Nd:YAG laser continuous wave pumped, Q-switched by hybrid "passive-active" methods

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The output characteristics of a continuous-wave flash lamp pumped Nd:YAG laser, passively Q- switched by Cr^{4+}:YAG and LiF:F_2^- crystals, are reported. In order to control the small-signal transmission of the passive Q-switch a new method, which made use of a miniature laser placed out of the resonator, is described theoretically and proved experimentally. Further, the combination of a Cr^{4+}:YAG passive Q-switch and an acoustooptic Q-switch that work together in a Nd:YAG CW pumped laser was investigated. A transversal mode selection at low input power was outlined. With a two-rod resonator and a Cr^{4+}:YAG crystal as saturable absorber an average laser output power over 180 W was reached. The pulse to pulse stability was 1%.

Keywords: Nd:YAG laser; Cr^{4+}:YAG passive Q-switch; acustooptical Q-switch; small signal transmission

Se reportan las características de salida de un láser de Nd:YAG de onda continua bombeado por una lámpara de flash, *Q-switcheando* pasivamente por cristales de Cr^{4+}:YAG y LiF:F_2^-. Con el fin de controlar la transmisión de señal pequeña del Q-switch pasivo, se describe teórica y experimentalmente un nuevo método, el cual hace uso de un láser en miniatura colocado fuera del resonador. Además, se investigó la combinación de un Q-switch pasivo de Cr^{4+}:YAG y un Q-switch acusto-óptico que trabajan juntos en un láser bombeado de Nd:YAG de onda continua. Se describe una selección de modo transversal a baja potencia de entrada. Con un resonador de dos barras y un cristal de Cr^{4+}:YAG como absorbedor saturable, se alcanzó una potencia de salida láser promedio de más de 180 W. La estabilidad pulso a pulso fue del 1%.

Descriptores: láser de Nd:YAG; Q-switch pasivo de Cr^{4+}:YAG; Q-switch acusto-óptico; transmisión de señal pequeña

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1. Introduction

The Q-switched continuous wave (CW) pumped solid state lasers have proved in the last years to have a very large applications area. Pulses with high repetition rate (kHz range) and a high average and high peak laser power are very attractive for various applications as frequency doubling and material processing. On the other hand, multiwatt low energy nanosecond pulse sources are specially suitable for medical applications, where high peak powers should be avoided to limit deleterious effects such as plasma clouds formation. In these applications the beam quality and thus the brightness of the laser radiation is an important parameter.

The Nd:YAG systems usually use active Q-switching methods (electrooptical and acoustooptical) to obtain pulses with high repetition rate and large average output power [1, 2]. Although an active Q-switch is more complicated compared with a passive device, its flexibility is very high. That means that the available ranges for principal parameters of the laser pulse (peak power, repetition rate, average power) are large enough. Nowadays, there are on the market CW pumped Nd:YAG lasers, Q-switched by acoustooptical (AO) devices. This kind of Q-switch has negligible insertion losses. However its switching speed is a function of the beam diameter and the depth of modulation and it depends on the beam divergence inside the Q-switching device. Usually the Nd:YAG lasers with high average power present poor beam quality. Therefore, to obtain 100% modulation of the beam, the acoustic power used by the AO Q-switch should be very high which means expansive electronic driver. Further, inside the resonator with laser active media acting as variable thermal lens, the divergence and radius of the laser beam change under various pumping levels. Consequently, the output laser beam performance is not constant over the entire range of operation. Especially at high pumping power the AO Q-switch cannot shut off properly the photon flux within the resonator and part of the laser light is emitted in continuous wave between laser pulses.

The passively Q-switch lasers (PQS) have been of interest since their first successful operation. The passive Q-switch is switched by the laser intensity inside the resonator itself. Therefore this Q-switch is simple because there is no need for drivers but at the same time the flexibility in choosing laser parameters is low. As an example, the repetition rate cannot be changed if the input pumping power is constant.

