

# Yb<sup>3+</sup>-doped YVO<sub>4</sub> 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<sup>3+</sup>:YVO<sub>4</sub> 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<sup>3+</sup>:YVO<sub>4</sub> crystal have been measured to be  $19 \times 10^{-16}$  cm<sup>2</sup>/W and  $15 \times 10^{-16}$  cm<sup>2</sup>/W for the  $\sigma$  and  $\pi$  polarizations, respectively, at 1080 nm. © 2005 Optical Society of America

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Yttrium orthovanadate (YVO<sub>4</sub>) is an attractive laser material for the development of efficient, compact, and high-power, diode-pumped, solid-state lasers when trivalent rare-earth ions (Nd, Er, Tm, and Ho)<sup>1</sup> are used as dopants. Such laser materials are characterized by relatively good thermomechanical properties in combination with large absorption and stimulated emission cross sections for the optical transitions in the rare-earth ions. Recently, efficient continuous-wave (cw) laser operation has been demonstrated in a new Yb-doped crystal: Yb<sup>3+</sup>:YVO<sub>4</sub>(Yb:YVO<sub>4</sub>) when pumped with either a Ti:sapphire laser<sup>2</sup> or a diode laser.<sup>3</sup> From the point of view of the development of new Yb-doped crystals for reliable and efficient femtosecond lasers, materials are preferred that possess high cross sections (in particular, the emission cross section)<sup>4</sup> together with broad gain spectra<sup>5-7</sup> and good physical and mechanical properties.<sup>8</sup> In this context, given the strong and broad absorption peak (FWHM of ~8 nm) at around 985 nm, which is compatible with optical pumping by well-developed InGaAs laser diodes, the extremely low quantum defect (~3.5%), and a relatively broad and smooth<sup>5</sup> (glasslike) emission spectrum, the Yb:YVO<sub>4</sub> crystal is a good candidate gain medium for incorporation into diode-pumped femtosecond lasers for the 1- $\mu$ m spectral region. Indeed, 120-fs pulses with an average power of 300 mW were generated from a diode-pumped Yb:YVO<sub>4</sub> laser that was passively mode locked by using a semiconductor saturable absorber mirror (SESAM).<sup>9</sup>

In fact, most of the work in the field of ultrashort Yb lasers has concentrated on the employment of SESAMs<sup>10</sup> for passive mode locking. Kerr-lens mode locking<sup>11</sup> (KLM) is another well-developed technique

for the generation of ultrashort pulses from lasers that are efficient, compact, and have reduced cavity component counts.<sup>12</sup> Reducing the intracavity losses by excluding a SESAM (nonsaturable losses) can lead to a substantial enhancement in the optical efficiency of such a femtosecond laser. In addition, the shortest pulse generated directly from a laser was produced using the KLM technique.<sup>13</sup> One of the critical parameters for reliable Kerr-lens mode locking is a high value of the nonlinear refractive index  $n_2$  of a laser medium. Although, Major *et al.* have shown that a number of Yb-doped crystals are characterized by relatively high  $n_2$  and are promising for KLM operation,<sup>14,15</sup> only the Yb:KYW laser has been mode locked successfully by using the optical Kerr effect under the conditions of direct diode pumping.<sup>16,17</sup>

In this Letter we describe the parameters of a new Yb-doped YVO<sub>4</sub> crystal, which was selected for possible exploitation in KLM solid-state lasers. Impressively, our KLM Yb:YVO<sub>4</sub> 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<sub>4</sub> crystal by using the z-scan technique and were found to be  $19 \times 10^{-16}$  cm<sup>2</sup>/W and  $15 \times 10^{-16}$  cm<sup>2</sup>/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<sup>3+</sup>-doped YVO<sub>4</sub> 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-

