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Laser–diode-pumped passively Q-switched Nd^{3+}:$NaY(WO_4)_2$ laser with GaAs saturable absorber

Shengzhi Zhao*, Lei Chen, Hongming Zhao, Guiqiu Li, Lu Zhang, Kejian Yang

Optics Department, Shandong University, Jinan 250100, People's Republic of China

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Abstract

A laser–diode-pumped passively Q-switched new type crystal Nd^{3+}:$NaY(WO_4)_2$ (known as Nd:NYW) laser with GaAs semiconductor saturable absorber has been realized. The dependence of pulse repetition rate, pulse energy, pulse width, and peak power on pump power for different output coupler reflectivities are measured. The coupled rate equations are used to simulate the Q-switched process of laser, and the numerical solutions agree with the experimental results.

Keywords: LD-pump; Passive Q-switch; Nd:NYW crystal; GaAs saturable absorber

1. Introduction

Laser–diode-pumped all-solid-state passively Q-switched lasers, due to the advantages of miniature, simplicity, compactness, high efficiency and low cost, have wide applications in the fields of remote sensing, ranging, medicine, etc. Passive Q-switching technique is usually accomplished with intra-cavity saturable elements such as dyes [1], color centers [2], Cr^{4+}:YAG crystals [3], semiconductors [4], and anti-resonant Fabry–Pérot [5]. Semiconductor saturable absorber GaAs has become another attractive candidate for passive Q-switchers due to the large optical nonlinearity. The energy of a photon at the wavelength of 1.06 μm is far below the GaAs band gap of 1.42 eV. The absorption at this wavelength is believed to be mainly due to the EL2 defect that forms deep donor levels $EL2^0/EL2^+$ about 0.82 eV below the band gap. However, at sufficient high laser intensities, the nonlinear absorption is dominated by two-photon absorption (TPA). Passively Q-switched laser with GaAs as saturable absorber was firstly realized by Kajava and Gaeta in 1996 [6]. Recently, GaAs has been successfully used as passive Q-switchers for a variety of laser medium, such as Yb:YAG [7], $Nd:YVO_4$ [8], Nd:GdCOB [9], etc.

Nd^{3+}-doped $NaY(WO_4)_2$, known as Nd:NYW, is a new crystal. According to our measurement, this crystal features a wide absorption bandwidth of 13.7 nm near 805 nm and a wide emission bandwidth of 14.2 nm near 1060.2 nm [10]. These bandwidths are much broader than those of other frequently used Nd^{3+} doped crystals, such as Nd:YAG, $Nd:YVO_4$ and Nd:SFAP [11]. Meanwhile, the emission life of 180 μs is nearly 2 times that of $Nd:YVO_4$. Thus, Nd:NYW is an attractive laser medium for diode pump in spite of its inferior thermal properties. By using the pulse Q-switched dye laser as pump source, the laser operation at 1.06 μm with this crystal was demonstrated [10]. By using xenon flash lamp as pump source, the passively Q-switched Nd:NYW laser with Cr^{4+}:YAG saturable absorber at 1.06 μm was realized [12]. Recently, we have successfully realized the passive Q-switching of a laser–diode-pumped intracavity-frequency doubling Nd:NYW/KTP laser with GaAs semiconductor saturable absorber [13]. In this paper, we present the performance of a laser–diode-pumped Nd:NYW laser passively Q-switched with GaAs saturable absorber at 1.06 μm. For different output coupler reflectivities, the pulse energy, the pulse width and the repetition rate of 1.06 μm laser have been measured. Also, the coupling wave rate equations for passively Q-switched laser are given and the experimental results are in fair agreement with the numerical solution of equations.

* Corresponding author.
E-mail address: shengzhi_zhao@sdu.edu.cn (S. Zhao).

