Yb$^{3+}$-doped YVO$_4$ crystal for efficient Kerr-lens mode locking in solid-state lasers

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We report the first demonstration, to our knowledge, of soft-aperture Kerr-lens mode locking in a diode-pumped femtosecond Yb$^{3+}$:YVO$_4$ laser. Near-transform-limited pulses as short as 61 fs are generated around a center wavelength of 1050 nm with an output power of 54 mW and a pulse repetition frequency of 104.5 MHz. This is, to our knowledge, the shortest pulse generated directly from an Yb laser having a crystalline host material. The femtosecond operation has a mode-locking threshold at an absorbed pump power of 190 mW. The nonlinear refractive indexes of the Yb$^{3+}$:YVO$_4$ crystal have been measured to be 19 $\times 10^{-16}$ cm$^2$/W and 15 $\times 10^{-16}$ cm$^2$/W for the $\sigma$ and $\pi$ polarizations, respectively, at 1080 nm.

In this Letter we describe the parameters of a new Yb-doped YVO$_4$ crystal, which was selected for possible exploitation in KLM solid-state lasers. Impressively, our KLM Yb:YVO$_4$ laser produced pulses as short as 61 fs at a center wavelength of 1050 nm with an average output power of 54 mW for an absorbed pump power of just 400 mW. The nonlinear refractive indices were measured for the Yb:YVO$_4$ crystal by using the $z$-scan technique and were found to be 19 $\times 10^{-16}$ cm$^2$/W and 15 $\times 10^{-16}$ cm$^2$/W for $\sigma$ and $\pi$ polarizations, respectively, at 1080 nm.

A schematic of the laser cavity and pumping geometry is shown in Fig. 1. For these experimental assessments, a 2 mm long, 3 at. % Yb$^{3+}$-doped YVO$_4$ Brewster-angled crystal was used and was oriented in the cavity for polarization parallel to the crystallographic axis $c$ ($\pi$ polarization). The pump source was a 0.5 W, single-mode, fiber-coupled (mode field diameter of 6.6 $\mu$m), polarization-maintaining InGaAs di-
With this cavity, the laser mode radius inside 1050 nm were selected for the observations reported. Plane-wedged output couplers (OC) with high reflection at wavelengths in the 1025–1100 nm range. Plane-wedged output couplers (OC) with high reflection at wavelengths in the 1025–1100 nm range. Curved mirrors (M1 and M2) have radii of curvature of 100 and 75 mm, respectively, and were designed for high transmittance at approximately 980 nm. Overall, the Yb:YVO4 laser was characterized. During the cw operation, an incident pump power on the crystal of 490 mW gave a maximum output power of 164 mW at 1033 nm (slope efficiency of 69%), and 146 mW at 1047 nm when 3% and 1% output mirrors, respectively, were employed. The Yb:YVO4 crystal absorbed approximately 77% (3% OC) and 81% (1% OC) of the incident pump radiation.

Initially, the cw performance of the diode-pumped Yb:YVO4 laser was characterized. During the cw operation, an incident pump power on the crystal of 490 mW gave a maximum output power of 164 mW at 1033 nm (slope efficiency of 69%), and 146 mW at 1047 nm when 3% and 1% output mirrors, respectively, were employed. The Yb:YVO4 crystal absorbed approximately 77% (3% OC) and 81% (1% OC) of the incident pump radiation.

With a 1% output coupler, the Kerr-lens mode-locking operation was easily achieved by adjustment of the separation of the curved mirrors M1 and M2 and the positioning of the laser crystal. After KLM was initiated, the intracavity dispersion was optimized by insertion of the SF10 prisms (tip-to-tip separation of 44 cm) such that pulses with durations of 61 fs (assuming a sech² intensity profile) were produced [Fig. 2(a)] at an average output power of 54 mW (400 mW absorbed pump power) and a pulse repetition frequency of 104.5 MHz. The corresponding spectral width was 21 nm at around of 1050 nm, as shown in Fig. 2(b) (solid curve), which implies a time–bandwidth product of 0.35. As can be seen, the spectrum of the mode-locked output extended over most of the 1015–1075 nm spectral range obtained during the cw operation of the Yb:YVO4 laser [Fig. 2(b), dashed curve]. A self-starting KLM operation was sometimes observed, but generally mode locking was initiated by a small mechanical perturbation or by fine translation of the mirror M2. The pulses were stable over an experimental period of more than 1 h. The pump threshold for Kerr-lens mode locking was measured to be as low as 190 mW of absorbed pump power where the laser generated 130 fs pulses with an average output power of 8 mW. The M² factors of the output beam were measured to be 1.2 and 1.4 in the sagittal and tangential directions, respectively. The deviation from the diffraction-limited value can be attributed to the nonideal overlapping of the pump and laser modes in the laser crystal during KLM operation.

