Total self-mode locking of multi-pass geometric modes in diode-pumped Nd:YVO_4 lasers

2013 Laser Phys. Lett. 10 105804

(http://iopscience.iop.org/1612-202X/10/10/105804)

Laser Phys. Lett. **10** (2013) 105804 (5pp) doi:10.1088/1612-2011/10/10/105804

LETTER

Total self-mode locking of multi-pass geometric modes in diode-pumped Nd:YVO_4 lasers

H C Liang, T W Wu, J C Tung, C H Tsou, K F Huang and Y F Chen[1]

Department of Electrophysics, National Chiao Tung University, Hsinchu, Taiwan

E-mail: yfchen@cc.nctu.edu.tw

Received 12 May 2013, in final form 30 July 2013
Accepted for publication 31 July 2013
Published 2 September 2013
Online at stacks.iop.org/LPL/10/105804

Abstract

We report for the first time on simultaneously longitudinal and transverse self-mode locking in a diode-pumped Nd:YVO_4 laser to achieve a pulse train traveling along the zigzag multi-pass trajectories in the degenerate cavity. At a pump power of 2.5 W, the average output powers in the mode-locked operation are 490 mW and 520 mW for the M-mode and Z-mode, respectively. The pulse widths are measured to be approximately 22.2 and 21.1 ps for the M-mode and Z-mode, respectively.

(Some figures may appear in colour only in the online journal)

1. Introduction

In 1954 Pierce [1] first analyzed the propagation of a paraxial electron beam in a periodic focusing system. In 1964 Herriott *et al* [2] used Pierce's analysis to demonstrate that an incident off-axis laser beam could be reflected by the two spherical mirrors forward and back to form closed zigzag paths when the cavity length is satisfied with the re-entrant condition. Since then, Herriott-type multi-pass cavities have been widely used in various applications, such as optical delay lines [3], absorption spectroscopy [4], Raman conversion [5–8], high-power laser systems [9] and low repetition rate ultrafast laser cavities [10–12]. Thanks to the advent of the diode-end-pumping scheme, multi-pass continuous-wave lasers have been efficiently realized in solid-state lasers with off-axis pumping [13, 14].

The re-entrant condition is given by $\Delta f_T/\Delta f_L = P/Q$, where P and Q are co-prime integers, Δf_L is the longitudinal mode spacing, and Δf_T is the transverse mode spacing. The laser resonator satisfying the re-entrant condition is called the degenerate cavity. Auston [15] and Smith [16] observed that simultaneous phase locking of longitudinal and transverse modes in a degenerate cavity could produce a mode-locked wavepacket traveling along the zigzag multi-pass orbit. Since the first experiments in the He–Ne laser [15, 16], simultaneous mode locking has been also reported for the Nd:glass, and CO_2 laser systems [17–20]. However, more practical investigations for simultaneous mode locking are hindered by the inefficiency and the lack of controllability. Recently, the diode-end-pumping approach has been widely used to achieve efficient self-mode-locked TEM_{00} operations in Yb-doped [21–24] and Nd-doped [25–28] crystal lasers. Here the self-mode locking means that no additional active or passive mode-locking elements (such as saturable absorbers) are used in the laser cavity. These successful experiments pave the way for employing the diode-pumping scheme to build an efficient multi-pass self-mode-locked laser.

In this letter we report for the first time on simultaneous self-phase-locking of longitudinal and transverse modes in a diode-pumped Nd:YVO_4 laser with the off-axis pumping

[1] Address for correspondence: Department of Electrophysics, National Chiao Tung University, 1001 TA Hsueh Road, Hsinchu, 30050, Taiwan.