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2. Experiment

2.1. Experimental setup

In the resonator configuration shown in Fig. 1, the cavity length was 9 cm. M_1 was a concave mirror with radius of curvature of 150 mm, anti-reflectance (AR) coated at 808 nm on the entrance face, high-reflectance (HR) coated at 1.06 μm and high-transmission (HT) coated at 808 nm on the other face; M_2 was a flat mirror acting as the output coupler of the resonator. The laser crystal utilized is 0.5 at% Nd^{3+}-doped a-cut Nd:NYW with dimension of $3 \times 3 \times 5$ mm^3 and has a absorption coefficient of 4.8 cm^{-1} for 808 nm π-polarized pump light. Both ends of the crystal were AR coated at 1.06 μm to reduce the cavity loss. To reduce the thermal loading in the laser crystal and hence prevent it from possible thermal fracture, the Nd:NYW crystal was wrapped with indium foil and held in a copper block which was cooled by using semiconductor coolers. The crystal temperature was kept at 20°C. A thin GaAs wafer (580 μm), AR coated at 1.06 μm, was placed near the output coupler. The laser diode pump source (made by Semiconductor Institute, Chinese Academic, maximum radiation of 5 W at 808 nm) was coupled out through fiber with 0.2 mm radius and a numerical aperture of 0.37, and focused into the gain medium through a gradient-index (GRIN) lens. The waist radius of the pump light in the gain medium was about 320 μm. The pump wavelength (808 nm) was tuned to the Nd:NYW absorption peak by means of a temperature controller. A fast photo-electronic diode (response time is less than 1 ns) was used to receive the generated pulse. The LPE-1B energy meter (Institute of Physics, Chinese Academy of Science) and the TDS620B digital oscilloscope (Tektronix Inc. USA) were used to measure the average output power, the pulse width and the pulse repetition rate, respectively. Two output couplers, whose reflectivity were 90% and 85%, respectively, were used to demonstrate the laser characteristics of Nd:NYW crystal in the experiment.

2.2. Experimental results

The average output power, repetition rate, and pulse width in the Q-switched operation were measured as functions of incident pump power. The pulse energy was determined from the average output power and the repetition rate. The peak power was determined from the pulse energy and the pulse width. Fig. 2 shows the average output power as a function of the incident pump power for GaAs saturable absorbers for two different output coupler reflectivities $R = 90$ and 85%, respectively. From Fig. 2 we can see that the average output power increases almost linearly with the incident pump power. The pump threshold powers are 1.1 and 1.4 W for the two different reflectivities $R = 90$ and 85%. The highest average output power is obtained with a lower reflectivity $R = 85\%$ at a maximum pump power of 4.15 W and the Nd:NYW laser generated an average output power of 92.6 mW. For the $R = 90\%$ output coupler, the maximum output power reduced to 57 mW. Just above the threshold, unstable 356 and 260 ns pulses for $R = 90\%$ and 85% were produced, respectively. The corresponding repetition rate were 41 and 38 kHz. Figs. 3–6 show the pulse repetition rate, the pulse energy, the pulse width and the peak power as functions of the incident pump power for the two output couplers. As can be seen from Fig. 3, the pulse repetition rate increased at first when the incident pump power was relatively low; after the pump power was greater than 3 W, it exhibited an irregular fluctuation, although the highest repetition rate were obtained at the maximum incident pump power for the both output couplers. Repetition rate of 130.8 and 145.3 kHz were measured at 4.15 W pump power for the output coupler $R = 90$ and 85%, respectively. The mechanism of the abnormal fluctuation of repetition rate shown in Fig. 3 is not very clear yet and it requires further research. But we suspect that this phenomenon is probably due to the high-intensity-related TPA and free-carrier absorption. In addition, because GaAs film was not cooled, the thermal

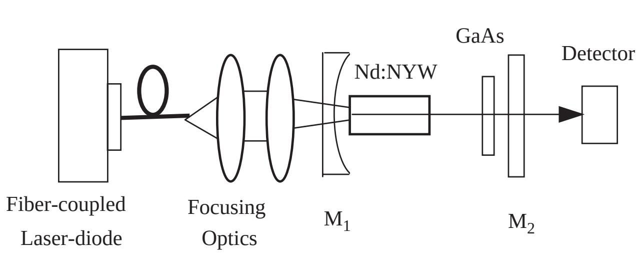

Fig. 1. Schematic diagram of the passively Q-switched Nd:NYW laser with a GaAs saturable absorber.

