Pulse width reduction in diode-pumped, doubly Q-switched Nd:GdVO$_4$/KTP green laser

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Using both acoustic-optic (AO) Q-switch and GaAs saturable absorber, a diode-pumped doubly Q-switched Nd:GdVO$_4$/KTP green laser is realized. This laser can generate a shorter and more symmetric pulse in comparison with purely AO and passively Q-switched lasers. In the meantime, the rate equations describing the operation of a diode-pumped, AO and GaAs doubly Q-switched Nd:GdVO$_4$/KTP green laser are introduced. These equations are solved numerically and the dependence of pulse width on incident pump power is obtained. The numerical solutions are in agreement with the experimental results.

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In recent years, diode-pumped, Q-switched solid-state lasers have attracted a great deal of attention because of their high efficiency, simplicity, compactness, and good frequency stability. All solid-state actively and passively Q-switched lasers have wide applications in the fields of remote sensing, information storage, coherent telecommunications, medicine, etc.. Acoustic-optic (AO) modulator is often used as the active Q-switch, and GaAs saturable absorber as the passive Q-switch[1−6]. Although AO Q-switched lasers can obtain short pulses and high peak powers, the pulse temporal profile of AO Q-switched lasers is usually asymmetric, with a sharp rising edge and a slow falling edge. In some applications, shorter and symmetric pulse is required. By using both the active and passive Q-switches in the same cavity, it is possible to compress the pulse width and obtain shorter and symmetric pulses[7−9]. As a new host material for Nd^{3+} ion, the GdVO$_4$ crystal was developed by Zagumennyi *et al.*[10], and Nd:GdVO$_4$ has been experimentally confirmed to be a promising laser medium for diode pumping[11]. During the past few years, diode-pumped Q-switched Nd:GdVO$_4$ lasers have been studied[12−14]. However, no theoretical and experimental performance of doubly Q-switched Nd:GdVO$_4$/KTP green laser with AO and GaAs was reported as far as we know.

The experimental setup is shown in Fig. 1. The pump source is a fiber-coupled laser diode (Semiconductor Institute, Chinese Academy of Sciences, maximum output power 5 W) which works at the maximum absorption wavelength of the Nd:GdVO$_4$ crystal (808 nm). The mirror M_1 with 150-mm curvature radius is high anti-reflection (AR) coated at 808 nm and high reflection (HR) coated at 1064 nm. The Nd:GdVO$_4$ crystal doped with 1.0 at.-% Nd^{3+} ions is $4 \times 4 \times 5$ (mm) in dimension and its absorption coefficient at 808 nm is 5.32 cm^{-1}. Its front surface is AR coated at 808 nm and its rear surface is high transmission (HT) coated at 1064 nm. It is near M_1. Both ends of the AO modulator are AR coated at 1064 nm. The distance between the front surface of the AO crystal and M_1 is 7 cm and that between the GaAs saturable absorber and M_1 is 11 cm. The mirror M_2 with 100-mm curvature radius is also used as the output mirror of the generated green light, and the distance between M_1 and M_2 is about 22 cm. The KTP crystal cut for type-II phase matching (Coretech Crystal Company, Shandong University, China) is $3 \times 3 \times 10$ (mm) in dimension and its both surfaces are AR coated at 1064 and 532 nm. The temperatures of the Nd:GdVO$_4$ crystal and the KTP crystal are controlled at 20 and 22 °C by means of a temperature controller, respectively. M_3 is a plane mirror and its surface is HR coated at 1064 and 532 nm. The KTP crystal is near M_3. The distance between M_2 and M_3 is about 8 cm. The filter is used for separating 532-nm green laser from the remainder 1064-nm fundamental wave leaking out from the resonator. A TED620B digital oscilloscope (Tektronix Inc., USA) is used to measure the generated green laser pulse.

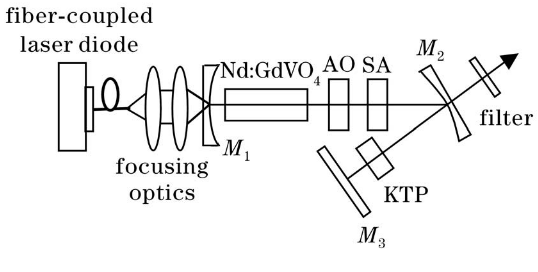

Fig. 1. Schematic of the experimental setup. SA: saturable absorber.

