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Optimization of the peak power of doubly Q-switched lasers with both an acousto-optic modulator and a GaAs saturable absorber

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ABSTRACT

The key parameters of an optimally coupled doubly Q-switched laser are determined by maximizing the peak power. A group of general curves are generated by considering the single-photon absorption (SPA) and two-photon absorption (TPA) processes in the GaAs, along with the Gaussian spatial distributions of the intracavity photon density, the initial population-inversion density and the influence of the acousto-optic (AO) Q-switch. These results are compared with the results obtained when maximizing the output energy of the doubly Q-switched laser, and the differences between these approaches are discussed. Sample calculations for a laser-diode-pumped Nd^{3+}:YVO_4 laser with both an AO modulator and a GaAs saturable absorber are presented to demonstrate the use of the curves and the relevant formulas.

1. Introduction

Q-switching is a technology widely used in lasers to generate short pulses with high peak powers. Such pulses are desirable in many laser applications such as micromachining, lidar, ranging, remote sensing, microsurgery, and so on. In solid-state lasers, Q-switching can be realized either actively using acousto-optic (AO) [1] or electrical–optical (EO) modulators, or passively using a semiconductor saturable absorber, such as GaAs [2–4]. Although single Q-switched lasers can produce short pulses and high peak powers, the pulse temporal profile of single Q-switched lasers is usually asymmetric, with a fast rising edge and a slow falling edge in the case of an AO Q-switched laser, and with a slow rising edge and a fast falling edge in the case of a GaAs Q-switched laser [2,3,5,6]. If we put an AO modulator and a GaAs saturable absorber in the same cavity simultaneously, known as double Q-switching, it is possible to obtain more symmetric and shorter pulses with high pulse peak powers, which has been experimentally proved. This doubly Q-switched laser is more useful in some applications [7–9]. The aim of this paper is the optimization of the properties of doubly Q-switched lasers that incorporate both an AO modulator and a GaAs saturable absorber.

Several theories for the optimization of single doubly Q-switched lasers have been put forward [10–21], and a single doubly Q-switched laser can be optimized for a certain pump condition and dissipative optical loss through appropriate choice of the reflectivity of the output coupler. By taking into account intracavity spatial distributions of the electric field, the optimization of a passively Q-switched laser may be achieved [17,20], and the optimization of a slowly active Q-switched laser has been reported [21], in which the turnoff time of the Q-switch is considered. Recently, the optimization of a doubly Q-switched laser with an AO modulator and Cr^{4+}-doped saturable absorber has been reported [22,23], and the optimization of the output *energy* of a doubly Q-switched lasers containing both an AO modulator and a GaAs saturable absorber has also been obtained [24]. However, the pulse peak power is also an important parameter for a number of applications of doubly Q-switched lasers. As far as we know, the optimization of peak power of doubly Q-switched lasers containing both an AO modulator and a GaAs saturable absorber has not been reported previously

In this paper, the key parameters of an optimally coupled doubly Q-switched laser are determined based on maximizing the peak power, and a group of general curves are generated for the first time. The curves clearly show the dependence of the optimal key parameters on the parameters of the gain medium, the GaAs saturable absorber, the AO Q-switch, the resonator, and the spatial distributions of the intracavity photon density. These results are compared with those of the optimized of a doubly Q-switched laser that contains both an acousto-optic modulator and a GaAs saturable absorber based on maximizing the output *energy,* and the differences are discussed. Sample calculations for a diode-pumped Nd:YVO_4 laser with both an AO modulator and a GaAs saturable absorber are presented to demonstrate the use of the curves and the relevant formulas.

