Compact, high-repetition-rate 336nm source based on a frequency quadrupled, diode-pumped Nd:YVO_4 laser

Hamish Ogilvy and James A. Piper
Centre for Lasers and Applications, Macquarie University, NSW 2109, Australia
Telephone- +61 2 9850 6367, Fax- +61 2 9850 8983 E-mail address: hogilvy@ics.mq.edu.au

Abstract: Intracavity nonlinear second harmonic generation from a Q-switched, diode-end-pumped Nd:YVO_4 laser (1342nm) and subsequent external fourth harmonic generation in BBO have been used to demonstrate up to 20mW average power at 336nm at multi-kilohertz repetition rates.

OCIS codes: 140.3580 Lasers, solid-state; 140.3610 Lasers, ultraviolet

1. Introduction

Compact, efficient laser sources emitting in the lower end (320-340nm) of the UV-A spectral band can be expected to find wide application in photobiology and photomedicine, particularly in various manifestations of fluorescence detection and imaging. There are many design issues to be considered in developing such a source. Strong thermal lensing makes power scaling of diode-end-pumped Nd:YVO_4 lasers difficult, especially so for 1342nm operation since the relatively high quantum defect and excited state absorption for 1342nm compared to 1064nm operation result in greater heat deposition in the pump volume [1, 2]. These thermal lensing problems can be substantially alleviated by using low Nd^{3+} dopant concentrations, in the range 0.25-0.5%, and there have been several recent reports of power-scaling of diode-end-pumped Nd:YVO_4 lasers to 10W output powers for both the 1064nm [3] and 1342nm [4, 5] transitions. Diode-side-pumped Nd:YVO_4 lasers have also achieved high 1064nm powers for grazing-incidence resonator [6, 7] and MOPA arrangements [8]. Note also there has been some recent interest in Nd:$GdVO_4$ as an alternative to Nd:YVO_4 for laser power scaling (due to the greater thermal conductivity of $GdVO_4$) but reduced thermal lensing has yet to be demonstrated for operation at 1342nm [9].

Nd:YVO_4 has comparatively short fluorescence lifetime (~100µsec) for the laser transitions, thus comparatively high repetition rates (tens kHz) are necessary for highest efficiency and high average powers to be achieved in Q-switched operation. This results in comparatively low pulse energies and peak powers, which pose further problems for efficient nonlinear fourth-harmonic generation to the UV. We have addressed these problems by using intracavity SHG of the 1342nm fundamental in LBO to get maximum 671nm output, followed by extracavity SHG of the 671nm output to 336nm in BBO arranged in single or double-pass configurations.

2. Experimental arrangement

The basic experimental arrangement for 671nm generation from the Q-switched 1342nm Nd:YVO_4 laser is shown in figure 1. The 0.3at% Nd:YVO_4 crystal sourced from Castech had dimensions 3x3x12mm long and was AR coated from 800-1342nm on both end faces. The 20W, 808nm output of a (Jenoptik) fibre-coupled diode was collimated and re-imaged through the end-mirror M1into the laser crystal, producing a pump waist radius of ~300um inside the laser crystal. A (NEOS) 20W AO Q-switch AR-coated 1342nm was positioned at the centre of the laser resonator. The 15mm-long LBO crystal, type I critically phase matched for second harmonic generation at 1342nm (theta = 85.4˚, phi = 0˚), was held in a TEC temperature-controlled copper mount positioned close to the coupling mirror M2.

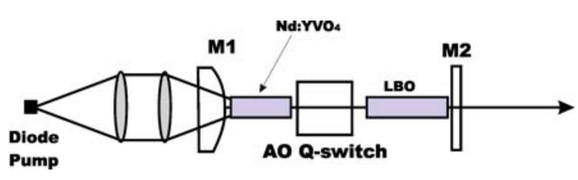


Figure 1: 671nm laser arrangement

A summary of mirror transmission characteristics is shown in table 1 below. The convex curvature of mirror M1 was chosen to compensate for the strong positive thermal lensing in the laser crystal as explained further in section 3. Note also M1 had high transmission at 671nm resulting in significant loss of red output from the pump end.

