High power, good beam quality Nd:YVO_4 laser using a resonator with high extinction ratio for higher-order mode thresholds

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Abstract. We demonstrated a cw side pumped Nd:YVO_4 laser with high power output and a improvement in beam quality. With one pass we demonstrated 63% optical-to-optical conversion efficiency, 74% slope efficiency and 22 watts output power in multimode, for a pump power of 34,9 watt. With the double pass configuration we achieved 17 watts, for a pump power of 45 watts, with M^2 of 3.4 x 3.8 in the horizontal and vertical directions, respectively. We verified the threshold for fundamental and higher-order modes with different resonators. Through simulations we showed a configuration with fundamental mode with a pump power higher than 400 watts.

Keywords: Nd:YVO_4, Solid state lasers, side pumped.
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INTRODUCTION

Diode pumped solid state laser are developing at a very fast rate mainly because of decreasing cost of diode lasers and increasing power, narrower spectral emission and better beam quality of the diodes. At the same time, materials that in some aspects have better characteristics than Nd:YAG are on the market such as Nd:YVO_4, Nd:$GdVO_4$, Yb:YAG and others. Grazing incidence with high gain media and pumped source until 40 watts has demonstrated high efficiency, Damzen et al. presented high power and a slope efficiency of 72% in multimode with near symmetric cavity [1].

Fundamental mode with high efficient was achieved using different configurations in side pumped lasers. High efficiency in fundamental mode was obtained with a concentric cavity by A. Minassian et al [2], F. He et al achieved recently a high efficiency in a Nd:$GdVO_4$ laser using a intracavity telescope for obtain TEM_{00} [3]. High efficiency in TEM_{00} was obtained with a pumped of 100 watts by Minassian et al. [4].

In this work we demonstrated experimentally a multimode high conversion efficiency laser using a Nd:YVO_4 crystal and a novel configuration that increases beam quality with high efficiency. We showed the parameters influence on the mode oscillation in this double pass configuration.

THEORICAL CALCULATIONS

On the basis of the space-dependent rate equation analysis, we obtain the relationship between the threshold of the *i*th mode when others *j*th modes are oscillating simultaneously [5].

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$$\iiint_{cavity} \frac{s_{0,i}(x,y,z) r_0(x,y,z)}{1+\sum_j S_j s_{0,j}(x,y,z)/I_0}\, dv = \frac{I_0 \gamma_i}{R} \qquad (1)$$

where $s_{0,i}(x,y,z)$ is the normalized distribution function of the photon density of the *i*th mode and $r_0(x,y,z)$ is the distribution function of the normalized pumping rate. R is the total pumping rate in the crystal, γ_i is the loss, S_j is the photon number of the *j*th mode in the cavity and I_0 and γ_i are

$$I_0 = \frac{1}{c\sigma_l \tau_f} \qquad (2)$$

$$\gamma_i = \frac{cL_{c,i}}{2l} \qquad (3)$$

where *c* is the light velocity in the medium, σ_l is the laser transition cross section, τ_f is the fluorescence lifetime, $L_{c,\,i}$ is the round-trip cavity loss including the transmission loss of the mirrors, *l* is the cavity length.

R is experimentally related to pump power P_{in}, as follow [5]:

$$R = \frac{\eta_a P_{in}}{h\nu_p} \qquad (4)$$

At the threshold of the *i*th mode S_i is equal to 0 and, using Eq. 1, we obtain the threshold when just one mode oscillates, as follows:

$$R_{th,i} = \frac{I_0 \gamma_i}{\iiint_{cavity} s_{0,i}(x,y,z) r_0(x,y,z)\, dv} = \frac{I_0 \gamma_i}{I_1} \qquad (5)$$

$$I_1 = \iiint_{cavity} s_{0,i}(x,y,z) r_0(x,y,z)\, dv \qquad (6)$$

The threshold pump power of one single mode oscillating is

$$P_{th} = \frac{L_{c,i} h\nu_p V_{eff}}{2l\sigma_l \tau_f \eta_a} \qquad (7)$$

where V_{eff} is the overlap between the pump beam and the laser beam that can be written as

