Efficient diode double-end-pumped Nd:YVO_4 laser operating at 1342nm

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Abstract: A Nd:YVO_4 laser producing over 8W cw TEM_{00} at 1342nm with slope efficiency of 42% and optical to optical conversion efficiency of 33% has been demonstrated. Low neodymium doping concentration helps to reduce thermal loading in the laser crystal and increase achievable output power. While single end pumping approaches the crystal fracture limit, double-end-pumping effectively divides the thermal loading between the two ends of the laser crystal, allowing for reduced risk of fracture and greater power-scalability. Intracavity frequency doubling in LBO generated cw output powers over 900mW at 671nm.

OCIS codes: (140.3580) Lasers, solid-state; (190.2620) Frequency conversion

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1. Introduction

Miniature and microchip configurations of diode-end-pumped $Nd:YVO_4$ lasers have been investigated extensively [1]. Devices giving watt-level cw powers on the strong 1064nm transition of Nd^{3+}, and hundreds of milliwatts at the 532nm frequency-doubled wavelength, are widely available commercially. However, power-scaling of diode-end-pumped $Nd:YVO_4$ lasers has been problematic due to the high heat loading of standard $Nd:YVO_4$ crystals at high pump powers (>5W) leading to gross thermal distortions and crystal fracture. The problem is exacerbated for generation on the 1342 nm Nd^{3+} transition because of the large quantum defect between pump and laser wavelength. Nevertheless $Nd:YVO_4$ is favoured for operation at 1342nm since the emission cross-section is roughly equal to that of the 1064nm transition in Nd:YAG [2].

The recent availability of large, high-quality $Nd:YVO_4$ laser crystals with low Nd^{3+} doping concentrations (< 0.5 at.%) has stimulated renewed interest in power scaling of diode-end-pumped $Nd:YVO_4$ lasers [3, 4]. For low doping the reduced absorption coefficient at the pump wavelength permits the deposited heat to be spread along the axis of the laser-crystal, reducing heat load, and consequent thermal lensing and other problems. This advantage is offset by the increased difficulty of matching the pump mode to the laser resonator mode, thus there is an optimum value for the Nd^{3+} doping concentration for high-power pumping which has been determined to be in the range 0.25-0.5% at % [5-7]. Cw output powers of 25W and 7W respectively at 1064mm and 1342 nm have recently been demonstrated for diode-end-pumped Nd: YVO_4 lasers using this approach [3, 4].

Side-pumping techniques have shown a reduction in thermal lensing by spreading the thermal load along a crystal edge (although the lens is more complex with thermal wedging effects, etc) [8]. Transverse pumping also has the added advantage of not requiring pump wavelength transmission through the resonator mirrors. However, this technique also has its disadvantages, most notably poorer beam quality: high beam quality output from grazing incidence lasers is usually obtained with a large sacrifice in output power. Intracavity lenses are also required to optimise the system, complicating cavity design. There are also additional costs associated with the fabrication of the laser crystal. Despite these disadvantages, very promising results have been demonstrated [9]. A grazing incidence vanadate laser producing 13.7W at 1342nm was recently presented (high beam quality output was much less), illustrating the potential of transverse pumping geometries for power scaling [10].

Efficient, compact all-solid-state lasers giving high cw powers with high beam quality at 1.3µm are of interest for pumping fibre Raman lasers and various other applications. Devices giving high powers with high beam quality at the frequency-doubled wavelength 671 nm are of considerable interest for a range of medical applications (e.g., photodynamic therapy) and for pumping Cr^{3+} solid -state tunable lasers [11]. We now report operation of a double-end-pumped $Nd:YVO_4$ laser delivering cw powers > 8W at 1342 nm and > 900mW intracavity frequency-doubled at 671 nm. Low (0.3 at.%) Nd^{3+} crystal doping and the double-end-pumped configuration are combined to minimise thermal loading effects in the laser crystal.

