Investigation of Effective Parameters on Pulsed Nd:YAG Passive Q-Switched Laser

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ABSTRACT— In this paper, we report the experimental results of a pulsed flash lamped Nd:YAG laser at wavelength of 1064 nm and Q-switched by Cr^{4+}:YAG solid state saturable absorber. We have obtained the output energy (E) and pulse-width (τ_p) of this laser for various initial transmissions of this saturable absorber. Furthermore, the effect of reflectivity of the output coupler (R), diameter of the rod (d), and optical length of the cavity (l) on the laser output has been investigated. We have used the corner cube as a back mirror. We have obtained pulse-width 15ns with 31 mJ output energy. We have also analyzed this laser theoretically which agrees well with our corresponding experimental results.

KEYWORDS: Q-switching, Passive Q-switching, Pulse width, Saturable Absorber, Cr^{4+}:YAG.

I. INTRODUCTION

Passively Q-switched solid-state lasers [1-4] are playing an important role in many applications, such as range finders, pollution detection, lidars, medical equipments, laser cutting and drilling, and nonlinear optical studies.

One method to Q-switch a laser passively is using a saturable absorber, in which a material with high absorption at the laser wavelength is placed inside the laser resonator and prevent laser oscillation until the population inversions reaches a value exceeding the combined optical losses inside the cavity [1, 5].

There are various kind of saturable absorbers in the literature to name a few, dyes [6] , bulk semiconductors [7], gases [8], and absorbing ions or color centers, either in a separate crystal [9] or co doped with the active laser medium in a monolithic structure [10].

In recent years, Cr^{4+} doped crystals have attracted a great deal of attention as passive Q-switchers [2-4,11-15] .These Cr^{4+}-doped crystal include Cr^{4+}:YAG [2,3,12,13,15,16] Cr^{4+}:GsGG [11], Cr^{4+}:Yso [4], etc. These crystals have a large absorption cross section and low saturable intensity at the laser wavelength. In comparison with other saturable absorber they are more photochemically and thermally stable and have a higher damage threshold. They can be used to Q-switch pulsed [2-4, 11, 12, 16] and continuously pumped lasers[13,15]. Moreover, Cr^{4+} can be co doped with amplifying medium in a monolithic structure to form self-Q-switching lasers [15].

Degnan has presented the theory of the optimally coupled Q-switched laser in 1989, in which the general equations describing Q-switched lasers operation has been reached [17]. He has also introduced the theory of optimization of passively Q-switched lasers in 1995, in which an estimate of lasers key parameters can be obtained simply and quickly [18].

Xiao and Bass in 1997 [5].by recognizing the effect of excited state absorption (ESA) in saturable absorber such as Cr^{4+}:YAG has extended a general model of Degnan's work.

Chen [19], has shown that in these lasers, the initial population density in the gain medium, n_i, depends on the initial transmission of the saturable absorber, T_0 and the output mirror reflectivity, R. Furthermore they have obtained the equations which relate the output parameters in terms of R and T_0.

In this paper, we have investigated the influence of R, T_0 and the effect of laser rod diameter and cavity length on the pulse width, τ_p output energy, E, and output peak power, P.

The paper is organized as fallows: the theory is described in Section II, the experimental setups and results are demonstrated in Section III and the paper is concluded in Section IV.

II. THEORY

Considering Cr^{4+}:YAG saturable absorber as a four-level system introduced by Fig. 1, we have the following rate equations [18, 21] :

$$\frac{d\varphi}{dt}=\frac{\varphi}{t_r}\left[2\sigma n l_g-2\sigma_{gs}n_{gs}l_s-2\sigma_{es}n_{es}l_s-\left(\ln\left(\frac{1}{R}\right)+L\right)\right] \tag{1}$$

$$\frac{dn}{dt}=-\gamma c\sigma\varphi n, \tag{2}$$

$$\frac{dn_{gs}}{dt}=-\frac{A}{A}c\sigma_{gs}\varphi n_{gs}, \tag{3}$$

$$n_{gs}+n_{es}=n_{so}, \tag{4}$$

where φ is intracavity photon density, n is population inversion density of the gain medium, l_g and l_s are gain medium length and saturable absorber thickness, respectively, A/A_s is the ratio of the effective area in the gain medium and in the saturable absorber, L is the round-trip dissipative optical loss, n_{gs}, n_{es}, and n_{so} are respectively the populations of the ground, excited and total densities, σ_{gs} and σ_{es} are respectively the ground state absorption (GSA) and excited state absorption (ESA) cross section in the saturable absorber, R is the output mirror reflectively, γ is the inversion reduction factor [18], and $t_r=\frac{2l}{c}$ is the round trip transit time of light in the cavity optical length l, and c is the speed of light in vacuum.

