Compact efficient multi-GHz Kerr-lens mode-locked diode-pumped Nd:YVO_4 laser

H. C. Liang, Ross C. C. Chen, Y. J. Huang, K. W. Su, and Y. F. Chen*

Department of Electrophysics, National Chiao Tung University, Hsinchu, Taiwan
yfchen@cc.nctu.edu.tw

Abstract: We demonstrate the compact efficient multi-GHz Kerr-lens mode locking in a diode-pumped Nd:YVO_4 laser with a simple linear cavity without the need of any additional components. Experimental results reveal that the laser system can be characterized in stable single-pulse and multiple-pulse mode-locked operations. With a pump power of 2.5 W, the compact laser cavity produces average output powers greater than 0.8 W with a pulse width less than 10 ps in the range of 2–6 GHz.

OCIS codes: (140.4050) Mode-locked lasers; (190.3270) Kerr effect; (140.3480) Lasers, diode-pumped.

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1. Introduction

The third-order nonlinear optical responses are closely related to the stimulated Raman scattering (SRS) process and the Kerr-lensing effect [1]. Yttrium vanadate crystals (YVO_4) were recently predicted to be promising Raman-active materials for a wide range of pump pulse durations from picoseconds to nanoseconds [2,3]. More recently, diode-pumped passively and actively Q-switched Nd:YVO_4 self-stimulated Raman lasers have been efficiently demonstrated [4-7]. Realization of the self-SRS laser operation elucidates that the tetragonal YVO_4 crystal possesses a considerable nonlinear refractive index. Experimental results revealed that third-order nonlinearity of YVO_4 crystal is significantly larger than that of BaF_2 crystal by a factor of (8.2 ± 2.1) [8]. The magnitude of the nonlinear refractive index is directly proportional to the strength of self-focusing effect that determines the capability for efficient Kerr-lens mode locking (KLM). As a consequence, the YVO_4 crystal is possible to be a promising host crystal for efficient self-starting KLM operation [9,10].

In addition to Ti:sapphire [11], lasers with KLM have been reported in materials such as Nd:YLF [12], Nd:YAG [13], Cr:YAG [14], Cr:forsterite [15], Cr:LiSAF [16], Cr:LiCAF [17], and Yb:Y_2O_3 [18]. However, from a review of the available literature, it appears that so far there has been no work on self-mode locked lasers based on Nd:YVO_4 crystals. Here, for what is believed to be the first time, a continuous-wave (CW) self-sustained mode-locked operation in a Nd:YVO_4 laser is reported. We experimentally demonstrate that a CW self-mode locking with multi-gigahertz (GHz) oscillations can be straightforwardly achieved in a Nd:YVO_4 laser with a simple linear cavity without the need of any additional components. With an incident pump power of 2.5 W, the compact laser cavity, operating in the range of 2-6 GHz, produces average output powers greater than 0.8 W with a pulse width as short as 7.8 ps. When the mode-locked repetition rate is significantly lower than 2 GHz, a single pulse per round trip was usually observed to split into several pulses. Since there is increasing interesting in multi-GHz mode-locked lasers for many applications such as high-speed electro-optic sampling, telecommunications, and optical clocking [19-21], the prospect of high-frequency self-mode-locked Nd:YVO_4 lasers is practically desirable.

2. Experimental setup

A schematic of the laser experiment is shown in Fig. 1. The cavity configuration is a simple flat-flat resonator. This concept was found nearly simultaneously by Zayhowski and Mooradian [22] and by Dixon *et al* [23]. A linear flat–flat cavity is an attractive design because it reduces complexity and makes the system compact and rugged. The active medium is *a*-cut 0.2 at.% Nd:YVO_4 crystal with a length of 10 mm. One facet of the laser crystal was normal to the crystal axis and was high-reflection coated at 1064 nm (>99.8%) and high-transmission coated at 808 nm. The second facet was antireflection coated at 1064 nm and wedged 0.5^o 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. A flat wedged output coupler with 15% transmission at 1064 nm was used throughout the experiment. The pump source was a 3-W

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808-nm fiber-coupled laser diode with a core diameter of 100 μm and a numerical aperture of 0.16. 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 radius was approximately 70 μm.

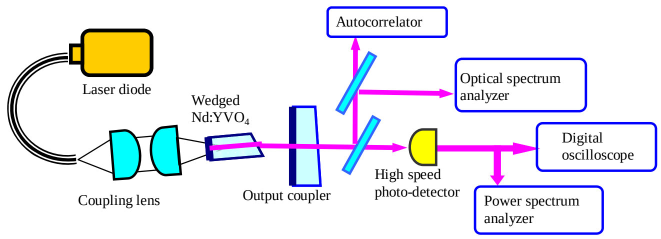

Fig. 1. Experimental setup for a diode-pumped self-mode locked $Nd:YVO_4$ laser.

