Stable, 12 W, continuous-wave single-frequency Nd:YVO$_4$ green laser polarized and dual-end pumped at 880 nm

Jianli Liu, Zhiyong Wang, Hong Li, Qin Liu, Kuanshou Zhang*

State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Opto-Electronics, Shanxi University, Taiyuan 030006, China
**kuanshou@sxu.edu.cn*

Abstract: Based on a polarized and dual-end pumping scheme and a ring resonator, a stable, high power and high beam quality continuous-wave single-frequency Nd:YVO$_4$ green laser directly pumped at 880 nm has been fabricated. A measured maximum output power of 12 W at 532nm was obtained with a conversion efficiency of 23.1%. The stability of the output was better than ±0.5% and no mode hopping was observed over a period of five hours. The output beam was almost diffraction limited with a measured beam quality of M^2_x=1.03 and M^2_y=1.02. The intensity noise reached the shot noise limit (SNL) for analysis frequencies above 3.5 MHz, and the phase noise was 1.3 dB above the SNL in the range of 2 to 20 MHz.

OCIS codes: (140.3480) Lasers, diode-pumped; (140.3515) Lasers, frequency doubled; (140.3560) Lasers, ring.

References and links

1. G. K. Samanta, G. R. Fayaz, Z. Sun, and M. Ebrahim-Zadeh, “High-power, continuous-wave, singly resonant optical parametric oscillator based on MgO:sPPLT,” Opt. Lett. **32**(4), 400–402 (2007).
2. J. M. Melkonian, T. H. My, F. Bretenaker, and C. Drag, “High spectral purity and tunable operation of a continuous singly resonant optical parametric oscillator emitting in the red,” Opt. Lett. **32**(5), 518–520 (2007).
3. C. Y. Lu, X. Q. Zhou, O. Gühne, W. B. Gao, J. Zhang, Z. S. Yuan, A. Goebel, T. Yang, and J. W. Pan, “Experimental entanglement of six photons in graph states,” Nat. Phys. **3**(2), 91–95 (2007).
4. A. S. Villar, K. N. Cassemiro, K. Dechoum, A. Z. Khoury, M. Martinelli, and P. Nussenzveig, “Entanglement in the above-threshold optical parametric oscillator,” J. Opt. Soc. Am. B **24**(2), 249–256 (2007).
5. R. Lavi, S. Jackel, Y. Tzuk, M. Winik, E. Lebiush, M. Katz, and I. Paiss, “Efficient pumping scheme for neodymium-doped materials by direct excitation of the upper lasing level,” Appl. Opt. **38**(36), 7382–7385 (1999).
6. X. Ding, R. Wang, H. Zhang, X. Y. Yu, W. Q. Wen, P. Wang, and J. Q. Yao, “High-efficiency Nd:YVO$_4$ laser emission under direct pumping at 880 nm,” Opt. Commun. **282**(5), 981–984 (2009).
7. Y. Sato, T. Taira, N. Pavel, and V. Lupei, “Laser operation with near quantum-defect slope efficiency in Nd:YVO$_4$ under direct pumping into the emitting level,” Appl. Phys. Lett. **82**(6), 844–846 (2003).
8. N. Pavel, and T. Taira, “High-Power Continuous-Wave Intracavity Frequency-Doubled Nd:GdVO$_4$-LBO Laser Under Diode Pumping Into the Emitting Level,” IEEE J. Sel. Top. Quantum Electron. **11**(3), 631–637 (2005).
9. L. McDonagh, and R. Wallenstein, “Low-noise 62 W CW intracavity-doubled TEM$_{00}$ Nd:YVO$_4$ green laser pumped at 888 nm,” Opt. Lett. **32**(7), 802–804 (2007).
10. L. McDonagh, R. Wallenstein, R. Knappe, and A. Nebel, “High-efficiency 60 W TEM($_{00}$) Nd:YVO($_4$) oscillator pumped at 888 nm,” Opt. Lett. **31**(22), 3297–3299 (2006).
11. G. D. Boyd, and D. A. Kleinman, “Parametric Interaction of Focused Gaussian Light Beams,” J. Appl. Phys. **39**(8), 3597–3639 (1968).
12. J. T. Lina, J. L. Montgomerya, and K. Katob, “Temperature-tuned noncritically phase-matched frequency conversion in LiB$_3$O$_5$ crystal,” Opt. Commun. **80**(2), 159–165 (1990).
13. Y. H. Zheng, H. D. Lu, F. Q. Li, K. S. Zhang, and K. C. Peng, “Four watt long-term stable intracavity frequency-doubling Nd:YVO($_4$) laser of single-frequency operation pumped by a fiber-coupled laser diode,” Appl. Opt. **46**(22), 5336–5339 (2007).
14. S. Machida and Y. Yamamoto, “Quantum-limited operation of balanced mixer homodyne and heterodyne receivers,” IEEE. QE **22**, 617–624 (1986).
15. T. C. Zhang, J. P. Poizat, P. Grelu, J. F. Roch, P. Grangier, F. Marin, A. Bramati, V. Jost, M. D. Levenson, and E. Giacobino, “Quantum noise of free-runing and externally-stabilized laser diode,” Quantum Semiclass. Opt. **7**(4), 601–613 (1995).

