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Mode-controlling in a 7.5 cm long, transversally pumped, high power Nd:YVO$_4$ laser

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Abstract
A side pumped Nd:YVO$_4$ laser with a very compact, 7.5 cm long resonator is presented. In single pass configuration this cavity provides 74% slope efficiency and 22 W output power in multimode operation. With a second pass through the gain media, using a double bounce configuration, this short and simple cavity results in 17 W and a large improvement in beam quality with an M^2 of 1.7 × 1.4 in the horizontal and vertical direction, respectively. A theoretical, experimental and numerical analysis of this double bounce configuration is made.

Keywords: Nd:YVO$_4$, solid state lasers, side pumping

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Recent achievements in output power, narrow spectral emission linewidth, beam quality and also decreasing costs of laser pump diodes have led to an increase in diode pumped solid state laser development. Nowadays, high power lasers have become more common, and different configurations and materials have been studied in order to obtain high efficiency. Some materials with high pump absorption cross section have been demonstrated to produce high efficiency using a grazing incidence configuration inside the active media. In this configuration, a total internal reflection is made at the pump face exploring the high inversion density in this area. As in other transversally pumped cavity designs this technique allows for power scaling through a variety of straightforward cavity additions. High efficiency has been demonstrated by Damzen *et al* using this configuration and Nd:YVO$_4$ as a gain media in a near symmetric cavity [1] and a pump source of 40 W.

Fundamental mode operation in this configuration is less efficient than in end-pumped lasers due to the poorer overlap between the pump beam and the laser beam. Moreover, at high power these materials suffer a strong thermal lens which causes instability in the laser operation, loss of efficiency and degradation in beam quality [2]. Consequently, different cavities have been studied that operate in fundamental mode trying to achieve stability and high efficiency. Minassian *et al* demonstrated 58% optical-to-optical conversion in TEM$_{00}$ operation using an asymmetric cavity geometry utilizing the thermal lens of the crystal to make the resonator stable [3], and He *et al* recently achieved high efficiency in a Nd:GdVO$_4$ laser using an intracavity telescope to obtain TEM$_{00}$ [4]. With a pump power of 100 W, high efficiency in TEM$_{00}$ operation was obtained using a multiple bounce configuration [5]. Two intracavity cylindrical lenses were used to match the laser mode size with the gain region in the vertical and horizontal direction and to produce the necessary large fundamental mode in the horizontal direction.

In this work we demonstrated a novel and very compact cavity configuration with two passes through the crystal that uses only three mirrors and increases the beam quality M^2 of 1.7 × 1.4 in the horizontal and vertical direction, respectively. We also demonstrate multimode laser operation using a single pass through the Nd:YVO$_4$ crystal with 63% optical-to-optical efficiency and 74% slope efficiency. No cylindrical intracavity optics is required.

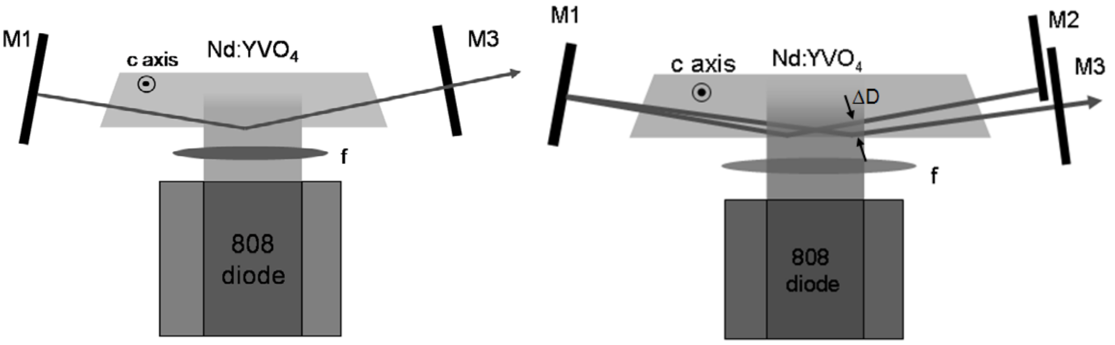

Figure 1. Single bounce (left) and double bounce cavity configuration (right): M1, folding mirror ($R = 50$ cm); M2, high reflector (flat); M3, plane output mirror with 36% transmission; f, 6.4 mm cylindrical lens.

