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The performance of a passively Q-switched Cr:YAG^{4+} in an end-pumped laser system

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Abstract: A characteristic study of a passively Q-switched diode pumped solid state laser system is presented in this work. For laser a comparison study for the theoretically calculated results with a simulation results using a software which calculates the Q-switched solid state laser parameters was such as energy, peak power and pulse width were performed. There was a good agreement between our theoretical calculations and the simulation values.

Introduction

Chromium doped yttrium aluminum garnet or Cr^{4+}:YAG crystal has high damage threshold and is mostly used in passively Q-switching diode pumped or lamp pumped passive Q - switching materials. Its main advantages are high damage threshold, and absorptions wavelength of 900nm--1200nm, and peak of around 1060nm with large absorption section [1]. Therefore, it is reasonable that Cr^{4+}:YAG is an ideal saturable absorber as a passive Q-switch for all high power and high repetition rate solid state lasers. A Cr^{4+}:YAG as a Q-switched elements used for Nd:host lasers has attracted great attention .The energy level diagram of Cr^{4+}:YAG crystal is shown in Fig. 1. The quantum efficiency of the transition $^3B_2 \rightarrow {}^3B_1$ is poor (15%) at room temperature and decreases as the temperature increases [2]. The strong photon interaction is responsible for a small value of the quantum efficiency. The energy balance at 1064 nm is as follows: from 9400 cm^{-1} a part of 2600 cm^{-1} is transformed into heat by photon interaction $^3E \rightarrow {}^3B_2$, 85% of the rest (6800 cm^{-1}) is transformed into heat because of the low quantum efficiency.

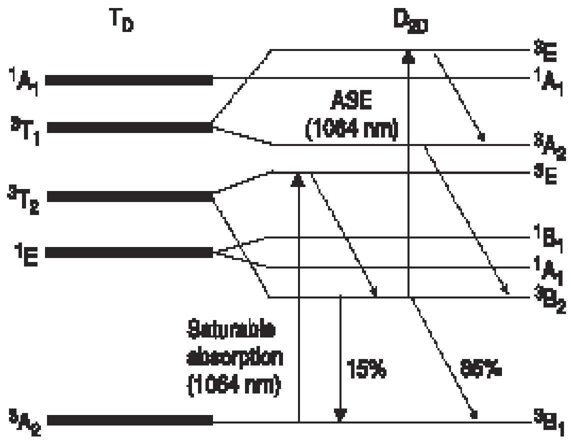

Fig. (1): Energy level diagram of a Cr4+:YAG crystal

Calculations of system parameters

A schematic set-up of the passive Q-switched device is shown in Fig.2. It consists of the driver unit, the laser head, which contains the pump diode laser emitting optical power about 1W CW of 808 nm wavelength and a collimator for collimating the beam by a focusing lens of 238 μm focal length in the active medium, type (Nd:YVO_4). One end has a high-reflection coating for the 1064nm wavelength to function as a mirror for the resonator and an antireflection (AR) coating for the 808nm wavelength to allow the pump beam to enter the rod. The other end has an AR coating for the 1064nm. The stimulated emission cross section equal to (2.5×10^{-18} cm^2) and spontaneous fluorescence lifetime equals to (98 μs) [3].

The passive Q-switching Cr:YAG crystal has 1 mm thickness, small signal transmission of 63.3 (%) and a ground state absorption cross section of (7×10^{-18} cm^2). This crystal was coated with AR/AR at 1064nm, with 90% transmission at 1064nm, and the output-coupling mirror with a radius of curvature of 800mm with 5% transmission at 1064nm. This mirror with another plane mirror constructs the optical resonator of hemispherical type having a length of 30 mm with a beam waist of 265 μm.

