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High-power diode-pumped actively Q-switched Nd:YAG laser at 1123 nm

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Abstract

A high-power diode-pumped Nd:YAG laser at 1123 nm is acousto-optically Q-switched at a pulse repetition rate range of 5–20 kHz. Experimental results reveal that the resonator mirrors need to suppress parasitic oscillations on lines in the 1064 nm as well as 1319 nm regions for actively Q-switching operation. With an incident pump power of 19.2 W, the pulse energy increases from 0.15 mJ at 20 kHz to 0.4 mJ at 5 kHz. The highest peak power is up to 8.0 kW at 5 kHz. Furthermore, a conventional model of coupled rate equations is used to analyze the experimental data. The general agreement indicates that the simple model is adequate for a first order prediction of the low-gain laser characteristics.

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Keywords: Nd:YAG; Diode-pumped; Acousto-optic Q-switching

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1. Introduction

The progress in diode-pumped solid-state lasers makes considerable advances in various fields of science and technology. Nd:YAG crystal is one of the prevalent active media among the diode-pumped Nd-doped lasers because of its excellent optical and mechanical properties. It is well-known that the emission at 1064 nm is the most commonly used wavelength in Nd:YAG lasers because of the highest gain [1–4]. However, Nd:YAG lasers can also operate in various Stark components of the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition [3,5,6], such as 1112 and 1123 nm. In spite of low gain, the operation of a highly efficient Nd:YAG laser with wavelengths of 1.11–1.12 μm is particularly desirable for a few practical applications. For example, the 1112 nm line that is close to the second overtone of the unsaturated hydrogen carbonates can be applied to the selective photo-ionization in laser chemistry [6]. Furthermore, the 1123 nm line can be used as a pump source for Thulium upconversion fiber lasers to generate blue light emission [7,8].

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Previously, Moore et al. [5] has demonstrated a cw output of 1.7 W at 1123 nm with an incident pump power of 5.6 W in a diode-pumped Nd:YAG laser. An uphill struggle for operation of Nd:YAG laser at 1123 nm is to utterly suppress the competing transition at 1064 nm because the stimulated emission cross section for the 1123 nm transition approximately 15 times smaller than that for the 1064 nm line [2]. In this work, we report present a high-power actively Q-switched diode-pumped 1123 nm Nd:YAG. With 19.2 W of incident pump power, the compact cavity produces the average power of 3 W and the peak power higher than 1 kW at 20 kHz repetition rate.

2. Experimental setup

Fig. 1 is a schematic of the actively Q-switched Nd:YAG laser on the low-gain 1123 nm line. The active medium was a 1.0 at.% Nd^{3+}, 5-mm-long Nd:YAG crystal. The laser crystal was wrapped with indium foil and mounted in a water-cooled copper block. The water temperature was maintained at 25 °C. Both sides of the laser crystal were coated for antireflection at 1123 nm ($R < 0.2\%$). The AO Q-switch (NEOS) was made by a 10-mm-long SF10 glass with antireflection coating at 1123 nm on both sides and was driven at an 80 MHz center frequency with 3.0-W of rf power. The pump source was a 20-W 808-nm fiber-coupled laser diode with a core diameter of 800 μm and a numerical aperture of 0.16. Focusing lens with 12.5 mm focal length and 96% coupling efficiency was used to re-image the pump beam into the laser crystal. The pump spot radius was around 310 μm. The input mirror, M1, was a 200 mm radius-of-curvature concave mirror with antireflection coating at the pump wavelength (~808 nm) on the entrance face ($R < 0.2\%$), high-reflection coating at 1123 nm ($R > 99.8\%$) and high-transmission coating at the pump wavelength on the other surface ($T > 95\%$). The output coupler is a flat mirror with a 6% transmission at 1123 nm. Note that all the coatings of the cavity mirrors were characterized by high losses at wavelengths corresponding to the stronger Nd^{3+} transitions (transmission >90% at 1064 nm, >60% at 1319 nm). Our experimental results reveal that the resonator mirrors only need to suppress parasitic oscillations on lines in the 1064 nm region for cw operation, as indicated in [5]. For Q-switching operation, however, another requirement on the mirror coatings is to suppress the lasing channel at 1319 nm. The effective cavity length was approximately 90 mm. The pulse temporal behavior at 1123 nm was recorded by a LeCroy 9362 digital oscilloscope (500 MHz bandwidth) with a fast InGaAs photodiode.

