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Modeling and optimization of actively Q-switched Nd:$GdVO_4$ 912 nm laser

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ABSTRACT

The simulation and optimization of Q-switched Nd:$GdVO_4$ quasi-three-level 912 nm laser under Gaussian pump beam distribution is conducted with considering the spatial distribution of intracavity photon density. The steady state rate equation for the population accumulation involves the energy transfer upconversion effects while the rate equations with ground state absorption are used to describe the pulse generation process. The influence of the energy transfer upconversion and ground state absorption effects on the output characters of pulsed 912 nm laser are estimated under different pump conditions. Based on the model, the optimized parameters of Q-switched Nd:$GdVO_4$ quasi-three-level 912 nm laser are obtained. This simulation method can be used to analyze and optimize the Q-switched quasi-three-level lasers under Gaussian beam pump.

1. Introduction

Lasers around 900 nm have been proved to be an efficient source to generate blue lasers by frequency doubling [1,2]. Blue lasers have numerous applications in the fields of high density optical data storage, color displays, underwater communication and imaging. Since Fan and Byer introduced laser diode (LD) end pumped Nd:YAG quasi-three-level laser at 946 nm, great efforts have been made to improve the laser performance both in continuous-wave (cw) and pulsed operation [3–8].

The vanadate, Nd:$GdVO_4$, is a promising crystal in quasi-three-level transition operation due to its big absorption and emission cross section, and the polarized output [9–11]. A maximum cw output power of 16.2 W at 912 nm is achieved with a slope efficiency of $\eta_s = 41.7\%$, while more than 2 W average output power is obtained in pulsed operation [12,13]. Though with a lower quantum deficiency, the lower gain with the lower-level population makes it hard to achieve the comparable laser performance as 1.06 μm laser. Many papers have also simulated quasi-three-level laser with different methods to analyze and optimize its performance [14–16]. The energy transfer upconversion (ETU) has detrimental effects on the quasi-three-level laser performance as an additional source of heat, furthermore reducing the population inversion and lowering the potential gain, especially for the Q-switched operation due to the high population density in the upper laser level [17–19]. As for the big ETU coefficient in neodymium doped vanadates [20], it is worthwhile to consider the ETU effects in the analysis and optimization of neodymium doped quasi-three-level laser.

In this paper, simulation and optimization of quasi-three-level Nd:$GdVO_4$ laser are conducted by a space dependent model under Gaussian pumping with considering ETU and ground state absorption (GSA) effects. The steady state rate equation with considering ETU effect is utilized to describe the population accumulation process. By solving the space-dependent rate equations with GSA, the influence of the ETU and GSA effects on the output characters of pulsed 912 nm laser are estimated under different pump conditions. Finally, the optimization for pulsed Nd:$GdVO_4$ 912 nm laser is conducted and determined.

2. Rate equations

In rapid Q-switched laser operation, the output laser pulse width is much shorter than the spontaneous life time, the spontaneous emission and the pump could be neglected during the laser pulse output process. In contrast, the upper level population accumulation $n_u(0,0)$ in the long term low-Q segment should consider the

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pump rate, spontaneous relaxation and multi-ion effects induced by ETU, which could be described as following:

$$\frac{dn_u(0,0)}{dt} = R_p - \frac{n_u(0,0)}{\tau_u} - Un_u(0,0)^2 \tag{1}$$

where τ_u is the lifetime of upper laser level and U is the ETU rate constant. The pump intensity R_p is given by:

$$R_p = \frac{\eta_\alpha P_{in}}{h\upsilon_p}\frac{1}{\pi\omega_p^2 l} \tag{2}$$

where P_{in} is the incident pump power, η_α is the pump absorbed efficiency, ω_p is the average pump beam radius in the laser medium, $h\upsilon_p$ is the pump photon energy. By solving Eq. (1) analytically, the initial accumulation population density $n_{u0}(0,0)$ in the upper level before the output pulse generation could be obtained. The population density in the lower laser level without pumping is given by:

$$n_{l0} = f_l N_0 \tag{3}$$

where N_0 is the total population density in the laser rod, f_l is the Boltzmann occupation at lower laser level.

The laser mode is assumed to be fundamental Gaussian mode with the photon density of the cavity mode expressed as following:

$$\phi(r,t) = \phi(0,t)\exp\left(\frac{-2r^2}{\omega_l^2}\right) \tag{4}$$

where ω_l is the Gaussian beam radius for the laser mode, $\phi(0,t)$ is the photon density along the crystal axis. Then the rate equations in the quasi-three-level transition during the Q-switched process could be given by [21]:

$$\frac{dn_l(r,t)}{dt} = f_l\sigma_e c[n_u(r,t) - n_l(r,t)]\phi(r,t) \tag{5}$$

$$\frac{dn_u(r,t)}{dt} = -f_u\sigma_e c[n_u(r,t) - n_l(r,t)]\phi(r,t) \tag{6}$$

where σ_e is the stimulated emission cross section, c is the speed of light, $n_l(r,t)$ and $n_u(r,t)$ are the average population density along the axial coordinate z, which could be given by

$$n_i(r,t) = \int_0^l \frac{n_i(r,z,t)dz}{l} \quad i = u, l \tag{7}$$

The differential equation describing $d\phi(r,t)/dt$ should be integrated over the beam cross section to guarantee the entire beam distribution in the formation process of Q-switched pulse. It can be given by:

$$\int_0^\infty \frac{d\phi(r,t)}{dt}2\pi r dr = \int_0^\infty \frac{\phi(r,t)}{t_r}\left\{2\sigma_e[n_u(r,t) - n_l(r,t)]l - \ln\left(\frac{1}{R}\right) - L\right\} \times 2\pi r dr \tag{8}$$

