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Control of the pulse width of a laser-diode end-pumped passively Q-switched solid-state laser

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Abstract

We theoretically and experimentally study different techniques to control the pulse width of a laser-diode-pumped passively Q-switched solid-state laser. It is shown that varying the laser beam radius in the saturable absorber and the pump beam radius in the gain medium provide an efficient means to control the pulse width. The experiments performed on a laser-diode-pumped Nd:YVO_4 laser passively Q-switched by a Cr^{4+}:YAG saturable absorber are consistent with the theoretical calculations obtained from the rate-equations model, in which the intracavity photon density is assumed to be Gaussian spatial distribution, and the longitudinal variation of the intracavity photon density and the pump beam spatial distribution are also considered.

Keywords: Pulse width; Passively Q-switched; Solid-state laser; Rate equations; Gaussian spatial distribution

1. Introduction

Laser-diode (LD) pumped solid-state Q-switched lasers have attracted a great deal of attention in recent years [1–6]. All solid-state Q-switched lasers have wide applications in the fields of remote sensing, information storage, coherent telecommunications, medicine, etc. Compared with actively Q-switched lasers, the passively Q-switched ones have the advantages of simplicity, compactness, high efficiency and low cost. The main characteristics of the emitted pulses are their width, peak power, and repetition rate. The pulse width and peak power are known to be ruled by the parameters of the gain medium, the saturable absorber, and the cavity. They are thus essentially fixed by laser construction. But applications request the control and adjustment of the pulse width. Theoretical descriptions of passively Q-switched lasers show that the pulse width relies on the pump and laser mode sizes [7]. By varying the laser beam radius in the saturable absorber and the pump beam radius in the gain medium, Lai et al. [8] have theoretically and experimentally studied to control the pulses emitted by passively Q-switched Nd:YAG solid-state lasers. But in their theoretical study, the rate equations are obtained under a plane-wave approximation, in which the assumption of uniform pump, uniform intracavity laser power, and uniform bleaching of the saturable absorber has been made. So by numerically solving their rate equations we cannot obtain the direct relation between the pulse width and the beam radii. When the intracavity photon density is assumed to be Gaussian spatial distribution and the longitudinal variation of the intracavity photon density and the pump beam spatial distribution are also considered in the rate equations, by numerically solving these rate equations we can obtain the direct relation between the pulse width and the beam radii in the theoretical study [9]. Moreover, when the Gaussian distribution of the intracavity photon density is taken into account in the rate equations, the theoretical results obtained by numerically solving these rate equations are more close to the experimental results than those

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obtained under the plane-wave approximation, especially for the pulse width [10–12].

In this paper, we first introduce the rate equations of a laser-diode end-pumped passively Q-switched Nd:YVO$_4$ laser with Cr^{4+}:YAG saturable absorber, in which the intracavity photon density is assumed to be Gaussian spatial distribution, the longitudinal variation of the intracavity photon density and the pump beam spatial distribution are also considered. By numerically solving these rate equations we obtain the dependences of the pulse width on the laser and pump beam radii. In the experiments, the pulse width is changed by varying the laser beam radius in the saturable absorber and the pump beam radius in the gain medium. The experimental results are consistent with the theoretical calculations.

2. Theoretical analysis

We consider the laser depicted in Fig. 1, in which Nd:YVO$_4$ works as the gain medium and Cr^{4+}:YAG works as the passive Q-switch. It is longitudinally pumped by a cw laser diode. If the intracavity photon density is assumed to be a Gaussian spatial distribution during the entire formatting process of the LD-pumped passively Q-switched laser pulse, the intracavity photon density $\phi(r,t)$ for the TEM$_{00}$ mode can be expressed as

$$\phi(r,t) = \phi(0,t)\exp\left(-\frac{2r^2}{w_1^2}\right), \tag{1}$$

where r is the radial coordinate, w_1 is the average radius of the TEM$_{00}$ mode, which is mainly determined by the geometry of the resonator, and $\phi(0,t)$ is the photon density in the laser axis. The photon densities $\phi_g(r,t)$, $\phi_s(r,t)$, and $\phi_r(r,t)$ at three positions Nd:YVO$_4$ crystal, saturable absorber and the output mirror can be expressed as [9]

$$\phi_g(r,t) = \frac{w_1^2}{w_g^2}\,\phi(0,t)\exp\left(-\frac{2r^2}{w_g^2}\right), \tag{2}$$

$$\phi_s(r,t) = \frac{w_1^2}{w_s^2}\,\phi(0,t)\exp\left(-\frac{2r^2}{w_s^2}\right), \tag{3}$$