TABLE 1 – Mirror Transmission characteristics

T (%)	671nm	808nm	1064nm	1342nm	Curvature
M1	83	79	92	0.08	50cm Convex
M2	88	95	85	0.14	Flat

3. Cavity modeling

Cavity mode sizes (radii) at the laser and LBO crystals were calculated for a range of focal lengths for the thermal lens in the laser crystal and are shown in figure 2a for a 120mm-long flat-flat resonator, and in figure 2b for the 120mm-long convex-flat resonator of figure 1 (M1 50cm convex). We have determined the focal length of the thermal lens experimentally to be close to ~75mm at a maximum pump power incident on the crystal of 18W.

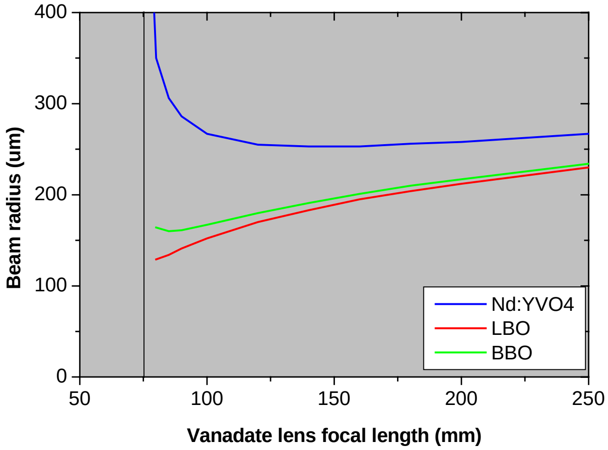
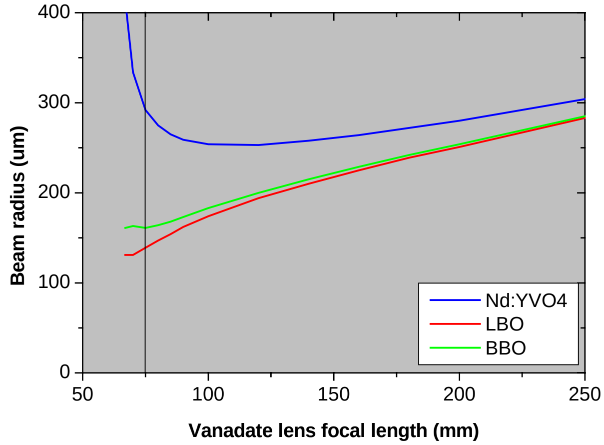


Figure 2a: Cavity mode radius for flat-flat resonator



2b: Cavity mode radius for convex-flat resonator

The calculations also show that cavity mode size at both the laser crystal and the intracavity LBO doubler varies comparatively rapidly with increasing thermal lens focal length (decreasing pump power) for the convex-flat resonator. It follows that the convex-flat resonator requires higher pump power to reach laser threshold and delivers lower efficiency at low pump powers due to poorer mode-matching in the gain region compared with the flat-flat resonator, but gives significantly better performance at maximum pump power.

4. 671nm generation

Maximum average output power at 671nm coupled from end-mirror M2 was 1.1W for repetition rate 40kHz. Note approximately 300mW of 671nm output leaked from the pump input mirror M1 but was not available for use. At repetition rates below ~30kHz the AO Q-switch was progressively unable to ‘hold off’ lasing with the result that pre-lasing occurred and the energy extracted in the Q-switched pulses declined, with consequent rapid decline in 671nm output.

5. 336nm generation

Fourth harmonic generation at 336nm was obtained by external second harmonic generation from the red output of the intracavity frequency-doubled 1342nm laser above in a BBO crystal cut for type I SHG at 671nm (theta = 35.4˚). In the simplest arrangement the BBO crystal was positioned 30mm beyond the end-mirror surface M2 for single-pass frequency conversion of the forward-going unfocussed 671nm beam. Alternatively, enhanced conversion efficiency was obtained using a double-pass geometry.

Average power generated at 336nm as a function of pulse repetition rate is shown in figure 3 for both single and double pass arrangements.

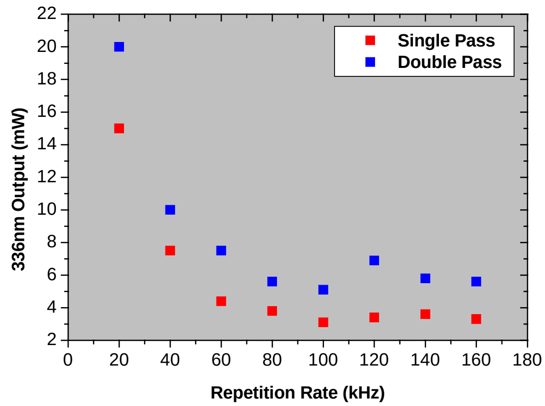


Figure 3: 336nm performance with repetition rate

For 20kHz operation, the 671nm and 336nm peak power reached a maximum of around 340W and ~11W respectively, with peak instantaneous conversion efficiency of 3.2%. At 40kHz, peak powers at 671 and 336nm are 155 and 4.2W respectively, corresponding to peak instantaneous conversion efficiency 2.75%. These optical conversion efficiencies are consistent with data previously reported for VIS-UV SHG at comparable peak power levels in BBO [10].

