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Access to the published version:
http://dx.doi.org/10.1364/OPEX.13.009465

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Compact, all solid-state, high-repetition-rate 336nm source based on a frequency quadrupled, Q-switched, diode-pumped Nd:YVO₄ laser

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Abstract: Intracavity nonlinear second harmonic generation from a Q-switched, diode-end-pumped Nd:YVO₄ laser operating on the 1342nm fundamental and subsequent external fourth harmonic generation in BBO have been used to demonstrate up to 20mW average power at 336nm at pulse repetition rates 20-140kHz.

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

References and Links
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. For example, important new developments of time-resolved fluorescence detection [1] including laser-scanning cytometry [2] and time-resolved flow cytometry [3, 4], rely on the availability of practical, high-repetition-rate (tens-hundreds kHz) pulsed lasers of moderate power (tens mW) operating at wavelengths around 335nm for excitation of lanthanide-chelate fluorescent probes. For such applications there are very few UV laser options at present: the (337nm) nitrogen laser, ubiquitous in photobiology, is seriously limited due to an inherently low repetition rate (<100Hz), and the available CW lasers (notably argon ion and He-Cd) are impractical for many purposes. We report here design and operating characteristics of a compact, all-solid-state pulsed 336nm source giving average powers up to 20mW based on frequency-quadrupling the 1342nm fundamental of a miniature diode-pumped Nd:YVO₄ laser, and which we believe meets many of the requirements for key applications in UV photobiology, photomedicine and other fields.

There are many design issues to be considered in developing such a source. In respect of the base laser material, YVO₄ is generally the Nd³⁺ host material of choice for laser generation on the 1.3µm transition, the emission cross-section for the 1342nm transition in Nd:YVO₄ roughly equaling that for the 1064nm transition in Nd:YAG [5]. However strong thermal lensing in the laser crystal makes power scaling of diode-end-pumped Nd:YVO₄ 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 [6, 7]. These thermal lensing problems can be substantially alleviated by using low Nd³⁺ dopant concentrations, in the range 0.25-0.5%, and there have been several recent reports of power-scaling of diode-end-pumped Nd:YVO₄ lasers to 10W output powers for both the 1064nm [8] and 1342nm [9, 10] transitions. Diode-side-pumped Nd:YVO₄ lasers have also achieved high 1064nm powers for grazing-incidence resonator [11, 12] and MOPA arrangements [13] but the comparatively low gain at 1342nm necessitates rather complicated multipass techniques to achieve adequate extraction efficiencies from MOPA arrangements. Note also there has been some recent interest in Nd:GdVO₄ as an alternative to Nd:YVO₄ for laser power scaling (due to the greater thermal conductivity of GdVO₄) but reduced thermal lensing has yet to be demonstrated for operation at 1342nm [14].

To achieve a simple and compact design, we have chosen to end-pump low-doped Nd:YVO₄ with a single fibre-coupled diode emitting at 808nm. For the pump powers ~20W necessary to achieve adequate fundamental powers, thermal lensing in the laser crystal is significant, requiring that careful attention be paid to design of the laser resonator to ensure both resonator stability and optimum resonator mode sizes with respect to the pump mode in the laser crystal and other intracavity elements, at the operating point. This is dealt with in the present design by using a resonator configuration that is unstable at low pump powers but which becomes stable as the thermal lens in the laser crystal increases at high pump power.

Efficient fourth-harmonic generation from the 1342nm fundamental of a Nd:YVO₄ laser of this scale clearly requires short-pulse operation. Q-switching of Nd:YVO₄ lasers has been extensively investigated for the dominant 1064nm transition, however Q-switching on the
1342nm transition has received substantially less attention, and presents a number of problems to be overcome, particularly arising from the difficulty of suppressing the competing 1064nm transition as the pump power is increased.

Nd:YVO₄ 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:YVO₄ laser is shown in Fig. 1. The 0.3at% Nd:YVO₄ crystal sourced from Castech had dimensions 3x3x12mm long and was AR coated from 800-1342nm on both end faces. The laser crystal was mounted in a temperature-controlled copper mount and held in place using 100µm thick indium foil. The 20W, 808nm output of a Jenoptik fibre-coupled diode was collimated and re-imaged through the end-mirror M1 into the laser crystal following the approach of Taira et al [15], producing a pump waist radius of ~300µm 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. To accommodate the physical size of each of the intracavity components, the resonator had a minimum overall length of 120mm.

A summary of mirror transmission characteristics is shown in table 1 below. For 671nm generation, mirrors M1 and M2 were both high reflectors for the 1342nm fundamental. Both these mirrors also had high transmission at 1064nm chosen to suppress lasing on the 1064nm transition. 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>
<thead>
<tr>
<th>Mirror</th>
<th>T (nm)</th>
<th>T (%) 671nm</th>
<th>T (%) 808nm</th>
<th>T (%) 1064nm</th>
<th>T (%) 1342nm</th>
<th>Curvature</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>83</td>
<td>79</td>
<td>92</td>
<td>0.08</td>
<td>50cm Convex</td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>88</td>
<td>95</td>
<td>85</td>
<td>0.14</td>
<td>Flat</td>
<td></td>
</tr>
</tbody>
</table>

3. Cavity modeling

Modeling of the laser resonator has been undertaken using the commercial resonator modeling package LASCAD. 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 Fig. 2(a) for a
120mm-long flat-flat resonator, and in Fig. 2(b) for the 120mm-long convex-flat resonator of Fig. 1. (M1 50cm convex).