2. Theoretical calculations

Using space-dependent rate equation analysis, a relationship is obtained between the threshold of the ith mode when other j modes are oscillating simultaneously [6].

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

where $s_{0,i}(x, y, z)$ is the normalized distribution function of the photon density of the ith 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 jth mode in the cavity, and I_0 and γ_i are given by

$$I_0 = \frac{1}{c\sigma_\mathrm{l}\tau_\mathrm{f}} \qquad (2)$$

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

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, and l is the cavity length.

R is experimentally related to the pump power P_in, as follows [6]:

$$R = \frac{\eta_\mathrm{a} P_\mathrm{in}}{h\nu_\mathrm{p}} \qquad (4)$$

where η_a is the absorption efficiency and $h\nu_\mathrm{p}$ the pump photon energy. The normalized distribution function of the pumping rate in a side pumped configuration is

$$r_0(x,y,z) = \sqrt{\frac{2}{\pi}}\frac{1}{w_\mathrm{p}}\frac{\alpha}{1-\mathrm{e}^{-\alpha L}}\exp(-\alpha x)\exp\left(\frac{-2y^2}{w_\mathrm{p}^2}\right). \qquad (5)$$

In a configuration with a total internal reflection at the pump face there is a superposition of the beam with itself. Therefore, for the fundamental mode we have a distribution function of the photon density given by

$$s_{00}(x,y,z) = \frac{2}{\pi w^2}\exp\left(\frac{-2y^2}{w_\mathrm{l}^2}\right)\left\{\exp\left[\frac{-2(x-D)^2}{w_\mathrm{l}^2}\right] + \exp\left[\frac{-2(x+D)^2}{w_\mathrm{l}^2}\right]\right\} \qquad (6)$$

where D is the distance from the pump face to the centre of the beam inside the crystal. This distance D depends upon the grazing incidence angle and z-position. Similar distribution functions of the photon density are obtained for the higher order modes.

3. Experimental set-up

The pump sources are two TM-polarized diode bars (Coherent Inc.) emitting at 808 nm, which corresponds to the absorption peak of Nd:YVO$_4$. One 40 W diode was used for the single pass resonator and a 48 W diode was used for the resonator which uses two passes inside the crystal. The emission is temperature stabilized to within ±0.1 °C using a temperature controlled re-circulating chiller. The TM polarization of the diodes is parallel to the c-axis of the crystal and hence accesses the high absorption coefficient of 31.4 cm^{-1} [7].

The Nd:YVO$_4$ laser crystal has 1.1 at.% neodymium doping and dimensions of $22 \times 5 \times 2$ mm^3 (Casix Inc.). The edge faces are angled at 5° to minimize parasitic self-lasing effects inside the gain media and have an anti-reflection (AR) coating for the 1064 nm laser wavelength. The crystal is pumped at the 808 nm, AR-coated, 22×2 mm^2 edge facet and mounted inside a copper block using 1 mm indium foil to guarantee good refrigeration.

For the single bounce, multimode cavity, a hemispherical resonator with a high reflector of 50 cm radius of curvature and a flat mirror of 36% transmission at 1064 nm was used (figure 1). The pump source is a 40 W, TM-polarized diode, focused into the crystal with a cylindrical lens of 6.4 mm focal length. This lens generates a line focus of 60 μm height and 12 mm width. The grazing incidence angle inside the crystal is 5° due to the AR-coated angled edge facets, which possess a V coating that rapidly increases the transmission losses for non-perpendicular incidence into the crystal. Overall, this compact cavity has a length of 7.5 cm.

