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# Optimization of GaAs semiconductor saturable absorber Q-switched lasers

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## Abstract

The expressions of pulse characteristics such as output energy, peak power, and pulse width are obtained by solving the coupled rate equations describing the operation of GaAs semiconductor saturable absorber Q-switched lasers. The key parameters of an optimally coupled GaAs saturable absorber Q-switched laser are determined and several design curves are generated from these expressions for the first time. These key parameters include the optimal normalized coupling parameters and the optimal normalized saturable absorber parameters that maximize the output energy or maximize the peak power, and the corresponding normalized energy, normalized peak power, and normalized pulse width. Using the expressions and design curves, one can predict the pulse characteristics and perform the design of an optimally coupled GaAs saturable absorber Q-switched laser.
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## 1. Introduction

Laser-diode-pumped all solid-state passively Q-switched lasers, due to the advantages of miniature, simplicity, high efficiency and low cost, have wide applications in the fields of remote sensing, ranging, medicine, etc. Passively Q-switched technique is usually accomplished with intra-cavity saturable elements such as dyes [1], color centers [2], $Cr^{4+}$:YAG crystals [3], semiconductors [4] and anti-resonant Fabry-Pérot [5]. In recent years, GaAs semiconductor saturable absorber has become another attractive candidate for passive Q-switches due to the large optical nonlinearity. Although the energy of a photon at the wavelength of 1.06 μm is far below the GaAs band gap of 1.42 eV, the absorption at this wavelength is believed to be the *EL2* defect that forms deep donor levels $EL2^0/EL2^+$ about 0.82 eV below the band gap. However, at sufficiently high laser intensities, the nonlinear absorption is dominated by two-photon absorption (TPA). Passively Q-switched laser with GaAs as saturable absorber was firstly realized by Kajava and Gaetain in 1996 [6]. Recently, GaAs has been successfully used as passive Q-switches for a variety of laser media, such as Yb:YAG [7], $Nd^{3+}$:$YVO_4$ [8], Nd:GdCOB [9], etc.

The performance of a Q-switched laser for each three-way combination of amplifying medium, saturable absorber medium, and pump level can be optimized through the proper choice of output coupler and the initial saturable absorber transmission [10,11]. Degan [11] obtained the key parameters of an energy-maximized passively Q-switched laser. Zhang et al. [10] considered the optimization of dye passively Q-switched lasers and the optimization of $Cr^{4+}$-doped saturable

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absorber Q-switched lasers [11,12]. But those results cannot be directly applied to GaAs saturable absorber Q-switched lasers, because the saturable absorption of GaAs include the single-photon absorption (SPA) and TPA as well as free-carrier absorption (FCA). As far as we know, the optimization of GaAs semiconductor saturable absorber Q-switched lasers has not been reported.

In this paper, we first solve the three coupled rate equations that describe the operation of GaAs saturable absorber Q-switched lasers to obtain the pulse characteristics such as output energy, peak power, and pulse width. We then determine the key parameters of an optimally coupled GaAs saturable absorber Q-switched laser as functions of two variables concerning the amplifying medium, saturable absorber medium, and pump level, and generate several design curves. These key parameters include the optimal coupling parameter and the optimal saturable absorber parameter that maximize the output energy or maximize the peak power. Using the expressions and the design curves, one can predict the pulse characteristics and perform the design of an optimally coupled passively Q-switched laser.

