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High repetition rate Q-switching of high power $Nd:YVO_4$ slab laser

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Abstract

A high power, diode-side-pumped $Nd:YVO_4$ laser with a grazing incidence cavity geometry was acousto-optically Q-switched at frequencies up to 500 kHz. In CW operation, the laser output power was 16.4 W at 30.5 W of diode pump, corresponding to optical conversion efficiency of 53.8%. In Q-switching operation, measurements were made of average output power, pulse duration, pulse energy and peak power as a function of Q-switching frequency. At 200 kHz repetition rate and pump power 30 W, the laser output had average power 15.9 W (optical conversion efficiency 53%), pulse duration 15 ns, pulse energy 80 μJ and peak power 5.3 kW. A numerical modeling of the Q-switched laser was performed and results compared with experimental data.

Keywords: $Nd:YVO_4$; Acousto-optic Q-switching; Laser modeling

1. Introduction

At present time, near-infra-red Q-switched solid-state Neodymium lasers ($\lambda = 1064$ nm) are important devices used for various applications including material processing, medicine, and remote sensing [1–3]. The high peak power in Q-switched operation is also convenient for optimizing the efficiency of nonlinear frequency conversion of the radiation. In most research and commercial systems, operation is generally at repetition rates up to tens of kHz but usually <100 kHz. For some applications it would be interesting to have even higher pulse repetition rate (>100 kHz) and at high powers (tens of Watts), e.g., in material processing with high speed scanning. It is difficult to obtain stable pulse energy and low temporal jitter at high repetition rates when the Q-switching regime is realized by passive methods [4–7]. Active methods of Q-switching [8–10] are preferable for this aim, however, at higher repetition rates the pulse duration becomes excessively

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lengthened especially in laser materials with long upper state lifetime, like Nd:YAG and Nd:YLF. One route to obtaining high repetition rate (>100 kHz) and short pulse duration is to use a laser material with short upper state lifetime and high gain and the $Nd:YVO_4$ crystal is an interesting candidate, characterized by higher emission cross-section and shorter fluorescence lifetime [11] than most other neodymium-doped materials.

In this paper, we describe the operation of a diode-pumped $Nd:YVO_4$ laser Q-switched with an acousto-optic (AO) modulator that operates at high repetition rate (100–500 kHz) with short pulse duration. We exploit a diode-side-pump grazing incidence configuration of the laser cavity, which leads to extremely high gains and favoring short pulse duration [12,13]. This geometry was used previously using quasi-CW diode pumping with an electro-optic Q-switch at repetition-rate up to 1 kHz and average powers less than 1 W [14,15]. Our experimental study is the first use of this geometry for Q-switching with CW diode pumping, where we employ AO Q-switching, repetition rate up to 500 kHz and output power up to 16 W. We study experimentally basic output parameters of the laser as well as compare with modeling results of the Q-switch laser operation.

The paper is organized as follows: Section 2 contains the description of the experimental laser system and a presentation of the results of its experimental operation. Section 3 addresses the modeling of the laser and the results of the numerical simulation of the AO Q-switching, as well as comparison of the latter with the experimental data. The main conclusions of the work are formulated in Section 4.

2. Experimental system

2.1. Experimental set-up

The laser (see Fig. 1) was based on a $Nd:YVO_4$ crystal a-cut slab with 1.1 at.% neodymium doping operating at a wavelength of 1064 nm and pumped by a semiconductor diode laser bar with the emitting line centered at a wavelength of 808 nm.

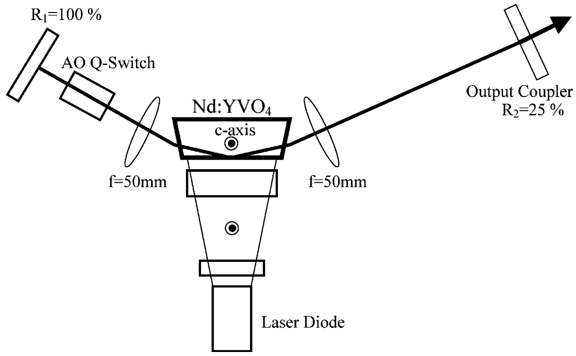

Fig. 1. Schematic of AO Q-switched diode-side-pumped $Nd:YVO_4$ laser.