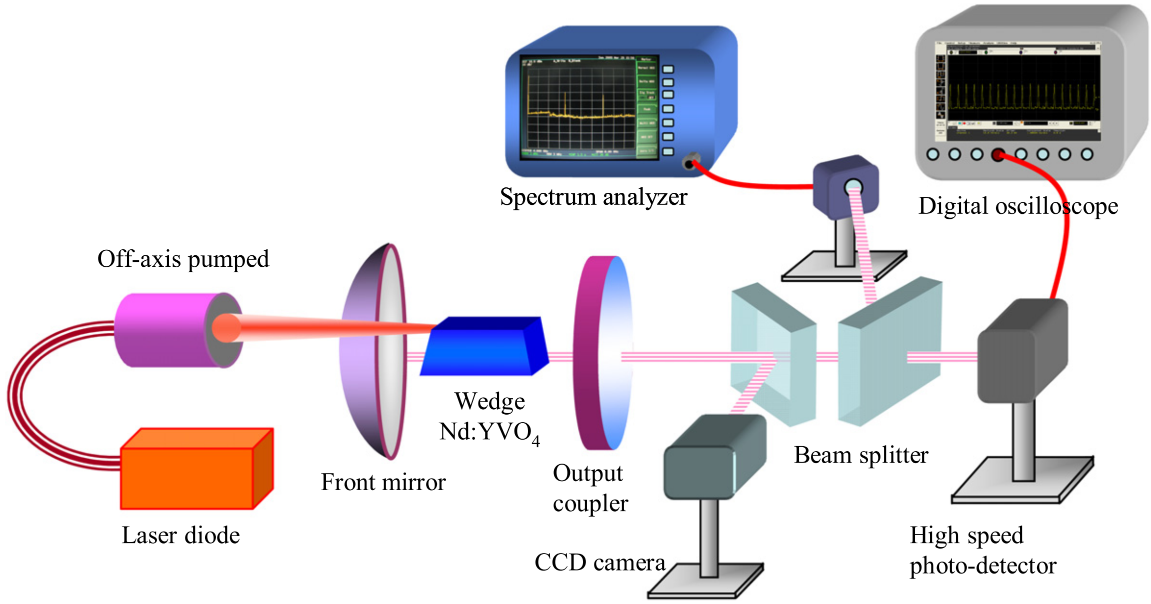

Figure 1. Experimental setup for simultaneous locking of longitudinal and transverse modes in a concave-plano resonator with the off-axis pumping scheme.

scheme in the degenerate cavity. With a pump power of 2.5 W, the average output powers are found to be 490 mW and 520 mW for the M-mode and Z-mode at the cavities of $\Delta f_T/\Delta f_L = 1/4$ and $\Delta f_T/\Delta f_L = 1/3$, respectively. The mode-locked pulse widths are approximately 22.2 and 21.1 ps for the M-mode and Z-mode, respectively. For the first time to the best of our knowledge we have realized the total self-mode locking of multi-pass geometric modes in a diode-pumped $Nd:YVO_4$ laser with the off-axis pumping scheme.

2. Experimental setup

Figure 1 depicts the experimental setup for simultaneous locking of longitudinal and transverse modes in a concave-plano resonator with the off-axis pumping scheme [25, 26]. The gain medium is *a*-cut 0.2 at.% $Nd:YVO_4$ crystal with a length of 10 mm. Both end surfaces of the $Nd:YVO_4$ crystal were coated for antireflection at 1064 nm ($R < 0.2\%$) and wedged 2° to suppress the Fabry–Perot etalon effect. The laser crystal was wrapped with indium foil and mounted in a water-cooled copper holder. The water temperature was maintained around 20 °C to ensure stable laser output. The front cavity mirror was a 30-mm radius-of-curvature concave mirror with antireflection coating at 808 nm on the entrance face and with high-reflectance coating at 1064 nm (>99.8%) and high transmittance coating ($T > 95\%$) at 808 nm on the second surface. The distance between the laser crystal and the front mirror was approximately 2–3 mm. The output coupler was a wedged flat mirror with 5% transmission at 1064 nm. The pump source was a 3.0-W 808-nm fiber-coupled laser diode with a core diameter of 100 μm and a numerical aperture of 0.16. A focusing lens with 5 mm focal length and 85% coupling efficiency was used to re-image the pump beam into the laser crystal. The average pump size was approximately 70 μm.

