# A High-Power Continuous-Wave Laser-Diode End-Pumped Nd:$YVO_4$ Laser of Single-Frequency Operation *

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*We design and build a cw high quality and high power Nd:$YVO_4$ laser of single frequency operation with a laser-diode dual-end-pumped geometry. The influence of the $Nd^{3+}$-doping concentration in the Nd:$YVO_4$ crystal on the output performance of laser is theoretically and experimentally studied. With a Nd:$YVO_4$ crystal of the $Nd^{3+}$-doping concentration 0.3 at.% and at pump power of 45 W, the output power of the single frequency laser is 18 W, and the slope efficiency is 48%.*

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Diode-pumped solid-state lasers are compact, reliable and high efficient sources of coherent radiation. High power stable single-frequency lasers are applied for high-precision laser-based metrology and spectroscopy. The Nd:$YVO_4$ crystal has often been used in diode-end pumped lasers[1,2] owing to its high absorption coefficient over a wide pumping wavelength bandwidth, large simulated emission cross section at the lasing wave, and production of polarized laser output.[3.4] Because of the poor thermal conductivity of the Nd:$YVO_4$ crystal, a large amount of thermal energy arises from the absorbed pump power accumulated near the pump region for the end-pumped geometry. The effect of thermal induced higher order spherical aberration on extraction efficiency and output beam quality depends on the complicated interaction of many resonator parameters. The mode size optimization in end-pumped lasers has been investigated by several researchers.[5,6] We notice that the thermal effects are related to the $Nd^{3+}$-doping concentration of laser crystals. It is useful to optimize the $Nd^{3+}$-doping concentration of Nd:$YVO_4$ crystals to obtain high quality and high power lasers at high pump power.

In this study, we design and build up a cw high quality and high power Nd:$YVO_4$ laser of single frequency operation with a laser-diode dual-end-pumped geometry. Based on investigating the influence of the $Nd^{3+}$-doping concentration of Nd:$YVO_4$ crystals on the output performance of the laser, the characteristics of the laser output are studied and the optimum $Nd^{3+}$-doping concentration is experimentally chosen.

The experimental setup of the cw high power Nd:$YVO_4$ laser of single frequency operation is shown in Fig. 1. The ring resonator with two concave mirrors and four plane mirrors was designed with a fibre-coupled laser-diode dual-end-pumped geometry.

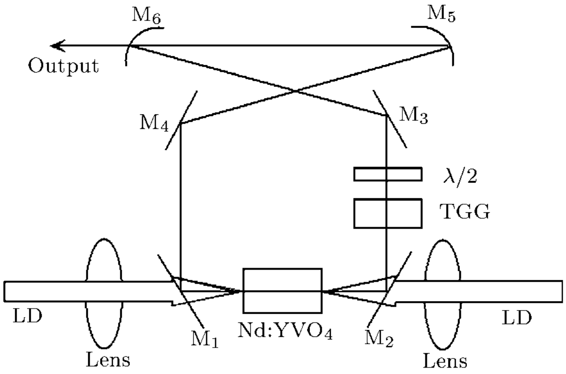

**Fig. 1.** Experimental setup of the cw high power Nd:$YVO_4$ laser of single frequency operation with a laser-diode dual-end-pumped geometry.

In the case of the laser-diode end-pumped geometry, it is easy to control the laser to be operated on the $TEM_{00}$ mode. The laser intensity inside the cavity is far above the saturation intensity when the pump power is higher. The laser output power and the threshold pump power can be written by[7,8]

$$P_{\rm out} = \eta_{abs}\eta_t\eta_Q \frac{\lambda_p}{\lambda}\frac{T}{\delta}\frac{m^2(m^2+2)}{(1+m^2)^2}(P_{in}-P_{th}), \tag{1}$$

$$P_{th} = \frac{\pi I_{\rm sat}\delta(\omega_{pa}^2+\omega_l^2)}{4\eta_{abs}\eta_t\eta_Q\lambda_p/\lambda}, \tag{2}$$

where $\lambda_p$ is the pump laser wavelength, $\lambda$ is the laser wavelength, $\omega_{pa}$ is the average radius of pump beam, $\omega_l$ is the radius of laser beam, $m=\omega_l/\omega_{pa}$; $I_{\rm sat}$ is the saturation intensity, $P_{in}$ is the output power of laser-diode, $\eta_t$ is the optical transfer efficiency of pump beam, and $\eta_Q$ is the quantum efficiency that is related