The $Nd:YVO_4$ slab ($2 \times 5 \times 20$ mm) had diode pumping face AR coating for wavelength 808 nm, whereas its front and end faces (tilted at 5° to prevent self-lasing) were AR coated for lasing wavelength 1064 nm. The slab was conduction cooled from its top and bottom faces. The diode bar was fast-axis collimated and a cylindrical lens used to form a line focus with dimensions of $\sim$0.1 mm $\times$ 15 mm on the $Nd:YVO_4$ crystal pumped face. Maximum CW power from the pumping laser diode was 30.5 W. The diode was TM polarized and parallel to the c-axis of the $Nd:YVO_4$ slab, thereby accessing the strongest absorption coefficient of the crystal.

The laser cavity was designed in a grazing incidence configuration, where the laser beam experiences a bounce (total internal reflection) at the pumped slab face. The internal grazing-incidence angle was $\sim$8°. A pair of plane mirrors formed the cavity with rear mirror reflectivity of 100% and the output-coupling mirror with reflectivity 25%. Two cylindrical lenses of 50 mm focal length were placed inside the cavity to match the laser mode to the small gain region in the vertical dimension of the $Nd:YVO_4$ crystal. The total cavity optical path length was 375 mm.

The cavity active Q-modulation was provided by an acousto-optic (AO) crystal placed between the $Nd:YVO_4$ crystal and rear mirror. The AO switch was mounted on a stage, providing translation and rotation control. The AO r.f. driver could be used to provide Q-switching at up to 500 kHz.

2.2. Experimental results

A plot of the laser output power as a function of the diode pump power in CW operation mode, when the AO Q-switch was removed from the cavity, is shown in Fig. 2. In this regime, the output was TEM_{00} at maximum output power 16.4 W at 30.5 W of pump, corresponding to optical conversion efficiency of 53.8%. The dip in the power curve is caused by the change in stability of the cavity due to the power dependence of the thermally induced lensing in the Nd:YVO_4 slab [16]. Below 18 W of pumping the cavity is stable, between 18 and 23 W the cavity is in an unstable regime and above 23 W the cavity has a second stability region. The cavity has been optimized for the pumping at $\sim$ 30 W of diode pumping where a stable TEM_{00} operation occurs and the M^2 of the beam is 1.3 in the horizontal and 1.1 in the vertical directions.

When operating in the AO Q-switch regime, a giant pulse formation was established in the laser. At frequencies exceeding ~80 kHz, single Q-switched pulse operation was observed. Fig. 3 shows the temporal profile of the Q-switched output pulse at 200 kHz with 15 ns pulse duration (FWHM). At frequencies below 80 kHz, subsidiary pulsing was observed and irregularity in shape of the pulses was seen. The behavior at lower frequency is due to the very high gain of the intensively pumped Nd:YVO_4 slab and the inability of the AO Q-switch to hold off lasing between each Q-switched pulse. The diffraction efficiency of the AO Q-switch was ~60%. With a higher diffraction efficiency lower repetition rates with single pulse operation should be possible. For the purposes of this study we wished to achieve high repetition rate operation, so the results we present are in the Q-switched range 100–500 kHz.

In the course of the experimental study of the high repetition rate Q-switching regime we measured dependences of averaged and peak power, energy, and duration of pulses generated versus the Q-switch modulation frequency at the fixed

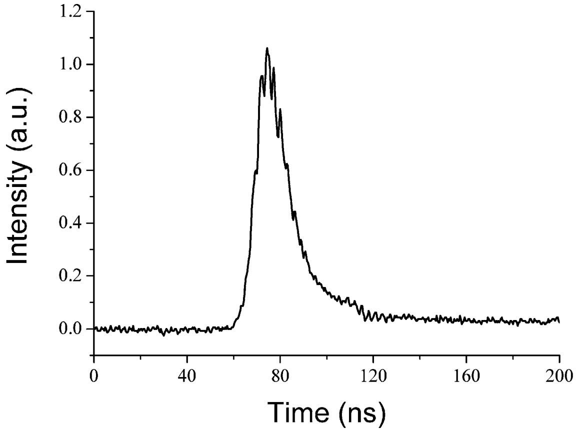

Fig. 3. Temporal profile of giant pulse in Q-switching regime at modulation frequency $f = 200$ kHz.