Single-pulse temporal profiles for the AO, passively, and doubly Q-switched lasers with a pump power of 2.31 W are shown in Fig. 2. The pulse width of the doubly Q-switched laser is 44 ns at 20 kHz as shown in Fig. 2(b). It is noticed that the pulse profile is rather symmetric with about 22 ns in both the rise and fall edges. Under the same conditions, the pulse width of the AO Q-switched laser is 66.8 ns as shown in Fig. 2(a), and the pulse profile is asymmetric with a rise time of about 27 ns and a slow falling edge of about 40 ns as well as a long decaying tail. The pulse width of the passively Q-switched laser is 69.6 ns as shown in Fig. 2(c). From Fig. 2, we can see that the doubly Q-switched laser has a shorter pulse width and a more symmetric pulse temporal profile in comparison with the AO Q-switched laser. This is mainly due to the nonlinear absorption of the GaAs absorber, which leads to a much faster falling edge

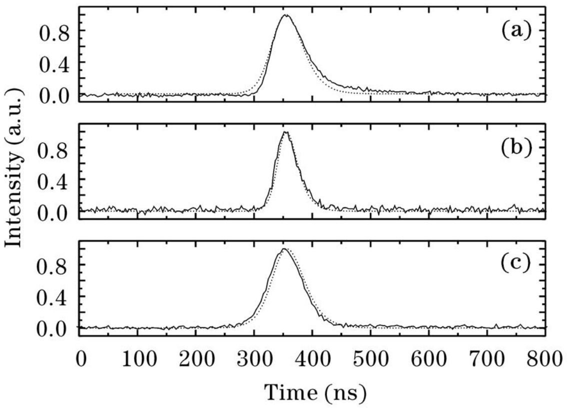

Fig. 2. Single-pulse temporal profiles of pure AO (a), doubly (b), and passively Q-switched (c) lasers. Solid cruves: oscilloscope traces; dotted curves: calculated results.

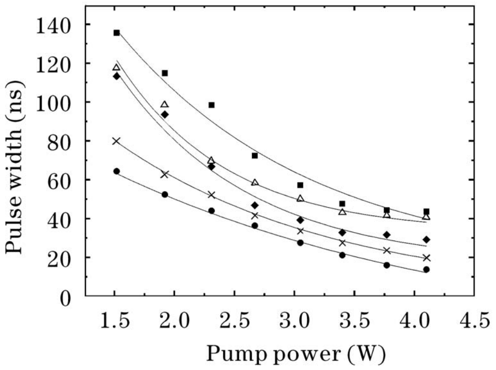

Fig. 3. Pulse width versus pump power. The diamonds represent pure AO Q-switching at 20 kHz, the squares pure AO Q-switching at 40 kHz, the dots double Q-switching at 20 kHz, the crosses double Q-switching at 40 kHz, and the triangles passive Q-switching. The curves are theoretical calculation results.

in the pulse profile.

The dependences of pulse width on incident pump power with the above-mentioned three types of Q-switching are shown in Fig. 3 by scattered dots. Figure 3 shows that the pulse width always increases with the repetition rate in both the AO and the doubly Q-switched lasers while the pulse width of the doubly Q-switched laser is always shorter than that of the AO Q-switched laser.

From Figs. 2 and 3, we can see that for a diode-pumped doubly Q-switched Nd:GdVO$_4$/KTP green laser with AO and GaAs, the pulse width is obviously compressed in comparison with the other two methods of Q-switching and the pulse profile is rather symmetric.

When the rate equations are used to analysis the performance of a Q-switched intracavity-frequency-doubling laser, the second-harmonic conversion can be considered as the nonlinear loss of the fundamental wave. The nonlinear loss δ_{N} for type-II phase-matching KTP crystal can be expressed as[15]

$$\delta_{\mathrm{N}} = \frac{K_{\mathrm{N}}}{2}\hbar\omega c l_{\mathrm{K}}^2\phi, \tag{1}$$

where $\hbar$ is Planck's constant, ω is the angular frequency of fundamental wave, c is the velocity of light in vacuum, l_{K} is the length of KTP, ϕ is the average photon density in the laser cavity, the coefficient K_{N} can be expressed as[15]