The optical cavity length was varied between 16 cm and 2.5 cm with the corresponding free spectral range (FSR) between 0.935 GHz and 6.0 GHz. The mode-locked pulses were detected by a high-speed InGaAs photodetector (Electro-optics Technology Inc. ET-3500 with rise time 35 ps), whose output signal was connected to a digital oscilloscope (Agilent DSO 90000) with 10 GHz electrical bandwidth and a sampling interval of 25 ps. At the same time, the output signal of the photodetector was analyzed by an RF spectrum analyzer (Advantest, R3265A) with a bandwidth of 8.0 GHz. The spectral information of the laser was monitored by an optical spectrum analyzer (Advantest Q8381A). The spectrum analyzer, which employs a diffraction lattice monochromator, can be used for high-speed measurement of pulse light with a resolution of 0.1 nm.

The cavity mode size in the gain medium is given by [24]

$$\omega_l = \sqrt{\frac{\lambda}{\pi}}\,\frac{\left(L\ f_{th}\right)^{1/4}}{\left(1-L/f_{th}\right)^{1/4}} \tag{1}$$

where f_{th} is the effective focal length of the thermal lens and L is the effective cavity length. Note that the difference between the effective cavity length L and the optical cavity length L_{opt} is given by $L_{opt} - L = l\,(n-1/n)$, where l is the length of the gain medium and n is the refractive index of the gain medium. The effective focal length for an end-pumped laser rod can be approximately expressed as $f_{th} = C\,\omega_p^2/P_{in}$, where ω_p is the average pump radius in the unit of mm, P_{in} is the incident pump power in the unit of watt (W), and C is a proportional constant in the unit of W/mm. The effective focal length at a given pump power can be experimentally estimated from the longest cavity length with which a flat-flat cavity can sustain stable. Therefore, we perform the laser experiments to obtain the critical cavity lengths for different pump powers at a fixed pump size. We fitted the experimental results and found the constant C to be approximately 6.5×10^4 W/mm. Figure 2 shows the cavity mode size as a function of the optical cavity length for three different pump powers. The cavity mode sizes were calculated with the parameters of $C = 6.5\times10^4$ W/mm, $\omega_p = 0.07$ mm, n=2.18, and l = 10 mm. The cavity mode size can be seen to be generally smaller than 0.2 mm for the optical cavity length shorter than 70 mm. On the other hand, the cavity mode size begins to be greater than 0.3 mm for the optical cavity length longer than 150 mm.

Based on the assumption of a parabolic laser-intensity-dependent index variation, the effective Kerr-lens focal length can be given by $f_{kr} = \omega_1^2/4\,n_2\,I_o$, where n_2 is the nonlinear refractive index and I_o is the laser peak intensity. For the present laser cavity, f_{kr} was calculated to be several meters. The mode size change in the laser crystal due to the Kerr self-focusing was estimated to be 0.05–0.2 μm, which could lead to a round-trip diffraction-loss modulation of 10^{-4} –10^{-5}. This loss modulation is sufficient for self-starting of mode locking [18].

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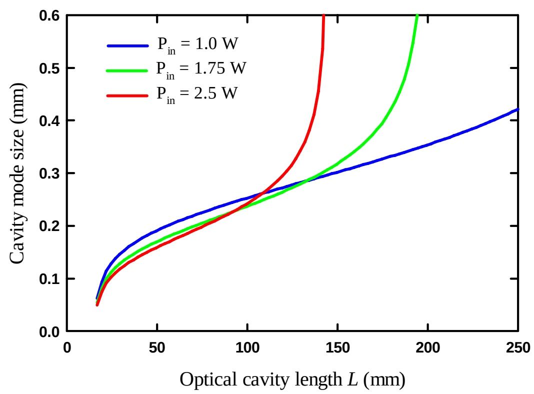

Fig. 2. Cavity mode size as a function of the optical cavity length for three different pump powers.

