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website : http:// jsci.utq.edu.iq Email: utjsci@utq.edu.iq

Influence of Absorption cross section of saturable absorber on Passive Q-switching laser pulse characteristics

Abdul-Kareem M. Salih Abdul-Allah S.Majly

Physics dep. - college of science Electrical dep. - college of engineering
Thi-Qar University

Abstract

The absorption cross section of saturable absorber influence on passive Q-switching laser pulse behavior has been studied by numerical solution of rate equations mathematical model. We report the passive Q-switching of the $Cr^{+4}:BeAl_2O_4$ (alexandrite) laser with the yttrium silicate $Cr^{+4}:Y_2SiO_5$ $(Cr:YSO)$ solid state saturable absorber. The study shows that the behavior pulse energy, initial value of population inversion, and the laser photon number is scaling up when the ground state absorption cross section of saturable absorber increasing, while the behavior of pulse duration is scaling down.

Keywords: Laser, high power pulse, passive Q-switching.

تأثير المقطع العرضي الامتصاصي للمادة الماصة القابلة للإشباع على خصائص نبضة ليزر التحويل السلبي لعامل النوعية

عبد الكريم مهدي صالح عبد الله صيوان مجلي

كلية العلوم – قسم الفيزياء كلية الهندسة – قسم الكهرباء

جامعة ذي قار

الخلاصة

درس تأثير المقطع العرضي الامتصاصي للمستوي الارضي للمادة الماصة القابلة للإشباع على سلوك نبضة ليزر التحويل السلبي لعامل النوعية باستخدام الحل العددي لأنموذج رياضي من معادلا ت المعدل التي تحاكي اداء ليزر الالكسندريت ($Cr^{+4}:BeAl_2O_4$) بطول موجي 750nm مع ($Cr^{+4}:Y_2SiO_5$) كمادة ماصة قابلة للاشعاع. بينت الدراسة ان طاقة النبضة ،القيمة الابتدائية (الحرجة) للتوزيع العكسي وعدد فوتونات نبضة الليزر تزداد قيمها مع زيادة المقطع العرضي الامتصاصي للمستوي الارضي للمادة الماصة القابلة للإشباع بينما تقل قيم امد النبضة.

1. Introduction

Short laser pulses are generated by solid state lasers using various active media types crystals, glasses or ceramic) operated in Q-switching techniques have a large number of applications in many civilian and military applications such as laser remote sensing, laser satellite networking, laser communication, many nonlinear optics experiments, material processing (

nanomaterials) formation by using ablation technique, projectile guidance over long distances and range finding applications [1-7]. Passive Q-switching is more economical, simple, and practical. Basically, Q-switching operation relies on a fast switching of laser resonator quality factor Q from a low value (corresponding to large optical losses) to a high one (representing low radiation losses). Alexandrite which is biaxial with emitted light polarized parallel to the b (axis), can act either as a three-level laser system or as a four-level vibronic laser system [8]. Since $Cr^{+4}:BeAl_2O_4$ has a broad absorption band in the visible spectral range, it can be efficiently pumped with flash lamps [9].On the other hand, a compact $Cr^{+4}:BeAl_2O_4$ laser system may be pumped by the laser diode [9]. The $Cr:YSO$ is a pure tetravalent chromium system. It is a blue in color and is a biaxial solid-state crystal [10]. Some of its important material parameters are as follow: It has a melting point as high as (2070 ºC), Cr atoms/mole % as (9.7x1019 atom/cm3), density as (4.6 gm/cm3), refractive index as (1.8), and the damage threshold as high as (30 J /cm2) [9,11] . Spectroscopic studies of the $Cr:YSO$, and the observation of laser action from (77) up to (257ºK) was reported by Deka et al. in 1992 [5]. Room-temperature laser operation of the $Cr:YSO$ was reported subsequently by Koetke et al. [5] . It has four absorption bands peaked near (390nm), (595nm), (695nm), and (750nm) [11] as shown in figure 1. It's absorption spectrum covers the visible, and near infrared spectral region, it can be used as a saturable absorber Q-Switch for the ruby, alexandrite, Cr:LiCAF, and Cr:LiSAF lasers [10-13] . See figure 1: $Cr:YSO$ absorption spectrum[11] , this Q-Switch crystal has an emission life time of (0.7 µsec) at room temperature [11] which is long compared to the duration of the Q-Switched laser pulses. Therefore, $Cr:YSO$ can be classified as a slow-relaxing saturable absorber [11]. The Cr:YSO crystal has many absorption cross-sections at a few different wave lengths for several Solid state lasers.

