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Numerical Simulation of a Diode-Laser-Pumped Self-Q-Switched Cr,Yb:YAG Microchip Laser

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The dynamic and laser characteristics of the self-Q-switched Cr,Yb:YAG laser were studied by solving the coupled rate equations; the effects of the pump rate, reflectivity of the output couplers and the concentrations of the saturable absorbers on the laser performance were investigated in detail and the numerical simulation of the Cr,Yb:YAG lasers was in good agreement with the experimental data. Better laser performance of the Cr,Yb:YAG self-Q-switched laser can be obtained by using high pump rate, higher concentration of the saturable absorber and suitable reflectivity of the output coupler according to our numerical calculations. A typical self-Q-switched laser pulse of 269.5 μJ pulse energy with 319 ps pulse width (FWHM) at a repetition rate of 3.1 kHz can be obtained with a monolithic laser cavity, which results in 843.5 kW peak power.

Key words: Cr,Yb:YAG crystal, self-Q-switched, numerical simulation

1. Introduction

Diode laser pumped passively Q-switched microchip solid-state lasers are compact and simple single-mode lasers that emit subnanosecond pulses with high pulse energies and peak powers in a diffraction-limited output beam, and have many applications such as remote sensing, range finders, pollution detection, lidar, material processing and medical systems, and so on. The passively Q-switched lasers are usually operated using a thin gain medium bonded with saturable absorber such as a semiconductor saturable-absorber mirror (SESAM)[1] and bulk Cr^{4+} doped crystals,[2,3] or deposit Cr^{4+} films on the gain medium by molecular beam epitaxy (MBE).[4] Compared with SESAM or the saturable absorber film deposited on the surface of the gain medium, Cr^{4+} doped bulk crystals as saturable absorber have several advantages: high damage threshold, low cost, and simplicity. For microchip passively Q-switched laser operation, optically bonding saturable absorber and gain medium is difficult to fabricate and is costly; the easiest way to realize such a goal is to co-dope saturable absorber and active ions in a host material to form a self-Q-switched laser material. The Cr,Nd:YAG crystal is a promising self-Q-switched laser material and microchip laser operation was demonstrated.[5,6] The low concentration of Nd in Cr,Nd:YAG crystal limits the microchip laser operation. Efficient laser operation requires absorbing sufficient pump power with short crystal length; a high concentration microchip laser material is required to realize subnanosecond laser operation. Researchers recently reported chromium and ytterbium co-doped YAG crystal used as self-Q-switched laser material.[7,8] The self-Q-switched Cr,Yb:YAG laser was first demonstrated using a Ti:sapphre laser as pump source by Dong *et al.*[9] The self-Q-switched laser pulse output with pulse width of 500 ps was achieved recently with 750 μm thick Cr,Yb:YAG crystal.[10] Compared with Cr,Nd:YAG self-Q-switched laser crystal, Cr,Yb:YAG crystal has several advantages for microchip laser operation: first, high ytterbium concentration and high quality Cr,Yb:YAG can be grown by traditional Czochralski (CZ) method; second, the optical properties of Yb^{3+} of smaller emission cross-section and longer lifetime are more suitable for realizing high energy and high peak power operation; and third, the thermal properties of Cr,Yb:YAG are better than those of Cr,Nd:YAG crystal. Compared to Nd ions in laser crystals, Yb ion is ideally suited for diode pumping since it has a very simple energy level scheme with desirable properties for a laser system. Furthermore, diode pumped Yb:YAG lasers have several advantages relative to Nd:YAG lasers: a long storage lifetime (951 μs)[11] which is suitable for storing energy and Q-switching operation; a very low quantum defect (8.6%), resulting in three times less heat generation during lasing than comparable Nd-based laser systems;[12] large absorption width around the InGaAs laser emission range;[13] a relatively large emission cross section; easy growth of high quality and moderate concentration crystal without concentration quenching, and strong energy-storing capacity. Another advantage of using Yb:YAG is that the 940 nm absorption feature is approximately eighteen times broader than the 808 nm absorption feature in Nd:YAG and therefore the Yb:YAG system is less sensitive to diode wavelength specifications.[14]

But there are no reports on the effects of the pump power, the concentration of the saturable absorbers and the reflectivity of the output coupler on the monolithic Cr,Yb:YAG laser performance (pulse energy, pulse width, peak power and repetition rate). In this paper, we present the numerical simulation results of a laser diode pumped monolithic Cr,Yb:YAG self-Q-switched laser. The modified coupled rate equations of the self-Q-switched laser were given and the numerical solutions of the rate equations agree with the experimental results previously reported. The effects of the pump rate, the reflectivity of the output coupler and the concentrations of the saturable absorbers on the performance of the Cr,Yb:YAG monolithic lasers were investigated in detail. The optimized laser pulse output was given based on the experimental setup and the numerical simulations.

