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Passively mode-locked performance of diode-pumped $Nd:Lu_{0.15}Y_{0.85}VO_4$ laser

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The mode-locking performance of diode-pumped $Nd:Lu_{0.15}Y_{0.85}VO_4$ laser is first demonstrated with a semiconductor saturable absorber mirror. Stable mode-locking with the pulse duration of 5.1 ps and the repetition rate of 106 MHz is achieved. An output power of 7 W is obtained at a pump power of 20 W, corresponding to an optical conversion efficiency of 35%. The maximum mode-locked pulse energy is estimated to be 66 nJ with the peak power of 12.9 kW.

OCIS codes: 140.3480, 140.3580, 140.4050, 140.3530, 140.3380.

1. INTRODUCTION

All-solid-state mode-locked lasers due to their particular attraction for nonlinear optics, military and industry have been well developed with various laser host materials. The neodymium doped single vanadate crystals have been proved to be excellent laser mediums for the diode-pumped mode-locked lasers. Among them, $Nd:YVO_4$ has been investigated in detail [1–5] and has become the most common medium for lasers operating at low pump power levels. On the other hand, $Nd:LuVO_4$, an isomorphism of $Nd:YVO_4$, has also been proved to be an efficient gain medium [6–9], especially at mode-locked laser systems due to its remarkably wide fluorescence line width ($\Delta\lambda \approx 1.5\,\text{nm}$ [7]). The important frontiers of mode-locked lasers are the short pulse width and the high average output power, which are ultimately determined by the property of the laser host materials. Adopting the laser medium with broad fluorescence line width in the mode-locked laser is one of the effective means to obtain ultrashort pulses. It has been proved that the fluorescence line widths of mixed vanadate crystals are always broader than that of single vanadate materials due to the inhomogeneous broadening in the fluorescence spectra. Actually, a number of previous experiments with $Nd:Lu_xGd_{1-x}VO_4$ and $Nd:Gd_xY_{1-x}VO_4$ also reveal that such mixed crystals are the better candidate for Q-switched and mode-locked performance than the single ones [10-13].

In this letter, we report on the performances of passively mode-locked laser with a semiconductor saturable absorber mirror and a $Nd:Lu_{0.15}Y_{0.85}VO_4$ mixed crystal which is fabricated by substituting a fraction of Y ions with the Lu ions. The maximum average output power of 7 W is obtained at the absorbed pump power of 20 W, corresponding to an optical conversion efficiency of 35%. Under the same conditions, stable mode-locked pulses with duration of 5.1 ps and a repetition rate of 106 MHz also have been achieved, giving a peak of 12.9 kW. In comparison with $Nd:YVO_4$ and $Nd:LuVO_4$ single crystals, $Nd:Lu_{0.15}Y_{0.85}VO_4$ can generate even shorter pulses and even higher peak powers because of its broader fluorescence line width.

2. EXPERIMENTAL SETUP

The $Nd:Lu_{0.15}Y_{0.85}VO_4$ mixed crystal used in experiment is fabricated by the Czochralski method and grown under a nitrogen atmosphere of containing ~3% oxygen in an iridium crucible with a diameter of 65 mm and a height of 40 mm. An rectangular YVO_4 (a-axis) single crystal bars, with the dimensions of 4 mm×4 mm×35 mm, is used as seed. The finished product crystal is cooled to room temperature with a rate of 30~50 $^{\circ}C/h$. When the sample is shined by a green laser, no light scattering which is caused by particulates in crystal is observed, indicting a good crystal quality. The $Nd{:}Lu_{0.15}Y_{0.85}VO_4$ crystal is an isomorph of $Nd{:}LuVO_4$ and $Nd{:}YVO_4$. The lattice sites formerly occupied by Y ions in $Nd{:}YVO_4$ crystal are now partly random occupied by Lu ions. This modification of the local crystal field neighboring the Nd ions will lead to the inhomogeneous broadening of the fluorescence line widths. Figure 1 shows the measured fluorescence spectrum of the mixed $Nd{:}Lu_{0.15}Y_{0.85}VO_4$ crystal. The central wavelength of the fluorescence band is 1064.9 μm with a full width at half-maximum (FWHM) of 5.1 nm which is much broader than those of $Nd{:}Lu_xGd_{1-x}VO_4$ (~4 nm) [10] and $Nd{:}Y_xGd_{1-x}VO_4$ (>3.5 nm) [13] mixed crystal. The physical properties of $Nd{:}Lu_{0.15}Y_{0.85}VO_4$ crystal are measured and shown in table 1 in company with those of $Nd{:}LuVO_4$ and $Nd{:}YVO_4$. As can bee seen that, the $Nd{:}Lu_{0.15}Y_{0.85}VO_4$ crystal has long fluorescence lifetime and a small emission cross-sections, making it suitable for the application in the pulsed laser systems. However, its thermal conductivity values is smaller than those of $Nd{:}LuVO_4$ and $Nd{:}YVO_4$, due to the reduction of the mean free path of the phonons [12] which will limit its developments in high output power laser.

