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Compact and high repetition rate Kerr-lens mode-locked 532 nm Nd:YVO_4 laser

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Abstract

A compact and feasible CW Kerr-lens-induced mode-locked 532 nm Nd:YVO_4 laser system was experimentally demonstrated for the first time with theoretical analysis. Kerr-lens mode locking with intracavity second harmonic generation provides a promising method to generate a high-repetition-rate picosecond green laser. With an incident pump power of 6 W, the average output power of mode locking was 258 mW at a high repetition rate of 1.1 GHz.

Keywords: Kerr-lens, continuous wave mode locking, high repetition rate, green laser

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

1. Introduction

With intracavity second harmonic generation (SHG), high repetition rate and moderate average power green lasers are important for many applications, such as for use in optical communication, surgery, medicine, surface hardening, solar cell manufacturing, etc. Neodymium-doped yttrium vanadate (Nd:YVO_4) crystal has been widely proved as an excellent material to generate pulsed green lasers for more than a decade with frequency doubling technology [1–12]. And most of them are Q-switched lasers [1–7], the others are mode-locked lasers, in which the usual passively saturable absorbers are Cr:YAG and SESAM [8–12]. The laser system operates in the Q-switched mode locked regime with the Cr:YAG [8–10], and continuous wave (CW) mode-locked green lasers with SESAM operate in a low repetition rate mode locked regime [11, 12]. So a new method to realize the operation of a high repetition rate CW mode-locked laser is necessary, which can be applied in many fields, such as solar cell manufacturing, light detection and ranging, geo-seismic sensing, etc. Kerr-lens mode-locking could be a promising method to generate a high repetition rate CW mode-locked picosecond green laser.

Three order nonlinear Kerr effect (or intensity-dependent index of refraction) is a possible nonlinear interaction to lock the phases of the oscillating longitudinal modes. Kerr-lens-induced mode locking (KLM) in a Nd:YVO_4 laser has been demonstrated in recent years [13–15], with which a fast saturable absorber action with a simple mechanism can be achieved. In KLM, because of the gain bandwidth limits of Nd-doped vanadate crystal, the intensity-dependent index of refraction in the gain medium results in self-focusing of the ps pulses. This Kerr lens effect can be combined with either a physical aperture (hard aperture) or a spatially narrow gain profile (soft aperture) in order to yield a higher net gain and stable waveform. A linear cavity is an attractive design because it reduces complexity and makes the system compact and rugged. In this experiment, a linear concave-flat cavity is strictly designed by using the ABCD matrix. $KTiOPO_4$ (KTP) crystal is often chosen as the SHG nonlinear crystal, which has highly effective nonlinear coefficient, large acceptance angle and large temperature bandwidth [16, 17].

In this paper, a diode-pumped KLM Nd:YVO_4 green laser with intracavity doubled second harmonic is reported for the first time. With a strict design and lots of experiments, a

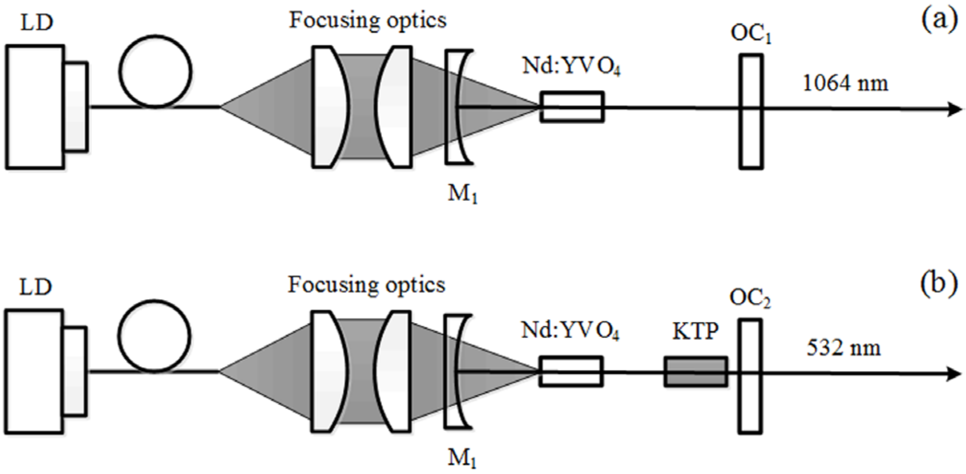

Figure 1. (a) Schematics for KLM Nd:YVO_4 1064 nm laser. (b) Schematics for KLM Nd:YVO_4 green laser.

compact and effective CW mode-locked green laser system is experimentally demonstrated. As for this laser, we found the intracavity KTP can influence the CW mode-locked waveform severely. With the incident pump power of 6 W, the mode locked pulse repetition rate, the maximum average output power and the slope efficiency are 1.1 GHz, 258 mW and 4.2%, respectively.