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2. The Model of Self-Q-Switched Cr,Yb:YAG Laser

According to the passively Q-switched theory,[15–17] the modified coupled rate equations of photon density and population inversion density of gain medium and the saturable absorber in the passively Q-switched resonator, which includes the excited-state absorption of the saturable absorber, the pump term and the population reduction factor of the laser, are as follows:

$$\frac{d\phi}{dt} = \frac{\phi}{t_r}\left(2\sigma Nl - 2\sigma_g N_g l_s - 2\sigma_e N_e l_s - \ln\left(\frac{1}{R}\right) - L\right) \quad (1)$$

$$\frac{dN}{dt} = -\gamma\sigma c\phi N - \frac{N}{\tau} + W_p \quad (2)$$

$$\frac{dN_g}{dt} = -\sigma_g c\phi N_g + \frac{N_{s0} - N_g}{\tau_s} \quad (3)$$

$$N_g + N_e = N_{s0} \quad (4)$$

where ϕ is the photon density in the laser cavity of optical length l_c, N is the population inversion density of the gain medium, σ is the stimulated emission cross section of the laser crystal, t_r is the cavity round-trip time, $t_r = 2l_c/c$, l is the length of the laser crystal, c is the speed of the light, σ_g is the absorption cross-section of ground state of the saturable absorber, σ_e is the absorption cross-section of the excited state, l_s is the length of the saturable absorber, N_g and N_e are the ground state and excited state population density of the saturable absorber, respectively, N_{s0} is the total population density of the saturable absorber, R is the reflectivity of the output coupler, L is the nonsaturable intracavity round-trip dissipative optical loss, γ is the inversion reduction factor, $\gamma = 2$ for Yb^{3+} doped three-level solid state lasers, W_p is the volumetric pump rate into the upper laser level and is proportional to the CW pump power, τ is the lifetime of the upper laser level of the gain medium, and τ_s is the excited-state lifetime of the saturable absorber.

Because the buildup time of the Q-switched laser pulse is generally quite short compared with the pumping and relaxation times of the gain medium, it is reasonable to neglect the effect of pumping and spontaneous decay of the laser population inversion density during pulse generation; with this assumption, Eq. (2) becomes,

$$\frac{dN}{dt} \cong -\gamma c\sigma\phi N \quad (5)$$

When the photon intensity is low, almost all the population of the saturable absorber is in the ground state, hence we can approximate the initial population inversion density before saturation of the saturable absorber by setting the right hand side of Eq. (1) to zero and assume that $N_g = N_{s0}$, so the initial population inversion density can be written as,

$$N_i = \frac{2\sigma_g N_{s0} l_s + \ln\left(\frac{1}{R}\right) + L}{2\sigma l} \quad (6)$$

When the photon intensity is high, most of the population in the ground state of the saturable absorber is excited to the excited state. Therefore, we can approximate the population inversion density after the bleaching of the saturable absorber by setting the right-hand side of Eq. (1) to zero and assuming that $N_g \cong 0$, and the threshold population inversion density can be written as,

$$N_{th} \cong \frac{2\sigma_e N_{s0} l_s + \ln\left(\frac{1}{R}\right) + L}{2\sigma l} \quad (7)$$

With expression (7) we can rewrite Eq. (1) as

$$\frac{d\phi}{dt} = \frac{\phi}{t_r}(2\sigma Nl - 2\sigma N_{th} l) \quad (8)$$

Dividing expression (8) by expression (5) gives,

$$\frac{d\phi}{dN} = -\frac{l}{l_c}\frac{N - N_{th}}{\gamma N} \quad (9)$$

Equation (9) can be integrated from the time of Q-switch opening to an arbitrary time t as follows:

$$\int_{\phi_i}^{\phi(t)} d\phi = -\frac{l}{l_c\gamma}\int_{N_i}^{N(t)}\left(1 - \frac{N_{th}}{N}\right) dN \quad (10)$$

Initial photon density ϕ_i is small compared with the value of ϕ anytime during the laser output pulse. Hence the solution of expression (10) is

$$\phi(t) \cong \frac{l}{l_c\gamma}\left[N_i - N - N_{th}\ln\left(\frac{N_i}{N}\right)\right] \quad (11)$$

As can be inferred from expression (8), the photon number reaches a peak value ϕ_{peak} when N is equivalent to N_{th}. Hence from expression (11), we have

$$\begin{aligned}\phi_{peak} &\cong \frac{l}{l_c\gamma}\left[N_i - N_{th} - N_{th}\ln\left(\frac{N_i}{N_{th}}\right)\right] \\ &= \frac{lN_i}{l_c\gamma}\left[\frac{N_i/N_{th} - 1 - \ln(N_i/N_{th})}{N_i/N_{th}}\right]\end{aligned} \quad (12)$$

Expression (12) indicates that, when N_i/N_{th} approaches infinity, the peak photon number approaches the maximum available population inversion density $lN_i/l_c\gamma$.

After the release of the Q-switched laser pulse, laser population inversion density N is depleted by the photon flux and is reduced to a value below N_{th}. We can derive this final population inversion density N_f from expression (11) by setting $\phi \cong 0$ because the photon density is small after the release of the Q-switched laser pulse. Let $N = N_f$ and $\phi = 0$, then expression (11) becomes,

$$N_i - N_f - N_{th}\ln\left(\frac{N_i}{N_f}\right) = 0 \quad (13)$$

Expression (13) is transcendental and can be solved numerically. When N_i and N_f are known, the output pulse energy E, peak power P and pulse width τ_p of self-Q-switched Cr,Yb:YAG laser can be written as:[18]

$$E = \frac{h\nu A}{2\sigma\gamma}\ln\left(\frac{1}{R}\right)\ln\left(\frac{N_i}{N_f}\right) \quad (14)$$

$$P = \frac{h\nu Al}{\gamma t_r}\ln\left(\frac{1}{R}\right)\left[N_i - N_{th} - N_{th}\ln\left(\frac{N_i}{N_{th}}\right)\right] \quad (15)$$

$$\tau_p \approx \frac{E}{P} \quad (16)$$

where $h\nu$ is the photon energy, and A is the active area of the beam in the laser medium.

