

Femtosecond pulse generation with a diode-pumped $\text{Yb}^{3+}:\text{YVO}_4$ laser

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A diode-pumped $\text{Yb}:\text{YVO}_4$ 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 $\text{Yb}:\text{YAG}$ 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 $\text{Yb}:\text{YVO}_4$,^{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 $\text{Yb}:\text{CaF}_2$. Here we report for the first time to our knowledge on femtosecond pulse generation with a diode-pumped $\text{Yb}:\text{YVO}_4$ 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 $\text{Yb}:\text{YVO}_4$ 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.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-

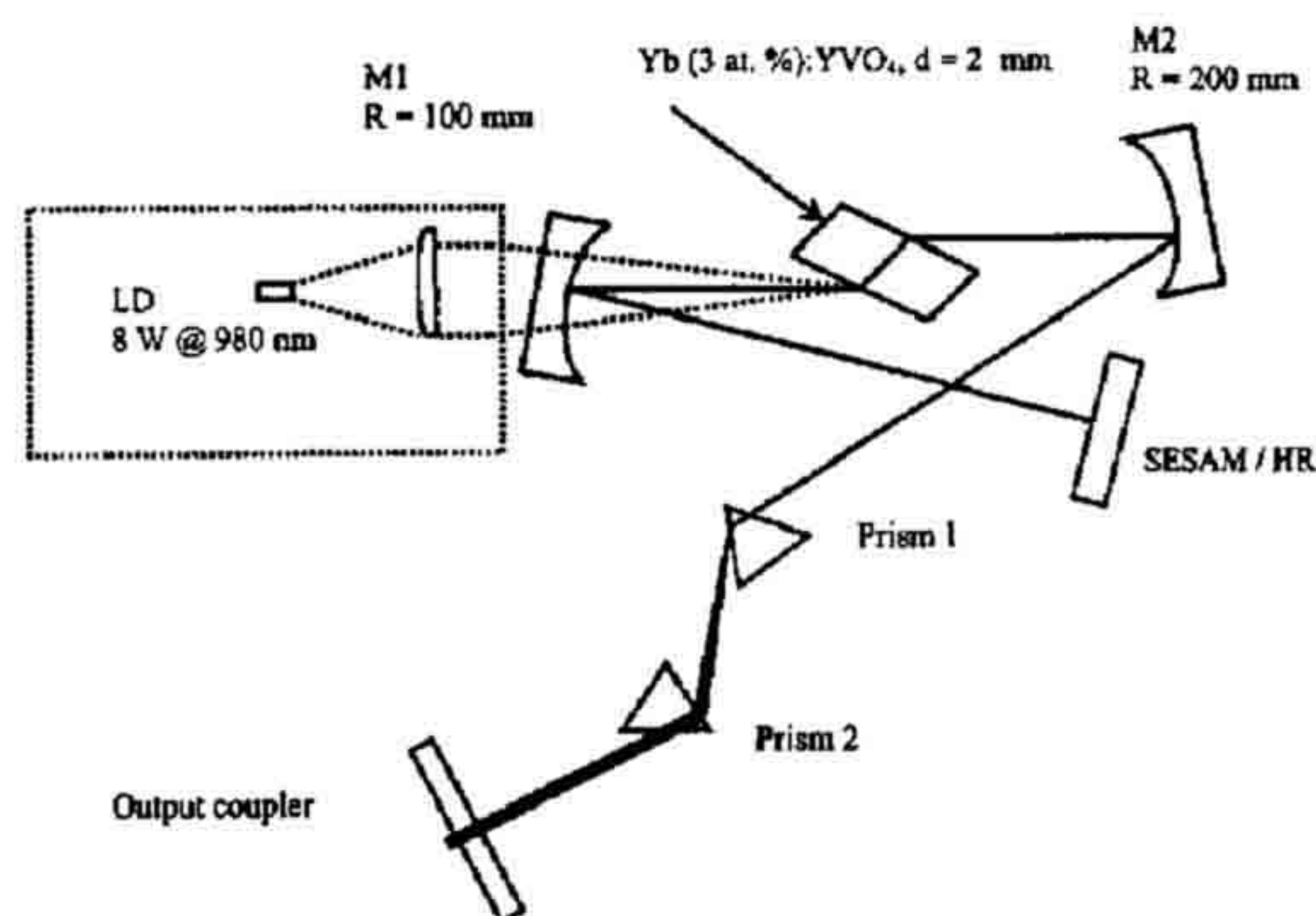


Fig. 1. Setup of the passively mode-locked diode-pumped $\text{Yb}:\text{YVO}_4$ laser.

