Simulation of saturable absorber material length effect on characteristics of Passive Q-switching and Stokes pulses

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Abstract

The effect of saturable absorber material length on characteristics of passive Q-switching and Stokes pulses has been simulated. A software computer program has been based for solving a rate equations model numerically by Rung –Kutta- Fehalberg method. ($Nd:GdVO_4$), (Cr^{+4}:YAG), and $Ba(NO_3)_2$ are used as a active medium, saturable absorber material, and Raman medium respectively. The study shows that an decrease in pulse duration for both pulses (passive Q- switching and Stocks) with saturable absorber material length increases. While the energy and the power are increase with saturable absorber material length increases.

Keyword: Physics, Laser, High power pulses

الخلاصة:

تضمنت الدراسة محاكاة تأثير طول المادة الماصة القابلة للإشباع عل خصائص نبضة التحويل السلبي لعامل النوعية ونبضة ستوك المتولدة من ظاهرة استطارة رامان في وسط رامان المضمَّن في تجويف الليزر. حيث تم بناء برنامج حاسوبي لحل معادلات المعدل التي تحاكي أداء منظومة الليزر المتكونة من (Nd:GdVO4), ($(Cr^{+4}$:YAG), $Ba(NO_3)$ كوسط فعال ومادة قابلة للاشباع ووسط رامان على التوالي، وقد استخدمت طريقة رونج –كوتا – فهلبرج العددية في الحل . بينت الدراسة تناقص امد نبضة التحويل السلبي لعامل النوعية ونبضة ستوك رامان مع زيادة طول المادة الماصة القابلة للتشبع، في ما اوضحت الدراسة زيادة الطاقة والقدرة للنبضات المتولدة مع زيادة طول المادة الماصة القابلة للاشباع .

1. Introduction

The laser system of passive Q-switching with solid state Raman conversion media is a good method to obtain high power pulses. Passive Q-switching pulse absorbed by the ions of Raman media caused stimulated

Raman scattering in it (E.T. Räikkönen, 2009; V. L. Kalashnikov *et al*., 2013; S, Ding. *et al*., 2013). In the result of these processes, the high power pulses are generated. Wide range of important applications of these high power pulses such as spectroscopy, environment sensing, range finder, laser radar, materials processing, communications, and medicine (Y. Wang and C. Q. Xu, 2006; A. Mahdi Salih,2012; C. J. Mercer, *et al.*, 2007).

Neodymium Gadolinium Vanadium ($Nd:GdVO_4$) crystal considers excellent laser crystals because of their good properties such a mechanical, optical, thermal conductivity , high absorption coefficient, large stimulated emission cross section at laser wavelength, low dependency on pump wavelength, and high laser induced damage threshold (M. M. AL-Sultani, 2013; E. Herault *et al*. 2006). Also the Chromium: Ytterbium Aluminum Garnet Cr^{4+}:YAG is an excellent crystal for passively Q-switching technique. It is characterized by its chemically stable, durability, UV resistant, good thermal conductivity and high damage threshold (M. M. AL-Sultani, 2013; J. Alcock 2013; D. J. Ripin *et al*. 2002; I. M. Azzouz and A. El-Nozahy 2006). So the mono crystals salt toxic composed of barium and the nitrate ion $Ba(NO_3)_2$ regards best for shifting the emission frequency of laser to different spectral region (R.P. Mildren *et al*. 2004). The $Ba(NO_3)_2$ it is soluble in water, and like other soluble barium compounds. $Ba(NO_3)_2$ properties make it suitable for use in various military applications, including the rmite grenades and incendiary ammunition (F. Grigsby *et al.* 2004; S. Shashi Devi *et al*. 2012).

2. Theory

A mathematical model of rate equations of Passive Q-switched laser with intracavity Raman conversion medium (Y. T. Chang, 2010) is improved in this study to the task at hand. The model describes the Raman laser operation includes a temporal processes taking place inside of gain medium, saturable absorber, and Raman medium at the period time of pulse buildup as shown in the following rat equations:

$$\frac{dn_l}{dt} = n_l\left[K_g N_g - K_a N_{ag} - \beta K_a N_{ae} - \frac{2ghc\nu_l n_R l_R}{t_{RT}} - \frac{1}{\tau_l}\right] \qquad (1)$$

$$\frac{dn_R}{dt} = n_R\left[\frac{2ghcv_l n_l l_R}{t_{RT}} - K_a N_{ag} - \beta K_a N_{ae} - \frac{1}{\tau_R}\right] + k_{sp} n_l \quad (2)$$

$$\frac{dN_g}{dt} = R_p - \gamma_g N_g - \gamma_p k_g N_g n_l \quad (3)$$

$$\frac{dN_{ag}}{dt} = -K_a N_{ag} n_l - K_a N_{ag} n_R + \gamma_a \quad (4)$$

$$\frac{dN_{ae}}{dt} = K_a N_{ag} n_l - \gamma_a N_{ae} + K_a N_{ag} n_R \quad (5)$$

