Continuous yellow-orange laser based on a diode-side-pumped Nd^{3+}:YVO_4 self-Raman laser

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Abstract: In this work we report the operation of the first diode-side-pumped continuous-wave (cw) self-Raman laser at 588 nm. The laser is based on the intracavity frequency doubling in LBO, of a cw Nd^{+3}:YVO_4 self-Raman laser operating at 1176 nm, whose cavity configuration is based on the total internal reflection of the laser beam at the pumped facet of the Nd^{+3}:YVO_4 crystal. This laser design provided a cw output power of 820 mW with a slope efficiency of 6.7% at the frequency doubled first Stokes wavelength of 588 nm. Operation of TEM_{00} transversal laser mode was also demonstrated for pump powers up to 14.5 W, yielding a maximum output power of 340 mW.

OCIS codes: (140.0140) Lasers and laser optics; (140.3530) Lasers, neodymium; (140.3550) Lasers, Raman; (140.3515) Lasers, frequency doubled; (140.7300) Visible lasers

1. Introduction

There has been great interested in the development of continuous-wave operation of solid state Raman lasers, for they offer a practical and efficient way of accessing regions of the electromagnetic spectrum that are hard to reach, and therefore permit access to uncommon visible wavelengths, by nonlinear conversion processes. Additionally the same resonator setup allows for oscillation at many different wavelengths within this same spectral region [1,2].

The orange-yellow region of the visible spectrum is very interesting because of applications in ophthalmology [3], display technology and biological techniques that are based on fluorescence excitation such as flow cytometry [4] and microscopy. The light sources for biological instrumentation usually require low cw power <100 mW, good beam quality, power stability and low cost [5]. All the cw devices based on Nd^{+3} Raman lasers reported to date are diode-end-pumped lasers, due to the fact that this resonator configuration can provide the high intracavity intensity necessary for stimulated Raman scattering (SRS) to occur (typically> 100 MW/cm^2). Self-Raman lasers, in which the same crystal provides the laser action and the Raman gain, are the most compact solid state Raman lasers. They benefit from less intracavity losses due to fewer optical interfaces, however, they have the disadvantage that the mode size cannot be optimized for both laser action and SRS. In addition, during cw operation the thermal load in the crystal can be exacerbated, since it receives two contributions, one due to the pump radiation and one due to the Raman scattering. The first cw self-Raman laser was reported in 2007 by Demidovich et al [6] and the highest output power obtained to this date for a Nd:YVO_4 cw self-Raman laser at 1176 nm was 1.53W, corresponding to an optical conversion efficiency of 6.8% [7].

The first solid state, cw, yellow-orange Raman laser was reported in 2007, consisting of a Nd:$GdVO_4$ laser Raman-shifted to 1176 nm by a KGW crystal and frequency doubled to 588 nm with an optical conversion efficiency of 5.1%. The maximum output power at was 704 mW [8]. Using the same laser crystal and a $BaWO_4$ Raman crystal, 2.9 W of CW output power at 590 nm was achieved with 11 % optical conversion efficiency [9]. The same group reported another yellow-orange laser based on a Nd:YVO_4 self-Raman laser, providing an optical conversion efficiency of 8.4 % at the maximum output power of 320 mW [10]. The highest cw output power at 589 nm reported so far for a self-Raman laser was 4.3 W (conversion efficiency of 17 %) achieved by using a self-Raman Nd:$GdVO_4$ crystal [11].

The cavity design proposed in this work is based on side-pumping and total internal reflection of the laser beam at the pumped facet, creating an excellent overlap between pump and laser beam in this region and allowing for efficient SRS. The design holds the additional benefit of being much more cost-efficient when compared to the traditional longitudinal pumping design because no fiber-coupled high power diodes are needed in order to circularize the pump diode radiation. The grazing-incidence configuration reported here has yielded 74% slope efficiency for a 1064 nm Nd:YVO_4 laser [12] and q-cw operation of a Nd:YVO_4 self-Raman laser at 1176 nm has provided 11.7% optical conversion efficiency and 8.4 W of peak output power [13].

2. Laser experimental setup

The self-Raman crystal used in this work was an a-cut $Nd:YVO_4$ crystal (Crystech) with 1.1 at.% Nd^{+3} doping concentration and dimensions of 22×5×2 mm³. The c-axis was oriented perpendicular to the larger surfaces, the 5×2 mm laser facets had antireflection coating for 1064 nm and 1175 nm and were cut at an angle of 5° to minimize possible parasitic self-lasing effects, as indicated in the experimental scheme shown in Fig. 1.