#141968 - $15.00 USD Received 1 Feb 2011; revised 16 Mar 2011; accepted 16 Mar 2011; published 24 Mar 2011

1. Introduction

All-solid-state continuous-wave (cw) single-frequency green lasers with high output powers have attracted great interest on account of their important applications in, for example, pumping Ti:sapphire lasers and optical parametric oscillators [1, 2], and being widely used in quantum optics and quantum communications [3, 4]. The development of cw single-frequency green lasers is currently concentrated on how to improve the beam quality and stability while increasing the output power. It is well known that excitation and lasing processes in solid-state lasers always give rise to heat generation, especially in those pumped by high incident powers. Heat generation would lead to thermal stress, stress birefringence and thermal-lens effects that could limit output power and efficiency, as well as decrease the beam quality and resonator stability. To deal with this problem, a direct pumping scheme has been demonstrated [5–7] in which the doped ions in the laser medium are directly excited into the upper lasing level. For Nd^{3+} ion doped lasers, the slope efficiency can be increased and the threshold pump power can be reduced by direct pumping at 880 nm. This mainly results from the larger Stokes factor of 8% compared with that for pumping at 808 nm. Moreover, a 28% smaller quantum defect ratio reduces heat generation which also improves the laser parameters. Generation of 532 nm emission by direct pumping has already been reported: for instance, 5.1 W at 531 nm with M^2=1.46 was obtained for 16.5 W of pump power at 879 nm [8], and 62 W at 532 nm with M^2=1.05 was achieved with a total pump power of 211 W at 888 nm [9]. However, these lasers only operated in a single-transverse-mode, and to our knowledge there have been no reports about directly pumped single longitudinal-mode cw green lasers.

The Nd:YVO_4 crystal is widely used to obtain high conversion efficiency and high beam quality lasers in an end pumping configuration, owing to its favorable characteristics including high gain, large stimulated emission cross section and a constantly polarized output due to natural birefringence. However, there are still some problems. The first is that in the one-end pumping configuration, thermal effects are very grave and pump absorption is inhomogeneous along the length of the crystal. The thermal load at the crystal’s input face is significantly greater than at the export face, so the incident pump power is limited by serious thermal aberrations, larger bulging of the crystal’s entrance face, and possible stress fracture. Secondly, a fiber-coupled laser diode is often used as the pump source, providing a very homogeneous spatial profile, but its output beam is usually unpolarized and the absorption coefficients of two polarizations in the crystal are greatly different, moreover, the absorption coefficients are much smaller at 880 nm than at 808 nm [10].

In this paper, a 12 W cw single-frequency intracavity frequency-doubled Nd:YVO_4 green laser with good beam quality and pumped directly at 880 nm is presented. A polarized and dual-end pumping scheme was used to resolve the problems of the different absorption coefficients of the two polarizations, as well as the inhomogeneous absorption along the length of the crystal in the one-end pumping configuration. A ring resonator was designed to obtain single-frequency laser oscillation. A long crystal was used to enhance the absorption efficiency because of the smaller absorption coefficient at 880 nm. A type-I noncritically phase-matched lithium borate (LBO) crystal was chosen as the intracavity frequency doubler. Stable, high power single-frequency output at 532 nm was obtained. The laser output characteristics such as linewidth, frequency stability, beam quality, and noise power spectrum were investigated in detail.

