Over Ten-millijoule Eye-safe Laser Generation by Extra-cavity Optical Parametric Oscillator Driven with a Diode-pumped Nd:YAG/Cr^{4+}:YAG Q-Switched Laser

Y. P. Huang[1], Y. J. Huang[2] and Y. F. Chen[2,3]
[1]*Department of Physics, Soochow University, Shih Lin, Taipei 11102, Taiwan*
[2]*Department of Electrophysics, National Chiao Tung University, Hsinchu 30010, Taiwan*
[3]*Department of Electronics Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan*

Keywords: Optical Parametric Oscillator, Eye-safe Laser, Q-switched, Nd:YAG Laser.

Abstract: An efficient diode-side-pumped Nd:YAG/$Cr4^{+}$:YAG Q-switched laser with a convex-concave resonator is employed to develop a high-pulse-energy eye-safe laser. We utilize a monolithic KTP crystal to be the optical parametric oscillator (OPO) crystal, and to form an extracavity OPO configuration. Based on the efficient Nd:YAG laser oscillator at 1064 nm carrying a pulse energy of 30 mJ, the OPO energy at 1573 nm of 13.3 mJ is obtained with a pulse width of 6 ns, corresponding to an OPO conversion efficiency of 44.3%.

1 INTRODUCTION

The high gain of Nd:YAG crystal makes it preferred for use in pulsed solid-state lasers and nonlinear wavelength conversions. Laser resonators with a large mode volume, efficiently utilizing the stored energy in the laser medium, are highly desirable for generating the high-energy laser oscillators. Chesler and Maydan (1972, p. 2254) reported that convex-concave resonator has the advantages of compactness, high efficiency, and insensitivity to perturbations. Therefore, it is valuable to develop a highly efficient laser oscillator with millijoule and nanosecond laser pulses based on a compact convex-concave resonator providing a large mode volume.

Thermal lensing of the laser rod dominantly affects the laser mode volume, stability of laser resonator, and output performances. Quasi-continuous-wave (QCW) laser bars and stacks, giving significantly weaker thermally induced lenses, have been frequently used to achieve multi-millijoule Q-switched neodymium-doped lasers and optical parametric oscillators (OPOs) (Agnesi et al., 2006; Zendzian, Jabczynski and Kwiatkowski, 2008; Huang et al., 2011; Schilling et al., 2006) .

In this work, we employ a convex-concave resonator, providing a large mode volume, to develop a high-pulse-energy diode-side-pumped passively Q-switched Nd:YAG/Cr^{4+}:YAG laser oscillator. At a diode pumped energy of 227 mJ, the output laser pulse reaches 30 mJ with a pulse width of 6 ns. The optical-to-optical conversion efficiency is 13.2%. With the developed Nd:YAG laser oscillator, the OPO is further investigated with a monolithic KTP crystal in an extracavity configuration. With the 1064-nm input energy of 30 mJ, the OPO energy at 1573 nm is found to be 13.3 mJ. The OPO conversion efficiency is 44.3%, illustrating the excellent performance of eye-safe OPO based on the efficient 1064-nm laser oscillator.

2 EXPERIMENTAL SETUP

Figure 1 (a) depicts the experimental setup for the QCW diode-side-pumped passively Q-switched Nd:YAG/Cr^{4+}:YAG/KTP eye-safe laser. The pump source was two QCW high-power diode stacks. Each diode stack consisted of six 10-mm-long diode bars generating a maximum output power of 90 W per bar at the central wavelength of 808 nm. The diode stack was constructed with 400 μm spacing between the diode bars so that the whole emission area was approximately 10 × 2.4 mm^2. The full divergence angles in the fast and slow axes are approximately 35° and 10°, respectively. The radii of curvature of cavity mirrors are chosen as R_1 = -500 mm and R_2 = 600 mm for the M_1 and M_2

