

Diode-pumped, passively Q-switched Nd:GdVO₄ green laser with periodically poled KTP and Cr⁴⁺:YAG saturable absorber

Kejian Yang, Shengzhi Zhao, Guiqiu Li, and Jing Zou

School of Information Science and Engineering, Shandong University, Jinan 250100, China

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With a laser diode as the pump source, a passive Q switching of an intracavity frequency-doubling Nd:GdVO₄ green laser with periodically poled KTP has been realized with a Cr⁴⁺:YAG saturable absorber. The dependences of the average output power, pulse width, pulse repetition rate, pulse energy, and peak power on incident pump power at different small-signal transmissions of Cr⁴⁺:YAG are measured. The rate equations considering the Gaussian spatial distribution of the intracavity photon density and the effects of the amplified spontaneous emission (ASE) are presented to simulate the Q-switching process of this laser, and the numerical solutions are in agreement with the experimental results. We have further discussed the influences of the ASE parameter ξ on the laser performance. © 2006 Optical Society of America

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1. INTRODUCTION

Laser sources with nanosecond order, high repetition rate, and visible pulses are of practical importance for wide applications such as information storage, coherent telecommunications, and medicine. Q-switching is the most popular method to obtain the laser pulses. Compared with actively Q-switched lasers, the passively Q-switched ones have the advantages of simplicity, compactness, high efficiency, and low cost. The Cr⁴⁺:YAG saturable absorber is found to be superior to dyes¹ and color centers² as a passive Q switcher because it has a large absorption cross section, good thermal conductivity, stable physical and chemical properties, a high doped-ion concentration, and no degradation. The Cr⁴⁺:YAG saturable absorber has been the most widely used saturable absorber for a variety of lasers.^{3–6}

Frequency doubling of diode-pumped Q-switched lasers by one's inserting a nonlinear crystal into the cavity is an attractive approach to realize the solid-state green lasers. Periodically poled nonlinear materials have the potential to serve as versatile devices for laser developers because of their ability to allow quasi-phase matching over long lengths of crystal and allow noncritical phase matching for tight focusing geometries, thereby enabling efficient frequency conversion. Many crystals have been successfully poled for frequency conversion, of which periodically poled LiNbO₃⁷ (PPLN) and periodically poled KTP^{8,9} (PPKTP) have demonstrated the most success. Compared with the PPLN crystal, the PPKTP crystal possesses a high damage threshold (>900 MW/cm² for 5 ns pulse) and low susceptibility for photorefractive effects, which allows it to work at room temperature, although its nonlinear coefficient is lower than that of PPLN crystal.¹⁰

Nd:GdVO₄, as an isomorph of Nd:YVO₄, which was developed first by Zagumennyi *et al.* in 1992,¹¹ has been a promising laser crystal for diode pumping. Nd:GdVO₄

possesses several advantages over Nd:YVO₄, such as a higher absorption coefficient and a much higher thermal conductivity of 11.7 (W m⁻¹)K⁻¹ along the <110> direction.¹² Therefore, it has been a new type of competitive laser crystal in high-power laser generation.^{13,14} With Nd:GdVO₄ as the gain medium and KTP as the frequency-doubling crystal, the lasers operating at 0.532 μ m in both cw and Q-switching regimes have made great progress.^{15–17} With PPKTP as the nonlinear crystal, we have realized the cw operation of the diode-pumped Nd:GdVO₄ laser.¹⁸ As far as we know, there have been no related reports on the passively Q-switched Nd:GdVO₄ green laser with PPKTP and a Cr⁴⁺:YAG saturable absorber.

Rate equations are usually utilized to analyze the performance of a Q-switched laser; especially, the model considering the Gaussian spatial distributions of photon density can give an accurate simulation of the performance of the laser.^{19,20} However, in the above theoretical analysis, the spontaneous-emission process has generally been ignored in the laser photon density because the effect is so weak. Recently, Li *et al.*²¹ stated that the influence of amplified spontaneous emission (ASE) on Q-switched laser performance depended on the Q-switching state, and, during the off state, ASE is the major factor causing depletion of the population inversion. So, in the presence of ASE, the conventional rate equations cannot accurately describe the dynamic behavior of the Q-switched laser.