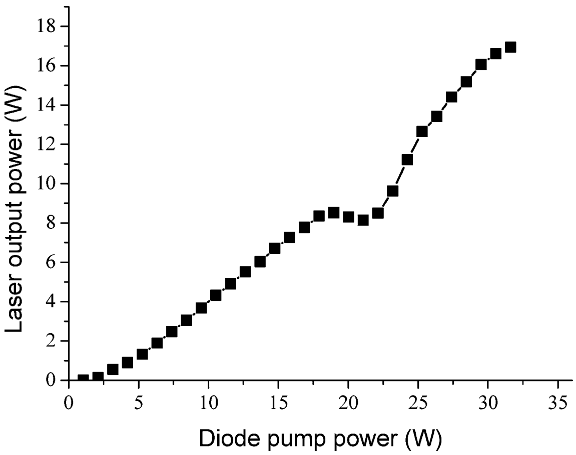

Fig. 2. Laser output-to-input power dependence (CW regime).

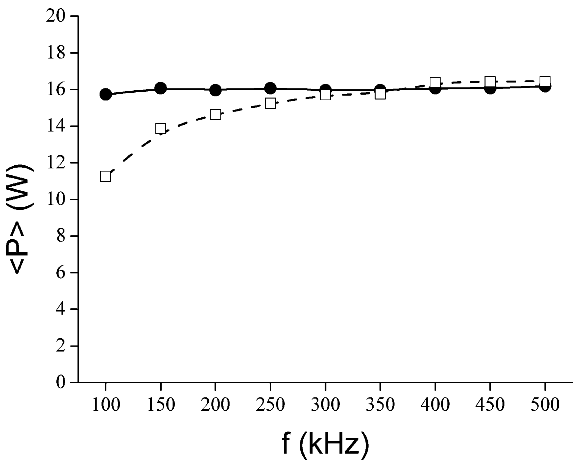

Fig. 4. Average power versus repetition rate in Q-switching regime (filled circles – experimental data; empty squares – modeling results). Pump power – 30 W.

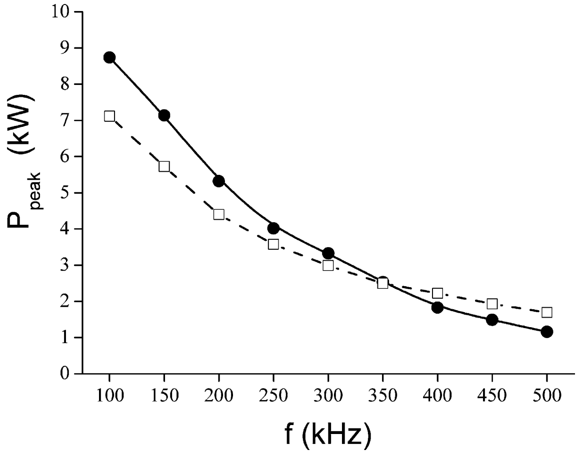

Fig. 5. Pulse peak power versus repetition rate in Q-switching regime (filled circles – experimental data; empty squares – modeling results). Pump power – 30 W.