The second experiment uses two total internal reflections inside the crystal (figure 1). The only difference with respect to the first configuration is the additional mirror M2 and the diode of higher output power (48 W instead of 40 W). This novel configuration has the advantage of being very compact (7.5 cm) with only three mirrors when compared to

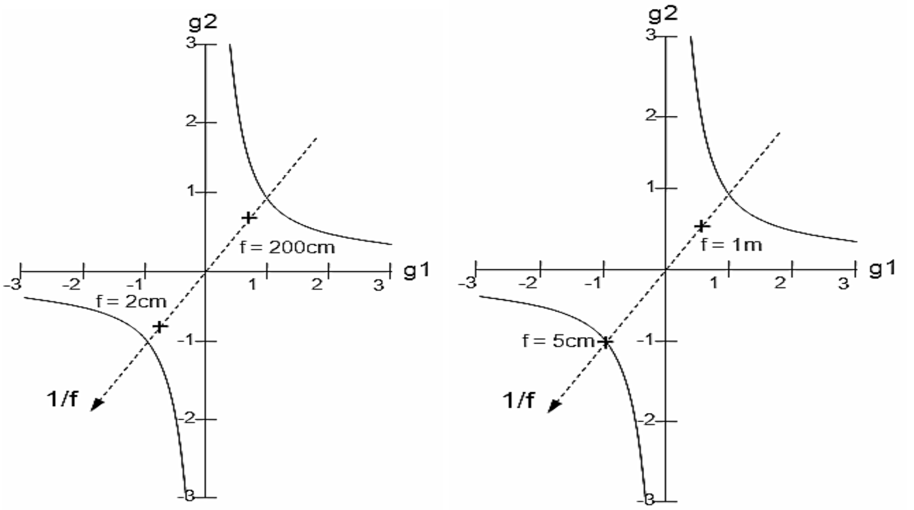

Figure 2. Stability diagrams of single bounce (left) and double bounce resonators (right). $1/f$ is the dioptric power of the thermal lens that increases with increasing pump power. $g1$ and $g2$ are the stability parameters [8].

the ultra-high efficiency cavity of Damzen *et al* in its TEM_{00} configuration (50 cm overall length with two intracavity cylindrical lenses, [3]).

The cavity comprised a highly reflective flat mirror, a flat output coupler with 36% transmission and folding mirror with 50 cm radius of curvature. The pump source is a 48 W diode bar (Coherent Inc.). The same crystal and cylindrical lens in front of the diode bar are used as in the previous experiment. Grazing incidence angles are kept close to 5°, because of the AR V coating of the 5° angled edge facets.

In order to design a cavity with joint stability zones, the distances from the crystal centre to mirrors 1, 2 and 3 were kept as closely the same as possible. This cavity has the advantage of being stable for a large range of thermal lenses, as is shown in figure 2. The area delimited by the coordinate axes and the hyperbola $g_1 g_2 = 1$ corresponds to stable cavities. The area enclosed with the upper branch of the hyperbola corresponds to the low power stability region number one, whereas the lower left area corresponds to the high power stability region number two. The fact that the resonator has joint stability regions is seen by the dotted arrow (the dioptric power) that crosses both regions at the origin of the coordinate system.

4. Results and discussions

In the 7.5 cm long single pass configuration, 22 W of output power was achieved in multimode operation for a pump power of 34.9 W with a slope efficiency of 74% (figure 3). This slope efficiency is higher than Damzen's ultra-high efficiency cavity [3] but the optical-to-optical efficiency is lower, mainly 63%. The measured M^2 values are 24.6×10.4 in the horizontal and vertical direction, respectively. It is important to remark that there is no roll-over in the input–output power curve, which indicates that higher optical-to-optical efficiencies could be achieved for higher pump powers. We therefore tried the higher power diode (up to 48 W of pump power) but we never achieved the same efficiencies. On closer inspection, we noted that the lower power diode showed at the focus inside the crystal an almost Gaussian beam profile in the y-direction of approximately 80 μm height (limited by the resolution of our CCD), whereas the higher power diode consisted clearly of two sharp peaks of approximately 80–100 μm separation, resembling a closely spaced TEM_{10} mode in the y-direction.