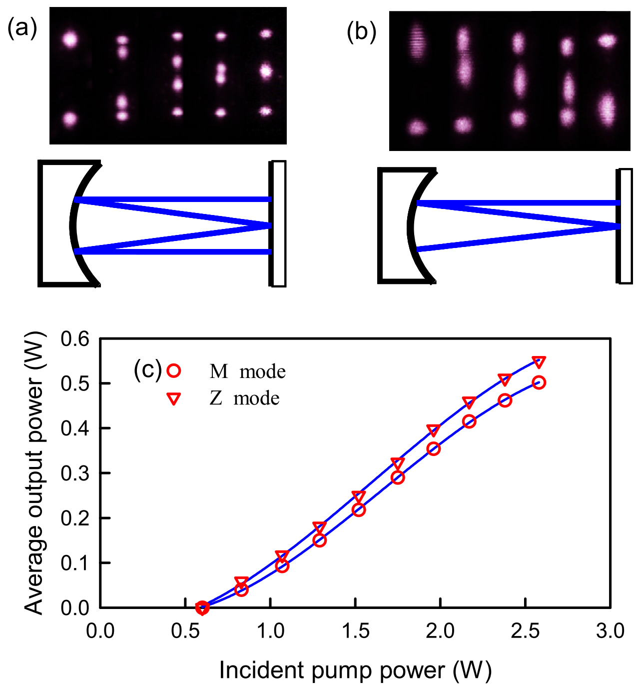

Figure 2. Experimental transverse patterns obtained at the cavity lengths of (a) $\Delta f_T/\Delta f_L = 1/4$ and (b) $\Delta f_T/\Delta f_L = 1/3$.
(c) Experimental results for the average output power versus the incident pump power.

3. Results and discussion

For a concave-plano resonator, the longitudinal and transverse mode separations are respectively given by $\Delta f_L = c/2L$ and $\Delta f_T = (\Delta f_L/\pi)\cos^{-1}[1 - (L^*/R)]^{1/2}$, where $L = L_{cav} + (n-1)L_{cry}$, $L^* = L_{cav} + [(1/n) - 1]L_{cry}$, R is the radius of curvature of the concave mirror, L_{cav} is the geometrical length of the cavity, L_{cry} is the length of the laser crystal,

