Actively Q-switched and Mode-Locked Diode-Pumped Nd:GdVO$_4$–KTP Laser

Ming Li, Shengzhi Zhao, Kejian Yang, Guiqiu Li, Dechun Li, Jing Wang, Jing An, and Wenchao Qiao

***Abstract*—By using a comparative simple configuration and a short cavity length, a diode-pumped actively Q-switched and mode-locked intracavity frequency doubled Nd:GdVO$_4$–KTP green laser with the modulation depth 100% was realized, from which the great average output power, the high efficiency were obtained and the mode-locked pulse inside the Q-switched pulse has a repetition rate of 476 MHz. Using the hyperbolic secant function methods and by considering the Gaussian distribution of the intracavity photon density, the influences of continuous pump rate, the upper state lifetime of the active medium and the turnoff time of the acousto-optic Q-switch, we proposed a developed rate equation model for actively Q-switched and mode-locked green lasers. With this developed model, the theoretical calculations are in good agreement with the experimental results and the width of the mode-locked green pulse is estimated to be about 185 ps.**

***Index Terms*—Actively Q-switched, mode-locking, Nd:GdVO$_4$ crystal.**

I. Introduction

EFFICIENT and high average power green-beam generation with high repetition rate in a simple and low cost system has been required in the medical and the other fields, such as surgery, angioplasty, dermatology, information storage, coherent telecommunications, micromachining, marking, trimming and surface hardening. This kind of laser resource can be efficiently obtained by inserting a nonlinear crystal into a simultaneous passively or actively Q-switching and mode locking (QML) in solid-state lasers working at the fundamental wavelength of 1.06 μm. In passive method, by means of a saturable absorber, the ultrashort pulses close to the limit set by the gain-bandwidth of the active material can be obtained [1], [2]. However, the pulse train is usually unstable. In comparison with passively QML, the Actively QML can obtain the more stable QML pulses. Especially, the actively Q-switching and mode locking by an acoustooptic (AO) modulator can lead to a stable QML regime of operation with considerable enhancement in peak power. So far, a variety of gain medium for actively QML have been investigated, such as Nd:YAG [3], Nd:YVO$_4$ [4], [5], and so on.

Nd:GdVO$_4$, as a novel isomorph of Nd:YVO$_4$, has been confirmed to be a promising laser medium for diode pumping [2], [6], [7]. Especially, because of its high absorption coefficient, large emission cross section, broad gain bandwidth and its much higher thermal conductivity along the $\langle 110 \rangle$ directions, it is more competent than other Nd doped crystals, such as Nd:YAG [7], [8], Nd:YVO$_4$ [2], [6], [9], when operated in mode-locking state. KTP crystal has high nonlinear conversion coefficient, so it is easy for the LD pumped QML Nd:GdVO$_4$–KTP lasers to obtain high second-harmonic (SH) conversion efficiency. As far as we know, there has not been any report on the AO QML operation using Nd:GdVO$_4$ crystal as the gain medium. In addition, the related theoretical investigations of this type of laser have not been carried out.

In this paper, we present the experimental observation of an actively Q-switched and mode locking Nd:GdVO$_4$–KTP frequency-doubled Nd:GdVO$_4$ laser with AO modulator in a short cavity operating at a high repetition rate of 476 MHz. By using a comparative simple configuration and a short cavity length, the great average output power and the high efficiency are obtained. According to the hyperbolic secant function methods for analyzing mode-locking lasers [10], [11] and by considering the Gaussian distribution of the intracavity photon density, the influences of continuous pump rate, the upper state lifetime of the active medium, and the influence of the turnoff time of the AO Q-switch, a rate equation model is given. The numerical solutions of equations are in fair agreement with the experimental results.