3. Experimental results and discussions

The optical cavity length was firstly set to be approximately 6.4 cm, corresponding to the FSR of 2.35 GHz. When the cavity alignment was optimized for generating the maximum average output power, the time trace of the output radiation revealed the laser to be in the spontaneous mode-locked state. Figures 3(a) and 3(b) show the pulse trains on two different timescales, one with time span of 10 ns, demonstrating mode-locked pulses, the other with time span of 5 μs, demonstrating the amplitude oscillation. The corresponding power spectrum is shown in Fig. 3(c). Although some amplitude fluctuation exists under the circumstance of the optimum output power, it can be definitely improved with the fine-tuning of the cavity alignment by monitoring the temporal behavior of the pulse train profile and the width of the power spectrum. Figures 4(a)-4(c) show the real-time traces and the power spectrum for the case of minimizing amplitude fluctuation. As shown in Figs. 4(a) and 4(b), the full modulation of pulse trains without any CW background indicates the realization of complete mode locking. Excellent performance on self-mode locking indicates that the YVO_4 crystal is a promising host medium for efficient self-starting KLM operation at GHz oscillations. Experimental results reveal that the relative frequency deviation of the power spectrum, $\Delta v/v$, is smaller than 5×10^{-5} over day-long operation, where v is the center frequency of the power spectrum and Δv is the frequency deviation of full width at half maximum. It is worthwhile to mention that the wedge shape of the laser crystal is vital for obtaining a complete stable mode-locked operation. When a laser crystal without a wedge is used in the flat-flat cavity, the pulse trains exhibit incomplete mode locking with CW background to a certain extent. On the other hand, when an oscilloscope with bandwidth less than 500 MHz is used to measure the present temporal characteristics, the result will display like a pure CW laser. Perhaps this is the reason why the phenomenon of self-mode locking in the range of GHz has not been discovered earlier.

Experimental results reveal that the average output power of the stable continuous-wave mode-locking is approximately 90% of the maximum average output power. Figure 5(a) shows the average output powers versus the incident pump power obtained at a mode-locked frequency of 5.32 GHz with the cavity alignments for maximum output and stable cw mode-locking, respectively. The slope efficiency for the stable mode-locked operation can be seen to be approximately up to 40% with respect to the incident pump power, corresponding to an optical-optical efficiency of 32%. As shown in Fig. 5(b), the FWHM width of the optical spectrum is approximately 0.21 nm around the central wavelength of 1064.3 nm. Figure 5(c) depicts the real-time traces with time span of 1 ns to measure the temporal duration of the mode-locked pulses. The pulse width can be clearly found to be approximately 50 ps (FWHM) from the real-time trace for the mode-locked frequency in the range of 2–6 GHz. However, the pulse duration was measured with a homemade autocorrelator and was found to

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be as short as 7.8 ps assuming a Gaussian-shaped temporal intensity profile, as shown in Fig. 5(d). The discrepancy comes from the condition that the impulse response of the present detector has a FWHM of 40 ps and the sampling interval of the present digital oscilloscope is 25 ps. Even though the experimental data shown in Figs. 5(b)-5(c) were obtained at a pump power of 2.5 W, these results were found to be almost the same for the pump power in the range of 0.5–2.5 W. Based on thorough experiments, it was confirmed that the pulse width obtained with the present real-time trace is approximately 40 ps greater than that derived from autocorrelation trace for the ps pulses. Therefore, the present real-time trace is a quick useful estimation for the temporal behavior of the ps mode-locked laser.

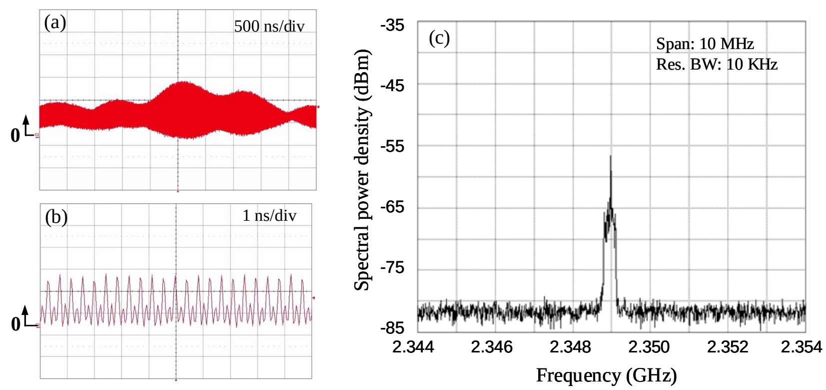

Fig. 3. Pulse trains on two different timescales. (a) time span of 10 ns, demonstrating mode-locked pulses; (b) time span of 5 μs, demonstrating the amplitude oscillation. (c) power spectrum.