2. Experiment setup

The scheme of the experimental setup was illustrated in figures 1(a) and (b). The pump source employed in the experiments was a fiber-coupled 808 nm laser diode (LD) with a core diameter of 200 μm and a numerical aperture of 0.22. The central wavelength of the laser diode was 807. 5 nm at 25 °C and can be tuned by changing the working temperature of the LD to match the best absorption of the laser crystal. A focusing lens system with a focal length of 75 mm and a coupling efficiency of 93% was used to reimage the pump beam into the laser crystal. The active medium was an a-cut 0.2 at. % Nd^{3+}:YVO_4 crystal which was wedged 1° to suppress the Fabry–Perot etalon effect and the dimensions were $3 \times 3 \times 10$ mm. The crystal was high-transmission (HT) coated at 808, 1064 nm (>99.8%). A $3 \times 3 \times 10$ mm KTP ($\theta = 90°$, $\phi = 23.5°$) is chosen as the intracavity doubled crystal which is cut for type II critical phase matching. Both sides of the KTP crystal are a coated antireflection layer at 1064 and 532 nm. The laser crystal and KTP were wrapped with indium foil and mounted in a water-cooled copper holder which the temperature was controlled to be 18 °C to ensure stable laser output. The resonator consists of two mirrors, M_1 and output coupler (OC_1 or OC_2). The mirror M_1 was a spherical mirror with a curvature radius of 300 mm which was antireflection (AR) coated at 808 nm (>98%) and high-reflection (HR) coated at 1064, 532 nm (>99.8%). The OC_1 was a flat mirror which was high-reflection (HR) coated at 808 and partial-transmission (PT) coated at 1064 nm ($T = 10\%$). And the OC_2 was a flat mirror which was high-reflection (HR) coated at 808, 1064 nm and high-transmission (HT) coated at 532 nm (>99.8). The total optical-cavity length was about 135 mm.

3. Theoretical analysis

The criterion of achieving the Kerr-lens-induced is that self-focusing effect is stronger than the diffraction effect; the diffraction effect is inverse in proportion to the square of mode radius in the active medium. So the radius of the beam on the crystal and the length of the laser rod should be appropriate.

The radius of spot sizes along the cavity axis ω is a function of the intracavity beam power P, then the effective beam area on the Kerr medium can be calculated. The matrix of Kerr lens can be written as [18]:

$$M_K = \sqrt{1-\gamma}\begin{vmatrix} 1 & \dfrac{d}{n_0} \\ \dfrac{-n_0\gamma}{(1-\gamma)d} & 1 \end{vmatrix}\gamma$$

$$= \left[1 + \frac{1}{4}\left(\frac{2\pi n_0\omega_L^2}{\lambda d} - \frac{\lambda d}{2\pi n_0\omega_0^2}\right)^2\right]^{-1}\frac{P}{P_c}$$

Where d is the length of the Kerr medium, n_0 is the refractive index, λ is the laser wavelength, P is the intracavity instantaneous power in the cavity, ω_L and ω_0 are the effective beam area on the medium and the beam waist radius calculated at $P/P_c = 0$, $P_c = c\varepsilon_0\lambda^2/2\pi n_1$ is the critical power for self-focusing, c is the speed of light, ε_0 is the dielectric permeability of vacuum, n_1 is the nonlinear refractive index of the Kerr medium.

Considering the distance between M_1 and laser medium, the distance between laser medium and M_2. According to the ABCD propagation laws and the nonlinear transmission matrix of the Kerr lens, the ω can be written as:

$$\omega(P)^2 = \frac{2\lambda B(P)}{\pi\sqrt{4 - [A(P) + D(P)]^2}}$$

Where A, B and D are the propagation matrix elements.

