High-power, diode-end-pumped, multigigahertz self-mode-locked Nd:YVO_4 laser at 1342 nm

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We report on a high-power, diode-pumped, self-mode-locked laser at 1342 nm with the Kerr effect arising from large third-order nonlinearity of Nd:YVO_4 crystal. At the pump power of 10.2 W, the average output power of 1.2 W was generated with a repetition rate in the range of 2–6 GHz. The mode-locked pulse width can be smoothly varied from 11.5 to 37 ps by controlling the amount of spatial hole burning. © 2009 Optical Society of America

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Numerous Nd-doped crystals have been developed for generating 1.3 μm lasers at cw or pulsed operation [1–5], because light sources at 1.3 μm have a wide variety of applications such as telecommunications, fiber sensing, range finding, and data storage. Nd-doped yttrium vanadate (Nd:YVO_4) has been identified as an excellent laser host material for diode-pumped solid-state lasers. Recent studies have further proved that YVO_4 crystals have a large value of third-order susceptibility [6] that has been exploited for efficient stimulated Raman scattering conversion [7–10]. More recently, it has also been demonstrated that the large third-order nonlinearity of Nd:YVO_4 crystals can be used to achieve an efficient self-starting Kerr-lens mode-locking operation at frequencies of several gigahertz [11]. This demonstration offers the promising prospect of developing a compact self-starting mode-locked Nd:YVO_4 laser at 1.34 μm.

In this Letter we report for the first time a compact multigigahertz, self-starting, mode-locked 1.34 μm Nd:YVO_4 laser without the need for any additional components. With an incident pump power of 10.2 W, the miniature linear laser cavity produces average output powers up to 1.2 W with repetition rates in the range of 2.0–6.0 GHz. The mode-locked pulse width can be varied smoothly from 11.5 to 37 ps by controlling the amount of spatial hole burning by moving the gain medium within the cavity [12].

An experimental setup is shown schematically in Fig. 1. The cavity configuration is a simple concave-plano resonator. The gain medium is a-cut 0.25 at. % Nd:YVO_4 crystal with dimensions of 3 mm $\times$ 3 mm $\times$ 10 mm. Both end surfaces of the Nd:YVO_4 crystal were antireflection coated at 1342 nm and wedged 2° to avoid the Fabry–Perot etalon effect. The laser crystal was wrapped with indium foil and mounted in a water-cooled copper holder. The water temperature was maintained at $\approx 20°$C to ensure stable laser output. The input mirror was a 50 cm radius-of-curvature concave mirror with antireflection coating at 808 nm on the entrance face and with high-reflectance coating at 1342 nm ($>99.8\%$) and high-transmittance coating at 808 nm on the second surface. A flat wedged output coupler with 7% transmission at 1342 nm was used throughout the experiment. The pump source was a 12 W, 808 nm fiber-coupled laser diode with a core diameter of 200 μm and NA of 0.22. A focusing lens with 5 mm focal length and 85% coupling efficiency was used to reimage the pump beam into the laser crystal. The average pump size was approximately 130 μm. The optical cavity length was varied between 2.5 and 7.5 cm for a corresponding free spectral range of 6 to 2 GHz. The separation between the laser crystal and the input mirror d could be freely adjusted in the range of 1–10 mm. It has been verified that the crystal/mirror separation may be exploited to control the amount of spatial hole burning [12].

The mode-locked pulses were detected by a high-speed InGaAs photodetector (Electro-optics Technology Inc. ET-3500, with rise time of 35 ps) whose output signal was connected to a digital oscilloscope (Agilent, DSO 80000) with 12 GHz electrical bandwidth and sampling interval of 25 ps. The output signal of the photodetector was also analyzed by a radio frequency spectrum analyzer (Advantest, R3265A) with a bandwidth of 8 GHz. The spectral information of the laser was monitored by a Fourier optical spectrum analyzer (Advantest, Q8347) containing a Michelson interferometer with resolution of 0.003 nm.

The laser cavity was first aligned to obtain the maximum average output power. Under this circumstance, the laser output was found to exhibit a spontaneous mode locking with fairly small amplitude

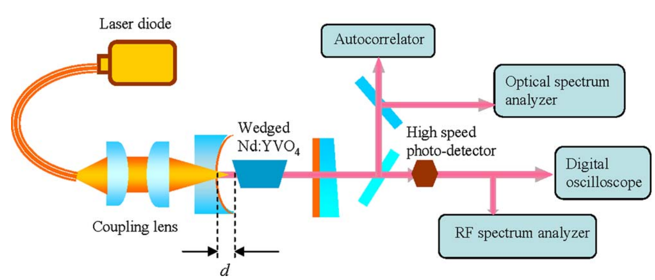

Fig. 1. (Color online) Schematic of a diode-pumped self-mode-locked Nd:YVO_4 laser at 1342 nm.