In this paper, we present the performance of a diode-pumped passively Q-switched Nd:GdVO₄ green laser with PPKTP and a Cr⁴⁺:YAG saturable absorber. For different small-signal transmissions of Cr⁴⁺:YAG, the dependences of pulse width, pulse repetition rates, pulse energy, and peak power of a 0.53 μ m laser on incident pump power are measured. Also, we introduce ASE into a rate equation model considering the Gaussian spatial distribu-

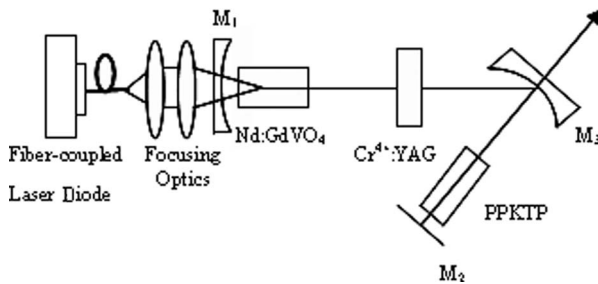
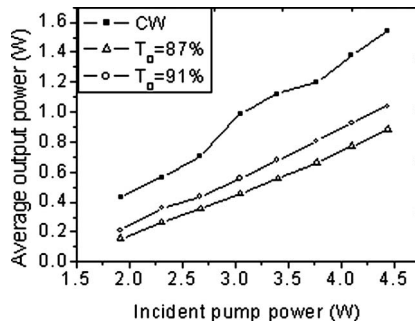


Fig. 1. Scheme of the experimental setup.

Fig. 2. Average output power of cw and passively *Q*-switched Nd:GdVO₄-PPKTP lasers with different Cr⁴⁺:YAG crystals.

tion of the intracavity photon density to simulate the performance of this laser, and the numerical solutions agree with the experimental results.

2. EXPERIMENTAL SETUP AND RESULTS

The experiment setup is schematically shown in Fig. 1. M_1 is a concave mirror with a radius of 150 mm, antireflection (AR) coated at 808 nm on its outside surface near the focusing optics and high-reflection (HR) coated at 1064 and 532 nm on the inside surface. M_2 is a flat mirror, HR coated at both 1064 and 532 nm. M_3 is also a concave mirror with a radius of 100 mm, HR coated at 1064 nm, high-transmission coated at 532 nm on the inside surface, and AR coated at 532 nm on the outside surface, and serves as the output coupler for the generated green light. The distance between M_1 and M_3 is about 21 cm, and the distance between M_2 and M_3 is about 9 cm. The pump source is a fiber-coupled laser diode (made by Semiconductor Institute, Chinese Academic) capable of emitting a maximum output power of 5 W with a center wavelength of 808 nm at 22°C. The output pump beam from the fiber bundle end, which is 800 μm in diameter, is focused into the laser crystal with a spot size of about 440 μm by a focusing optics. The Nd:GdVO₄ crystal, doped with 1.0 at. % Nd³⁺ ions, is 4 mm $\times$ 4 mm $\times$ 5 mm, and its absorption coefficient at 808 nm is 5.49 cm⁻¹. The pumped face is AR coated for 99.9% transmission at both 808 and 1064 nm, and the other face is AR coated for 99.8% transmission at 1064 nm. Two pieces of the Cr⁴⁺:YAG crystal with the small-signal transmissions of 87% and 91% are used to study the performance of the passively *Q*-switched Nd:GdVO₄-PPKTP lasers. Both faces of them are AR coated at 1064 nm. The PPKTP crystal (made by Raicol Crystal Ltd., Israel) is 10 mm long, 1 mm thick, and 2 mm

high and has a 9 μm grating period with an AR coating at 1064 and 532 nm on both surfaces. The temperatures of the Nd:GdVO₄ crystal and the PPKTP crystal are controlled at 20°C and 30°C by means of a temperature controller, respectively. A MAX 500AD laser power meter (Coherent, Inc., USA) is used to measure the generated green laser power. The green light pulses's temporal behavior is recorded by a fast photoelectronic diode (with response time of less than 1 ns) and a TDS620B digital oscilloscope (Tektronix, Inc., USA).