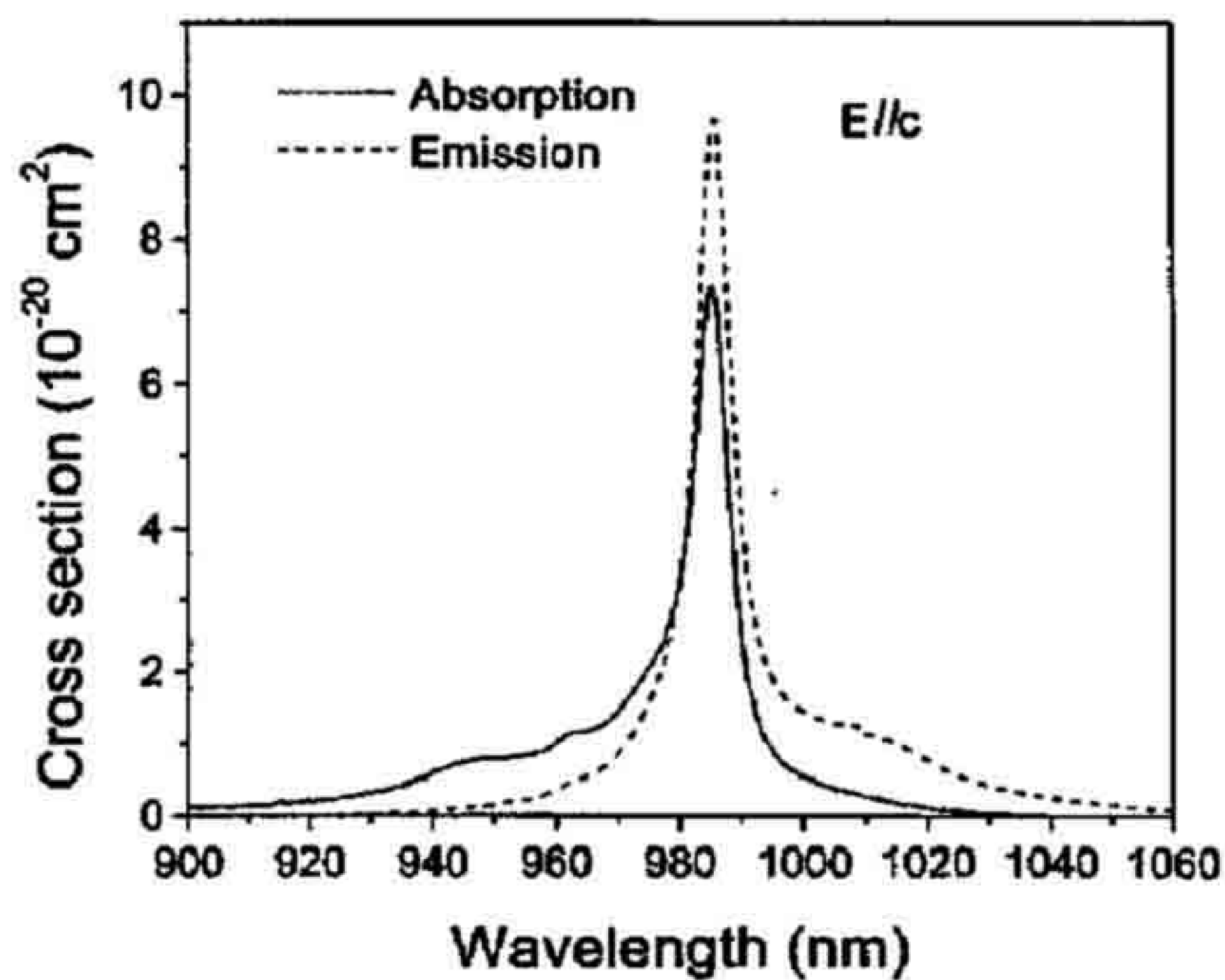


Fig. 2. π -polarized absorption and emission cross-section spectra of $\text{Yb}^{3+}:\text{YVO}_4$ at room temperature.

imum 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 $\text{Yb}:\text{YVO}_4$ crystal¹³). The pump beam was focused with four lenses to a spot with a $55 \times 110 \mu\text{m}$ radius inside the laser crystal. The cavity mode radius in the gain medium was close to the pump beam radius. The $\text{Yb}:\text{YVO}_4$ 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 $65 \mu\text{m}$. The $\text{Yb}:\text{YVO}_4$ 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

