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888 nm pumped dual Nd:YVO_4 crystals acousto-optic Q-switched laser

Wenqi Zhang, Yijie Shen, Yuan Meng, Mali Gong *

State Key Laboratory of Precision Measurement Technology and Instruments, Department of Precision Instrument, Tsinghua University, Beijing 100084, China

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ABSTRACT

888 nm pumped acousto-optic (AO) Q-switched laser with high output power and high efficiency under dual Nd:YVO_4 crystals configuration is firstly demonstrated and rate equations for dual-crystal lasers are further ameliorated and investigated. In continuous wave (CW) operation, we experimentally achieve a maximum output power exceeding 50 W. The global optical efficiency reaches 49.5% and the slope efficiency attains 55.5% via using a 1.5 at.% crystal with a 0.5 at.% crystal. In Q-switch operation, by utilizing double 0.5 at.% crystals, the global optical efficiency rises from 25.6% to 45.6% and the pulse duration varies from 26.2 to 42.4 ns when pulse repetition frequency (PRF) increases from 10 to 100 kHz. The measured beam quality factors M^2 at 100 kHz are 1.012 and 1.041 with 52.8 W output power in the two orthogonal directions respectively.

1. Introduction

Thermal-induced refractive index gradient in gain medium evidently influences the mode distribution and exerts great limitations to the power scaling capability [1,2]. To reduce the thermal power density and thermal-induced refractive index gradient in the gain medium, multiple gain medium especially dual crystals in resonant cavity are utilized to extend output power. Compared with the solo-crystal lasers, dual-crystal lasers also possess the advantage of a broadened stable range under the same pump condition, as shown in Fig. 1. So far, several results of dual-crystal lasers in CW operation have been reported [3–6]. In Q-switched operation, Chen et al. [7] demonstrated a 808 nm end pumped Nd:YVO_4 laser by utilizing two Nd:YVO_4 crystals to form a thermally stabilized planar cavity. While in Q-switched mode, an average power of 25 W at a PRF of 100 kHz and 0.9 mJ pulse energy at a PRF of 10 kHz were obtained. In 2001, Hodgson et al. [8] showed a dual-rod Nd:YVO_4 resonator with 48 W average output power at the repetition of 100 kHz, with the optical–optical efficiency reaching 46%. In 2009, Yan et al. [9] reported a 808 nm pumped high-repetition-rate double-rod AO Q-switched composite Nd:YVO_4 laser. In CW operation, 78 W TEM_{00} mode output power were achieved, with a corresponding optical–optical efficiency of 46.5%. In Q-switching operation, the stable repetition frequency range for two different cavities was 30–350 kHz and 80–650 kHz respectively. In 2010, the same group [10] exhibited an AO Q-switched dual-rod laser pumped by 808 nm laser diode with different gain crystals in the cavity with a combination of Nd:YAG crystal and Nd:YVO_4 crystal. In Q-switched operation, 500 kHz output with 64.2 W average power was achieved for the Nd:YAG-Nd:YVO_4 laser.

Another effective way to diminish the variety of heat dependent phenomena is to reduce quantum defect between pumping wavelength and emitting wavelength with in-band pumping. Using single gain medium in resonator, in-band pumped Nd:YVO_4 lasers have been demonstrated in CW operation with 880 nm [11,12], 888 nm [13] or 914 nm [14,15] pumping and Q-switched operation [2,16,17]. Using two gain medium in resonator, dual Nd:YVO_4 crystals with 888 nm pumped laser was presented in CW operation [6]. However, In-band pumped dual Nd:YVO_4 crystals AO Q-switched laser was not reported as well so far as we know. Besides the CW case of the in-band pumped dual gain crystals lasers, the further developed pulsed laser operation have stimulated our great interest for the rising requirements of the pulsed lasers as compact, efficient, and power scaling sources for a variety of applications [18].

Rate equations are an efficient method for analyzing the performance of a Q-switched laser. Investigations upon rate equations are massively presented, including AO Q-switch [16,19], electro-optic Q-switch [20], passive Q-switch [21] and Q-switch based upon plural AO and passive mechanisms [22–25], yet these theories can only be applied to single gain medium. Although the dual-crystal Q-switched lasers with impressive output properties have been experimentally achieved, the relative theoretical model of rate equation theory for dual-crystal has not been perfectly established to the best of our knowledge. Thus, it is significant to establish a more comprehensive model to deal with the complex cavity cases for instructing Q-switched lasers design.