With the double bounce configuration 17 W of output power was achieved for a pump power of 45 W (figure 3). A small unstable region in the double bounce configuration near 38 W of pump power can be observed, which is due to a small mismatch between the stability zones. We noted that this dip in the output power depends strongly on how closely mirrors 2 and 3 are positioned to each other. The closer they are, the smaller the discontinuity of the output power curves. This shows clearly the importance of joint stability zones in this kind of set-up.

The double bounce configuration showed much less susceptibility to the pump beam profile in the y-direction, when compared to the single bounce configuration. Different from the single bounce configuration, this resonator can be pumped by both 40 and 48 W diodes, without loss of efficiency. For high power operation with the 48 W diode, we noted an offset between the two beams in the y-direction, which indicates that they undergo total internal reflection inside the crystal at different heights. This might be connected to the fact that this diode shows two maxima in the y-direction at the focus as explained earlier. It also could explain why the double bounce cavity works better in conjunction with the 48 W diode than the single bounce cavity.

Our crystal showed the best performance when pumped very closely (0.2 mm) to the top surface. When mounted upside down, the crystal showed best performance close to the bottom surface. We therefore concluded that this behaviour is due to inhomogeneities inside the crystal and not to uneven refrigeration on the top and bottom surfaces that could cause distortion of the thermal lens.

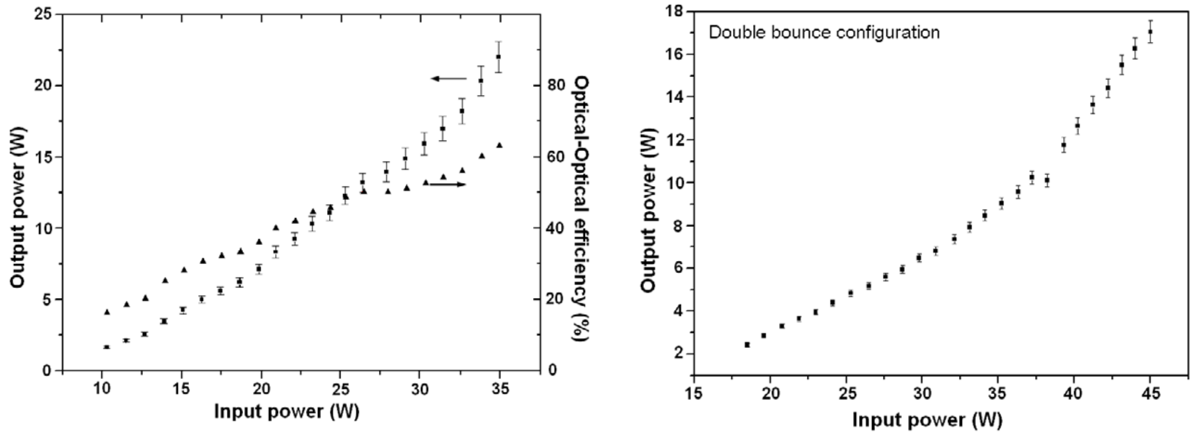

Figure 3. Output power and efficiency versus diode pump power for a single bounce configuration (left) and double bounce configuration (right).

