Characteristics of passive Q-switching laser pulse as a function of cavity decay rate

Abdul-Kareem M.Salih[a] and Abdul-Muneim K. Al-Kamil[b]
[a]Physics dep., college of science, Thi-Qar University
[b]Physics dep., college of science, Basrah University

Abstract

The characteristics of passive Q- switching laser pulse have been simulated as a function of cavity decay rate (γ_c). The simulation performed by numerical solution for passive Q-switching rate equations model for Cr:YSO ($Cr^{4+} : Y_2SiO_5$) saturable absorber with ruby laser. This study shows that the photon number, energy, and duration for output laser pulse are decreasing when the cavity decay rate increasing. The study explained that to a high dissipation of photons by absorption, reflection and scattering mechanisms per round-trip transit time in the cavity.

Keywords*:* Laser, High power pulse, Passive Q-switching.

Introduction

High power laser pulse may be obtained by Q-switching techniques, where energy is stored in the gain medium through optical pumping while the quality factor (Q) of the laser resonator is decreased to prevent laser oscillation. Passive Q-switching is more economical, simple, and practical. Consequentially, this technique was widely studied (Yen-Kuang and Yi-An 2003), (Iftitan and Adel 2006), (Liu et al. 2003), and (Yen-Kuang and Jih-Yan 2001), so widely used in applications such as laser remote sensing, laser satellite networking, laser communication, range finding, and many nonlinear optics experiments (Hua et al. 1997), (Yen-Kuang et al. 2000), (Abdul_muneim and Abdul-Kareem 2008).

There are always losses; in brief, γc is the coefficient which contains all the mechanisms of the photons loss in the cavity per round- trip associated with any mode. The main types of loss mechanisms are the finite reflectivities of the mirrors (with the remaining energy partially absorbed and partially transmitted as the useful laser beam), scattering and absorption in the medium filling the resonance cavity (Thyagarajain and Ghatak 1981).

Theory

The simulation has been performed using the rate equations model (Abdul-Kareem 2008) as the following

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

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

$$\frac{dN_{ag}}{dt} = \gamma_a N_{ae} - K_a N_{ag} n \quad (3)$$

$$\frac{dN_{ae}}{dt} = K_a N_{ag} n - \gamma_a N_{ae} \quad (4)$$

Where; n is the photon number in the laser cavity. Ng 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 σ_g is the laser emission cross section, τ_r is the cavity round-trip transit, A_g is effective laser beam area in the laser gain medium. N_{ag} 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 σ_{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 σ_{ae} to the ground-state absorption cross section σ_{ag} of the saturable absorber. N_{ae} is the population of the excited state of saturable absorber; $\gamma_c = 1/\tau_c$ is the cavity decay rate, where $\tau_c = \tau_r / \gamma$ is the cavity lifetime, where $\gamma = 2\alpha_0 l_r - \ln r_1 r_2$ is the total loss, where α_0 is the absorption coefficient per unit length, l_r is the length of the laser rod, and r_1,r_2 are the reflectivity's of cavity mirrors. R_p is the pumping rate. $\gamma_g = 1/\tau_g$ is the decay rate of the upper laser level, τ_g is the upper laser level lifetime. γ_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 τ_a is the saturable absorber first excited state lifetime.

At initial time, the most population of saturable absorber molecules is in the ground state (N_{ag}) ,that mean at initial time the absorption activity of saturable absorber is very high, then we regard $N_{ag} \approx N_{a0}, N_{ae} \approx 0.0$ and $\frac{dn}{dt} \approx 0.0$.