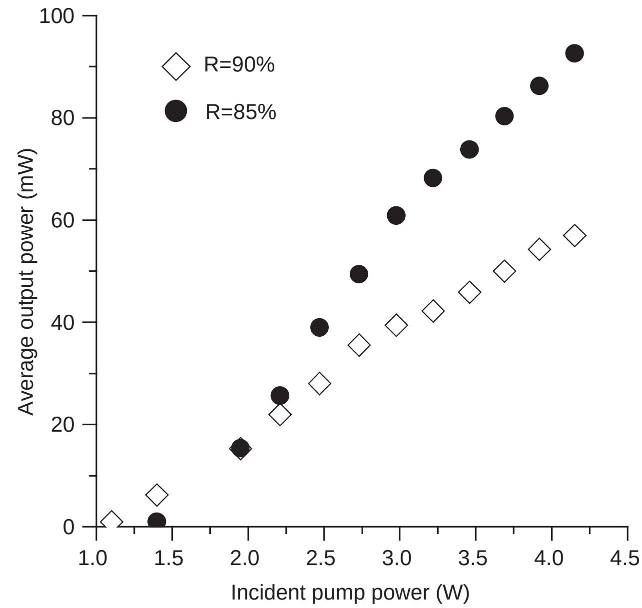

Fig. 2. Average output power versus incident pump power for GaAs saturable absorber with different output coupler reflectivities.

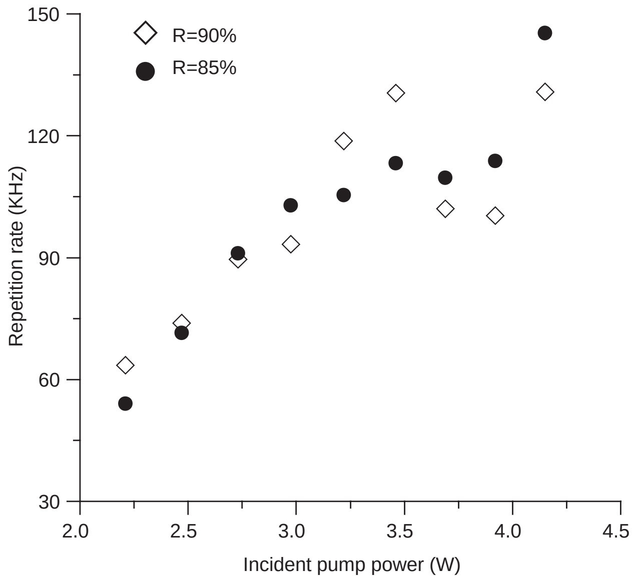

Fig. 3. Pulse repetition rate versus incident pump power for GaAs saturable absorber with different output coupler reflectivities.

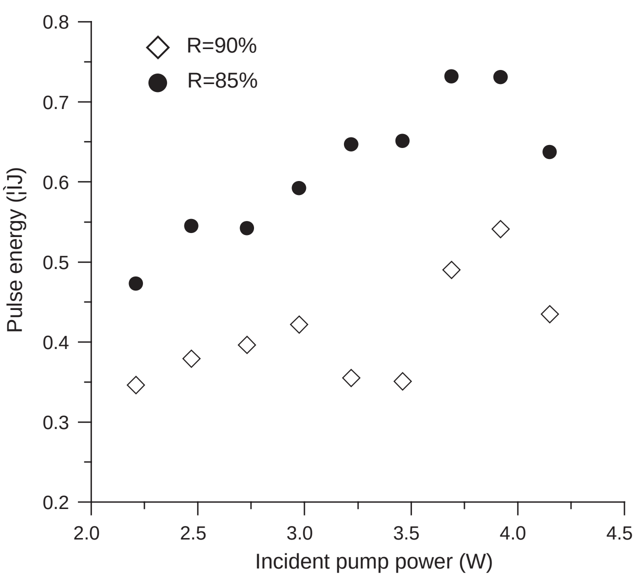

Fig. 4. Pulse energy versus incident pump power for GaAs saturable absorber with different output coupler reflectivities.