Nd:YVO_4 crystal has a large nonlinear refraction index (1×10^{-18} m^2 W^{-1}) [19] which is much larger than that of Ti:sapphire (5.1×10^{-19} m^2 W^{-1}). It means the critical power for Nd:YVO_4 self-focusing can be achieved under a

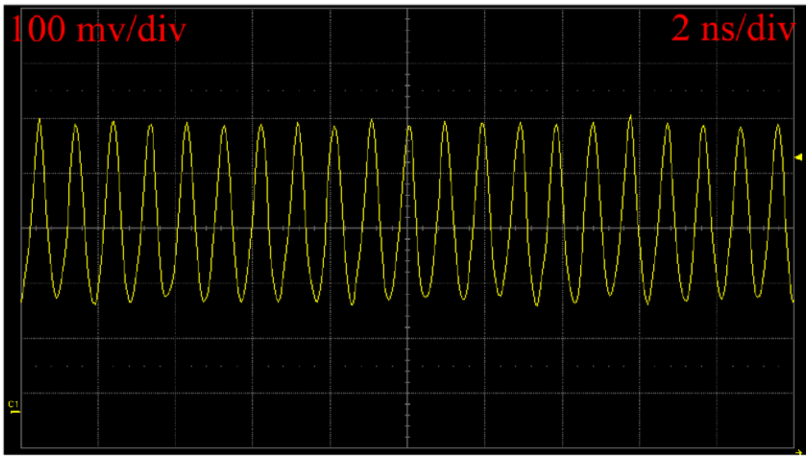

Figure 2. 1064 nm CW mode locking without a hard aperture on time scale: 2 ns/div.

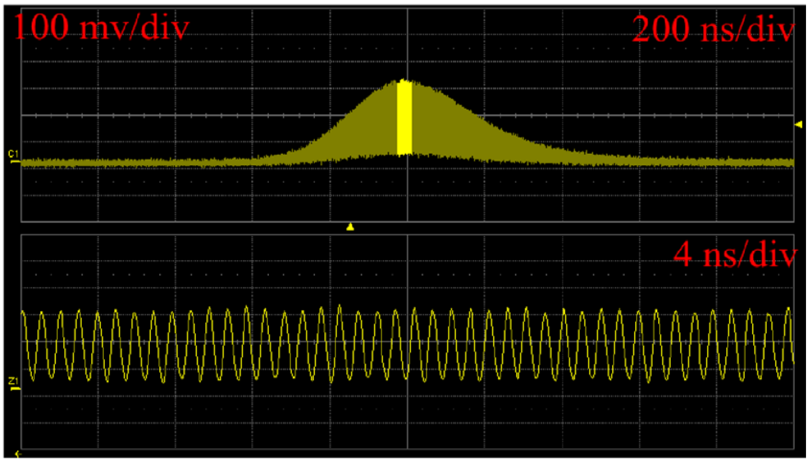

Figure 3. 532 nm Q-switched mode locking on two different types of time scales: 200 ns/div, 4 ns/div.

lower power, which P_c is calculated about 102 W. The refraction index of Nd:YVO$_4$ is 2.19. And through the above formula, the average beam size in the Kerr medium is calculated about 236 μm. The effective area of the pump source could be smaller than the effective area in the active medium. It means the incident pump beam can be regarded as an aperture. In this case, the laser mode is mismatched, and the KLM can occur easier, even though the efficiency will be decreased.

The strength for Kerr lens mode locking can be given by the Kerr-lens sensitivity $\delta(z)$ [20, 21]:

$$\delta(z) = -\left(\frac{1}{\omega}\frac{\mathrm{d}\omega}{\mathrm{d}p}\right)\Big|_{p=0}$$

Where δ is the small-signal relative spot size variation, ω is the Gaussian beam spot size in the direction in which the aperture cuts the beam, and $p = P/P_c$. In our experiment, a spatially narrow gain profile in the laser crystal was acting as a soft aperture. By choosing suitable pump beam size in crystal, enough nonlinear gain modulation will be produced for self-focusing. The δ parameter is described as the distribution of the Kerr nonlinear intensity in the cavity [14], as it measures the ability of the cavity to discriminate between the high-power (pulsed) and the low-power (continuous) regimes [22]. The larger the value of δ, the easier the KLM occurs and sustains. In this experiment, the value of δ is calculated about 0.87×10^{-2} on the crystal.