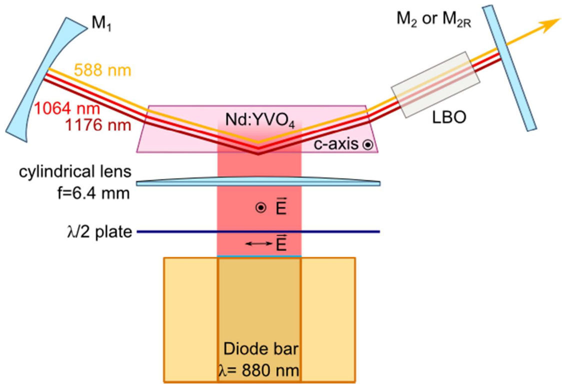

Figure 1: Experimental setup of the intracavity frequency doubled, diode-side-pumped Nd:YVO4 self-Raman laser.

For the π-polarization (polarization parallel to the c-axis), this crystal provides an energy shift of 890 cm^{-1}, thus shifting the fundamental 1064 nm to provide a first-order Raman Stokes line at 1176 nm with a Raman gain coefficient of 4.5 cm/GW [17]. A non-critically phase-matched LBO crystal (Castech) was used of dimensions 5×5×10 mm with antireflection coating for 1064 nm, 1176 nm and 586 nm, maintained inside a temperature-controlled oven at45°C. The pump source was a 70 Watt TE-polarized diode bar (Jenoptik) with its output wavelength temperature tuned to 880 nm. An achromatic half wave plate was used to rotate the polarization of the pump laser to address the crystal's highly absorbing π-polarization. The cylindrical lens of 6.4 mm focal length created a line focus with a height of 50 μm and width of 11 mm at the crystal pump facet. The 10 cm long cavity was comprised by two mirrors, both with high reflectivity (>99.99%) for the fundamental and first-order Stokes wavelengths and less than 1% reflectivity at 588 nm. M_1 had a radius of curvature of 15 cm and M_2 was a plane mirror.

3. Results

The fundamental laser at 1064 nm was observed to be a combination of higher order transverse modes, while the Raman and yellow-orange lasers operated with TEM_{00} transverse mode when the pump power was below 14.5 W, and in multimode for higher values. The output power at 588 nm as function of the incident pump power is shown in Fig. 2.

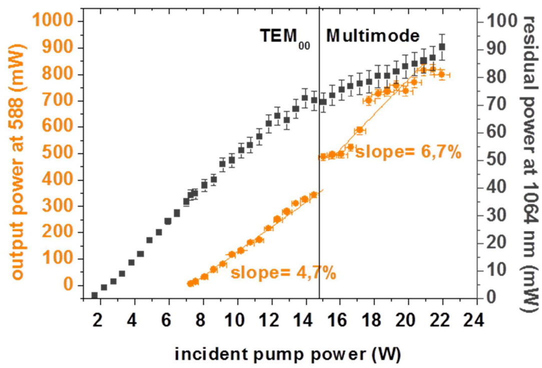

Figure 2: output power at 588 nm as function of incident pump power

The measured output powers account for only half the visible light generated in the LBO, as a similar amount was generated in the opposite direction, where it is largely absorbed in the laser crystal. A maximum output power of

820 mW was achieved in multimode operation at an incident pump power of 22 W with a slope efficiency of 6.7 %. In single transverse mode operation, the laser yielded a maximum output power of 340 mW, with a slope efficiency of 4.7%.

The M^2 value of the output beam was measured during single transversal mode operation at 10.5 W of pump power generating a measurement of the quality factor of less than 1.3 in the horizontal and vertical directions.

4. Conclusion

In this work we reported, for the first time to our knowledge, the continuous-wave operation of a laser emitting at 588 nm, based on a the operation of an intracavity-converted, side-pumped Raman laser.

The maximum output power at 588 nm achieved in multimode operation was 820 mW, corresponding to a slope efficiency of 6.7%. With single transverse mode operation the laser yielded 340 mW of output power, corresponding to 4.7% of slope efficiency, and the measured M^2 values were $M^2 < 1.3$.

We believe that the thermal load is a limiting factor for the output power achieved in this experiment. The thermal load is due to the sum of three processes: the Stokes shift between absorbed pump wavelength and fundamental emission wavelength at 1064 nm corresponds to ~17% of the pump power; the inelastic nature of the Raman scattering at 1176 nm corresponds to ~4% of the pump power, and finally the third process, the absorption of the yellow-orange laser by the laser crystal corresponding to ~2% of the pump power.

To optimize the system, the Nd:YVO_4 crystal could use a high reflectivity coating for 588 nm at its facet next to the LBO crystal, or this coating could be present in the LBO facet next to the laser crystal, alternatively. By doing this, the thermal load in the Nd:YVO_4 crystal would also diminish, and the orange-yellow beam would propagate towards the output mirror, increasing its total output power.

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