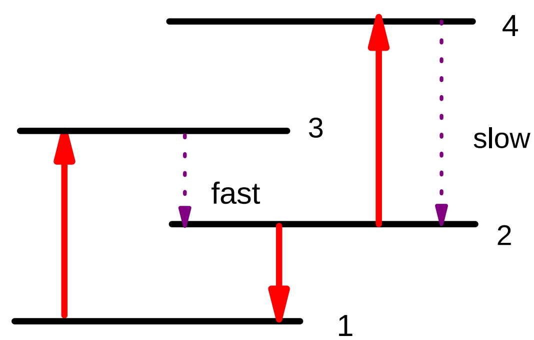

Fig. 1: The four-level model of Cr^{4+}:YAG saturable absorber.

The corresponding absorption cross section of levels 1-3 and 2-4 near by the laser wavelength are $\sigma_{gs}=8.7\times10^{-19}cm^2$ and $\sigma_{es}=2\times10^{-19}cm^2$, respectively [2] and:

$$n_{gs}=n_{so}\left(n/n_i\right)^{\alpha}. \tag{5}$$

where $\alpha=\frac{\sigma_{gs}A}{\gamma\sigma A_s}$ and n_i is the initial population inversion density in the gain medium. n_i is determined form the condition that the round trip gain is exactly equal to the round trip losses just before the Q-switch opens(the first threshold condition for starting pulse build up). Thus:

$$n_i=\frac{Ln\left(1/T_0^2\right)+Ln\left(1/R\right)+L}{2\sigma l}. \tag{6}$$

where T_0 is the initial transmissions of the saturable absorber and is given by:

$$T_0 = \exp\left(-\sigma_{gs} n_{so} l_s\right) \tag{7}$$

The saturated transmission of the saturable absorber is:

$$T_s = \exp\left(-\sigma_{es} n_{so} l_s\right) \tag{8}$$

From (7) and (8), we obtain:

$$\beta = \frac{\sigma_{es}}{\sigma_{gs}} = \frac{Ln\left(T_s\right)}{Ln\left(T_0\right)} \tag{9}$$

where β is an important parameter of saturable absorber and indicates the degree of ESA to (GSA), which can be obtained by the measurement of T_0 and T_s as discussed in [2].

Now we see the effects of the intracavity focusing (α) and ESA (β) in the coupled rate equation.

It is worth mentioning that the parameters α and β are determined from the cavity configuration and the physical properties of the gain medium and the saturable absorber.

In order to have growth of the photon intensity, the following threshold condition should be satisfied [19]:

$$\left.\frac{d^2\varphi}{dn^2}\right|_{n=n_i} > 0 \tag{10}$$

This is called the second threshold condition. $T_{0,Max}$ is obtained from(10):

$$T_{0,MAX} = \exp\left(-\frac{L-\ln\left(R\right)}{2\left(\alpha\left(1-\beta\right)-1\right)}\right) \tag{11}$$

this gives a giant pulse.

On the other hand, we need E, P, and τ_p which are given by [17] and [19, 20]:

$$E_{out} = \frac{h\nu A}{2\sigma\gamma} \ln\left(1/R\right) \left[\frac{\left(1-\beta\right)\ln\left(1/T_0^2\right)}{\beta\ln\left(1/T_0^2\right)+\ln\left(1/R\right)+L}\right]\times \left[1-\left(T_0/T_{0\max}\right)^{\varepsilon}\right] z\left(\alpha,\beta\right) , \tag{12}$$

$$P = \frac{h\nu A l_g}{\gamma t_r} Ln\left(1/R\right)\left[n_i - n_t - n_{t_0} Ln\left(n_i/n_f\right) - \left(n_i - n_{t_0}\right)1/\alpha\left(1-\left(n_t/n_i\right)^{\alpha}\right)\right] \tag{13}$$

$$\tau_p = E/P. \tag{14}$$

where n_i and n_t are the population density of the gain medium when the laser action starts and when the laser output power peaks respectively. n_f indicates the population density of the gain medium for zero photon density and:

$$n_{t0} = \frac{Ln\left(1/R\right) + \beta Ln\left(1/T_0^2\right) + L}{2\sigma l} \tag{15}$$