Figure 2 shows the average output power of the cw and the passively *Q*-switched Nd:GdVO₄-PPKTP lasers with different Cr⁴⁺:YAG crystals. As can be seen, the average output power increases almost linearly with the incident pump power. The output power of 1.54 W at CW green operation is obtained at the maximum incident pump power of 4.44 W, corresponding to an optical conversion efficiency of 34.7%. When the Cr⁴⁺:YAG crystals with the initial transmissions of 87% and 91% are used, the average output powers at the 532 nm wavelength are measured to be about 0.885 and 1.04 W at the maximum incident pump power of 4.44 W, corresponding to optical conversion efficiency of about 20% and 23.4%, respectively.

The pulse width, the repetition rate, and the corresponding pulse energy and peak power of the *Q*-switched Nd:GdVO₄-PPKTP lasers with different Cr⁴⁺:YAG crystals are shown as scattered symbols from Figs. 3 and 6, respectively. As can be seen, the maximum pulse energy of 16.7 μJ and the highest peak power of 495 W are obtained when the Cr⁴⁺:YAG crystal with the initial transmission of 87% is used. The corresponding pulse duration and the repetition rate are 30 ns and 53 kHz, respectively, which are narrower and less than those when the 91% Cr⁴⁺:YAG crystal is used. In that case, the pulse width and the repetition rate are 35 ns and 75 kHz at the incident pump power of 4.44 W. The corresponding pulse energy and peak power are only 13.4 μJ and 395 W, respectively. The temporal profile of the green laser pulses with 35 ns is shown as solid curve in Fig. 7.

3. THEORETICAL ANALYSIS

A. Nonlinear Loss Due to Harmonic Conversion in PPKTP

The harmonic conversion in a frequency-doubling *Q*-switched laser is always considered a nonlinear loss of the fundamental wave in the theoretical analysis. For

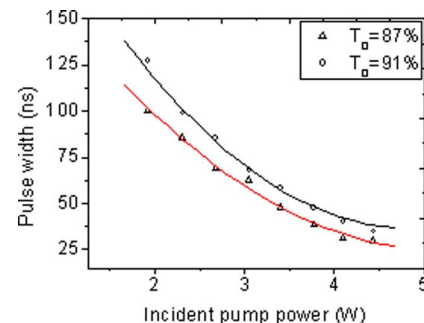


Fig. 3. (Color online) Pulse width with the incident pump power.

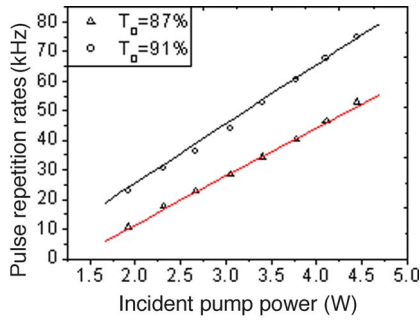


Fig. 4. (Color online) Pulse repetition rates versus the pump power.

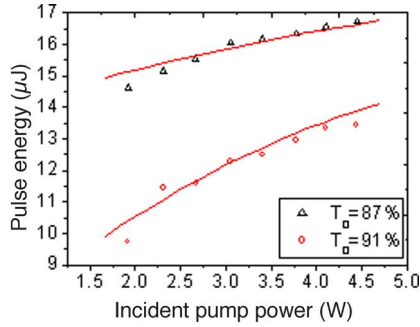


Fig. 5. (Color online) Pulse energy versus the incident pump power.