Expression (11)–(16) may be used to quantitatively evaluate the optical performance of a laser that is passively Q-switched with a slow-relaxing saturable absorber without actually executing the numerical calculation. N_i, N_{th}, N_f are the population inversion densities at the start of Q-switching, the point of maximum power and the end of the Q-switched pulse, respectively.

With continuous-wave pumping, the laser will be passively Q-switched as soon as the gain exceeds the combined saturable and unsaturable losses in the resonator. As the incident pump power is increased, the laser eventually reaches a threshold condition and begins to repetitively Q-switched operation with a time interval between pulses, t_c. The pulse energy and pulse repetition rate will be increased and the pulse width will be decreased with further increase of the incident pump power.

For continuous-wave pumped repetitive Q-switching laser at a repetition rate f, the maximum time available for the inversion to build up between pulses is $t_c = 1/f$. Therefore, the initial inversion density of the Q-switch under the influence of the absorbed pump power can be written as:[17)]

$$N_i = N_{cw} - (N_{cw} - N_f)\exp\left(\frac{-1}{\tau f}\right) \tag{17}$$

in order to have the inversion return to its original value after each Q-switch cycle, where N_{cw} is the continuous-wave pumping inversion density inside the resonator, $N_{cw} = W_p\tau$, W_p is the volumetric pump rate into the upper laser level and is proportional to the continuous-wave pump power, $W_p = P_p[1 - \exp(-2\alpha l)]/(h\nu_p A_p l)$, P_p is the incident pump power, $h\nu_p$ is the pump photon energy, A_p is the pump beam area, α is the absorption coefficient of gain medium at pump wavelength, and l is the length of the gain medium. Equations (17) and (13) can be solved numerically to obtain the initial inversion density, N_i and final inversion density, N_f for continuous-wave pumped repetitively Q-switched lasers.

3. Results and Discussion

The spectral parameters of Cr,Yb:YAG crystal used for numerical simulation of microchip $Cr^{4+}Yb^{3+}$:YAG self-Q-switched laser are taken from Refs. 7 and 8 and listed in

Table 1. The parameters used in numerical simulations.

Constant	Value
σ	2.3×10^{-19} cm^2
σ_g	4.6×10^{-18} cm^2
σ_e	8.2×10^{-19} cm^2
τ	951 µs
τ_s	3.4 µs
γ	2
$h\nu_p$	2.12×10^{-19} J
$h\nu$	1.93×10^{-19} J
R	90%
L	0.15
A	1.17×10^{-4} cm^2
N_{s0}	2.6×10^{17} cm^{-3}
l	0.75 mm
λ_p	940 nm
λ	1030 nm

Table 1. The ground state absorption cross section of the saturable absorber, Cr^{4+} (4.6×10^{-18} cm^2) is substantially greater than the emission cross section of Cr,Yb:YAG (2.5×10^{-20} cm^2) at the laser wavelength of 1.03 µm. Therefore, the effective laser beam area on the laser gain medium is equal to that on the saturable absorber for the self-Q-switched Cr,Yb:YAG laser, and self-Q-switched Cr,Yb: YAG lasers are satisfied with the second threshold condition.[15)] Zhou *et al.*[10)] experimentally demonstrated a laser diode end-pumped self-Q-switched Cr,Yb:YAG laser doped with 5 at.% Yb and 0.5 at% Cr. A single Q-switched laser pulse of 20 µJ in energy and 500 ps in duration at the laser wavelength of 1.03 µm was obtained. The schematic diagram of a laser diode pumped Cr,Yb:YAG self-Q-switched laser experiments is shown in Fig. 1, a monolithic microchip Cr,Yb:YAG crystal was used as a resonator (the thickness of the Cr,Yb:YAG crystal is less than 2 mm). The surface facing the pump beam was coated for high reflectivity at 1030 nm and high transmission at pump wavelength of 940 nm. The output surface of the monolithic laser resonator was coated with high reflectivity at the pump wavelength and certain reflectivity (from 80 to 95%) at the laser wavelength of 1030 nm.

According to Eq. (1), the loss of the Q-switched laser can be defined as

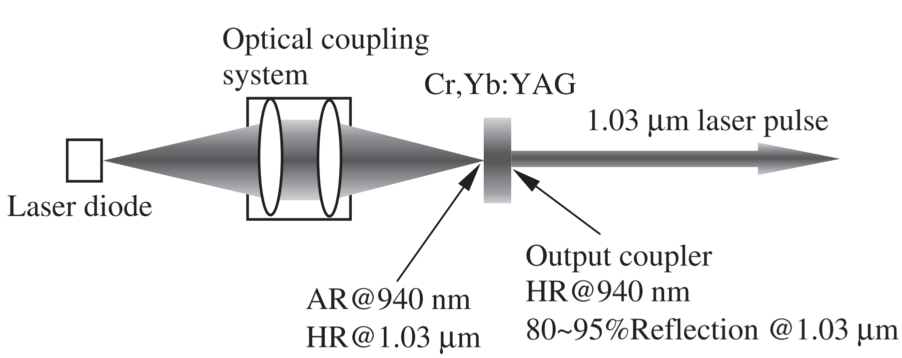

Fig. 1. The experimental setup of laser diode (LD) pumped Cr,Yb:YAG self-Q-switched laser.

