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High-power diode-end-pumped Nd:YVO$_4$ laser: thermally induced fracture versus pump-wavelength sensitivity

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Abstract. We report two kinds of compact and efficient diode-end-pumped TEM$_{00}$ lasers with output power > 25 W at ≈ 50 W of incident pump power. One laser consists of a single 0.3 at. % Nd:YVO$_4$ crystal in a V-type cavity, the other laser includes two 0.5 at. % Nd:YVO$_4$ crystals in a linear cavity. Experimental results show that lowering Nd^{3+} concentration can be beneficial in extending the fracture-limited pump power but it also increases the sensitivity of the pump wavelength due to the overlapping efficiency.

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Diode-end-pumped solid-state lasers with high beam quality and output power in the range of several tens of watts are rapidly becoming the preferred laser sources in numerous potential applications [1, 2]. Nd:YVO$_4$ crystal has been often used in diode-pumped lasers because of its large stimulated-emission cross section at lasing wavelength and its high absorption over a wide pumping wavelength bandwidth. However, power scaling with Nd:YVO$_4$ crystal has been greatly hindered by the thermally induced fracture [3, 4].

In a recent study [4], we found that the fracture-limited pump power for an end-pumped laser is inversely proportional to the absorption coefficient, i.e.,

$$P_{\mathrm{lim}} = \frac{1}{\alpha}\frac{4\pi R_{\mathrm{T}}}{\xi}\,, \tag{1}$$

where ξ is the fractional thermal loading, α is the absorption coefficient at the pump wavelength and R_{T} is the thermal shock parameter which depends on the mechanical and thermal properties of the host material. The absorption coefficient of the laser crystal linearly increases with increasing doping concentration. Therefore, lowering Nd^{3+} concentration can be beneficial in extending the fracture-limited pump power. In this letter, we demonstrate two kinds of compact and efficient diode-end-pumped Nd:YVO$_4$ lasers with TEM$_{00}$ output powers greater than 25 W at the pump power around 50 W. The laser setups are a V-type cavity with a 0.3 at. % Nd:YVO$_4$ crystal and a linear cavity with two 0.5 at. % Nd:YVO$_4$ crystals, respectively. Experimental results show that even though the output efficiency is rather similar for both laser setups, the sensitivity of the output power to the diode temperature is quite different. The difference is attributed to the fact that the dependence of the overlapping efficiency on the pump wavelength is more critical for a YVO$_4$ crystal with lower Nd^{3+} concentration.

1 Experiment

The pump power consists of two 30-W fiber-coupled diode-laser arrays (Coherent, FAP-81-30C-800-B) with the central wavelength of the lasers at 28 °C around 809 nm. The fibers were drawn into round bundles of 0.8-mm diameter and a numerical aperture of 0.2. The first cavity was a V-type resonator formed by two reflection mirrors M1 and M2, an output coupler and a 0.3 at. % Nd:YVO$_4$ crystal with 10-mm length, as shown in Fig. 1a. The mirror M1 was a 100-cm-radius-of-curvature concave mirror with antireflection coating at 809 nm on the entrance face and with high-reflection coating at 1064 nm and high-transmission coating at 809 nm on the second surface. The coating of the flat mirror M2 was the same as the mirror M1. The output coupler was a flat mirror with 85% reflection at 1064 nm. The total cavity length was around 80 mm. The second laser cavity was a linear cavity including an reflection mirror, an output coupler and two 0.5 at. % Nd:YVO$_4$ crystal with 6-mm length, as shown in Fig. 1b. The specifications of the mirror M3 and the output coupler are the same as those of M1 and the output coupler used in the first cavity, respectively. The total cavity length was also around 80 mm.

All laser crystals were a-cut to obtain the high-gain π transition and were wrapped with indium foil and mounted in water-cooled copper blocks. The water temperature was maintained at 20 °C. Both end surfaces of the Nd:YVO$_4$ crystal were antireflection coated for 1064 nm ($R < 0.2\%$). A focusing lens with 25-mm focal length and 85% coupling efficiency was used to re-image the pump beam into

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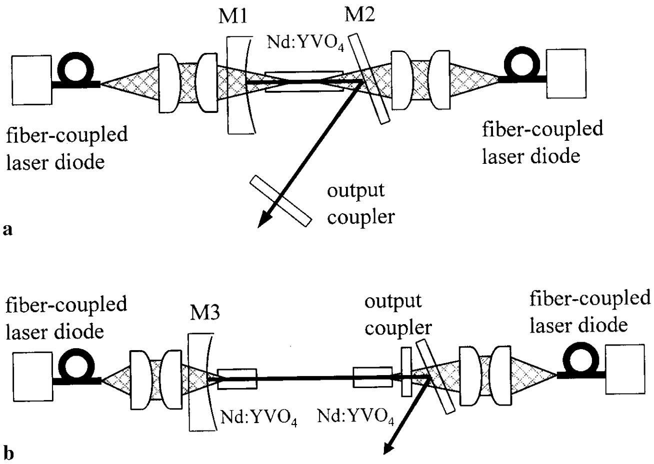