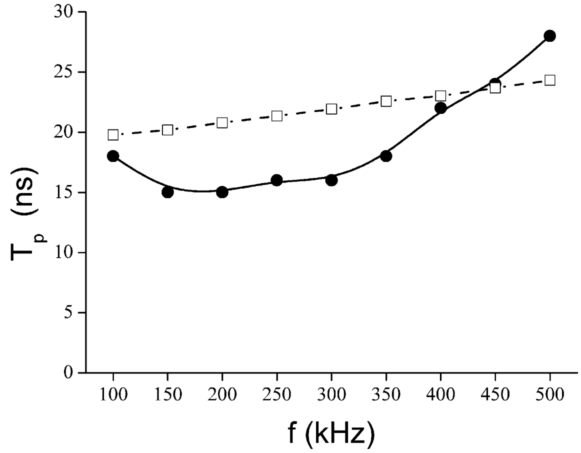

Fig. 7. Pulse duration versus repetition rate in Q-switching regime (filled circles – experimental data; empty squares – modeling results). Pump power – 30 W.

diode pump power 30 W. Figs. 4–7 present such experimental dependences (circles and solid curves) with Q-switch frequencies within the 100–500 kHz range, where stable single giant pulses are generated. The main observations relating to the AO Q-switching mode are as follows: (i) averaged power $\langle P \rangle$ of giant pulses remains practically unchanged within the whole range of modulation frequency, (ii) peak power P_{peak} and energy E_p of a giant pulse in the train decreases with the increase in frequency f, and (iii) the pulse duration τ_p has a minimum duration of 15 ns near 150 kHz and the duration increases slowly above 200 kHz.

We did not proceed to experiments at the modulation frequencies of $f > 500$ kHz, since this was the limit of the RF drive electronics used in the experiment.

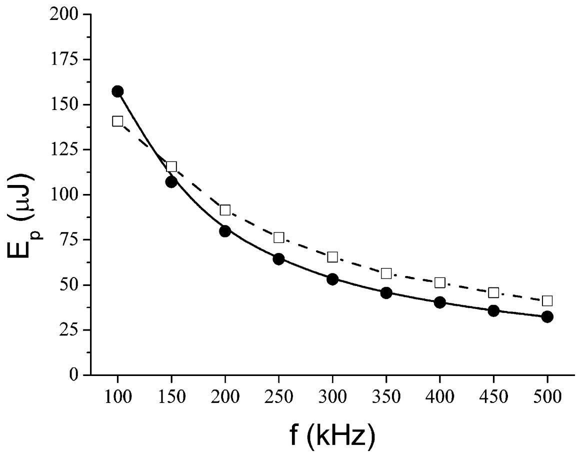

Fig. 6. Pulse energy versus repetition rate in Q-switching regime (filled circles – experimental data; empty squares – modeling results). Pump power – 30 W.

3. The laser modeling

~~*3.1. The laser model*~~

~~The analysis presented below assumes an ideal four-level scheme for the laser active medium, which holds for a Nd:YVO$_4$ crystal. We take, consequently, that transitions from the pump band to the upper laser level occur very rapidly and the lower laser level is depopulated (also very rapidly) by relaxation processes to the ground state. Therefore, the total neodymium population density (n_t) is shared, at all stages of oscillation, between the ground state population density (n_0) and upper laser level population density (n) only. Using a conventional model of coupled rate equations [17–20], governing the variations of population density n and the photon flux density ϕ, we write equations as follows:~~

$$\cancel{\frac{\partial n}{\partial t} = R_p(n_t - n) - c\sigma\phi n - \frac{n}{\tau},} \tag{1}$$

$$\frac{\partial\phi}{\partial t} = (2l\sigma n - \zeta)\frac{\phi}{\tau_R} + k\frac{n}{\tau}, \quad (2)$$

where R_p is the pumping rate ($R_p = P/n_t h\nu_p V \xi$, where P is the diode pump power, n_t is the total population density, $h\nu_p$ is the pump photon energy, V is the volume and ξ is the Stokes loss parameter given by the pump-to-generation wavelength ratio); σ is the stimulated emission cross-section; τ_R is the photon round-trip time in the cavity ($\tau_R = 2l'/c$, c is the speed of light and l' is the cavity length); τ is the fluorescence lifetime of the upper laser level; l is the Nd:YVO$_4$ crystal length; ζ is the cavity losses; and k is the factor accounting for the fraction of spontaneous photons contributing in the lasing.