II. Experimental Setup and Results

The experimental setup is depicted in Fig. 1. A V-type folded cavity is designed to allow mode matching with the pump beam and to provide the proper spot sizes in the pump beam. The pump source is a fiber-coupled laser-diode (FAP system, COHERENT Inc., USA) which works at the maximum absorption wavelength (808 nm) of the Nd^{3+} ions with the maximum output power of 10 W. A 1.0-at. % Nd^{3+}, $4 \times 4 \times 5$ mm^3 Nd^{3+} : GdVO$_4$ crystal is used as the laser active material. One surface of the crystal is coated high transmission (HT) at 808 nm, whereas the other surface of the crystal is antireflection (AR) at 1064 nm. The temperatures of the Nd^{3+} : GdVO$_4$ crystal is controlled at 20 °C by using semiconductor cooler. KTP crystal, which is cut for type-II ($\theta = 90°$ and $\varphi = 23.3°$) phase matching, is $3 \times 3 \times 8$ mm^3 and both of its surfaces

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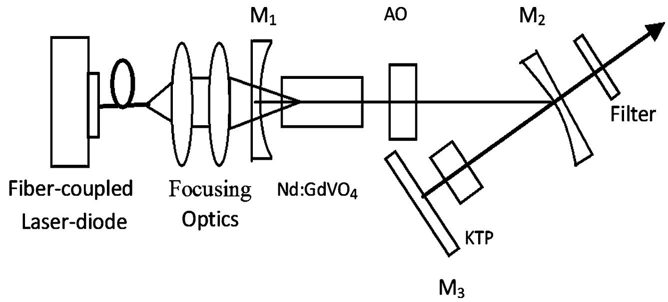

Fig. 1. Schematics for self-Q-switched and mode-locked Nd:GdVO$_4$–KTP green laser.

are antireflection coated at 1064 and 532 nm. To take advantage of high intracavity fundamental intensity, the KTP crystal is put near the flat mirror M_3 In order to prevent frequency shift [12] and to obtain stable, efficient QML pulse, the temperature of the KTP crystal is controlled at 22 °C by using semiconductor cooler, too. The QSGSU-6Q AO modulator (The 26th Electronics Institute, Chinese Ministry of Information Industry), whose effective length and the highest repetition rate of which are 24 mm and 40 kHz, respectively, is placed near Nd:GdVO$_4$ crystal. Both ends of the modulator are AR coated at 1064 nm, and 532 nm. The radio-frequency (RF) and the power of AO modulator are 70 MHz and 2.3 W, respectively. The input mirror M_1 is a concave with 150 mm curvature radius, with HT at 808 nm and high reflection (HR) at 1064 nm. The folded mirror M_2 with 100 mm radius is used as the output mirror of the generated green laser, which is coated HR at 1064 nm and HT at 532 nm. M_3 is a flat mirror with HR at both 1064 nm and 532 nm. The angle between $\mathrm{M}_1\mathrm{M}_2$ and $\mathrm{M}_2\mathrm{M}_3$ is less than 10°. The length between M_1 and M_2 is about 22 cm and the length between M_2 and M_3 is about 7 cm. The filter is used for separating the 532-nm green lasers from the remaining 1064 nm fundamental wave leaking out from the resonator. In this arrangement, the whole cavity length adds up to 29 cm. The temporal shape of the output laser pulse is recorded with a digital oscilloscope (TED620B, 500-MHz bandwidth and 2.5-Gs/s sampling rate, Tektronix Inc., USA) and a fast Si PIN photodiode with a rising time of about 0.8 ns. A MAX 500AD laser power meter (COHERENT Inc., USA) is used to measure the generated average output power.

