Performance simulation of passive Q-switched laser system with intracavity Raman conversion medium

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Abstract

The system performance of intra-cavity Stimulated Raman Scattering SRS with passive Q-switching has been simulated. Neodymium :Gadolinium Vanadium ($Nd:GdVO_4$), Chromium : Yttrium Aluminum Garnet(Cr^{+4}:YAG), and Barium Nitrate $Ba(NO_3)_2$ are utilizing as a active medium(AM), saturable absorber material (SAM), and Raman medium (RM) respectively. Mathematical model of rate equations has been formulated in this study. The model solved numerically by Rung –Kutta- Fehalberg method. Significant passive Q-switching and Stokes pulses to be simulated, also the effect of optical length on characteristics(duration and energy) of these pulses has been investigated. The study conclude that the power decrease while the optical length increase.

Keyword: Physics, Laser, passive Q- switching , Raman conversion

1. Introduction

Utilization of passive Q-switching laser with solid state Raman active media is more useful method to obtain high power pulses, that is related to the stimulated Raman scattering SRS in Raman medium [1-3]. wide range of important applications of these high power pulses such as spectroscopy, environment sensing, range finder, laser radar, materials processing, communications, and medicine [4-6].Nd: $GdVO_4$ crystal considers excellent laser medium, it is distinguishable by 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[7-9]. Nd: $GdVO_4$ crystal using advanced growth technology, the high grade with Nd doping from 0.1 atm% to 4.0 atm%. In addition, crystal components of various sizes and coatingsare available[8,9].Cr4+:YAG ($Y_3A_{l5}O_{12}$) is an excellent crystal for passively Q-switching technique ,it is suitable for work with different active media such that Nd: $GdVO_4$, Nd:YAG, Nd:YLF, Yb:YAG. It is characterized by its chemically stable, durability, UV resistant, good thermal conductivity and high damage threshold. [7,10-12].$Ba(NO_3)_2$ is a mono crystals salt toxic composed of barium and the nitrate ion. It regards the best solid state materials for shifting the emission frequency of laser to different spectral region. $Ba(NO_3)_2$ nitrate exists as a white solid at room temperature, it is soluble in water, and like other soluble barium compounds[13]. This properties make it suitable for use in various military applications, including the rmite grenades and incendiary ammunition [14,15].

2. Theory

Based on the mathematical models of rate equations of Passive Q-switched laser with intracavity Raman conversion medium [16,17], rate equations model has been formulated in this study. The model describes the Raman laser operation includes a temporal processes taking place inside of gain medium, saturable absorber energy , and Raman medium as shown in the following rat equation.

$$\frac{dn_l}{dt} = n_l\left[K_gN_g - K_aN_{ag} - \beta K_aN_{ae} - \frac{2ghcv_ln_Rl_R}{t_{RT}} - \frac{1}{\tau_l}\right] \quad (1)$$

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

$$\frac{dN_g}{dt} = R_p - \gamma_gN_g - \gamma_pk_gN_gn_l \quad (3)$$

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

$$\frac{dN_{ae}}{dt} = K_aN_{ag}n_l - \gamma_aN_{ae} + K_aN_{ag}n_R \quad (5)$$

Eq. (1) represent the time variation of laser photons density inside the cavity. n_l is the laser photons density inside the cavity, $Kg = \frac{2\sigma_gl_g}{\tau_{RT}}$ 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. $\boldsymbol{l_a}$ 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 $\boldsymbol{\tau_R}$ is the lifetime of Raman photons in the cavity,$\boldsymbol{k_{sp}}$ 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 [18](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[19] (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:

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

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

3. Calculation

In this study, a software computer program has been based to solving a rate equations shown in the set equations (1), (2), (6), (7), (8) numerically by using Rung – Kutta – Fehelberg method. For validity of physics and mathematics of this set of rate equations, there is a good agreement in the fundamental (Q-switched) and Raman pulses behaviors with that shown in the study[20,21]. The input data shown in table (1) has been feed to program .The performance of Nd^{+3}:$GdVO_4$ as active medium with Cr^4:YAG as saturable absorber material to generate passive Q-switching laser pulse and $Ba(NO_3)_2$ crystal as a Raman conversion medium to generate Raman Stokes pulse by stimulated Raman scattering SRS has been simulated. The characteristics of passive Q-switching laser and Stokes pulses are investigated as a function of optical length.