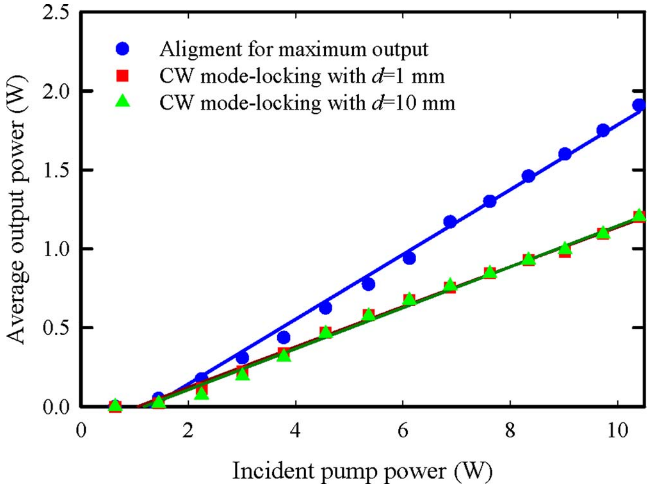

Fig. 2. (Color online) Average output power at 1342 nm versus incident pump power in cw and mode-locked operation.

fluctuations. With fine adjusting of the cavity, the amplitude instability was minimized to obtain a nearly perfect stable mode-locking operation. The average output power of the stable cw mode locking was found to be approximately 65% of the maximum average output power. Figure 2 depicts the average output power at 1342 nm with respect to the incident pump power in the optimum power-output operation and in the mode-locked operation with a frequency of 3.365 GHz. In the optimum power-output regime the laser had a slope efficiency of 20.1%; the output power reached 1.85 W at an incident pump power of 10.2 W. As shown in Fig. 2, the laser had a slope efficiency of 13%; the output power reached 1.2 W at an incident pump power of 10.2 W. It can also be seen that the average output power was nearly independent of the crystal/mirror separation d.

Note that once the pump power reaches the lasing threshold, the laser system instantaneously steps into a stable mode-locked operation, i.e., no threshold for the self-mode-locking. The thermal lens in the gain medium was estimated to be 20–30 cm at a pump power of 10 W. The mode sizes in the gain medium and on the output coupler were calculated to be $\approx$190 μm and 170 μm, respectively. The overall M^2 beam quality factor was found to be better than 1.4. The transverse beam profile did not reveal significant change between the optimum power output and the mode-locking regime. It is worth mentioning that the wedge shape of the output coupler is vital for obtaining a completely stable mode-locked operation. When an output coupler without a wedge is used in the laser cavity, the pulse trains exhibit incomplete mode-locking with cw background to a certain extent.

Figures 3(a) and 3(b) show the pulse trains on two different time scales, one with time span of 5 ns, demonstrating mode-locked pulses, and the other with time span of 5 μs, demonstrating the amplitude stability. It can be seen that the pulse trains display full modulation and complete mode-locking is achieved. The power spectrum reveals that the relative frequency deviation of the power spectra $\Delta\nu/\nu$ is experimentally found to be significantly smaller than 10^{-4} over day-long operation, where ν is the center frequency of the power spectrum and $\Delta\nu$ is the frequency deviation of FWHM. Experimental results reveal that the laser system can be stably operated in a single-pulse mode-locked state as long as the cavity length is shorter than $\approx$7.5 cm (mode-locked repetition rate >2 GHz). For cavity length longer than 8.5 cm, a single pulse per round trip was usually observed to split into several pulses. This characteristic is the same as the result in self-mode-locked lasers at 1.06 μm [11].

The pulse width during cw mode-locked operation was measured with an autocorrelator (APE Pulse Check, Angewandte Physik & Elektronik GmbH). For a crystal/mirror separation of d=1 mm, the FWHM of the autocorrelation trace was measured to be 17.3 ps, as shown in Fig. 4(a). Assuming a sech^2-shaped temporal profile, the pulse width was thus estimated to be 11.5 ps. Figure 4(b) shows the FWHM width of the optical spectrum to be approximately 0.22 nm at the central wavelength of 1342.1 nm. Consequently, the time–bandwidth product of the mode-locked pulse is 0.43, indicating the pulses to be frequency-chirped. Even though the pulse width is slightly longer than the 7.3 ps obtained in a passively mode-locked laser with semiconductor saturable absorber [13], the average output power of 1.2 W is significantly higher than the result in that case of 40 mW. More important, the self-mode-locked operation can be implemented without the need for any additional components. To confirm the peak power of the pulses, an experiment of the extra-cavity second-harmonic generation (SHG) was performed. The conversion efficiency for the average power was found to be enhanced by approximately 10 times, quite consistent with the theoretical simulation. The ratio of the peak to background for the SHG power was found to be increased by up to 2 orders of magnitude.