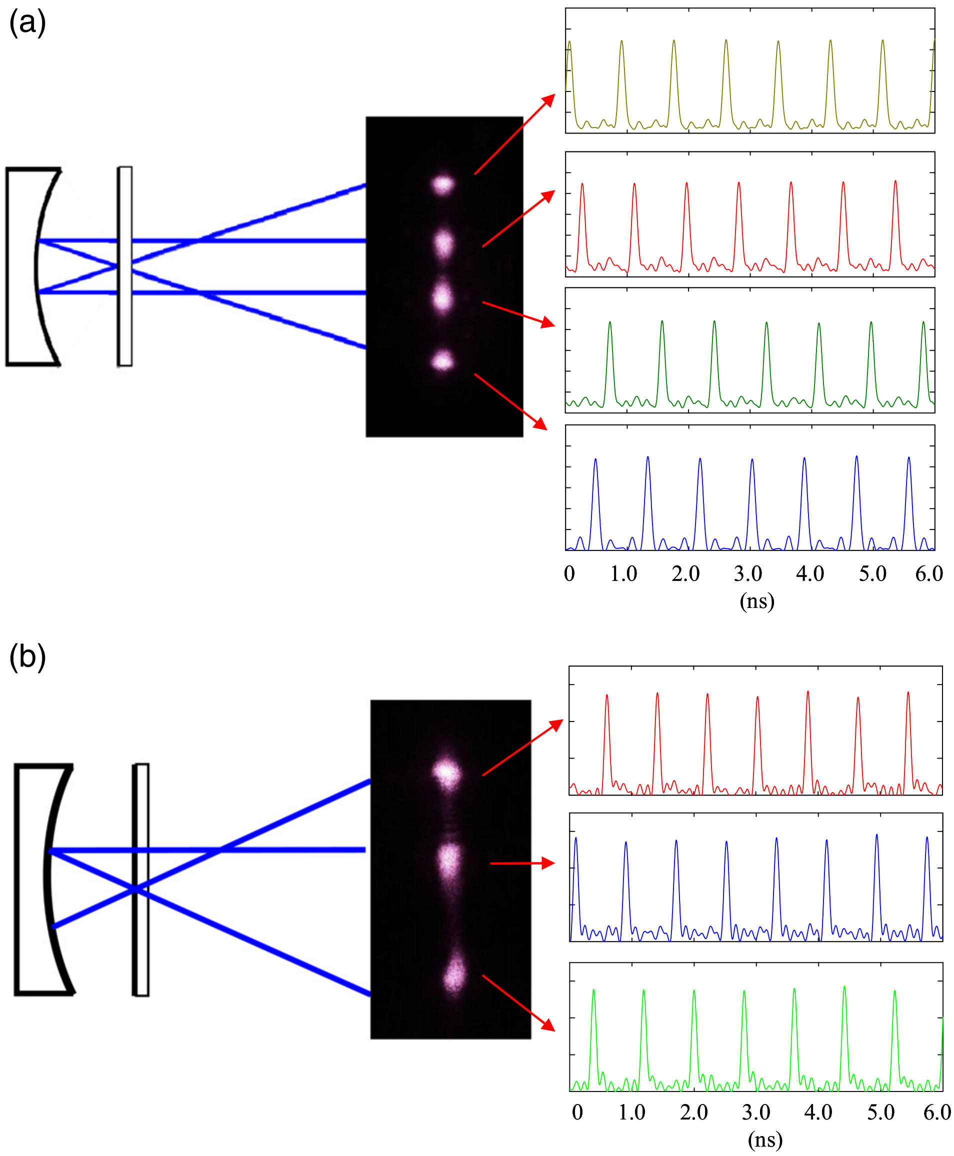

Figure 3. Experimental pulse trains of (a) M-mode and (b) Z-mode.

and n is the refractive index of the laser crystal. As observed in the previous work [29], longitudinal self-mode locking with single pure high-order transverse modes could be generated in a usual cavity length with off-axis pumping. Here we systematically change the cavity length to observe the variation of the self-mode-locking phenomenon. We confirm that when the cavity length is adjusted to be the degenerate cavity, simultaneous phase locking of longitudinal and transverse modes can be achieved and produces a wavepacket traveling along the closed ray paths. We use the re-imaging lens to record the transverse patterns at the different longitudinal positions of the cavity. Figures 2(a) and (b) show the experimental transverse patterns obtained at the cavity lengths to fulfil the conditions of $\Delta f_T/\Delta f_L = 1/4$ and $\Delta f_T/\Delta f_L = 1/3$, respectively. It can be seen that the transverse patterns in figures 2(a) and (b) display the laser modes to be localized on M-shape and Z-shape trajectories, respectively. Figure 2(c) depicts the experimental results for the average output power versus the incident pump power. At an incident pump power of 2.5 W, the average output powers are found to be 490 mW and 520 mW for the M-mode and Z-mode, respectively.