* Corresponding author.
E-mail address: gongml@mail.tsinghua.edu.cn (M. Gong).

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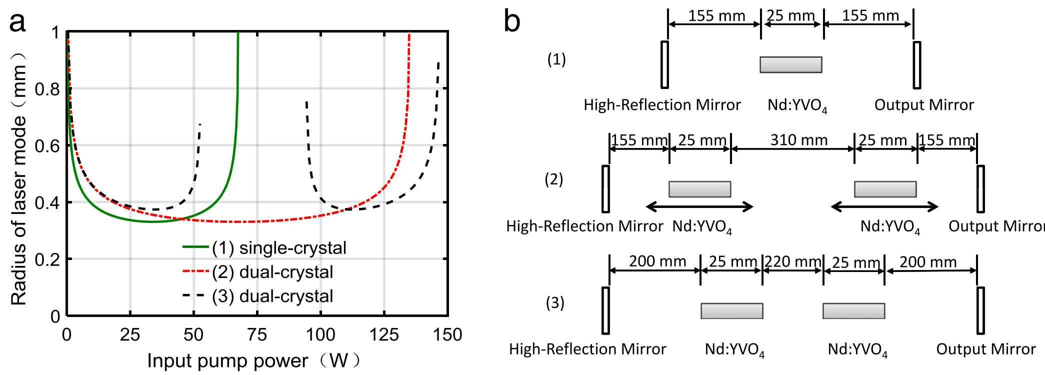

Fig. 1. (Color online) (a) Comparison of resonator stability between single-crystal laser and dual-crystal laser under the identical pump condition. (b) Schematic sketch of single-crystal laser and dual-crystal laser. One can tailor the variation of the stable range by altering the positions of the crystals within the laser cavity. In simulation, we assume the pump spot radius of 0.5 mm, the $Nd:YVO_4$ crystal length of 25 mm, the doping concentration of 0.5 at.%, the pump wavelength of 888 nm.

In this paper, we further tailor the rate equations model for dual-crystal lasers and experimentally demonstrate an in-band pumped double $Nd:YVO_4$ crystals AO Q-switched laser for the first time. Using our ameliorated rate equations model, the Q-switched conditions with different PRFs and two different doping gain crystals are numerically simulated. Additionally, we discuss the influence of different PRFs and crystal parameters to the output properties. The experiment results enjoy good agreement with our theory.

2. Theoretical calculations

As is wide-accepted in practical emulations with conciseness and accuracy [16,19,23], it can be assumed that lasers are homogeneously broadened. We also considered the energy transfer upconversion (ETU) [26] effects in our model. Thus, the dual-crystal Q-switched rate equations can be obtained as:

$$\frac{d\phi}{dt} = \frac{l_{c1}}{l_{eff}}\left[S_{21}\frac{n_{21}}{\tau_{21}} + (n_{21}-n_{11})\,\sigma_{e1}\phi v_1\right] + \frac{l_{c2}}{l_{eff}}\left[S_{22}\frac{n_{22}}{\tau_{22}} + (n_{22}-n_{12})\,\sigma_{e2}\phi v_2\right] - \frac{\phi}{\tau_c} \tag{1}$$

$$\frac{dn_{21}}{dt} = R_{p1}\left(N_{t1}-n_{11}-n_{21}\right) - \frac{n_{21}}{\tau_{21}} - (n_{21}-n_{11})\,\sigma_{e1}\phi v_1 - 2W_{up1}{n_{21}}^2 + \frac{n_{up1}}{\tau_{up1}} \tag{2}$$

$$\frac{dn_{11}}{dt} = \frac{n_{21}}{\tau_{21}} - \frac{n_{11}}{\tau_{11}} + (n_{21}-n_{11})\,\sigma_{e1}\phi v_1 + W_{up1}{n_{21}}^2 \tag{3}$$