Fig. 1a,b. Schematic of diode-end-pumped experimental setup: **a** V-type cavity with a single 0.3 at. % Nd:YVO$_4$ crystal and **b** linear cavity with two 0.5 at. % Nd:YVO$_4$ crystals

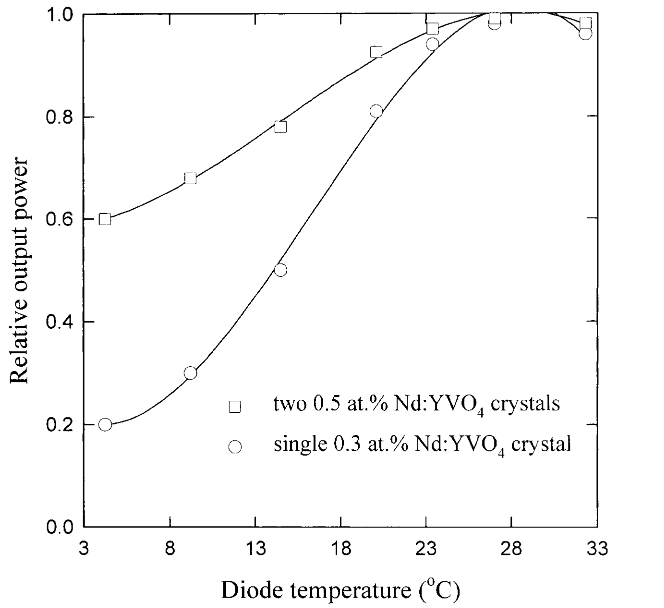

Fig. 3. Plot of dependence of the relative output power on the temperature of the laser diode

the laser crystal. The average pump-spot radius was around 320 μm. Considering the thermal effect, the TEM$_{00}$ radii at the Nd:YVO$_4$ crystal are found to be about 200–250 μm. In other words, the present mode-to-pump size ratio was around 0.6–0.8. Use of a mode-to-pump size ratio less than unity is based on the fact that a central portion of the highly aberrated thermal lens presents less loss to the TEM$_{00}$ mode [5].

Figure 2 shows the input–output characteristics for the present laser systems. It can be seen that the laser setup with two 0.5 at. % Nd:YVO$_4$ crystals has a lower threshold pump power and a slightly higher slope efficiency. With the linear cavity shown in Fig. 1b, the highest output power of 25.5 W was achieved at the total pump power of 48 W. However, experimental result shows that, once the incident pump power in any end exceeded around 25 W, the output power with two 0.5 at. % Nd:YVO$_4$ crystals immediately dropped, and output characteristics were not reproducible when the pump power was decreased. On the other hand, the highest output power in the cavity shown in Fig. 1a was 25.2 W at the maximum pump power of 52 W. No immediate damage of the laser crystal was observed in the experiment shown in Fig. 1a because the fracture-limited pump power of 0.3 at. % Nd:YVO$_4$ crystal exceeded the available pump power. The output beam quality was nearly the same for both laser cavities and the M^2 parameter has been estimated to be < 1.3 over the complete output power range with the algorithms of knife-edge technique [6]. According to the present result, it is possible to scale the output power to 50 W with two 0.3 at. % Nd:YVO$_4$ crystals pumped from both ends with total pump power of ≈ 100 W. Recently, a composite crystal structure [3], which is fabricated by diffusion-bonding a doped crystal to an undoped piece of the same cross section, was used to reduce the thermally induced stress. We believe that higher output power with better beam quality can be achieved with a composite crystal structure.