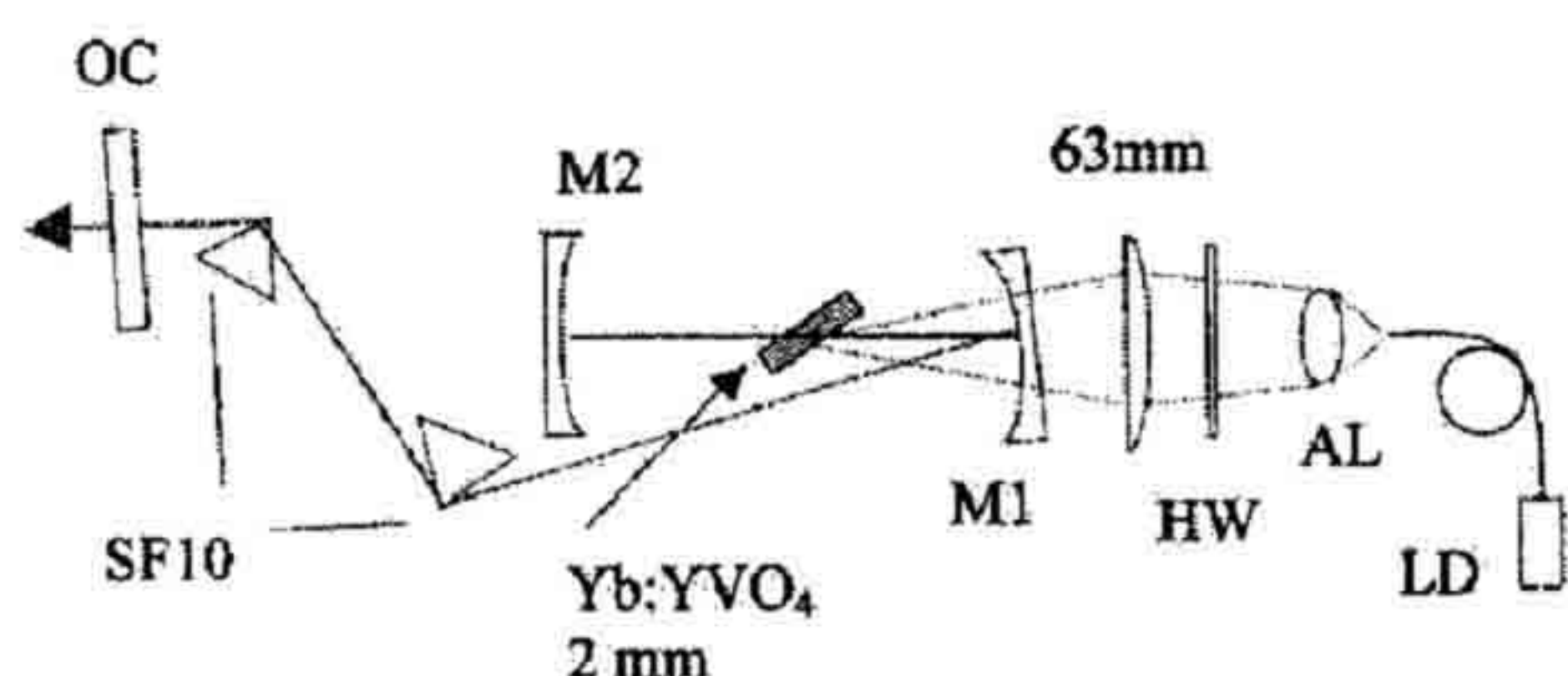


Fig. 1. Schematic of the KLM Yb:YVO<sub>4</sub> laser. LD, single-mode fiber-coupled InGaAs laser diode; AL, 15 mm aspherical lens; HW, half-wave plate; M1, M2, high-reflector curved mirrors ( $r_1=100$  mm,  $r_2=75$  mm); OC, output coupler ( $T=1\%$  and  $3\%$ ).