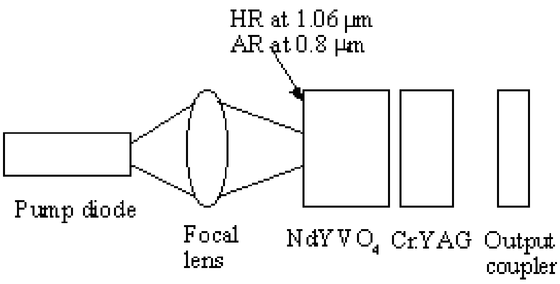

Fig (2): Schematic set-up of the passive Q-switched device

Calculation of output laser pulse parameters

When a CW power is applied to the active medium, the population inversion would reach a maximum value and decreases thereafter and the cavity losses are periodically switched from high to low value, then the laser output consists of a continuous train of Q-switched pulses .During each pulse inversion falls from its initial value N_i (before Q- switching) to the final value N_f (after the Q-switched pulse). The population inversion is restored to its initial value N_i by the pumping process before the next Q-switched event. Since the time taken to restore the inversion is roughly equal to the upper–state lifetime (τ) of active medium, the time between two consecutive pulses must equal or be shorter than (τ). The typical range of repetition rates for CW – pumped Q-switched lasers is from few kilohertz to few tens of kilohertz. The following equations are used to express pulse energy (E), pulse peak power (P_m) and real pulse duration (W) [4, 5].

$$E = \frac{\pi * h\nu * W_o^2}{4 * \gamma * \sigma} \ln\left(\frac{1}{R}\right) * \Phi_{integ} \qquad (1)$$

$$P_m = \frac{\pi * h\nu * W_0^2}{4 *} \left[\ln\left(\frac{1}{R}\right) + \ln\left(\frac{1}{T_o^2}\right) + L \right] * \ln\left(\frac{1}{R}\right) * \Phi_m \qquad (2)$$

$$W = \frac{t_r * \Delta\tau}{\ln\left(\frac{1}{R}\right) + \ln\left(\frac{1}{T_o^2}\right) + L} \qquad (3)$$

where:
σ : is the stimulated emission cross-section of the active medium.
L : is the remaining round-trip dissipative optical loss.
W_p : is the radius of the pump beam in the gain medium
Wo : is the beam waist
R : is the reflectivity of the output mirror
T_o : small –signal transmission of the saturable absorber is equal
Δτ : is the normalized pulse duration
Φ_m : is the maximum value of photon density
Φ_{integ} : is the integral of photon density over τ from zero to infinity

A saturable absorber is designed to have large ground state absorption (σ_{gsa}) at the lasing wavelength. This prevents laser oscillation until the population inversion gives gain exceeding the losses provided by the output mirror and saturable absorber. The ratio of the laser saturation energy to the absorber saturation energy is defined by (α) [6].

$$\alpha = \frac{\sigma_{gsa}}{\gamma * \sigma} \qquad (4)$$

The inversion reduction factor is equal to ($\gamma = f_a + f_b$) where fa ,fb are, respectively, the Boltzman occupation factors of the upper and lower laser levels of the gain medium. For a Nd:YVO4 gain medium, fa = 0.48 and fb = 0.23 at room temperature [7]. The ratio of the initial population inversion density to the threshold population inversion density can be expressed in equation (5).

$$N = \frac{\ln\left(\frac{1}{R}\right) + \ln\left(\frac{1}{T_o^2}\right) + L}{\ln\left(\frac{1}{R}\right) + \left(\frac{\sigma_{esa}}{\sigma_{gsa}}\right) * \ln\left(\frac{1}{T_o^2}\right) + L} \qquad (5)$$

where:

σ_{esa} : is the excited –state absorption cross-section area of the saturable absorber.

σ_{gsa} : is the ground-state absorption cross-section area of the saturabel absorber.

Integrated photon density (Φ_{integ}) can be determined using the values of τ (where τ is the upper state lifetime) having the values from zero to infinity, maximum value of photon density(Φ_m) and normalized pulse duration($\Delta\tau$) as shown in Fig. [3,4&5] respectively,[8].