The passive Q-switching (PQS) of CW pumped Nd:YAG laser is possible by using LiF:F_2^- colour centres crystals or Cr^{4+}:YAG crystals. Stable pulse-periodic laser operation at high repetition rate was obtained at low average output power by using colour centres crystals LiF:F_2^- [3–5].

Cr^{4+}:YAG crystal is a new potential saturable absorber with impurity centres characterized by a long time stability, a high optical strength and thermal conductivity, and good chemical stability. These crystals have been used as saturable absorbers in Q-switching of neodymium lasers [6–9]. Cr^{4+} ions in garnet seem to be stable whereas LiF:F_2^- passive Q-switch working in high average output power shows degradation with time [10]. A pulsed Nd:YAG laser with Cr^{4+}:YSGG passive Q-switch that deliver an average laser output power of 17.5 W in transverse multimode operation was reported in [11]. Eichler *et al.* obtained 13 W average output laser power when the Cr^{4+}:YAG crystal works as passive Q-switch in the Nd:YALO pulse pumped laser [12]. Both of the passive and active Q-switch methods offer advantages and have disadvantages. Using the active one, the repetition rate can be controlled by external driver, whereby for passive Q-switch the repetition rate is given by internal parameters of the laser. The passive Q-switch has higher residual losses and therefore the efficiency is lower than in the AO Q-switch. Some other disadvantages of passive Q-switch are the large fluctuations of laser pulse build-up time and intensity instability from pulse to pulse.

This work aims to improve performances of the Nd:YAG CW pumped lasers, passive Q- switched by Cr^{4+}:YAG crystal and LiF:F_2^- crystals. There are two ways to do this:

a) combining a passive Q-switch with the AO Q-switch (that work at low acoustic power) both placed into the laser resonator. This solution removes the main disadvantages of each Q-switch (large fluctuations of laser pulse build-up time and the intensity fluctuations for passive Q-switch, low depth modulation at high input laser pumping power for AO Q-switch) and preserves its advantages (flexibility, wide range of the peak power);

b) external control of initial transmission of the Cr^{4+}:YAG or LiF:F_2^- crystals by using an external laser pulse (delivered by a diode laser) as a "trigger" for the PQS; this method offers to PQS a large flexibility.

2. Crystals with saturable absorption at $\lambda = 1.064\,\mu$m: Cr^{4+}:YAG and LiF:F_2^-

Until several years ago, PQS was practically the only working with low average power lasers due to poor durability of the saturable absorbers then available. The saturable absorbers were based on different organic dyes or thin films of celulose acetate. The development of inorganic saturable absorbers revived the use of PQS.

2.1. Li:F_2^- colour centres crystals

The first report concerned with LiF:F_2^- color center crystal was published by Kalitsev *et al.* [13]. To describe the saturation process in this crystal a three level system was adopted. In this model first level is the ground state and the second and third ones, which involves a long lived level such that $1/\tau_{21} \rightarrow 0$ are excited states. Other relaxation times τ_{32}, τ_{31} are fast as compared with the duration of the investigation pulse.

F_2^- colour centres obtained by gamma, electron or neutron irradiation are characterized by broad absorption and emission bands centred at 300 K around 960 nm and 1170 nm, respectively. The F_2^- centres consist of two $\langle 100 \rangle$ neighbouring and anion vacancies binding three electrons. It is an example of defect with weak electron-phonon coupling showing pronounced zero- and one-phonon line absorption in the absorption and transmission bands up to relatively high temperature. Characteristic for this system is the absorption cross section at the Nd:YAG laser wavelength (1.5–2×10^{-17} cm^2), a lifetime of 70–100 ns at 300 K, good stability against both thermal destruction at room temperature and bleaching by $1.064\,\mu$m irradiation. The Li:F_2^- passive Q-switch has been characterized by a set of parameters as: (i) the small signal absorption coefficient α at $1.064\,\mu$m; (ii) the coefficient of residual losses β at $1.064\,\mu$m; (iii) the absorption coefficient γ at $1.3\,\mu$m which can be taken as a measure of losses which are not generated by F_2^- colour centres absorption. A variety of LiF: F_2^- saturable absorbers (0.31 cm^{-1} $< \alpha <$ 0.54 cm^{-1}) were used in our measurements.