Huang Y., Huang Y. and Chen Y..
Over Ten-millijoule Eye-safe Laser Generation by Extra-cavity Optical Parametric Oscillator Driven with a Diode-pumped Nd:YAG/Cr4+:YAG Q-Switched Laser.
DOI: 10.5220/0005254001720176
In *Proceedings of the 3rd International Conference on Photonics, Optics and Laser Technology* (PHOTOPTICS-2015), pages 172-176
ISBN: 978-989-758-093-2

mirrors, respectively. The M_1 mirror was coated for high reflection at 1064 nm on the convex surface. The M_2 mirror was coated for partial reflection at 1064 nm on the concave surface. The gain medium was a 1.0 at. % Nd:YAG crystal with a length of 25 mm, and cut with 2°-wedged end facets to avoid etalon effects. Both end facets of the laser crystal were coated for anti-reflection at 1064 nm, and the pump face was coated for anti-reflection at 808 nm. The diode stacks were placed close to the lateral surface of the laser crystal to have good pump efficiency, and were driven to emit optical pulses of 300 μs to match the upper-level lifetime of Nd:YAG laser crystal. The Cr^{4+}:YAG crystal with the initial transmission of 30%. The nonlinear crystal KTP with a length of 25 mm was cut along *x* axis ($\theta = 90°$ and $\varphi = 0°$) for type-II non-critically phase-matched OPO. The pump face of the KTP crystal, acting as the front mirror of the OPO cavity, was coated for high transmission at 1064 nm and high reflection at 1573 nm. The other face of the KTP crystal was coated for high reflection at 1064 nm and partially reflection at 1573 nm, which enables a double pass of the 1064-nm input light within the KTP crystal to lower the threshold and to enhance the efficiency for OPO conversion. Note that a slight misalignment of the OPO cavity, replacing the need of an optical isolator, was applied to prevent the feedback of 1064-nm input light into the laser oscillator. An anti-reflection coated half-waveplate at 1064 nm and a polarizer were combined to be a variable attenuator for adjusting the input pulse energy at 1064 nm. All crystals were wrapped with indium foil and mounted in conductively cooled copper blocks. The pulse temporal behavior was recorded by a LeCroy digital oscilloscope (Wavepro 7100, 10 G samples/s, 1 GHz bandwidth) with a fast InGaAs photodiode.

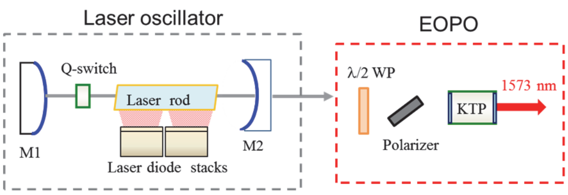

Figure 1: Experimental configuration for an extracavity OPO with a monolithic KTP crystal pumped by the passively Q-switched Nd:YAG/Cr^{4+}:YAG laser oscillator with a convex-concave resonator.

3 EXPERIMENTAL RESULTS

First, the QCW free-running operation without the Cr^{4+}:YAG crystal was performed to confirm the reliability of the laser configuration. Figure 2 depicts the experimental results of the output energy as a function of the diode pump energy in the free-running operation. The threshold pump energy is approximately 64 mJ. With a diode pump energy of 298 mJ, the output energy at 1064 nm is 122 mJ, corresponding to an optical-to-optical conversion efficiency of 41%. The temporal shape of the laser pulse, as showed in Fig. 3, reveals a train of spikes caused by the relaxation oscillation. The overall slope efficiency is found to be 54%. We then inserted the Cr^{4+}:YAG crystal into the laser resonator to implement the passively Q-switched Nd:YAG/Cr^{4+}:YAG laser oscillator. The threshold pump energy for the Q-switched operation is measured to be about 227 mJ, and the output pulse energy at 1064 nm is about 30 mJ, corresponding to an optical-to-optical conversion efficiency of 13.2%. Compared with the results of the passively Q-switched Nd:YAG/Cr^{4+}:YAG laser with a QCW diode side-pumping system to date (Zendzian, Jabczynski and Kwiatkowski, 2008; Afzal **et al.**, 1997; Sauder, Minassian and Damzen, 2006), the energy extraction efficiency is the highest to our knowledge thanks to the superior cavity design of a convex-concave resonator.