The criterion for self-starting of passive mode locking can be given by [22, 23]:

$$L_{\mathrm{nl}} > \frac{\pi \cdot T_{\mathrm{R}} \cdot \Delta\upsilon_{3\,\mathrm{dB}}}{\ln(m_i)}$$

Where L_{nl} is the nonlinear loss modulation, $L_{\mathrm{nl}} = \delta \cdot p$, $\Delta\upsilon_{3\,\mathrm{dB}}$ is the 3 dB full width of the first beat note, T_{R} is the round-trip time, and m_i is the number of modes initially oscillating. For the present laser, $\Delta\upsilon_{3\,\mathrm{dB}}$ was measured about 50 kHz with an RF spectrum analyzer (RIGOL DSA1030A), T_{R} was estimated about 910 ps. Assuming $\ln(m_i) = 5.2$. As a result, this loss modulation of the present laser is sufficient to meet the self-starting condition of $L_{\mathrm{nl}} > 2.75 \times 10^{-5}$.

4. Result

The mode-locked 532 nm laser pulses were detected by a high speed Si photo detector (2 GHz bandwidth), and a digital oscilloscope (LeCroy Wave pro 7300A) with 3 GHz electrical bandwidth. And the mode-locked 1064 nm laser pulses were detected by a high speed InGaAs photo detector (5 GHz

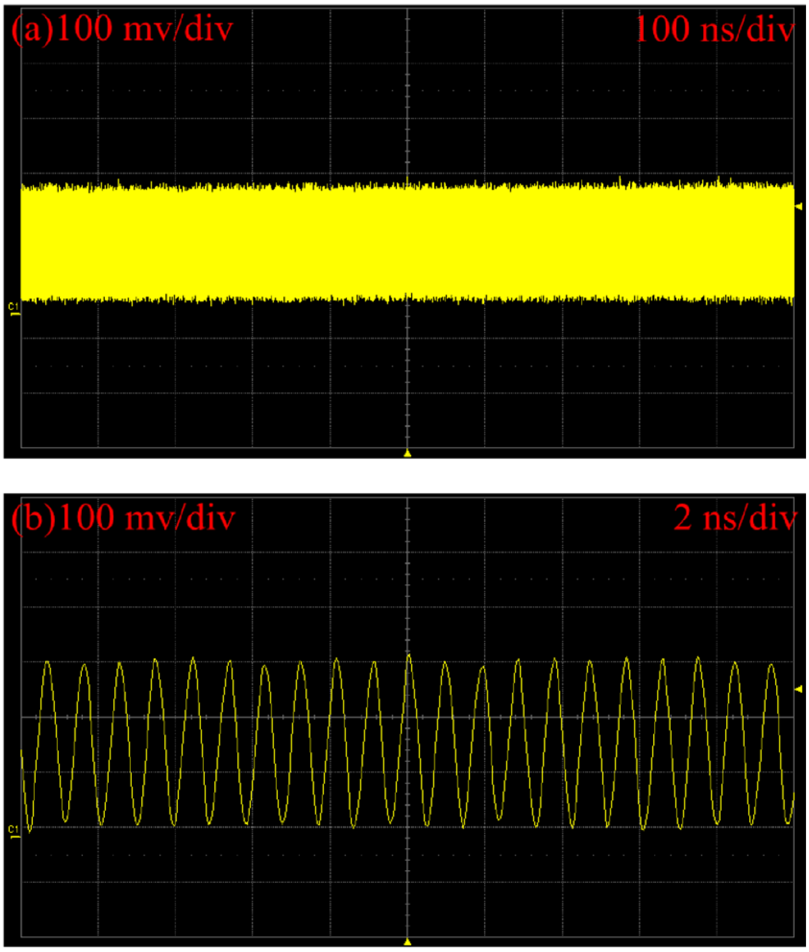

Figure 4. 532 nm CW mode locked pulse trains envelope on two different types of time scales: (a) 100 ns/div, (b) 2.00 ns/div.