PPKTP, the single-pass conversion efficiency coefficient E_n can be expressed as follows⁸:

$$E_n = d_{\text{eff}}^2 \frac{2\omega^2}{n_\omega^2 n_{2\omega} c^3 \epsilon_0} \frac{|J_{2\omega}|^2}{A_k}, \quad (1)$$

where ω is the angle frequency of the fundamental wave; n_ω and $n_{2\omega}$ are the refractive indices of the fundamental wave and the second-harmonic wave; c is the light velocity in vacuum; ϵ_0 is the dielectric permeability of vacuum; A_k is the area of the fundamental wave at the position of PPKTP; $d_{\text{eff}} = (2d_{33}/\pi m) \sin \pi m D$ is the effective nonlinear coefficient of PPKTP,⁸ d_{33} is its nonlinear coefficient, and, for our PPKTP, it is designed for optimal second-harmonic generation, i.e., $m=1$ and the duty cycle $D=0.5$; and

$$J_{2\omega} = \int_0^{l_k} \frac{\exp(i\Delta k z)}{(1 + 2iz/b)} dz. \quad (2)$$

Equation (2) describes the second-harmonic generation using a Gaussian beam, where l_k is the length of PPKTP; $b = \pi n_\omega \omega_k^2 / \lambda$ is the confocal parameter, in which λ is the wavelength of the fundamental wave and ω_k is the radii of the TEM₀₀ mode at the position of KTP; and $\Delta k = \Delta k' - k_g$ is the total phase-mismatching factor,⁸ where $k_g = 2\pi/\Lambda_g$ is the wave vector defined by the grating period Λ_g and $\Delta k' = (4\pi/\lambda)(n_{2\omega} - n_\omega)$ is a particular (no-zero) wave-vector mismatch.

According to the relationship of power and photon density, the fundamental power at the position of PPKTP is

$$P(\omega, r, t) = \frac{1}{2} A_k \hbar \omega c \phi_k(r, t), \quad (3)$$

where $\hbar \omega$ is the single photon energy of the fundamental wave and $\phi_k(r, t)$ is the photon density at the position of PPKTP.

So the nonlinear loss due to harmonic conversion can be expressed as

$$\delta_n(r, t) = \frac{P(2\omega, r, t)}{P(\omega, r, t)} = E_n P(\omega, r, t) = \delta_k \phi_k(r, t), \quad (4)$$

where

$$\delta_k = \frac{1}{2} E_n A_k \hbar \omega c. \quad (5)$$

B. Rate Equations and Theoretical Estimation

On the basis of the model proposed in Ref. 19 and considering the effects of the ASE, we can obtain the modified rate equations for the passively Q-switched Nd:GdVO₄-PPKTP green laser with Cr⁴⁺:YAG as

$$\begin{aligned} \int_0^\infty \frac{d\phi(r, t)}{dt} 2\pi r dr = \int_0^\infty & \left(\frac{1}{t_r} \{ 2\sigma n(r, t) l \phi_g(r, t) \right. \\ & - 2\sigma_g n_{s1}(r, t) l_s \phi_s(r, t) - 2\sigma_e [n_{s0} \\ & - n_{s1}(r, t)] l_s \phi_s(r, t) - \delta_n(r, t) \phi_k(r, t) \\ & \left. - L\phi(r, t) \} + \xi \frac{n(r, t)}{\tau_{21}} \right) 2\pi r dr, \end{aligned} \quad (6)$$

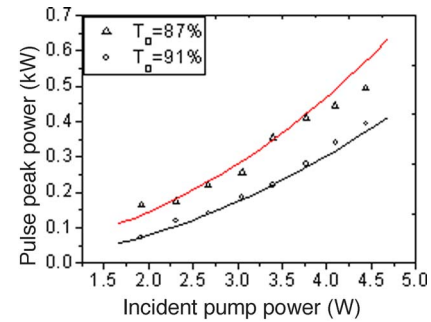


Fig. 6. (Color online) Pulse peak power versus the incident pump power.

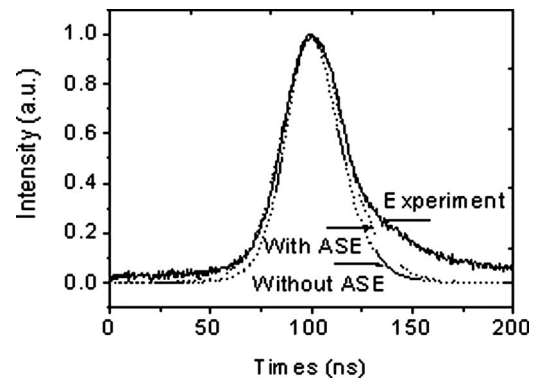


Fig. 7. Temporal profile of the passively Q-switched Nd:GdVO₄-PPKTP green laser pulse of 35 ns with 91% Cr:YAG at the maximum incident pump power of 4.44 W. Solid curve, oscilloscope trace; dotted curve, calculated result with ASE; dashed curve, calculated result without ASE.