The far-field pattern of the simultaneously longitudinal and transverse mode-locked laser displays a characteristic of multiple Gaussian spots. We used two high-speed InGaAs photodetectors (Electro-optics Technology Inc. ET-3500 with rise time 35 ps) to identify the time sequence of the mode-locked pulse train by comparing reference measurements. The first photodetector was employed to measure the temporal behavior in one fixed spot of the far-field pattern for reference. The second photodetector was used to measure the temporal signals in different spots of the far-field pattern for comparison. The output signals of the photodetectors were connected to a digital oscilloscope (Agilent DSO 80000) with 10 GHz electrical bandwidth and a sampling interval of 25 ps. Figures 3(a) and (b) show the experimental results for the pulse trains of the M-mode and Z-mode, respectively. It can be seen that the relative shifts of the time sequences between

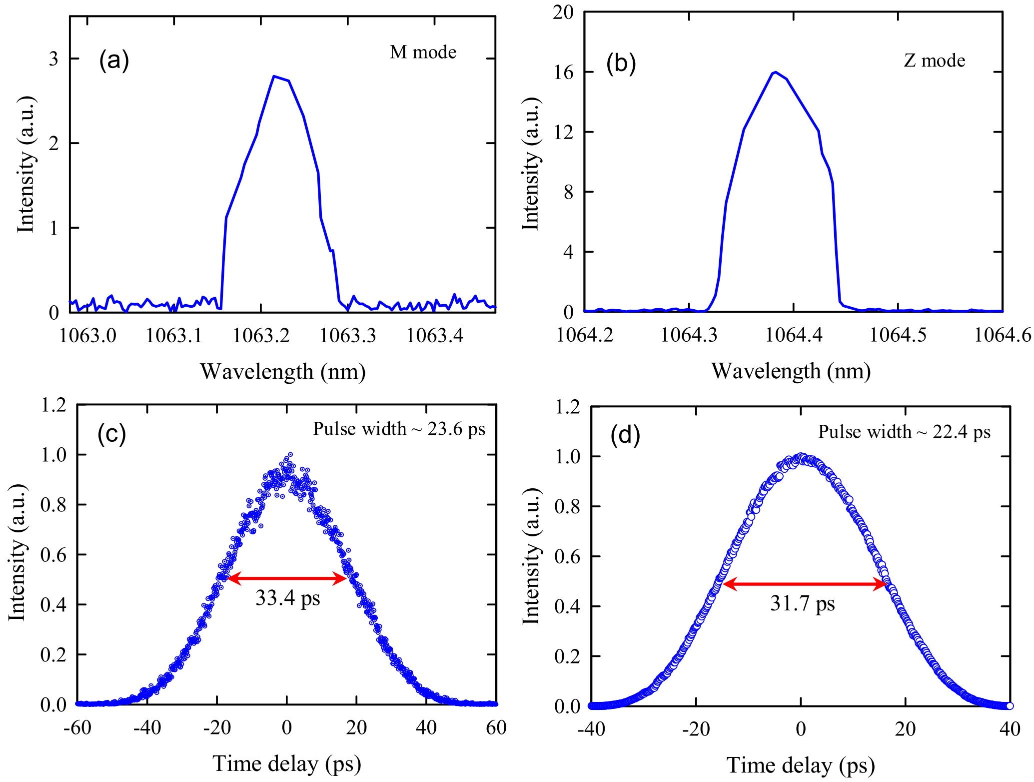

Figure 4. Experimental lasing spectra for (a) M-mode and (b) Z-mode. (c) and (d) Measured autocorrelation traces corresponding to the optical spectra shown in (a) and (b), respectively.

different spots are utterly consistent with the dynamics of the wavepacket traveling along the geometric trajectories inside the cavity. Note that the optical cavity lengths are given by $L = (R/2)+[n-(1/n)]L_{\rm cry}$ and $L = (3R/4)+[n-(1/n)]L_{\rm cry}$ for the M-mode and Z-mode, respectively. Consequently, the optical cavity lengths are approximately 32.7 mm and 40.2 mm for the M-mode and Z-mode, respectively. With the optical cavity lengths, the round trip times for the M-mode and Z-mode can be calculated to be approximately 872 ps and 804 ps, respectively. As seen in figures 3(a) and (b), the experimental round trip times agree very well with the calculated results.