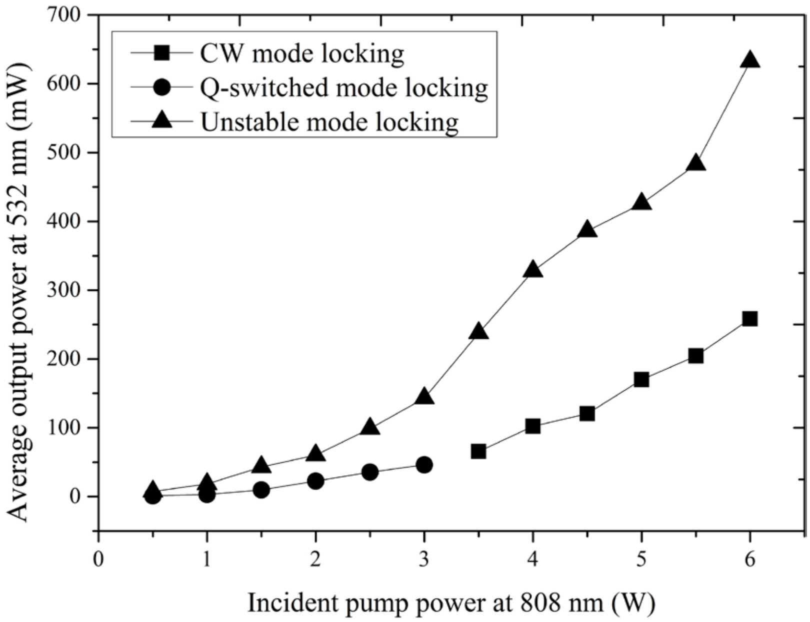

Figure 5. Output power at 532 nm with respect to the incident diode pump power.

bandwidth). The spectrum of the 532 nm laser was detected by an ocean spectrometer (HR 2000+).

KLM strongly depended on the laser cavity adjustment and alignment. The amplitude instability was minimized to obtain a relatively stable mode-locking operation with fine adjusting of the cavity. In this experiment, an output coupler of high-transmission (HT) coated at 532 nm (>99.8) was used, which can prevent partial reconversion of the second harmonic into

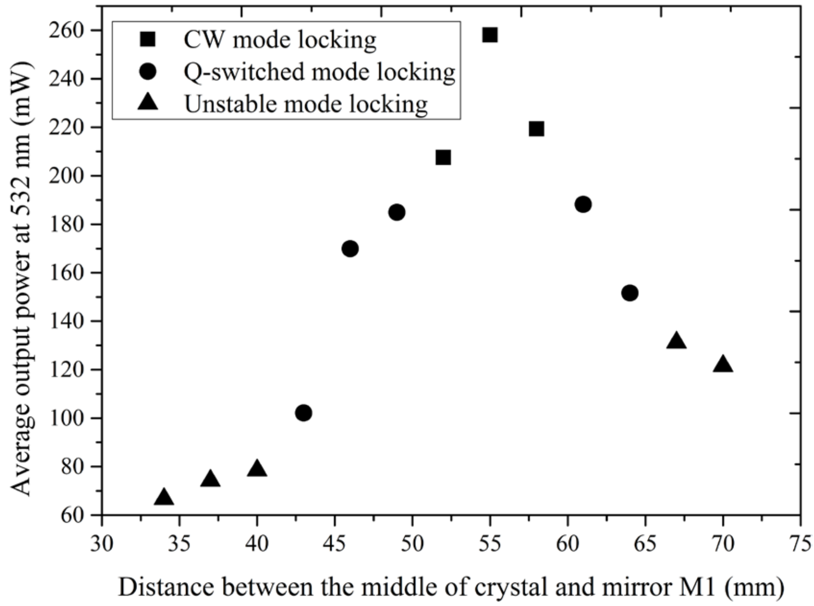

Figure 6. Output power at 532 nm with respect to the l_1 with different modes of pulses.