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** To whom correspondence should be addressed. Email: kuanshou@sxu.edu.cn to the $Nd^{3+}$-doping concentration of the laser crystal and can be written as[9]

$$\eta_Q = \frac{1}{1+(\rho/\rho_0)^6},$$

where $\rho$ is the $Nd^{3+}$-doping concentration in units of atomic percentage; $\rho_0 = 3.5\,\text{at.\%}$; $\eta_{abs} = 1-\exp(-\alpha l)$ is the absorption efficiency of pump radiation with $\alpha$ and $l$ being the absorption coefficient and the length of the Nd:$YVO_4$ crystal. It should be noticed that it is difficult to give an exact expression for the relationship between the $Nd^{3+}$-doping concentration and the absorption coefficient of the Nd:$YVO_4$ crystal because both are related to the fabrication procedure of the crystal and test methods. We can approximately give $\alpha = C \times \rho^b$ ($\text{cm}^{-1}$). In our experiment, the fibre-coupled laser diode is in partial polarization with the wavelength of 808 nm, $b = 0.96$, and $C = 10.5$ was obtained experimentally. Inside the resonator the round-trip loss $\delta = T + \delta_f + \delta_d$, where $T$ is the transmissivity of the output coupler, $\delta_f$ is the nondiffraction round-trip losses (such as impurity absorption and scattering at interfaces), and $\delta_d$ is the diffraction loss due to the thermally induced spherical aberration and can be calculated by[10]

$$\delta_d = 1 - \left|\frac{\int_0^{r_b} e^{i\Delta\varphi(r)} e^{-2r^2/\omega_l^2} r\,dr}{\int_0^{r_b} e^{-2r^2/\omega_l^2} r\,dr}\right|^2, \qquad (3)$$

where $r_b$ is the laser rod radius and the phase shift $\Delta\varphi$ induced by the wave aberration is given by

$$\Delta\varphi(r) = \frac{\frac{dn}{dT}\xi P_{in}\eta_{abs}\eta_t\eta_Q}{K_c\lambda}\Big(1+\ln\frac{r_b^2}{\omega_{pa}^2}\Big), \ (r^2 \le \omega_{pa}^2),$$

$$\Delta\varphi(r) = \frac{\frac{dn}{dT}\xi P_{in}\eta_{abs}\eta_t\eta_Q}{K_c\lambda}\Big(\frac{r^2}{\omega_{pa}^2}+\ln\frac{r_b^2}{r^2}\Big), \ (r^2 \ge \omega_{pa}^2), \qquad (4)$$

where $dn/dT$ is the thermal dispersion, $\xi$ is the fraction of the absorbed pump power converted to the heat, $K_c$ is the heat conductivity.

Figure 2 shows a plot of the dependence of the thermally-induced diffraction loss on the pump power for several $Nd^{3+}$-doping concentrations and $m = 1$. It can be noticed that thermally-induced diffraction loss will increase with increasing pump power and increasing $Nd^{3+}$-doping concentration.

Obviously, it can be noticed that the thermally-induced diffraction loss could be improved by using lower $Nd^{3+}$-doping concentration and lower pump power. However, the power conversion efficiency is generally greater for the Nd:$YVO_4$ crystal with higher $Nd^{3+}$-doping concentration because of its higher absorption coefficient. Therefore, an optimum $Nd^{3+}$-doping concentration exists for the high power Nd:$YVO_4$ laser.

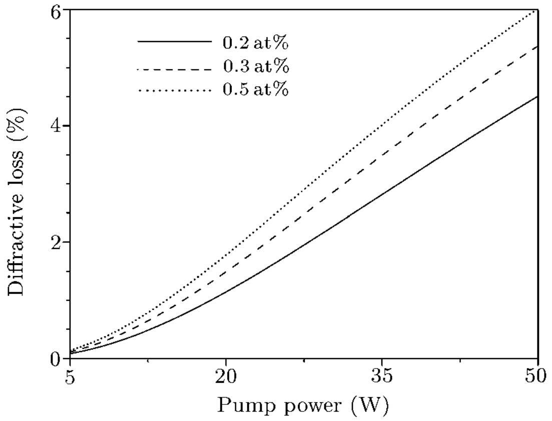

**Fig. 2.** Dependence of the thermally-induced diffraction loss on the pump power for several $Nd^{3+}$-doping concentrations with $m = 1$.