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2. Maximization of peak power

For a doubly Q-switched laser containing both an AO modulator and a GaAs saturable absorber, we can obtain the following normalized rate equations [24]:

$$\begin{aligned}\frac{d\phi(0,\tau)}{d\tau} &= \phi(0,\tau)(1+\Delta_a)\int_0^t \exp\{-A(\tau)u^B\}\,du \\ &\quad - \chi_1[1-(x+z)]\phi(0,\tau) - \chi_2[1-(x+z)]\phi(0,\tau) \\ &\quad \times \phi(0,\tau)\frac{1-\exp[-\alpha A(\tau)]}{\alpha A(\tau)} \\ &\quad - (x+z)\phi(0,\tau) - \phi(0,\tau)\Delta_a \\ &\quad \times \exp\left(-\frac{\tau^2}{\tau_s^2}\right) - \frac{B}{8L'}\chi_3[1-(x+z)] \\ &\quad \times \alpha[\phi(0,\tau)]^2 \qquad (1)\end{aligned}$$

where the normalized τ and τ_s are the ratio of the time t and the turnoff time of the AO switch t_s to the photon decay time t_c, i.e.

$$\tau = \frac{t}{t_c} = \frac{t}{t_r}\left[\ln\left(\frac{1}{R}\right) + \ln\left(\frac{1}{T_0^2}\right) + L\right] = \frac{t}{t_r}[2\beta\sigma n(0,0)l - \delta_a],$$

$$\tau_s = \frac{t_s}{t_c} = \frac{t_s}{t_r}\left[\ln\left(\frac{1}{R}\right) + \ln\left(\frac{1}{T_0^2}\right) + L\right] = \frac{t_s}{t_r}[2\beta\sigma n(0,0)l - \delta_a].$$

x, z, y are the ratios of the output coupling loss (useful loss), the round-trip dissipative optical loss (nonuseful loss), the transmission loss of the GaAs saturable absorber, to the round-trip unsaturable small-signal gain (or the sum of transmission loss in the laser resonator), respectively. The normalized intrinsic diffraction loss of AO Q-switch Δ_a is the ratio of the intrinsic diffraction loss of AO Q-switch to the sum of transmission losses in the laser resonator,

$$\begin{aligned} x &= \frac{\ln(1/R)}{2\beta\sigma n(0,0)l - \delta_a} = \frac{\ln(1/R)}{\ln(1/R) + \ln(1/T_0^2) + L}, \\ y &= \frac{\ln(1/T_0^2)}{2\beta\sigma n(0,0)l - \delta_a} = \frac{\ln(1/T_0^2)}{\ln(1/R) + \ln(1/T_0^2) + L}, \\ z &= \frac{L}{2\beta\sigma n(0,0)l - \delta_a} = \frac{L}{\ln(1/R) + \ln(1/T_0^2) + L}, \\ \Delta_a &= \frac{\delta_a}{2\beta n(0,0)\sigma l - \delta_a} = \frac{\delta_a}{\ln(1/R) + \ln(1/T_0^2) + L}. \end{aligned}$$

$\Phi(r,\tau)$ u, β, $A(\tau)$ are introduced in Refs. [22–24]. χ_1, χ_2, and χ_3, are constants for the GaAs saturable absorber, and L' is the normalized optical length of the resonator, which are all defined in Ref. [24].

Here α is not only an indicator of how easily the process of SPA is saturated, but also a parameter showing the strength of two-photon absorption (TPA) process in GaAs, which can be derived from the last term of Eq. (1), $-(B/8l_n)\chi_3[1-(x+z)]\alpha[\Phi(0,\tau)]^2$, which describes how the TPA process in GaAs increases with α.

By using the method of Zayhohowski and Kelley (1991) [12], we can obtain the following expressions for peak power P_m, pulse energy E, and pulse width W. Then we define the normalized parameters e, p, and w

$$p = \frac{1}{(2\beta\sigma n(0,0)l - \delta_a)^2}\frac{4\gamma\sigma t_r}{\pi\omega_L^2 h\nu}P_m, \qquad (2)$$

$$e = \frac{4\gamma\sigma}{\pi\omega_L^2 h\nu}\frac{1}{2\beta\sigma n(0,0)l - \delta_a}E, \qquad (3)$$

$$w = \frac{2\beta\sigma n(0,0)l - \delta_a}{t_r}W, \qquad (4)$$

which can be expressed as

$$e = x\phi_{\text{int}}, \qquad (5)$$

$$p = x\phi_m, \qquad (6)$$

$$w \approx \frac{e}{p} \qquad (7)$$

where ϕ_{int} is the integral of $\phi(0,\tau)$ over τ from zero to infinity, i.e. $\phi_{\text{int}} = \int_0^\tau \phi(0,\tau)d\tau$ and ϕ_m is the maximum value of $\phi(0,\tau)$.

