Femtosecond pulse generation with a diodepumped Yb³⁺:YVO₄ laser

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A diode-pumped Yb:YVO4 laser has been passively mode locked for the first time, to our knowledge. 120 fs pulses with an average output power of 300 mW and a peak power as high as 14.5 kW are obtained by use of a semiconductor saturable-absorber mirror for passive mode locking. The optical spectrum has a 10 nm bandwidth (full width at half-maximum) and is centered at 1021 nm. © 2005 Optical Society of America $OCIS\ codes:\ 140.3480,\ 140.4050,\ 160.5690.$

Yb³⁺-doped crystals are attractive materials for highpower directly diode-pumped femtosecond lasers. The highest output powers in the mode-locked regime have been demonstrated with Yb:YAG crystals,² having a comparatively high thermal conductivity of 11 W/mK. However, the emission bandwidth of this material limited the pulse duration to 700-800 fs, or to 340 fs in a low-power laser.³ Much shorter pulses (near 100 fs and less) were obtained with a number of crystals with a broader emission band, such as Ybdoped KYW, KGW, GdCOB, BOYS, etc., 4-10 and with Yb:glass. 11 However, these materials have a low thermal conductivity of approximately 2-3 W/mK, which severely limits their potential for high-power operation. Recently, what is believed to be the first demonstration of a femtosecond laser based on Yb-doped CaF₂, which has a thermal conductivity near 10 W/mK, was reported. 12 Pulses as short as 150 fs were obtained with this crystal. Very recently, efficient continuous-wave laser operation has been demonstrated with the new laser crystal Yb:YVO4, which exhibits strong absorption near 985 nm with a bandwidth [full width at half maximum (FWHM)] of ~9 nm (that is suitable for pumping by commercially available laser diodes), and a broad and smooth gain spectrum comparable to that of the crystals mentioned above. The thermal conductivity of yttrium vanadate crystals is 5.23 W/mK along the c axis and 5.10 W/mK along the a axis, ¹⁵ i.e., lower than in YAG; however, approximately 40% higher than, e.g., in the well-known KGW, whereas the gain spectrum is smoother than for Yb: CaF₂. Here we report for the first time to our knowledge on femtosecond pulse generation with a diode-pumped Yb:YVO₄ laser that is passively mode locked with a semiconductor saturable-absorber mirror (SESAM). 16,17

The laser experiments were carried out with a simple delta cavity (Fig. 1). To obtain good alignment stability, the laser cavity was designed to operate in

stability zone ${\rm I.}^{18}$ As the gain medium we used a 2 -mm-thick Yb:YVO₄ crystal with 3-at. % ytterbium concentration at Brewster incidence. The crystal orientation was chosen for π polarization $(E \parallel c)$ where the absorption and stimulated-emission cross sections have higher values than for σ polarization, as shown in our previous work. Absorption and stimulated-emission cross-section spectra are presented in Fig. 2. An 8-W continuous-wave (cw) fibercoupled diode laser with a core diameter of 100 µm and a numerical aperture of 0.22 operated around 980 nm with a spectral bandwidth of 6 nm was used for longitudinal pumping of the gain medium along the a axis. Longitudinal pumping through spherically curved mirror M1 has problems because of the narrow spectral interval (of ~40 nm) between the pump and the laser wavelengths. Because we used a standard $\lambda/4$ coating optimized for high reflectivity at wavelengths longer than 1030 nm, mirror M1 had a transmission of only 60% at 980 nm, and the maxi-

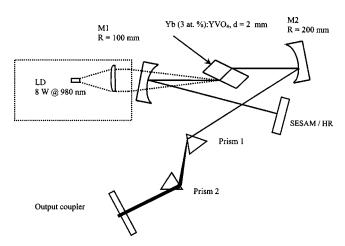


Fig. 1. Setup of the passively mode-locked diode-pumped Yb: YVO_4 laser.

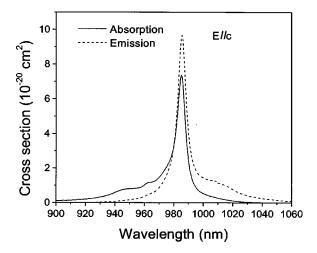


Fig. 2. π -polarized absorption and emission cross-section spectra of Yb³⁺:YVO₄ at room temperature.

mum incident pump power at the crystal was reduced to 4.5 W. The pump beam was not polarized, thus the maximum absorbed pump power was only 2.4 W (due to reflections from the Brewster-oriented crystal surfaces and the difference between the absorption coefficients in σ and π polarizations of the Yb:YVO $_4$ crystal 13). The pump beam was focused with four lenses to a spot with a $55\times110~\mu{\rm m}$ radius inside the laser crystal. The cavity mode radius in the gain medium was close to the pump beam radius. The Yb:YVO $_4$ crystal was mounted on a copper heat sink kept at 10 °C.