Fig. 2 shows the schematic diagram for mode-locked $Nd{:}Lu_{0.15}Y_{0.85}VO_4$ laser with folded z-configuration. The laser medium is cut along a-axis with the dimensions of 3×3×8 mm^3 and the Nd-doping concentration of 0.38 at. %. Both faces of the crystal are polished and antireflection (AR) coated at 808 nm and 1064 nm. In order to efficiently dissipate the heat deposition, the laser crystal is wrapped with indium foil and mounted in a copper block cooled by thermo-electric cooler. The pump source is a fiber-coupled diode laser, emitting at 808 nm with the maximum output power of 30 W (FAP system, Coherent, Inc.). The core size of the fiber is

400 μm in radius, with a numerical aperture of 0.22. The emission wavelength of the LD pump source is adjusted to be 809 nm which is the absorption spectrum centre of the laser medium. The pump light is delivered into the laser crystal through a focusing system with a pump spot radius of 400 μm. The folded laser cavity consisted of four mirrors. Flat mirror M_1 as one resonator mirror is antireflection (AR) coated at 808 nm and high-reflection (HR) coated at 1064 nm. Concave mirror M_2 with radium of curvature (ROC) of 500 mm is HR coated at 1064 nm, acting as one resonator mirror. M_3 is the output coupler with ROC of 100 mm and a transmission of 10% at 1064 nm, hence inducing a total output coupler of 20%. The SESAM acting as a flat mirror is positioned 5.4 cm away from M_3. The lengths of the two arms of the cavity, L_1 and L_2, are 55.5 cm and 80 cm, respectively.

3. RESULTS AND DISCUSSION

The cw laser operation is first tested by using a flat mirror which is HR coated at 1064 nm to substitute the SESAM. The laser threshold is about 0.8 W. The output power linearly increased with the incident pump power, with the maximum output power of 7.5 W at 20 W incident pump power, corresponding to an optical conversion efficiency of 37.5%, as indicated with solid curve in Fig. 3. Beyond the pump power of 20 W, the output power exhibited the tendency of power saturation caused by the cavity instability which may be induced by the thermal lens and aberration effects.

The mode locking performance of the laser is investigated with the SESAM back again to replace the HR coated flat mirror. The SESAM used in the experimental is grown on GaAs substrate by metal-organic chemical-vapor deposition. This saturable absorber is consisted of 22 pairs of GaAs/AlAs quarter-wave Bragg layers with high-reflection at 1064 nm (~ 99.5%). A 15 nm relaxed $In_{0.3}Ga_{0.7}As$ single quantum well fabricated at the temperature of 500 ℃ is embedded in the top layer of the Bragg stack for achieving saturable absorption at laser wavelength. Three pairs of SiO_2/Al_2O_3 are coated on the surface of SESAM wafer as the protective film with the reflectivity of 50% at 1064 nm.

The oscillation threshold of the mode-locked laser is about 1 W, which is just a little bit higher than that in cw laser due to the insert loss of the SESAM. In comparison with cw operation, the cw mode-locked laser output power is only slightly decreased. At the incident pump power of 20 W, the mode-locked average output power reaches 7 W, leading to an optical conversion efficiency of 35%, which is shown with dash curve in figure 3. The main obstacles for high-power passively mode-locked lasers are the thermal effects of laser medium and the optical damage to the saturable absorber. For the experimental configuration shown in Fig. 2, using the well-known ABCD matrix method and considering the thermal lens effect of the laser medium, we can obtain the TEM_{00} mode on the SESAM with the values of 46–84 μm. In addition, the radius of the TEM_{00} mode increases with pump power, which releases the elevation of the intracavity power intensity and keeps it under the SESAM's damage threshold [14]. During the experiment, no damage to the SESAM is observed.

