Diode side pumped, quasi-CW $Nd:YVO_4$ self-Raman laser operating at 1176 nm

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ABSTRACT

In this work we demonstrate for the first time, to the best of our knowledge, quasi-continuous wave (qcw) laser operation of a diode-side-pumped $Nd:YVO_4$ self-Raman laser operating at 1176 nm. The double beam mode controlling (DBMC) technique used in this work allows fundamental mode laser oscillation, resulting in a beam quality M^2 of 2.42 and 2.18 in the horizontal and vertical directions, respectively. More than 3.5 W of peak output power at 1176 nm was achieved with TEM_{00} laser mode, corresponding to an optical conversion efficiency of 5.4%.With multimode operation, more than 8W of peak output power was achieved, corresponding to 11.7% optical conversion efficiency.

Keywords: $Nd:YVO_4$, Raman Lasers, Self-Raman Lasers, Side-pumped Raman Lasers, DBMC technique

1. INTRODUCTION

In the past two decades, there has been great interest in the development of solid state Raman lasers. Their wavelength agile character provides a practical means for extending the fundamental wavelengths to several longer ones. The nowadays readily available high quality optical coating technology allows the development of Raman lasers operating near quantum efficiency, providing high output powers and high pulse energies[1]. When this technique is combined with nonlinear conversion processes it gives access to hard to reach wavelengths in the visible range[2]. The yellow-orange region of the spectrum presents potential applications in various areas, such as medicine, biomedicine and remote sensing[3].

The first cw solid state Raman laser was reported in 2004 by Grabtchikov et al[4]. The best result found in the literature of a cw intracavity Raman laser in the infrared was reported in 2009, achieving an output power of 3.36 W at 1180 nm using a $Nd:YVO_4/BaWO_4$ crystal combination, corresponding to 13.2 % of optical conversion efficiency[5].

The most compact, simple and low-cost Raman lasers are the self-Raman lasers, in which both the fundamental laser field as the stimulated Raman scattering (SRS) occurs in the same crystal. The small number of optical components inside the cavity of a self-Raman laser reduces the intracavity loss. The reduction of intracavity loss is of great importance for the laser efficiency, as the optical gain provided by the SRS is small compared to an ordinary rare earth doped laser gain medium. Self-Raman lasers present essentially two disadvantages: firstly, it is not possible to separately optimize the mode sizes in the laser crystal and in the Raman crystal in order to achieve the highest efficiency and, secondly, the additional thermal load of the SRS causes a major limitation to power scale self-Raman lasers. The first cw self-Raman laser was demonstrated by Demidovich et al. in 2005[6], achieving an output power of 54 mW.

The YVO_4 crystal was first seen as a promising Raman active medium in 2001 by Kaminskii et al[7]. Since then, this crystal has been exploited as laser/Raman gain media for Q-switched devices[8,9] and more recently, cw devices, achieving an output power of 1.53 W at 1176 nm corresponding to a slope efficiency of 8.1%[10]. The thermal load inside the crystal causes a major limitation for the output power in a cw self-Raman laser, therefore in-band pumping of $Nd:YVO_4$ becomes highly interesting. In-band pumping at 880 nm eliminates a large part of the quantum efficiency loss compared to the traditional pumping at 808 nm, improving the laser efficiency[11,12].

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Nonlinear Frequency Generation and Conversion: Materials, Devices, and Applications XIV, edited by Konstantin L. Vodopyanov, Proc. of SPIE Vol. 9347, 934718 · © 2015 SPIE
CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2077976

When the system is pumped at the traditional 808 nm wavelength, the Nd ion is excited from the fundamental $^4I_{9/2}$ level to the $^4F_{5/2}$ level and decays by a non-radiative transition to the upper laser level $^4F_{3/2}$ from where the laser transition occurs, emitting a photon at 1064 nm. Then, the atom decays to the fundamental $^4I_{11/2}$ Stark level. When pumping the system at 880 nm, the atom is excited directly to the upper laser level, reducing the Stokes shift between the pump and the laser photon and causing a heat reduction of ~25%[13].

Diode-end-pumping configuration requires expensive pump schemes such as fiber-coupled diodes, it does not permit power scalability, and presents strong thermal lensing[14,15]. An attractive configuration is a side-pumping scheme with single or double beam (DBMC) technology, in which the laser beam performs a total internal reflection at the pumped facet of the crystal[16-19]. This geometry has shown high output powers at 1064 nm and a slope efficiency of 74% using a $Nd:YVO_4$ crystal[20,21]. With grazing incidence geometry and single bounce configuration, the laser operates in a variety of Hermite-Gauss laser modes depending on mirror alignment. Using the DBMC technology, one can perform mode-controlling by changing the angle that the laser beam makes with the pump surface and by adjusting the distance between the two beams, which creates an efficient overlap between the two laser beams and the inverted population in the pumped region. The DBMC technology prevents higher modes to oscillate, and allows for generation of a stable high quality TEM_{00} laser mode.