In this study, the influence of absorption cross section for the ground states of saturable absorber on passive Q- switching performance of the Alexandrit**e** $Cr^{+4}:BeAl_2O_4$ laser (four-level system) with $Cr:YSO$ solid state saturable absorber is studied by numerical solving of four coupled rate equations model by Runge –Kutta-Fehlberge method.

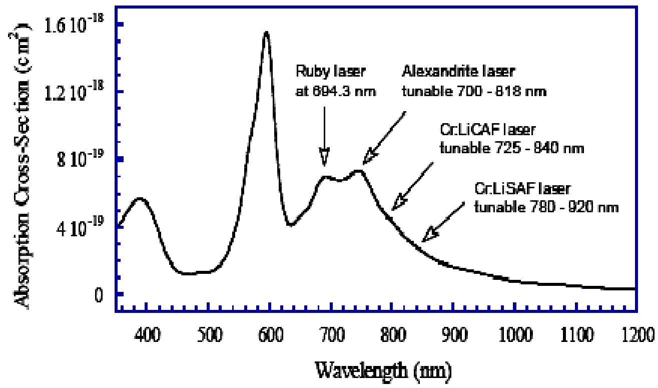

Figure 1: $Cr:YSO$ absorption spectrum [10]

2. Theory

The ground level absorption cross section of the saturable absorber (σ_{ag}) influence on passive Q-switching laser pulse behavior has been studied by the rate equations [14] 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. Kg =2σg/τr Ag, is a coupling coefficient between photons and the active medium, where σg is the laser emission cross section, τr is the cavity round-trip transit, Ag is effective laser beam area on the laser gain medium. Nag is the ground-state population of saturable absorber. Ka = 2σag/τrAa is a coupling coefficient between photons and the saturable absorber molecules, where σag is the saturable absorber ground –state absorption cross section, Aa 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 σae to the ground-state absorption cross section σag of the saturable absorber. Nae 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 α0 is the absorption coefficient per unit length, l_r is the length of the laser rod, and r1,r2 are the reflectivity's s of cavity mirrors. Rp is the pumping rate. γg = 1/τg is the decay rate of the upper laser level, τg is the upper laser level lifetime. γp is the population reduction factor (bottlenecking parameter), γp = 1, 2 for a four –level and three level laser active medium, respectively. γa =1/τa is the spontaneous relaxation rate of the saturable absorber, where τa is the saturable absorber first excited state lifetime.

At initial time, the most population of saturable absorber molecules is in the ground state (Nag) ,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 Nao is the total number of saturbel 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)

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

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;

$$N_{th} = \frac{\beta K_a N_{ae} + \gamma_c}{K_g} \tag{6}$$

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[15], then from equation (1) and equation (2) ,we get

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

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

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

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

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:-

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

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

$$P_P \approx \frac{n_P h\upsilon}{\tau_C}(\frac{N_{go} - N_f}{N_{go}}) \tag{10}$$

$$P_P \approx \frac{h\upsilon}{\gamma_P \tau_C}(N_{th} - N_{g0} - N_{th}\ln(\frac{N_{go} - N_{th}}{N_{go}}))$$

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

$$\tau_{pulse} \approx \frac{E_{out}}{P_P} \tag{11}$$

3. Calculations, Results, and Discussion

The set of equations (1) to (4) have been numerically solved by Rung –Rung –Fehelberge method by computer program to study the influence of the ground level absorption cross section of saturable absorber on laser passive Q-switching pulse characteristics. In this study, we report the passive Q-switching of the $Cr^{+4}:BeAl_2O_4$ (alexandrite) laser with the $Cr^{+4}:Y_2SiO_5$ $(Cr^{+4}:YSO)$ solid state saturable absorber operated near 750 nm, the published parameters values for alexandrite with the Cr: YSO [5] have been used as follows;

$K_g = 2.23\times10^{-10}\sec^{-1}$, $\gamma_g = 3.85\times10^{3}\sec^{-1}$ 1, $\beta = 0.33$, $\gamma_a = 1.43\times10^{6}\sec^{-1}$, $\gamma_c = 1\times10^{8}$, $R_p = 1.0\times10^{22}\sec^{-1}$, $N_{ao} = 1.0\times10^{15}$ molecules, Length of laser cavity =30 Cm , $\lambda = 750nm$, $\sigma_g = 7\times10^{-21}Cm^2$, $\sigma_{ag} = 7.2\times10^{-19}Cm^2, R = 0.8$, $\gamma = 1$, effective beam diameter=2 mm.