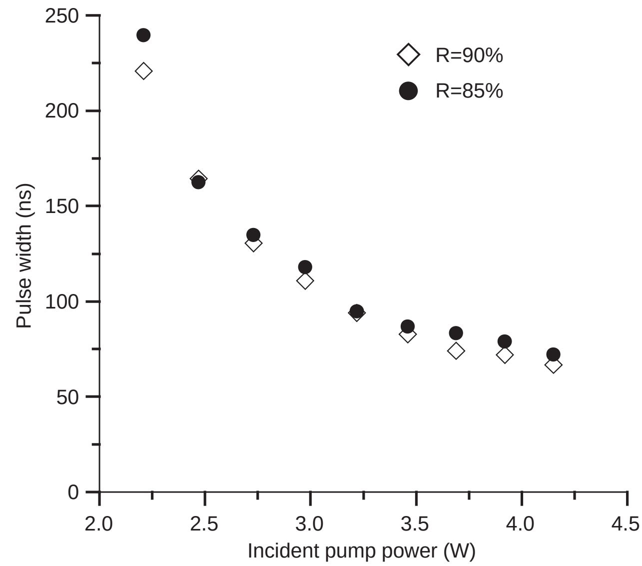

Fig. 5. Pulse width versus incident pump power for GaAs saturable absorber with different output coupler reflectivities.

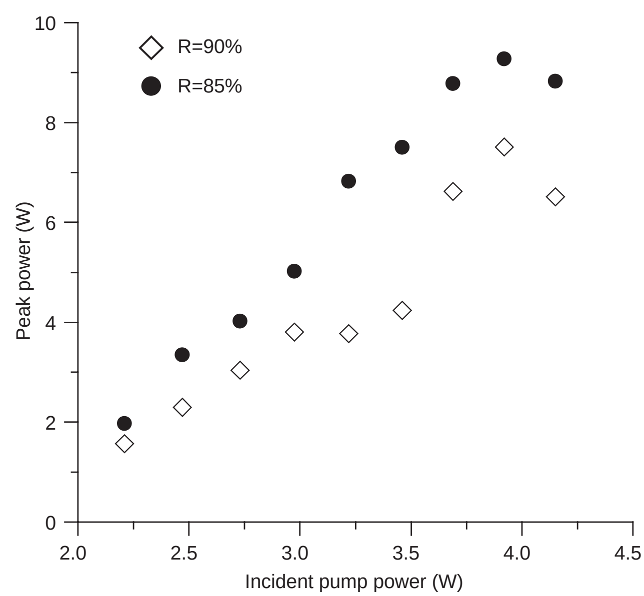

Fig. 6. Peak power versus incident pump power for GaAs saturable absorber with different output coupler reflectivities.

lens effects of GaAs may be playing a role. From Figs. 4–6, we can see that an increase in the pump power resulted in a sharp decrease of the pulse width because of the more rapid saturation of GaAs under high laser intensity. For the $R = 90\%$ output coupler, 72 ns pulse width was obtained at the incident pump power 3.9 W. The corresponding pulse energy and the peak power were 0.54 μJ and 7.5 W, respectively. When the output coupler with a lower reflectivity was used, the higher pulse energy and the peak power while the broader pulse width were observed. The $R = 85\%$ output coupler generated the highest pulse energy of 0.73 μJ with a pulse width 78.8 ns at the incident pump power 3.9 W, corresponding to the highest peak power 9.27 W. Fig. 7 gives an oscilloscope Q-switch pulse (solid line) of the output laser for the $R = 90\%$ output coupler with a pulse width 72 ns at the incident pump power of 3.9 W. Fig. 8 shows a typical oscilloscope trace of a train of pulses with a pulse repetition rate of approximately 53 kHz. We also investigated the Q-switching behavior with a flat $R = 96\%$ output coupler. When the incident pump power reached 4 W, 52 ns pulses were obtained with a repetition rate 90 kHz, and the average output power was 27 mW, corresponding to a pulse energy 0.3 μJ.

