Study the effect of output coupler mirror reflectivity on Stokes Raman laser pulse characteristics

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Abstract

The effect of output coupler mirrors reflectivity on characteristics of Stokes Raman pulse, which is generated from passive Q-switching intracavity Raman media laser system has been studied. A software computer program based on this study to solve the rate equations of instantaneous performance of the mentioned system ($Nd:YVO_4$, Cr^{+4}:YAG and $BaWO_4$) numerically by Runge- kutta-Fehalberg method. The study shows that the energy, duration, and the power of the pulse increasing when the output coupler mirrors reflectivity increasing.

Keyword: Physics, Laser, High power pulses, Raman pulse

الخلاصة

درس تأثير انعكاسية مرآة الخرج على خصائص نبضة رامان ستوك المتولدة في نظام التحويل السلبي لعامل النوعية المتضمن لوسط رامان , حيث اعد برنامج حاسوبي لحل انموذج معادلات المعدل التي تصف الأداء اللحظي للنظام المتكون من $Nd:YVO_4$ ¸Cr^{+4}:YAG ،$BaWO_4$ كوسط فعال, مادة ماصة قابلة للإشباع ووسط رامان على التوالي , وقد استخدمت طريقة رونج - كوتا - فهلبرج العددية في حل ذلك الانموذج . وخلصت الدراسة الى تزايد قيمة طاقة وامد وقدرة نبضة ستوك مع زيادة انعكاسية المرآة لفوتونات ستوك.

1. Introduction

Since the development of the laser, many new application methods have been developed. Among others scientists discovered that light not only generates linear effects in materials, also nonlinear effects occur at high intensity of light such as laser ray. The importance of those nonlinear effects increases with every year, high power pulses is the one examples of the development of laser. Wide range of important applications of high power pulses such as spectroscopy, environment sensing, range finder, laser radar, materials processing, communications, and medicine [1, 2].

There are many methods to generate high power pulses such as Q-switching, mode locking, and Raman conversion [3,4]. Raman conversion method represent the types of stimulated Raman-scattering (Stokes and anti-Stokes scattering) which occur in Raman media.

$BaWO_4$ a universal Raman-active crystal for its high gain in both the steady state and the transient state. However, the samples of $BaWO_4$ used in stimulated Raman-scattering experiments as intracavity Raman media [5] the crystal used in this study as a Raman media.

The first trivalent rare earth ion Nd^{+3} is used in generating the Neyodenium Yttrium Orthovanadate (YVO_4) laser . Nd:YVO_4 was proposed for use as a laser material , however it took until 1987 for the optical quality of the crystals to become good enough to be comparable to Nd:YAG for efficiency [6].

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 [7,8].

2. Theory

The time variation of essential parameters to describes the performance of passive Q-switching intracavity Raman medium laser system illustrated as the following rate equations model [9].

$$\frac{dn_l}{dt} = n_l\left[k_g N_g - k_a N_{ag} - \beta k_a N_{ae} - \frac{2ghcv_l n_R l_R}{t_{RT}} - \frac{1}{\tau_l}\right] \tag{1}$$

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

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

$$\frac{dN_{ag}}{dt} = -k_a N_{ag} n_l - k_a N_{ag} n_R + \gamma_a N_{ae} \tag{4}$$

$$\frac{dN_{ae}}{dt} = k_a N_{ag} n_l - \gamma_a N_{ae} + k_a N_{ag} n_R \tag{5}$$

Eq.(1) represents the time variation of laser photons density inside the cavity. Where n_l is the laser photons density inside the cavity, $K_g = \frac{2L_g\sigma_g}{t_{RT}}$ is the coupling coefficient between the photons and the active medium, where; σ_g is laser stimulated emission cross section, Lg is the active medium length, $t_{RT} = \frac{2l_c}{c}$ is the Round-trip transit time of laser 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 σ_{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, $\tau_l = \frac{2l_c}{c[L-\ln(R_l)]}$ is the lifetime of laser photons in the cavity, where L is the roundtrip losses in the cavity .Eq.(2) represents the time variation of Raman photons density inside the cavity. Where $\tau_R = \frac{2l_c}{c[L-\ln(R_R)]}$ the lifetime of Raman photons in the cavity is, k_{sp} is the spontaneous Raman scattering factor.