The output pulse train of the $Nd:Lu_{0.15}Y_{0.85}VO_4$ laser is detected by a fast response photo-detector connected to the oscilloscope (Tek.TDS 5104). During the pump power ranges from 1 W to 5 W, the laser operates in Q-switching and mode-locking with a repetition rate of 90–260 kHz, depending upon the pumping power level. When the pump power rises above 5 W, the laser keeps typically cw mode-locking operation. Fig. 4 a, b shows the cw mode-locked pulse train with per division time scales of 40 ns and 200 ns, respectively. It is found that the repetition period of the pulses is about 9.4 ns, which is determined by the cavity round trip time and gives the pulse repetition rate of 106 MHz.

Fig. 5 shows the autocorrelation trace of the mode-locked pulse which is measured with an autocorrelator (FR-103XL, Femtochrome Research Inc). The FWHM of autocorrelation is around 233 μs and the pulse duration is correspondingly fitted to be 5.1 ps. The maximum pulse peak power is thus calculated to be 12.9 kW for the average output power of 7 W. The cw mode-locked laser spectrum is also measured by using an optical spectrum analyzer (ANDO AQ–6315 A) as shown in Fig. 5 (inset). It is found that the bandwidth of the laser spectrum is about 0.36 nm, corresponding to $\Delta\nu$ = 95 GHz. The time-bandwidth product of the pulses is 0.46, which could support pulses of 5.1 ps.

The pulse width and the peak power are the important parameters for the mode-locked laser. For the comparisons among different crystals, we also study the mode-locked performances of the Nd:YVO_4 and Nd:$LuVO_4$ crystal under the same conditions. The related results are shown in table 2. At the incident pump power of 20 W, the pulses widths of Nd:YVO_4 and Nd:$LuVO_4$ mode-locked lasers are 11.2 ps and 7.9 ps, respectively. Although with the higher average output power, the peak powers of the two lasers with the values of 7.3 KW and 8.7 KW are obviously lower than 12.9 KW of the Nd:$Lu_{0.15}Y_{0.85}VO_4$ laser. The results we obtained show that the Nd:$Lu_{0.15}Y_{0.85}VO_4$ crystal is a promising laser host material for mode-locking, and the mixed crystal is an efficient way to obtain the laser crystals with broader fluorescence line widths. *Yu et al* [11] has proved that the fluorescence line width increased with x approaching 0.5. If the ratio of Lu ion in Nd:$Lu_xY_{1-x}VO_4$ crystal is elevated properly, an even shorter pulse width would be obtained.

4. CONCLUSIONS

In conclusion, we have successfully demonstrated a passively mode-locked $Nd:Lu_{0.15}Y_{0.85}VO_4$ laser with a SESAM. The mode-locked output power of 7 W with 5.1 ps pulse width is obtained at the incident pump power of 20 W, giving an optical conversion efficiency of 35%. The repetition rate of the output pulse is detected to be 106 MHz and the pulse peak power is calculated to be 12.9 kW. With its broad fluorescence linewidth, $Nd:Lu_{0.15}Y_{0.85}VO_4$ will definitely be a promising laser host material for mode-locking. It is believed that if the Nd-doping concentration and the ratio between Lu and Y ions are optimized, the performance of the laser could be further improved. This related work is underway.

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REFERENCES

[1] Y. X. Fan, J. L. He, Y. G. Wang, S. Liu, H. T. Wang, and X. Y. Ma, "2-ps passively mode-locked Nd:YVO_4 laser using an output-coupling-type semiconductor saturable absorber mirror," Appl. Phys. Lett. **86**, 1–3 (2005).

[2] L. Krainer, R. Paschotta, J. Ausder, C. Honninger, U. Keller, M. Moser, D. Kopf, K. J. Weigarten, " Passively mode-locked Nd:YVO_4 laser with up to 13 GHz repetition rate,"Appl. Phys. B. **69**, 245–247 (1999).

[3] Y. F. Chen, S. W. Tsai, Y. P. Lan, S. C. Wang, and K. F. Huang, "Diode-end-pumped passively mode-locked high-power Nd:YVO_4 laser with a relaxed saturable Bragg reflector," Opt. Lett. **26**, 199–201 (2001).

[4] L. McDonagh, R. Wallenstein, and A. Nebel, "111W, 110 MHz repetition-rate, passively mode-locked TEM_{00} Nd:YVO_4 master oscillator power amplifier pumped at 888 nm," Opt. Lett. **32**, 1259–1261 (2007).