2.2. Cr^{4+}:YAG crystal. Energy level diagram

YAG crystal belongs to an Oh point group with the symmetry order of 48. AlO_4 tetrahedral sites have S_4 symmetry. Cr^{4+} ions in fundamental configuration 3d2 are believed to occupy tetrahedral sites in the garnets [14]. The actual site symmetry is believed to be D_{2d}. This gives a $^3B_1$ ($^3A_2$) ground state, as shown in Fig. 1. The $^3T_2$ first excited state splits into $^3B_2$ and ^3E states. The $^3T_1$ second excited state splits into the $^3A_2$ and ^3E states.

The ^1E level splits in $^1A_1$ and $^1B_1$. The absorption of the radiation with wavelength $1.064\,\mu$m is made in the level ^3E ($^3T_2$). After the interaction, excitation relaxes by phonons interaction to the level $^3B_2$ ($^3T_2$) which relaxes by photon's emission. The quantum efficiency of the transition $^3B_2$–$^3B_1$ is poor (only 15%) at room temperature [15] and decreases with the temperature increasing. The strong phonon's interaction is responsible by small value of the quantum efficiency. Absorption energy balance at $1.064\,\mu$m follows: from 9400 cm^{-1} a part of 2600 cm^{-1} transformed in heat by phonons interaction ^3E–$^3B_2$; 85% from the rest (6800 cm^{-1}) is transformed in heat because of the quantum efficiency. Total energy losses are 89% which are converted in heat. By heating the crystal, the quantum efficiency decreases and

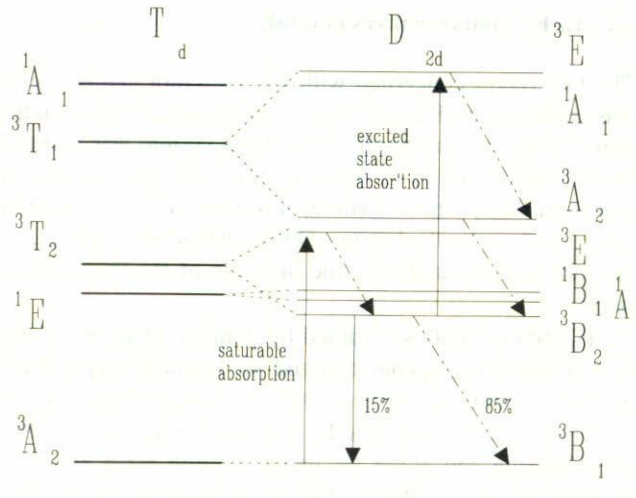

FIGURE 1. Cr^{4+}:YAG energy level diagram.

more heat is added to the crystal. This explanation does not take into account the excited state absorption ESA that appears between $^3B_2$ and $^3E(^3T_1)$ levels [16]. Relaxation of $^3E(^3T_1)$ level is supposed to be entirely phononical. The $^3B_2$ fluorescence lifetime, at room temperature, is approximately $\tau = 3.5\,\mu s$. The transition $^3A_2$–$^3E(^3T_2)$ has the cross section $\sigma_1 = 1.5 \times 10^{-18}$ cm^2 and the transition $^3B_2(^3T_2)$–$^3E(^3T_1)$ has $\sigma_2 = 1 \times 10^{-19}$ cm^2. As one can see from Fig. 1 a four level model can explain the saturable effects at 1.064 μm.

2.3. Physical characteristics of Cr^{4+}:YAG and LiF:F_2^- crystal

In our measurements four crystals of Cr^{4+}:YAG, which were cut from the same boule, were used. Their mechanical-optical properties are listed in Table I. The small signal absorption coefficient was calculated from small signal transmission and length data measurements with an accuracy better than 3%.