Also the following relations exist between n_t/n_i , n_f/n_i , and n_{t0}/n_i [20]:

$$\frac{n_t}{n_i} = \frac{n_{t0}}{n_i} + \left(1-\frac{n_{t0}}{n_i}\right)\left(\frac{n_t}{n_i}\right)^{\alpha} \tag{16}$$

$$1-\frac{n_f}{n_i} + \left(\frac{n_{t0}}{n_i}\right) \ln\left(\frac{n_f}{n_i}\right) - \frac{1}{\alpha}\left(1-\frac{n_{t0}}{n_i}\right)\left[1-\left(\frac{n_f}{n_i}\right)^{\alpha}\right] = 0 \tag{17}$$

In order to determined the output energy ,E , the output peak power, P, and the pulse-width, τ_p, from the above equations, we need the following parameters: T_0, R, d, t_r, n_t/n_i , n_f/n_i , $z(\alpha,\beta)$, ε and n_{t0}/n_i .

By using relations (6) and (15) n_i and n_{t0} can be obtained. $z(\alpha,\beta)$, ε can also be obtained numerically [19]. To obtain n_t/n_i and n_f/n_i we have plotted the Figs. (2) and (3) to extract there values.

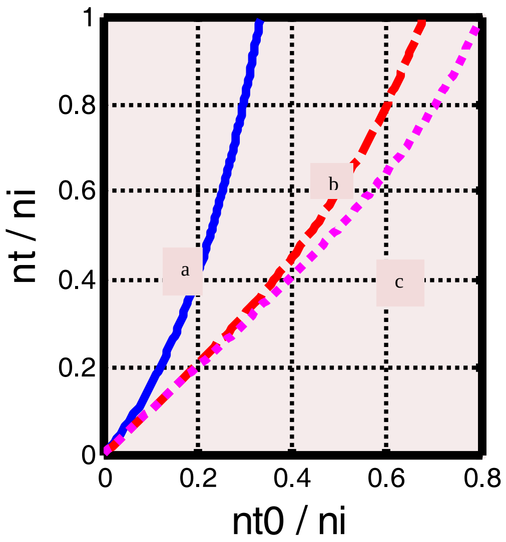

Fig. 2 Dependence of n_t/n_i to n_{t0}/n_i for different α values of (a) 1.5 (b) 3.11, and (c) 5.

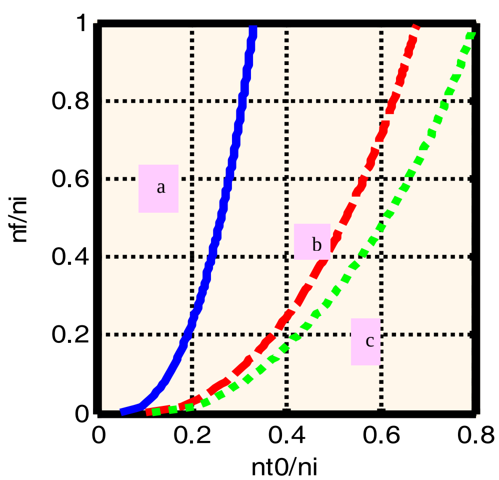

Fig. 3 Dependence of n_f/n_i to n_{t0}/n_i for different α values of (a) 1.5 (b) 3.11, and (c) 5.

To give an example, for R=50%, T_0=40%, $d = 4\,mm$, $l = 45\,cm$ we have calculated $E = 29\,mJ$, and τ_p=17ns which agrees well with experimental results as discussed in section 3 (Table1).

For theoretically investigation the effect of R and T_0 on output energy, we draw E_{out} according to relation (12). As we see in Fig. (4) for the constant value of T_0, by increasing output mirror reflectivity output energy has also been increased until output reflectivity reached near T_0.