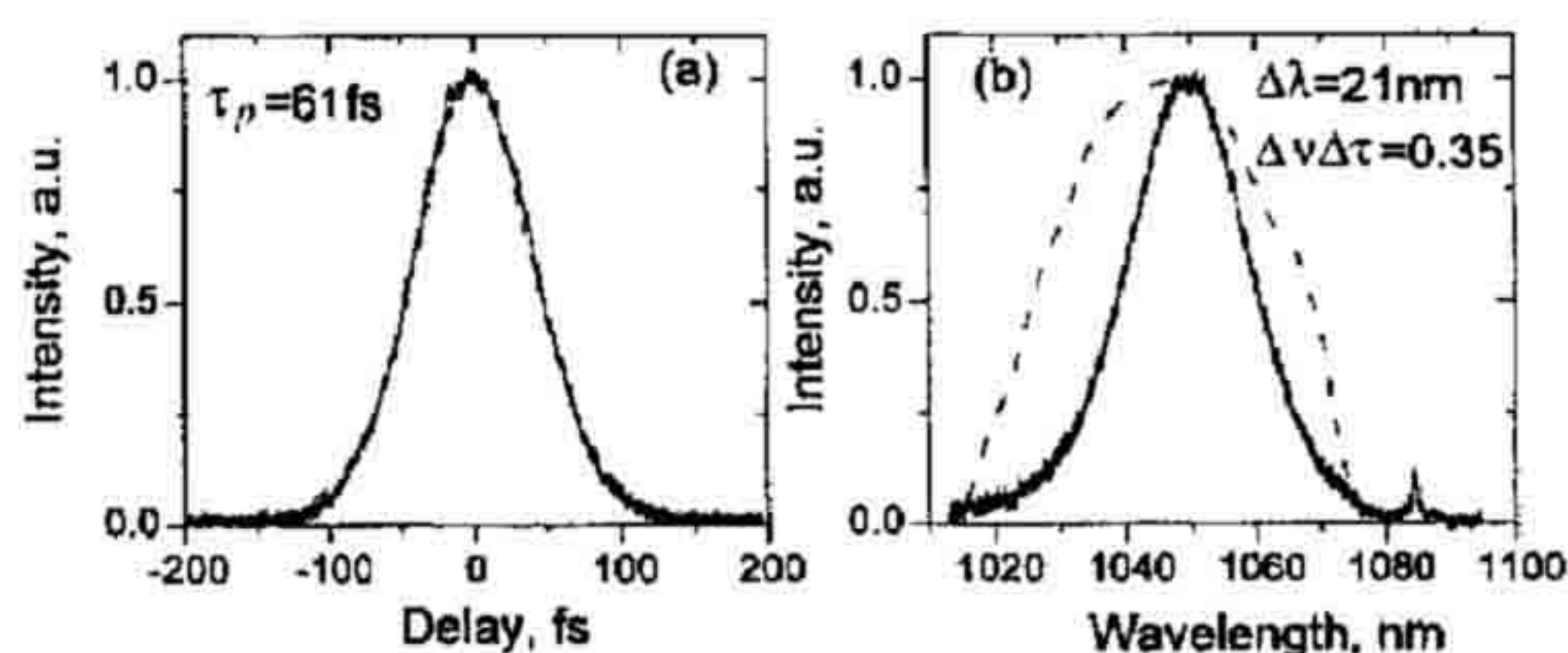


Fig. 2. Intensity autocorrelation (a) (dotted curve is fitted assuming an ideal sech<sup>2</sup> pulse shape) and spectrum (b) of the KLM Yb:YVO<sub>4</sub> laser pulses. The dashed curve on the graph on the right-hand side represents the tunability of the Yb:YVO<sub>4</sub> laser in cw operation.

ode laser (JDS Uniphase) emitting at 980.5 nm. Aspherical ( $f=15$  mm) and spherical ( $f=63$  mm) lenses were used to collect and focus the pump beam into the gain medium, and the pump beam spot radius was measured to be  $17 \mu\text{m}$  ( $1/e^2$  intensity). The mirrors M1 and M2 have radii of curvature of 100 and 75 mm, respectively, and were designed for high transmission at approximately 980 nm ( $\approx 98\%$ ) and high reflection at wavelengths in the 1025–1100 nm range. Plane-wedged output couplers (OC) with transmissions of 1% and 3% at approximately 1050 nm were selected for the observations reported here. With this cavity, the laser mode radius inside the gain medium was calculated to be  $18 \mu\text{m} \times 36 \mu\text{m}$ .