Eq.(3) represents 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). 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 [10].Then Eq.(3) can be written as the following

$$\frac{dN_g}{dt} = -\gamma_p k_g N_g n_l \qquad (6)$$

Eq.(4) represents the time variation of the ground-state population of SAM. Where $\gamma_a = {}^{1}/_{\tau_a}$ is the spontaneous relaxation rate of the (SAM, τ_a is the saturable absorber first excited state lifetime. The lifetime of the first exited level of SAM is much longer than the time scale considered [11], and then the third term of equation can be neglect. Then Eq. (4) can be written as the following

$$\frac{dN_{ag}}{dt} = -k_a N_{ag} n_l - N_{ag} n_R \qquad (7)$$

Eq. (5) represents the time variation of the first exited level of SAM. The second term can be neglect. Then Eq. (5) can be write as

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

At initial time, can be regards the variables $N_{ag} \simeq N_{a\circ}$,$N_{ae} \simeq 0.0$, $\frac{dn_L}{dt} \simeq 0.0$,$N_{aeg} \simeq 0.0$,$N_g \simeq N_{g\circ}$

Where $N_{g\circ}$ initial value of population inversion. From Eq. (1)

$$N_{g\circ} = \frac{k_a N_{a\circ} + \frac{2ghcv_l n_R l_R}{t_{RT}} + \frac{1}{t_l}}{k_g} \qquad (9)$$

Eq. (9): represent the initial value of population inversion. After very short time

$$N_{ag} \simeq 0.0 \quad ,N_{ae} \simeq N_{a\circ} \quad , \frac{dn_L}{dt} \simeq 0.0 \quad ,N_g \simeq N_{th}$$

From eq. (1) can be obtain ;

$$N_{th} = \frac{\beta k_a N_{a\circ} + \frac{2ghcv_l n_R l_R}{t_{RT}} + \frac{1}{t_l}}{k_g}$$

Eq. (10): represent the threshold value of population inversion. From Eqs. (1,6) can be obtain

$$P = -\frac{hv}{\gamma_p t_c}\left[\mathrm{N_{th}} - \mathrm{N_{g\circ}} - \mathrm{N_{th}}\ln\left(\frac{\mathrm{N_{g\circ}} - \mathrm{N_{th}}}{\mathrm{N_{g\circ}}}\right)\right] \qquad (11)$$

3. Results and discussion

The rate equations model that illustrated in set of equations (1, 2, 6, 7 and 8) have been solved numerically by using Rung – Kutta – Fehelberg method. The input data shown in table (1) has been feed to program. The calculations display the significant effect of output coupler mirrors reflectivity at Raman photons (R_R) on characteristics of Stokes Raman pulse, the base effect concerning on the Stokes Raman photon life time (τ_R) in the laser cavity, it is proportional with the increment of output coupler mirrors reflectivity value as shown in Fig.(1). The increase of photon life time mean that the cavity photons loss became a low value; Fig.(2) confirm this conclusion, it is appear the increase in the photons density with the increment of output coupler mirrors reflectivity.

Fig.(3) demonstrates the increase which occurs in the energy of Raman laser pulse with increase of the output coupler reflectivity at Raman photons, the study related that to increase in the photons density as shown in Fig.(2).

Figure (4) shows that the increase in the duration of Raman laser pulse whenever the value of output coupler reflectivity at Raman photons increases. The study explains that due to slow lapse which occurs in the pulse behaviour according to the slow lapse in population inversion after the threshold value, that lead to increase in the falling time of the pulse, finally, caused the broadening (increasing) in the pulse duration.

Figure (5) shows the power increasing of Raman laser pulse with the increase of the output coupler reflectivity at Raman photons, that is because of the increase in the pulse energy as shown in Fig. (3) Which was more influential than the increase in the duration time as shown in Fig. (4) to specify its pulse power value.