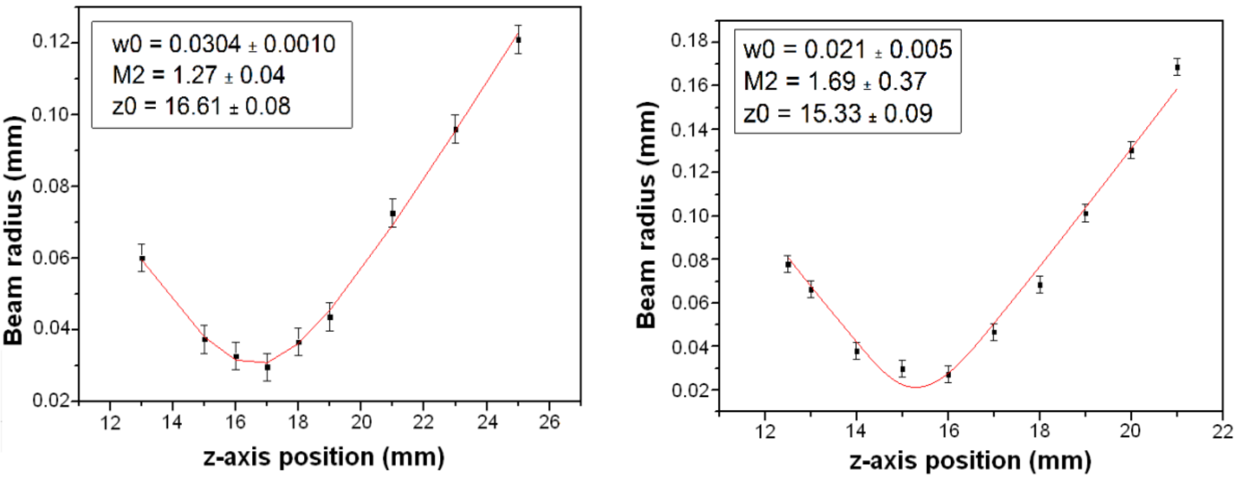

Figure 4. Measurements of the beam radius and calculated M2 parameters for the double bounce configuration in the vertical (left) and horizontal (right) directions versus z-axis position.

A significant improvement in the beam quality is obtained with the double bounce configuration, resulting in an M^2 of 1.7×1.3 in the horizontal and vertical direction, respectively (figure 4).

Equations (1) and (6) show that TEM_{00} operation in the double bounce configuration is a function of the beam size, separation and grazing incidence angle inside the crystal. For large beam sizes, the overlap integral (see equations (1)) with the pump distribution is always larger for the TEM_{00} mode than for the higher order modes, even in the single bounce configuration (as shown in [1–3]), favouring therefore TEM_{00} mode oscillation. Our compact cavity uses spherical optics as opposed to cylindrical optics and therefore has much smaller beam diameters. Our results show that, in order to achieve a higher overlap integral in the TEM_{00} mode, a second pass through the cavity is necessary. This second pass needs to occur at a specific distance ΔD from the first pass (equation (6)), which is large enough to increase the overall width of both beams together to a point where there is not enough gain for the next higher mode to oscillate. On the other side, if the distance is too large, sufficient gain remains between both beams permitting the next higher order mode to oscillate. Experimentally this behaviour is easily noted: as the distance between the beams increases from almost total superposition to several millimetres, the beam changes from highly multimode to TEM_{00} and back to multimode. The highest output power during this procedure is obtained for the TEM_{00} mode (and not for multimode operation), close to the middle of the interval during which the double bounce cavity operates in TEM_{00}. This interval is about 0.5 mm at maximum pump power.

To further investigate this behaviour, we extended the left and right arms in figure 1 to 13 cm (distance from crystal centre to folding mirror) to permit large separation between both beams without clipping at the crystal border. For very small separations, diffraction effects due to the borders of the plane mirrors were observed. In this set-up, the cavity becomes unstable in the y-direction for pump powers above 11 W, whereas in the x-direction, the thermal lens is always longer than several metres [2]. We therefore operated the cavity at a