2. Experimental setup

The experimental setup is schematically depicted in Fig. 1. A fiber-coupled laser diode with a center wavelength of 880 nm and core diameter of 400 μm was used as the pump source. A polarizing beam splitter (PBS) was used to split the beam from the fiber which was then collimated by the lens L1 into two orthogonally polarized beams. One pump beam of spot size diameter 1100 μm was focused through lens L2 into one end of the Nd:YVO_4 crystal, with its polarization along the c axis. The polarization of the other pump beam was rotated 90 degree

#141968 - $15.00 USD Received 1 Feb 2011; revised 16 Mar 2011; accepted 16 Mar 2011; published 24 Mar 2011

by a half-wave plate (HWP) so that it was also along the c axis. After reflection by mirrors M7-M9 and focusing by lens L3, this beam was then coupled into the other end of the crystal, also with a spot size of 1100 μm. The gain medium was a 20 mm long composite Nd:YVO$_4$ crystal consisting of a 15 mm long 0.2 at.% Nd-doped central portion and two 2.5 mm long undoped end caps. Both end faces were polished and anti-reflection coated at 1.06 μm and 880 nm ($R_{1.06\ \mu m,\ 880nm} < 0.25\%$). The crystal was tightly wrapped with indium foil for reliable heat transfer and mounted in a copper block which was maintained at 20° C by a temperature controller with an accuracy of ±0.01° C (YG-4S, YuGuang Co., Ltd). The pump absorption efficiency of the Nd:YVO$_4$ crystal was measured to be 95.3% in our experiment.

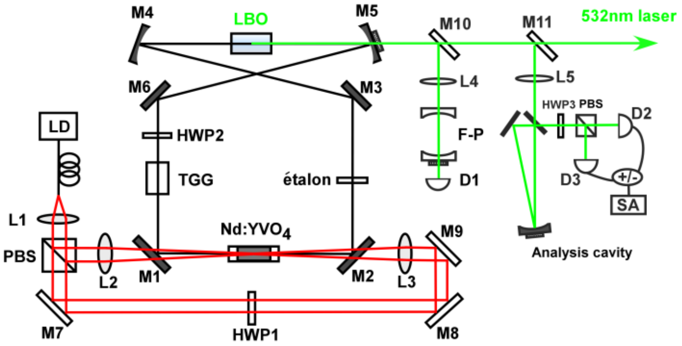

Fig. 1. Experimental setup of the cw single-frequency green laser. LD: fiber-coupled laser diode; L1: collimating lens; L2-L5: focusing lenses; PBS: polarizing beam splitter; HWP: half-wave plate; F-P: Fabry-Perot interferometer; D1-D3: photodiode detectors; SA: spectrum analyzer.

In order to obtain single-frequency laser oscillation, a ring resonator formed by four plane mirrors (M1, M2, M3 and M6) and two plane-concave mirrors (M4, M5) was designed, as shown in Fig. 1. Two input couplers (M1, M2) were high reflection (HR) coated at 1.06 μm ($R_{1.06\ \mu m} > 99.7\%$) and high transmission (HT) coated at 880 nm ($T_{880\ nm} > 95\%$). Two plane mirrors (M3, M6) and one concave mirror (M4) with a curvature radius of 100 mm were HR coated at 1.06 μm ($R_{1.06\ \mu m} > 99.7\%$). The output coupler (M5) was HR coated at 1.06 μm ($R_{1.06\ \mu m} > 99.7\%$) and HT coated at 532 nm ($T_{532\ nm} > 95\%$) with a curvature radius of 100 mm. The incidence angle of the oscillation beam on the concave mirrors was designed to be 6.5° to reduce astigmatism. An optical diode formed by a half-wave plate (HWP2) and a terbium gallium garnet (TGG) crystal was used to enforce unidirectional operation. To ensure stable oscillation, the cavity length was designed by ABCD matrix analysis, taking into account the thermal lensing effect of the crystal. The measured thermal focal length was about 400 mm at a pump power of 52 W. The optimal cavity length was 101.5 mm (between M4 and M5) plus 560 mm (residual path length). The waist radius in the center of the crystal was about 580 μm, and good mode matching between the pump and oscillation beams was achieved. The waist radius between M4 and M5 where the frequency doubling crystal was placed was 38.5 μm, so that high frequency-doubling efficiency could be obtained with a focusing parameter of $\xi = L/b = 2.86$ that is almost equal to the optimum value of 2.84 [11]. Here L is the crystal length (20 mm) and $b = k\omega^2$ the confocal parameter, where ω is the waist radius and k the propagation constant of the fundamental pump beam inside the frequency doubling crystal.