Table 1. Parameters of Type-II Phase-Matching KTP Crystal*

n_{e1}^{ω}	n_{e2}^{ω}	$n_{e2}^{2\omega}$	d_{eff} (pm/V)	ε_0 (c^2/N·m^2)
1.83	1.746	1.79	7.2	8.855×10^{-12}

*These data are provided by Coretech Crystal Company, Shandong University.

$$K_{\mathrm{N}} = \frac{\omega^2 d_{\mathrm{eff}}^2}{c^3\varepsilon_0 n_{e2}^{2\omega} n_{e2}^{\omega} n_{e1}^{\omega}}, \tag{2}$$

where d_{eff} is the effective nonlinear coefficient, ε_0 is the dielectric permeability of vacuum, $n_{e2}^{2\omega}$, n_{e2}^{ω}, and n_{e1}^{ω} are harmonic and fundamental wave refractive indices, respectively.

The corresponding parameters for type-II phase-matching KTP crystal are listed in Table 1.

If neglecting the spontaneous radiation during the pulse formation and concerning all these absorption processes of GaAs: single-photon absorption (SPA), two-photon absorption (TPA), and free-carrier absorption (FCA), the rate equations of a diode-pumped doubly Q-switched Nd:GdVO$_4$/KTP green laser under the plane-wave approximation can be written as[6]

$$\frac{\mathrm{d}\phi}{\mathrm{d}t} = \frac{\phi}{t_r}[2\sigma n l - 2\sigma^{+}n^{+}l_{\mathrm{s}} - 2\sigma^{0}(n_0 - n^{+})l_{\mathrm{s}} - 2\sigma_{\mathrm{f}}Nl_{\mathrm{s}} - Bl_{\mathrm{s}}\phi - \delta_{\mathrm{A}}(t) - \delta_{\mathrm{N}} - L], \tag{3}$$

$$\frac{\mathrm{d}n}{\mathrm{d}t} = R_{\mathrm{in}} - \sigma c n\phi - \frac{n}{\tau}, \tag{4}$$

$$\frac{\mathrm{d}n^{+}}{\mathrm{d}t} = c\phi[(n_0 - n^{+})\sigma^{0} - \sigma^{+}n^{+}] - \gamma_{\mathrm{et}}n^{+}N + \gamma_{\mathrm{hd}}(n_0 - n^{+})p, \tag{5}$$

$$\frac{\mathrm{d}N}{\mathrm{d}t} = c\phi\left[(n_0 - n^{+})\sigma^{0} + \frac{B\phi}{2}\right] - \gamma_{\mathrm{et}}n^{+}N - \gamma_{\mathrm{eh}}Np, \tag{6}$$

$$\frac{\mathrm{d}p}{\mathrm{d}t} = c\phi\left(\sigma^{+}n^{+} + \frac{B\phi}{2}\right) - \gamma_{\mathrm{hd}}(n_0 - n^{+})p - \gamma_{\mathrm{eh}}Np. \tag{7}$$

In the above equations, ϕ is the average photon density in the laser cavity; t_{r} is the round-trip time of light in the resonator ($t_{\mathrm{r}} = [2n_1 l + 2n_2 l_{\mathrm{A}} + 2n_3 l_{\mathrm{s}} + 2n_4 l_K + 2(L_e - l - l_{\mathrm{A}} - l_{\mathrm{s}} - l_{\mathrm{K}})]/c$, in which n_1, n_2, n_3, and n_4 are the refractive indices of Nd:GdVO$_4$ gain medium, AO crystal, GaAs saturable absorber, and KTP crystal, respectively, L_e is the physical cavity length, l is the length of Nd:GdVO$_4$, l_{A} is the length of the AO crystal, l_{s} is the thickness of GaAs, l_{K} is the length of KTP); 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; n^{+} is the population density of positively charged EL2$^+$; N is the density of electrons; p is the density of holes; σ is the stimulated-emission cross section of Nd:GdVO$_4$; σ^0 and σ^+ are the absorption cross sections of EL2^0 and EL2^+, respectively; σ_f is the free carriers absorption cross section; $B = 6\beta h\gamma c(w_0/w_q)^2$ is the coupling coefficient of TPA in GaAs, where β is the absorption coefficient of two photons, $h\gamma$ is the single photon energy of the fundamental wave, w_0 and w_q are the spot sizes of the beam in the gain medium and GaAs wafer, respectively; δ_N is the nonlinear loss which is given in Eq. (1); L is the loss of the cavity; τ is the stimulated-radiation lifetime of the gain medium; γ_et, γ_eh, and γ_hd are the recombination coefficients of EL2^+-electron, electron-hole, and EL2^0-hole, respectively; $R_\mathrm{in} = P_\mathrm{in}[1 - \exp(-\alpha l)]/h\gamma_\mathrm{p}\pi w_\mathrm{p}^2 l$ is the pump rate, where P_in is the pump power, $h\gamma_\mathrm{p}$ is the single-photon energy of pump light, w_p is the radius of the pump beam in the gain medium, α is the absorption coefficient of the gain medium; $\delta_\mathrm{A}(t)$ is the loss function of the AO Q-switch, which is defined as[7]