Dependence of output energy on rod diameter has been depicted in Fig. (5). For the different value of rod radius r =0.15, 0.2, and 0.25 (cm) we draw $E_{out}(J)$ according to relation (12). It is clear that by increasing rod diameter, E_{out} has also been increased.

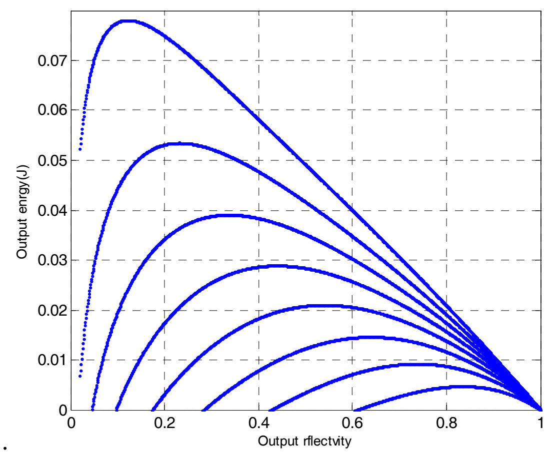

Fig. 4 Dependence of E_{out} on output reflectivity for different T_0, from up to down: T_0=0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8.

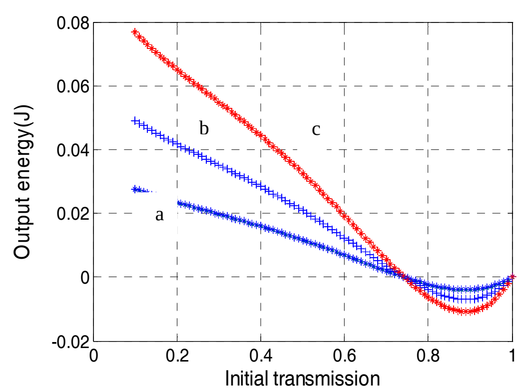

Fig. 5 Dependence of $E_{out}(J)$ on rod radius for different r values of (a) 0.15, (b) 0.2, and (c) 0.25.

III. Experimental Setup

To investigate the effect of parameters such as 1) reflectivity of the output coupler, R, 2) initial transmission of the saturable absorber, T_0, 3) diameter of the gain medium, d , and 4) cavity optical length, l, on the output parameters such as peak power, P , output energy, E ,and pulse-width, τ_P, we have used our homemade experimental arrangement as show in Fig. (6). In this figure we have utilized the corner cube as a back mirror (1), the Cr:YAG crystal as saturable absorber (2), the Nd:YAG (3) as a gain medium and finally the output coupler(4). We have used a flash lamp to pump the gain medium.

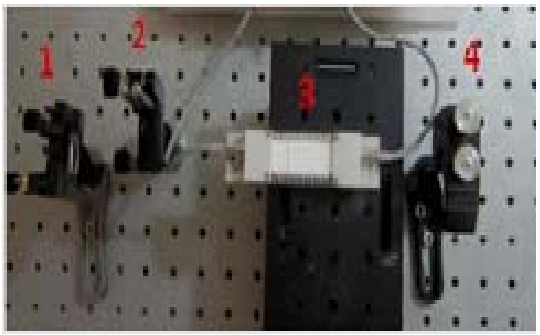

Fig. 6 Cr:YAG Q-switched Nd:YAG laser: 1- corner cube, 2- Cr:YAG, 3- Nd:YAG, and 4- output coupler.

We have used various rod diameter, and cavity length, and also different T_0, and R in these investigation, which are explained in the following three set ups.

A. *First Setup*

We have used the Nd:YAG rod with $d = 4\,mm$ and have measured the pulse width (FWHM) and the output energy for the output coupler of R=40%, 50% and the Cr:YAG with T_0=40%, and 50%. These results are demonstrated in table1.

We notice a significant change on output energy. As we can see by increasing T_0, pulse-width has been increased but output energy decreased. Also, by increasing R the output energy has been increased.

TABLE 1: LASER OUTPUT ENERGY (MJ) AND PULSE-WIDTH (NS) FOR VARIOUS R AND T_0, $d = 4\,mm$ AND $l = 45\,cm$.