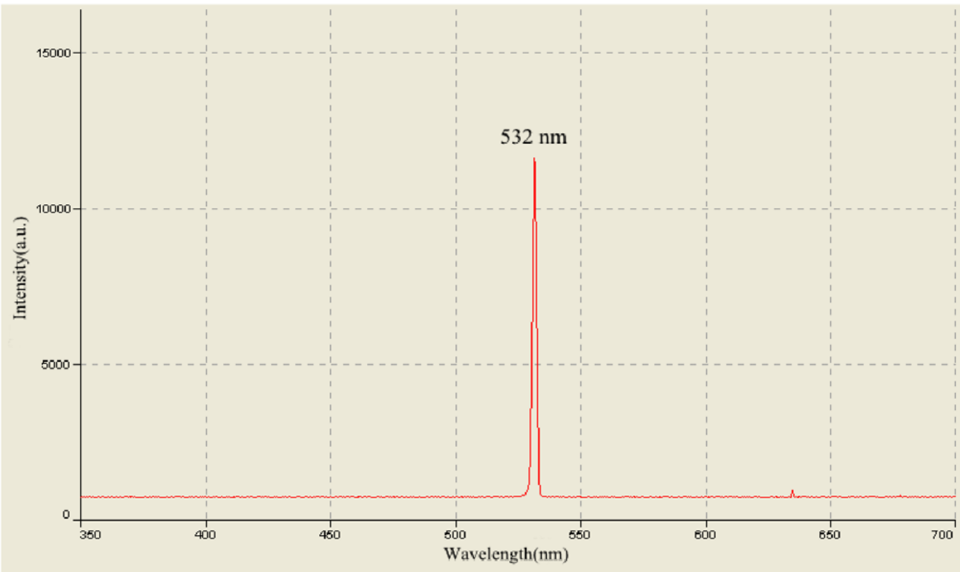

Figure 7. Spectrum of the 532 nm picosecond laser.

fundamental waveform from taking place. It could reduce the nonlinear effect of the KTP to the Kerr-lens mode locking for the present laser. In this experiment, the Kerr effect in the $Nd:YVO_4$ with a spatially narrow gain profile can be seen as a fast saturable absorber action. Figure 2 shows the mode locking operation of the laser at 1064 nm.

According to the doubling efficiency formula $\eta = kI_{(\omega)}$(k is a conversion factor to the nonlinear crystal), the doubling efficiency is directly proportional to the fundamental intensity, and namely, the effective area in the KTP should be relatively small. In this experiment, the KTP was placed near the OC in order to get the higher fundamental intensity. Nevertheless, the efficiency of the green laser was decreased in order to achieve the stable self-mode-locking. Meanwhile, in this laser system, the laying angle of KTP had an impact on the output laser amplitude fluctuations.

With the Si photo detector and an optical filter (1064HR, 532HT), the 532 nm laser pulse train trace was showed on the oscilloscope. In this laser, Q-switched mode locking was observed with the low incident pump power, speculating that the low power intensity on the crystal leads to the unstable nonlinear loss modulation, which generated this phenomenon. Figure 3 shows similar 532 nm Q-switched mode locking corresponding to the incident pump power of 1 W. When the pump power increased to 3 W, this phenomenon disappeared.

Figures 4(a) and (b) showed the 532 nm pulse trains on two different time scales at the same incident pump power of 6 W, with the cavity operating in the critical state. Figure 4(a) proved the 532 nm CW mode locking on time scale of 100 ns/div. Figure 4(b) showed the pulse trains on time scale of 2 ns/div, which showed the 532 nm CW mode-locked separated pulse. The laser amplitude fluctuations were relatively small and stable. The fundamental frequency peak could be measured about 1.1 GHz, which corresponded exactly to the free spectral range of the self-mode-locked optical cavity length 135 mm. The pulse width showed on the oscilloscope was about 320 ps. And the average fluctuation of mode-locked laser amplitude was less than 8%.

Figure 5 showed the output CW mode-locked, Q-switched mode-locked and unstable mode-locked power at 532 nm with respect to the incident pump power, in view of coupling efficiency of the focusing lens system. At the maximum incident pump power of 6 W, the average output power at CW mode locking operation of the laser at 532 nm was about 258 mW, which the slope efficiency was nearly 4.5%. The average output power at unstable mode locking was about 632 mW. As to obtain robust stable Kerr-lens mode-locked green laser, the efficiency of the green laser was decreased. The distance between the middle of crystal and mirror M_1 is l_1. When the incident pump power was 6 W, figure 6 showed the output power at 532 nm with respect to the l_1 with different modes of pulses. In the process of cavity length change, the mirror don't be adjusted. Figure 7 shows the spectrum of the Nd:YVO_4 532 nm Kerr-lens mode-locked laser.

5. Conclusion

An efficient diode-pumped KLM Nd:YVO_4 532 nm laser was demonstrated with the intracavity SHG technology, which can be a potential light in many fields, such as laser machining, light detection and ranging, geo-seismic sensing for oil & gas, etc. Kerr-lens mode locking with intracavity frequency doubling has been proved a promising and valuable method to achieve a high-repetition-rate CW mode-locked green laser.

Acknowledgments

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