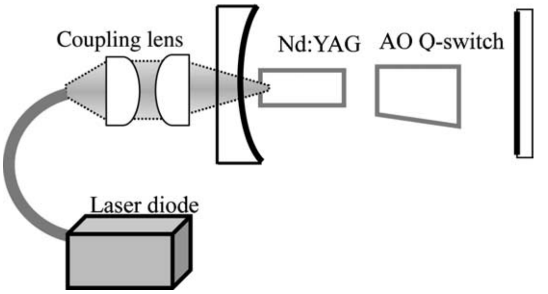

Fig. 1. Schematic of a diode-pumped actively Q-switched Nd:YAG laser at 1123 nm.

3. Experimental results and theoretical analysis

Fig. 2 shows the average output power at 1123 nm in cw mode and Q-switched mode as a function of the incident pump power. The maximum cw output power of 3.8 W was obtained at an incident pump power of 19.2 W, corresponding to a slope efficiency of 25.0% and a threshold power of 4.4 W. The beam quality M^2 factor was found to be less than 1.6 for all pump powers. As seen in Fig. 2, the highest average output power of 3.0 W was measured at 19.2 W of incident pump power in a Q-switch regime at a repetition rate of 20 kHz, corresponding to a slope efficiency of 22.8% and a threshold power of 6.1 W. The spectral information of the laser was monitored by an optical spectrum analyzer (Advantest Q8381A). The present spectrum analyzer employing diffraction lattice monochrometor can be used for high-speed measurement of pulse light with the resolution of 0.1 nm. The measurement of the optical spectrum for the laser beam is depicted in Fig. 3.

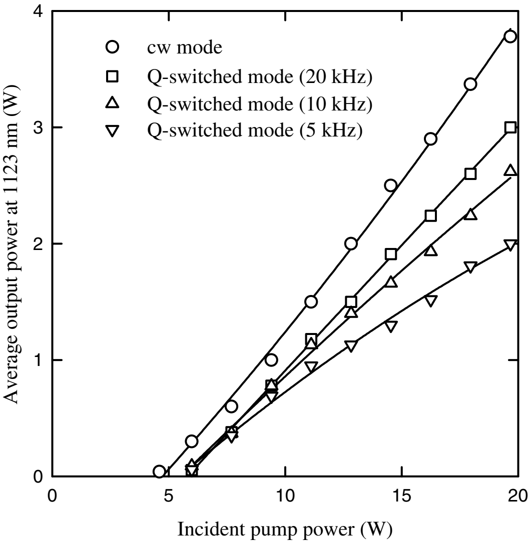

Fig. 2. Average output power versus incident pump power in actively Q-switching and cw operations at 1123 nm.

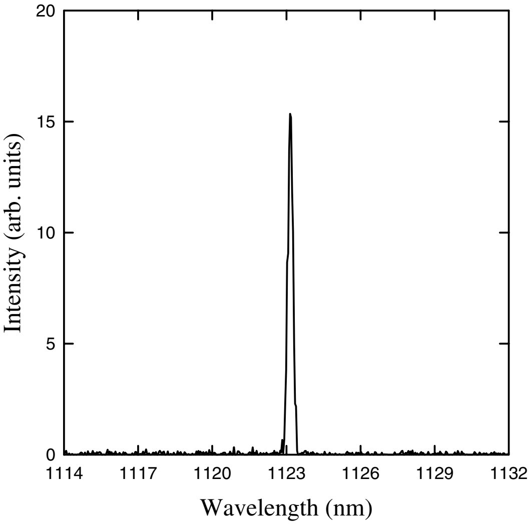

Fig. 3. Measured spectral output of the diode-pumped actively Q-switched Nd:YAG laser at 1123 nm.