[5] D. Burns, M. Hetterich, A. I. Ferguson, E. Bente, M. D. Dawson, J. I. Davis, and S. W. Bland, "High-average-power (>20W) Nd:YVO_4 lasers mode locked by strain-compensated saturable Bragg reflectors," J. Opt. Soc. Am. B **17**, 919–926 (2000).

[6] H. Yu, H. Zhang, Z. Wang, J. Wang, Y. Yu, M. Jiang, D. Tang, G. Xie, and H. Luo, "Passively mode-locked Nd:$LuVO_4$ laser with a GaAs wafer," Opt. Lett. **33**, 225–227 (2008).

[7] C. Maunier, J. L. Doualan, R. Moncorgé, A. Speghini, M. Bettinelli, and E. Cavalli, "Growth, spectroscopic characterization, and laser performance of Nd:$LuVO_4$, a new infrared laser material that is suitable for diode pumping," J. Opt. Soc. Am. B **19**, 1794–1800 (2002).

[8] S. Zhao, H. Zhang, J. Liu, J Wang, X. Xu, Z. Zhao, J. Xu and M. Jiang, "Growth of excellent-quality Nd:$LuVO_4$ single crystal and laser properties," Cryst. Growth **279**, 146–53 (2005).

[9] H. Yu, H. Zhang, D. Tang, Z. Wang, J. Wang, Y. Yu, G. Xie, H. Luo and M. Jiang, "Diode-end-pumped passively mode-locked Nd:$LuVO_4$ laser with a semiconductor saturable-absorber mirror,"Appl. Phys. B **91**, 425–428 (2008).

[10] H. Yu, H. Zhang, Z. Wang, J. Wang, Y. Yu, D. Tang, G. Xie, H. Luo, and M. Jiang, "Passive mode-locking performance with a mixed Nd:$Lu_{0.5}Gd_{0.5}VO_4$ crystal," Opt. Expre. **17**, 3264–3269 (2009).

[11] H. Yu, H. Zhang, Z. Wang, J. Wang, Y. Yu, Z. Shao, and M. Jiang, "Enhancement of passive Q-switching performance with mixed Nd:$Lu_xGd_{1-x}VO_4$ laser crystals," Opt. Lett. **32**, 2152–2154 (2007).

[12] Y. Yu, J. Wang, H. Zhang, H. Yu, Z. Wang, M. Jiang, H. Xia, and R. I. Boughton, "Growth and characterization of Nd:$Y_xGd_{1-x}VO_4$ series laser crystals," J. Opt. Soc. Am. B, **25**, 995–1001 (2008).

[13] J. Liu, Z. Wang, X. Meng, and Z. Shao, B. Ozygus, A.Ding, and H. Weber, "Improvement of passive Q-switching performance reached with a new Nd-doped mixed vanadate crystal Nd:$Gd_{0.64}Y_{0.36}VO_4$," Opt. Lett. **28**, 2330–2332 (2003).

[14] T. Li, S. Zhao, Z. Zhuo, Y. Wang, "Thermal effects investigation and cavity design in passively mode-locked Nd:YVO_4 laser with a SESAM," Opt. Commun. **282**, 940–943 (2009).

Fingure Captions

Fig.1. (Color online) Fluorescence spectrum of Nd:$Lu_{0.15}Y_{0.85}VO_4$ crystal at an excitation wavelength of 808 nm.

Fig. 2. (Color online) Schematic configuration of the passively mod-locked laser.

Fig. 3. (Color online) Output power versus incident pump power.

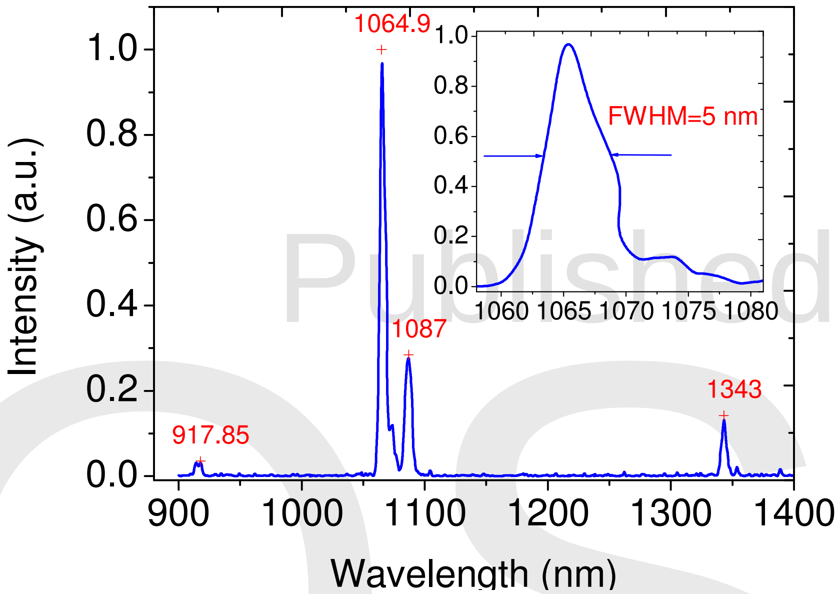
Fig.4. (Color online) Pulse train of cw mode-locked Nd:$Lu_{0.15}Y_{0.85}VO_4$ laser.

