Design of efficient high-power diode-end-pumped TEMoo Nd:YVO$_4$ laser

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ABSTRACT

A systematic investigation on a series of Nd:YVO$_4$ crystals with different dopant concentrations is conducted to scale the diode-end-pumped laser performance to higher powers. The analysis reveals that lowering the dopant concentration linearly extends the fracture-limited pump power and the thermal shock parameter plays an important role in the estimation of the fracture-limited pump power. The thermal shock parameter in Nd:YVO$_4$ crystals has been determined from the laser experiments. Based on the analysis, we demonstrate a compact and efficient diode-end-pumped TEMoo laser with output power of25.2-W for 52-W of incident pump power by use of a single YVO4 crystal with a Nd concentration of 0.3 at.%. In Q-switched operation 21-W of average power at a pulse repetition rate of 100 kHz and ~1.1-m pulse energy at a pulse repetition rate of 10 kHz were produced.

Keyword: thermal fracture, end-pumped, Nd-doped laser, Q-switched

INTRODUCTION

Diode-pumped solid-state lasers with high beam quality and output power in the range of several tens watt are rapidly becoming the preferred laser sources in micromachining applications [1]. However, progress in power scaling of TEMoo operation has been limited by thermal fracture of the laser crystal [2]. Nowadays, the avoidance of thermally induced fracture plays a key role in laser design. The Nd:YVO$_4$ crystal has been often used in diode- end-pumped lasers owing to its high absorption over a wide pumping wavelength bandwidth and large stimulated emission cross-section at the lasing wavelength. Unfortunately, the thermal shock parameter of Nd:YVO$_4$ is ~3 times lower than that of Nd:YAG. Therefore, the maximum output power of Nd:YVO$_4$ is usually several times lower than that of Nd:YAG. For a conventional 1.0 at %

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Nd:YVO$_4$ crystal, the maximum output power limited by thermal fracture is approximately 6-W for one-end pumping. On the other hand, Tidwell et al. [3] Estimated that the fracture-limited pump power for Nd;YAG is around 50~70W. In our recent study [4], we found that the fracture-limited pump power, P_{lim}, for an end-pumped laser is inversely proportional to the absorption coefficient

$$P_{abs,\lim} = \frac{1}{\alpha}\frac{4\pi R}{\xi} \tag{1}$$

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 the dopant concentration. Experimental results show that the absorption coefficient of Nd:YVO$_4$ crystals, α, for a typical laser diode with the center wavelength of 808nm is given by

$$\alpha = 20 \cdot N_d \tag{2}$$

where Nd is the Nd dopant concentration on the unit of atomic %. In other words, lower Nd^{+3} concentrations can be beneficial in extending the fracture-limited pump power. Even though lowering dopant concentrations can extend the fracture-limited pump power, the efficiency in the TEMoo mode may be reduced because of a poorer overlapping efficiency. Therefore, a good laser design must integrate these factors to obtain the optimum concentration for scaling the output power at high beam quality. Our theoretical analysis shows that the dopant concentration in Nd:YVO$_4$ crystal must be larger than 0.25 at.% to obtain a slope efficiency in TEMoo mode higher than 45%. In this letter, we demonstrate an efficient diode-pumped Nd:YVO$_4$ laser with a cw TEMoo output of >25-W by use of a Nd concentration of 0.3 at.%. The performance in Q-switched operation of this laser is also reported.

Figure 1 is a schematic of the three-mirror laser cavity utilized in the experiment. The pump power consists of two 30-W fiber-coupled diode-laser arrays (FAP-81-30C-800-B) with the output wavelength of the lasers at 25℃ ranging from 807 to 810-nm. The fibers were drawn into round bundles of 0.8-mm diameter and a numerical aperture of 0.2. The mirror M1 was a 100-cm radius-of curvature concave mirror with antireflection coating at 808-nm on the entrance face and with high-reflection coating at 1064-nm and high-transmission coating at 808-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 70% reflection at 1064-nm. The total cavity length was around 90-mm. The Nd:YVO$_4$ crystal, which has a 0.3 at. % Nd-ion concentration, was 12-mm long. The laser crystal was a-cut to obtain the high-gain π transition and was wrapped with indium foil and mounted in a water-cooled copper block. The water temperature was maintained at 16℃. Both end surfaces of the Nd:YVO$_4$ crystal were antireflection coated for 1064-nm (R<0.2%). The 20-mm-long Q switcher (Gooch and Housego) had antireflection coatings at 1064-nm on both faces and was driven at a 40.7-MHz center frequency with 3.0-W of rf power. Focusing lens with 12.5-mm focal length and 87% coupling efficiency was used to re-image the pump beam into the laser crystal. The pump-spot radius was around 350 μm. Considering the thermal lensing effect, the TEMoo radii at the Nd:YVO$_4$ crystal are calculated as 260-300 μm. In other words, the present mode-to-pump size ratio was around 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 TEMoo mode [5]. For a fiber-coupled laser diode, the thermal lens power can be given by [6]