In the experiment of the cw high power Nd:$YVO_4$ laser of single frequency operation we designed and built, the pump sources were two 25 W fibre-coupled laser-diodes with central wavelength of 808 nm by controlling the temperature of laser-diode. The diameter of coupled fibre is 800 $\mu$m and the numerical aperture is 0.20. Laser-diode beam was focused to the Nd:$YVO_4$ crystal by the collimation and focus system with $\eta_t = 85\%$. The temperature of the Nd:$YVO_4$ crystal was controlled by a home-made temperature controller with the precision of 0.01°C. The size of the a-cut Nd:$YVO_4$ crystal was 3 mm×3 mm×6 mm. Both the end faces of the Nd:$YVO_4$ crystal were antireflection coated at 1.064 $\mu$m and 808 nm. The ring cavity mirrors of $M_1$ and $M_2$ were 45-deg plane input couplers with antireflection at 808 nm and high reflection at 1.064 $\mu$m, $M_3$ and $M_6$ were 45-deg mirrors with high reflection at 1.064 $\mu$m, $M_5$ was a 0-deg concave mirror with high reflection at 1.064 $\mu$m, $M_4$ was a 0-deg concave output coupler with the transmission of 18.5% at 1.064 $\mu$m. The radius of both the concave mirrors was 100 mm. The optical length between the two concave mirrors was 98 mm and the rest optical length of the resonator was 480 mm. Such a kind of design could make the resonator stable condition of $|A+D| \le 2$ and the mode matching between the pump beam and laser beam to be satisfied. Using an optical diode formed by a TGG crystal and a half-wave-plate in the resonator, high power Nd:$YVO_4$ laser of single frequency operation could be obtained. Three pieces of the Nd:$YVO_4$ crystal with the $Nd^{3+}$-doping concentration of 0.2 at.%, 0.3 at.% and 0.5 at.% were used to build the high power Nd:$YVO_4$ laser of single frequency operation. The relation between the laser output power and the pump power is shown in Figs. 3(a), 3(b), and 3(c). The squares represent the experimental data and the solid lines denote the theoretical prediction using Eqs. (1)–(4) with the experimental parameters. Obviously, the experimental results were in good agreement with the theoretical predictions.

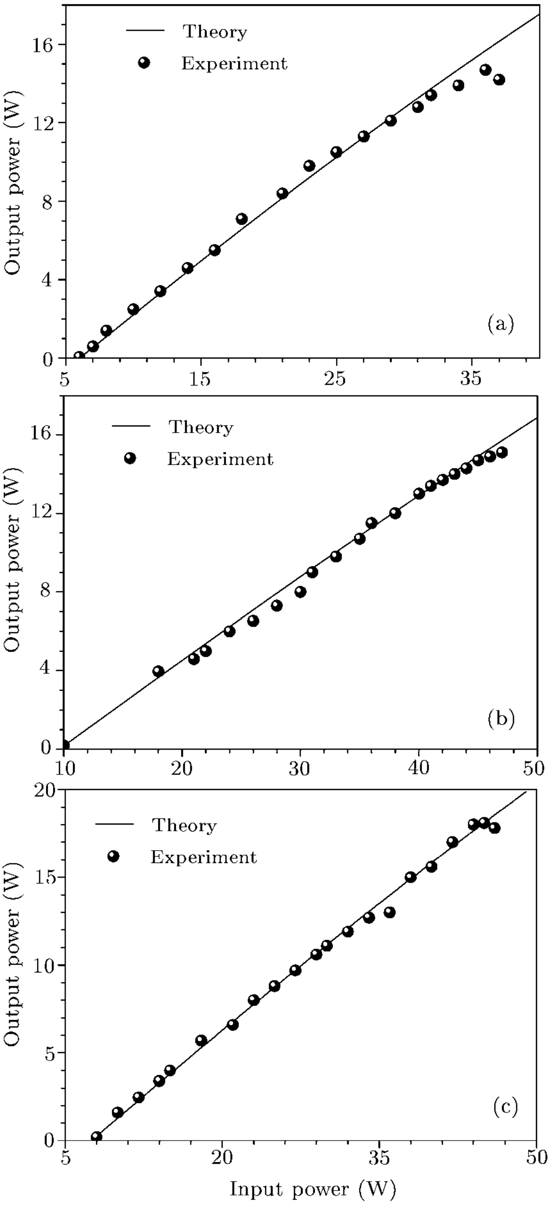

**Fig. 3.** The laser output power versus pump power: (a) $\rho = 0.5$ at.%, (b) $\rho = 0.2$ at.%, (c) $\rho = 0.3$ at.%.

