

# Simulation of passive Q- switching laser pulse Characteristics as a function of output coupler reflectivity

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## Abstract

The effect of output coupler reflectivity ( $R_1$ ) on characteristics ( energy and duration) of a Passive Q- switching Laser Pulse has been studied theoretically by numerical analysis (runga- kata method) for mathematical description (rate equations model) for temporal performance of  $Cr^{+4} : YSO$  crystal Chromium yttrium which was used as a storable absorber material (passive switch ) with  $Nd : GdVO_4$  neodymium cadimium vanadium laser. The study shows that the pulse energy is increasing with increase of the output coupler reflectivity, while the pulse duration decreasing with increase of the output coupler reflectivity.

**Keywords:** Laser , passive Q-switching.

## 1. Introduction

Pulsed solid-state laser widely used in scientific, medical, industrial and military systems, the efficiency and the cost are important factors. For this, the passive Q-switching is suitable for these applications [1,2].The saturable absorber material (S.A.M.) ( passive Q- switch) performance depends on its characteristics such as the energy and lifetime of levels, chemical stability, surface tension, absorption cross section, and optical quality [2-4]. Many different Q-switching techniques developed in the past, passive Q-switching was considerable advantages in terms of device simplicity and economy because it is requires less optical element inside the laser cavity and no outside driving circuitry[5,6].

## 2.Theory

The effect of resonance reflectivity effect on passive Q- switching Laser pulse characteristics has been studied by the following rate equations model [7] .

$$\frac{dn}{dt} = (K_g N_g - K_a N_{ag} - \beta K_a (N_{a0} - N_a) - \gamma_c) n \quad (1)$$

$$\frac{dN_g}{dt} = R_p - \gamma_g N_g - \gamma_p K_g N_g n \quad (2)$$

$$\frac{dN_a}{dt} = \gamma_a (N_{a0} - N_a) K_a N_{ag} n \quad (3)$$

Where  $n$  is the photon number in the laser cavity.  $N_g$  is the population inversion of the laser medium.  $K_g = 2\sigma_g/\tau_r$   $A_g$ , is a coupling coefficient between photons and the active medium, where  $\sigma_g$  is the laser emission cross section,  $\tau_r$  is the cavity

round-trip transit time,  $A_g$  is effective laser beam area on the laser gain medium.  $N_a$  is the ground-state population of saturable absorber.  $K_a = 2\sigma_{ag}/\tau_r A_a$  is a coupling coefficient between photons and the saturable absorber molecules, where  $\sigma_{ag}$  is the saturable absorber ground –state absorption cross section,  $A_a$  is the effective laser beam area on the saturable absorber.  $\beta = \sigma_{ae} / \sigma_{ag}$  is the ratio of the excited-state absorption cross section  $\sigma_{ae}$  to the ground-state absorption cross section  $\sigma_{ag}$  of the saturable absorber.  $\gamma_c = 1/\tau_R (\log(1/R_2) + \Gamma)$  is the cavity decay rate, where  $(\tau_R = 2L_c / c)$  is the round trip transit time, where  $(L_c)$  is cavity length,  $c$  is the speed of light,  $l_r$  is the length of the laser rod, and  $(R_2)$  is the reflectivity of output mirrors,  $(\Gamma)$  is the remaining round-trip cavity dissipation.  $R_p$  is the pumping rate.  $\gamma_g = 1/\tau_g$  is the decay rate of the upper laser level,  $\tau_g$  is the upper laser level lifetime.  $\gamma_p$  is the population reduction factor (bottlenecking parameter),  $\gamma_p = 1, 2$  for a four –level and three level laser active medium, respectively.  $\gamma_a = 1/\tau_a$  is the spontaneous relaxation rate of the saturable absorber, where  $\tau_a$  is the saturable absorber first excited state lifetime. At the initial time the photon number inside the laser resonator is low, so most population of saturable absorber molecules are in the ground state  $N_{ag} \approx N_{ao}$ , then

Where  $N_{ao}$  is the total number of saturable absorber molecules. At this time the absorption activity of saturable absorber is very high (i.e.  $dn/dt \approx 0.0$ ) and one can predict the initial value of population inversion for laser medium ( $N_{g0}$ ), then from Eq. (1) as [9].

$$N_{g0} = (K_a N_{a0} + \gamma_c) / K_g \quad (4)$$

When the photon number inside the laser resonator is high, most population of saturable absorber molecules are in the excited state