In this work, we report for the first time a diode-side-pumped, quasi-continuous $Nd:YVO_4$ self-Raman laser emitting at 1176nm.

2. LASER EXPERIMENTAL SETUP

Figure 1 shows the two configurations of grazing incidence geometry used in this work with (a) a single bounce and (b) a double bounce configuration based on the DBMC technology.

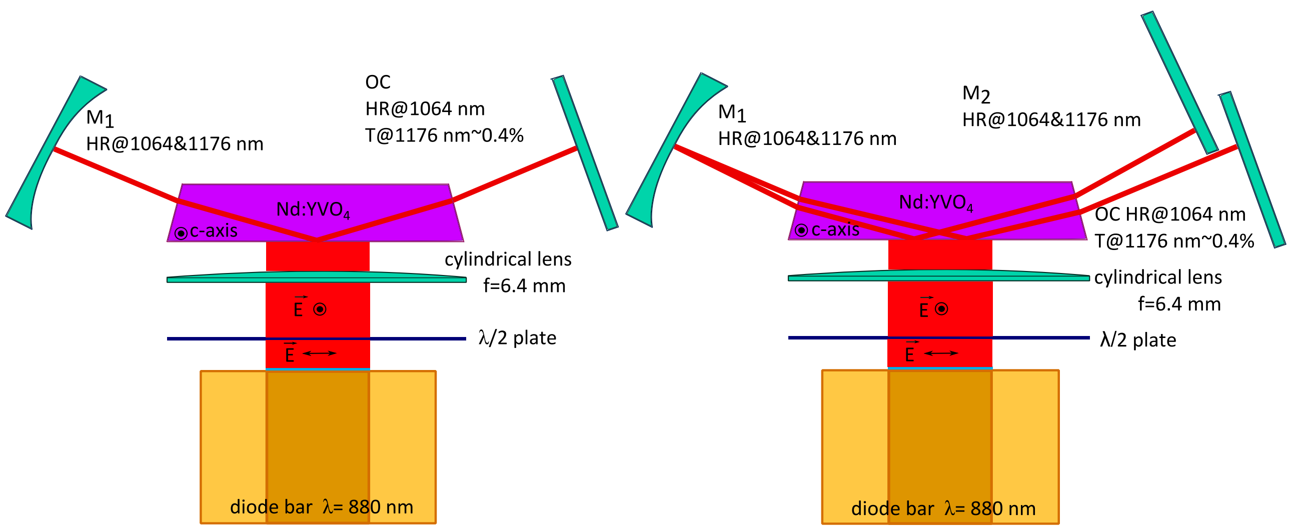

Figure 1. Configuration of the laser set up with (a) single bounce and (b) double bounce geometries.

The laser active medium used in our experiment was an a-cut $Nd:YVO_4$ crystal with 1.1 at.% Nd^{+3} doping concentration and dimensions of 22×5×2 mm³. The c-axis was orientation perpendicular to the larger surfaces. The 5×2 mm facets were antireflection coated for 1064 nm and 1175 nm, and cut at an angle of 5° to minimize possible parasitic self-lasing effects. The 22×5 mm surface, which was the pump surface, was coated for high transmission at 808 nm and 880 nm. The crystal was mounted on a copper heat sink refrigerated by a re-circulating chiller. A 0.125 mm thick indium foil was placed between the crystal and the holder in order to facilitate efficient heat exchange.

A 70 watts TE-polarized diode bar (Jenoptiks) was used as pumping source, mounted onto a temperature controlled copper plate, using indium foil for thermal contact. Its output wavelength was temperature tuned to 880 nm, which was around 39º C for q-cw operation. An achromatic half wave plate (Thorlabs) was used to control the polarization of the pump laser in order to address the crystal's π-polarization, having the higher absorption cross-section of $\sigma_{abs} = 45 \cdot 10^{-20} cm^2$ at 880 nm[22] as shown in figure 2.