$$\text{Loss} \equiv \frac{2\sigma_g N_g l_s + 2\sigma_e N_e l_s + \ln\left(\frac{1}{R}\right) + L}{2\sigma l} \tag{18}$$

The laser pulse generation of the self-Q-switched laser starts when the amplification in the gain medium is equal to the loss defined by expression (18), when the inversion density of the gain medium, N_i, achieves a high enough value of the generation condition to satisfy:

$$N_i \geq \text{Loss} = \frac{2\sigma_g N_g l_s + \ln\left(\frac{1}{R}\right) + L}{2\sigma l} \tag{19}$$

The excited state absorption is neglected because there is almost no absorption of the excited state of saturable absorber before the beginning of the laser pulse, so the excited absorption term in expression (19) is absent. The output energy of the self-Q-switched laser increases with the increase of the initial inversion density, N_i, according to expression (14). From expression (19), we can see that the initial inversion density is determined by the concentration of saturable absorber, the length of the saturable absorber, and the reflectivity of the output coupler; the inversion density is directly proportional to the saturable absorber optical density, $D_0 = -\ln T_0 = \sigma_g N_g l_s$. The output energy will increase if the initial transmission, T_0, decreases. The output energy increases with the decrease of the reflectivity of the output coupler. However, the decrease of the initial transmission of the saturable absorber and the reflectivity of the output coupler may lead to a situation where the generation condition (19) is not satisfied at a certain pumping rate W_p. At a fixed pump power, the maximum achievable value of the inversion density of the laser pulse is $N_{max} = \eta P_p \tau / h\nu_p V$, which is obtained from Eq. (2) with ϕ equals to 0, where η is the absorption efficiency of the gain medium, P_p is the total pump power incident on the crystal, h is the Planck constant, ν_p is the frequency of the pump laser, and V is the pump volume. The maximum achievable inversion density should be no more than the doping concentration of gain medium. Figure 2 shows the achievable output pulse energy as a function of initial transmission, T_0, and the reflectivity of the output coupler, R. The output pulse energy increases with the decrease of the initial transmission of the saturable absorber and the reflectivity of the output coupler. The threshold pump power also increases with the decrease of the initial transmission and the reflectivity of the output coupler according to Eq. (7).

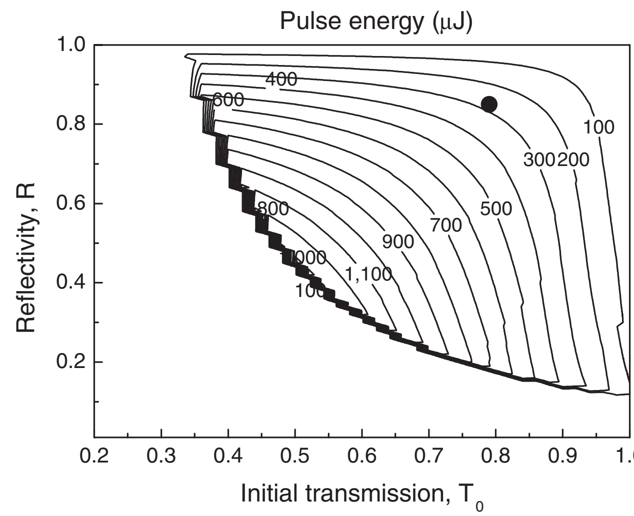

Fig. 2. The laser pulse energy as a function of the initial transmission of the saturable absorber, T_0, and the output coupler reflectivity, R, for Cr,Yb:YAG self-Q-switched laser. Solid circle shows the achievable output energy with 2-mm thick Cr,Yb:YAG crystal with 85% reflectivity.

Figure 3(a) show the pulse train of the numerical stimulation for the self-Q-switched Cr,Yb:YAG lasers obtained by solving Eqs. (1)–(4) with the Runge–Kutta method when pump rate $W_p = 15 \times 10^{23}\,\text{s}^{-1}\,\text{cm}^{-3}$ and the other parameters are as follows; these are taken from the experimental condition in Ref. 10: γ is 2 for a quasi-three-level system of Yb:YAG laser, laser wavelength is 1030 nm, the length of the cavity is 0.075 cm, reflectivity of the output coupler R is 90%, the intracavity loss is estimated to be 0.15, the initial ground state population density, N_{s0}, is $26 \times 10^{16}\,\text{cm}^{-3}$ which is the concentration of saturable absorber determined in the experiments, the emission cross section of Cr,Yb:YAG is $2.3 \times 10^{-20}\,\text{cm}^2$ and the lifetime is about 951 μs,[11] the ground-state absorption cross section of Cr^{4+} is $4.6 \times 10^{-18}\,\text{cm}^2$, the excited-state absorption cross section of Cr^{4+} is $8.2 \times 10^{-19}\,\text{cm}^2$ and lifetime of the Cr^{4+} saturable absorber is 3.4 μs, the pump spot radius is about 25 μm, and the output laser beam diameter is about 120 μm. It takes about 88 μs to develop the first Q-switched laser pulse, the time interval between subsequent Q-switched laser pulses is about 53 μs, which is shorter than that required for developing the first laser pulse because inversion density, N, does not decrease to zero after the release of the first laser pulse. The repetition rate is estimated to be 18.7 kHz. Figure 3(b) is an expanded picture of Fig. 3(a) near the occurrence of the first laser pulse. When the photon density inside the laser cavity increases, the loss decreases accordingly as a result of the bleaching effect of the Cr^{4+}:YAG saturable absorber. The photon density reaches its peak value when the laser inversion population equals the cavity loss, i.e., when $N = \text{Loss} = 8.32 \times 10^{19}\,\text{s}^{-1}\,\text{cm}^{-3}$, corresponding to the value calculated by Eq. (17). Beyond this point the laser inversion density (gain) is smaller than the total loss of the laser system, and the Q-switched laser pulse dies out quickly while the laser inversion population decreases gradually to a minimum value of $\sim 5.2 \times 10^{19}\,\text{s}^{-1}\,\text{cm}^{-3}$. The increase of the loss after the release of the Q-switched laser pulse is due to the relaxation of the saturable absorber population. The initial laser inversion population required for laser action, $12.6 \times 10^{19}\,\text{s}^{-1}\,\text{cm}^{-3}$, calculated by Eq. (6), is lower than that obtained by numerical simulation, $12.7 \times 10^{19}\,\text{s}^{-1}\,\text{cm}^{-3}$. The cause of this difference is that we assume that $N = \text{Loss}$ in deriving Eq. (6), whereas it is required that $N > \text{Loss}$ for the laser action to occur. From Fig. 3(b), the pulse width (full width at half-maximum) is about 292 ps, the output pulse energy is about 35 μJ, which is calculated by integration of the Q-switched laser pulse over a time range