The threshold pump power for the actively QML Nd:GdVO$_4$ green laser was found to be 0.5 W with the repetition rate of 5 kHz. Fig. 2 shows the average output power of the actively Q-switched pulses with respect to the incident pump power. The maximum average output power of 602 mW is obtained at the incident pump power of 5.1 W, corresponding to a conversion efficiency of 12%. According to the average output power and the repetition rate, the pulse energy of the second-harmonic (SH) Q-switched pulse versus the incident power is experimentally shown as dots in Fig. 3. The pulse energy increases with the pump power, and reaches 120 μJ at the maximum pump power of 5.1 W. Fig. 4 shows the temporal shape of a single actively Q-switched green pulse envelope, which was recorded at the pump power of 2.7 W. The nearly 100% modulation depth of the Q-switched mode-locked green pulses could be achieved at any pump power over the threshold power. The mode-locked pulse interval within the Q-switched envelope is about 20 ns. The expanded oscilloscope traces of a train of mode-locked pulses are showed in Fig. 5, from which we obtain that the mode-locked pulses within the Q-switched envelope are separated by 2.1 ns, which matches exactly with the cavity round-trip transmit time and corresponds to a repetition rate of

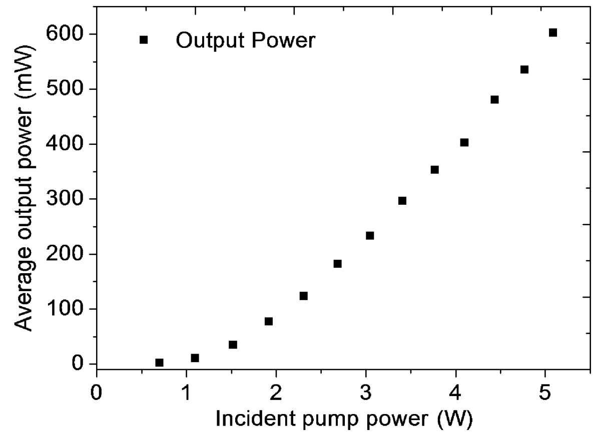

Fig. 2. Dependence of the average output power on the incident pump power.

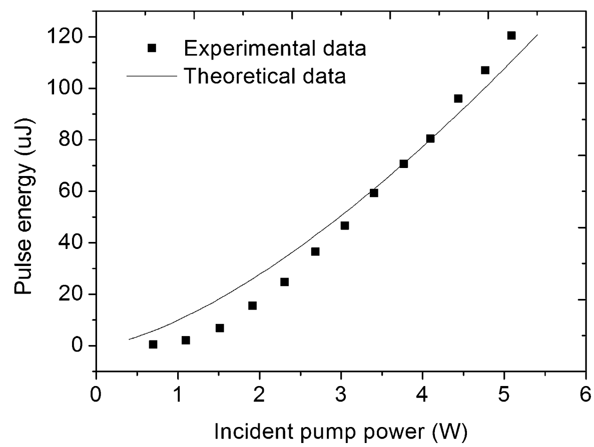

Fig. 3. Theoretical and experimental dependence of the pulse energy of the Q-switched pulse on the incident pump power.

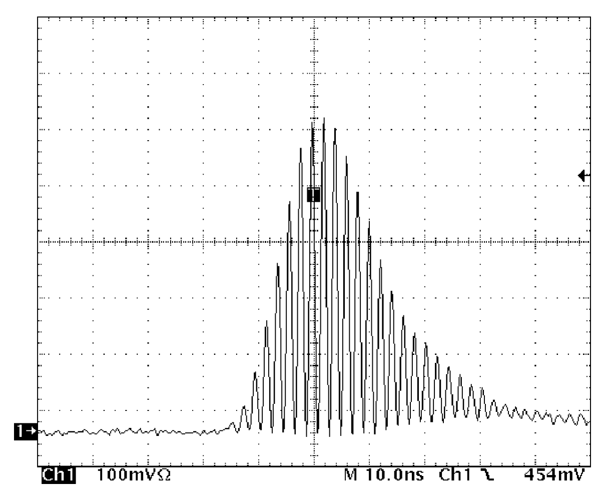

Fig. 4. Oscilloscope traces of a typical actively Q-switched and mode-locked green laser pulse envelope at the incident pump power of 2.7 W.