Where N_{ao} is the total number of saturabel absorber molecules, according to these approximations we get a good estimate for the initial value of population inversion for laser medium (N_{g0}) . Then from equation (1)

$$N_{g0} = (K_a N_{ag} + \gamma_c)/K_g \quad (5)$$

After very short time (depending of the life time of saturable excited state) the most of saturable absorber molecules are in the excited state (N_{ae}), then we can regard $N_{ae} \cong N_{a0}$, $N_{ag} \cong 0.0$, and $\frac{dn}{dt} \approx 0.0$. By utilizing this approximation in equation (1) we can predict the threshold population inversion (N_{th}) as following;

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

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 (τ_g), then it is possible to neglect pumping rate and spontaneous decay of laser population inversion during pulse generation (Sigman 1986), then from equation (1) and equation (2) , we get

$$\int_{n_i}^{n_p} dn = -\frac{1}{\gamma P}[(\int_{N_{g0}}^{N_{th}} dN_g) - \{(K_a N_{ag} + \beta K_a N_{ae} + \gamma_c)/K_g \quad (7)$$

From equation (7) the photon number reaches a peck value (n_p) when population inversion (N_g) is equivalent to N_{th} , also N_{ag} approaches zero ($N_{ag} \approx 0.0$) ,then we have

$$\int_{n_i}^{n_p} dn = -\frac{1}{\gamma_P}[\int_{N_{g0}}^{N_{th}} dN_g - N_{th}\int_{N_{g0}}^{N_{th}} \frac{dN_g}{N_g}],$$

$n_p >> n_i$, then

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

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 by using the following equation:-

$$E_{out} = (\frac{N_{go} - N_f}{\gamma_P})(\frac{N_{go} - N_f}{N_{go}})h\upsilon \quad (9)$$

$h\upsilon$ is the laser radiation energy. The peak power of the Q-switched laser output can approximately calculated by using eq.(9) as:

$$P_P \approx \frac{n_P h\upsilon}{\tau_C}(\frac{N_{go} - N_f}{N_{go}}) \approx -\frac{h\upsilon}{\gamma_P \tau_C}\left[N_{th} - N_{g0} - N_{th}\ln(\frac{N_{go} - N_{th}}{N_{go}})\right] \quad (10)$$

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

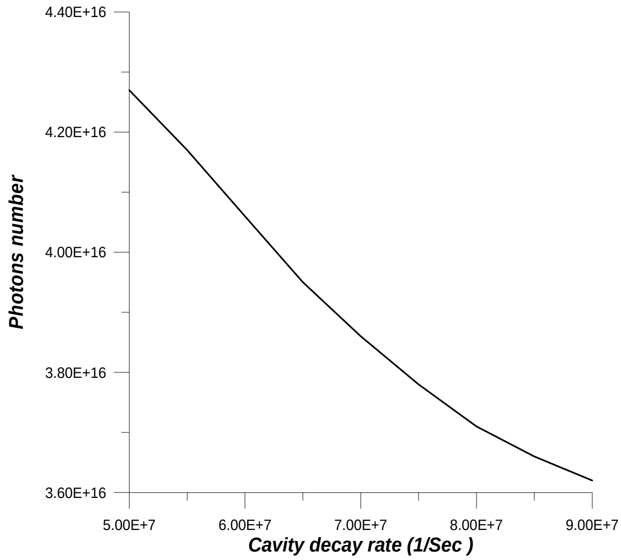
$$\tau_{pulse} \approx \frac{E_{out}}{P_P} \qquad (11)$$

Calculations Results & Discussion

The set of equations (1) to (4) have been solved numerically, using Runge-Kutta-Fehlberg to study the effect of cavity decay rate (γ_c) on passive Q-switching pulse characteristics (pulse duration, pulse energy, and the photon number). In this study, used γ_p= 2 and the published parameters values for ruby with the Cr: YSO saturable absorber material (Yen-Kuang et al. 2001) also have been used as follows;

$K_g = 7.96 \times 10^{-10} \sec^{-1}$,
$K_a = 3.15 \times 10^{-8} \sec^{-1}, \gamma_g = 333 \sec^{-1\,1}$,
$\gamma_a = 1.43 \times 10^{6} \sec^{-1}, \beta = 0.33$,
$R_p = 1.0 \times 10^{22} \sec^{-1}$, and $N_{ao} = 1.0 \times 10^{16}$ molecules.