2. Experimental details

The laser pump and resonator configuration is illustrated in Fig. 1. The double-end- pumping design used two 15W 808nm Optopower diodes coupled into 1mm fibre bundles with a measured NA=0.11. Following the approach of Taira *et al*. [12], the outputs from the fibre bundles were collimated and focussed through the dichroic mirrors M1 and M2 into either end of the crystal with 0.4 magnification giving a pump mode radius of ~200µm. The confocal length of the pump beam (~5mm) was approximately twice the 1/e absorption depth (~2mm) in the crystal; for a confocal length of 12mm (the crystal length) the pump mode radius would be over 260µm. For an overall resonator length 10cm, M1 flat, M2 25cm CC and M3 25cm

CC, the calculated laser mode radius in the crystal was ~180μm, giving excellent mode matching for the 5mm confocal length of the pump beam.

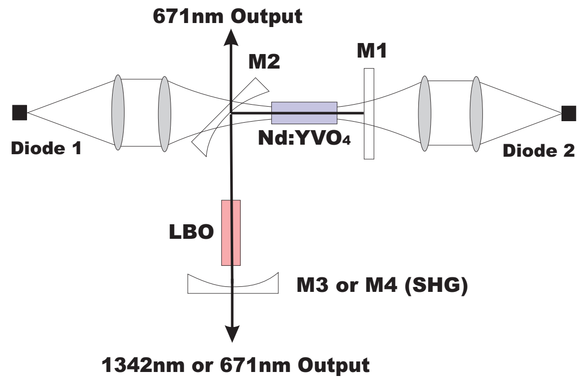

Fig. 1. Laser configuration

Coretech supplied the a-cut Nd:YVO_4 crystal, which had 0.3at.% Nd^{3+} concentration and 3x3x12mm dimensions. Both crystal faces were AR coated for 808, 1064 and 1342nm. The laser crystal was wrapped in indium foil and placed inside a water-cooled copper mount, which was held at 15°C (the laser crystal and diodes were in the same cooling loop, thus independent optimisation of the crystal temperature was not performed). The LBO doubling crystal (dimensions 4x4x15mm) was cut for type I critical phase matching at 1342nm (θ = 86.1°, ϕ = 0.0°, XZ principal plane). The LBO crystal, for which both end faces were AR coated for 1342 and 671nm, was wrapped in indium foil and fixed inside a copper mount. No attempt was made to actively cool the LBO mount.

Resonator mirror transmission characteristics are shown in Table 1. The crystal was pumped through M1 and M2, these mirrors requiring high transmission at the diode pump wavelength, low reflectance (high transmission) at the stronger 1064nm laser transition, as well as high reflectance at 1342nm. The coupling transmission (M3) at 1342nm was 4.8%.

Table 1. Selected Mirror Characteristics

Mirror	Transmission (%)				Curvature (mm)
	671nm	808nm	1064nm	1342nm	
M1	82	90	5.8	0.07	Flat
M2*	87	85	40	0.15	25cm CC
M3	68	88	46	4.8	25cm CC
M4	84	91	5.9	0.09	Flat

*Note M2 transmissions are for 45° incidence, vertical polarisation, except for 808nm where the quoted transmission is for unpolarised light.

For second harmonic generation the 1342nm output coupler M3 was replaced with M4, having high reflectance at 1342nm. Ideally M4 should also have high reflectance at 671nm to ensure the red output is primarily from M2. In the present experiment, the frequency-doubled output was coupled roughly equally through M2 and M4. Efficient frequency-doubled operation required a large laser mode size in the laser crystal (for efficient energy extraction) and a small laser mode size in the nonlinear crystal (to increase power density and conversion efficiency). The LBO crystal was positioned at a beam waist between M2 and M4, the separation of which was adjusted (increased) to minimise the beam waist diameter at the doubler without exceeding the stability limit for the resonator length (the overall resonator length was ~11cm). Given both end mirrors M2 and M4 were flats, the resonator mode was elliptical in both the laser crystal and the LBO: calculated dimensions of the mode radius in the laser crystal were 640x240µm. Since the pump mode was circular with a radius ~200µm, mode matching was rather poor for this resonator arrangement.

3. Results and discussion

3.1 1342nm operation

Figure 2 shows 1342nm output power as a function of total diode pump power incident on the crystal for the 4.8% output coupler. Threshold pump power was around 4W; slope efficiency and optical to optical conversion efficiency were 42% and ~33% respectively. The laser operated in TEM_{00} mode with very good power stability (< 3% power drift over 30min). Spectral analysis revealed three overlapping laser lines between 1341.97 and 1342.65nm when the laser was operating around threshold. As the laser power was increased to well above threshold, the longer wavelength line dominated and the spectral width dropped to less than 0.1nm FWHM.