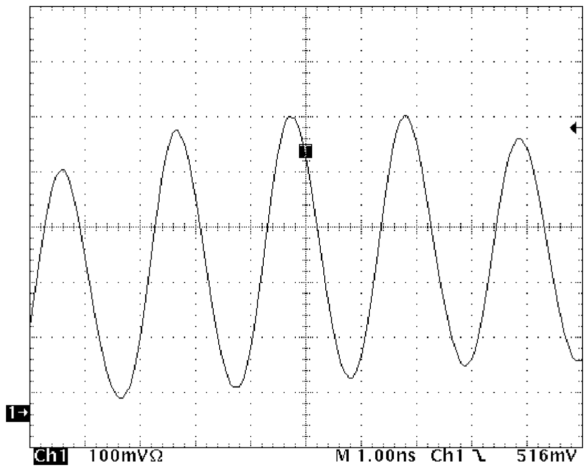

Fig. 5. Expanded oscilloscope traces of a train of mode-locked green pulses.

476 MHz. By using a CCD camera, the measured beam-quality M_2 is 1.16, from which we consider that this laser operates in a Gaussian single transverse mode. In addition, removing the KTP crystal from the cavity, and replacing the mirror M_3 with a flat mirror with transmission of 10%, we found the laser could also operate in QML regime. So it was not the nonlinear mirror mode-locking mechanism that played a role in our laser [13].

III. Theoretical Analysis and Discussion

A. Nonlinear Loss Due to Harmonic Conversion

For a Q-switched and mode-locked intracavity-frequency-doubled laser, the second-harmonic conversion is generally considered as the nonlinear loss of the fundamental wave as introduced in references [14], [15]. Under the small-signal approximation and ignoring the mismatch of the nonlinear crystal, the single-pass second harmonic power converted from the kth mode-locked pulse for type-II phase matching is [14], [15]

$$P_{k,2\omega}(r,t) = \frac{K_N}{A_K} P_{k,\omega}^2(r,t) = \frac{AK_N}{4}(chv)^2 \frac{A}{A_K}\phi_k^2(r,t) \quad (1)$$

where $K_N = \omega^2 d_{\mathrm{eff}}^2 d^2 / c^3 \varepsilon_0 n_{\mathrm{e2}}^{2\omega} n_{\mathrm{e2}}^{\omega} n_{\mathrm{e1}}^{\omega}$, $h\nu$ is the single photon energy of the fundamental wave, ω is the angle frequency of fundamental wave, d_{eff} is the effective nonlinear coefficient; ε_0 is the dielectric permeability of vacuum; d is the length of KTP; $n_{\mathrm{e2}}^{2\omega}$, n_{e2}^{ω}, n_{e1}^{ω} are the harmonic and fundamental wave refractive indices, respectively. $A_K = (1/2)\pi w_{Ktp}^2$ is the area of fundamental wave at the position of KTP, $\boldsymbol{w}_{Ktp}$ is the radius of TEM_{00} mode at the positions of KTP; $A = (1/2)\pi w_l^2$ is the mode area at the gain medium, and w_l is the average TEM_{00} mode in the cavity. $\phi_k(r,t)$ is the average photon intensity for the pulse at the kth round-trip.

So the nonlinear loss due to harmonic conversion under Gaussian distribution at the kth round-trip can be obtained [16]:

$$\begin{aligned}\delta_k(r) &= \frac{P_{k,2\omega}(r,t)}{P_{k,\omega}(r,t)} = K_N hvcd^2 \frac{w_l^2}{w_{ktp}^2} \exp\left(-\frac{2r^2}{w_{ktp}^2}\right)\phi(0,t)\\ &= \delta_K \phi_{Ktp}(r,t) \qquad (2)\end{aligned}$$

where $\delta_K = K_N hvcd^2$, $\phi_{Ktp}(r,t) = (w_l^2/w_{ktp}^2)\phi(0,t)$ $\exp(-(2r^2/w_{ktp}^2))$ is the photon density at the position of KTP, $\phi(0,t)$ is the photon density in the laser axis.