$$\frac{1}{f_{th}} = \int_0^l \frac{\xi P_{abs}}{2\pi K_c \omega_p^2(z)} \frac{\alpha \exp(-\alpha z)}{1-\exp(-\alpha l)} \left[\frac{dn}{dT} + (n-1)(1+\nu)\alpha_T + \alpha_T C_r n^3 \right] dz \qquad (3)$$

where K_c is the thermal conductivity, P_{abs} is the absorbed pump power, n is the refractive indices along the c-axis of the Nd:YVO$_4$ crystal, dn/dT is the thermal-optic coefficients of n, α_T is the thermal expansion coefficient along the a-axis, l is the crystal length, and $\omega_p(z)$ is the pump size in the active medium. Using the usual M^2 propagation law, the pump beam is given by

$$\omega_p^2(z) = \omega_{po}^2 \left\{ 1 + \left[\frac{\lambda_p M_p^2}{n\pi\omega_{po}^2} (z - z_o) \right] \right\} \qquad (4)$$

where $\omega_p(z)$ is the radius at the waist, λ is the pump wavelength, M^2_p *is* the pump beam quality factor, and z_o is focal plane of the pump beam in the active medium. The refractive powers were calculated by using the following parameters: ξ= 0.24, K_c = 0.0523W/K-cm, dn/dT=3.0x 10^{-6}/ K, ω_{po}=0.35mm, M^2_p~310, n= 2.165, l=12mm, and α_T= 4.43x 10^{-6}/K. The refractive power is around 8.4 diopters at 52-W of absorbed pump power. With the calculated refractive power, the stability of the resonator can be confirmed from the value of the factor $(g_1^* g_2^*)$. Figure 2 shows the dependence of the $(g_1^* g_2^*)$ on the pump power for several resonator lengths. It can be seen that the resonator with L^* = 90 mm is in the stable region for the pump power up to 60-W. On the other hand, the resonator with L^* = 120 mm steps into the unstable region for the pump power higher than 46-W. The theoretical predictions agree very well with the experimental results.

Figure 3 shows the average output power in cw mode and Q-switched mode at a repetition rate of 100 kHz as a function of the incident pump power. The output power in cw mode was measured before insertion of the Q-switch into the resonator. The highest output power of 25.2-W was achieved at the maximum pump power of 52-W. The average slope efficiency was ~50% with respect to the incident pump power. The M^2 parameter has been measured to be <1.3 over the complete output power range. According to the present result, it is possible to scale the output power to 50-W with two 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. With the Q-switch in the cavity, stable Q-switched mode operation at a pulse repetition rate up to 100-kHz was accomplished. As shown in Fig. 3, the highest average output power obtained at a 100-kHz pulse repetition rate was 21-W at pump power of 52-W.

Figure 4 shows the average output power and pulse width at a pump power of 52-W as a function of the pulse repetition rate. It can be seen that at low pulse repetition rates the pulse width is short and the energy per pulse is high, whereas at higher pulse repetition rates the energy per pulse is low and the pulse width is long but the average power is high. The highest Q-switched pulse energy of 1.1-mJ was achieved at 10 kHz. Below 10 kHz, no further increase of the pulse energy was observable due to the 90-100 μs lifetime of the upper laser level of Nd:YVO_4 crystal. The major advantage of Nd:YVO_4 crystal is its ability to retain short pulse width even at very high pulsed repetition rates. At full pump power, the pulse width varies from 10ns at 10 kHz to 18ns at 100 kHz. With a Nd:YAG crystal in the present cavity, the pulse width increases from 20ns at 10 kHz to 50ns at 100 kHz. The pulse width in Nd:YVO_4 crystal is about 2~3 times shorter than that in Nd:YAG due to a shorter lifetime in Nd:YVO_4 crystal. Although the average output power of Nd:YVO_4 crystal at 10 kHz drops by 50% compared with operation at 100 kHz, the short pulse width leads to peak power greater than 100-kW. This compares with the peak power in diode-pumped Nd:YAG and Nd:YLF lasers at low pulse repetition rates [7,8]. For high pulse repetition rates (>30 kHz), the output performance of the Nd:YVO_4 system is generally better than that of the Nd:YAG or Nd:YLF system due to higher optical-to-optical conversion efficiency. We have demonstrated a highly efficient, high-power Nd:YVO_4 laser in cw and Q-switched modes. To scale up output power, a YVO4 crystal of low Nd concentration (0.3 at.%) was used to avoid thermally induced fracture. 25.2-W of TEMoo cw mode output power with good beam quality was obtained at a 52-W pump power. This result indicates that there is substantial scope for further power scaling of end-pumped Nd:YVO_4 lasers with a low Nd concentration. In Q switched operation, we demonstrate the potential of the YVO_4 crystal to generate a pulse energy in the mJ range with high pulse repetition rates. Such a laser source will be interesting for micro-materials processing applications.

