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Operational characteristics of dual gain single cavity $Nd:YVO_4$ laser

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Abstract. Operational characteristics of a dual gain single cavity $Nd:YVO_4$ laser have been investigated. With semiconductor diode laser pump power of 2 W, 800 mW output was obtained with a slope efficiency of 49%. Further, by changing the relative orientation of the two crystals the polarization characteristics of the output could be varied. In particular by keeping the two $Nd:YVO_4$ crystals with their *c*-axes orthogonal to each other and adjusting the gain of the crystals so that both operate at approximately the same power level, completely unpolarized beams could be obtained.

Keywords. Dual gain single cavity laser; thermal lens; diode pumping; depolarization effect.

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1. Introduction

The scaling-up of diode laser pumped solid state lasers to high power is limited by the thermally induced fracture of the gain medium. One approach to overcome this limitation is the use of two similar crystals as gain media in a single laser cavity [1]. Since two crystals share the total pump power, the system is scalable to higher pump power. This approach also leads to higher extraction efficiency because the laser output from one crystal sees some gain at the other crystal which would otherwise have remain unextracted. Further, due to reduced thermal loading the pump power induced thermal aberrations and birefringence effects are less in dual gain systems which leads to better beam quality [2].

In this communication we describe the results of investigations on operational characteristics of a dual gain single cavity $Nd:YVO_4$ laser. With semiconductor diode laser pump power of 2 W, 800 mW output was obtained with a slope efficiency of 49%. Further, by changing the relative orientation of the two crystals the polarization characteristics of the output could be varied. In particular by keeping the two $Nd:YVO_4$ crystals with their *c*-axes orthogonal to each other and adjusting the gain of the crystals so that both operate at approximately the same power level, completely unpolarized beams could be obtained.

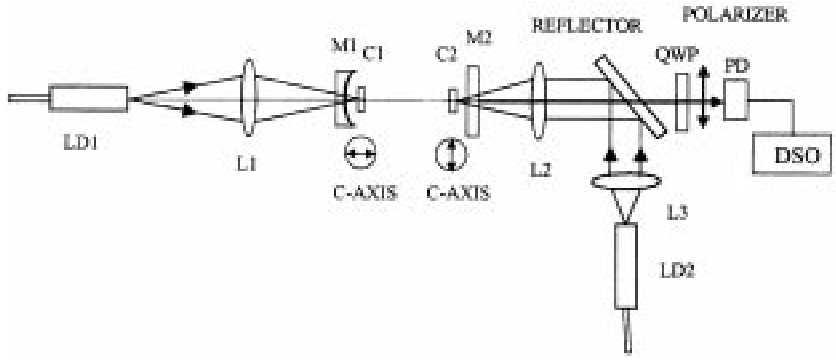

Figure 1. A schematic of the dual gain single cavity Nd:YVO_4 laser. Two fiber coupled laser diodes LD1 and LD2 were used. L1, L2 and L3 were the lenses, C1 and C2 were two 1 at. % doped 1 mm thick Nd:YVO_4 crystals with their *c*-axes orthogonal to each other. M1 was a curved mirror of ROC 80 mm with high reflection coating at the lasing wavelength 1064 nm and M2 is a flat coupler mirror with 5% transmission at the lasing wavelength. The reflector had high reflection coating (>98%) at the pump wavelength and AR coating at the laser wavelength. The quarter waveplate (QWP) and the polarizer combination were used to analyse the state of polarization of the output laser beam. The transmitted beam from the polarizer was detected with the help of a photo-diode (PD) after attenuation and displayed on a digital storage oscilloscope.

2. Experimental setup

A schematic of the laser cavity used in the experiment is shown in figure 1. The pump source consisted of two 1-W fiber coupled diode lasers (coherent F-81-1000C-SM-M). The wavelength of the maximum emission at 25°C for these were 808.7 nm and 809.0 nm respectively and the spectral width (FWHM) was 1.2 nm. The fiber tip had a diameter of 100 μm and a numerical aperture of 0.1. We shall refer to the pump source for crystal 1 as LD1 and that for crystal 2 as LD2. At the maximum operating current the spatial intensity profile of LD1 was circular in shape with a maximum at the center and a far field divergence (FWHM) of 7.34° in the horizontal and 6.66° in the vertical directions respectively. The spatial intensity profile of LD2 had a dip at the center with a symmetric far field divergence of 9°.