6. Discussion and Conclusion

We have reported design and operating characteristics of a compact, all-solid-state 336nm source based on fourth harmonic generation from a Q-switched 1342nm Nd:YVO_4 laser. For a single 20W 808nm diode pump, UV powers up to 20mW have been demonstrated for pulse rates 20-160kHz. The simple linear laser resonator accommodates strong thermal lensing in the laser material and provides excellent pump-mode overlap and small beam waists at both the intracavity frequency-doubling and extracavity quadrupling crystals.

Scaling of the UV power towards 100mW is desirable for a number of other applications, including photochemical materials processing (such as writing fibre Bragg gratings in germanium-doped silica fibre [11, 12]). Optimising the laser operating characteristics to generate shorter 671nm pulses can be expected to yield substantial improvements in VIS-UV conversion efficiencies.

6. References

1. Y.F. Chen, "Design criteria for concentration optimization in scaling diode end-pumped lasers to high powers: Influence of thermal fracture" IEEE Journal of Quantum Electronics **35**, 234-239 (1999).
2. H.J. Zhang, J.H. Liu, J.Y. Wang, C.Q. Wang, L. Zhu, Z.S. Shao, X.L. Meng, X.B. Hu, Y.T. Chow, and M.H. Jiang, "Laser properties of different Nd-doped concentration Nd : YVO4 laser crystals" Optics & Lasers in Engineering **38**, 527-536 (2002).
3. Y.F. Chen, T.M. Huang, C.C. Liao, Y.P. Lan, and S.C. Wang, "Efficient high-power diode-end-pumped TEM00 Nd : YVO4 laser" IEEE Photonics Technology Letters **11**, 1241-1243 (1999).
4. H. Ogilvy, P. Dekker, M.J. Withford, and J.A. Piper, "Efficient diode double-end-pumped Nd:YVO4 laser operating at 1342nm" Optics Express **11**, 2411-2415 (2003).
5. A. Di Lieto, P. Minguzzi, A. Pirastu, and V. Magni, "High-Power Diffraction-Limited Nd:YVO4 Continuous-Wave Lasers at 1.34 um" Journal of Quantum Electronics **39**, 903-909 (2003).
6. A. Minassian and M.J. Damzen. *13.7 W output at 1342 nm from a diode side-pumped Nd:YVO4 bounce laser*. in *ECLEO*. 2003. Munich, Germany.
7. A. Minassian and M.J. Damzen, "20 W bounce geometry diode-pumped Nd:YVO4 laser system at 1342 nm" Optics Communications **230**, 191-195 (2004).
8. A. Minassian, B.A. Thompson, G.R. Smith, and M.J. Damzen. *104W Diode-Pumped TEM00 Nd:GdVO4 Master Oscillator Power Amplifier*. in *Advanced Solid State Photonics*. 2005. Vienna, Austria.
9. M. Okida, M. Itoh, T. Yatagai, H. Ogilvy, J.A. Piper, and T. Omatsu, "Heat generation in Nd doped vanadate crystals with 1.34 µm laser action" Optics Express **13**, 4909-4915 (2005).
10. D.W. Coutts, "Optimization of Line-Focusing Geometry for Efficient Nonlinear Frequency Conversion from Copper-Vapor Lasers" IEEE Journal of Quantum Electronics **31**, 2208-2213 (1995).
11. D.S. Starodubov, V. Grubsky, J. Feinberg, B. Kobrin, and s. Juma, "Bragg grating fabrication in germanosilicate fibers by use of near-UV light: a new pathway for refractive-index changes" Optics Letters **22**, 1086-1088 (1997).
12. D.S. Starodubov, V. Grubsky, and J. Feinberg, "Efficient Bragg grating fabrication in a fibre through its polymer jacket using near-UV light" Electronics Letters **33**, 1331-1333 (1997).