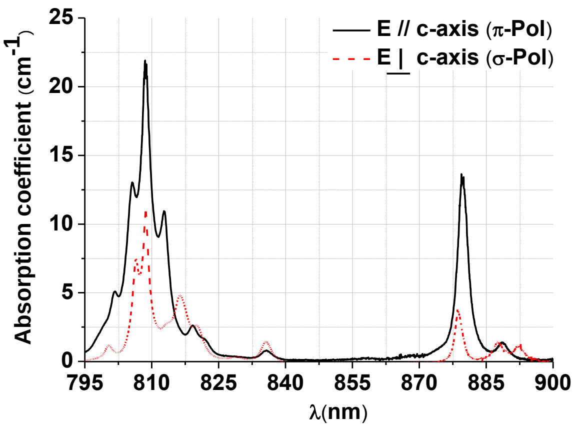

Figure 2. Absorption spectrum of the $Nd:YVO_4$ crystal used in this experiment, measured with a Cary-5000 (Agilent) spectrometer.

A 6.4 mm focal cylindrical lens was used to create a line focus of approximately 50 μm in the vertical direction and 12 mm in the horizontal direction. The cavity used for the single bounce experiment, shown in figure 1a, was 7 cm long and comprised two mirrors: M1 was a high reflector (R> 99.99 %) for 1064 nm and 1175 nm, with 15 cm radius of curvature and M2 was a flat output coupler with R>99.99 % at 1064 nm and T=0.47 % at 1175 nm. In the single bounce geometry, the laser can operate in a variety of Hermite-Gauss modes, depending on the cavity alignment.

Fig. 1b shows a schematic representation of the experimental setup used for the double bounce experiment. A third folding mirror (M3) was added having the same coating as M1. With the double bounce geometry, the distance between the two beams is such that the overlap region between the laser beams and the pumped region makes it possible to generate a stable TEM_{00} mode.

The TEM_{00} mode size inside the cavity was simulated with an ABCD matrix resonator model (LASCAD GmbH) providing a 150 μm beam diameter in the laser/Raman crystal, in the absence of thermal lensing.

With both configurations the laser was studied under quasi-cw operation, in which the pump was pulsed with a duty cycle of 0.3 % at a repetition rate of 20 Hz corresponding to a pulse duration of 150 μs. Therefore, thermal effects can be neglected. The short pulse duration is approximately twice the lifetime of the upper laser level[22]. In order to measure output power from the Raman laser, a longpass filter was used (FEL1150 Thorlabs) to block the residual power at 1064 nm. The laser output energy was measured using a pyroelectric energy sensor (Thorlabs- ES111C) and the peak power was calculated.

With the DBMC configuration, the beam quality factor M^2 of the TEM_{00} was measured, by using a biconvex lens (f=30 mm) to focus the beam in a CCD camera, which was translated in z-direction through the focal plane. The calculations of the beam waist were made using the second moment beam analysis in the horizontal and vertical directions.

3. RESULTS AND DISCUSSION

The spectrum of the Raman laser, along with the fundamental laser, was recorded with a spectrophotometer (Ocean Optics NIR Quest) with resolution of 3.3 nm (figure. 3), when the laser operated in the single bounce configuration.

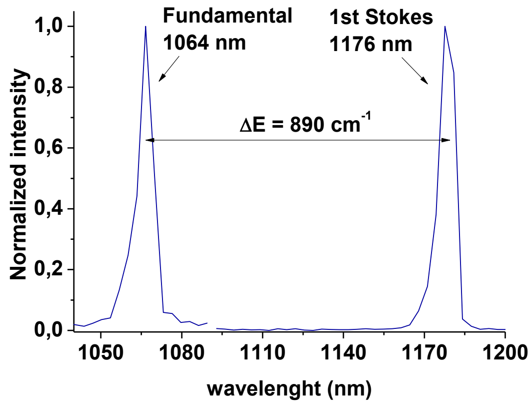

Figure 3. Emission spectrum of the Raman laser, centered at 1176 nm, along with the fundamental laser, centered at 1064 nm.

In the single bounce configuration, the 1st Stokes at 1176 nm delivered a maximum peak power of 8.4 W in multimode, corresponding to optical conversion efficiency from the incident diode radiation to the output Stokes radiation of 11.7%, as shown in the linear fit of the graph in Figure 4.

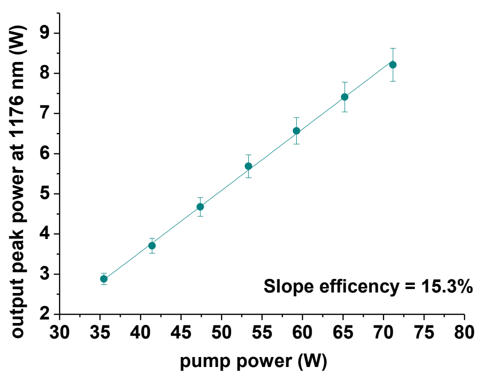

Figure 4. Output peak power as a function of pump power, for the laser with single bounce operating in multimode.