With the conventional model of coupled rate equations [9,10], the pulse energy E_p, peak power P_{peak}, and pulse width τ_p, are given by:

$$E_p = h\nu\left(\pi w_o^2 l\right)\frac{\ln(1/R)}{\ln(1/R)+L}(n_i - n_f), \tag{1}$$

$$P_{peak} = h\nu\frac{\left(\pi w_o^2 l\right)}{t_r}\ln(1/R)\{n_i - n_t[1+\ln(n_i/n_t)]\}, \tag{2}$$

$$\tau_p = \frac{t_r}{\ln(1/R)+L}\left\{\frac{n_i - n_f}{n_i - n_t[1+\ln(n_i/n_t)]}\right\}, \tag{3}$$

where $h\nu$ is the photon energy, n_i is the initial inversion density, n_f is the final inversion density, $n_t = [\ln(1/R)+L]/(2\sigma l)$ is the population inversion density at threshold, σ is the emission cross section, πw_o^2 is the cavity mode area, l is the crystal length, t_r is the roundtrip transit time in the laser resonator, R is the output mirror reflectivity, and L is the roundtrip dissipated optical loss. For Q-switching at a repetition rate f, the values of n_i and n_f are determined from solving the following system of equations [11]:

$$n_i - n_f = n_t \ln(n_i/n_f), \tag{4}$$

$$n_i = R_p\tau\left[1-\exp\left(\frac{-1}{\tau f}\right)\right] + n_f\exp\left(\frac{-1}{\tau f}\right), \tag{5}$$

where R_p is the pump rate and τ is the fluorescence lifetime of the upper laser level. In terms of the

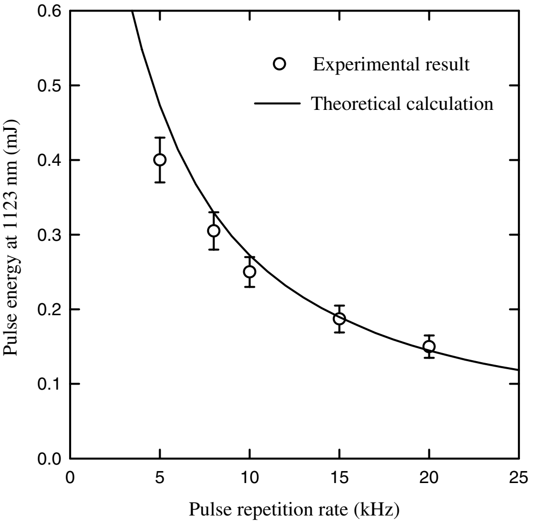

Fig. 4. Pulse energy versus pulse repetition rate in Q-switching regime at an incident pump power of 19.2 W.

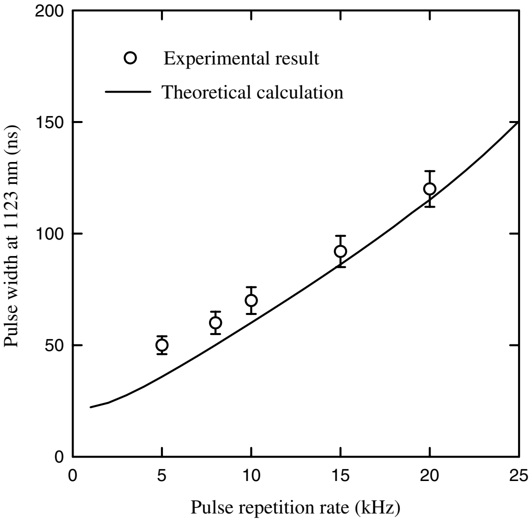

Fig. 5. Pulse width versus pulse repetition rate in Q-switching regime at an incident pump power of 19.2 W.

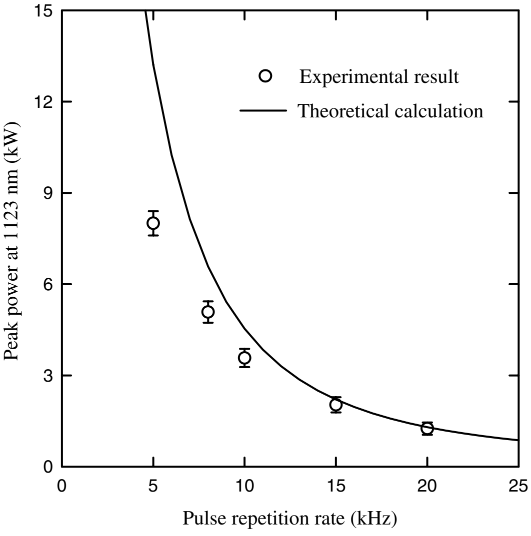

Fig. 6. Pulse peak power versus pulse repetition rate in Q-switching regime at an incident pump power of 19.2 W.