$$V_{eff} = I_i^{-1} \qquad (8)$$

The normalized distribution functions of the photon density and pumping rate in a side pumped configuration are:

$$s_{00}(x,y,z) = \frac{2}{\pi w^2} \exp\left[\frac{-2x^2}{w_l^2}\right] \exp\left[\frac{-2y^2}{w_l^2}\right] \qquad \text{(for TEM}_{00}\text{ mode)} \qquad (9)$$

$$s_{10}(x,y,z) = \frac{8}{\pi w^4} x^2 \exp\left[\frac{-2x^2}{w_l^2}\right] \exp\left[\frac{-2y^2}{w_l^2}\right] \qquad \text{(for TEM}_{10}\text{ mode)} \qquad (10)$$

$$r_0(x,y,z)=\sqrt{\frac{2}{\pi}}\frac{1}{w_p}\frac{\alpha}{1-e^{-\alpha L}}\exp[-\alpha x]\exp\left[\frac{-2y^2}{w_p^2}\right] \qquad \text{(side pumped)} \qquad (11)$$

EXPERIMENTAL SETUP

The laser crystal is a Nd:YVO_4 with 1.1 at.% neodymium doping with dimensions $22\times5\times2$ mm^3 (Casix Inc.). The end faces (5×2 mm^2) have AR coating for the 1064 nm laser wavelength and are angled at 5º to minimize parasitic self-lasing effects inside the gain. The crystal is pumped on the 22mm $\times$ 5mm edge face, which has AR coating for the 808 nm wavelength. The c-axis orientation is perpendicular to the large surfaces used for heat removal. The crystal was mounted inside a copper block and good refrigeration was guaranteed using 1 mm indium foil between crystal and copper.

In a first experiment the pump source was a 40 watts TM-polarized diode bar (Coherent Inc.) operating at 808 nm. The TM polarization is parallel to the c-axis of the crystal and hence accesses the high absorption coefficient of 31.4 cm^{-1} [3]. The pump radiation was focused into the crystal with a 6.4 mm focal cylindrical lens generating a line focus of 60 mm diameter. The temperature of the diode was fixed at 29 ºC with a thermoelectric cooler in order to obtain the diode emission at 808 nm. A re-circulating chiller was used for heat removal from the crystal and the diode. The cavity comprised two mirrors, one flat mirror with 36% transmission and other of 50cm radius of curvature. We did one single pass through the gain media with one total internal reflection (figure 1). This cavity was very compact with less than 8 cm length.

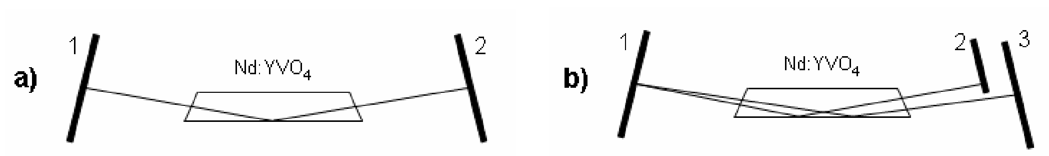

Fig. 1: Cavities configuration: **a)** Single bounce: 1) end mirror (R=50cm); 2) plane output mirror with 36% transmission; **b)** Double bounce: 1) folding mirror (R=50cm); 2) high reflector (plane mirror); 3) plane output mirror with 36% transmission.

In a second experiment we used a double pass configuration (figure 1) with a second total internal reflection at the pump face. We used a novel configuration with only three mirrors, a high reflector flat mirror, a flat mirror with 36% transmission and other of 50 cm radius of curvature. The pump source was a 48 watts TM-polarized diode bar (Coherent Inc.) operating at 808 nm. The temperature of the diode was fixed at 23 ºC. The same crystal and cylindrical lens in front of the diode bar was used. The distance from the crystal center for mirrors 1, 2 and 3 was approximately the same. Therefore, this cavity had joint stability zones as shown in figure 2.