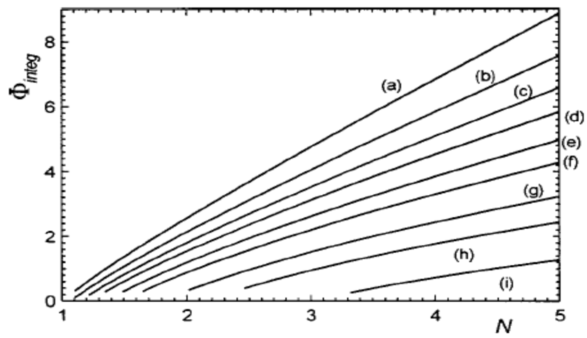

Fig. (3): Relation between Φ_{integ} and N for different α in the caseW_0 =W_P : (a) α- ∞, (b) α =20, (c) α =10, (d) α = 7, (e) α = 5, (f) α = 4, (g) α = 3, (h) α =2.5, and (i) α = 2.

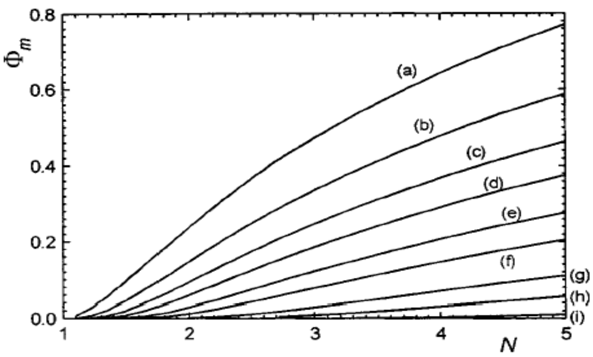

Fig. (4): Relation between Φ_m and N for different α in the case W_o =W_P : (a) α- ∞, (b) α =20, (c) α =10, (d) α = 7, (e) α = 5, (f) α = 4, (g) α = 3, (h) α =2.5, and (i) α = 2.

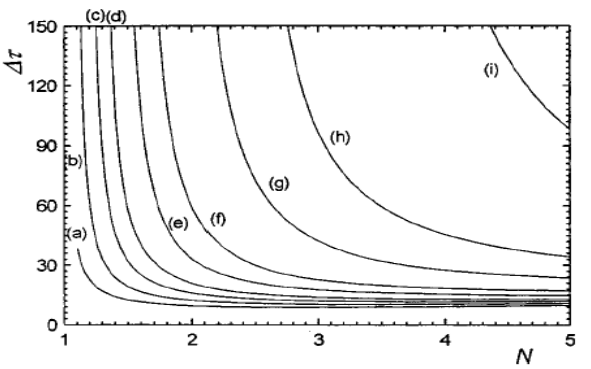

Fig. (5): Relation between pulse duration $\Delta\tau$ and N for different α in the caseW_0 =W_P : (a) α- ∞, (b) α =20, (c) α =10, (d) α = 7, (e) α = 5, (f) α = 4, (g) α = 3, (h) α =2.5, and (i) α = 2.

Results and Discussion

In the present work, pulse energy (E), Peak power (Pm), and real pulse width (W) have been calculated using equations [1, 2&3] respectively, at N= 3, α = 4, Φ_{integ} =2.2, Φ_m = 0.06 and $\Delta\tau$ = 28. The obtained Pulse energy (E), Peak power (Pm) , and Real pulse width (W) are equal to 6.6 μj, 1.1KW and 6 ns respectively .

Thickness of passive Q-switched (Cr:YAG) has been investigated. Figure (6) shows the relation between pulse duration with different thicknesses of Cr:YAG passive Q-switch. The pulse duration decreases slightly to less than 3ns when the thickness increased to 0.7cm.