Initially, the cw performance of the diode-pumped Yb:YVO<sub>4</sub> 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:YVO<sub>4</sub> 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 sech<sup>2</sup> 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:YVO<sub>4</sub> 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  $M^2$  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:YVO<sub>4</sub> laser, we could predict that a Yb-doped YVO<sub>4</sub> crystal should possess a relatively high nonlinear refractive index  $n_2$ . To confirm this, measurements of  $n_2$  by using the standard  $z$ -scan technique<sup>18</sup> were performed. Moreover, an accurate knowledge of  $n_2$  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:YVO<sub>4</sub> crystal was used for  $z$ -scan measurements. A passively mode-locked Nd<sup>3+</sup>:YAlO<sub>3</sub> laser operating at a 1 Hz repetition rate and generating 100 ps pulses at  $1.08 \mu\text{m}$  with a peak power of 4.7 MW was employed as a pump source. The  $M^2$  factor of the laser output beam was determined to be  $<1.1$ . The laser radiation was focused to an  $\sim 32 \mu\text{m}$  ( $1/e^2$  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.<sup>18</sup> 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-

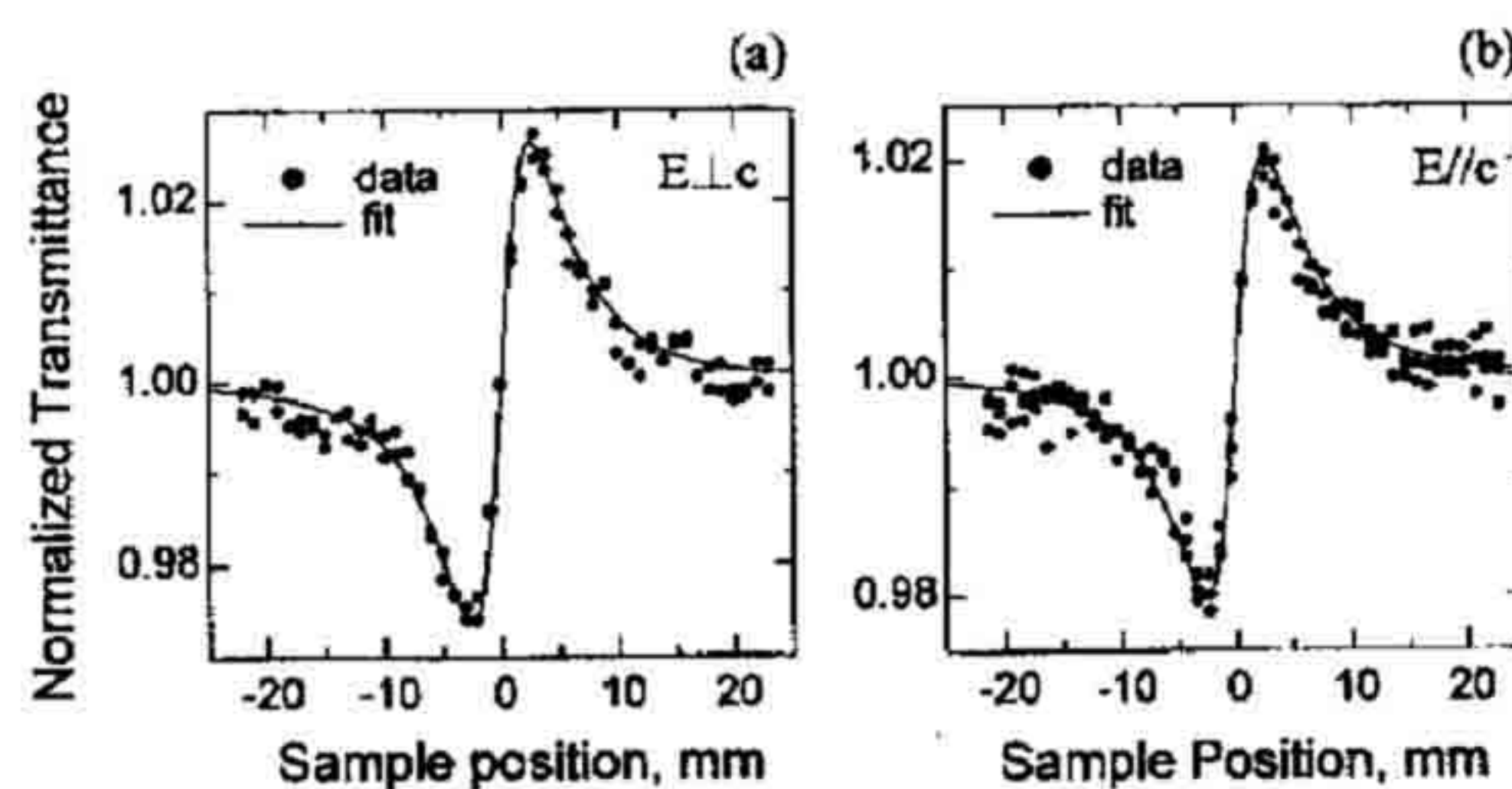


Fig. 3. Normalized  $z$ -scan data for the Yb:YVO<sub>4</sub> crystal for (a)  $E \perp c$  and (b)  $E \parallel c$  polarizations at  $1.08 \mu\text{m}$ . The solid curves are the theoretical fits.