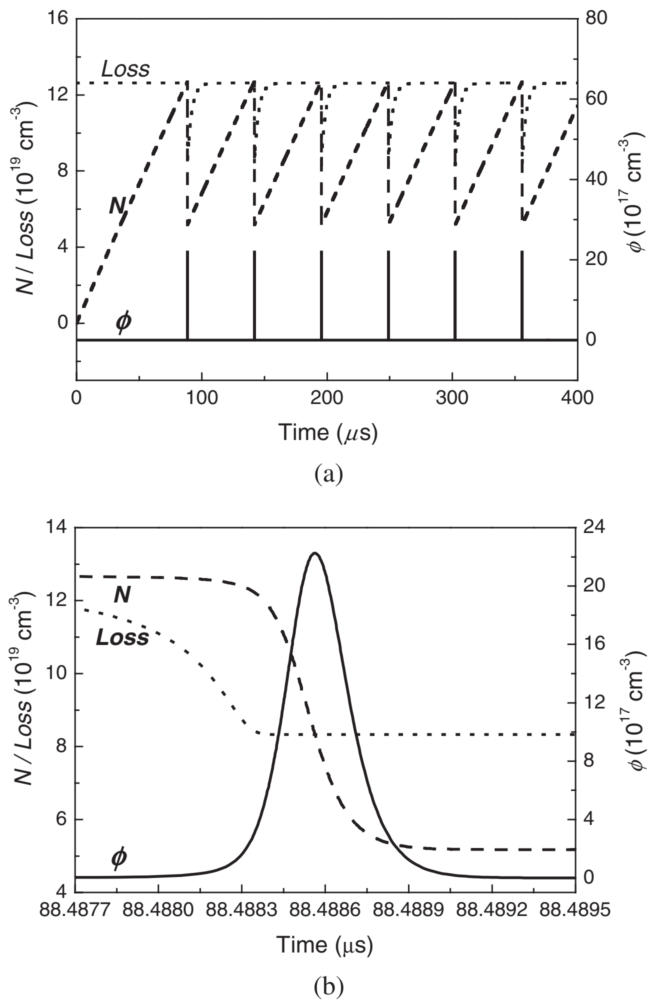

Fig. 3. The numerical calculations of the laser diode pumped Cr,Yb:YAG laser pulse train and the dynamic of the pulse development. (a) Evolution of the photon density, gain inversion density and the loss on the time scale of the repetition period for $W_p = 15 \times 10^{23}\ s^{-1}\ cm^{-3}$; (b) Evolution of the photon density, gain inversion density and the loss on the time scale of the pulse width for $W_p = 15 \times 10^{23}\ s^{-1} cm^{-3}$.

covering the entire laser pulse according to the expression[18)]

$$E_{out} = \frac{h\nu_l A l \ln(1/R)}{2l_c/c} \int_0^\infty \phi(t)\, dt \qquad (20)$$

so the peak power can be determined to be 119 kW. Although there is some difference between the numerical calculation results and the experimental data,[10)] the calculated pulse energy of 35 μJ and pulse width of 292 ps can be considered to be in fair agreement with the experimental data of 20 μJ and 500 ps. The remaining discrepancy between the numerical calculation results and the experimental data may be caused by the precise concentration of the Cr^{4+} ions in the laser crystal, the pump power beam variation along the thickness, and the beam diameter of the laser output. Furthermore, although the thermal lens is one critical condition for forming the laser cavity in a plane-parallel resonator, the existence of the thermal lens will have an effect on the laser performance. In the numerical simulation, the variation of the thermal lens and the absorbed pump power along the thickness of the crystal and radius was not taken into consideration.