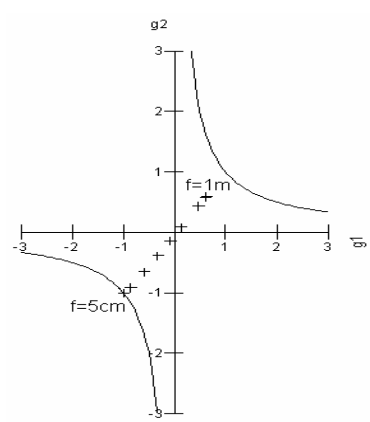

Fig 2: Stability diagram and zones (I and II). 1/f is the dioptric power of the thermal lens.

To the case of a second bounce in the media laser, a numerical simulation was done to obtain the threshold pump power for TEM_{10} and TEM_{20} in the presence of TEM_{00}, using different resonators. Three parameters were changed – the distance between the laser beams inside the crystal (fig 1b), the beam radius and the grazing incidence angle. It is assumed that the pump beam is matched to the laser mode size inside the crystal.

We used a commercial finite-element program to calculate the thermal lens (LASCAD) and a MATLAB software program to calculate pump - and laser beam overlap in three dimensions and resultant TEM_{00} and higher order mode thresholds.

RESULTS AND DISCUSSIONS

In the first experiment we achieve 22 watts output power in multimode to a pump power of 34,9 watts (figure 3). A high slope efficiency of 74% was achieved. The value for the M^2 was 24.6×10.4. Using a second pass through the gain media we achieved 17 watts of output power to a pump power of 45 watts (figure 3). The beam quality was improved with a M^2 of 3.4 x 3.8 in the horizontal and vertical direction, respectively.

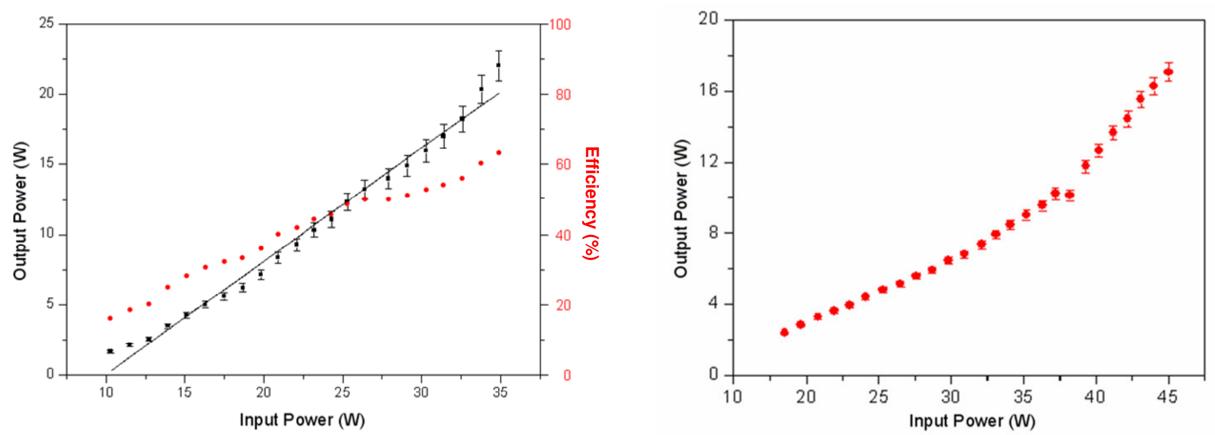

Fig 3: Output power and efficiency versus diode pump power for a single bounce configuration (left) and double bounce configuration (right).

In figure 3 we notice that there is a small unstable region in the double bounce configuration for 38 watts of pump power, because of a small mismatch between stability zones due to the fact that mirrors 2 and 3 can not be positioned at exactly the same distance from crystal center. Crystal quality was not good and the crystal had to be pumped very close (0.2 mm) to the top surface in order to achieve efficient laser action. Better beam quality is expected with more homogeneous crystals.