Based on these results for this ultralow threshold, stable, and efficient Kerr-lens mode locking in a Yb:YVO4 laser, we could predict that a Yb-doped YVO4 crystal should possess a relatively high nonlinear refractive index n₂. To confirm this, measurements of n₂ by using the standard z-scan technique were performed. Moreover, an accurate knowledge of n₂ is necessary for optimization of the KLM operation and for the evaluation of Kerr lensing in high-power solid-state laser and amplifier configurations. A 0.96 mm long, 2 at. % doped Yb:YVO4 crystal was used for z-scan measurements. A passively mode-locked Nd³⁺ :YAlO₃ laser operating at a 1 Hz repetition rate and generating 100 ps pulses at 1.08 μm with a peak power of 4.7 MW was employed as a pump source. The M² factor of the laser output beam was determined to be <1.1. The laser radiation was focused to an ~32 μm (1/e² level) radius spot that corresponded to a 3 mm long confocal parameter. At these conditions the “thin” medium analysis for the z-scan data was applied. An aperture of 0.5 mm in diameter was placed at a distance of 40 cm from the beam waist, so that the far-field, on-axis, z-scan transmittance could be measured. Systematic noise, predominantly due to scatter, was reduced by sub-bracketing the measurement locations.

Fig. 3. Normalized z-scan data for the Yb:YVO4 crystal for (a) E⊥c and (b) E∥c polarizations at 1.08 μm. The solid curves are the theoretical fits.

![Fig. 1. Schematic of the KLM Yb:YVO4 laser. LD, single-mode fiber-coupled InGaAs laser diode; AL, 15 mm aspheric lens; HW, half-wave plate; M1, M2, high-reflector curved mirrors (r₁=100 mm, r₂=75 mm); OC, output coupler (T=1% and 3%).](image1)

![Fig. 2. Intensity autocorrelation (a) (dotted curve is fitted assuming an ideal sech² pulse shape) and spectrum (b) of the KLM Yb:YVO4 laser pulses. The dashed curve on the graph on the right-hand side represents the tunability of the Yb:YVO4 laser in cw operation.](image2)

![Fig. 3. Normalized z-scan data for the Yb:YVO4 crystal for (a) E⊥c and (b) E∥c polarizations at 1.08 μm. The solid curves are the theoretical fits.](image3)
tracting a low-intensity z scan from the high-intensity counterpart. The overall experimental error of \(n_2\) measurements was in range of ±20%. The measurements were carried out for both \(\pi\) (\(E \parallel c\)) and \(\sigma\) (\(E \perp c\)) orientations of the Yb:YVO\(_4\) crystal. The values of \(n_2\) were obtained from the z scans reproduced in Fig. 3. These scans were recorded by using a 317 kW peak power resulting in focal on-axis intensities of 19.6 GW/cm\(^2\). The valley–peak configuration of the z-scan signals implies a positive sign of \(n_2\). From the best fits to the experimental data we derived the values of \(n_2\) to be 19 \(\times\) 10\(^{-16}\) cm\(^2\)/W and 15 \(\times\) 10\(^{-16}\) cm\(^2\)/W for \(E \perp c\) and \(E \parallel c\) polarizations, respectively. Additionally, we performed measurements of the nonlinear refractive index of a Yb:KYW crystal (doped with 5 at. % of Yb\(^{3+}\)), which proved itself to be an excellent candidate for KLM operation.\(^{16,17}\) The value of \(n_2\) was found to be 10 \(\times\) 10\(^{-16}\) cm\(^2\)/W for \(E \parallel N_m\) polarization, which is in a good agreement with the magnitude of 8.7 \(\times\) 10\(^{-16}\) cm\(^2\)/W reported recently for Yb:KYW with \(E \parallel a\) at 1.08 \(\mu\)m.\(^{19}\) Thus the nonlinear refractive index of Yb:YVO\(_4\) crystal for the preferred \(\pi\) polarization is higher by a factor of \(\sim 1.5\) at 1.08 \(\mu\)m than that for a Yb:KYW crystal (\(E \parallel N_m\)) and the highest value of \(n_2\) in Yb:YVO\(_4\) is observed for the \(\sigma\) polarization.

In conclusion, we have demonstrated a low-threshold and efficient diode-pumped Kerr-lens mode-locked Yb:YVO\(_4\) laser. Near-transform-limited pulses of 61 fs duration (21 nm FWHM spectral width) at a center wavelength of 1050 nm were produced at an average mode-locked power of 54 mW. We believe that these are the shortest pulses generated directly from an Yb laser utilizing a crystalline host. It should be noted that 69-fs pulses were generated from a diode-pumped Yb:SO\(_4\)(BO\(_3\))\(_3\) laser that incorporated a SESAM for passive mode locking.\(^8\) Our results implied a relatively high nonlinear refractive index coefficient, and by using the z-scan technique the nonlinear refractive indices of the Yb\(^{3+}\):YVO\(_4\) crystal were measured to be 19 \(\times\) 10\(^{-16}\) cm\(^2\)/W and 15 \(\times\) 10\(^{-16}\) cm\(^2\)/W for the \(\sigma\) and \(\pi\) polarizations, respectively, at 1080 nm.

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