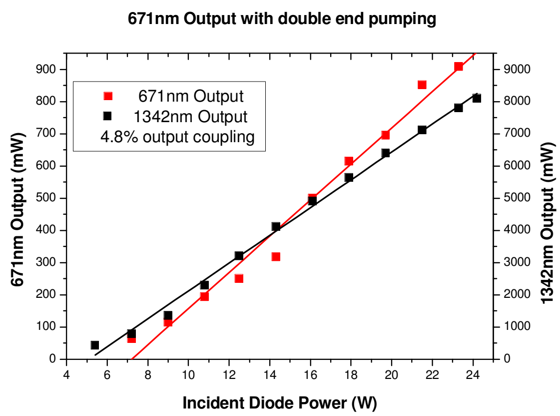

Fig. 2. 1342nm laser characteristic

The laser diode water temperature was varied between 10 and 20°C corresponding to pump wavelength variation ~3nm. Within this range less than 5% variation in laser output power was observed. No attempt was made to temperature tune the diodes individually, so they were never at the peak absorption wavelength at the same time. The crystal is longer (x6) than the 1/e absorption depth, thus even for significant wavelength variation, the change in deposited power is small.

The slope efficiency obtained in the present experiments is essentially identical to that reported by Di Lieto *et al.* [4] for 1342nm operation of a 0.3at.% Nd:YVO_4 single-end-pumped with incident powers up to 23W. More recently [13] this work has been extended with the addition of a second laser crystal (single end-pumping had approached the pump fracture limit) and pump diode to increase the achievable output power to 12W, though at a somewhat reduced slope efficiency of 38%. Chen *et al.* [3] have reported a double-end-pumped 0.3at.% Nd:YVO_4 laser operating at 1064nm, which can tolerate 52W total incident power without fracture. The thermal independence of the two pump regions (when double-end-pumping a long laser crystal) effectively doubles the available pump power fracture limit. This suggests that the incident pump power for the present device could be scaled to ~50W without crystal fracture, yielding cw powers at 1342nm approaching 20W.

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3.2 671nm operation

Figure 2 also shows total output power at 671nm as a function of incident diode power for intracavity second harmonic generation in LBO. The highest second harmonic output obtained was 910mW, produced from ~6W fundamental, corresponding to diode-to-red optical conversion efficiency ~4%. The output beam was TEM_{00} with a linewidth of ~0.05nm FWHM, centred at 671.13nm. Heating of the LBO was observed; this had the effect of temperature tuning the crystal away from the phase matching condition. As a result the medium term power stability of the second harmonic output was poor. This detuning occurred over multiple seconds, so no attempt was made to examine amplitude noise in the output commonly referred to as the ‘green problem’. It has previously been reported that vanadate and LBO does not suffer significant power instabilities due to the green problem at low powers [14]. High power frequency doubled output from Vanadate and LBO has also recently been shown to exhibit very little amplitude noise, especially in a type I configuration where no de-polarization effects occur [15].

Agnesi *et al.* [11] have recently demonstrated over 700mW of 671nm output from ~2W fundamental at diode-to-red optical conversion efficiency ~8% for an intracavity, frequency-doubled, diode-pumped $Nd:YVO_4$ laser with optimised Z-folded resonator. Preliminary details of a 2.4W 670nm source based on intracavity, frequency-doubled $Nd:GdVO_4$ from <10W diode pump power have also been presented by Agnesi and Guandalini [15]. These results suggest that optimisation of resonator configuration and mirror coatings (as demonstrated for practical mirrors by Agnesi *et al* [15]) for the present double-end-pumped $Nd:YVO_4$ laser should result in multiwatt output at 671nm. Output power stability in the red is expected to improve significantly with temperature control of the LBO crystal.

4. Conclusion

Reduction of thermal loading using a low doped $Nd:YVO_4$ crystal and a diode double-end-pumping arrangement has enabled cw output powers over 8W to be obtained on the 1342nm transition in TEM_{00} mode at 42% slope efficiency. Second harmonic generation using type I critically-phase-matched LBO demonstrated over 900mW of cw red radiation at 671nm in TEM_{00}. Input power scaling to 50W and further optimisation of resonator design is expected to yield cw powers at 1342nm up to 20W and multiwatt cw powers at 671nm.

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