Since the quality of the pump beam (M^2-parameter) is an important parameter to optimize the overlap of the pump and cavity mode [3], the M^2 parameter and its variation with the laser diode power was measured by imaging method [4]. For this purpose a plano-convex lens of known focal length was used to image the diode laser beam and spot-sizes at several locations around the waist position were estimated by a knife-edge. Variation of the diode beam spot-size was plotted with distance from the secondary principal plane of the lens and the beam quality factor was estimated by least square fitting of the usual M^2 propagation law given by

$$\omega_p^2(z) = \omega_{p0}^2 \left\{ 1 + \left[\frac{\lambda_p M_p^2}{n\pi\omega_{p0}^2}(z - z_0) \right]^2 \right\}, \tag{1}$$

where ω_{p0} is the radius at the waist, λ_p the pump wavelength, M_p^2 the pump beam quality factor and z_0 the waist location from the focusing lens. The measured beam quality parameter for LD1 and LD2 were 17 and 20 at the maximum operating current. For LD1 we found that the M^2 parameter increases linearly from a value 17 to 20 as the power is decreased from 1 W to 0.2 W. This behavior is opposite to what one normally gets with bare diode lasers and may arise due to changes in diode laser output profile with current. For LD2, the M^2-parameter remained almost constant at 20 for the full power range. Also the divergence of the fiber coupled diode laser beam did not vary significantly with the variation of the diode laser power. Thus the focused pump spot-size at the gain medium can be assumed to remain almost constant as the output power of the fiber coupled laser diodes was varied by changing the diode laser current.

The laser cavity consisted of a curved mirror (M1) with radius of curvature 80 mm. This mirror was coated for high reflectivity at the lasing wavelength (1064 nm) and high transmission at the pump wavelength (808 nm). A Nd:YVO$_4$ crystal (C1) was placed close to this mirror. The output coupler mirror (M2) was a plane mirror having 5% transmission at the lasing wavelength and with AR coating for the pump wavelength. The second Nd:YVO$_4$ crystal (C2) was kept close to this mirror. Both the Nd:YVO$_4$ crystals were 1 mm thick and anti-reflection coated at the lasing wavelength. The Nd^{3+} concentration of the Nd:YVO$_4$ crystals were 1 at. %. Both the laser crystals were a-cut, which yielded a high gain π transition. The *c*-axis of the crystal C1 was kept horizontal whereas the *c*-axis of the crystal C2 was oriented orthogonal to that of crystal C1. The equivalent free space of the cavity is given by

$$L = L_{\mathrm{geo}} + l_{c1}\left(\frac{1}{n_{c1}} - 1\right) + l_{c2}\left(\frac{1}{n_{c2}} - 1\right), \tag{2}$$

where L_{geo} is the geometric cavity length, l_{c1} and l_{c2} are the lengths of the crystals C1 and C2, n_{c1} is the refractive index of Nd:YVO$_4$ for extra-ordinary beam and n_{c2} is the refractive index of Nd:YVO$_4$ for the ordinary beam. With the value of n_{c1} and n_{c2} as 2.165 and 1.957 respectively and $L_{\mathrm{geo}} = 23.3$ mm the calculated spot radius of the cavity mode were 130 μm at mirror M1 and 110 μm at the flat mirror M2. The pump beam from LD1 was re-imaged by a plano-convex lens L1 of 25 mm focal length onto the crystal C1 through the mirror M1, with a magnification of nearly 2. The focused spot radius at the crystal C1 was 108.6 μm. The pump beam from LD2 was collimated with the help of a plano-convex lens L3 of 25 mm focal length. This beam was reflected along the axis of the resonator with the help of a flat plate reflector kept at 45° to the pump beam direction. When this plate was kept at 45° to the propagation direction it reflected $>$99% at 808 nm and transmitted $>$90% at 1064 nm. The collimated beam from LD2 was focused onto the crystal C2 through the mirror M2 with the help of a plano-convex lens of focal length 50 mm to a focused spot radius of 106 μm. Both the crystals absorbed around 84% of the incident pump power. The overall losses by the coupling optics were not greater than 5%.