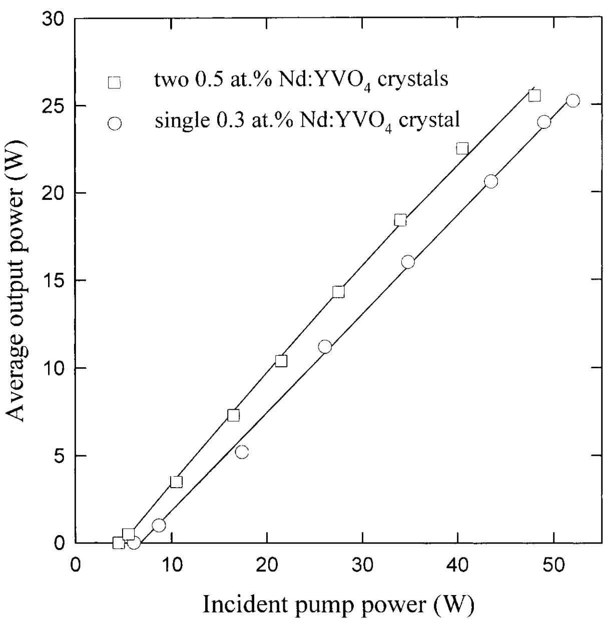

Fig. 2. Plot of the input–output characteristics for the present laser setups

Since the emission wavelength of the laser diode varies with its junction temperature at a rate: $\Delta\lambda/\Delta T \cong 0.3\,\text{nm}/°\text{C}$, a few degrees change can scan the absorption band of the present laser systems. We have measured the output power as a function of the diode temperature in a range of about 30 °C, i.e., about 9 nm around the optimum wavelength. The output powers relative to the optimum result at 27 °C are displayed in Fig. 3. It is seen that the sensitivity of the output power is quite different for both laser setups. As analyzed later, we believe that this difference arises from the dependence of the overlapping efficiency on the pump wavelength.

2 Analysis

Even though lowering the absorption coefficient can extend the fracture-limited pump power in end-pumped lasers, the efficiency in the TEM$_{00}$ mode may be reduced because of a poorer overlapping efficiency. On the basis of spacedependent rate equation analysis, the slope efficiency S_e are given by [7]

$$S_e = \frac{T}{T+L}\eta_Q\left(\frac{\lambda_p}{\lambda_l}\right)\eta_o\ , \quad (2)$$

where T is the power transmission of the output coupler, η_Q is the quantum efficiency, and L denotes the round-trip cavity excess losses which include thermally induced diffraction losses, nondiffraction round-trip losses such as scattering at interfaces, imperfect reflection, and excited-state absorption. If concentration quenching is not significant, the quantum efficiency η_Q is almost equal to unity. The overlapping efficiency η_o are given by [7]

$$\eta_o = \frac{\left(\iiint s_l(x,y,z) r_p(x,y,z)\,\mathrm{d}\nu\right)^2}{\iiint s_l^2(x,y,z) r_p(x,y,z)\,\mathrm{d}\nu}\ , \quad (3)$$

where $r_p(x,y,z)$ is the normalized pump intensity and $s_l(x,y,z)$ is the normalized cavity mode intensity distribution. The beam profile of a fiber-coupled laser diode, $r_p(x,y,z)$, can be approximately described as a top-hat distribution [5]:

$$r_p(x,y,z) = \frac{\alpha\,\mathrm{e}^{-\alpha z}}{\pi\omega_p^2(z)[1-\mathrm{e}^{-\alpha l}]}\Theta(\omega_p^2(z)-x^2-y^2)\ , \quad (4)$$

where $\omega_p(z)$ is the pump size in the active medium, and $\Theta()$ is the Heaviside step function. Using the usual M^2 propagation law, the pump size is given by

$$\omega_p^2(z) = \omega_{po}^2\left\{1+\left[\frac{\lambda_p M_p^2}{n\pi\omega_{po}^2}(z-z_o)\right]^2\right\}\ , \quad (5)$$

where ω_{po} is the radius at the waist, λ_p is the pump wavelength, M_p^2 is the pump beam quality factor, and z_o is focal plane of the pump beam in the active medium. For a single transverse mode TEM_{00}, $s_l(x,y,z)$ can be given by

$$s_l(x,y,z) = \frac{2}{\pi\omega_l^2(z)l}\exp\left(-2\frac{x^2+y^2}{\omega_l^2(z)}\right)\ , \quad (6)$$

and

$$\omega_l(z) = \omega_o\sqrt{1+[(z-z_l)\lambda_1/\pi\omega_o^2]^2} \approx \omega_o\ . \quad (7)$$

Here ω_o is the beam waist of the laser mode, z_l is the position of the beam waist, and the point $z=0$ is taken to be the incident surface of the active medium. Substituting (4) and (6) into (3), the overlapping efficiency η_o can be expressed as

$$\eta_o = \frac{F(\alpha,\omega_o)^2}{F(\alpha,\omega_o/\sqrt{2})}\ , \quad (8)$$

and

$$F(\alpha,\omega_o) = \frac{1}{2}\frac{\alpha}{1-\mathrm{e}^{-\alpha l}}\int_o^l\left(\frac{\omega_o}{\omega_p(z)}\right)^2 \times\left[1-\exp\left(-\frac{2\omega_p(z)}{\omega_o}\right)^2\right]\mathrm{e}^{-\alpha z}\,\mathrm{d}z\ . \quad (9)$$

