Femtosecond pulse generation with a diode-pumped $Yb^{3+}:YVO_4$ laser

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A diode-pumped $Yb:YVO_4$ 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

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Yb^{3+}-doped crystals are attractive materials for high-power directly diode-pumped femtosecond lasers.[1] 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 Yb-doped 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 CaF_2, 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 $Yb:YVO_4$,[13,14] 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,[4] whereas the gain spectrum is smoother than for $Yb:CaF_2$. Here we report for the first time to our knowledge on femtosecond pulse generation with a diode-pumped $Yb:YVO_4$ 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 I.[18] As the gain medium we used a 2-mm-thick $Yb:YVO_4$ crystal with 3-at. % ytterbium concentration at Brewster incidence. The crystal orientation was chosen for π polarization ($E \| c$) where the absorption and stimulated-emission cross sections have higher values than for σ polarization, as shown in our previous work.[13] Absorption and stimulated-emission cross-section spectra are presented in Fig. 2. An 8-W continuous-wave (cw) fiber-coupled 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-

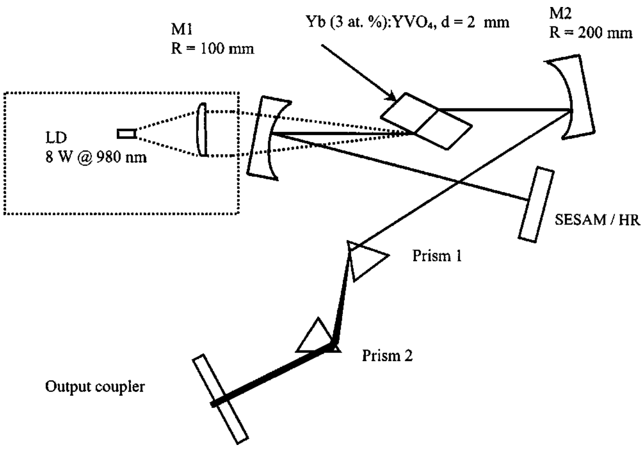

Fig. 1. Setup of the passively mode-locked diode-pumped $Yb:YVO_4$ laser.

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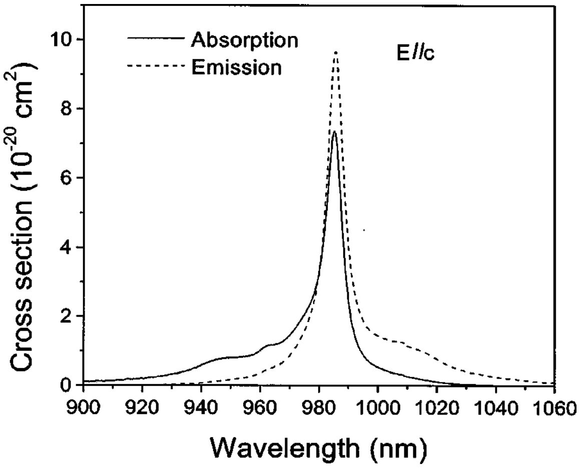

Fig. 2. π-polarized absorption and emission cross-section spectra of Yb^{3+}:YVO_4 at room temperature.

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 55×110 μm 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 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:YVO_4 laser are presented in Fig. 3. The pulse repetition rate was $\sim$150 MHz, resulting in a peak power of 14.5 kW. The time–bandwidth product was $\approx$0.348, not far from the transform limit for soliton pulses ($\tau_p \Delta\nu = 0.315$). We did not observe any tendency for Q-switched mode locking above the mode-locking threshold. This is to the best of our knowledge the first demonstration of a cw mode-locked Yb:YVO_4 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 Yb^{3+} ion.[20] The effective gain cross-section spectra $g(\lambda)$ of the Yb:YVO_4 crystal as a function of excitation parameter β have been calculated from the following expression[20]:

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

where $\beta = N_e/N_t$ is the ratio of the number of excited ions to the total number of ions, σ_{se} and σ_{abs} are the stimulated-emission and absorption cross section, respectively. The results are presented in Fig. 4. The calculations show that gain of Yb:YVO_4 has a broad and smooth shape. Gain spectra with β=0.15 and 0.25 correspond to the cavity losses of the cw Yb:YVO_4 laser for output coupler transmittances of 3% and 6.3% with maxima at 1023 and 1019 nm, respectively. Excitation parameter β in the mode-locked laser was $\approx$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).

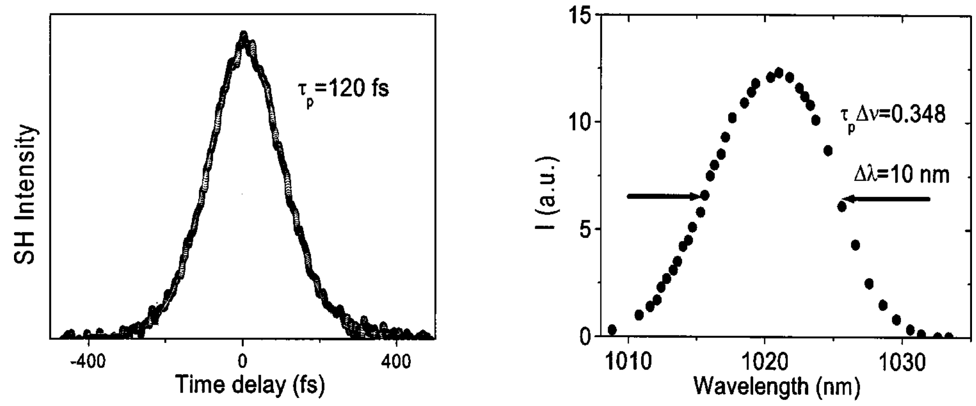

Fig. 3. Intensity autocorrelation (left) with a sech^2 fit and optical spectrum (right) of the Yb:YVO_4 laser.

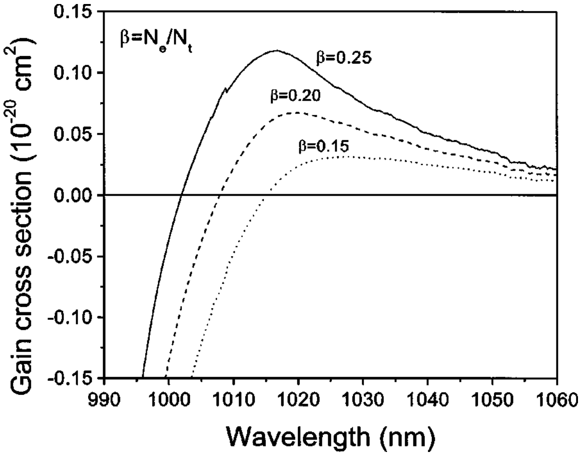

Fig. 4. π-polarized gain cross-section spectra of Yb^{3+} in YVO_4 at room temperature for different values of excitation parameter β.

In conclusion, we have demonstrated for the first time to our knowledge femtosecond pulse generation from a diode-pumped $Yb:YVO_4$ 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, $Yb:YVO_4$ 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 $Yb:YVO_4$ 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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