Table 1. Parameters of the Theoretical Calculation¹⁸⁻²¹

Parameters	Values	Parameters	Values
σ	$7.6 \times 10^{-19} \text{ cm}^2$	n_ω	1.83
α	5.49 cm^{-1}	$n_{2\omega}$	1.889
σ_g	$4.3 \times 10^{-18} \text{ cm}^2$	l	0.5 cm
σ_e	$8.2 \times 10^{-19} \text{ cm}^2$	l_k	1.0 cm
n_{s0}	$2.0 \times 10^{17} \text{ cm}^{-3}$	Λ_g	9 μm
τ	95 μs	L	0.12
τ_s	3.2 μs	ζ	0.85
τ_{21}	110 μs	$\bar{\omega}_p$	250 μm
n_1	2.19	ω_g	350 μm
n_2	1.81	ω_a	120 μm
n_3	1.83	ω_k	88 μm
d_{33}	16.9 pm/v	ω_ℓ	220 μm

$$\frac{dn(r,t)}{dt} = R_{\text{in}} \exp\left(-\frac{2r^2}{\bar{\omega}_p^2}\right) - \frac{n(r,t)}{\tau} - \sigma cn(r,t) \phi_g(r,t) - \xi \frac{n(r,t)}{\tau_{21}}, \quad (7)$$

$$\frac{dn_{s1}(r,t)}{dt} = \frac{n_{s0} - n_{s1}(r,t)}{\tau_s} - \sigma_g cn_{s1}(r,t) \phi_s(r,t), \quad (8)$$

where $n(r,t)$ is the average population-inversion density; $n_{s1}(r,t)$ and n_{s0} are the ground-state and total population densities of the $\text{Cr}^{4+}:\text{YAG}$ saturable absorber, respectively; σ and l are the stimulated-emission cross section and length of the $\text{Nd}:\text{GdVO}_4$ gain medium, respectively; σ_g and σ_e are the ground-state and excited-state absorption cross sections of the saturable absorber, respectively; l_s is the length of the saturable absorber; $t_r = 2[n_1 l + n_2 l_s + n_3 l_k + (L_p - l - l_s - l_k)]/c$ is the round-trip time in the resonator in which n_1 , n_2 , and n_3 are the refractive indices of the $\text{Nd}:\text{GdVO}_4$ gain medium, $\text{Cr}^{4+}:\text{YAG}$, and PPKTP crystal, respectively, L_p is the physical cavity length, and l_k is the thickness of PPKTP; L is the intrinsic loss; τ is the spontaneous fluorescence lifetime of the gain medium, and τ_s is the excited-state lifetime of the saturable absorber; $\xi[n(r,t)/\tau_{21}]$ is the term considering the ASE, ξ is a parameter related to ASE and its value can be adjusted to fit the experimentally measured pulse width, and τ_{21} is effective radiative lifetime associated with the laser transition; $R_{\text{in}} = P_{\text{in}}[1 - \exp(-\alpha l)]/h\nu_p \pi \bar{\omega}_p^2 l$ is the pump rate, where $h\nu_p$ is the photon energy of the pump light, and $\bar{\omega}_p$ is the average radius of the pump beam; $\phi(r,t) = \phi(0,t) \exp(-2r^2/\omega_1^2)$ is the average intracavity photon density, where $\phi(0,t)$ is the photon density in the laser axis; $\phi_g(r,t)$, $\phi_a(r,t)$, and $\phi_k(r,t)$ are the photon densities at the positions of the $\text{Nd}:\text{GdVO}_4$ crystal, $\text{Cr}^{4+}:\text{YAG}$, and PPKTP crystal, respectively, and $\phi_i(r,t) = (\omega_1^2/\omega_i^2) \phi(0,t) \exp(-2r^2/\omega_i^2)$ ($i=g,a,k$); ω_g , ω_a , ω_k , and ω_l are the radii of the TEM_{00} mode at the above positions and the average radius of the TEM_{00} mode in the cavity, which can be calculated by *ABCD* matrix theory,¹⁹ and the calculated values are shown in Table 1.