A typical temporal shape of the laser pulse, as depicted in Fig. 4, displays the mode-locked modulation resulted from the multi-longitudinal mode beating. The separation of the mode-locked pulses is verified to be correspondent with the cavity round-trip frequency of 1.36 GHz. The Q-switched pulse envelope is approximately 6 ns. The Q-switched mode-locked pulses enhance the peak power, which is estimated to be up to 6.3 MW. The laser beam quality was measured employing the z-scan method. The beam width was evaluated by the scanning knife-edge method. Figure 5 shows the experimental results of the beam widths in the horizontal and vertical directions as a function of the position along the propagation direction, respectively. The beam quality factors M^2 are estimated to be 5.0 × 3.0 (horizontal × vertical).

We then employ the developed Nd:YAG laser oscillator to explore the performance of the extracavity OPO. The dependence of the output pulse energy at 1.57 μm on the input pulse energy at 1.06 μm is shown in Fig. 6. The OPO threshold energy is approximately 6.0 mJ. With maximum available input energy of 30 mJ at 1.06 μm, the OPO output energy of 13.3 mJ is obtained, leading to a high slope efficiency of 54.8%. The OPO conversion efficiency is also presented in Fig. 7 as a function of the input pulse energy at 1.06 μm. With increasing the input energy at 1.06 μm the OPO conversion efficiency increases substantially; however, there is a tendency toward saturation at the higher input energy. The maximum OPO conversion efficiency of 44.3% is obtained at the highest input energy of 30 mJ, in which the excellent performance is attributed to the superior cavity design for the 1064-nm laser oscillator. Figure 8 shows the temporal shape of the OPO pulse for the maximum output energy of 13.3 mJ, which exhibits a considerably less pronounced modulation with the same beating frequency as 1064-nm input pulses. The OPO pulse width is similar to that of the 1064-nm input pulse of approximately 6 ns. The corresponding OPO peak power is calculated to be approximately 2.1 MW. The optical spectrum of OPO, as shown in Fig. 9, was measured with an optical spectrum analyzer (Advantest Q8381A) which has the resolution of 0.1 nm. In addition, the beam quality M^2 factors of the OPO beam are measured to be less than 3.0 in both directions. The better beam quality than that of input

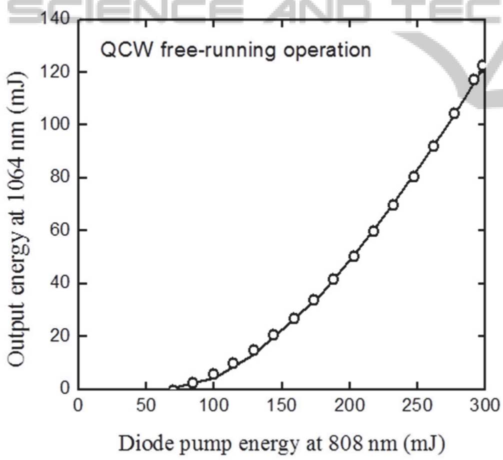

Figure 2: Output energy at 1064 nm with respect to the diode pump energy at 808 nm in the QCW free-running operation.

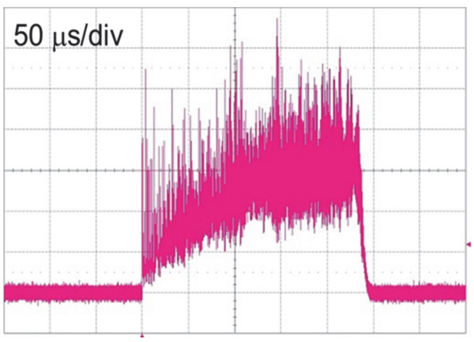

Figure 3: Temporal shape for the laser pulse at the maximum diode pump energy of 298 mJ.