## 2. Rate equations and solutions

The saturable absorptions of GaAs include the SPA and the TPA. The energy level responsible for absorption around 1 μm is believed to be the *EL2* defect (include $EL2^0$ and $EL2^+$) level between conduction and valence bands. To model the operation of a passively Q-switched laser, the distributions in the transverse section of pump light, and the intra-cavity optical intensities in the gain medium and in the absorber should be assumed uniform. We neglect the spontaneous emission of the saturable absorber during the formation of short Q-switched pulse (~ns). If the influence of longitudinal attenuation of the pump light is also neglected, the Q-switched rate equations under the plane-wave approximation can be used to analyze the performance of the laser. By combining the SPA and TPA processes, the coupled rate equations describing the operation of GaAs Q-switched laser can be written as [9]

$$\frac{d\phi}{dt} = \frac{\phi}{t_r}\left[2\sigma n l - 2\sigma^+ n^+ d - 2\sigma^0(n_0 - n^+)d - B\phi - \ln\left(\frac{1}{R}\right) - L\right] \tag{1}$$

$$\frac{dn}{dt} = -\gamma\sigma c n \phi \tag{2}$$

$$\frac{dn^+}{dt} = [\sigma^0(n_0 - n^+) - \sigma^+ n^+]c\phi \tag{3}$$

where $\phi$ is the photon density inside the laser resonator, $n$ is the population inversion density, $n_0$ is the total population density of the *EL2* defect level (including $EL2^0$ and $EL2^+$) of GaAs saturable absorber, $n^+$ is the population density of positive charged $EL2^+$, $\sigma$ is the stimulated emission cross section of the laser crystal, $\gamma$ is the inversion reduction factor, $t_r$ is the round-trip time in the cavity of optical length $l'$, $t_r = 2l'/c = [2n_1 l + 2n_2 d + 2(L_c - l - d)]/c$, $c$ is the light velocity in the vacuum space, $n_1$ is the refractive index of the laser crystal, $n_2$ is the refractive index of GaAs, $l$ is the length of the gain medium, $d$ is the thickness of GaAs, $L_c$ is the cavity length. $\sigma^0$ and $\sigma^+$ are the absorption cross section of $EL2^0$ and $EL2^+$, respectively, $R$ is the output coupler reflectivity, $L$ is the loss of the cavity, $B$ is the coupling coefficient of TPA in the GaAs, which is defined as [13]

$$B = 6\beta h\nu c d(\omega_0/\omega_q)^2 \tag{4}$$

where $\beta$ is the absorption coefficient of two photons, $\omega_0$ and $\omega_q$ are the spot size of the beam in the gain medium and GaAs wafer, respectively. The small-signal transmission $T_0$ of GaAs can be expressed by

$$T_0 = \exp\{-[\sigma^0(n_0 - n_0^+) + \sigma^+ n_0^+]d\} \tag{5}$$

where $n_0^+$ is the initial population density of positive charged $EL2^+$.

Dividing Eq. (2) by Eq. (3) and integrating the result, we obtain

$$n^+ = \frac{1}{1+\delta}\left\{[(1+\delta)n_0^+ - n_0]\left(\frac{n}{n_i}\right)^\alpha + n_0\right\} \tag{6}$$

where $n_i$ is the initial population inversion density at the start of Q-switching, $\alpha$ is a constant concerning the amplifying medium and the saturable absorber medium

$$\alpha = \frac{\sigma^0(1+\delta)}{\gamma\sigma} \tag{7}$$

and $\delta$ is an important parameter of saturable absorbers

$$\delta = \frac{\sigma^+}{\sigma^0} \tag{8}$$

We define a new parameter $T_{0i}$ as

$$T_{0i} = \exp\left(-\frac{2\delta}{1+\delta}\sigma^0 n_0 d\right) \tag{9}$$

Dividing Eq. (1) by Eq. (2) and substituting Eqs. (5)–(9) into the result yield

$$\frac{d\phi}{dn} = -\frac{l}{\gamma l'}\left\{1 - \frac{\ln(1/R) + \ln(1/T_0^2) + L}{2\sigma n l} - \frac{\ln(1/T_{0i}^2) - \ln(1/T_0^2)}{2\sigma n l}\left[1 - \left(\frac{n}{n_i}\right)^\alpha\right]\right\} + \frac{B}{2\sigma\gamma n l'}\phi \tag{10}$$

Since laser action begins at the moment that the population inversion density crosses the initial threshold

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