$$\frac{dn_{22}}{dt} = R_{p2}\left(N_{t2}-n_{12}-n_{22}\right) - \frac{n_{22}}{\tau_{22}} - (n_{22}-n_{12})\,\sigma_{e2}\phi v_2 - 2W_{up2}{n_{22}}^2 + \frac{n_{up2}}{\tau_{up2}} \tag{4}$$

$$\frac{dn_{12}}{dt} = \frac{n_{22}}{\tau_{22}} - \frac{n_{12}}{\tau_{12}} + (n_{22}-n_{12})\,\sigma_{e2}\phi v_2 + W_{up2}{n_{22}}^2 \tag{5}$$

$$\frac{dn_{up1}}{dt} = W_{up1}{n_{21}}^2 - \frac{n_{up1}}{\tau_{up1}} \tag{6}$$

$$\frac{dn_{up2}}{dt} = W_{up2}{n_{22}}^2 - \frac{n_{up2}}{\tau_{up2}} \tag{7}$$

where

$$l_{eff} = l + (n_{C1}-1)\,l_{c1} + (n_{C2}-1)\,l_{c2} + (n_{AO}-1)\,l_{AO} \tag{8}$$

$$\frac{1}{\tau_c} = \frac{c}{2l_{eff}}\left[\ln\left(\frac{1}{R}\right) + \delta + \varepsilon(t)\right] \tag{9}$$

$$R_{p1} = \frac{\sigma_{\alpha1}P_{in1}\left(1-\exp(-\alpha_1 l_{c1})\right)\lambda_{p1}}{\pi\omega_{p1}^2 hc} \tag{10}$$

$$R_{p2} = \frac{\sigma_{\alpha2}P_{in2}\left(1-\exp(-\alpha_2 l_{c2})\right)\lambda_{p2}}{\pi\omega_{p2}^2 hc}. \tag{11}$$

The meaning of various parameters and relative symbols are shown in Table 1 and the values used in this work are referring to previous works [26–28]. For AO Q-switched conditions, the loss function of AOM can be written as [22]:

$$\varepsilon(t) = \varepsilon_0 \exp\left[-\left(\frac{t}{\tau_{AO}}\right)^2\right]. \tag{12}$$

The pulse peak power P can be approximately given as Eq. (13).

$$P = \frac{hc}{\lambda_l}\frac{\pi{\omega_l}^2 l_{eff}}{\tau_c}\frac{\ln(\frac{1}{R})}{\left[\ln\left(\frac{1}{R}\right)+\delta\right]}\phi_{\max}. \tag{13}$$

Where, hc/λ_l is the photon energy of the laser light and $\pi{\omega_l}^2 l_{eff}$ represents the rough laser mode volume. The fraction $\ln(1/R)/\left[\ln(1/R)+\delta\right]$ appears as laser output. $\phi_{\max}$ is the maximum value of photon number density.

According to the parameters in Table 1, the coupled rate Eqs. (1)–(13) can be numerically solved. The simulated relationship between pulse width with doping concentration can be shown in Fig. 2(a) and the relationship between peak power with doping concentration can be presented in Fig. 2(b) when the PRF is 80 kHz. It illustrates that the pulse width decreases and the peak power increases as the increment in doping concentration.

3. Experimental setup

The experimental setup of the dual-rod AO Q-switched resonator is schematically illustrated as Fig. 3. The resonator is a Z-shape folded geometry, with the folding angle of 45°. The pump sources are fiber-coupled laser diode (LD) with the maximum output power 110 W at 888 nm. The coupling fibers of the LD modules are with numerical aperture of 0.17 and core diameter of 0.4 mm. Focusing lens groups are used to image the pump mode from the fiber onto the $Nd:YVO_4$ crystal, and the diameters of the pump spots in the crystal are about 1.0 mm corresponding to the magnification of the coupling system. The temperature of the laser diodes are controlled by the thermoelectric cooling module (TECM) and the center wavelength of the laser diodes can be temperature-tuned by adjusting the temperature of the LD with TECM. One gain medium is an a-cut $Nd:YVO_4$ bulk crystal with doping concentration of 0.5 at.% and $4\times4\times30\ mm^3$ in dimension. The other is an a-cut $Nd:YVO_4$ bulk crystal with $2\times2\times25\ mm^3$ in dimension, but we change the doping concentration of 0.3 at.%, 0.5 at.%, 1.0 at.%, 1.5 at.%