The cw pump power has a great effect on the Q-switched laser performance. The average output power increases with the increase of the absorbed pump power. The pump rate is proportional to the absorbed pump power according to the expression, $W_p = P_{abs}/h\nu_p A_p l$, where $P_{abs} = P \times (1 - e^{-2\alpha l})$ for two pass pumping geometry, P is the incident pump power on the surface of the crystal, $h\nu_p$ is the pumping photon energy, A_p is the pump beam area at the entrance of the Cr,Yb:YAG crystal, and l is length of the crystal; it is reasonable to assume that the pump beam area inside the crystal does not change along the pump axis for such a short cavity. The lines in Fig. 4 show the self-Q-switched laser pulse energy, pulse width, repetition rate, average output power and peak power as functions of the pump rate, W_p, at 1.03 μm with reflectivity of the output coupler, $R = 90\%$ and different concentration of the saturable absorbers, N_{s0}. From Fig. 4(a), the Q-switched laser pulse energy keeps nearly the same with the pump rate for certain concentration of the saturable absorbers (for the same length of the saturable absorber), and the higher the concentration of the saturable absorber, the higher the pulse energy obtained. The pulse width decreases with the increase of the pump rate for certain concentration of the saturable absorbers, the higher the concentration of the saturable absorber, the shorter the pulse width [Fig. 4(b)]. At the lower pump rate near the pump power threshold, the pulse energy increases a little and the pulse width decreases a little with increase of the pump rate. When the pump rate reaches a certain value, the pulse energy remains nearly the constant and the pulse width decreases very slowly with the increase of the pump rate. It is obvious that a better Q-switched laser performance (shorter pulse width and high output pulse energy) can be achieved by using high concentration of the saturable absorber, as expected from the theory, and also as demonstrated by our analytical simulations (Fig. 2). Figure 4(c) shows the repetition rate as a function of the pump rate for different concentrations of the saturable absorbers. The repetition rate of Q-switched lasers increases linearly with the pump rate, the higher the concentration of the saturable absorber, the lower the repetition rate. Figure 4(d) shows the calculated average pump power as a function of the pump rate for different concentrations of the saturable absorbers, the average output power increases linearly with the pump rate, the higher the concentration of the saturable absorber, the lower the average output power at the same pump rate; this may be caused by the increase of the cavity loss owing to the higher concentration of the saturable absorber, the higher the concentration of the saturable absorber, the more defects in the laser crystals. The peak power increases a little bit with the pump rate near the pump threshold for different concentrations of the saturable absorbers and then nearly independent of the pump rate for a certain concentration of the saturable absorber; the higher the concentration of the saturable absorber, the higher the peak power [as shown in Fig. 4(e)].

The reflectivity of the output coupler also has a great

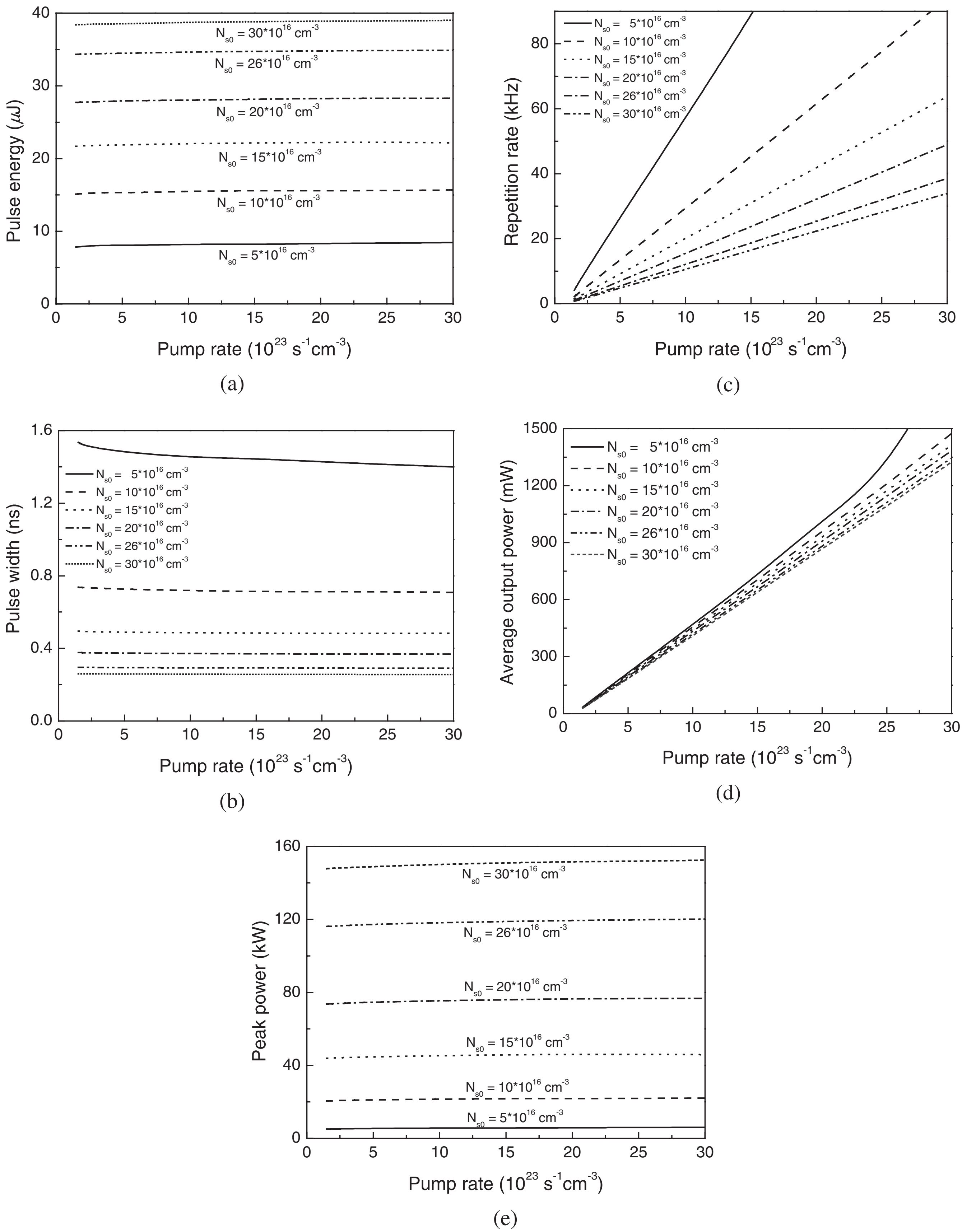

Fig. 4. The laser characteristics (a) pulse energy, (b) pulse width, (c) repetition rate, (d) average output power and (e) peak power as a function of pump rate for different concentrations of the saturable absorber; length of the Cr,Yb:YAG crystal is 0.75 mm.