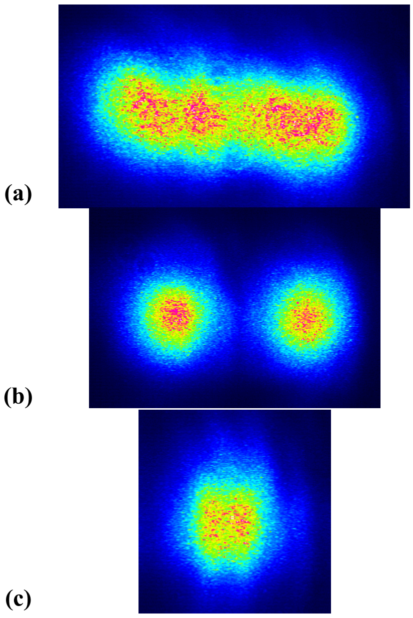

Figure 5. (a) Two multimode beams for a separation ΔD smaller than 0.6 mm. (b) Maximum output power for a separation larger than 0.6 mm and TEM_{00} mode operation. Both beams are shown. (c) Multimode operation for separations larger than 2.1 mm. Only one beam is shown because of limited CCD size.

constant pump power of 10 W. The images of the beams, shown in figure 5, were recorded with a CCD that was positioned behind the curved folding mirror.

For a separation below 0.6 mm, this cavity generated approximately 1 W of output power in the TEM_{10} mode. Above this distance, the output power increased up to 1.2 W in TEM_{00} mode. For a separation above 1.05 mm the cavity was again clearly in multimode (0.3 W of power), although this transition occurred very gradually.

A computer simulation was done to demonstrate the influence of the geometrical cavity parameters on the fundamental mode oscillation. Using a commercial finite element program (LASCAD), the index variation inside the crystal and the thermal deformation of the surface are calculated and fed to a MATLAB software program that makes the ray tracing and numerical simulation using the above theory. Pump absorption in the Nd:YVO_4 crystal, overlap between the pump and the two TEM_{00} laser beams and the steady-state inversion density for a TEM_{00} mode with 10% of the saturation intensity are shown in figure 6. The extension of the z-direction shown in the graphs corresponds to the dimension of the diode emission width at the crystal pump face.

In this simulation, which corresponds to figure 5(b), we assumed 10 W of pump power, grazing incidence angle of 5°, and a beam radius inside the crystal of 470 μm with the pump beam size matched in the y-direction. In figure 6(c) we can see that this configuration effectively removes the inversion at the crystal pump face up to a depth which corresponds to the total width of both beams together. Given the high absorption cross section of Nd:YVO_4, the remaining inversion deep inside the crystal is not enough to permit higher order mode oscillation, as is demonstrated by our experiment.

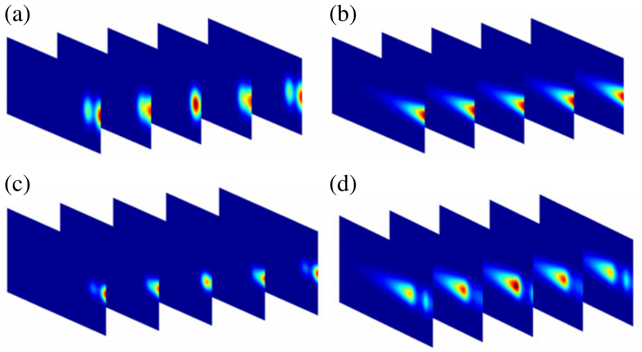

Figure 6. Five xy-slices of the diode-side pumped region of the crystal: (a) two TEM_{00} modes undergoing total internal reflection at the pump face, (b) pump absorption and (c) overlap with TEM_{00} modes, (d) steady-state inversion density for a TEM_{00} mode with 10% saturation intensity.

5. Conclusions

In this experiment, a high slope efficiency of 74% with 22 W of output power is achieved in single bounce configuration. With the double bounce configuration, we achieve 17 W and a significant improvement in beam quality resulting in an M^2 of 1.7 × 1.4 in the horizontal and vertical directions, respectively. This novel three mirror cavity is very compact, measures only 7.5 cm in length and is neither telescopic nor does it need cylindrical intracavity optics. It is also much less affected by changes in the thermal lens or the pump beam profile than the single bounce configuration.

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