When the Nd:YVO$_4$ crystal with the Nd$^{3+}$-doping concentration 0.5 at.% was used, the maximum output power was obtained to be 14.7 W at the 35 W pump power, the threshold pump power was 6 W and the slope-efficiency was 50%. When the pump power was more than 35 W, the output power dropped because of the thermal fracture limit. When the Nd:YVO$_4$ crystal with the Nd$^{3+}$-doping concentration 0.2 at.% was used, the maximum output power was obtained to be 15.1 W at the maximum pump power 47 W, the threshold pump power was 9 W and the slope-efficiency was 42%. No thermal fracture limit was observed. When the Nd:YVO$_4$ crystal with the Nd$^{3+}$-doping concentration 0.3 at% was used, the maximum output power was obtained to be 18 W at the 45W pump power, the threshold pump power was 7.5 W and the slope-efficiency was 48%. When the pump power was more than 45 W, the output power also dropped because of the thermal fracture limit. At the output power of 15 W, the laser frequency was monitored by a confocal F-P cavity, and the transmission intensity of the F-P cavity is shown in Fig. 4. It is shown that the laser was in single-frequency operation and the frequency shift of the laser output was 60 MHz (1 min). Figure 5 shows the measured laser output power stability that is better than 1% (more than 4 hours). When the laser output was attenuated by an attenuator, the beam quality factor was measured by a beam propagation analyser (Modemaster) from Coherent Inc. and the $M^2$ of the laser output beam was 1.05.

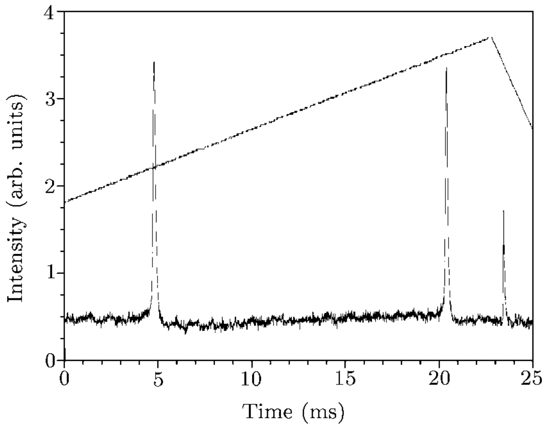

**Fig. 4.** Transmission intensity of the confocal F-P cavity.

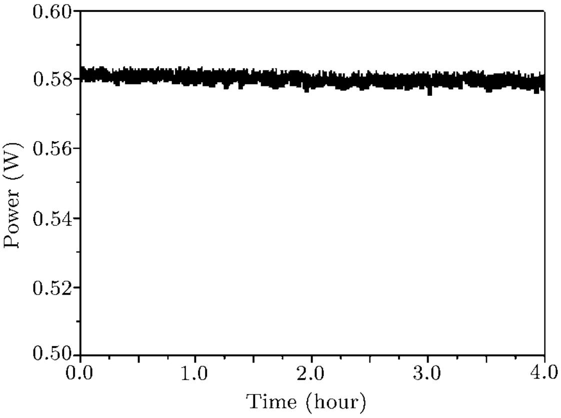

**Fig. 5.** The measured laser output power stability.

In conclusion, we have designed and built a cw high quality and high power Nd:YVO$_4$ laser of single frequency operation with a laser-diode dual-end-pumped geometry. The influence of the Nd$^{3+}$-doping concentration in the Nd:YVO$_4$ crystal on the output performance of the laser is theoretically investigated The characteristics of the laser output is experimental studied using three pieces of Nd:$YVO_4$ crystals with the $Nd^{3+}$-doping concentration of 0.2 at.%, 0.3 at.% and 0.5 at.%. The experimental results were well agreement with the theoretical predictions. In our experiment, the optimum $Nd^{3+}$-doping concentration was 0.3 at.%, and at the pump power 45 W, the output power of single frequency laser is 18 W, and the slope-efficiency is 48%.

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