The double bounce cavity is very compact, with only three mirrors, compared with the cavity used by Damzen et al.[4] that used four mirrors, and permits, in theory, power scalability by using several diodes disposed laterally to the gain media.

The numerical simulations showed the influence of the three parameters on the higher order mode threshold (Figure 4). It is seen that the higher order mode threshold can be very high and with some resonators it is possible to maintain TEM_{00} for pump power higher than 400W. The parameters used in these simulations are grazing angle of 7º, a distance between the laser beams at crystal center of 0,08cm and a beam radius of 0,06cm.

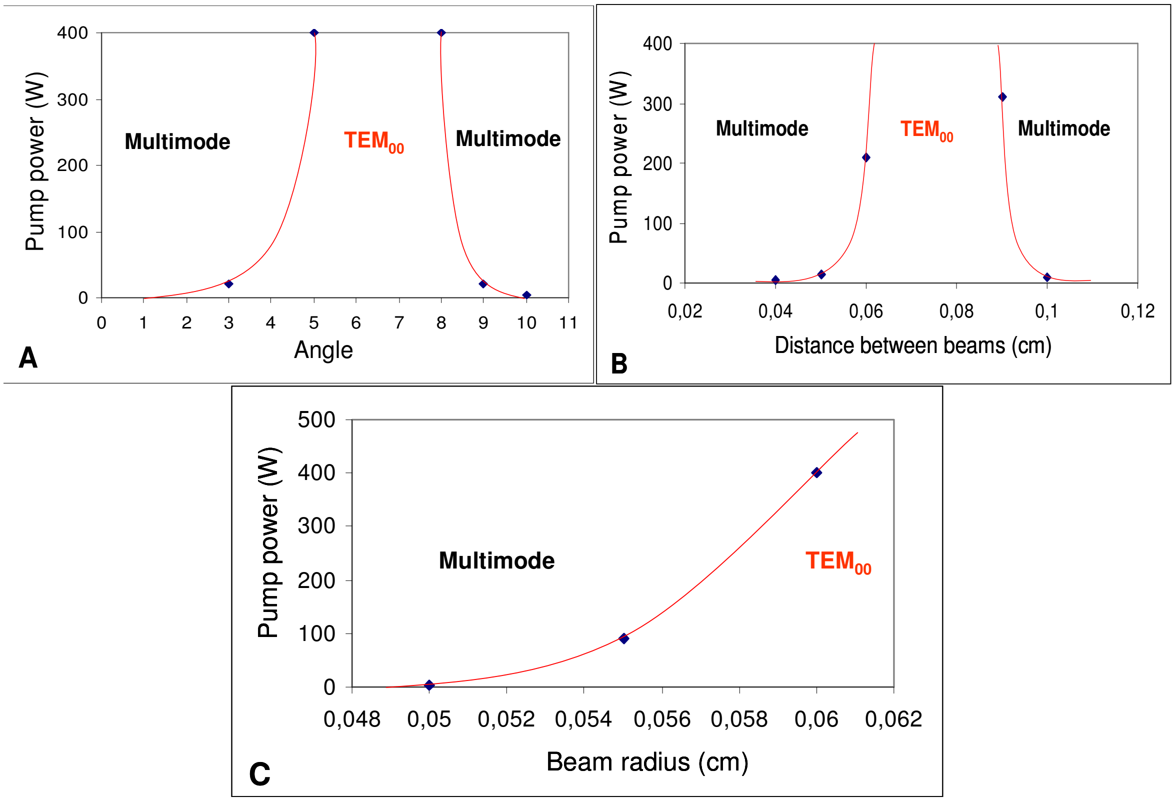

Fig 4: Numerical simulation: A) higher modes threshold in function of the grazing angle, B) higher order threshold in function of the distance between the beams inside the crystal and C) higher order modes threshold in function of the beam radius.

In the Figures 4 the red lines show the tendency for the higher order mode thresholds and the blue points the simulation data. It is clearly seen that, in order to increase the threshold of the higher order modes, the intracavity beam radius must be bigger than 0.05 cm and that this mechanism works only for a very tight interval of grazing angles and distances between the two beams. With a grazing angle from 5º to 7º there is just fundamental mode, the same occurs for distance between beams from approximately 0,075 to 0,09 cm.