B. Theory of Fluctuation Mechanism and Rate Equations

The fluctuation mechanism has been proposed to explain the generation of picosecond pulses in simultaneously Q-switched and mode-locked lasers with saturable absorbers [16]. Using the theoretical model in reference [17], considering the Gaussian spatial distribution of the intracavity photon intensity by introducing the coefficient of the Gaussian spatial distribution $\exp(-(2r^2/w_l^2))$, the average photon intensity shape can be described as

$$\phi(r,t) = \sum_{k=0} \Phi_k f(t-t_k) \exp\left(-\frac{2r^2}{w_l^2}\right) = \phi(0,t) \exp\left(-\frac{2r^2}{w_l^2}\right) \quad (3)$$

where $\phi(0,t) = \sum_{k=0} \Phi_k f(t-t_k)$, $t_k = kt_r$, Φ_k is the relative amplitude of the mode-locked pulses at the kth round-trip, $t_r = 2[n_1 l + n_2 l_A + n_3 d + (L_c - l - l_A - d)]/c$ is the cavity round-trip time, n_1, n_2 and n_3 are the refractive indexes of the gain medium, AO modulator and KTP, respectively, l and l_A are the lengths of the gain medium and AO modulator, respectively, L_c is the physical length of the cavity, c is the light velocity; $f(t)$ is the mode-locked pulse evolving from the noise and satisfies $\int_{-\infty}^{\infty} c\sigma f(t)dt = 1$. If $f(t)$ is a hyperbolic secant function, it can be written as [11]

$$f(t) = \frac{1}{2\sigma c\tau_p} \sec h^2\left(\frac{t}{\tau_p}\right) \quad (4)$$

where σ is the stimulated emission cross section of the gain medium, τ_p is related to the full-width at half-maximum (FWHM) mode-locked pulse duration τ at fundamental wavelength by $\tau = 1.76\tau_p$.

So the temporal Gaussian shape of the average photon intensity for the pulse at the kth round-trip can be described as:

$$\phi_k(r,t) = \Phi_k f(t) \exp\left(-\frac{2r^2}{w_l^2}\right). \quad (5)$$

Using the rate equations method [17], also considering the influence of the turnoff time of the AO Q-switch, we can obtain the recurrence relation of the relative amplitude for diode-pumped simultaneously actively Q-switched and mode-locked Nd:$\mathrm{GdVO_4}$–KTP laser with AO modulator

$$\begin{aligned}\Phi_k = \Phi_{k-1} \exp\Bigg\{\frac{2}{\pi w_l^2}\int_0^{\infty}\Bigg[&2\sigma n(r,t_k) l \frac{w_l^2}{w_G^2}\exp\left(-\frac{2r^2}{w_G^2}\right)\\ &- \delta_A(t)\frac{w_l^2}{w_A^2}\exp\left(-\frac{2r^2}{w_A^2}\right)\\ &- \delta_k \frac{w_l^4}{w_{ktp}^4}\exp\left(-\frac{4r^2}{w_{ktp}^2}\right)\\ &\times \Phi_{k-1} - \left[L + \ln\left(\frac{1}{R}\right)\right]\\ &\times \exp\left(-\frac{2r^2}{w_l^2}\right)\Bigg]2\pi r dr\Bigg\} \quad (6)\end{aligned}$$

TABLE I
THE PARAMETERS OF THE THEORETICAL CALCULATION [14], [15], [17]