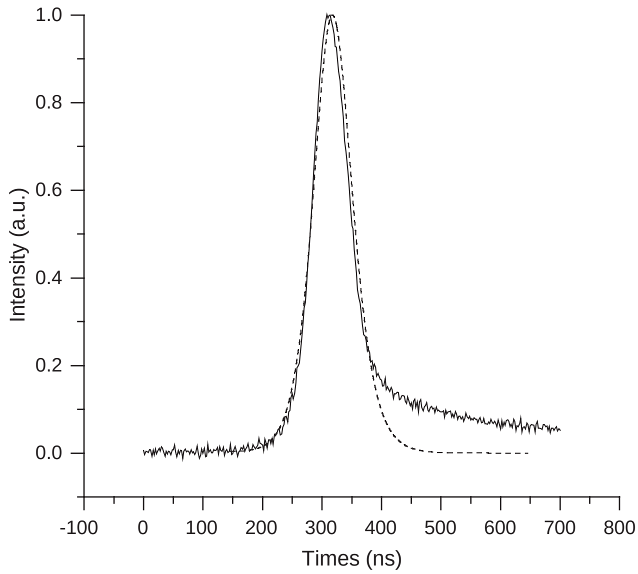

Fig. 7. Temporal profile of single Q-switched pulse when $R = 90\%$. Solid line, oscilloscope trace; dashed line, calculated result.

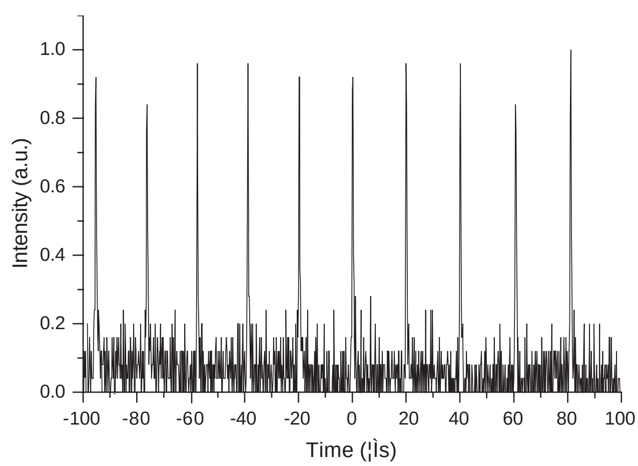

Fig. 8. Oscilloscope trace of a train of GaAs passively Q-switching pulses with a repetition rate of approximately 53 kHz.

3. Theoretical estimation and discussion

The saturable absorptions of GaAs wafer include the single-photon absorption (SPA) and two-photon absorption (TPA) as well as free-carrier absorption (FCA). The energy level responsible for absorption around 1 μm is believed to be the EL2 defect (including $EL2^0$ and $EL2^+$) level between conduction and valence bands. To model the operation of a passively Q-switched laser, the distribution in the transverse section of pump light, and the intra-cavity optical intensities in the gain medium and in the absorber should be assumed uniform. We also neglect the spontaneous emission of the saturable absorber. If the influence of longitudinal attenuation of the pump light is neglected, the Q-switched rate equations under the plane-wave approximation can be used to analyze the performances of the laser. By combining the SPA and TPA processes and including the influence of pump power, the coupled rate equations describing the operation of GaAs Q-switched laser can be written as [9]

$$\frac{dI_1}{dt} = \frac{I_1}{t_r}\left[2\sigma n l - 2\sigma^+ n^+ d - 2\sigma^0 (n_0 - n^+) d - B I_1 - \ln\left(\frac{1}{R}\right) - L\right], \quad (1)$$

$$\frac{dn}{dt} = R_{in} - \frac{4\sigma n I_1}{h\nu} - \frac{n}{\tau}, \quad (2)$$

$$\frac{dn^+}{dt} = \frac{[(n_0 - n^+)\sigma^0 - \sigma^+ n^+] I_1}{h\nu}, \quad (3)$$