( $N_{ae}$ ), then

$$N_a \cong 0.0 \quad (5)$$

At this time the absorption activity of saturable absorber is very low, then we can regard  $dn/dt \approx 0.0$ , also we can predict the threshold population inversion  $N_{th}$

$$N_{th} = \frac{\beta K_a N_{a0} + \gamma_c}{K_g} \quad (6)$$

In general, the build-up time of Q-switched laser pulse is very short compared to pumping rate  $R_p$  and the relaxation time of active medium  $\tau_g$ , then it is possible to neglect pumping rate and spontaneous decay of laser population inversion during pulse generation [5], then from Eq. (1) and Eq.(2), we get

$$\frac{dn}{dt} = (K_g N_g - K_a N_a - \beta K_a (N_{a0} - N_a) - \gamma_c) / (-\gamma_p K_g N_g)$$

$$\int_{n_i}^{n_p} dn = -\frac{1}{\gamma_p} \left( \left( \int_{N_{g0}}^{N_{th}} dN_g \right) - \left( (K_a N_a + \beta K_a (N_{a0} - N_a) + \gamma_c) / K_g \right) \int_{N_{g0}}^{N_{th}} \frac{dN_g}{N_g} \right) \quad (7)$$

From Eq. (6), the photon number reaches a peak value  $n_p$  when population inversion  $N_g$  is equivalent to  $N_{th}$ , also  $N_a$  approaches zero ( $N_a \approx 0.0$ ), then

$$\int_{n_i}^{n_p} dn = -\frac{1}{\gamma_p} \left( \int_{N_{g0}}^{N_{th}} dN_g - N_{th} \int_{N_{g0}}^{N_{th}} \frac{dN_g}{N_g} \right)$$

but  $n_p \gg n_i$ , then

$$n_p = -\frac{1}{\gamma_p} (N_{g0} - N_{th} - N_{th} \ln(\frac{N_{th}}{N_{g0}})) \quad (8)$$

After the release of the Q-switched laser pulse, the population inversion is reduced to the final value  $N_f$ , this value can be utilized to calculate the output energy of Q-switched pulse using the following equation

$$E_{out} = \left( \frac{N_{g0} - N_f}{\gamma_p} \right) \left( \frac{N_{g0} - N_f}{N_{g0}} \right) h\nu \quad (9)$$

Where  $h\nu$  is the laser radiation energy. The peak power of the Q-switched laser output can approximately be calculated by using Eq.(10) as

$$P_p \cong \frac{n_p h\nu}{\tau_c} \left( \frac{N_{g0} - N_f}{N_{g0}} \right) \approx -\frac{h\nu}{\gamma \tau_c} (N_{th} - N_{g0} - N_{th} \ln(\frac{N_{g0} - N_{th}}{N_{g0}})) \quad (10)$$

The pulse width of the Q-switched laser pulse can be calculated approximately by the following formula

$$\tau_{pulse} \approx \frac{E_{out}}{P_p} \quad (11)$$

### 3 . Results, and discussion

The numerical analysis by Rung-Kuta method has been used in this study. The published parameters values of saturable absorber  $Cr^{+4} : YSO$  and of active medium  $Nd : GdVO_4$  are used in study as the following table.

Table ( 1 ) : The input data

Parameter	Value	Referenc e	Parameter	Value	Reference

$\beta$	0.33	[ 7 ]	$\tau$	90 $\mu s$	[ 8 ]
$K_a$	$3.15 \times 10^{-8} \text{ sec}^{-1}$	[ 7 ]	$\gamma_g$	$0.11 \times 10^5 \text{ sec}^{-1}$	[ 8 ]
$\gamma_a$	$1.43 \times 10^6 \text{ Sec}^{-1}$	[ 7 ]	$K_g$	$1.5 \times 10^{-9} \text{ sec}^{-1}$	[ 8 ]
$\lambda$	1064 nm	[ 8 ]	$\Gamma$	0.2	[ 8 ]
$L_c$	60 mm	[ 8 ]	$\gamma_p$	1	[8].
$N_{a0}$	$1 \times 10^{16}$	[ 7 ]	$Rp$	$1 \times 10^{20}$	[7]

Figures (1) and (2) show the decreasing in pulse duration and increasing in pulse energy respectively, that is related to the low photon loss occurring with the increasing of output coupler reflectivity that leads to increasing in photons feedback to the active medium and release the stored energy in it through the increasing of laser photon number caused increasing in pulse energy, also shortly rising and falling time of pulse lead to shortly pulse duration.