tracting a low-intensity  $z$  scan from the high-intensity counterpart. The overall experimental error of  $n_2$  measurements was in range of  $\pm 20\%$ . The measurements were carried out for both  $\pi$  ( $E \parallel c$ ) and  $\sigma$  ( $E \perp c$ ) orientations of the Yb:YVO<sub>4</sub> 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<sup>2</sup>. 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<sup>2</sup>/W and  $15 \times 10^{-16}$  cm<sup>2</sup>/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<sup>3+</sup>), which proved itself to be an excellent candidate for KLM operation.<sup>16,17</sup> The value of  $n_2$  was found to be  $10 \times 10^{-16}$  cm<sup>2</sup>/W for  $E \parallel N_m$  polarization, which is in a good agreement with the magnitude of  $8.7 \times 10^{-16}$  cm<sup>2</sup>/W reported recently for Yb:KYW with  $E \parallel a$  at 1.08  $\mu$ m.<sup>19</sup> Thus the nonlinear refractive index of Yb:YVO<sub>4</sub> 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<sub>4</sub> is observed for the  $\sigma$  polarization.

In conclusion, we have demonstrated a low-threshold and efficient diode-pumped Kerr-lens mode-locked Yb:YVO<sub>4</sub> 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:Sr<sub>3</sub>Y(BO<sub>3</sub>)<sub>3</sub> laser that incorporated a SESAM for passive mode locking.<sup>6</sup> Our results implied a relatively high nonlinear refractive index coefficient, and by using the  $z$ -scan technique the nonlinear refractive indices of the Yb<sup>3+</sup>:YVO<sub>4</sub> crystal were measured to be  $19 \times 10^{-16}$  cm<sup>2</sup>/W and  $15 \times 10^{-16}$  cm<sup>2</sup>/W for the  $\sigma$  and  $\pi$  polarizations, respectively, at 1080 nm.

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