TABLE I. Optical data for Cr^{4+}:YAG used as passive Q-switch.

Length (mm)	Diameter (mm)	Small-signal Transmission %	Saturation Transmission %	Q-switch contrast $\ln T_0/\ln T_f$	Small signal absorption coefficient [1/cm]
1.00	6.1	90.5	98.5	6.60	0.998
1.20	6.1	88.9	98.6	8.34	0.98
1.50	6.1	85.5	98.3	9.13	1.04
1.75	6.1	83.6	98.1	9.33	1.02

TABLE II. Optical data for LiF:F_2^- used as passive absorber.

Length (mm)	Dimensions (mm)	Small-signal Transmission %	Saturation Transmission %	Q-switch contrast $\ln T_0/\ln T_f$	Small signal absorption coefficient [1/cm]
3.3	10 × 15	89.3	95	2.2	0.3436
4.85	10 × 15	85.7	94.5	2.7	0.3179
2.85	10 × 15	87.3	94.2	2.7	0.541
4.85	10 × 15	83.9	93.3	2.5	0.3614
3.5	10 × 15	87.5	94	2.15	0.3815
5	10 × 15	83.9	93.1	2.45	0.3506

The Cr^{4+}:YAG crystals are characterized by thermal conductivity = 0.13 W/cm/K; specific heat = 0.59 Ws/g/K; thermal diffusivity = 0.046 cm^2/s; thermal expansion = 7.5×10^{-6} K^{-1}.

Six samples of LiF colour centre crystal, whose data are listed in Table II, were also investigated. Thermophysical properties of LiF:F_2^- crystal with thermal conductivity = 0.14 W/cm/K; specific heat = 1.562 Ws/g/K; and thermal expansion = 28.1–34.8 × 10^{-6} K^{-1} were considered.

The intensity level required for the saturable absorption can be taken as the necessary value to make pumping rate equal to decay rate, and therefore the saturation intensity parameter I_s is: $I_s \approx (\sigma\tau_f)^{-1}$, [1]. That means, the Cr^{4+}:YAG crystal has $I_s = 1.9 \times 10^{17}$ photons/cm^2/μsec and LiF:F_2^- crystal has $I_s(\mathrm{LiF{:}F_2^-}) = 6.25 \times 10^{17}$ photons/cm^2/μsec. We can see that it is easier to obtain saturable absorption in Cr^{4+}:YAG than in LiF:F_2^- crystals. The second condition to have passive Q-switch in laser resonator is, $\sigma_{Nd}/\sigma_{\text{saturable-absorber}} < 1$ and this condition is also satisfied by both crystals.

3. Theory

3.1. Rate equations

The rate equations, that describe the Cr^{4+}:YAG Q-switch working together with an external controller (AOM or laser diode) in the laser resonator, have approximately the same form as the equations for passive Q-switching. Now, the timing phenomenon is governed by the repetition rate of external controller. That means, at the start of the giant pulse generating, the population inversion in the Nd:YAG crystal could be higher than the population inversion just before the start as passive Q-switch only. The peak power and repetition rate can be controlled separately.

$$\frac{dn_a}{dt} = -n_a\sigma_a c\varphi - \frac{n_a}{\tau_{fa}} + W_p(n_{a0} - n_a), \quad (1)$$

$$\frac{dn_s}{dt} = -\sigma_1 c n_s\varphi + \frac{n'_s}{\tau_{fs}}, \quad (2)$$

$$\frac{d\varphi}{dt} = \left\{2\sigma_a n_a l_a - 2\sigma_1 n_s l_s - 2\sigma_2 n'_s l_s - \left[\ln\frac{1}{R} + L\right]\right\}\frac{\varphi}{t_r}, \quad (3)$$