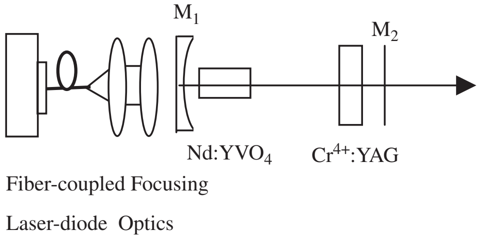

Fig. 1. Schematic of the experimental setup.

$$\phi_r(r,t) = \frac{w_1^2}{w_r^2}\,\phi(0,t)\exp\left(-\frac{2r^2}{w_r^2}\right), \tag{4}$$

where w_g, w_s and w_r are the radii of the TEM$_{00}$ mode at the above-mentioned three positions, respectively.

So for this laser, if neglecting the spontaneous radiation during the pulse formation, we can obtain the coupling rate equations [9,13]

$$\begin{aligned}\int_0^\infty \frac{\mathrm{d}\phi(r,t)}{\mathrm{d}t}\,2\pi r\,\mathrm{d}r &= \int_0^\infty \frac{1}{t_r}\Big\{2\sigma n(r,t) l \phi_g(r,t) - 2\sigma_g n_{s1}(r,t) l_s \phi_s(r,t) \\ &\quad - 2\sigma_e[n_{s0} - n_{s1}(r,t)] l_s \phi_s(r,t) - \ln\left(\frac{1}{R}\right)\phi_r(r,t) \\ &\quad - L\phi(r,t)\Big\}\,2\pi r\,\mathrm{d}r,\end{aligned} \tag{5}$$

$$\frac{\mathrm{d}n(r,t)}{\mathrm{d}t} = f_a R_{in}(r) - (f_a + f_b)\sigma c n(r,t)\phi_g(r,t) - \frac{n(r,t)}{\tau}, \tag{6}$$

$$\frac{\mathrm{d}n_{s1}(r,t)}{\mathrm{d}t} = \frac{n_{s0} - n_{s1}(r,t)}{\tau_s} - \sigma_g c n_{s1}(r,t)\phi_s(r,t), \tag{7}$$

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 Cr^{4+}:YAG saturable absorber, respectively, σ and l are the stimulated-emission cross-section and length of Nd:YVO$_4$ 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 is the round-trip time of light in the resonator $\{t_r = [2n_1 l + 2n_2 l_s + 2(L_e - l - l_s)]/c\}$, n_1 and n_2 are the refractive indices of Nd:YVO$_4$ gain medium and Cr^{4+}:YAG saturable absorber, respectively, L_e is the cavity length, c is the velocity of light in vacuum, R is the reflectivity of the output mirror, L is the intrinsic loss, f_a and f_b are the Boltzman Occupation fraction of the upper and lower levels, respectively, τ is the stimulated-radiation lifetime of the gain medium, τ_s is the excited-state lifetime of the saturable absorber, $R_{in}(r) = P_{in}[1 - \exp(-\alpha l)] \times \exp(-2r^2/w_p^2)/h\gamma_p \pi w_p^2 l$ is the pump rate, where P_{in} is the pump power, $h\gamma_p$ is the single-photon energy of the pump light, w_p is the average radius of the pump beam in the gain medium, α is the absorption coefficient of the gain medium.

The initial conditions of Eqs. (6) and (7) can be written as [9]

$$n_{s1}(r,0) = n_{s0}, \tag{8}$$

$$n(r,0) = n(0,0)\exp\left(-\frac{2r^2}{w_p^2}\right), \tag{9}$$