The optical spectrum of the laser output was measured with a Fourier optical spectrum analyzer (Advantest Q8347) containing a Michelson interferometer with resolution of 0.003 nm. The mode-locked pulse duration was measured with an autocorrelator (APE pulse check, Angewandte physic and Elektronik GmbH). Figures 4(a) and (b) show the lasing spectra for the operations of M-mode and Z-mode, respectively. The optical spectral widths for the M-mode and Z-mode can be seen to be approximately 0.08 nm and 0.09 nm, respectively. Figures 4(c) and (d) depict the measured autocorrelation traces corresponding to the optical spectra shown in figures 4(a) and (b), respectively. It can be seen that the autocorrelation traces are approximately 33.4 ps and 31.7 ps for the M-mode and Z-mode, respectively. Assuming temporal intensity to be a Gaussian shape, the mode-locked pulse durations for the M-mode and Z-mode can be calculated to be approximately 23.6 ps and 22.4 ps, respectively. Consequently, the time–bandwidth product of the mode-locked pulse can be found to be nearly 0.51, which is slightly larger than the Fourier-limited value of 0.44. The chirped pulses mainly come from the group velocity dispersion introduced by the gain medium.

4. Conclusions

In summary, we have experimentally demonstrated that simultaneous self-phase-locking of longitudinal and transverse modes can be achieved in a diode-pumped Nd:YVO_4 laser with the off-axis pumping scheme in the degenerate cavity. The self-mode-locked operation for the M-mode and Z-mode has been presented in the cavities with $\Delta f_{\rm T}/\Delta f_{\rm L} = 1/4$ and $\Delta f_{\rm T}/\Delta f_{\rm L} = 1/3$, respectively. At a pump power of 2.5 W, the average output powers are found to be 490 mW and 520 mW for the M-mode and Z-mode, respectively. The mode-locked pulse widths are measured to be approximately 22.2 and 21.1 ps for the M-mode and Z-mode, respectively.

Acknowledgment

The authors acknowledge the National Science Council of Taiwan for their financial support of this research under contract NSC 100-2628-M-009-001-MY3.

References

[1] Pierce J R 1954 *Theory and Design of Electron Beams* (New York: Van Nostrand) pp 194–7