The cavity overall losses ζ in Eq. (2) are written as

$$\zeta = \ln\left(\frac{1}{R_2}\right) + L + \Gamma(t), \quad (3)$$

where the terms on the right-hand side represent, respectively, the output coupling losses given by the reflectivity, R_2, of the output coupling mirror, the residual (passive) losses per round trip L, and the variable losses inserted by the AO modulator (we assume a temporal periodic rectangular shape of the modulated losses, as used in the experiment).

Theoretical values of the main laser parameters in the Q-switching mode (pulse energy, E_p, peak power, P_{peak}, and duration, τ_p), were obtained from numerical calculation of the set of Eqs. (1)–(3), using a Runge–Kutta method. Neglecting pumping and spontaneous emission and provided that the shape of the output pulse can be reasonably represented by an asymmetric "triangle" E_p (with a height of P_{peak} and baseline of τ_b, where $\tau_p = \tau_b/2$), the above parameters are given by the following approximate expressions [20,21]:

$$E_p \approx \frac{Vh\nu}{2}(n_i - n_f)\frac{\ln(1/R_2)}{\ln(1/R_2) + L}, \quad (4)$$

$$P_{peak} = \frac{Vh\nu}{t_R}\ln\left(\frac{1}{R_2}\right)\left\{n_i - n_{th}\left[1 + \ln\left(\frac{n_i}{n_{th}}\right)\right]\right\}\frac{l}{l'}, \quad (5)$$

$$\tau_p \approx \frac{E_p}{P_{peak}} = \frac{l'}{2l}\frac{(n_i - n_f)}{\left\{n_i - n_{th}\left[1 + \ln\left(\frac{n_i}{n_{th}}\right)\right]\right\}}, \quad (6)$$

where $h\nu$ is the laser photon energy, V is the volume of the laser beam in the active medium, and n_{th} is the threshold population inversion, which, in turn, is determined as

$$n_{th} = \frac{1}{2\sigma l}\left[\ln\left(\frac{1}{R}\right) + L\right]. \quad (7)$$

Note that the initial and final population inversions in the active medium, n_i and n_f, were determined numerically. The averaged output power

Table 1
The laser parameters used for calculations

	Parameters	Values
N_T	Total density of Nd^{3+} ions	1.37×10^{20} cm^{-3}
σ	Stimulated emission cross-section	2.5×10^{-18} cm^2
σ_{abs}	Absorption cross-section	2.7×10^{-19} cm^2
n	Refractive index	1.95
τ	Spontaneous fluorescence lifetime	98 μs
$\tau_R = 2l'/c$	Cavity round-trip time	2.5 ns
$h\nu$	Laser photon energy	1.86×10^{-19} J
ω_0	Beam waist size	$\sim 70 \times 10^{-4}$ cm
c	Speed of light	3×10^{10} cm/s
$h \times w \times l$	Nd:YVO4 crystal size	$2 \times 5 \times 20$ mm^3
l'	Cavity length	37.5 cm
P	Maximum pump power	30 W
V	Pumped volume	0.31 mm^3
R_2	Reflectivity mirror output	0.25
L	Round-trip dissipative optical losses	0.01
ξ	Stokes parameter (ratio of photon energies)	0.76
k	Spontaneous emission factor	0.01

~~$\langle P \rangle$ of the laser in the Q-switching mode was calculated as $\langle P \rangle = E_{p} f$. Table 1 gives the parameter values taken in the numerical calculations.~~

~~*3.2. The modeling results and their comparison with the experiment*~~

~~The results of the numerical modeling of the Q-switch operation are shown as the square symbols and dashed curves in Figs. 4–7. It is seen that there is some reasonable agreement of main parameters of the AO Q-switching mode in Nd:YVO_4 laser with those measured experimentally for the modulation frequencies lying in the 100–500 kHz range. The main discrepancy is the mismatch of pulse duration dependence with Q-switch frequency. This may be due to a weak pre-lasing at the 100 kHz frequency in the experiment due to poor hold-off by the AO modulator, and this is consistent with the difference in average output power between model and experiment at the lower frequencies. It is also likely that a shorter upper state lifetime might be required in the modeling caused by the effects of energy transfer up-conversion that leads to a further loss channel of the upper laser level, and also by the presence of amplified spontaneous emission. Despite the discrepancies, the general agreement allows one to conclude that the simple model of the laser is adequate for a first order prediction of the laser characteristics and with extension to include other mechanisms such as up-conversion should allow better prediction and use in optimizing laser parameters. We mention that even for lower repetition rate, <100 kHz (not shown), the modeling gives rise to results in qualitative agreement with the experimental data; for instance, the appearance of multiple spiking instead of a single smooth giant pulse.~~