Initial Transmission (T_0)	**50%**		**40%**	
Output Reflectivity (R)	50%	40%	50%	40%
Output Energy (mJ)	23	18	29	23
Pulse-width (ns)	18	17	17	16
Input Energy (J)	6	5	7	6

B. *Second Setup*

We have shortened the cavity length from 45cm to 30 cm and have repeated the above experiment and the results are summarized in Table 2.

The shortest pulse width that we have obtained in this set up was about τ_P=15ns and output energy was about E=31mJ.

TABLE 2: LASER OUTPUT ENERGY (MJ) AND PULSE-WIDTH (NS) FOR VARIOUS R AND T_0 $d = 4\,mm$ AND $l = 30\,cm$.

Output Reflectivity (R)		**50%**	
Initial Transmission (T_0)	60%	50%	40%
Input Energy (J)	5	6	7
Output Energy (mJ)	17	22	31
Pulse-width (ns)	16	16	15

C. *Third Setup*

We have investigated the effect of the diameter of gain medium on output energy. For this reason we have used the Nd:YAG rod with diameter of d=5mm instead of 4 mm. In this case due to high heat generation we have water cooled the rod. In this stage we have repeated the experiment as explained in first set up and we have attained the results as shown in Table 3. Again we tested the effect of reflectivity of the output coupler and initial transmission of the saturable absorber on output energy and pulse width just like first set up.

TABLE 3: LASER OUTPUT ENERGY (MJ) AND PULSE-WIDTH (NS) FOR VARIOUS R AND T_0, AND $d = 5\,mm$.

Initial Transmission (T_0)	**50%**		**40%**	
Output Reflectivity (R)	50%	40%	50%	40%
Output Energy (mJ)	30	25	41	38
Pulse-width (ns)	20	22	17	20

As the rod diameter increases, the output energy increases, which is due to the increasing the effective area in the gain medium (A).

Figs. 7 and 8 show the experimental values (shown as dots) and the theoretical prediction, (for only two values of output mirrors, R=40% and 50%). Unfortunately, future experimental data could not be achieved due to lake of required output mirrors. It is worth mentioning that in Fig. 7, for rod diameter of d=4mm we have analytically drawn output energy as a function of output reflectivity for different T_0=40%, and 50% corresponding to our experimental values (as labeled). In Fig. 8, we have repeated above but with the rod diameter of *d*=5 mm.

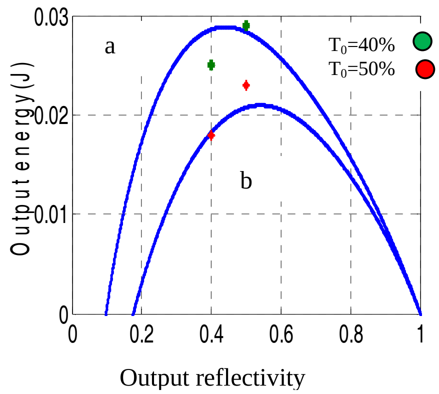

Fig. 7 Output energy as a function of output reflectivity for rod diameter 4mm: a) T_0=40%, b) T_0=50%.

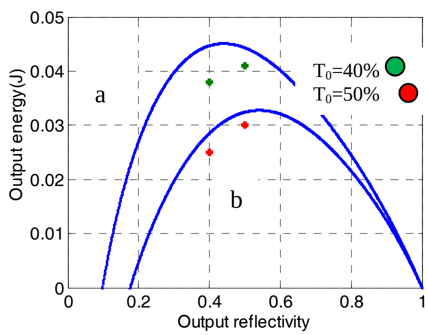

Fig. 8 output energy as a function of output reflectivity for rod diameter 5mm: a) T_0=40%, b) T_0=50%.

It is worth mentioning that in all these three set ups we have obtained our measurement on the basis of single pulse operation as indicated in Fig. 9.

On the other hand, by increasing the input energy, we have also observed output profile in the form of multi-pulse [2] as expected and is shown in Fig. 10.