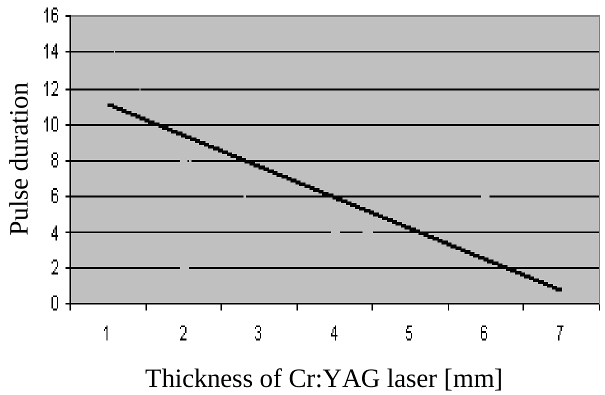

Fig.(6): The relation between pulse duration [ns] and various thickness of Cr:YAG [mm]

The thickness of Cr:YAG in this will yield a decrease in quality factors which yield increased losses and this turned to decrease the small signal transmission at 1064 nm as shown in Fig. (7).

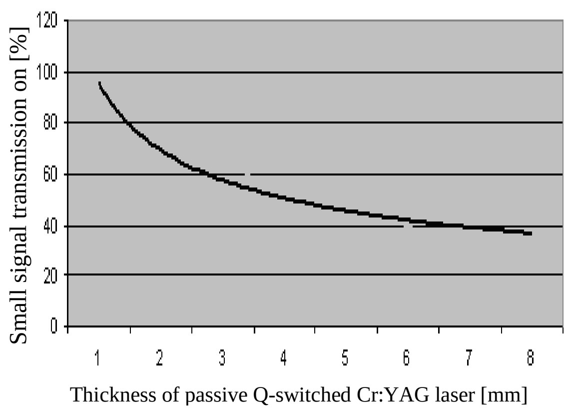

Fig. (7): The relation between single transmission [%] and various thickness of Cr:YAG [mm]

Exceeding these losses with more pumping power means large energy store which is achieved by preventing laser oscillation until the population inversion gives a high gain exceeding the losses yielding fast oscillation and fast decreasing to the population inversion. Hence getting shorter pulse duration. Normally when the pulse duration decreased, the peak power increased. This can be shown in Fig. (8).

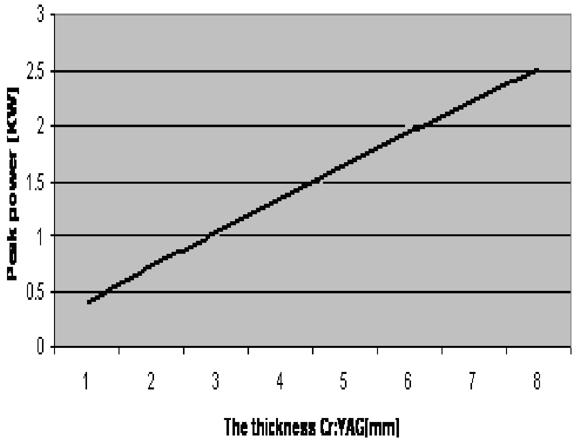

Fig.(8): The relation between peak power [KW] and various thickness of Cr:YAG [mm]

The crystal of efficient passive Q-switching must have large ground-state absorption cross section at the lasing wavelength and greater than the absorption cross-section of the active medium. Using Cr:YAG as a Q-switch and Nd:YVO4 as an active medium this ratio equals to 10.

This may prove that the Cr:YAG as an efficient Q- switch. Any photon generation from spontaneous emission and absorption from saturable absorber leads to an increase in absorption of the active medium IF the Ground-state absorption cross section of the saturable absorber equals absorption cross-section of the active medium, no Q-switch operation will present. Figure(9) shows the relation between pulse duration with the Ground-state absorption cross section of Cr:YAG.

When the absorption cross section of Cr:YAG is increased this will reduce the saturation intensity, therefore the population inversion value will not be affected, it will still have a large value after saturation therefore the losses are very small, yielding shorter pulses.
Normally when the generated pulse has a narrow duration, this pulse will have a high peak power as shown in the linear relation of Figure (10).