Table 1. The input data of parameters

Parameter	Value	Ref.
Laser stimulated emission cross section (σ_g)	7.6×10^{-19} cm^2	[12]
Upper laser level life time (τ_g)	$90\times10^{-6} Sec$	
population reduction factor (γ_p)	1	
Total population density of SAM $(n_{a\circ})$	12×10^{17} cm^{-3}	[21]
Spontaneous Raman scattering (K_{sp})	$2\times10^{-10} Sec^{-1}$	
Ground-state absorption cross section (σ_{ag})	5.4×10^{-18} cm^2	[19]
Excited absorption cross section (σ_{ae})	2×10^{-18} cm^2	
Raman gain coefficient (g)	11 cm.Gw^{-1}	[22]

4. Results and discussion

4.1 Simulation of System Performance for Passive Q-switching and Stokes Pulses Generation

Fig.1 shows the profiles of Stocks pulse which generated by SRS in RM $(BaNo_3)_2$ crystal and passive Q-switching laser pulse which is generate by mutual effect between the AM

(Nd^{+3}:$GdVO_4$) and SAM (Cr^4:YAG). We can notice that, at the initial time of performance a slowly and gradual growth for passive Q-switching laser pulse due to high efficiency of SAM activity. That gives a good chance for active medium ions in lower energy level to absorbing the optical pumping photons and transferring into high energy levels. The population inversion reaching the maximum value before the optical bleaching state occurred in SAM.

The period time between (30 -40) ns shows the decreasing of the population inversion from maximum to threshold value to releasing the energy which accumulated in the AM as a laser photons. These photons leading to fast buildup of passive Q-switching laser pulse to reaching the peak value at (40) ns approximately. This time indicates the start of sudden and quick growth for Stokes pulse as shown in Fig. 1. The study explains that due to inelastic scattering phenomena in $Ba(NO_3)_2$ crystal, which is produced from absorption of principle laser photons (passive Q-switching pulse) by crystal ions of RM and transferring to excited energy level. That mean high energy will be accumulated in RM crystal. The continuity of principle laser photons interaction with ions of RM ions leads to stimulated emission in RM crystal. Then it's ions return to low excited levels and realize sharp pulse with energy and duration time range less than the passive Q-switching laser pulse.

4.2 Study of Optical Length Effect on Passive Q-switching and Stokes Pulses Power

Fig. 2 shows that the pulse duration of both passive Q-switching and Stokes pulses will increase with the increase of optical length. But the increment in the Stokes pulses duration less than passive Q-switching laser pulse. The study related this increment due to increasing in the round trip transition time of the laser photons in cavity (t_{RT}) which is leads to decreasing the absorption reaction of photons in both AM and SAM ions as shown in fig.3. Consequently, the transformation of AM ions from ground energy level to the excited levels accomplished slowly. That mean the population inversion will be growth slow with long period causes slow pulse rising time. In the same time the stimulated emission processed from the excited energy level in AM performs gradually and causes slow falling time of passive Q-switching laser pulse. In final result, this behavior leading to get pulses characterized by long duration time. The decreasing of absorption activity of SAM ions allowance to laser photons return back to the AM to make gradual accumulation of ions in the excited level (the AM ions close to good initial value of population inversion and vary to low final population inversion with more long period). This behavior leads to increase of rising and falling times of passive Q-Switching laser pulse which mean in final result gradual pulse buildup. The gradual buildup of passive Q-switching laser pulse leads to the similar buildup of Stokes pulse. Also the increasing of optical length leads to decreasing of photon decay rate that is shown in fig.4. This results leads to slowly growth of population inversion synchronous with obtain optical bleaching state in SAM) crystal. That releases passive Q-switching laser pulse distinguishes by long rising and falling times. Finally the pulse duration time increase. Fig.5 shows the profiles of passive Q-switching as a function of different optical length. That appearing the pulse which is significance by longer duration time according to the long optical length system. In Fig.6 the energy value of passive Q-switching laser and Stocks pulses increase with the increase of optical length. The study related that due to the minimization of final value of population inversion in term of optical length as shown in Fig. 7. Which mean realizing the energy stored as a population inversion in active medium causing an increase in passive Q-switching laser and Stocks pulses energy. In Fig.8 the power of passive Q-switching laser and Stocks pulses decrease with the increase the optical length. That is related to the variation value of energy and duration time depends on which of them to be more effective. We can see from the study that an increase in pulse duration time as shown in Fig.2 more effective from than the increase in energy as shown in Fig. (6) leads to decrease the pulse power as shown in Fig.8.

5. Conculusion

The duration and the energy of passive Q-switching and Stokes pulse are increasing with the optical length increase. But the increase in pulse duration time more effective from than the increase in energy. That leads in the final result to decrease the pulse power .