impact on the Cr,Yb:YAG self-Q-switched laser characteristics. Figure 5 shows the pulse energy, the pulse width, the repetition rate, the average output power and the peak power of Cr,Yb:YAG laser as a function of reflectivity of the output coupler for different concentrations of the saturable absorbers; the pump rate, $W_p = 15 \times 10^{23}\,s^{-1}\,cm^{-3}$ was used in these numerical calculations and the other parameters were kept the same. The Q-switched pulse energy increases and the pulse width decreases for a specific reflectivity of the output coupler when the concentrations of the saturable absorber increase. And the repetition rate of the Q-switched pulse decreases with increase of the concentration of the saturable absorber. The results show that a better self-Q-switched Cr,Yb:YAG laser performance, such as a short pulse width and a high pulse energy output, can be obtained by using a higher concentrated saturable absorber. From Fig. 5(a), the Q-switched pulse energy decreases dramatically when the reflectivity of the output coupler is high, especially when the reflectivity is close to unity, because the output energy is related to the amount of the output coupling. With different concentrations of the saturable absorber, the higher the concentration of saturable absorber, the higher the pulse energy obtained. The pulse energy decreases slowly when the reflectivity of the output coupler is in the range from 40 to 70% for a certain concentration of the saturable absorber. As indicated in Fig. 5(b), the pulse width is nearly independent of the reflectivity of the output coupler for a saturable absorber concentration is greater than $15 \times 10^{16}\,cm^{-3}$. The pulse width decreases with the increase of the reflectivity of the output coupler when the concentration of the saturable absorber is less than $10 \times 10^{16}\,cm^{-3}$. The Q-switched pulse repetition rate increases with the reflectivity of the output coupler; the higher the concentration of the saturable absorber, the lower the repetition rate for a certain reflectivity of the output coupler [as shown in Fig. 5(c)]. The average output power decreases dramatically with the increase of the reflectivity of the output coupler for different concentrations of the saturable absorbers when the reflectivity is greater than 80%, and there is an optimum reflectivity for obtaining highest average output power [as shown in Fig. 5(d)]. There is a little decrease of the average output power with increase of the concentration of the saturable absorber; this is caused by increase the concentration of saturable absorber that results in an increase of the cavity loss. From Fig. 5(e), the peak power decreases with increase of the reflectivity of the output coupler for different concentrations of the saturable absorber.

According to the numerical calculations of the laser performance of 0.75 mm thick Cr,Yb:YAG microchip self-Q-switched lasers, the output pulse energy is nearly independent of the pump rate when the pump rate is above the threshold pump rate. And the output energy is mainly determined by the initial transmission of the saturable absorber and the reflectivity of the output coupler. From the relationship of the output energy as functions of the initial transmission of the saturable absorber and the reflectivity of the output coupler (as shown in Fig. 2), the higher output energy can be obtained by using lower initial transmission of the saturable absorber and lower reflectivity of the output coupler. For example, over 0.2 mJ output energy can be obtained by varying the initial transmission of the saturable absorber and the reflectivity of the output coupler (as shown in Fig. 2). However, for a practical design of a compact, monolithic Cr,Yb:YAG self-Q-switched laser, adequate pump power should be absorbed by the gain medium to make the laser more efficient, and the loss of the cavity should be kept as low as possible. The absorption efficiency is over 95% and the initial transmission of the saturable absorber is about 79% using 2 mm thick Cr,Yb:YAG crystal[7,9] co-doped with 10 at.% Yb and 0.025 at.% Cr as gain medium. Because there is a strong re-absorption of Yb^{3+} ions at the laser wavelength of 1030 nm, which increases with the length of Cr,Yb:YAG crystal, there is about 20% intracavity loss for 2 mm length Cr,Yb:YAG crystal doped with 10 at.% Yb and 0.025 at.% Cr. Therefore, an output coupler reflectivity of 85% is chosen to obtaine sufficient laser output. The combination of 2 mm thick Cr,Yb:YAG crystal doped with 10 at.% Yb and 0.025 at.% Cr with 85% reflectivity of the output coupler will satisfy this target (over 0.2 mJ output energy as a closed circle in Fig. 2). Then the laser performance of this 2-mm Cr,Yb:YAG laser is calculated according to the coupled rate equations. A Q-switched laser pulse of 269.5 μJ with pulse width of 319 ps can be obtained when the incident pump power is 4 W with a pump beam diameter of 150 μm, which corresponds to the pump rate of about $5 \times 10^{23}\,cm^{-3}\,s^{-1}$. The repetition rate of such a laser system is 3.1 kHz, and the peak power is about 843.5 kW. The thermal loading of ytterbium doped YAG crystal is about 11%, and this is only one third of the Nd:YAG crystal. However, the nature of the quasi-three-level system makes Yb doped crystal more sensitive to the temperature. Better laser performance could be achieved by cooling the temperature of crystal.