Fig. (3) shows the increasing of power with the increasing of output coupler reflectivity, that is related to increasing of laser photon number and decreasing in pulse duration. Fig.(4) shows the profile of passive Q-switching pulses, that is appear the difference in energy and duration of pulse as a function of output coupler reflectivity.

#### 4. Conclusions

The pulse energy is increasing with increase of the output coupler reflectivity, while the pulse duration decreasing with increase of the output coupler reflective

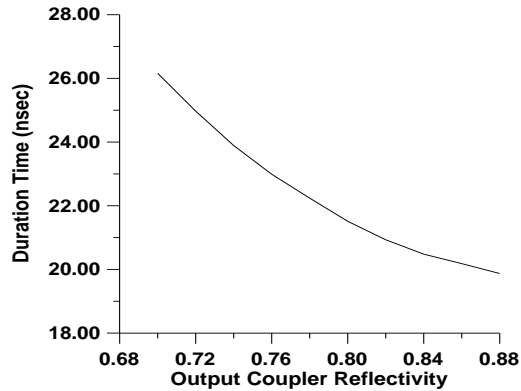


Fig.(1) : The pulse duration as a function of output coupler reflectivity

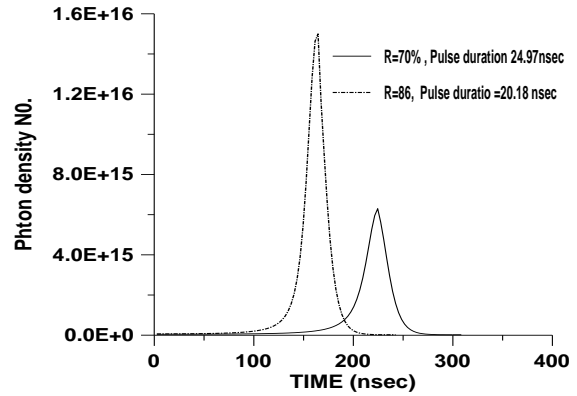


Fig.(4): The profile of pulse as a function of output coupler mirror reflectivity

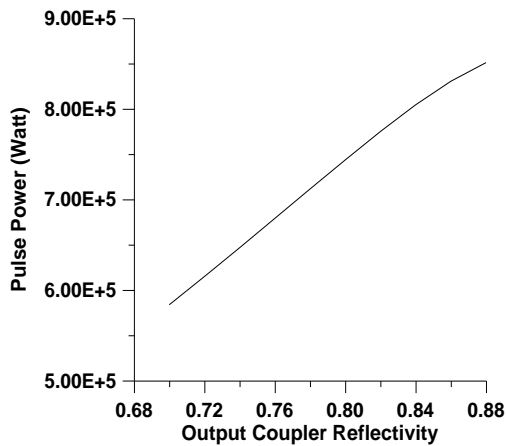


Fig.(3): The pulse power as function of output coupler reflectivity

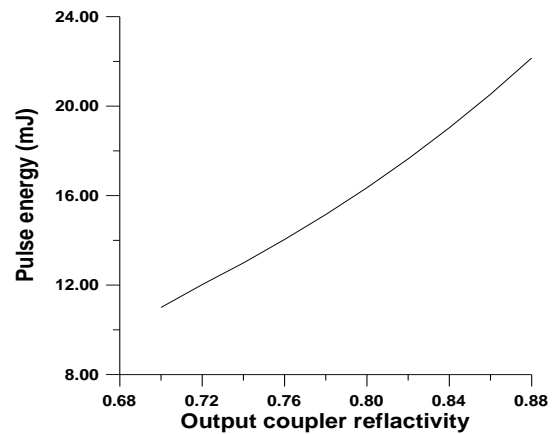


Fig.(2): Pulse energy as a function of output coupler reflectivity

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## محاكاة خصائص نبضة التحويل السلبي لعامل النوعية بدلالة مرآة خرج الليزر

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### الخلاصة

درس تأثير قيمة انعكاسية مرآة خرج الليزر على خصائص نبضة التحويل السلبي لعامل النوعية (الطاقة والامد) نظريا باستخدام الحل العددي باستخدام طريقة (رونج – كوتا) لأنموذج معادلات المعدل التي تصف التصرف الزمني اللحظي لبلورة  $YSO : Cr^{+4}$  كمادة ماصة قابلة للتشبع مع ليزر  $Nd : GdVO_4$  . واطهرت الدراسة نقصان قيمة امد النبضة وزيادة طاقتها مع زيادة قيمة انعكاسية مرآة خرج الليزر.