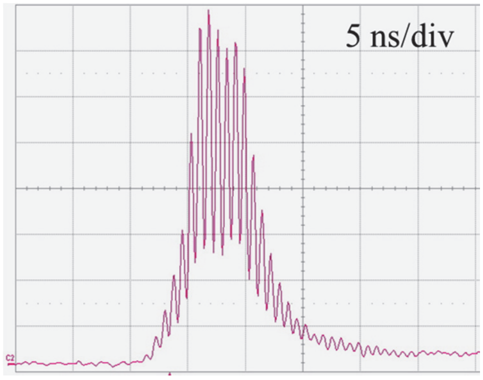

Figure 4: Temporal shape for the 1064-nm laser pulse.

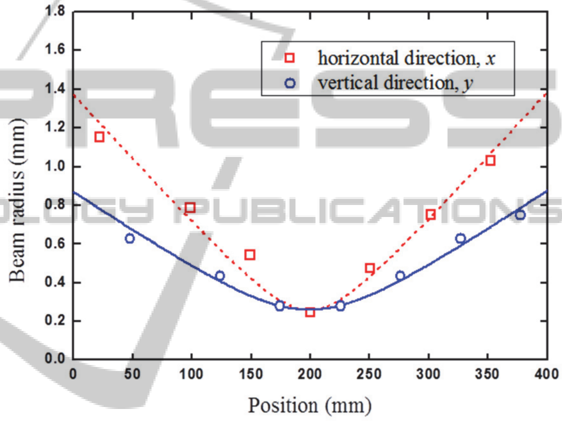

Figure 5: Dependence of the beam width at 1064 nm in the horizontal and vertical directions on the position along the propagation direction.

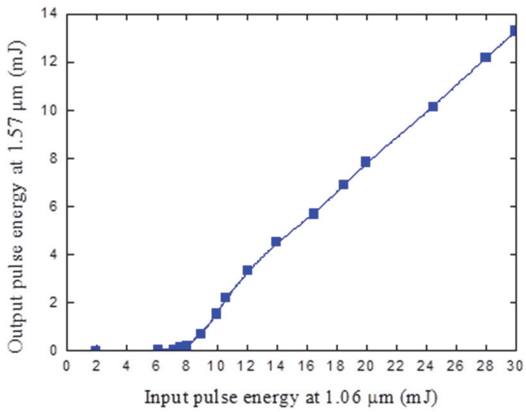

Figure 6: Output pulse energy at 1.57 μm as a function of the input pulse energy at 1.06 μm.

1064-nm beam results from the spatial cleaning effect in the OPO conversion process. It is worth noting that both the eyesafe pulse energy of 13.3 mJ and the diode-to-signal conversion efficiency of 5.9%, obtained with the extracavity OPO driven by the present side-pumped Nd:YAG laser oscillator, are comparable to Schilling et al. (2006, p. 6607) attained with an intracavity OPO scheme by end pumping.

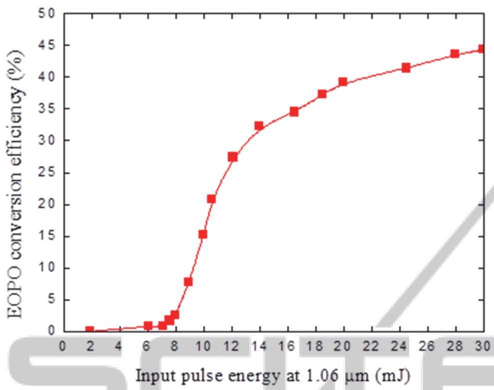

Figure 7: EOPO conversion efficiency as a function of the input pulse energy at 1.06 μm.