Eq. (1) represent the time variation of laser photons density inside the cavity. n_l is the laser photons density inside the cavity, $Kg = \frac{2\sigma_g l_g}{\tau_{RT}}$ is coupling coefficient between the photons and the active medium, where; σ_g is laser stimulated emission cross section, l_g is the active medium length, $t_{RT} = \frac{2L_c}{c}$ is the Round-trip transit time of light in the cavity, L_c is the optical length in cavity, c is the light speed in vacuum. N_g is the population inversion density of the laser medium. $K_a = \frac{2\sigma_{ag} l_a}{t_{RT}}$ is Coupling coefficient between the photons and saturable absorber material SAM molecules, σ_{ag} is the ground-state absorption cross section of SAM. l_a is the length of SAM. N_{ag} is the ground-state population of SAM. $\beta = \frac{\sigma_{ae}}{\sigma_{ag}}$ is the ratio of the excited state absorption cross section $\sigma_{ae}$to the ground state absorption cross section σ_{ag} of the SAM. N_{ae} is the population of the excited state of SAM. g is the Raman gain coefficient, h is Plank constant, v_l is the laser frequency, l_R is the Raman medium length, n_R is the Raman photons density inside the cavity, τ_l is the lifetime of laser photons in the cavity. Eq. (2) represent the time variation of Raman Stokes photons density inside the cavity, where τ_R is the lifetime of Raman photons in the cavity,k_{sp} is the spontaneous Raman scattering factor. Eq. (3) represent the time variation of population inversion density in active medium, where 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 , $\gamma_p = 1,2$ for four level and three level laser active medium respectively. Eq. (4) represents the time variation of the ground-state population of SAM, where $\gamma_a = {}^1/_{\tau_a}$the spontaneous relaxation rate of SAM, τ_a is the saturable absorber first excited state lifetime. Eq. (5) represents the time variation of the first exited level population of SAM.

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. It is possible to neglect pumping rate and spontaneous decay of laser population inversion during pulse generation (A. E. Sigman, 1986). Then Eq. (3) can be written as the following formula:

$$\frac{dN_g}{dt} = -\gamma_p k_g N_g n_l \tag{6}$$

The life time of the first exited level of SAM is much longer than the timescale considered (Sang- Hoon 1998). The third term of Eq. (4) can be neglected. Then eq.(4) can be written as the following:

$$\frac{dN_{ag}}{dt} = -k_a N_{ag} n_l - k_a N_{ag} n_R \tag{7}$$

Also the second term of Eq. (5) can be neglected. Then Eq. (5) can be written as the following :

$$\frac{dN_{ae}}{dt} = k_a N_{ag} n_l + k_a N_{ag} n_R \tag{8}$$

At initial time, some physical approximation can be dependent such as the following:

$$N_{ag} \simeq N_{a\circ}\ ,\ N_{ae} \simeq 0\ ,\ \frac{dn_L}{dt} \simeq 0\ ,\ N_{ae} \simeq 0\ ,\ N_g \simeq N_{g\circ}, n_R = 0$$

where $\boldsymbol{N_{g\circ}}$ represent the initial value of population inversion. Then from Eq. (1), can be get the following expression:

$$N_{g\circ} = \frac{k_a N_{a\circ} + \frac{1}{\tau_l}}{k_g} \tag{9}$$

After short time (at peak of pulse), some physical approximation can be dependent such as the following

$$N_{ag} \simeq 0 \, , N_{ae} \simeq N_{a\circ} \, , \ \frac{dn_l}{dt} = 0 \ \, , N_g \simeq N_{th,}$$

where N_{th} represents the threshold value of population inversion. Then from Eq. (1) and (3) can be represents the peak value of photons laser pulse as the following:

$$n_{max} = \frac{1}{-\gamma_p}\left[N_{th} - N_{g\circ} - N_{th}(ln \frac{N_{th}}{N_{g\circ}})\right] \tag{10}$$

After the release of the Q-switch laser pulse, the population inversion reduced to final value of N_{gf}. Then the energy of Q-switch pulse can be expression as the following:

$$E = \left(\frac{N_{g\circ} - N_{gf}}{\gamma_p}\right)\left(\frac{N_{g0} - N_{gf}}{N_{g\circ}}\right) . h\nu_l \tag{11}$$

where $(h\nu_l)$ is the laser radiation energy.