The aim is to maximize the peak power by selecting the optimal $\ln(1/R)$ and $\ln(1/T_0^2)$ for a given amplifying medium, a given saturable absorber medium (σ^0 and σ^+ is fixed, T_0 is changeable), and a given pump level (i.e. a given $n(0,0)$ and ω_P/ω_L). This means maximizing p by selecting the optimal x and y under the condition $x+y+z = 1$.

By numerically solving Eqs. (1) and (5)–(7), we can derive a series of numerical solutions for the normalized peak power p versus x for a given z, α, ω_P/ω_L, Δ_a, and τ_s, then we can maximize it and determine the optimal x, y and the corresponding e, w. The other relevant parameters of GaAs are given in Ref. [24].

According to the definition of x, z, y, we can obtain R_{opt}, T_{opt}, and the real maximum pulse peak power $P_{\max}$, the corresponding real output energy E, and the real pulse width W.

3. Results and discussion

The results are shown in Figs. 1–13, respectively.

From Figs. 1–9, we can see the influence of the AO Q-switch on the operation of a doubly Q-switched laser when the laser is peak-power-maximized. Comparing Figs. 1–9 with Figs. 1–9 in Ref. [24], we find that the basic variation tendency is similar, but that x_{opt} is different, being smaller than that of an energy-maximized doubly Q-switched laser. So, we find that the R_{opt} of the peak-power-maximized doubly Q-switched laser is larger than that of the energy-maximized doubly Q-switched laser under the similar conditions. This is easily understood. If we want to obtain larger laser pulse energy, we must increase the reflectivity of the output mirror in order to retain more energy in the resonator. We should also notice that, after increasing the reflectivity of the output mirror, the pulse width of the laser will increase. Then the peak power of the laser pulse will reduce.

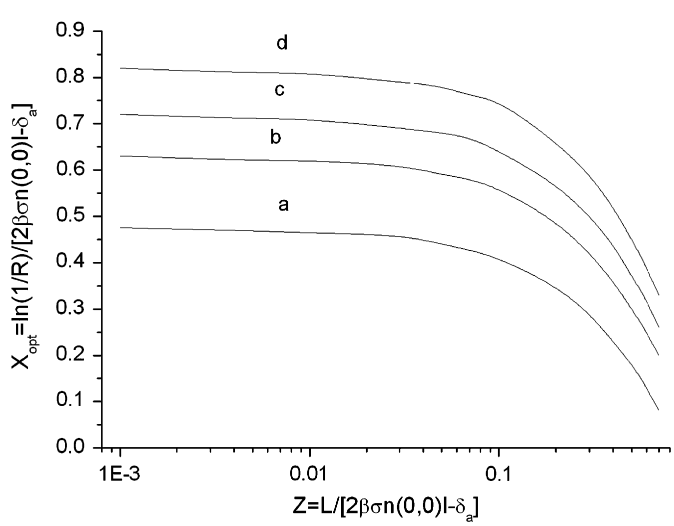

Fig. 1. Dependence of x_{opt} on z for different Δ_a in the case of $\omega_L/\omega_p = 1$, $\alpha = 50$, and $\tau_s = 5$ when the laser is a peak-power-maximized doubly Q-switched laser. (a) $\Delta_a = 0$, (b) $\Delta_a = 0.1$, (c) $\Delta_a = 0.15$, and (d) $\Delta_a = 0.2$.