Efficiency of diode pumped solid state lasers also depends on the overlap of cavity mode and pumping geometry. The latter will get affected by thermal lensing [5]. Therefore thermal lensing needs to be estimated. For a fiber coupled laser diode, the thermal lens can be given by [6]

$$\frac{1}{f_{\text{th}}} = \int_0^l \frac{\xi P_{\text{abs}}}{4\pi K_c} \frac{\alpha e^{-\alpha z}}{1 - e^{-\alpha l}} \frac{\left(\frac{dn}{dt} + n\alpha_T\right)}{\omega_p^2(z)} dz, \tag{3}$$

where f_{th} is the thermal lens focal length, ξ the fractional thermal loading, K_c the thermal conductivity, P_{abs} the absorbed pump power, α the absorption coefficient at the pump wavelength, n the refractive index of the gain medium, dn/dT the thermal-optic coefficient of n, α_T the thermal expansion coefficient along the a-axis, l the crystal length and $\omega_p(z)$ the pump size in the active medium. The first and the second terms in the parenthesis of eq. (4) arise from the thermal dispersion and the axial strain, respectively. With the following parameters of the Nd:YVO_4 crystal [8]: $dn/dT = 3.0 \times 10^{-6}$/K, $n = 2.165$, $\alpha_T = 4.43 \times 10^{-6}$/K, $\xi = 0.24$, $K_c = 0.0523$ W/K-cm, $\omega_{p0} = 108$ μm, $M^2 = 17$ and $l = 1$ mm, focal length of the thermal lens varies from 1.2 meter for an absorbed pump power of 100 mw to 12 cm for an absorbed pump power of 1 W. With the two intracavity thermal lenses corresponding to the two laser crystals the mode radius at M1 varies from 130 μm to 110.6 μm and the mode radius at the flat mirror changes from 110 μm to 90 μm for a total absorbed pump power of 0 to 2 W. This shows a cavity mode to pump waist size ratio variation from 1.0 to 0.8 at M2 and 1.2 to 1.0 at M1.

The output laser beam was passed through a quarter wave plate (QWP) and an analyser to analyse the state of polarization of the laser beam. The c-axis of the quarter wave plate was kept at 45° to the c-axes of both the Nd:YVO_4 crystals.

3. Results and discussion

Figure 2 shows the slope efficiency curve obtained with only crystal C1 in the cavity. The pump power from laser diode (LD1) was varied by changing the diode current. The laser output power was measured with the help of a power meter and plotted with respect to the absorbed pump power. The absorbed pump power at the threshold was estimated by a linear fit to the experimental data. This configuration showed a slope efficiency of 66% with 146 mW absorbed pump power at the threshold. The threshold and efficiency values suggest that the performance of the cavity was optimized. The maximum power obtained from this single crystal laser was 430 mW at an absorbed pump power of 800 mW.

We show in figure 3 the slope efficiency curves for dual gain laser when only crystal 1 or crystal 2 was pumped. The laser beam from C1 pumped by LD1 (with LD2 off) is designated as laser 1 and that from C2 pumped by LD2 (with LD1 off) as laser 2. The absorbed pump power at the threshold for laser 1 was 200 mw with a slope efficiency of nearly 52.3% and laser 2 showed a slope efficiency of 42.6% with the absorbed pump power at the threshold of 112 mw. Though the focused pump spot-size at the two crystals are nearly the same, laser 1 and laser 2 show different thresholds. The reason for this is that the cavity mode sizes at crystals C1 and C2 are different. The reason for lower slope efficiencies obtained in dual gain configuration is the increased intra-cavity losses. Each of the Nd:YVO_4 crystal has 2% intrinsic loss at the lasing wavelength and also in this configuration the number of intra-cavity surfaces is increased. From figure 3 it can be seen that though laser 2 showed lower threshold, the slope efficiency is lower compared to laser 1. This is because the cavity mode size at C2 decreases as the pump power is increased which causes reduction in the overlap efficiency and consequently reduction in the value of slope efficiency.