3. Calculations

A software computer program has been based for solving a rate equations model is shown in the set equations (1), (2), (6), (7), (8) numerically by using Rung – Kutta – Fehelberg method. The Physical approximations and boundary conditions for solution used in simulation. The input data shown in table (1) has been feed to program .The characteristics of passive Q-switching laser and Stokes pulses are investigated as a function of SAM length.

Table(1) : The values of (Nd:$GdVO_4$), (Cr^{+4}:YAG), $Ba(NO_3)_2$ parameters

Param.	Value	Refer.
σ_g	7.6×10^{-19} cm^2	(I. M. Azzouz and A. El-Nozahy, 2006)
τ_g	$90\ \mu s$	
γ_p	1	
G	11 cm/W	(G.M. Ahmed, 2003)
σ_{ag}	5.4×10^{-18} cm^2	(S. H. Yim *et al*. 1998)
σ_{ae}	2×10^{-18} cm^2	
$n_{a\circ}$	12×10^{17} cm^{-3}	(W. Chen *et al*. 2001)
K_{sp}	$2\times10^{-19}\ s^{-1}$	

4. Results and discussion

Fig.1 shows that the increasing in the length of SAM (lead to an increase in the values of coupling coefficient (K_a). The increment of (K_a) causes the increase of wave –matter interaction probability in SAM, in the result lead to increase the absorption activity of SAM. The absorption activity of SAM reduces the laser photons oscillation in the resonator. That make good chance for energy still stored in the active medium through the molecules accumulation in the excited energy level. The molecules accumulation in the excited energy level lead to high value of initial population inversion in the active medium as indicated in Fig. 2.

Fig. 2 shows the increasing of initial population inversion values as a function of l_a . The SAM activity a broaches to the optical bleaching state after short time to allow to the laser photons returned to active medium and reacts with the high population inversion. Then fast build-up of giant laser pulse (passive Q-switching) characterize by high photon density leads to an increase in the Stocks pulse photon density through SRS processes in Raman medium, but the passive Q-switching pulse high photons density comparing with the Stokes pulse as a function of $\boldsymbol{l_a}$ as shown in Fig. 3. The fast buildup for passive Q-switching and Stokes pulses causes significant shorting in duration of these pulses. The duration time of passive Q-switching pulse shorting than the Stokes pulse duration as a function of $\boldsymbol{l_a}$ which is indicated in Fig. 4. The study attributes that to the high deference in maximum photons density of pulses as shown in Fig. 3.

Fig. 5 shows that the increase in the length of SAM causes an increase in the energy of both essential pulse (passive Q-switching pulse) and Stokes pulse. That is related to increase the values of the initial density of population inversion indicated in Fig. 2. The increase in energy accompanied with decay in duration for generated pulses as shown in Figs. 5 and 4 respectively. That makes available to get pulses with high power as shown in Fig. 6.