[2] Herriott D R, Kogelnik H and Kompfner R 1964 Off-axis paths in spherical mirror interferometers *Appl. Opt.* **3** 523–6
[3] Herriott D R and Schulte H J 1965 Folded optical delay lines *Appl. Opt.* **4** 883–9
[4] Owyoung A, Patterson C W and Mcdowell R S 1978 CW stimulated Raman gain spectroscopy of the v_1 fundamental of methane *Chem. Phys. Lett.* **59** 156–62
[5] Byer R L and Trutna W R 1978 16-mm generation by CO_2-pumped rotational Raman scattering in H_2 *Opt. Lett.* **3** 144–6
[6] Rabinowitz P, Stein A, Brickman R and Kaldor A 1978 Stimulated rotational Raman scattering from para-H_2 pumped by a CO_2 TEA laser *Opt. Lett.* **3** 147–8
[7] Midorikawa K, Tashiro H, Aoki Y, Nagasaka K, Toyoda K and Namba S 1985 Room-temperature operation of a para-H_2 rotational Raman laser *Appl. Phys. Lett.* **47** 1033–5
[8] Trutna W R and Byer R L 1980 Multiple-pass Raman gain cell *Appl. Opt.* **19** 301–5
[9] Xin J G, Duncan A and Hall D R 1989 Analysis of hyperboloidal ray envelopes in Herriott cells and their use in laser resonators *Appl. Opt.* **28** 4576–84
[10] Cho S H, Bouma B E, Ippen E P and Fujimoto J G 1999 Low-repetition-rate high-peak power Kerr-lens mode locked Ti:Al_2O_3 laser using a multiple-pass cavity *Opt. Lett.* **24** 417–9
[11] Kowalevicz A M, Zare A T, Kaertner F X, Fujimoto J G, Dewald S, Morgner U, Scheuer V and Angelow G 2003 Generation of 150-nJ pulses form a multiple pass cavity Kerr-lens mode-locked Ti:Al_2O_3 oscillator *Opt. Lett.* **28** 1597–9
[12] Sennaroglu A, Kowalevicz J A M, Ippen E P and Fujimoto J G 2004 Compact femtosecond lasers based on novel multipass cavities *IEEE J. Quantum Electron.* **40** 519–28
[13] Dingjan J, van Exter M P and Woerdman J P 2001 Geometric modes in a single-frequency Nd:YVO_4 laser *Opt. Commun.* **188** 345–51
[14] Chen Y F, Jiang C H, Lan Y P and Huang K F 2004 Wave representation of geometrical laser beam trajectories in a hemiconfocal cavity *Phys. Rev.* A **69** 053807
[15] Auston D H 1968 Transverse mode locking *IEEE J. Quantum Electron.* **4** 420–2
[16] Smith P W 1970 Mode-locking of lasers *Proc. IEEE* **58** 1342–57
[17] Michon M, Ernest J and Auffert R 1969 Passive transverse mode locking in a confocal Nd^{3+} glass laser *IEEE J. Quantum Electron.* **5** 125–6
[18] Mak A A and Fromzel V A 1969 Observation of self-synchronization of transverse modes in a solid-state laser *JETP Lett.* **10** 199–201
[19] Ito H and Inaba H 1969 Self mode locking of the transverse modes in the CO_2 laser oscillator *Opt. Commun.* **1** 61–3
[20] Arakelyan V S, Karlov N V and Prokhorov A M 1969 Self synchronization of transverse modes of a CO_2 laser *JETP Lett.* **10** 178–80
[21] Liu H, Nees J and Mourou G 2001 Diode-pumped Kerr-lens mode-locked Yb:KY$(WO_4)_2$ laser *Opt. Lett.* **26** 1723–5
[22] Lagatsky A A *et al* 2005 Yb^{3+}-doped YVO_4 crystal for efficient Kerr-lens mode locking in solid-state lasers *Opt. Lett.* **30** 3234–6
[23] Xie G Q, Tang D Y, Zhao L M, Qian L J and Ueda K 2007 High-power self-mode-locked Yb:Y_2O_3 ceramic laser *Opt. Lett.* **32** 2741–3
[24] Uemura S and Torizuka K 2008 Kerr-lens mode-locked diode-pumped Yb:YAG laser with the transverse mode passively stabilized *Appl. Phys. Express* **1** 012007
[25] Liang H C, Chen R C C, Huang Y J, Su K W and Chen Y F 2008 Compact efficient multi-GHz Kerr-lens mode-locked diode-pumped Nd:YVO_4 laser *Opt. Express* **16** 21149–54
[26] Chen Y F, Liang H C, Tung J C, Su K W, Zhang Y Y, Zhang H J, Yu H H and Wang J Y 2012 Spontaneous subpicosecond pulse formation with pulse repetition rate of 80 GHz in a diode-pumped Nd:$SrGdGa_3O_7$ disordered crystal laser *Opt. Lett.* **37** 461–3
[27] Liang H C, Huang Y J, Huang W C, Su K W and Chen Y F 2010 High-power, diode-end-pumped, multigigahertz self-mode-locked Nd:YVO_4 laser at 1342 nm *Opt. Lett.* **35** 4–6
[28] Chen Y F, Lee Y C, Liang H C, Lin K Y, Su K W and Huang K F 2011 Femtosecond high-power spontaneous mode-locked operation in vertical-external cavity surface-emitting laser with gigahertz oscillation *Opt. Lett.* **36** 4581–3
[29] Liang H C, Huang Y J, Lin Y C, Lu T H, Chen Y F and Huang K F 2009 Picosecond optical vortex converted from multigigahertz self-mode-locked high-order Hermite–Gaussian Nd:$GdVO_4$ lasers *Opt. Lett.* **34** 3842–4