According to the parameters in Table 1, by numerically solving the rate equations (6)–(8), we can obtain the rela-

tionship between $\phi_k(0,t)$ and t , from which we can obtain the pulse width (FWHM) and the pulse repetition rate of the generated green light pulses. The single-pulse energy E and the pulse peak power P can be given as

$$E = \frac{1}{4} \zeta E_n (A_k \hbar \omega c)^2 \phi_{\text{int}}^2, \quad (9)$$

$$P = \frac{1}{4} \zeta E_n (A_k \hbar \omega c)^2 \phi_{km}^2, \quad (10)$$

where ζ is the fraction that coupled out the resonator; ϕ_{int} is the integral of $\phi_k(0,t)$ over t from the beginning time t_1 to ending time t_2 of the single pulse; and ϕ_{km} is the maximum value of $\phi_k(0,t)$.

The theoretical calculation curves for the pulse repetition rate, the pulse energy, the pulse width, and the peak power versus pump power are shown as solid curves from Figs. 3 to 6, respectively. The estimation of the ASE parameter ξ in Eqs. (6) and (7) is made by our varying the value used in the theoretical model until a best fit between the experimentally measured pulse width and the theoretical prediction. The value leading to the best fitting was found to be about 5×10^{-5} , which is similar to that in Ref. 21, and the calculated dependences of the pulse widths on the incident pump power with different $\text{Cr}^{4+}:\text{YAG}$ crystals are shown as solid curves in Fig. 3. With this value, the simulation data of the other laser performance shown as solid curves from Figs. 4 to 6 are also found to fit well with the experimental results. The dotted curve in Fig. 7 shows the theoretical pulse shape with a pulse width of 36 ns at $T_0=0.91$ and a pump power of 4.44 W. The ASE-excluded simulation yields an almost symmetric pulse shape with a narrower pulse width of about 30 ns, which is also shown as a dashed curve in Fig. 7. From Figs. 3 to 7, we can see that the theoretical calculations considering the ASE are in agreement with the experimental results.

As detailed above, the value of the ASE parameter ξ at about 5×10^{-5} has been deduced experimentally by our fitting the experimental results with the modified model. To show the influence of the ASE on the laser performance, we calculate the relationship of the pulse width on the ASE parameter ξ at $T_0=0.91$ and an incident pump power of 4.44 W, which are shown in Fig. 8. As can be seen, the pulse width at the same condition increases with the increasing of the ASE parameter ξ .

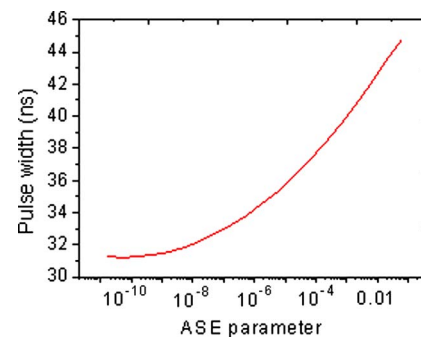


Fig. 8. (Color online) Pulse width versus the ASE parameter ξ at $T_0=0.91$ and an incident pump power of 4.44 W.

4. CONCLUSIONS

We have successfully demonstrated the performance of a diode-pumped passively Q -switched Nd:GdVO₄-PPKTP green laser with an Cr⁴⁺:YAG saturable absorber. The dependences of pulse width, pulse repetition rate, pulse energy, and peak power on incident pump power are obtained for the generated green light pulses. A rate equation model is introduced to theoretically analyze the results obtained in the experiment, in which the spatial distribution of the intracavity photon density and the effects of ASE are taken into account. The numerical solutions of the rate equations are consistent with the experimental results.

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K. Yang, the corresponding author, can be reached by e-mail at k.j.yang@sdu.edu.cn.

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