with

$$t_r = \frac{2l'_r}{c_0} = \frac{2[l_r + (l_a + l_s)(\eta - 1)]}{c_0}, \quad (4)$$

$$n_s = n_{s0} - n_s. \quad (5)$$

Here φ is the photon flux, w_p is pumping rate, l_a, l_s, l_r are the Nd:YAG rod length, passive Q-Switch length, and the optical resonator length; n_{a0}, n_{s0} are Nd^{3+} and Cr^{4+} ions concentrations; n_a, n_s and n'_s are the population inversions for $^4F_{3/2}$ Nd:YAG level, $^3A_2$ and $^3B_2$ Cr^{4+}:YAG levels; σ_a, σ_1, σ_2 are the cross sections for Nd:YAG and the respectively transitions $^3A_2$ to $^3T_2$ and $^3T_2$ to $^3T_1$ in Cr^{4+}:YAG; L represents the total optical losses in the resonator; τ_{fa} and τ_{fs} are the metastable level lifetime of Nd:YAG, respectively the $^3B_2$ ($^3T_2$) level lifetime in Cr^{4+}:YAG; c, c_0 and η are the light speed in YAG crystal and vacuum and the refractive index of YAG crystal. In the case of LiF:F_2^- crystal, Eqs. (1)–(5) are identical but the cross section coefficient $\sigma_2 = 0$.

When the losses inside the optical resonator are externally controlled, supplimentary equations that describe the population inversion at the start, n_{ai}, and at the end, n_f, of Q-switch operation have to be used, [1]:

$$n_{ai} = n_\infty - (n_\infty - n_f)\exp\left(-\frac{1}{\tau_{fa} f}\right), \quad (6)$$

$$n_\infty = w_p\tau_{fa}n_{\text{tot}}. \quad (7)$$

Here f is the repetition rate and w_p represents the pumping rate; n_{tot} is the density of Nd^{3+} ions and n_∞ is the maximum population density that can be achieved.

3.2. External control by laser diode

The key of the control method suggested by us follows: if the small signal transmissivity of the passive Q-switch located inside of the laser resonator is low enough to prevent laser oscillation at maximum active medium gain, only external action which increases the small signal transmissivity, allow laser oscillation.

Let's consider a passive Q-switch located inside of the laser resonator that has an initial transmission T_0 large enough to prevent the laser oscillation at the highest pumping level. Sending to the passive Q-switch an external laser pulse provided by a laser diode, one can increase the Q-switch transmission to the intermediate level. This increase of the transmission, which is produced by the saturable absorption of the crystal, happens during a limited time correlated with the lifetime of the metastable level (3.5 μs for Cr^{4+}:YAG and 70–100 ns for LiF:F_2^-). The highest efficiency of the saturation process is at 980 nm and 970 nm laser wavelength for Cr^{4+}:YAG and LiF:F_2^-, respectively.

The transmissivity changes under a short pulse irradiation, which have a photon energy $h\nu$ can be founded out by solving the following equation [17]:

$$\frac{dE}{dz} = -h\nu n_{s0}\left(\left(1 - \frac{\sigma_2}{\sigma_1}\right)\left\{\left[1 - \exp\left(-\frac{\sigma_1 E}{h\nu}\right)\right] + \frac{\sigma_2 E}{h\nu}\right\}\right) - \alpha E, \quad (8)$$

where E is the fluence and n_{s0} is the Cr^{4+} ions concentration, α is the absorption coefficient for nonsaturable absorption. Because of the large life time of $^3B_2$ level the decay to the ground state $^3B_1$ was neglected. In addition, the $^3T_1$(^{3}E) and $^3T_2$(^{3}E) relaxations following excited state absorption (ESA) were assumed to be fast compared with the 1.064 μm pulse duration [14].