4. Conclusions

The dynamic and laser characteristics of the self-Q-switched Cr,Yb:YAG laser were investigated by numerically solving the coupled rate equations. The modified coupled rate equations including the pump rate term and the excited state absorption of the saturable absorber of Q-switched Cr,Yb;YAG lasers were solved numerically. The laser characteristics of the self-Q-switched laser performance as functions of the initial population of the ground state of the Cr^{4+} saturable absorber, the pump rate and the reflectivity of the output coupler were studied in detail. The simulation results show that the output pulse energy is nearly independent of the pump rate, and depends on the initial transmission of the saturable absorber and the reflectivity of the output coupler for a certain microchip cavity. Better laser performance can be achieved using a high concentration saturable absorber, higher pump rate and the suitable reflectivity of the output coupler for the specific concentration of the saturable absorber. By varying the parameters in the simulations, we can predict the output laser characteristics, this is important for the development of LD pumped Cr,Yb:YAG Q-switched laser used in various applications such as remote ranging, pollution monitoring, and so on.

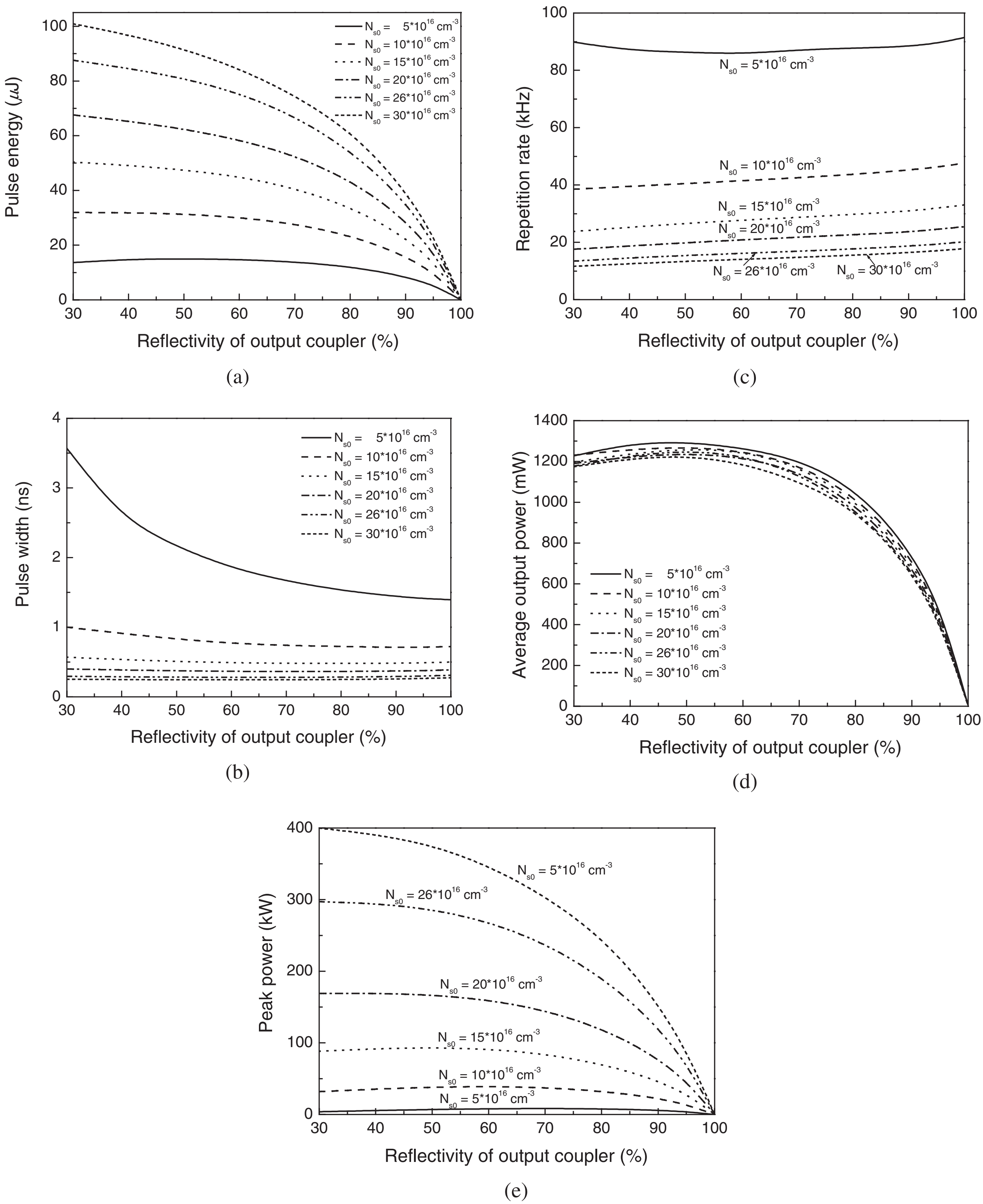

Fig. 5. The laser characteristics (a) pulse energy, (b) pulse width, (c) repetition rate, (d) average output power and (e) peak power as a function of reflectivity of the output coupler for different concentrations of the saturable absorber. The pump rate used in these simulations is $15 \times 10^{23}\ s^{-1}\ cm^{-3}$, length of the crystal is 0.75 mm.

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