$\text{Yb}:\text{YVO}_4$ laser are presented in Fig. 3. The pulse repetition rate was $\sim 150 \text{ MHz}$, 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 mode-locking threshold. This is to the best of our knowledge the first demonstration of a cw mode-locked $\text{Yb}:\text{YVO}_4$ 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 $\text{Yb}:\text{YVO}_4$ crystal as a function of excitation parameter β have been calculated from the following expression²⁰:

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

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 $\text{Yb}:\text{YVO}_4$ has a broad and smooth shape. Gain spectra with $\beta = 0.15$ and 0.25 correspond to the cavity losses of the cw $\text{Yb}:\text{YVO}_4$ 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 ≈ 0.2 (dashed line). For this value of excitation parameter, the FWHM gain bandwidth is $\approx 32 \text{ nm}$ (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 wavelength-dependent losses of the cavity mirrors (which are due to rapidly increasing transmission of mirror M1 at shorter wavelengths).

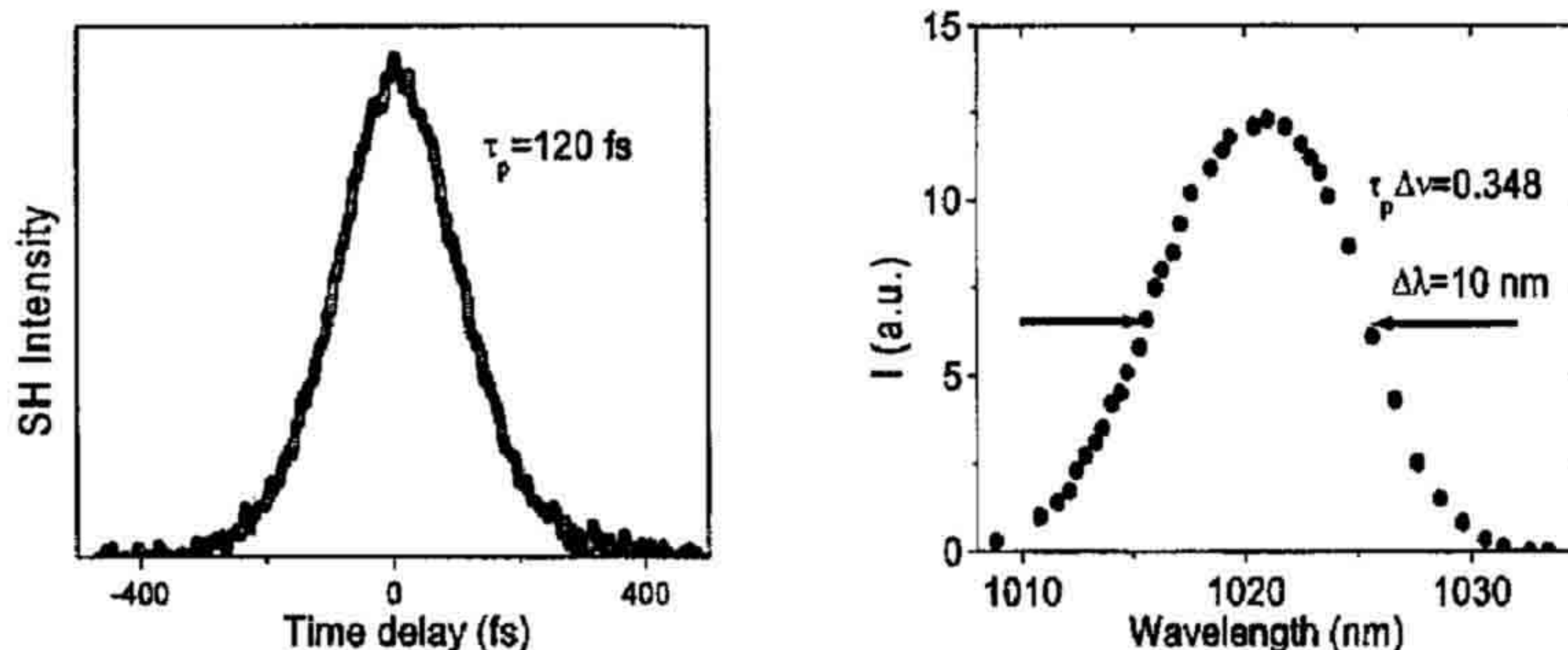


Fig. 3. Intensity autocorrelation (left) with a sech^2 fit and optical spectrum (right) of the $\text{Yb}:\text{YVO}_4$ laser.