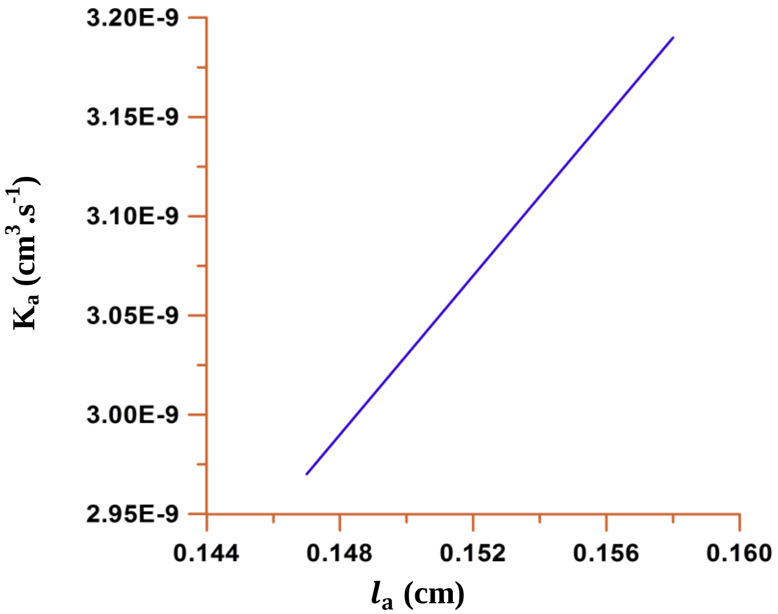


Fig. 1: The variation of coupling coefficient (K_a) as a function of saturable absorber material length.

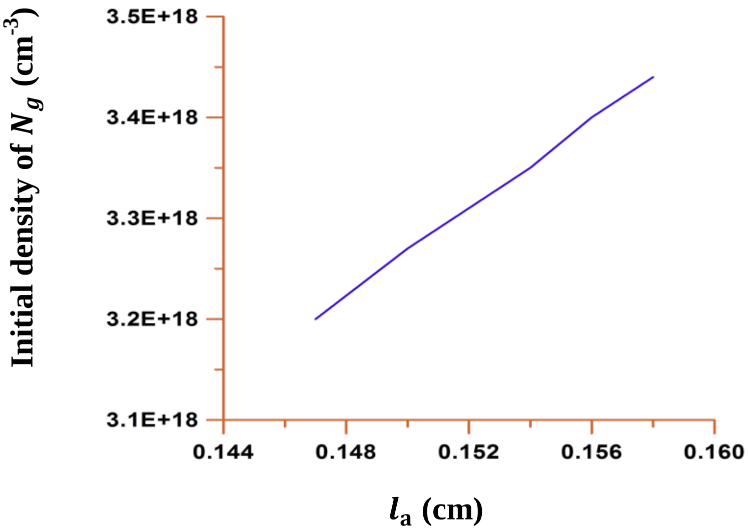


Fig. 2: Initial values of population inversion density as a function of saturable absorber material length.

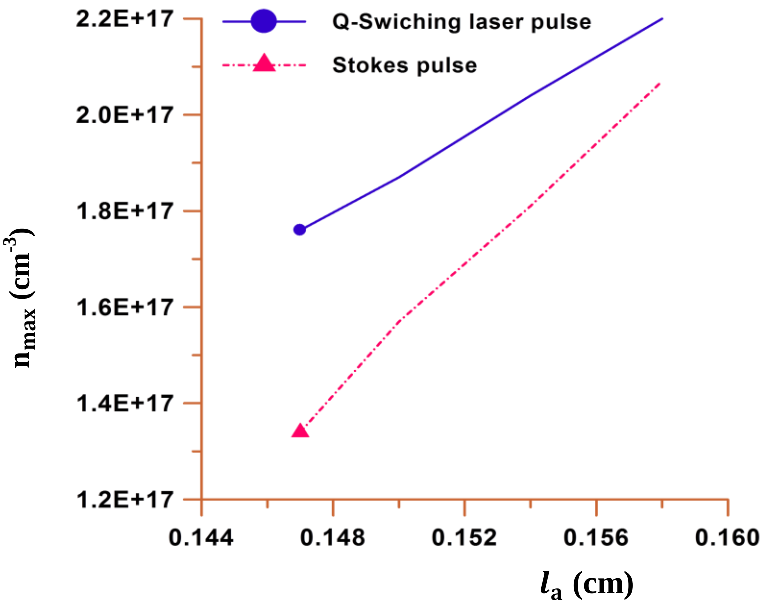


Fig. 3: The variation of maximum values of photons density as a function of saturable absorber material length.