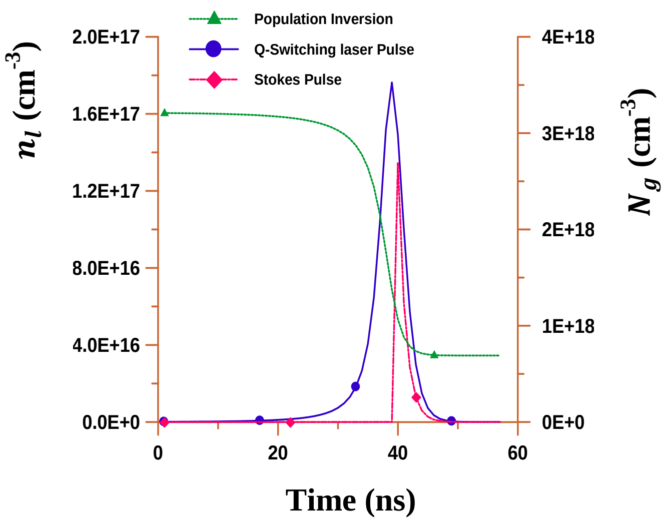

Fig.1: Q-Switching pulse, Stokes pulse and population inversion Profile.

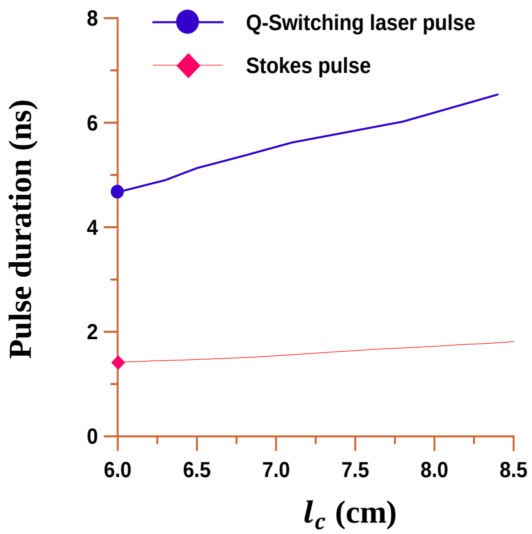

Fig.2:Pulse duration for Q-switching pulse and Stokes pulse as function of optical length

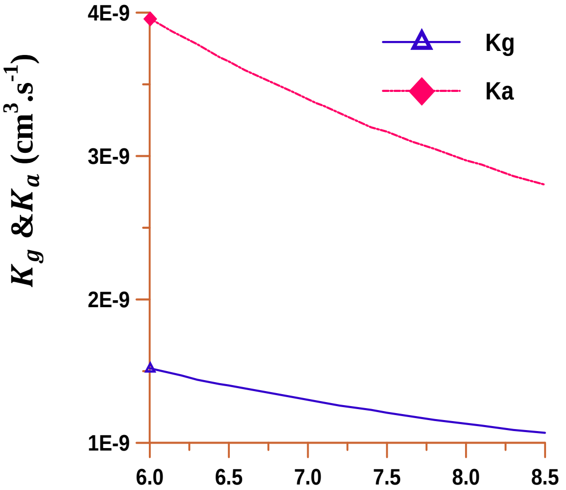

Fig. 3: Coupling Coefficients(K_g & K_a) as a function optical length

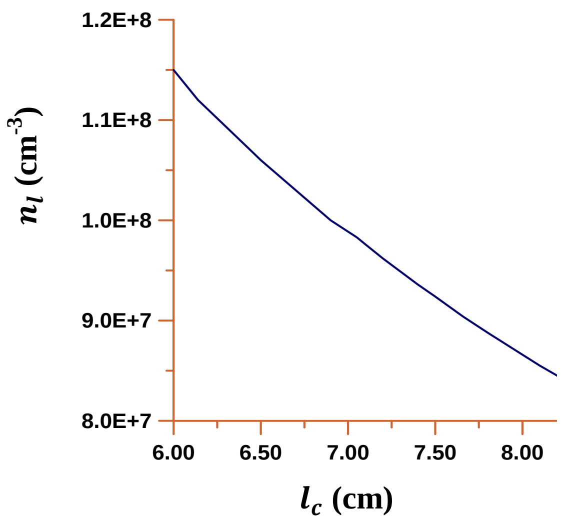

Fig. 4: Photon decay rate behavior as a function of optical length (l_c).