In our experiments we were not able to show pure fundamental mode because our precision in adjusting the grazing angle and the distance between the two beams is limited. Another reason is that the thermal lens inside the medium has to be taken into account. This thermal lens is difficult to model due to the geometry of a side pumped, grazing incidence laser. Although we used finite-elements to characterize the thermal load inside the crystal and then calculated the induced refractive index chance which was subsequently approximated by parabolic fits for the optical path difference (OPD) in each cross sectional area perpendicular to the laser propagation axis, the calculation error is still bigger than acceptable given the very tight tolerances of grazing angle and distance between beams.

In a next step, we will use a carefully designed resonator at lower pump powers and therefore, with smaller thermal lens in order to study the exact dependence with grazing angle, beam radius and distance between beams.

The figure 5 was made using the same calculus and shows the double-beam, TEM_{00} intensity mode inside the crystal at five difference positions inside the crystal along the propagation direction. It is possible to see the beams entering the crystal, each beam bouncing of the crystal surface and the two beams crossing each other in the middle of the crystal.

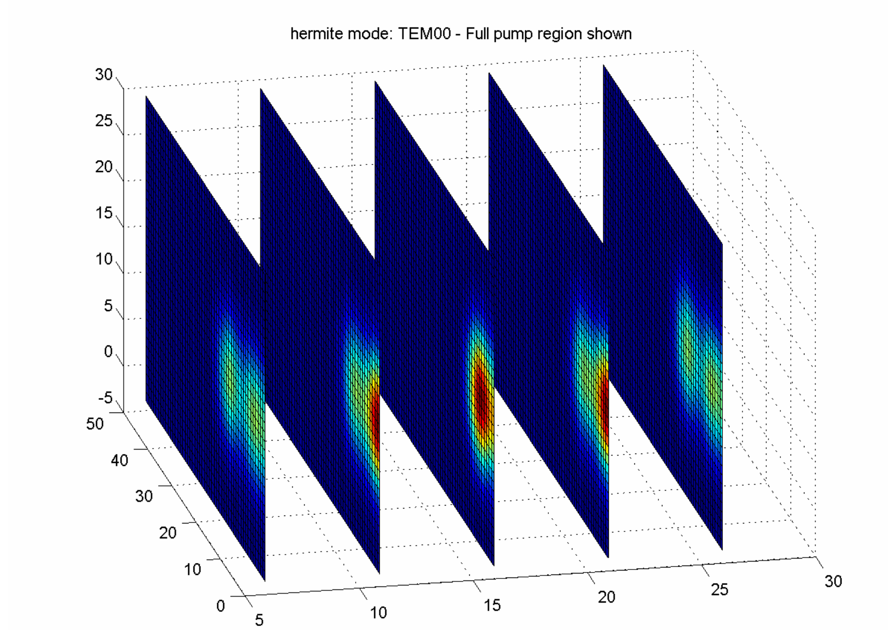

Fig 5: The intensity distribution of the two laser beams inside the crystal with a grazing angle of 7º, a distance between the beams of 0,08cm and a beam size of 0,06cm.

CONCLUSIONS

We conclude that when a second pass is made through the gain media a high beam quality factor is achieved. In the single pass configuration we achieved a slope efficiency of 74% with 22 watts of output power in multimode with M^2 of 24.6×10.4 in horizontal and vertical directions, respectively, while with the double pass configuration we achieved 17 watts with M^2 of 3.4 x 3.8 in the horizontal and vertical directions, respectively. We conclude that a second pass improved the beam quality and demonstrated this with a compact three mirrors cavity.

A software program was build which calculates the higher order mode threshold in the presence of a thermal lens. This program shows that the beam radius, grazing incidence angle and the distance between the laser beams are essential in order to suppress higher order modes. Simulations show that a resonator oscillating in fundamental mode with pump powers up to 400 watts should be possible.

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