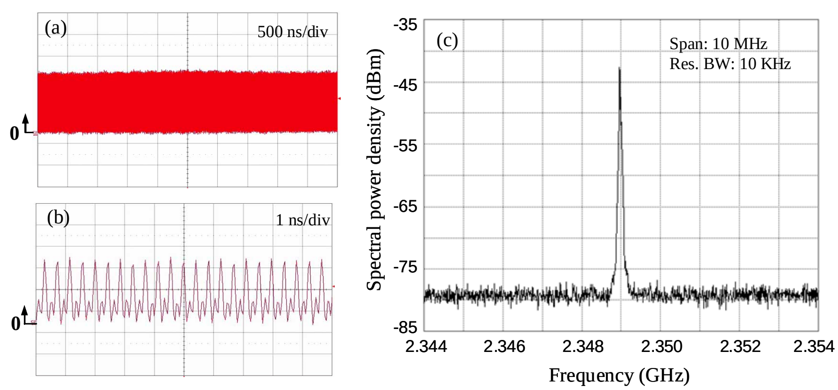

Fig. 4. Same as Fig. 3 for the stable CW mode-locked operation.

We performed the same experimental procedure for different cavity lengths to investigate the influence of the intracavity power intensity on the performance of the mode locking. We found that the laser system can be easily operated in a stable single-pulse mode-locked regime when the cavity length is approximately shorter than 7.5 cm (the mode-locked repetition rate >2 GHz). For the cavity length longer than 8.5 cm, a single pulse per round trip was usually observed to split into several pulses. Figure 6(a) shows the experimental time traces for the cavity length at 11.3 cm; the corresponding optical spectrum is depicted in Fig. 6(b). The interpulse spacing of the stable multiple-pulse state can be found to be associated with the spectral modulation. From Fig. 2, we can conclude that the cavity mode size needs to be smaller than 0.2 μm for a stable single-pulse mode-locked operation.

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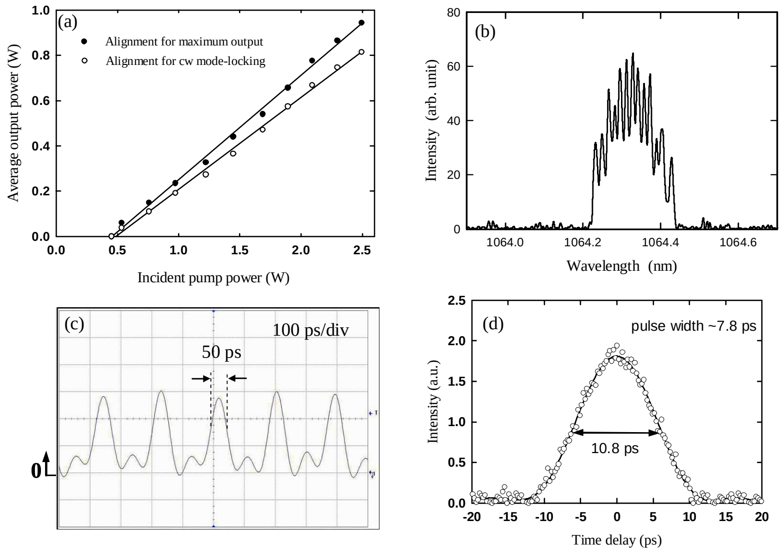

Fig. 5. (a). Average output powers versus incident pump power obtained with the cavity alignments for maximum output and stable CW mode-locking, respectively; (b). corresponding optical spectrum of the mode-locking; (c). mode-locked pulse trains in time span of 1 ns; (d). autocorrelation trace.

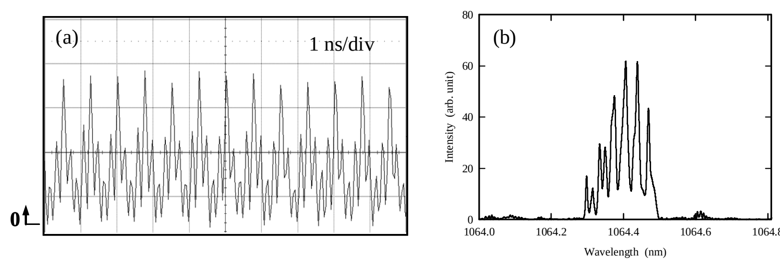

Fig. 6. (a). Experimental time traces for the multiple-pulse mode-locked operation at the cavity length of 11.3 cm (b) corresponding optical spectrum of the mode-locking.

4. Summary

In summary, we have demonstrated a compact efficient CW self-sustained mode-locked operation in the range of several GHz in a Nd:YVO_4 laser with a simple linear cavity without the need of any additional components. We found that the laser system can be operated in stable single-pulse and multiple-pulse mode-locked regimes for the cavity length shorter and longer than approximately 7.5 cm, respectively. At a pump power of 2.5 W, a maximum average output power of 0.8 W was obtained, which gives an optical conversion efficiency of 32%. The pulse width is generally less than 10 ps for the mode-locked frequency of 2-6 GHz. The present KLM performance confirms the large third-order nonlinearity of YVO_4 crystals found in the efficient self-Raman lasers [2-7].

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