where I_1 is the intensity of oscillating laser, n is the population inversion density, n_0 is the total population density of the EL2 defect level (including $EL2^0$ and $EL2^+$) of GaAs saturable absorber, n^+ is the population density of positively charged $EL2^+$, σ is the stimulated emission cross-section of the laser crystal, t_r is the round-trip time in the cavity, $t_r = [2n_1 l + 2n_2 d + 2(L_c - l - d)]/c$, c is the light velocity in the vacuum space, n_1 is the refractive index of the laser crystal, n_2 is the refractive index of GaAs, l is the length of the gain medium, d is the thickness of GaAs, L_c is the cavity length. σ^0, σ^+ are the absorption cross-sections of $EL2^0$ and $EL2^+$, respectively, τ is the emission lifetime of laser crystal, R is the output coupler reflectivity, L is the loss of the cavity, $h\nu$ is the photon energy, R_{in} is the volume pumping rate which can be approximately given by: $R_{in} = P_{in}[1 - \exp(-\alpha l)]/h\nu_p \pi \omega_p^2 l$, P_{in} is the incident pump power, $h\nu_p$ is the photon energy of the pump light, and ω_p is the effective radius of the pump light in the gain medium, α is the absorption coefficient of laser crystal. B is the coupling coefficient of TPA in GaAs which is defined as [14]

$$B = 6\beta h\nu c d(\omega_0/\omega_q)^2, \quad (4)$$

where β is the absorption coefficient of two photons, ω_0 and ω_q are the spot size of the beam in the gain medium and GaAs wafer, respectively. The small-signal transmission T_0 of GaAs can be expressed by $T_0 = \exp\{-[\sigma^0(n_0 - n^+) + \sigma^+ n^+]d\}$. It can be calculated that $T_0 = 93.8\%$ for the used GaAs film.

Table 1
Related parameters for Eqs. (1)–(3)

$n(t=0)$	$[2\sigma^0(n_0 - n^+)d + 2\sigma^+ n^+ d + \ln(1/R) + L]/\sigma l$		
σ	6.0×10^{-20} cm^2	τ	180 μs
σ^0	1.0×10^{-16} cm^2	β	2.6×10^{-8} cm W^{-1}
σ^+	2.3×10^{-17} cm^2	η_1	1.9
n_0	1.2×10^{16} cm^{-3}	η_2	3.48
n^+	1.4×10^{15} cm^{-3}	l	0.5 cm
ω_0	252 μm	d	580 μm
ω_q	156 μm	L	0.09

Data from Refs. [8–10,13].

Table 2
Comparison of theoretical calculations and experimental results

Experimental conditions		Pulse energy (μJ)		Pulse width (ns)	
R (%)	P_{in} (W)	Theory	Experiment	Theory	Experiment
90	2.2	0.359	0.346	227.3	220.8
	3.0	0.439	0.422	115.0	110.8
	3.9	0.552	0.541	73.3	72
85	2.2	0.483	0.473	244.3	239.6
	3.0	0.601	0.592	120.1	118
	3.9	0.739	0.731	80.8	78.8

By using computer, we obtain the numerical solutions of Eqs. (1)–(3) and the analogue output characteristics of Nd:NYW Q-switched laser with GaAs saturable absorber. If the effective pumping radius ω_p is 0.32 mm, the pumping rate will be $R_{in}=2.3\times10^{21}P_{in}$ cm^{-3} s^{-1}. The related parameters are given in Table 1. ω_0, ω_p, ω_q and L among them are the measured values according to the cavity configuration.

The experimental results and the theoretical calculations of pulse energy and pulse width for different output reflectivities are given in Table 2. We can see that the experimental results are in fair agreement with the theoretical calculations. The dashed line in Fig. 7 is the calculated pulse shape for $R = 90\%$ output coupler at the incident pump power of 3.9 W with a pulse width of 73.3 ns. The corresponding pulse energy is 0.552 μJ. The experimentally measured pulse width of 72 ns is in good agreement with the calculated pulse width of 73.3 ns.

4. Conclusion

In conclusion, we have successfully demonstrated the performance of a laser–diode-pumped Nd:NYW laser passively Q-switched with GaAs semiconductor saturable absorber. Pulses of duration of 72 ns and energy of 0.541 μJ are obtained. The shortest pulse duration that we observed were 52 ns. The numerical solutions of Q-switched coupling rate equations are in fair agreement with the experiment results.

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