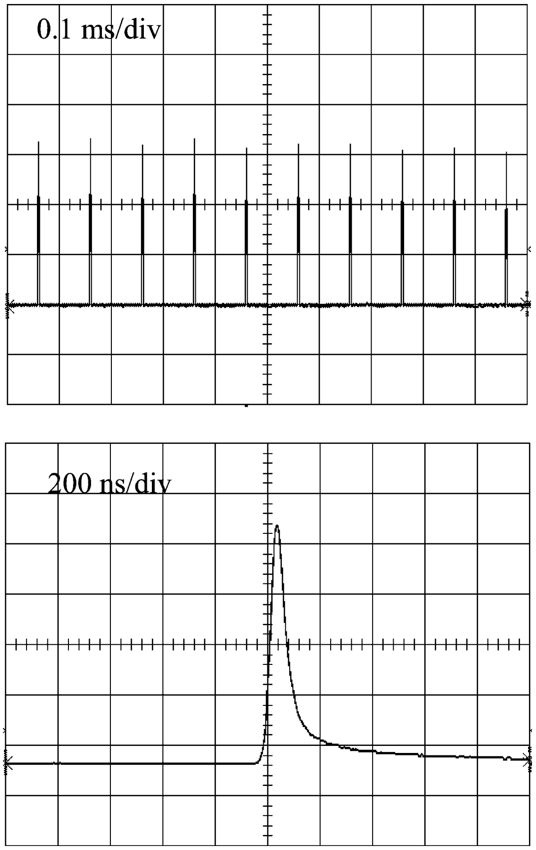

Fig. 7. A typical oscilloscope trace of a train of pulses; lower trace is an expanded shape of a single pulse.

absorbed pump power P_{abs}, the pump rate is given by

$$R_{\mathrm{p}} = \frac{P_{\mathrm{abs}}}{h\nu_{\mathrm{p}}} \cdot \frac{1}{\pi w_{\mathrm{p}}^2 l}, \tag{6}$$

where $h\nu_{\mathrm{p}}$ is the pump photon energy and πw_{p}^2 is the pump beam area.

The results of the numerical analysis of the Q-switch operation are shown in Figs. 4–6. The parameters used in the calculation are as follows: $\tau = 230$ μs, $l = 5$ mm, $w_{\mathrm{p}} = 310$ μm, $w_{\mathrm{o}} = 200$ μm, $L = 0.006$, $R = 0.94$, $t_{\mathrm{r}} = 0.6$ ns, $P_{\mathrm{abs}} = 19.2$ W, and $\sigma = 3 \times 10^{-20}$ cm^2 [2]. For comparison, the experimental data was also plotted in the same figure. It is seen that the theoretical analysis can reasonably describe the experimental data. The main discrepancy in the low frequency range (5–10 kHz) may arise from other mechanics such as energy transfer up-conversion (ETU). It has been demonstrated that the ETU effect leads to a lengthening of the pulse duration and a reduction of the pulse energy [12]. Despite the discrepancies, the general agreement indicates that the simple model of the laser is adequate for a first order prediction of the low-gain laser characteristics. As shown in Fig. 4, the pulse energy at an incident pump power of 19.2 W increases from 0.15 mJ at 20 kHz to 0.4 mJ at 5 kHz. With an incident pump power of 19.2 W, the overall peak power is higher than 1.0 kW at a pulse repetition rate range of 5–20 kHz. A typical oscilloscopic trace of a train of output pulses is also presented in Fig. 7. The pulse-to-pulse amplitude fluctuation of Q-switched pulse train was measured to be less than ±10%.

4. Conclusions

In summary, a diode-pumped actively Q-switched Nd:YAG laser at 1123 nm has been demonstrated. It is found that 0.4 mJ pulses of 50 ns duration at a pulserepetition rate of 5 kHz can be obtained at an incident pump power of 19.2 W. The numerical analysis was found to be in general good agreement with the experimental results. The significant peak power achievable with the present laser might allow for interesting applications in other fields, such as second harmonic generation into the yellow light at 561 nm.

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