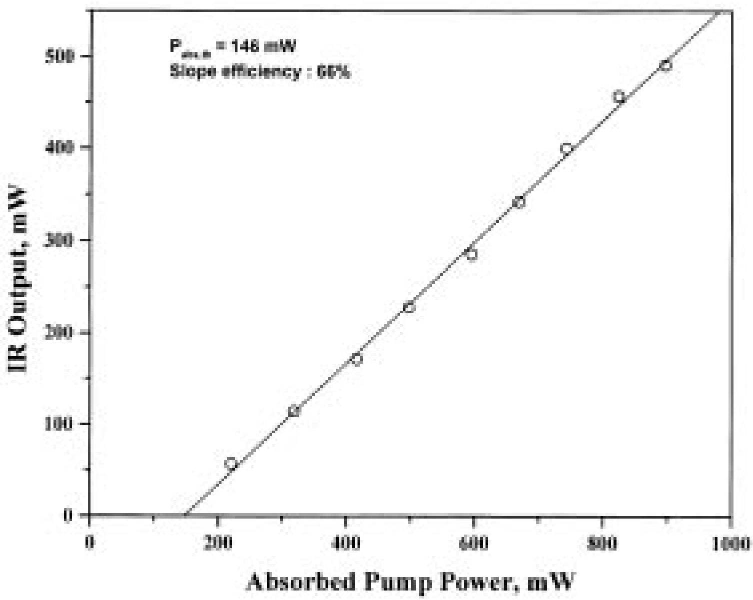

Figure 2. Slope efficiency curve of the laser with the crystal C1 only. The absorbed pump power at the threshold was 146 mW and the slope efficiency was 66%. Points are the experimental data and the solid line was the linear fit.

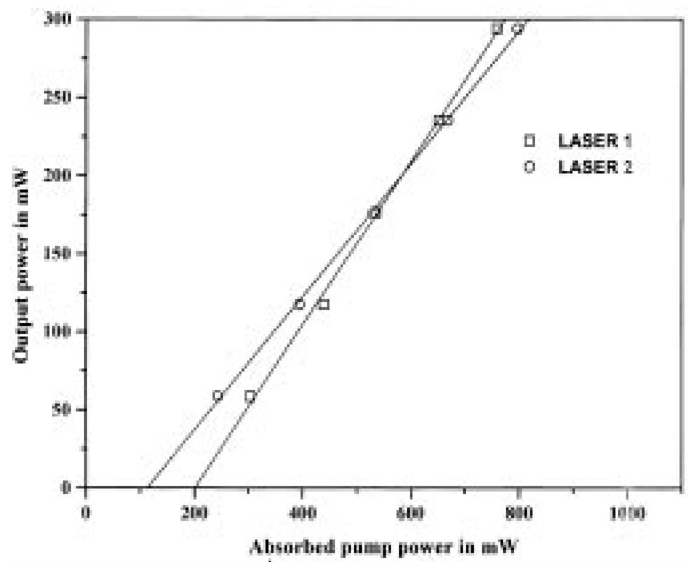

Figure 3. Slope efficiency curves for lasers when only crystal 1 or crystal 2 were pumped. Laser 1 showed a slope efficiency of 52.3% with the threshold at 200 mw and laser 2 showed a slope efficiency of 42.6% with a threshold of 112 mw.