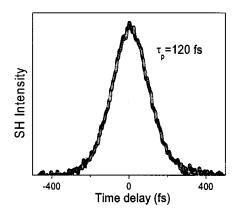
For passive mode locking we used a SESAM with a 15-nm-thick InGaAs quantum-well absorber, a standard antiresonant design, 17 and a Bragg mirror centered at 1040 nm. The modulation depth was $\approx 1\%$. A pair of SF10 prisms with a 45 cm spacing allowed us to achieve a total negative group delay dispersion of $-3000~\rm fs^2$ per round trip as needed for soliton mode locking. 19 Stable cw mode-locked operation was obtained with an output coupler transmittance of $\sim 3\%$. The mode-locking threshold was 2.2 W of the absorbed pump power with a cavity mode radius at the SESAM of 65 μm . The Yb:YVO $_4$ laser produced up to 300-mW average output power with a pulse duration of 120 fs at a central wavelength of 1021 nm. The intensity autocorrelation and optical spectrum of the

Yb:YVO₄ laser are presented in Fig. 3. The pulse repetition rate was ~ 150 MHz, resulting in a peak power of 14.5 kW. The time—bandwidth product was ≈ 0.348 , not far from the transform limit for soliton pulses ($\tau_p\Delta\nu=0.315$). We did not observe any tendency for Q-switched mode locking above the modelocking threshold. This is to the best of our knowledge the first demonstration of a cw mode-locked Yb:YVO₄ laser.

In the cw regime, without prisms inside the cavity, with a high reflector substituted for the SESAM, and with an output coupler transmittance of 6.3%, a slope efficiency with respect to the absorbed pump power of 45% was obtained with an output power of 370 mW at 1019 nm. The maximum output power of 415 mW with a slope efficiency of 38% at 1023 nm was obtained for an output coupler transmittance of $\approx\!3\%$. The longer laser wavelength for lower cavity losses results from the reabsorption losses at shorter wavelengths as a result of the three-level laser scheme of the Yb³+ ion. The effective gain cross-section spectra $g(\lambda)$ of the Yb:YVO4 crystal as a function of excitation parameter β have been calculated from the following expression 20 :

$$g(\lambda) = \beta \sigma_{\rm se}(\lambda) - (1 - \beta) \sigma_{\rm abs}(\lambda),$$
 (1)

where $\beta = N_e/N_t$ is the ratio of the number of excited ions to the total number of ions, $\sigma_{\rm se}$ and $\sigma_{\rm abs}$ are the stimulated-emission and absorption cross section, respectively. The results are presented in Fig. 4. The calculations show that gain of Yb: YVO₄ has a broad and smooth shape. Gain spectra with β =0.15 and 0.25 correspond to the cavity losses of the cw Yb:YVO₄ laser for output coupler transmittances of 3% and 6.3% with maxima at 1023 and 1019 nm, respectively. Excitation parameter β in the modelocked laser was ≈ 0.2 (dashed line). For this value of excitation parameter, the FWHM gain bandwidth is \approx 32 nm (with the gain maximum at 1021 nm), confirming the possibility of sub-100-fs pulse generation. The narrower spectra of the pulses obtained in the experiments can be explained with wavelengthdependent losses of the cavity mirrors (which are due to rapidly increasing transmission of mirror M1 at shorter wavelengths).



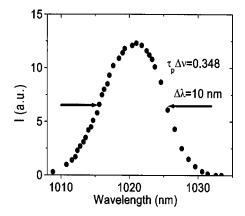


Fig. 3. Intensity autocorrelation (left) with a sech² fit and optical spectrum (right) of the Yb:YVO₄ laser.

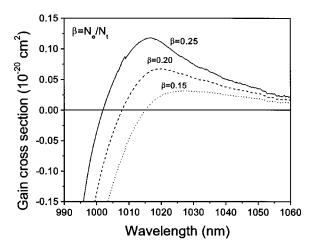


Fig. 4. π -polarized gain cross-section spectra of Yb³⁺ in YVO₄ at room temperature for different values of excitation parameter β .

In conclusion, we have demonstrated for the first time to our knowledge femtosecond pulse generation from a diode-pumped Yb: YVO₄ laser passively mode locked with a SESAM. Laser pulses of 120-fs duration were obtained with an average output power of 300 mW and a repetition rate of 150 MHz. We believe that sub-100-fs pulses could be generated with this crystal with optimized laser parameters (i.e., group delay dispersion in the cavity and modulation depth of a SESAM). Further, Yb: YVO₄ looks promising for high-power thin-disk femtosecond lasers because of its extremely low heat generation (the quantum defect is only 3.9% in the mode-locked regime) and comparatively good thermal conductivity. We believe that a diode-pumped thin-disk Yb: YVO₄ laser could produce more than 30-W average power and <150-fs pulse duration, while avoiding the need for pumping through a dielectric mirror with high discrimination of the closely located pump and laser wavelengths.

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