In quasi-three-level transition of neodymium doped crystals, the occupation ratio in the lower laser level is much lower than that in the upper laser level. Thus, the population of the ground state is not reduced significantly with population inversion. Therefore, the initial conditions of Eqs. (5) and (6) can be given by

$$n_l(r,0) = n_{l0} \tag{9}$$

$$n_u(r,0) = n_{u0}(0,0)\exp\left(\frac{-2r^2}{\omega_p^2}\right) \tag{10}$$

By using Eqs. (5) and (6), (9) and (10), the inversion population density could be obtained:

$$n_u(r,t) - n_a(r,t) = \left[n_u(0,0)\exp\left(\frac{-2r^2}{\omega_p^2}\right) - n_{l0}\right] \times \exp\left[-\gamma\sigma c\int_0^t \phi(0,t)dt\ \exp\left(\frac{-2r^2}{\omega_l^2}\right)\right] \tag{11}$$

Substituting Eqs. (4) and (11) into Eq. (8) and performing the integration over time, one obtains

$$\frac{d\phi(0,t)}{dt} = \frac{4\sigma_e l\phi(0,t)}{\omega_l^2 t_r}\int_0^\infty \left[n_u(0,0)\exp\left(\frac{-2r^2}{\omega_p^2}\right) - n_l(0,0)\right] \times \exp\left[-\gamma\sigma_e c\int_0^t \phi(0,t)dt\ \exp\left(\frac{-2r^2}{\omega_l^2}\right)\right] \times \exp\left(\frac{-2r^2}{\omega_l^2}\right)2ndr - \frac{\phi(0,t)}{t_r}\left[\ln\left(\frac{1}{R}\right) + L\right] \tag{12}$$

This is the basic differential equation describing $\phi(r,t)$ as a function of time (t) in the Q-switched quasi-three-level lasers under Gaussian beam pumping. The threshold condition is that the intracavity gain over the cavity mode exceeds the round-trip loss. When Eq. (12) equals to zero at $t=0$, the threshold condition along the laser axis is shown as following:

$$\begin{aligned} n_{u\_th}(0,0) &= \frac{\ln(1/R) + L + 2\sigma_e n_{l0} l}{2\sigma_e l}\left(1 + \frac{\omega_l^2}{\omega_p^2}\right) \\ &= n_{u\_th1}(0,0) + n_{u\_th2}(0,0) \end{aligned} \tag{13}$$

$$n_{u\_th1}(0,0) = \frac{\ln(1/R) + L}{2\sigma_e l}\left(1 + \frac{\omega_l^2}{\omega_p^2}\right) \tag{14}$$

$$n_{u\_th2}(0,0) = n_{l0}\left(1 + \frac{\omega_l^2}{\omega_p^2}\right) \tag{15}$$

Compared with four-level transition, Eq. (13) involves the additional term n_{l0} due to the existence of the lower level population [22]. The threshold for upper level population density $n_{u\_th}(0,0)$ includes two parts: $n_{u\_th1}(0,0)$ is the intracavity loss induced by the output mirror transmission and the round-trip dissipative optical loss; $n_{u\_th2}(0,0)$ comes from the reabsorption losses in the quasi-three-level transition.

To simply the equations, we introduce normalized time (τ), normalized photon density $\Phi(r,\tau)$, normalized upper level population density N and reabsorption parameter M:

$$\tau = \frac{t}{t_r}\left[\ln\left(\frac{1}{R}\right) + L\right] \tag{16}$$

$$\Phi(r,\tau) = \phi(r,\tau)\frac{2\gamma\sigma_e l'}{\ln(1/R) + L} \tag{17}$$

$$N = \frac{n_u(0,0)}{n_{u\_th1}(0,0)} \tag{18}$$

$$M = \frac{n_{u\_th2}(0,0)}{n_{u\_th1}(0,0)} \tag{19}$$

Substituting Eqs. (16)–(19) into Eq. (12), it yields

$$\frac{d\Phi(0,\tau)}{dt} = N\Phi(0,\tau)\int_0^1 \exp\{-A(\tau)y^{1/(1+(\omega_l^2/\omega_p^2))}\}dy - M\Phi(0,\tau)\frac{1-\exp(-A(\tau))}{A(\tau)} - \Phi(0,\tau) \tag{20}$$