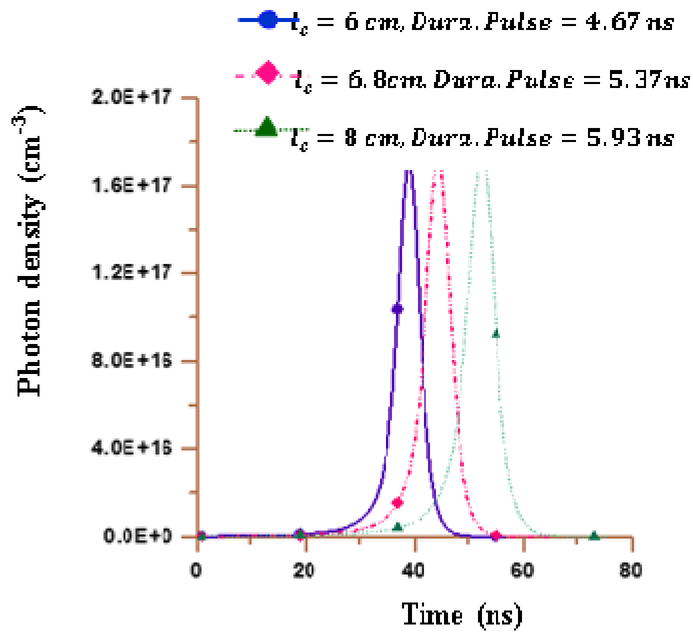

Fig. 5: Passive Q-switching laser pulses as a function of optical length

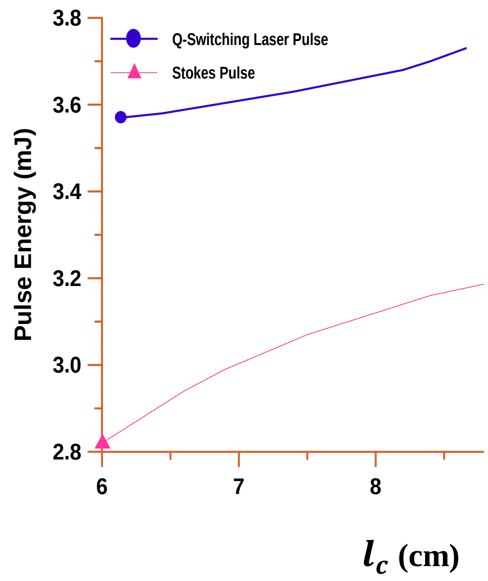

Fig. 6: Energy of passive Q-switching and Stokes pulses as a function of op-

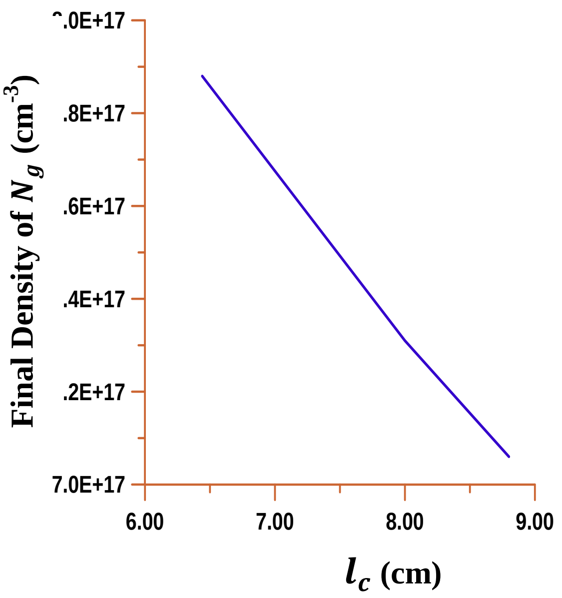

Fig. 7: The variation of final values of population inversion of active medium.

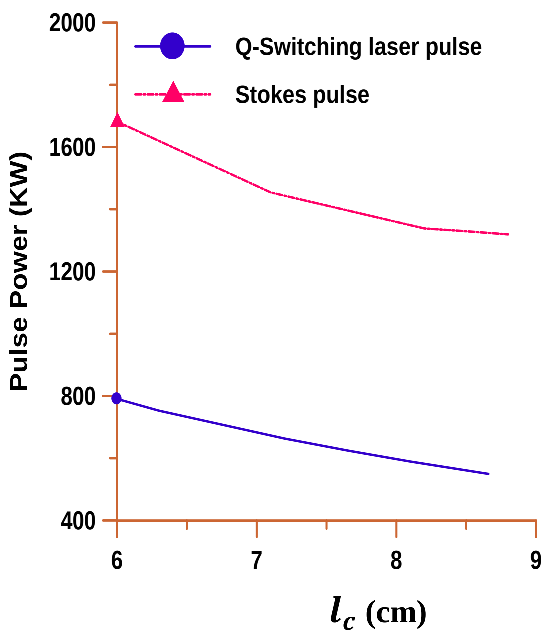

Fig. 8: The decreasing of Q-switching and Stokes pulse power as a function of optical length.

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