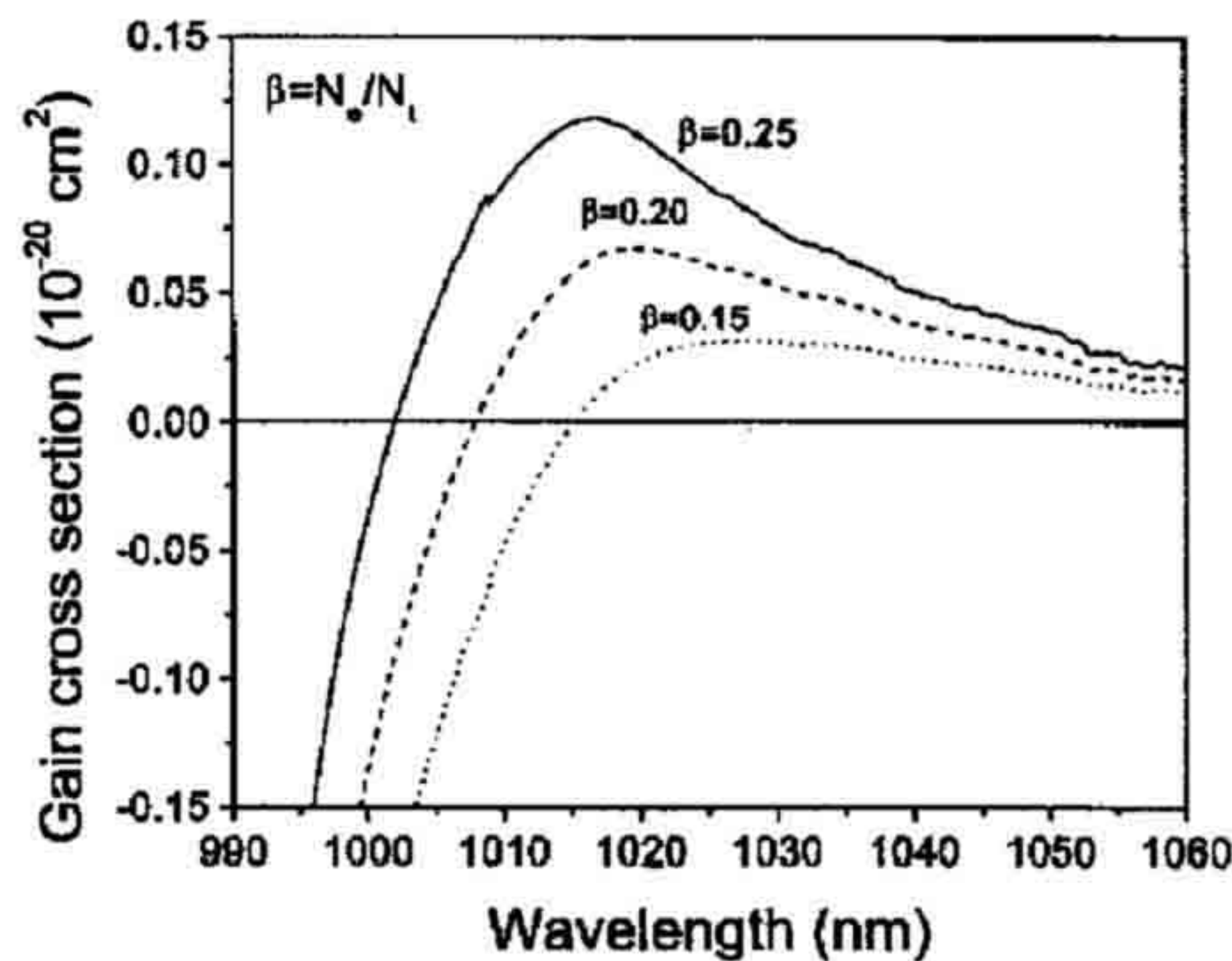


Fig. 4. π -polarized gain cross-section spectra of Yb^{3+} in YVO_4 at room temperature for different values of excitation parameter β .

In conclusion, we have demonstrated for the first time to our knowledge femtosecond pulse generation from a diode-pumped $\text{Yb}:\text{YVO}_4$ 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, $\text{Yb}:\text{YVO}_4$ 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 $\text{Yb}:\text{YVO}_4$ 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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