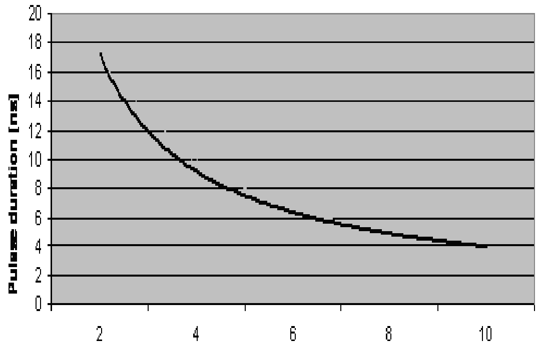

Fig. (9): The pulse duration [ns] with ground state absorption cross section of Cr:YAG [mm]

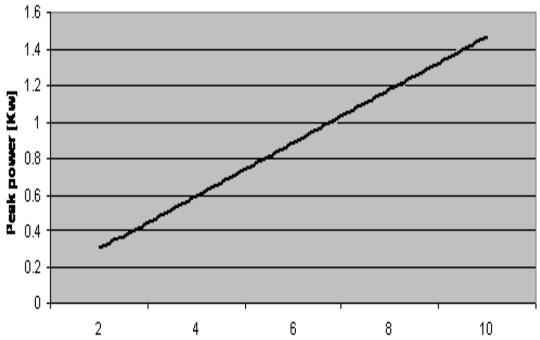

Fig.(10): The relation between peak power with ground state absorption cross section of Cr:YAG

Simulation Results

To check the theoretically calculated results we tried to compare such results with some simulation results that were evaluated using a software package (Laser train version 4.01, this software is designed by Optical material Technological Center) for Q-switched solid state laser dynamics to evaluate the pulse energy (E), peak power (Pm), and pulse width (W) .The output of such package is shown in Figure (11). The pulse energy E = 7.2μJ, peak power Pm =1.125 kW, and real pulse width W = 6.4 ns .The results calculated used the fundamental parameters (output coupler, optical resonator length, thickness of Cr:YAG crystal,………..etc). The theoretical and simulation results showed a high degree of agreement.

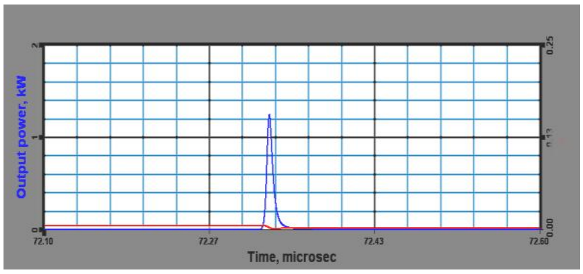

Fig. (11): Laser pulse

Conclusions

The two important parameters of Cr:YAG passive Q-switched affecting the pulse energy ,peak power and pulse duration ,which have been studied in this work are the absorption cross section and the thickness. The thickness increase leads to a decrease in pulse duration and an increase peak power. And when the absorption cross section is increased the pulse duration will decrease and the peak power will increase. Thus it can be concluded that a careful choice of Q-switched crystal thickness and absorption cross section should be satisfied.

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تأثير خصائص المفتاح السلبي نوع (Cr^{4+}:YAG) على خصائص نبضة الليزر

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الخلاصة تم في هذا البحث دراسة تأثير خصائص المفتاح السلبي نوع (Cr^{4+}:YAG) على خصائص نبضة الليزر الخارجة من حيث القدره , الطاقة وعرض النبضه في منظومة الليزر ذات مفتاح عامل النوعيه السلبي .ان نتائج الحسابات النظرية المستخلصة تمت مقارنتها مع نتائج تشبيهيه مأخوذة من برنامج معد لغرض حساب معلمات ليزرات الحالة الصلبة ذات مفتاح عامل نوعيه والتي أظهرت توافقا جيداً فيما بينها.