4. Conclusions

The design of an effective AO Q-switched diode-side-pumped high-gain Nd:YVO_4 laser with the plane-plane grazing incidence cavity geometry was operated, allowing high-power short giant pulse oscillation at high repetition rates (>100 kHz). The laser output power was measured to be >16 W at 30 W of pump, corresponding to overall optical conversion efficiency of approximately 54%. The pulse duration was as short as 15 ns even at 200 kHz and high efficiency operation near 16 W was achieved across the repetition rate 100–500 kHz. The experimental results were compared to a numerical model and giving generally good agreement. The presented laser is therefore demonstrated to be an excellent source for high power, ultra-high repetition rate pulses with short pulse duration. Shorter pulse duration should be achievable by use of a shorter cavity length than in our system, which was not optimized for compactness.

References

[1] N.D. Lai, M. Brunel, F. Bretenaker, A. Le Floch, Appl. Phys. Lett. 9 (2001) 1073.
[2] M. Fromager, K. Ait Ameur, Opt. Commun. 191 (2001) 305.
[3] N.N. Arev, B.F. Gorbunov, G.V. Pugachev, Meas. Tech. 36 (1993) 524.
[4] J. Gu, F. Zhou, W. Xie, S. Chung Tama, Y.L. Lam, Opt. Commun. 165 (1999) 245.
[5] Y.F. Chen, S.W. Tsai, C.S. Wang, Opt. Lett. 25 (2000) 1442.
[6] B. Braun, F.X. Kartner, G. Zhang, M. Moser, U. Keller, Opt. Lett. 22 (1997) 381.
[7] A.V. Kir'yanov, V. Aboites, N.N. Il'ichev, J. Opt. Soc. Am. B 17 (2000) 11.
[8] W. Xie, Y.L. Lam, Y.C. Chan, S.C. Tam, J. Gu, F. Zhou, H. Yang, G. Zhao, Appl. Opt. 39 (2000) 978.
[9] A. Agnesi, S. Dell'Acqua, C. Penncachio, G. Reali, P.G. Gobbi, Appl. Opt. 37 (1998) 3984.
[10] G.J. Friel, R.S. Conroy, A.J. Kemp, B.D. Sinclair, J.M. Ley, Appl. Phys. B 37 (1996) 267.
[11] Z. Wang, L. Sun, S. Zhang, X. Meng, R. Cheng, Z. Shao, Opt. Laser Technol. 33 (2001) 47.
[12] M.J. Damzen, M. Trew, E. Rosas, G.J. Crofts, Opt. Commun. 196 (2001) 237.
[13] J.H. García-López, V. Aboites, A. Kir'yanov, S. Holmgren, M.J. Damzen, Opt. Commun. 201 (2002) 425.
[14] J.E. Bernard, A.J. Alcock, Opt. Lett. 19 (1994) 1862.
[15] A.J. Alcock, J.E. Bernard, IEEE J. Select. Top. Quantum Electron. 3 (1997) 3.
[16] V. Magni, Appl. Opt. 25 (1986) 107.
[17] W. Koechner, Solid-State Laser Engineering, third ed., Springer, Berlin, Germany, 1992.
[18] A. Yariv, Quantum Electronics, third ed., Wiley, New York, USA, 1989.
[19] W.G. Wagner, B.A. Lengyel, J. Appl. Phys. 34 (1963) 2040.
[20] J.J. Degnan, IEEE J. Quantum Electron. 25 (1989) 214.
[21] R. Powell, Physics of Solid-State Laser Materials, Springer, New York, USA, 1998.