

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Research in optical clocking,[1] high-speed electro-optic sampling,[2,3] frequency metrology,[4,5] and a variety of other fields has proved the need for and the applicability of clean and stable high-repetition-rate optical pulses in the 1-μm regime. Although the span of possible applications is broad, the ideal pulse source usually has the following features: the emitted pulse train has to consist of femtosecond or picosecond pulses with high contrast ratio, high pulse energy, and low timing jitter, and the source should be cheap, compact, and reliable. Diode-pumped, passively mode-locked solid-state lasers have already proved their potential as high-repetition-rate pulse sources in different wavelength regimes[6,7] and as seed lasers for high-repetition-rate optical parametric oscillators,[8] fulfilling the above-mentioned requirements. The advantages of diode-pumped passively mode-locked solid-state lasers compared with other approaches, such as fiber lasers[9] or edge-emitting semiconductor lasers,[10] are manifold: Material costs are determined mainly by the prize of the pump diodes, which is steadily decreasing. Their size can be scaled to miniature levels.[6] Passive mode locking results in excellent timing jitter and long-term stability.[11] The lack of any drive electronics for pulse generation and their good electrical-to-optical efficiency allow for low power consumption, high reliability, and turnkey operation.[12]

Repetition rates of up to 160 GHz have already been demonstrated with passively mode-locked Nd:YVO$_4$ lasers.[6,13] However, compared with yttrium-doped vanadate, Nd:GdVO$_4$ shows additional promising properties, which makes it suitable for high-power, high-repetition-rate passively mode-locked lasers: the thermal conductivity of 12 W/mK is comparable with that of Nd:YAG, whereas the areas of the absorption and emission cross sections are similar to those of Nd:YVO$_4$.[14] The absorption bandwidth of 1.6 nm at 808 nm of Nd:GdVO$_4$ is larger than for Nd:YVO$_4$ or Nd:YAG, making it more suitable for diode pumping.[14] Only recently it was shown that diode pumping Nd:GdVO$_4$ at 879 nm can lead to a record high slope efficiency of 78%.[15] So far the highest repetition rate of a passively mode-locked Nd:GdVO$_4$ laser of which we are aware is 154 MHz.[16] In this Letter we show that Nd:GdVO$_4$ is also well suited for multigigahertz repetition-rate operation and that our laser setup shows excellent performance in terms of timing jitter, compactness, and stability.

Figure 1 shows our laser setup. By using a 2-W 808-nm laser diode with a 50-μm stripe size from Fuji

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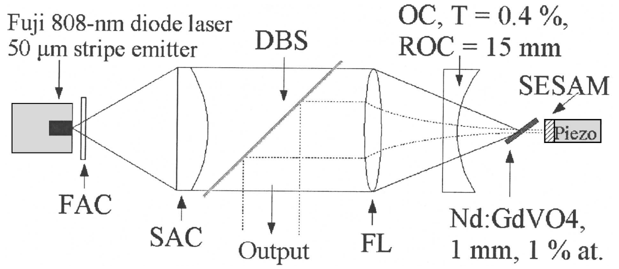

Fig. 1. Setup of the 10-GHz laser: DBS, dichroic beam splitter; FL, focusing lens; OC, output coupler; T, transmission.

Photo Film,[17] we were able to achieve a small pump spot in the Nd:GdVO$_4$ crystal (1% atm. doping) while maintaining a compact pump setup. The measured M^2 values were 12 along the slow axis and 1 along the fast axis. The diode was temperature controlled and the diode mount was air cooled. We used a 0.9-mm focal-length fast-axis collimator cylindrical lens (FAC) in combination with a 50-mm slow-axis collimator cylindrical lens (SAC) to obtain a collimated pump beam that was focused into the crystal with a 30-mm focal-length achromat. The linear cavity consisted of a 15-mm curved output coupler (0.4% transmission at 1063 nm) and a 1-mm-thick Nd:GdVO$_4$ crystal, placed 2 mm before a semiconductor saturable absorber mirror (SESAM).[18,19] The calculated beam waist was 37 μm on the SESAM and slightly larger in the gain medium. The output beam was separated from the pump beam by a dichroic beam splitter, mounted under 45°. The footprint of the laser system was only 130 mm × 30 mm.

For a pump power of 1.8 W incident upon the crystal (2.1 W out of the laser diode), we obtained 500 mW of average output power, resulting in an optical-to-optical slope efficiency of 27%. The M^2 of the output beam was measured to be <1.1 in the vertical and <1.3 in the horizontal axis. The antiresonant SESAM consisted of a 4-nm-thick InGaAs absorber grown on top of a GaAs/AlAs Bragg mirror. Three GaAs/AlAs Bragg pairs were placed on top of the absorber to increase the linear reflectivity and to decrease the modulation depth. The measured SESAM parameters were 60 μJ/cm^2 saturation fluence, 0.3% modulation depth, <0.1% nonsaturable losses, and a recovery time of 28 ps. Figure 2 shows the power spectral density of the microwave spectrum.