Fig. 5. (Color online) Autocorrelation signal (solid curve) of cw mode locked Nd:$Lu_{0.15}Y_{0.85}VO_4$ laser pulses and $Sech^2$ fitting (cycle symble). The spectrum of the mode-locked pulses (inset).

Table 1. The physical properties of Nd:$Lu_{0.15}Y_{0.85}VO_4$, Nd:$LuVO_4$ and Nd:YVO_4 laser crystals.

Table 2. The output parameters of mode-locked laser systems with different laser mediums.

Figure 1



1064.9
1087
1343
917.85
FWHM=5 nm
Intensity (a.u.)
Wavelength (nm)
0.0
0.2
0.4
0.6
0.8
1.0
900
1000
1100
1200
1300
1400
1060
1065
1070
1075
1080

Figure 2

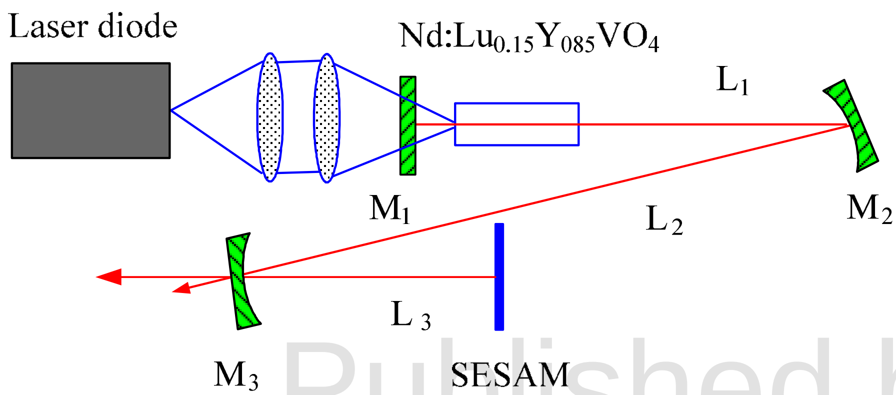


Figure 3

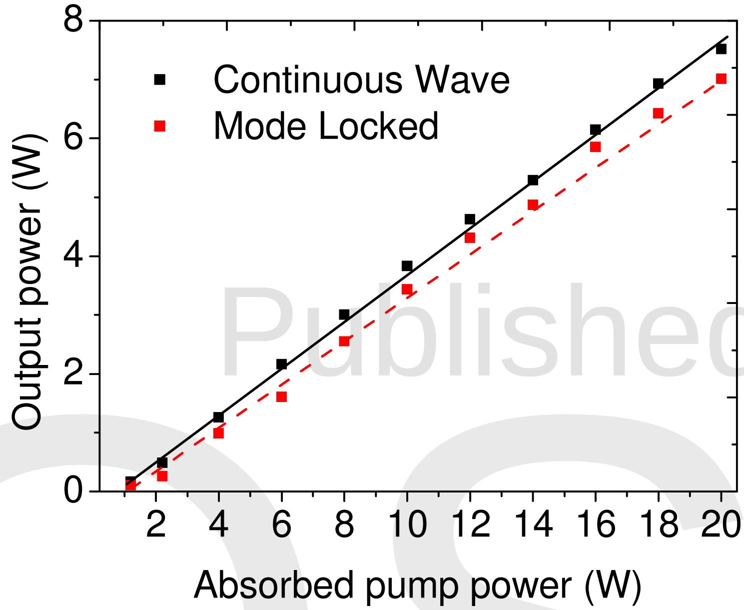

Continuous Wave
Mode Locked
Output power (W)
Absorbed pump power (W)
0
2
4
6
8
2
4
6
8
10
12
14
16
18
20