$$\delta_\mathrm{A}\,(t) = \delta_\mathrm{A} \exp\left[-\left(t/t_\mathrm{s}\right)^2\right], \tag{8}$$

where δ_A is the intrinsic diffraction loss of the AO Q-switch; t_s is the turnoff time of the AO Q-switch.

From Eq. (4), we can deduce the initial population-inversion density n^0 accumulated during a modulation period of the AO modulator

$$n^0 = R_\mathrm{in}/f_\mathrm{p}, \tag{9}$$

where f_p is the modulation frequency of the AO modulator.

If neglecting the terms concerning GaAs wafer in the above-mentioned rate equations, we can obtain the rate equations describing a diode-pumped AO Q-switched Nd:GdVO$_4$/KTP green laser as

$$\frac{\mathrm{d}\phi}{\mathrm{d}t} = \frac{\phi}{t_\mathrm{r}}[2\sigma nl - \delta_\mathrm{A}(t) - \delta_\mathrm{N} - L], \tag{10}$$

$$\frac{\mathrm{d}n}{\mathrm{d}t} = R_\mathrm{in} - \sigma cn\phi - \frac{n}{\tau}. \tag{11}$$

If neglecting the terms concerning the AO Q-switch in Eq. (3), we can obtain the rate equations describing a diode-pumped passively Q-switched Nd:GdVO$_4$/KTP green laser with GaAs saturable absorber.

Table 2. Parameters of the Theoretical Calculation[6,12]

Parameter	Value	Parameter	Value
σ	7.6×10^{-19} cm^2	n_1	2.19
σ^0	1.0×10^{-16} cm^2	n_2	1.6
σ^+	2.3×10^{-17} cm^2	n_3	3.48
σ_f	6×10^{-18} cm^2	n_4	1.83
n_0	1.2×10^{16} cm^{-3}	l	0.5 cm
n_0^+	1.4×10^{15} cm^{-3}	l_A	2.4 cm
τ	90 μs	l_s	580 μm
α	5.49 cm^{-1}	l_K	1.0 cm
β	2.6×10^{-8} cm·W^{-1}	w_0	419 μm
γ_et	1.9×10^{-8} cm^3·s^{-1}	w_q	145 μm
γ_eh	2.0×10^{-10} cm^3·s^{-1}	w_p	330 μm
γ_hd	3.4×10^{-11} cm^3·s^{-1}	t_s	14 ns
L	0.15	δ_A	0.85

According to the corresponding parameters shown in Table 2, by numerically solving the above-mentioned rate equations, we obtained the theoretical pulse profiles for the AO, doubly, and passively Q-switched lasers with a pump power of 2.31 W as shown by the dotted curves in Fig. 2. The pulse width of the doubly Q-switched laser is 42 ns at 20 kHz. Under the same conditions, the pulse width of the AO Q-switched laser is 64 ns and that of the passively Q-switched laser is 66 ns. The dependences of pulse width on incident pump power with the three types of Q-switching are shown in Fig. 3 by the solid curves. From Figs. 2 and 3, we can see that the theoretical calculations are in agreement with the experimental results.

In conclusion, we have realized a diode-pumped doubly Q-switched Nd:GdVO$_4$/KTP green laser using both AO Q-switch and GaAs saturable absorber. This laser can generate a shorter and more symmetric pulse in comparison with purely AO and passive Q-switching. In the meantime, we give the rate equations to simulate a diode-pumped doubly Q-switched Nd:GdVO$_4$/KTP green laser. By numerically solving these rate equations, we obtained the dependence of pulse width on incident pump power and the theoretical calculations are consistent with the experimental results.

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