To investigate the concentration dependence of the overlapping efficiency, we have measured the absorption coefficient for *a*-cut 0.3 and 0.5 at. % $Nd:YVO_4$ crystals with Lambda 900 spectrometer. The lengths used in the measurement are 10 and 6 mm for 0.3 and 0.5 at. % $Nd:YVO_4$ crystals. Since the light source in the spectrometer was unpolarized, the measured absorption spectra were the combination of absorption spectra in the π and σ components of the $Nd:YVO_4$ crystal. The present results are practically useful because the pump source from a fiber-coupled laser diode is unpolarized. With the measured spectra, the absorption coefficients were deduced from the exponential law of absorption and shown in Fig. 4. It is seen that the amplitude is proportional to the doping concentration, and the observed structure and peak positions are insensitive to the doping concentration.

Even though a longer crystal can be used to increase the absorption efficiency for a lower doping concentration, the overlapping efficiency may become poorer because of the divergence of the pump beam. Applying the measured absorption coefficients to (8) and (9), we calculated the dependence of the overlapping efficiency on the diode temperature for the present cavities. The cavity mode size was determined by the ABCD matrix approach with the thermal lensing effect. For a fiber-coupled laser diode, the thermal lens is given by [1, 8]

$$f_{th}^{-1} = \int_0^l \frac{\xi P_{abs}}{4\pi K_c}\frac{\alpha\,\mathrm{e}^{-\alpha z}}{1-\mathrm{e}^{-\alpha l}}\frac{[\mathrm{d}n/\mathrm{d}T+(n-1)\alpha_T]}{\omega_p^2(z)}\,\mathrm{d}z\ , \quad (10)$$

where ξ is the fractional thermal loading, K_c is the thermal conductivity, P_{abs} is the absorbed pump power, $\mathrm{d}n/\mathrm{d}T$ is the thermal-optic coefficients of n, α_T is the thermal expansion coefficient along the *a* axis. The parameters used in the calculation are as follows: $\xi = 0.24$, $\omega_{po} = 0.32$ mm, $M_p^2 \approx 310$, $K_c = 0.0523$ W/K cm, $\mathrm{d}n/\mathrm{d}T = 3.0\times10^{-6}$ /K, $\alpha_T = 4.43\times10^{-6}$ /K, and $n = 2.165$. The value of z_o was

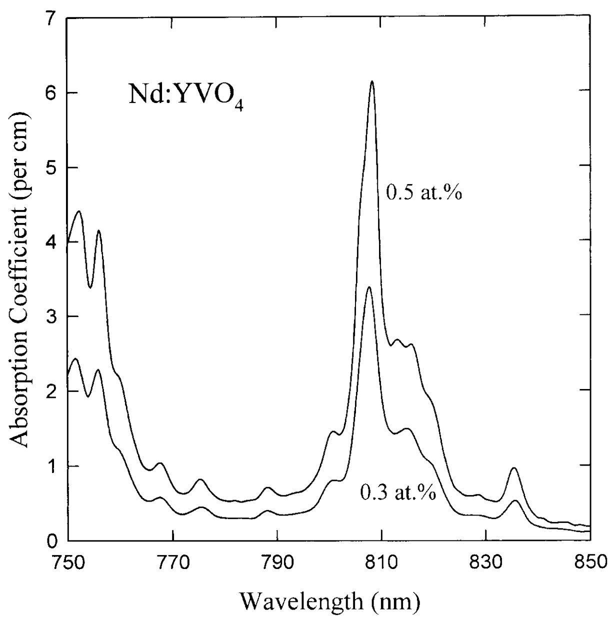

Fig. 4. The absorption coefficient for unpolarized light as a function of the incident wavelength for 0.3 and 0.5 at. % $Nd:YVO_4$ crystals