Table 1: Parameters Input values

Par.	Value	Ref.
σ_g	$6.5\times10^{-19}\,cm^2$	[6]
τ_g	$98\mu s$	[12]

γ_p	1	[13]
γ_g	$0.01\times10^{6}\,s^{-1}$	
G	8.5 cm/W	[14,15]
K_{sp}	$1\times10^{-10}\,S^{-1}$	[16]
σ_{ag}	5.4×10^{-18} cm^2	[11]
σ_{ae}	2×10^{-18} cm^2	
$n_{a\circ}$	12×10^{17} cm^{-3}	[17]
λ_l	1.064 μm	[6]

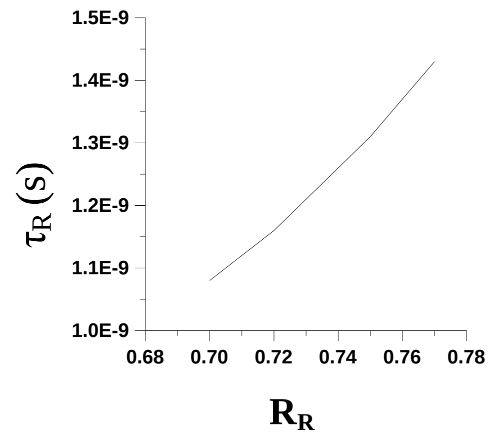

Fig. (1): Raman photons life time behavior as a function of R_R

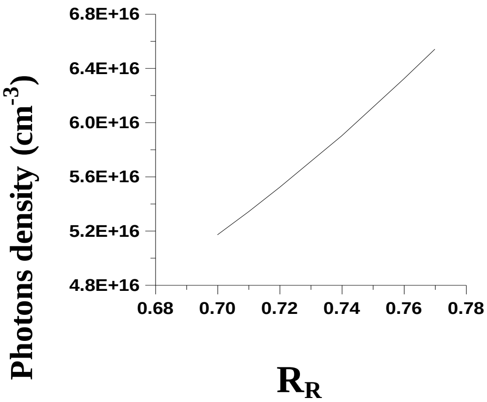

Fig. (2): Maximum photons density of Stokes Raman pulse as a function R_R

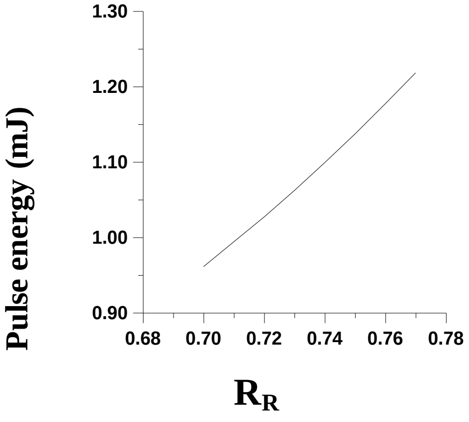

Fig. (3): Raman pulse energy behavior as a function R_R

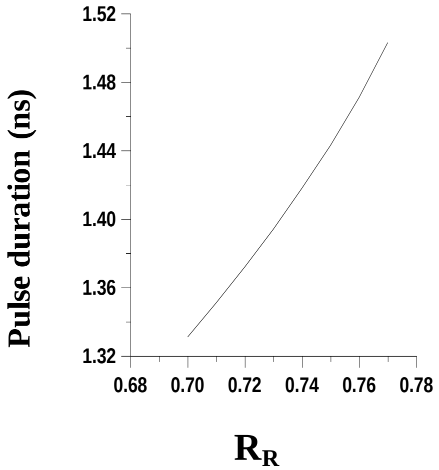

Fig. (4): Raman pulse duration behavior as a function of R_R

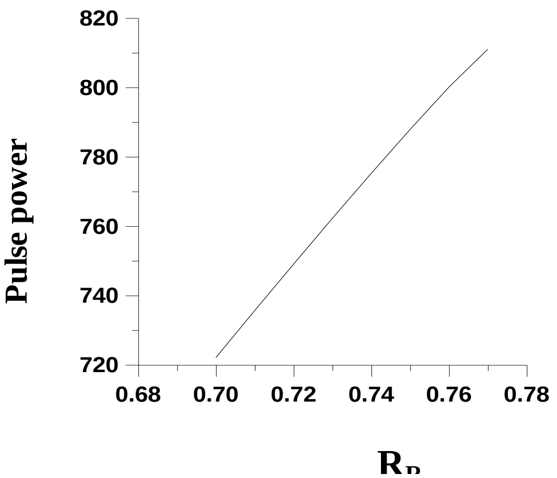

Fig. (5): Raman pulse power behavior

Conclusion

The calculations display the Stokes Raman photon life time in the laser cavity, photon density, the energy, duration, and the power of Stokes Raman pulse proportional with the increment of output coupler mirrors reflectivity.

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