The results of the numerical solution have been utilized in equations (6), (8), (9) and (11) to calculate these characteristics. The calculations show that, the increasing of cavity decay rate (γ_c) lead to decreasing of photon number (n) (shown in fig. (1)), that mean the energy is still conserved (non released) in the active medium as accumulated population inversion , that appears from the increment of initial values of population inversion (shown in fig.(2)). Unreleased energy causes decreasing of pulse energy (shown in fig. (3)) and fast build-up time of Q-switching pulse. The fast build-up time of the pulse decreases the duration time of laser pulse (shown in fig. (3) as well as increases the threshold and final values of population inversion which are clear in fig. (2). Unreleased energy causes decreasing of pulse energy (shown in fig. (3)), and fast build-up time of Q-switching pulse. The fast build-up time of the pulse decreases the duration time of laser pulse (shown in fig. (4)) as well as increases the threshold and final values of population inversion which are clear in fig. (2).



Fig(1): Photon number of the output laser as a function of cavity decay rate.

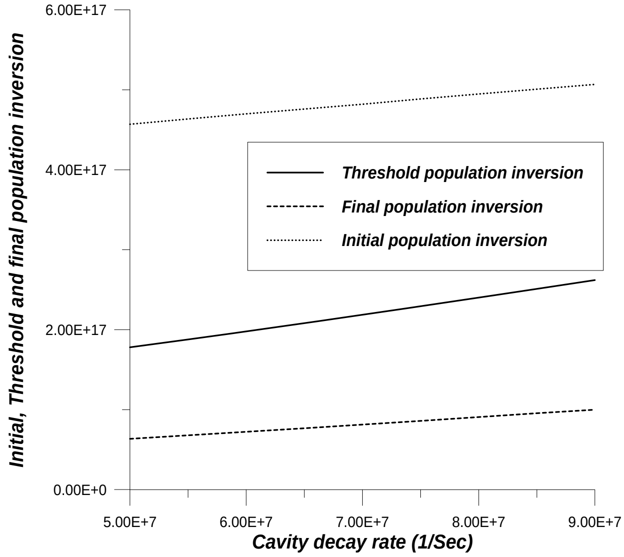


Fig. (2): The initial, threshold, and final population inversion in the active medium as a function of cavity decay rate.

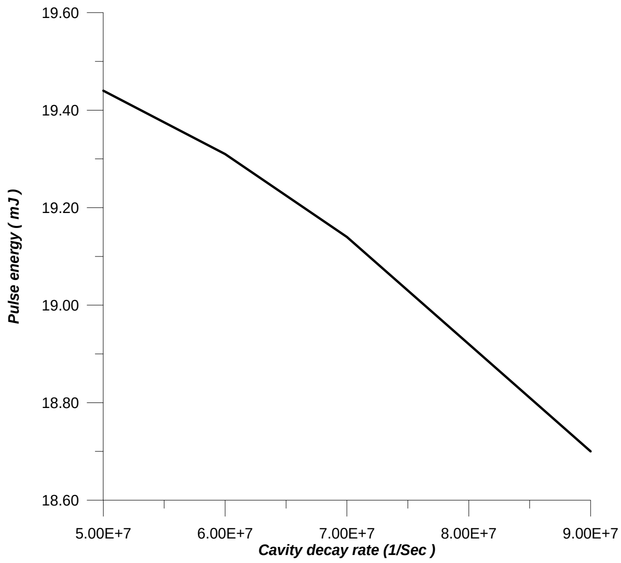


Fig.(3): The pulse energy as a function of cavity decay rate.

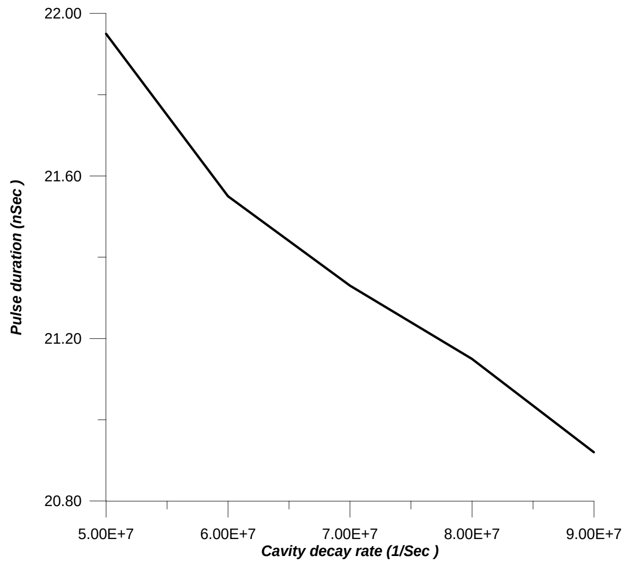


Fig.(4): The Pulse duration as a function of cavity decay rate.