Parameters	Values	Parameters	Values
σ	7.6×10^{-19} cm^2	l_A	2.4 cm
τ_G	90 µs	α_G	5.49 cm^{-1}
n_1	2.19	t_s	14 ns
n_2	1.6	$n_{e2}^{2\omega}$	1.79
n_3	1.83	n_{e2}^{ω}	1.746
L_c	29 cm	n_{e1}^{ω}	1.833
w_p	330 µm	d	0.8 cm
w_l	210 µm	d_{eff}	7.2 pm/V
w_G	300 µm	L	0.09
w_A	280 µm	ε_0	8.855×10^{-12} C^2/N·m^2
w_{KTP}	100 µm	R	0.995
l	0.5 cm		

$$n(r,t_k)= \exp\left(-\frac{t_k}{\tau_G}\right)\prod_{m=0}^{k-1}\exp\left[-\frac{w_l^2}{w_G^2}\exp\left(-\frac{2r^2}{w_G^2}\right)\Phi_m\right] \times\left\{R_{\rm in}(r)\exp\left(\frac{t_k}{\tau_G}\right) \times\int_0^{t_k}\prod_{m=0}^{k-1}\exp\left[\frac{w_l^2}{w_G^2}\exp\left(-\frac{2r^2}{w_G^2}\right)\Phi_m\right]dt +n_i\exp\left(-\frac{2r^2}{w_p^2}\right)\right\} \quad (7)$$

where $n(r,t_k)$ is the population density of the gain medium population density at the kth roundtrip; L is the intrinsic loss, R is the reflectivity at 1.06 μm of the output coupler; w_G and w_A are the radii of TEM_{00} mode at the positions of gain medium and AO modulator in the cavity, respectively. The value of w_G, w_A, w_{ktp} and w_l can be calculated by ABCD matrix theory. $R_{\rm in}(r) = P_{\rm in}\exp(-2r^2/w_p^2[1-\exp(-\alpha_G l)]/hv_p\pi w_p^2 l$ is the pump rate, where $P_{\rm in}$ is the pump power, hv_p is the single-photon energy of the pump light, w_p‘ is the average radius of the pump beam, α_G is the absorption coefficient of the gain medium; τ_G is the stimulated-radiation lifetime of the gain medium; $n_i = [\ln(1/R)+L]/(2\sigma l)$ is the initial population inversion density in the gain medium. $\delta_A(t)$ is the loss function of the AO Q-switch, which is defined as $\delta_A(t)=\delta_A\exp[-(t/t_s)^2]$, where δ_A is the intrinsic diffraction loss of the AO Q-switch; t_s is the turnoff time of the AO Q-switch. With the parameters in Table I, Φ_k can be obtained by numerically solving (6) and (7) for a given initial value Φ_0.

Then according to (1), (3), and (4), the output second-harmonic power coupled out of the cavity can be expressed as

$$P_{k,2\omega}(r,t)=\frac{AK_N}{8}\left(\frac{hv}{\sigma\tau_p}\right)^2\frac{A}{A_K}\exp\left(-\frac{4r^2}{w_l^2}\right) \times\sum_{k=0}^{\infty}\Phi_k^2\sec h^4\left(\frac{t-t_k}{\tau_p}\right) \quad (8)$$

By integrating (8) over time from zero to infinity, the output energy of the Q-switched mode-locked green pulse can be obtained as:

$$E_{2\omega}=\frac{AK_N}{6\tau_p}\frac{A}{A_K}\left(\frac{hv}{\sigma}\right)^2\exp\left(-\frac{4r^2}{w_l^2}\right)\sum_{k=0}^{\infty}\Phi_k^2 \quad (9)$$

From (9), we can see that the total pulse energy of the Q-switched envelope of the green pulse depends on τ_p. Using the parameters in Table I and (9), we can obtain the dependence of the total SH Q-switched pulse energy on τ_p. Fig. 6 shows such dependences at different pump powers. Comparing the theoretical results in Fig. 6 with the corresponding experimental results shown as dots in Fig. 3, we can estimate τ_p in our experiment to be around 150 ps. According to the relation between the FWHM mode-locked pulse duration τ at fundamental wavelength and τ_p, i.e., $\tau = 1.76\tau_p$, we can estimate the FWHM duration τ of mode-locked pulse at fundamental wavelength to