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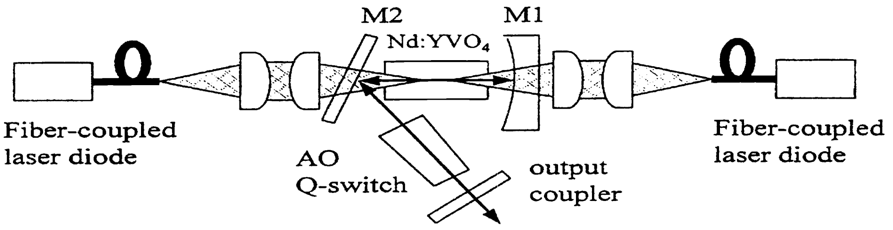
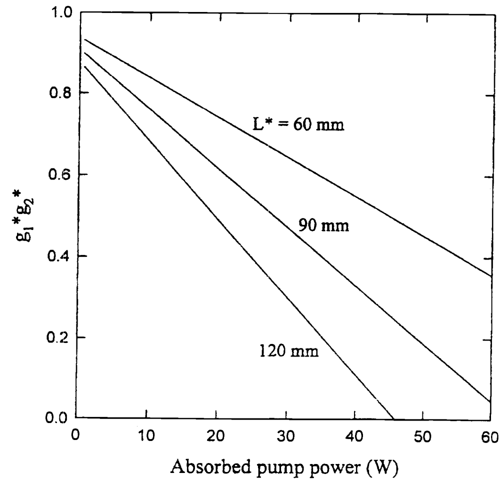


Fig. 1. Scheme of the experimental setup.



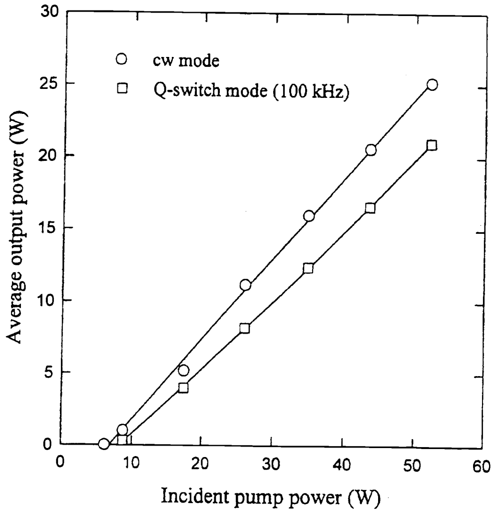


Fig. 2. A plot of the dependence of the (g_1*g_2*) on the pump power for several resonator lengths.

Fig. 3. A plot of the average output power as a function of the incident pump power circle: cw mode operation; squares: Q-sitched mode at a repetition rate of 100kHz.

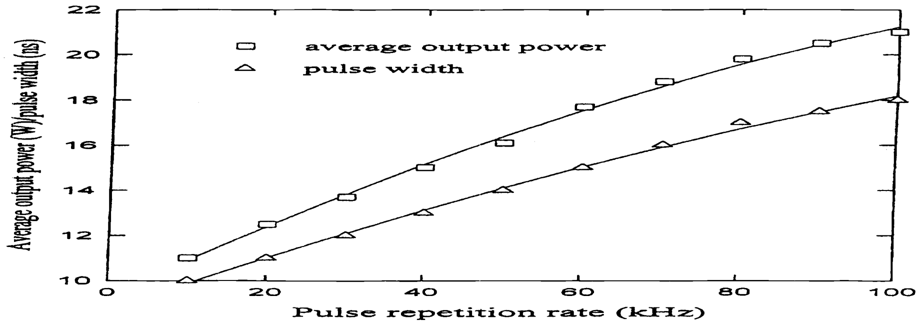


Fig. 4. A plot of average output power and pulse width as a function of the Q-switched pulse repetition frequency.