A type-I noncritically phase-matched LBO crystal with the dimensions of 20×3×3 mm^3 (length×width×thickness) was chosen for intracavity frequency doubling because of its high damage threshold and large temperature and angular acceptances [12]. It was inserted into the ring laser cavity between M4 and M5 and temperature controlled to an accuracy of ±0.005° C (YG-2009B, YuGuang Co., Ltd). The phase-matching temperature of around 148° C was fine adjusted during the experiment to obtain the maximum green output. To ensure stable laser operation, a 0.5 mm thick uncoated silica quartz plate was used as an étalon to narrow the gain spectra and suppress mode hopping [13]. Mirrors M10 and M11 were used as beam splitters to reflect out 1% of the 532 nm for measuring the various laser parameters.

3. Experimental results

The laser could oscillate when the incident pump power was above 35 W. The reason for such a high threshold value is that the ring resonator was designed for high pump power (above 50 W) and stability when the thermal focal length is shorter than 530 mm, corresponding to pump powers greater than 35 W. At the optimum LBO temperature of 148° C, the measured maximum 532 nm green laser output was 12 W at an incident pump power of 52 W, with a conversion efficiency of 23.1%. The stability at an average output of around 11.6 W was measured by a power meter (LabMax-TOP, Coherent) and recorded by a computer. As shown in Fig. 2, it was better than ±0.5% (peak-to-peak) and no mode hopping was observed over a period of five hours.

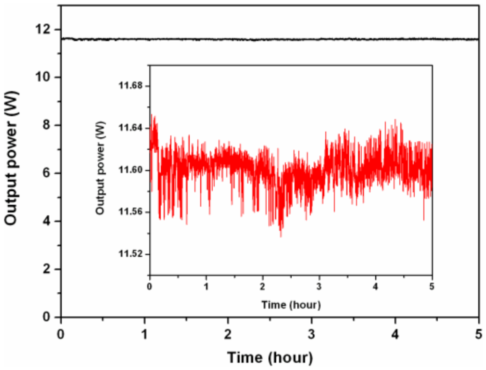

Fig. 2. Stability of the laser at an average output power of around 11.6 W over 5 hours.

The longitudinal mode of the green laser was monitored by a scanning Fabry-Perot (F-P) interferometer with a free spectral range of 150 MHz and finesse of 1000, and recorded by a digital storage oscilloscope (Tektronix DPO 4054). As shown in Fig. 3, there was only a single longitudinal-mode, and the frequency drift was better than 15 MHz in 1 minute. Using the data of Fig. 3, the instantaneous linewidth was measured to be 150 kHz, which was limited by the resolution of the F-P interferometer.

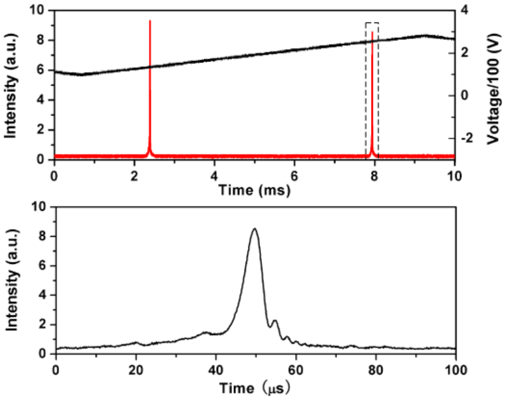

Fig. 3. Transmission intensity of the scanning F-P interferometer.

The beam quality was measured by a laser beam analyzer (DataRay, WinCamD+M2DU M^2 system). Figure 4 (left) shows the recorded energy distribution of the green output beam. The intensity along two orthogonal axes exhibited a perfect Gaussian intensity profile in the

Received 1 Feb 2011; revised 16 Mar 2011; accepted 16 Mar 2011; published 24 Mar 2011

TEM_{00} mode. The output beam was almost diffraction limited and of very high beam quality, with measured M^2 values of M^2_x=1.03 and M^2_y=1.02.

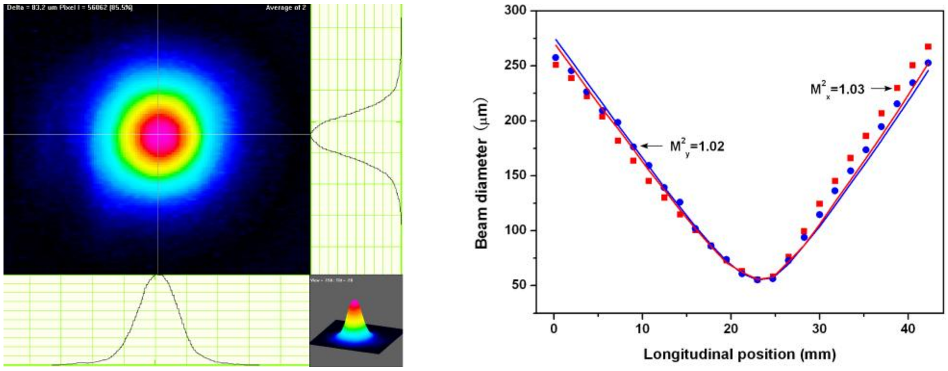

Fig. 4. Beam quality. Left: energy distribution and intensity profile along two orthogonal axes. Right: the measured beam quality.