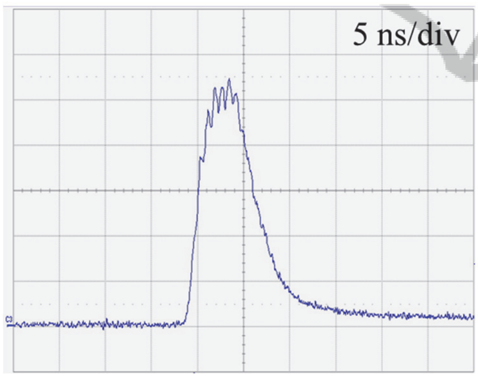

Figure 8: Temporal behavior of the OPO pulse at 1.57 μm.

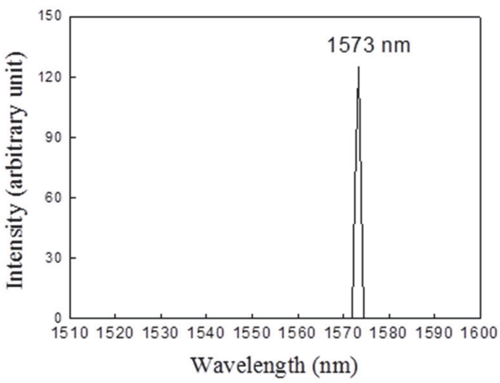

Figure 9: Optical spectrum measurement for the OPO.

4 CONCLUSIONS

A compact convex-concave resonator has been demonstrated in a QCW diode-side-pumped passively Q-switched Nd:YAG/Cr^{4+}:YAG laser oscillator. The output pulse energy at 1064 nm reaches 30 mJ with a pulse width of 6 ns. The optical-to-optical conversion efficiency is as high as 13.2%. With the passively Q-switched Nd:YAG laser oscillator, the extracavity OPO with a monolithic KTP crystal is investigated and performed. The maximum output energy at 1573 nm of 13.3 mJ is obtained with a pulse width of 6 ns, corresponding to an OPO conversion efficiency of 44.3%. Efficient extracavity wavelength conversions validates that our compact convex-concave resonator is potentially valuable for the laser oscillator with high extraction efficiency and low beam divergence.

ACKNOWLEDGEMENTS

The authors thank the National Science Council for their financial support of this research under Grant No. NSC 102-2112-M-031-001-MY3.

REFERENCES

Chesler, RB, Maydan, D, 1972 'Convex-concave resonators for TEM_{00} operation of solid-state ion lasers', *Journal of Applied Physics,* vol. 43, no. 5, pp. 2254-7.

Agnesi, A, Pirzio, F, Reali, G & Piccinno, G, 2006 'Subnanosecond diode-pumped passively Q-switched Nd:$GdVO_4$ laser with peak power >1 MW', *Applied Physics Letters,* vol. 89, no. 10, p. 1120.

Zendzian, W, Jabczynski, JK & Kwiatkowski, J, 2008 'High peak power Nd:YAG laser pumped by 600-W diode laser stack', *Optics & Laser Technology,* vol. 40, no. 3, pp. 441-4.

Huang, YP, Chiang, PY, Huang, YJ, Su, KW, Chen, YF & Huang, KF, 2011 'High-repetition-rate megawatt millijoule pulses from a Nd:YVO_4 laser passively Q-switched by a semiconductor saturable absorber', *Applied Physics B,* vol. 103, no. 2, pp. 291-4.

Schilling, BW, Chinn, SR, Hays, AD, Goldberg, L & Trussell, CW, 2006 'End-pumped 1.5 □m monoblock laser for broad temperature operation', *Applied Optics*, vol. 45, no. 25, pp. 6607-15.

Afzal, RS, Yu, AW, Zayhowski, TJ, Fan, TY, 1997 'Single-mode high-peak-power passively Q-switched diode-pumped Nd:YAG laser', *Optics Letters,* vol. 22, no. 17, pp. 1314-6.

Sauder, D, Minassian, A & Damzen, MJ, 2006 'High efficiency laser operation of 2 at. % doped crystalline

Nd:YAG in a bounce geometry', *Optics Express,* vol. 14, no. 3, pp. 1079-85.