Previous studies of how the focal length of the thermal lens in Nd:YVO$_4$ varies as a function of absorbed power for cw laser operation at 1342nm have demonstrated that the lens power increases by a factor of two above laser threshold [14]. This effect has been attributed to strong excited state absorption of 1342nm laser photons resulting in increased heat deposition in the laser crystal. 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. This is illustrated in Fig. 2(a), where the cavity mode radius at the laser crystal is seen to blow up at $f = \approx 80$mm for the 120mm-long flat-flat resonator corresponding to the onset of cavity instability at maximum pump power.

The substitution of the convex ($r=50$cm) mirror for the flat end mirror (M1) introduces a small degree of compensation for the thermal lens in the laser crystal so that for maximum pump power, the resonator remains stable, mode-matching at the gain region is optimized, and a small beam radius (145\(\mu\)m) is provided at the intracavity LBO frequency-doubler, as illustrated in Fig 2(b).

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.

The convex-flat resonator has the added advantage of slightly reducing the divergence of the output beam, which is advantageous for frequency conversion in BBO (which has a comparatively small angular acceptance of 0.52mrad cm for the 671 to 336nm type I interaction).

4. 671nm generation

The data of Fig. 3 show output power of the intracavity-doubled laser as a function of Q-switch repetition rate from 20-140kHz for maximum pump power incident on the laser crystal of 18W. 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. Above 160kHz, an output pulse only formed only for every second Q-switch opening as the interpulse storage decreased.
Figure 3 also shows 671nm output pulse duration (FWHM) as a function of pulse repetition rate. At maximum 671nm average output power (1.1W at 40kHz) the FWHM pulse duration was ~120ns corresponding to single pulse energy 27.5 µJ and peak power around 200W. Details of 671nm pulse shapes (averaged over 64 pulses) are given in Fig. 6.

We have previously reported operation of a Q-switched diode-double-end-pumped Nd:YVO\(_4\) operating on the 1342nm fundamental and intracavity frequency-doubled to 671nm [16]. In that case effectively all red output was collected to give 1.7W at 100kHz for total pump power incident on the crystal (both ends) of 14W. Taking account of red output lost from the pump mirror, overall diode-to-red optical conversion efficiency of the present, more compact, device is somewhat less at ~8%. Note the repetition rate (40kHz) corresponding to maximum 671nm output of the present device is significantly lower than that for the double-end-pumped laser (100kHz) due to the rather shorter Q-switched pulse durations (40ns) obtained in the latter case.

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°). The 4x4x10mm-long BBO crystal was protection coated on the polished end faces to prevent moisture absorption. 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 as illustrated in Fig. 4, in which the flat mirror M3 is highly transmitting (96%) at 671nm and highly reflecting (99.84%) at 336nm, and flat mirror M4 is highly transmitting (91%) at 336nm and highly reflecting (99.86%) at 671nm. M4 transmits the forward-going 336nm second harmonic and reflects the residual 671nm back through the BBO for a second pass, M3 reflecting the backward-going 336nm second harmonic beam into the forward direction through M4. The 336nm UV output is finally separated from residual 671nm passing through M4 by a UV prism separator.
Average power generated at 336nm as a function of pulse repetition rate is shown in Fig. 5 for both single and double pass arrangements. Maximum UV output of 20mW was measured for double-pass conversion and 13mW for single-pass conversion at 20kHz pulse repetition rate. For both single and double pass arrangements, the power falls quite rapidly as repetition rate is increased, consistent with the requirement of high peak power for efficient harmonic conversion. Despite this, ~5mW of 336nm output was obtained for pulse repetition rates up to 160kHz for double-pass conversion and 3mW for single-pass conversion.

Output pulse shapes for both the 671 and 336nm pulses are shown in Fig. 6 together with the corresponding instantaneous conversion efficiency. Note the 336nm power is scaled x20 to enable pulse shape comparison. 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 [17]. Substantial improvements in conversion efficiency are likely to be achieved if the 671nm pulse width can be reduced to 50ns or less, as for the double-end-pumped laser previously reported [16].
Fig. 6. Instantaneous peak power and conversion efficiency for (a) 20kHz repetition rate (b) 40kHz repetition rate

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:YVO₄ 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 laser/pump-mode overlap and small beam waists at both the intracavity frequency-doubling and extracavity quadrupling crystals. The 336nm wavelength is very well matched to the requirements of time-resolved fluorescence detection based on europium-chelate fluorophores, and the very high pulse repetition rates well matched to the requirements of high-throughput applications such as flow cytometry [3, 4].

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 [18, 19]) and laser stereolithography [20]. Optimising the laser operating characteristics to generate shorter 671nm pulses can be expected to yield substantial improvements in VIS-UV conversion efficiencies. The use of Nd:YVO₄ with lower doping concentration (~0.2%) would permit higher diode pump powers to be employed without thermal lensing becoming unmanageable. Alternatively, quasi-continuous pumping could be used to increase available peak power whilst maintaining acceptable thermal loading in the laser crystal. Additionally, either resonant cavity or quasi-phase matched doubling processes could also be introduced to greatly increase the conversion efficiency of the 671 to 336nm process, although both solutions add cost and complexity into an otherwise simple and compact UV laser solution.