The laser was cw mode locked at 9.659 GHz, with only weak noise at the relaxation oscillation frequency around 3 MHz. The Q-switched mode-locking threshold[20] was at 200-mW average output power. The measured pulse duration was 12 ps, assuming a sech^2 pulse shape, at a center wavelength of 1063.1 nm with 0.2-nm bandwidth. The calculated pulse energy was 50 pJ, resulting in a pulse peak power of 3.3 W. The sealed laser has been operated for more than 100 h with stable mode locking and no decrease of output power.

For applications in telecommunications as well as in other areas it is crucial that the pulses are synchronized with a clock signal supplied by the system. This synchronization is naturally given for actively or hybrid mode-locked lasers, while a passively mode-locked laser needs to be actively synchronized to the clock signal. This can be done by use of a simple phase-locked loop, which locks the cavity length to the clock signal.[21] For this purpose we mounted the SESAM on a piezo element (Fig. 1). By using a low-bandwidth (~5 kHz) phase-locked loop we are able to synchronize the laser to a microwave reference clock (Agilent E8241A with a low-noise option UNJ). To avoid unnecessary air currents that could increase the timing jitter, the cavity was hermetically sealed in a stainless-steel box. The output coupler as well as the piezo was also attached to the same steel box, reducing unwanted mirror vibrations.

Figure 3 shows the noise sidebands around the first harmonic (9.66 GHz) of the photodiode signal of the synchronized laser (gray, dotted curve) and of the reference clock (gray, dashed curve) and the noise sidebands of the laser around the fourth harmonic (black, solid curve). All spectra were recorded with a Hewlett Packard HP 8565EC spectrum analyzer, with corrections to account for logarithmic averaging and the effective noise bandwidth. Pure intensity noise would result in the same noise level for the first and fourth harmonics, whereas pure phase noise leads to a 12-dB-higher level for the fourth harmonic.[22] This shows that the relaxation oscillations around 3 MHz hardly affect the phase noise (timing jitter), whereas phase noise is dominating above 1 kHz, where the above-mentioned 12-dB difference between the first and fourth harmonics is observed. Note, however,

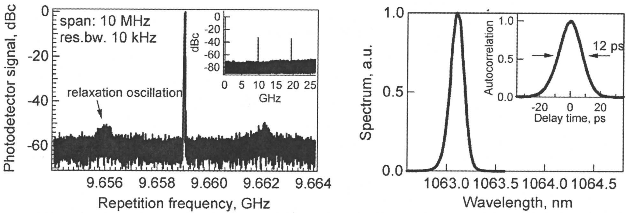

Fig. 2. Left, microwave spectrum of the 9.659-GHz cw mode-locked Nd:GdVO$_4$ laser. Noise at the relaxation oscillation frequency (3 MHz) is seen but is quite weak. Right, optical spectrum and autocorrelation trace (inset).

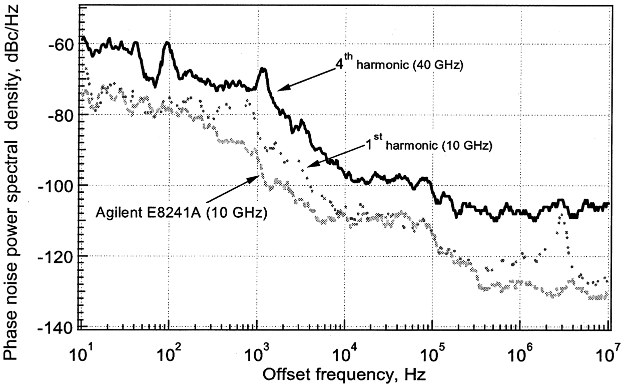

Fig. 3. Phase noise power spectral density, measured at the first and fourth harmonics of the 10-GHz Nd:GdVO$_4$ laser and the Agilent E8241A reference clock (with a low-noise option UNJ).

that phase noise can result not only from the laser or from the reference oscillator but also from the local oscillator of the spectrum analyzer. Indeed, it turns out that in a large part of the frequency range the recorded noise approximately agrees with the phase noise specifications of the HP 8565EC. The same holds for the noise trace recorded with the Agilent oscillator, which is also dominated by the phase noise of the local oscillator, except that the phase noise of the HP 8565EC is weaker around 10 GHz. In conclusion, the recorded noise comes mostly from the spectrum analyzer, and the calculated rms jitter value of 146 fs for integration from 10 Hz to 10 MHz is only an upper limit for the actual timing jitter of the laser. We expect to get significantly lower jitter values when applying improved measurement techniques. Analytical estimates[23] show that the quantum fluctuations would set a limit well below 10 fs rms for the timing jitter of such a laser, even when one is using feedback electronics with a moderate loop bandwidth of only a few kilohertz.

We have demonstrated a passively mode-locked Nd:GdVO$_4$ laser, operating at a 9.66-GHz repetition rate with an average output power of 0.5 W and 12-ps pulse duration. By locking the cavity length to an external clock source, we achieved an integrated timing jitter from 10 Hz to 10 MHz of only 146 fs, limited by the measurement setup. The laser fits on a footprint of only 130 mm × 30 mm and showed no degradation in output power or mode-locking stability over 100 h.

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