In figure 4 we show the slope efficiency curve for laser output when both the laser crystals are pumped. The overall slope efficiency for the dual gain single cavity laser is 49.1%. For comparison the sum of the laser output power from individual gain is also plotted for the same amount of absorbed pump power. It is clear from figure 4 that the output power from combined laser is always higher than the sum of the individual laser powers. Since in our experiment the thermal loading for the Nd:YVO_4 crystals in dual gain configuration was the same and not lower than that for the single gain configuration, the contribution of the thermal population of the lower laser levels to the observed power enhancement is ruled out. The higher extraction efficiency for laser oscillation in our configuration arises because longitudinal modes in solid state lasers with birefringent intra-cavity elements are split into two orthogonal polarization modes [7] which are preferentially amplified either by crystals C1 or C2. The residual gain in one crystal will therefore be extracted by the laser beam from the other crystal. Even if gain in one of the crystals was kept below threshold, increase in output power was observed. The inset in figure 4 shows the variation of the ratio of power enhancement (ΔP) in the dual gain cavity with the sum of the individual laser power (P_{sum}) in case two crystals pumped separately with respect to the absorbed pump power. The relative power enhancement (G) is defined as

$$G = \frac{\Delta P}{P_{\mathrm{sum}}}. \tag{4}$$

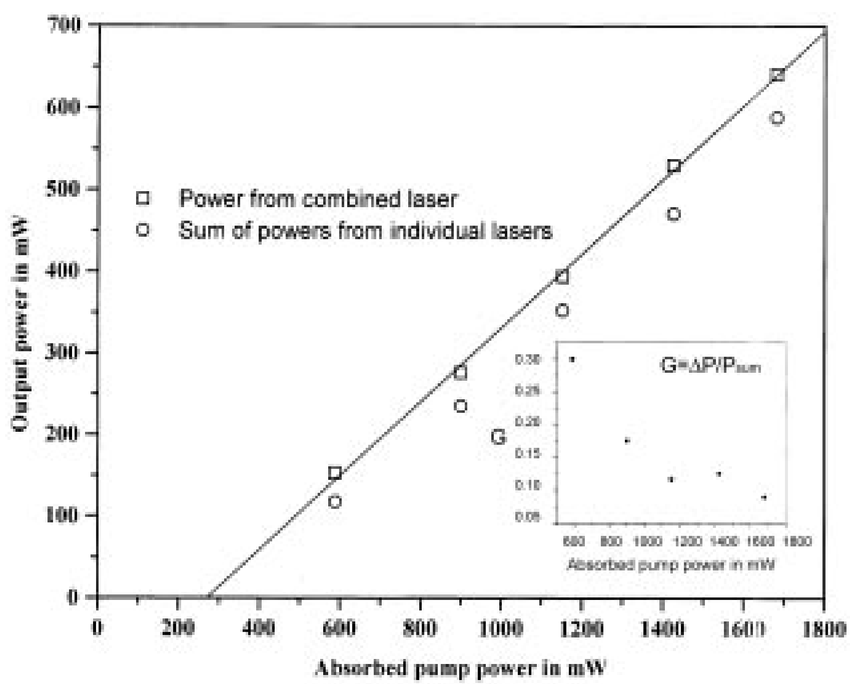

Figure 4. Comparison of power obtained from two crystal Nd:YVO_4 laser with the sum of the individual powers from laser 1 and laser 2 at the same amount of the absorbed pump power. Inset gives the variation of the ratio of power enhancement to the sum of the individual powers with the total absorbed pump power.