It was demonstrated [12] that the pulse width in diode-end-pumped actively mode-locked lasers can be

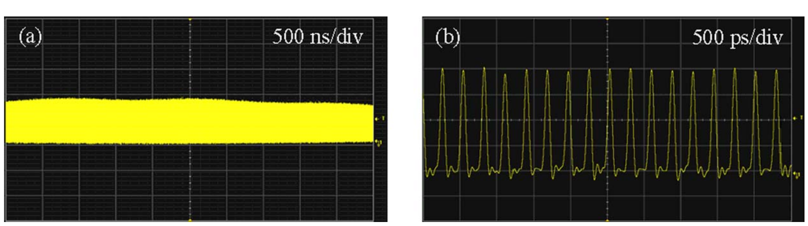

Fig. 3. (Color online) Pulse trains on two different time scales: (a) time span of 5 μs, demonstrating mode-locked pulses; (b) time span of 5 ns, demonstrating amplitude oscillation.

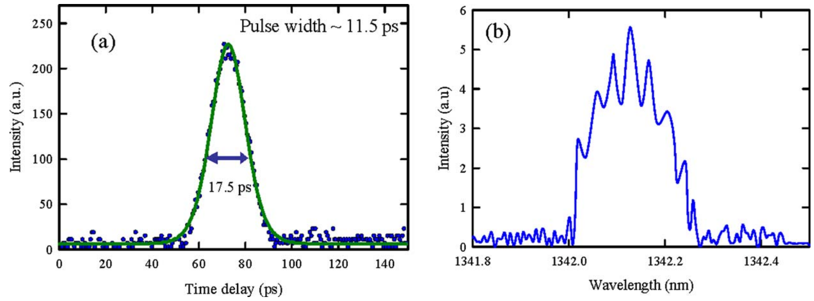

Fig. 4. (Color online) (a) Autocorrelation trace of the output pulses from the cw mode-locked Nd:YVO_4 laser; (b) corresponding optical spectrum of the laser.

adjusted by changing the crystal/mirror separation d to control the amount of spatial hole burning. This spatial-hole-burning effect is also speculated to be functioning in passively mode-locked lasers. We use the present simple linear cavity to investigate the pulse-width dependence on the crystal/mirror separation. With increasing crystal/mirror spacing up to 10 mm, the mode-locked pulse width varies smoothly from 11.5 to 37 ps, and the spectral bandwidth varies from 37 to 12 GHz, as shown in Fig. 5. This result confirms the speculation that spatial hole burning is also effective in passively mode-locked lasers [12].

In conclusion, we have realized a compact efficient self-mode-locked 1.34 μm Nd:YVO_4 laser in which the pulse repetition rate can be operated in the range of 2–6 GHz. The average output power was up to 1.2 W at an incident pump power of 10.2 W, which gives an optical conversion efficiency of 11.7%. The mode-locked pulse width could be smoothly varied from 11.5 to 37 ps by increasing the crystal/mirror separation from 1 mm to 10 mm to control the amount of spatial hole burning. We believe that a compact efficient GHz self-mode-locked Nd:YVO_4 laser at 1.34 μm can be a potential light source for many applications such as high-capacity telecommunication systems, photonic switching devices, optical interconnections, and optical clocking.

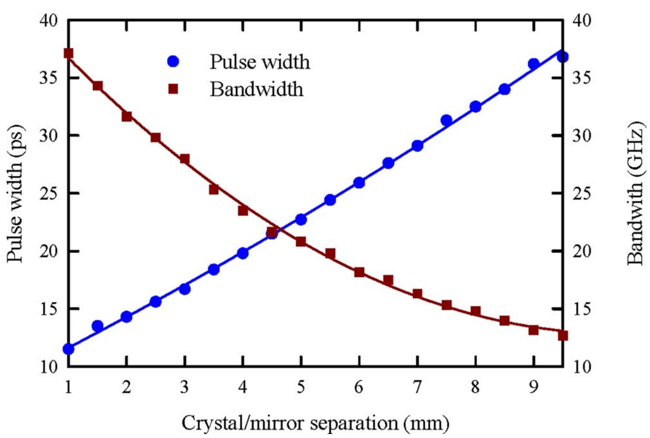

Fig. 5. (Color online) Mode-locked pulse width and bandwidth as functions of the crystal/mirror separation.

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