The exited level absorption cross section of the saturable absorber (σ_{ae}) is calculated as a input data to get the values of β according of the ground level absorption cross section of the saturable absorber values (σ_{ag}) which are feed to program with validation of criterion condition for saturable absorber Q switching $[(\sigma_a/\sigma_g)\times(A_g/A_a)>1]$.

Figure (2) shows the behavior of the pulse energy as function of the ground state absorption cross section of saturable absorber, it is indicate that the pulse energy increases when the ground state absorption cross section increases, the study explain that related to increasing of absorption activity of saturable absorber, thet mean low feedback can be obtained, then; the energy is still accumulated in the active medium by increasing of initial value of population inversion which is shown in figure (3). When the saturabele absorber is bleaching, The fast released of energy can be obtained and the population inversion is reaches low final value after short time as shown in figure (3) and (4) causes increasing of pulse energy and fast build-up time of Q-switching pulse. The fast build-up time of the pulse decreases the duration time of laser pulse as shown in figure (5) which is describes the behavior of the pulse duration as function of the ground state absorption cross section of saturable absorber. Figure (6) shows the profile of passive Q-swiching pulse as function of the ground state absorption cross section of saturable absorber, the number of photons is increasing while the absorption cross section increasing, the study explain that also related to the increasing of population inversion which is obtained due the low number of photons feedback in laser cavity at earlier time of saturable absorber performance (before optical bleaching) .bsorption ac to active medium

4. Conclusions

The behavior of passive Q-switch pulse energy, initial value of population inversion, and the laser photon number is scaling up if the ground state absorption cross section of saturable absorber increasing, while the behavior of pulse duration is scaling down.

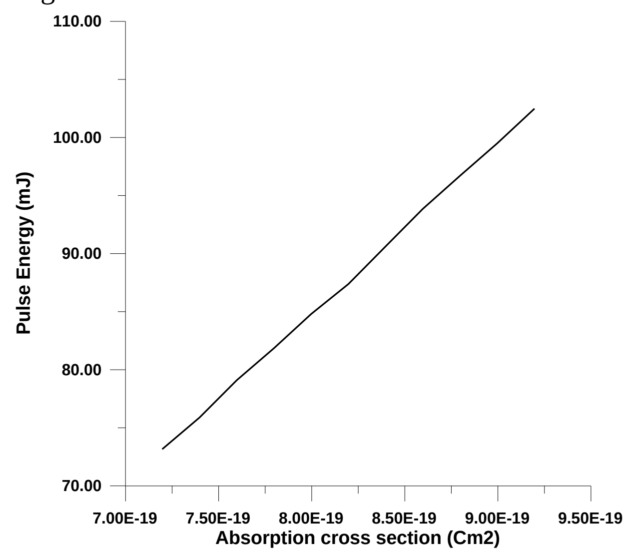

Fig.(2): The behavior of pulse energy as function of the ground state absorption cross section of saturable absorber

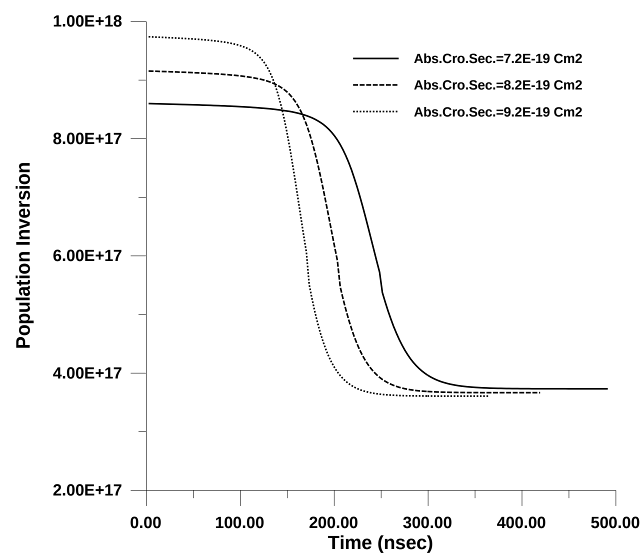

Fig.(3): The behavior of population inversion as function of the ground state absorption cross section of saturable absorber