Noise is a critical parameter in quantum optics experiments. The intensity noise of the green laser was measured using a balanced homodyne detection system [14], formed by HWP3, PBS2 and a pair of low noise, broadband photodetectors (D2 and D3). The sum and difference of the detected signals were recorded by a spectrum analyzer (N9010A, Agilent) with a resolution bandwidth of 100 kHz, a video bandwidth of 100 Hz, and a sweep time of 1.4 s. As shown in Fig. 5, the sum signal gives the intensity noise power of the green laser (red line) and the difference signal gives the shot noise limit (SNL) (black line), which was calibrated by a thermal white light source. It can be seen that the intensity noise reached the SNL for frequencies above 3.5 MHz. The electronic noise level of the balanced homodyne detector is 10.5 dB below the SNL (not shown in the figure). To investigate the phase noise, an empty off-resonance ring cavity (the analysis cavity in Fig. 1) was used as a phase-to-amplitude converter [15]. This cavity had a bandwidth of 1.65 MHz, allowing for a complete conversion of phase to amplitude noise for analysis frequencies higher than 2.3 MHz. The phase noise power was measured at each frequency by scanning the cavity with triangular wave of 2 Hz. As shown in Fig. 5, the measured phase noise was about 1.3 dB above the SNL from 2 to 20MHz.

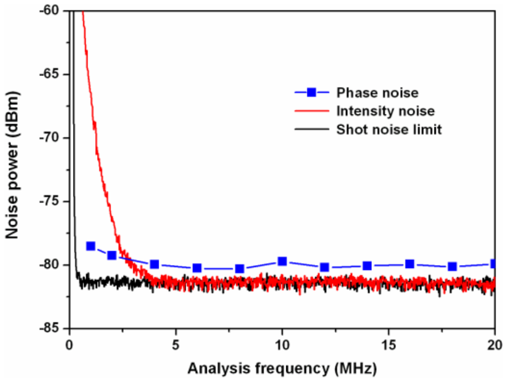

Fig. 5. Measured intensity noise and phase noise. Parameters of the spectrum analyzer: resolution bandwidth 100 kHz, video bandwidth 100 Hz, sweep time 1.4 s.

4. Conclusion

We have demonstrated a cw single-frequency green laser at 532 nm by direct pumping at 880 nm. High output power, excellent beam quality, good stability and low noise were realized through the use of a polarized and dual-end pumping scheme and a ring laser resonator of

#141968 - $15.00 USD Received 1 Feb 2011; revised 16 Mar 2011; accepted 16 Mar 2011; published 24 Mar 2011

special design. A dual-end pumping scheme was employed to realize the homogeneous absorption along the length of the laser crystal, so that defects such as serious thermal aberration, bulging of the entrance faces, and stress fracture risks that are encountered in the one-end pumping configuration were decreased. A single-polarization direction for the pump beams was selected to solve the problem of different absorption coefficients of orthogonal polarizations in the Nd:YVO_4 crystal. The measured maximum green laser output was 12 W with a conversion efficiency of 23.1%. The stability of the output power was better than ±0.5% and no mode hopping was observed over a period of five hours. The instantaneous linewidth was less than 150 kHz and frequency drift was better than 15 MHz in 1 minute. The beam quality parameters were measured to be M^2_x=1.03 and M^2_y=1.02, and was very nearly diffraction limited. The noise characteristics were also investigated. The intensity noise reached the SNL at an analysis frequency of 3.5 MHz, and the phase noise was 1.3 dB above the SNL in the range of 2 to 20MHz. This high quality green laser can be used as a pump source for Ti:sapphire lasers, optical parametric oscillators, and for generating nonclassical light in quantum optics experiments.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (NSFC) (60878003), the National Program for Basic Research in China (2010CB923101), and the National High-tech R&D Program of China (2011AA030203).