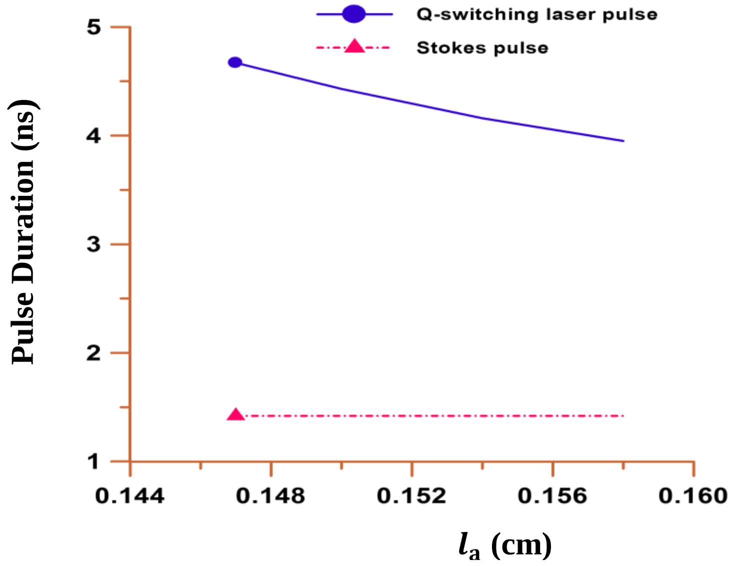
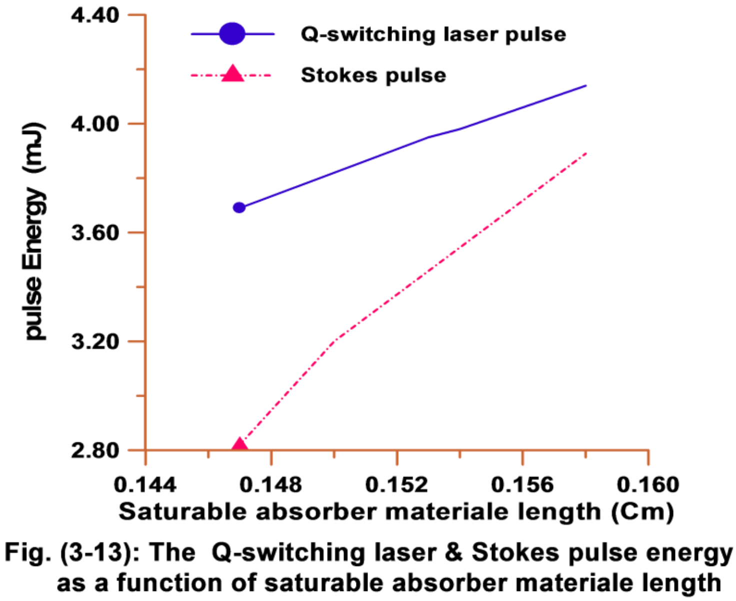


Fig. 4: Pulse duration as a function of saturable absorber material length for Q-Switching laser and Stokes pulses.



l_a (cm)

Fig. 5: The Q-Switching laser and Stokes pulse energy as a function of saturable absorber material length.

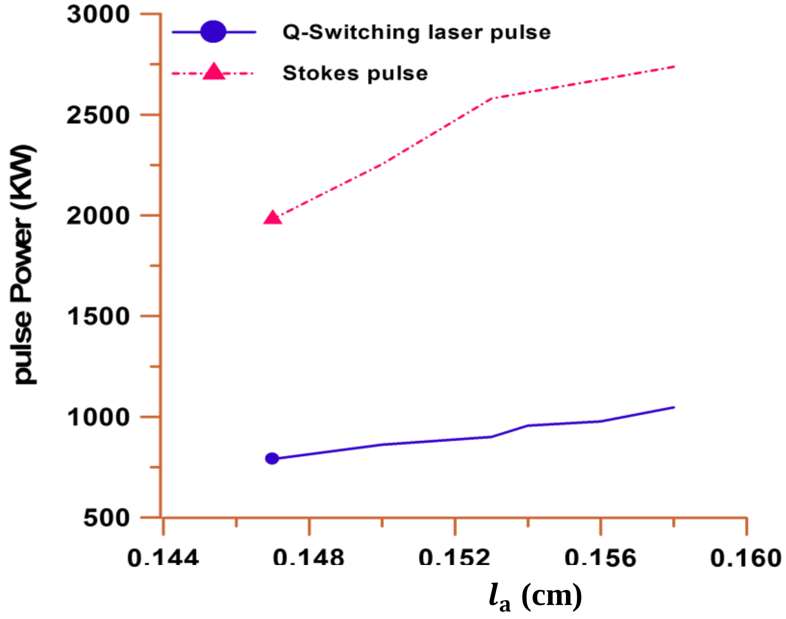


Fig. 6: The increasing of Q-Switching and Stokes pulses power as a function of saturable absorber material length.

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