References

Abdul-Kareem M. Salih. ," Photons Loss Simulation during Cr:YSO Passive Q-switched Ruby Laser Pulse Generation", J. of Education College, Vol.(3), (2008).

Abdul-Muneim K. AL-Kamil, Abdul-Kareem M. Salih, " Solvent surface tension on passive liquid Q-swithch pulse duration ", Journal of Thi-Qar Science, Vol.(1),No. (1), P. (73), (2008).

Hua Liu, Osmany Hornia, Y. C. Chen, and Shou-Huan Zhou," Single – frequency Q-switched Cr-Nd:YAG laser operating at 946-nm wavelength", IEEE Journal of selected topics in Quantum Electronics , Vol. (3), No. (1),P. (26), (1997).

Iftitan M. Azzouz and Adel EL-Nozahy, "Numerical study of Cr^{4+}:YAG passively Q- switching Nd:$GdVo_4$ laser ", Egypt, J. Solids, Vol.(29), No.(1), P.(215), (2006).

J.Liu, B.Ozygus, S.Yany et al., J. Opt. Soc. Am B 20, P.(652), (2003).

K. Thyagarajain and A.K.Ghatak," LASERS, Theory and applications ", Pelnum publishing corporation, New York, P. (116), (1981).

Liu J., Ozygus B., Yany S. et al., J. Opt.Soc.Am B 20, P.(652), (2003).

Sigman A.E ," Lasers ", University Science, Millvally, California, P.(1025), (1986).

Yen-Kung Kuo, Horng-Min Chen, and Chia-Ching Lin,"A theoretical study of the Cr:$BeAl_2O_4$ laser passively Q-switched with Cr:YSO solid state saturable absorber" ,Chinese Journal of Physics, Vol.(38), No. (3-I), p. (443), (2000).

Yen-Kuang Kuo, Horng-Min Chen, and Jih-Yuan Chang, "Numerical study of the Cr:YSO Q- switched ruby laser", Opt.Eng., Vol. (40), No. (90), P. (2031), (2001).

Yen-Kuang Kuo and Jih-Yan Chng," Numerical study of passive Q switching of tunable Cr:LiCAF laser with Cr:YSO solid slate saturable absorber", Jpn J. Appl. Phys. Vol. (4o), No. (10),P. (5949), (2001).

Yen-Kuang Kuo and Yi-An Chng, "Numerical study of passive Q switching of Tm:YAG laser with a Ho:YLF solid-state saturable absorber", Appl. Opt.,Vol. (42), No.(9), P.(1685), (2003).

الخلاصة

درست خصائص نبضة التحويل السلبي لعامل النوعية بدلالة معدل أضمحلال التجويف الليزري (γ_c) وذلك من خلال الحل العددي لنموذج رياضي من معادلات المعدل للتحويل السلبي لعامل النوعية. أستخدمت ما دة $Cr^{4+}:Y_2SiO_5$ (Cr:YSO) كما دة ماصة مشبعة مع ليزر الياقوت. بينت الدراسة ان كل من عدد فوتونات وطاقة وامد النبضة (نبضة التحويل السلبي) يقل كلما أزداد معدل اضمحلال التجويف الليزري، وتفسر الدراسة ذلك الى زيادة نسبة الضياع في الفوتونات بسبب زيادة تاثير العمليا ت المختلفة من ألآمتصاص وألآنعكاس والآستطارة التي تحدث داخل التجويف الليزري خلال زمن تذبذب الفوتونات فيه.