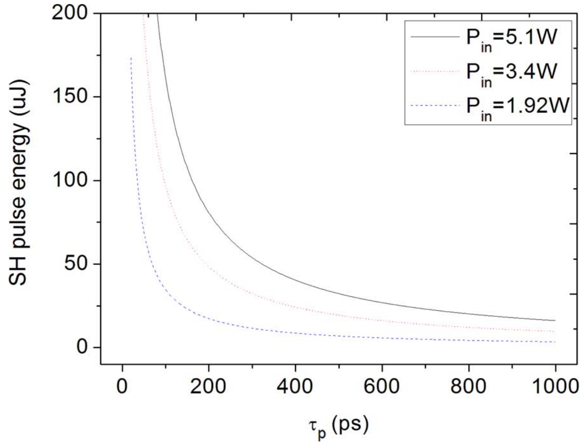

Fig. 6. Calculated dependence of the total energy of a single SH Q-switched envelope on τ_p at different pump powers.

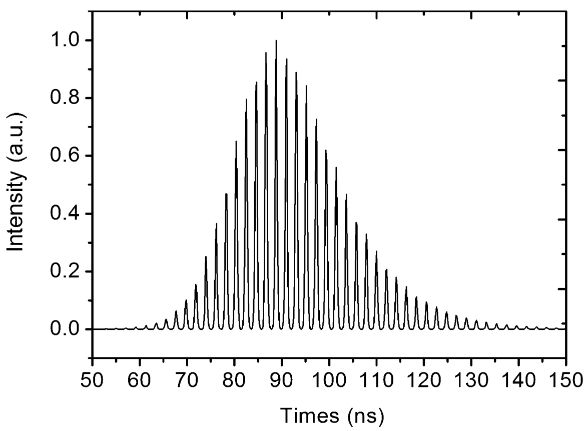

Fig. 7. Calculated results for the temporal shape of a single Q-switched green pulse at the pump power of 2.7 W.

be about 260 ps. Since the duration for the mode-locked pulse at fundamental wavelength is about $\sqrt{2}$ times of that for the SH wavelength [10], the SH mode-locked pulsewidth can be estimated to be 185 ps. Considering the value of $\tau_p = 150$ ps, we also can obtain the theoretical dependence of the total pulse energy of the self-Q-switched green pulse on the incident pump power, which is shown as solid line in Fig. 3. From Fig. 3, it can be seen that the theoretical results are in good agreement with the experimental results. The calculated temporal shape of a single Q-switched green pulse at pump power of 2.7 W is shown in Fig. 7, which agrees with the experimental results shown in Fig. 4. From Fig. 7, we can see that the duration of the SH Q-switched pulse envelop is about 25 ns, which is very close to the experimental results of 20 ns.

IV. Conclusion

We have demonstrated the intracavity second harmonic generation in an actively Q-switched and mode-locked $Nd:GdVO_4$–KTP green laser. The modulation depth for the green mode-locked pulses was about 100% at any pump power over the threshold power. The repetition rate for the mode-locked green pulses inside the actively Q-switched pulse envelope was about 476 MHz, corresponding to one cavity round-trip time. Based on the hyperbolic secant function methods, a developed rate equation model for actively Q-switched and mode-locked green lasers was presented, in which the Gaussian distribution of the intracavity photon density, the influences of continuous pump rate, the upper state lifetime of the active medium and the influence of the turnoff time of the AO Q-switch were considered. With this developed model, the theoretical calculations are in good agreement with the experimental results and the width of the mode-locked green pulse was estimated to be about 185 ps.

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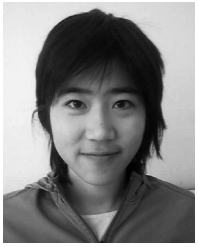

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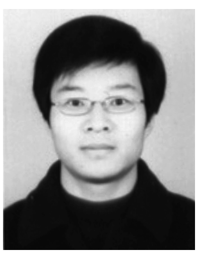

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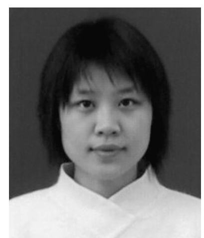

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