Figure 4

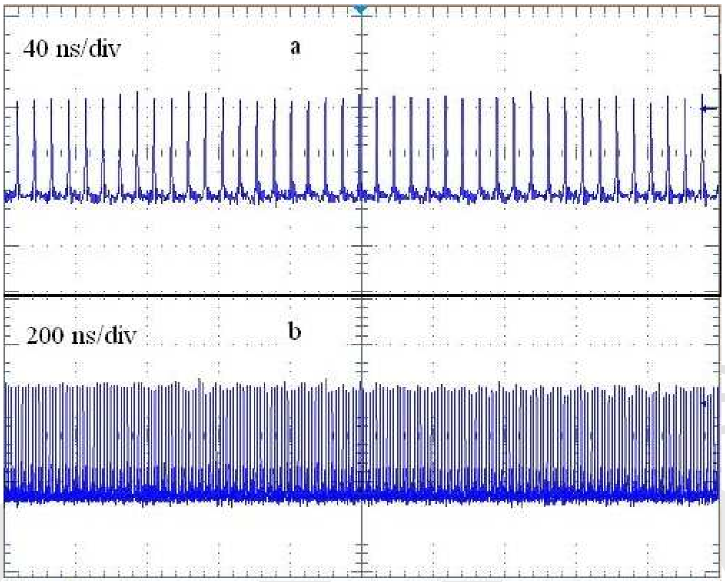
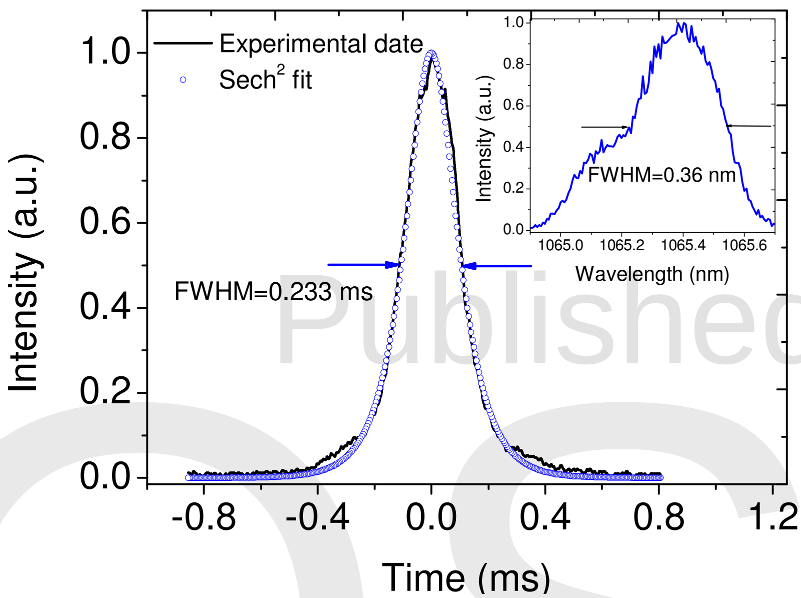


Figure 5



Experimental date
Sech^2 fit
FWHM=0.233 ms
Intensity (a.u.)
Time (ms)
1.0
0.8
0.6
0.4
0.2
0.0
-0.8
-0.4
0.0
0.4
0.8
1.2
FWHM=0.36 nm
Intensity (a.u.)
Wavelength (nm)
1065.0
1065.2
1065.4
1065.6

Table 1

Crystals	$Nd:Lu_{0.15}Y_{0.85}VO_4$	$Nd:LuVO_4$	$Nd:YVO_4$
Absorption cross section (cm^2)	1.5×10^{-19}	6.9×10^{-19}	5.7×10^{-19}
Stimulation cross section (cm^2)	6.4×10^{-19}	1.46×10^{-18}	1.35×10^{-18}
Fluorescence line width (nm)	5.1	1.5	0.8
Thermal conductivity coefficiency ($Wm^{-1}K^{-1}$)	4.5	9.9	5.1
Fluorescent Lifetime (μs)	106	95	98

Table 2

Crystals		$Nd:Lu_{0.15}Y_{0.85}VO_4$	$Nd:LuVO_4$	$Nd:YVO_4$
Continuous wave output power	(W)	7.52	7.33	9.30
Mode-locked output power	(W)	7.01	7.25	9.25
Pulse width	(ps)	5.1	7.9	11.2
Repeat rate	(MHz)	106	105	113
Peak power	(KW)	12.9	8.7	7.3