The temporal behavior of the Raman laser was measured (Thorlabs DET01CFC) simultaneously with the pump beam (biased photodetector Newport 818-BB-21A), and the output from these fast detectors was observed using an oscilloscope as shown in figure 5. The measurement was made at 24 A of applied pump current corresponding to approximately 14 Watt of diode pump power which corresponds to threshold of lasing.

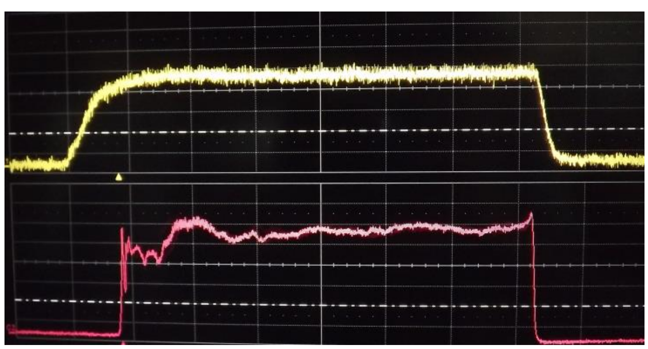

Figure 5. Temporal behavior of the pump beam (upper curve) and Stokes beam (lower curve), with 20µs/div.

Using the DBMC technology, the laser mode size becomes smaller due to the competition between the two beams in the gain medium, favoring TEM_{00} oscillation. The maximum Raman TEM_{00} peak output power was 3.7 W corresponding to an optical to optical conversion efficiency of 5.4 %, as shown in figure 6.

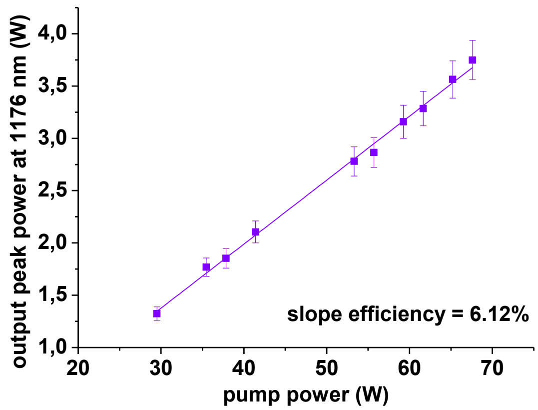

Figure 6. Peak output power as a function of diode pump power for the DBMC-Raman laser, operating in TEM_{00} mode.

The measurements of the M² quality factor of the laser beam in the DBMC set-up provided a value of 2.42 in the horizontal direction and 2.18 in the vertical direction, as shown in Figure 7.

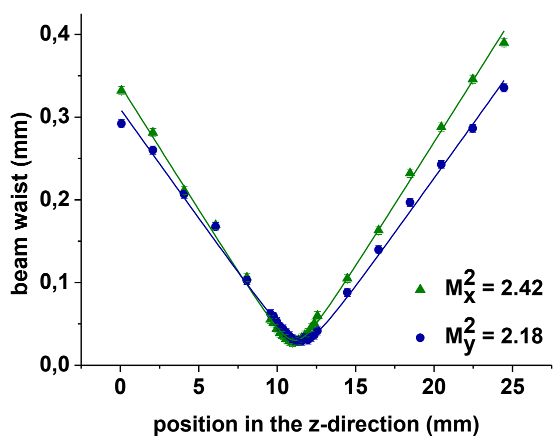

Figure 7. M^2 measurement of the Raman laser beam in the DBMC configuration.

4. CONCLUSION

We have demonstrated, to the best of our knowledge, the first side pumped self-Raman laser under q-cw regime. Stable, high quality TEM_{00} laser output is achieved thanks to the unique mode controlling characteristics of the DBMC technology.

In the grazing incidence geometry and with a single bounce configuration, the laser provided a maximum multimode peak output power of 8.4 W with 11.7% optical conversion efficiency (diode to Stokes). With the DBMC configuration, it was possible to generate a stable high quality TEM_{00} mode with a measured M² of M_x^2=2.42 and M_y^2=2.18 in the horizontal and vertical directions, respectively, and maximum peak output power of 3.7 W corresponding to 5.4% of optical conversion efficiency.

5. ACKNOWLEDGEMENTS

We gratefully acknowledge the award of Cristine Cores' CAPES scholarship, the FAPESP research grant 2012 11437-8 and the CNPq research grant 2012-1 401580.

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