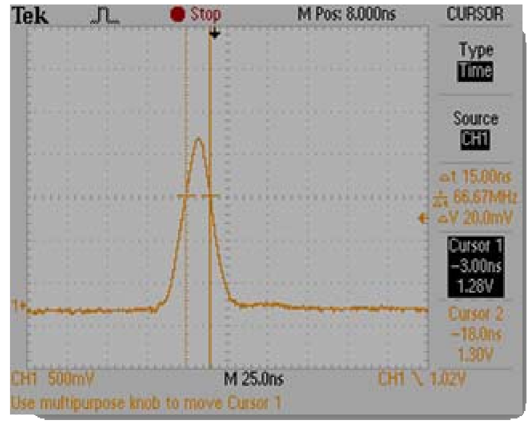

Fig. 9 Single pulse output τ_p =15ns.

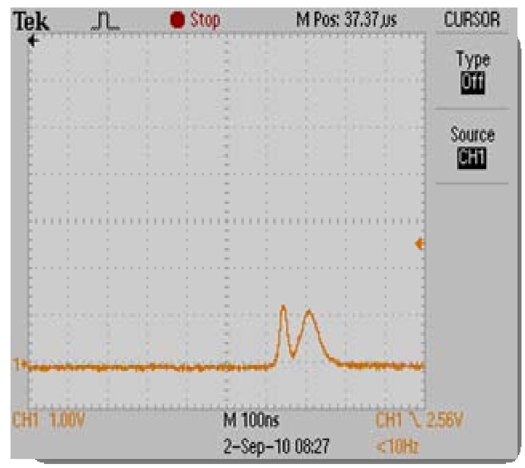

Fig. 10 Double pulse output.

The multiple spikes on Fig. 8 results from bleaching of the Cr^{4+} absorption centers in the Cr^{4+}:YAG samples, which then allows the buildup of a new population inversion in the laser rod while flash is pumping and this leads to establishing the conditions for a new spike. By increasing input energy the output energy has been increased suddenly and double pulse has been generated (Fig. 11).

Using corner cube as a back mirror leads to output profile seems to petal like and that is due to incident of light on vertex angle of corner cube prism as shown in Fig. 12.

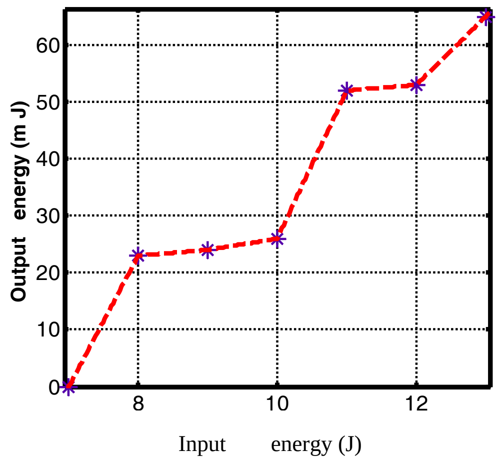

Fig. 11 Output energy vs. input energy.

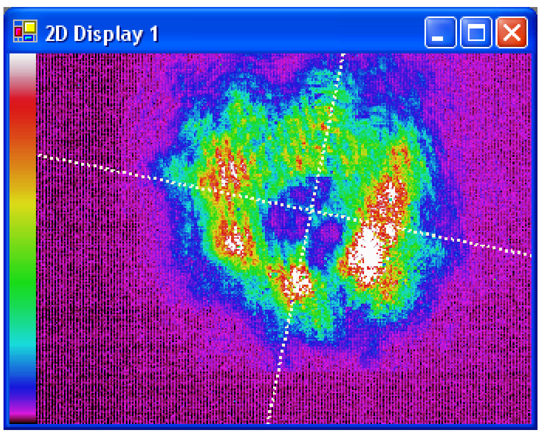

Fig. 12 Output beam profile.

IV. Conclusion

By using pulsed Nd:YAG passive Q-switched laser with Cr^{4+}:YAG crystal, we have investigated the influence of different initial transmission of saturable absorber, reflectivity of the output coupler, diameter of the rod, and optical length of the cavity theoretically and have obtained first and second condition to produce the giant pulses. Furthermore , we have introduced three experimental set up to investigate the influence of different initial transmission of the saturable absorber, reflectivity of the output coupler, diameter of the rod, and optical length of the cavity on pulse-width and output energy. The results agree well with those of theory predicted.

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