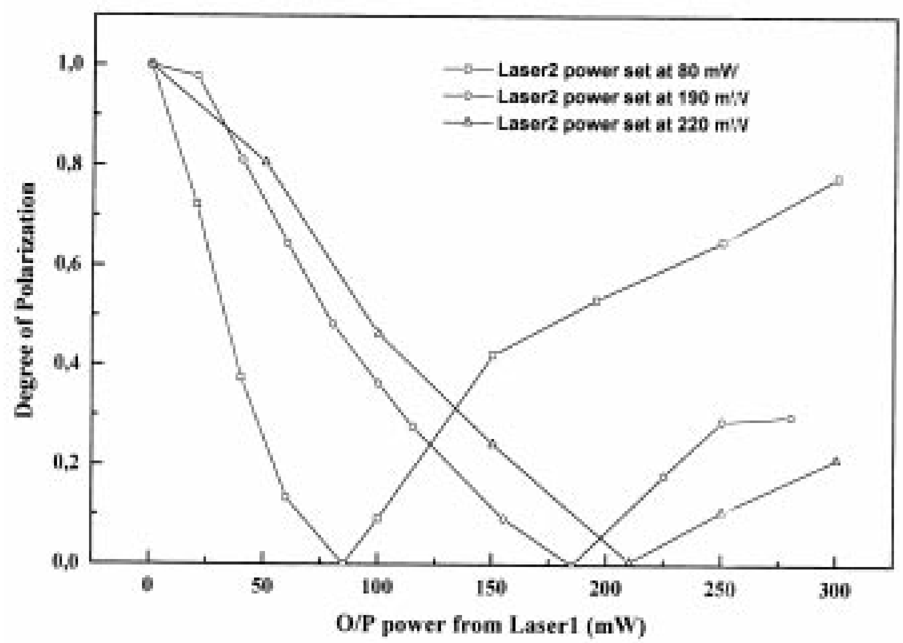

Figure 5. Depolarization of the output beam in the dual gain single cavity Nd:YVO_4 laser. Power from laser 2 was set at three different values. When laser 1 power is zero, output is linearly polarized with degree of polarization equal to unity. As laser 1 power increases, output becomes partially polarized and when both the powers become equal the output becomes totally unpolarized.

At lower absorbed pump power the power enhancement was 30% which saturated to a value less than 10% at the higher absorbed pump power. The maximum power obtained from this laser configuration is 800 mw at a total 2 W of the incident pump power.

Polarization state of the output laser beam from this dual gain laser was analysed with the help of a quarter wave plate (QWP) and an analyser. The latter had an extinction coefficient of $\sim 10^{-5}$ in crossed condition. The output from laser 1 and laser 2 were linearly polarized with polarization direction in the horizontal and the vertical directions respectively. This was further confirmed by inserting the QWP with its *c*-axis at 45° to the *c*-axes of the crystals. Both the laser beams became circularly polarized after passing through the QWP confirming that the output from the dual gain laser with only C1 or C2 pumped was orthogonally polarized. With gain in both the crystals the output beam becomes partially polarized and when gains for the two crystals are exactly equal then the output beam becomes totally unpolarized with a degree of polarization equal to zero. The degree of polarization (DOP) of the dual cavity laser was defined as

$$\mathrm{DOP} = \frac{P_{\max} - P_{\min}}{P_{\max} + P_{\min}}, \tag{5}$$

where $P_{\max}$ and $P_{\min}$ are the maximum and minimum power transmitted by the analyser. In figure 5 we show the degree of polarization of the output from the dual gain laser when the output power from one of the gain sections is varied. For this experiment the output power from laser 2 was adjusted to three different values of 80, 190 and 220 mw, and the output power from laser 1 was varied from 0 mw to 300 mw.

From figure 5 it is clear that DOP=1 when laser 1 power is zero. As the power of laser 1 is increased DOP decreases and when both the powers are equal the dual gain laser output is totally depolarized. To confirm that the beam is unpolarized a quarter wave plate (QWP) was inserted before the polarizer. If the beam was circularly or elliptically polarized, the QWP will transform it to a linearly polarized beam which will show a variation of transmission through the analyser with rotation across the beam. However, QWP had no effect on the transmission through the analyser as it was rotated across the beam confirming that the beam from the dual gain laser cavity was unpolarized when powers from laser 1 and laser 2 are equal. The observed polarization behavior is to be expected because the two gain laser was oscillating in orthogonally polarized mutually incoherent modes. The resulting polarization direction and the degree of polarization is therefore determined by the relative power of the two modes.

4. Conclusion

To conclude, our studies show that the two gain single cavity Nd:YVO_4 not only leads to higher extraction efficiency, but also provide an approach to control the polarization states of the output beam.

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