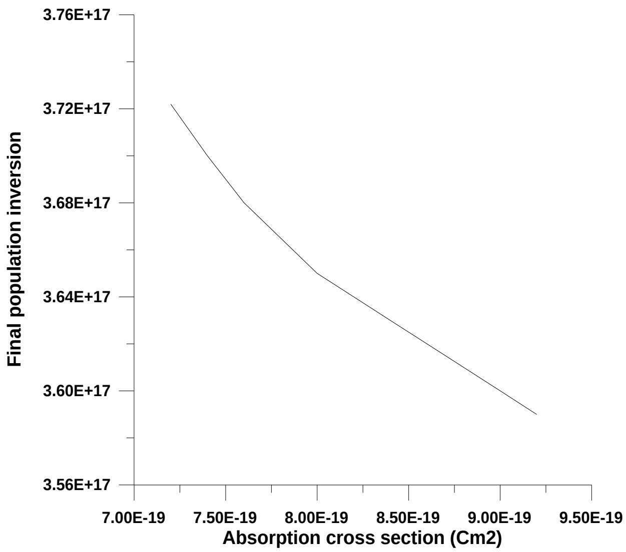

Fig.(4): The behavior of final population inversion as function of the ground state absorption cross section of saturable absorber

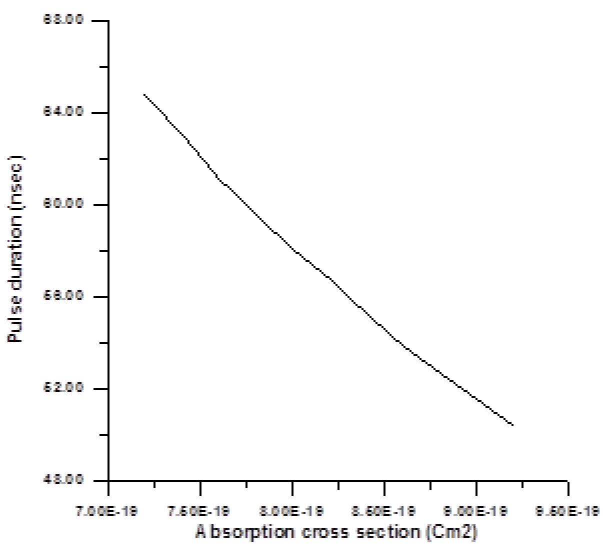

Fig.(5): The behavior of pulse duration as function of the ground state absorption cross section of saturable absorber

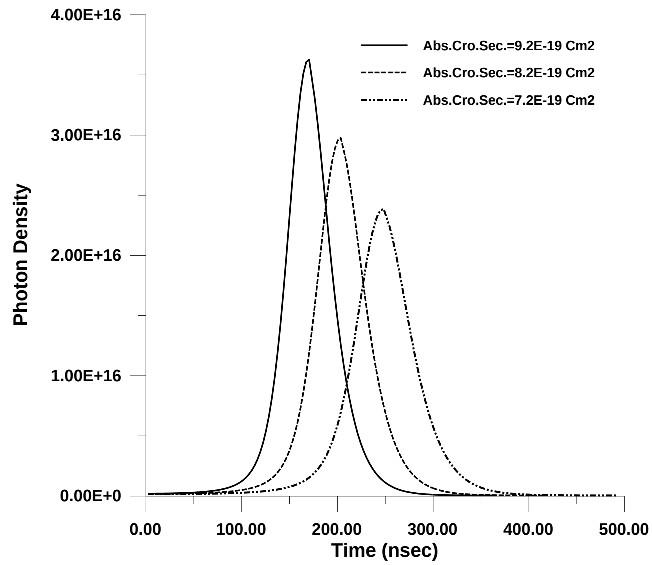

Fig.(6): profiles of pulse as function of the ground state absorption cross section of saturable absorber

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