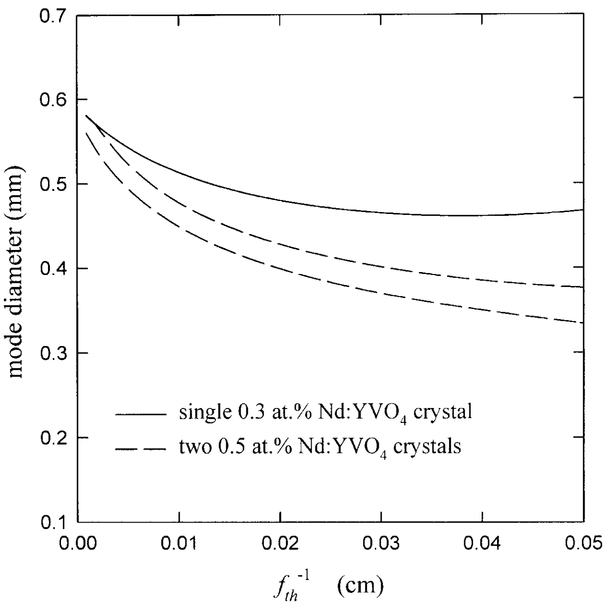

Fig. 5. Calculation result for the influence of thermal lens on the cavity mode diameter

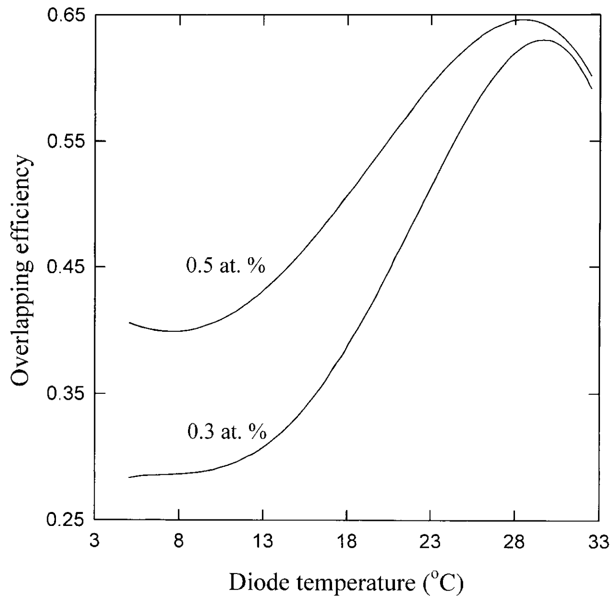

Fig. 6. The theoretical analysis for the dependence of the overlapping efficiency on the temperature of the laser diode

found to be 2.5 and 2 mm for 0.3 and 0.5 at. % Nd:YVO_4 crystals under the condition of the optimum result. Figure 5 shows the calculation result for the influence of thermal lens on the cavity mode diameter. It can be seen that the mode diameter in resonator shown in Fig. 1a is slightly larger than that in resonator shown Fig. 1b due to the cavity structure and the thermal lensing effect. Even so, the mode size is weakly sensitive to the thermal lens for most of the pump-power range studied here. Figure 6 shows the dependence of the overlapping efficiency on the diode temperature for 0.3 and 0.5 at. % Nd:YVO_4 crystals. It can be found that the dependence is in agreement with the result shown in Fig. 3.

3 Conclusion

We have demonstrated two types of compact and efficient TEM_{00} Nd:YVO_4 lasers with output power greater than 25 W. We utilized the YVO_4 crystals with low doping concentrations to avoid the thermally induced fracture. One laser was to use a single 0.3 at. % Nd:YVO_4 crystal in a V-type cavity and the other laser was to use two 0.5 at. % Nd:YVO_4 crystals in a linear cavity. From the experimental results it can be concluded that even though there is substantial scope for further power scaling of end-pumped Nd:YVO_4 lasers with low Nd concentrations, the temperature regulation of the laser diode becomes severe because of the overlapping efficiency.

References

1. S.C. Tidwell, J.F. Seamans, M.S. Bowers, A.K. Cousins: IEEE J. Quantum Electron. **QE-28**, 997 (1992)
2. J. Machlan, R. Moyer, D. Hoffmaster, J. Zamel, D. Burchman, R. Tinti, G. Holleman, L. Marabella, H. Injeyan: Technical. Digest, ASSL, OSA, 262 (1998)
3. M. Tsunekane, N. Taguchi, T. Kasamatsu, H. Inaba: IEEE J. Select. Top. Quantum Electron. **3**, 9 (1997)
4. Y.F. Chen: IEEE J. Quantum Electron. **QE-35**, 234 (1999)
5. Y.F. Chen, T.M. Huang, C.F. Kao, C.L. Wang, S.C. Wang: IEEE J. Quantum Electron. **QE-33**, 1424 (1997)
6. A.E. Siegman, M.W. Sasnett, T.F. Johnston, Jr.: IEEE J. Quantum Electron. **QE-27**, 1098 (1991)
7. P. Laporta, M. Brussard: IEEE J. Quantum Electron. **QE-27**, 2319 (1991)
8. C. Pfistner, R. Weber, H.P. Weber: IEEE J. Quantum Electron. **QE-30**, 1605 (1994)