As an example, Fig. 2 shows by continuous lines, the numerical solutions of Eq. (8) against some experimental data. Two Cr^{4+}:YAG crystals of 85% and 90% initial transmission at 1.064 μm and two LiF crystals with 84% and 89% initial transmission are represented. Numerical solving of the Eq. (8) is shown in Fig. 2a for Cr^{4+}:YAG, while Fig. 2b shows the results for LiF:F_2^- together with experimental data. In the case of LiF:F_2^- color centers Q-switch, the Eq. (8) is valid if $\sigma_2 = 0$.

Solving the Eq. (8) one can find out the fluency of the external pulse which produces the desired increase of the initial transmissivity T_0. The time scale of the saturation process is slow compared with the transit time of the light across the 1–5 mm crystal length. Then the saturation phenomenon for the excited state population, n, and the photon flux at the position

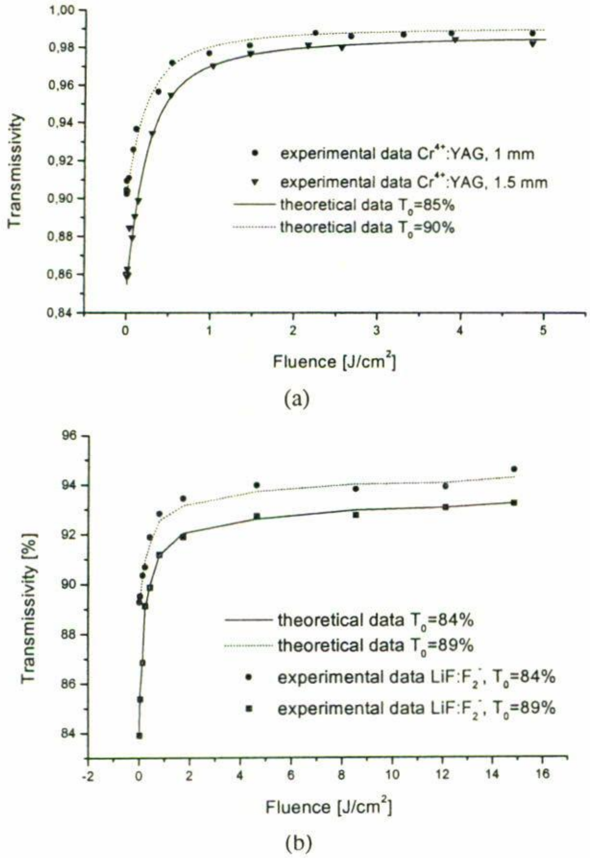

FIGURE 2. Experimental data (signs) and theoretical curves of Eq. (8) (continuos and dot lines) for (a) two Cr^{4+}:YAG crystals and (b) two LiF:F_2^- probes.

x in the material, $I(x,t)$ can be written as [18]

$$\frac{\partial n}{\partial t} = n_s \sigma_1 I(x,t) - 2n(\sigma_1 + \sigma_2) I(x,t) - \frac{n}{\tau_f}, \quad (9)$$

$$\frac{\partial I}{\partial t} = 2n\sigma_1 I(x,t) - n_s \sigma_1 I(x,t). \quad (10)$$

Here τ_f is the fluorescence lifetime of the excited level. Again for LiF:F_2^- the cross section coefficient $\sigma_2 = 0$.

Following the procedure described in Ref. 19 one can obtain the time dependence of the transmissivity for the phototropic crystals irradiated by a laser pulse.

The integral transmission T_r which is defined as a ratio between the total energy of the transmitted pulse and that of incident one, can be estimated by

$$T_r = \frac{\int f(\tau) T(\tau)\, d\tau}{\int f(\tau)\, d\tau}, \quad (11)$$

where the integration is performed over the incident pulse duration. The function $f(\tau)$ take into account that the temporal behaviour of the $T(\tau)$ leads to a distorsion of the transmitted pulse. We can see from the Figs. 2a and 2b that large temporarily changes in small signal transmissivity can be induced by irradiation with small fluence laser pulses centred on the absorption band of YAG:Cr^{4+} and LiF:F_2^-, respectively. The transmissivity rises very rapidly with the laser fluence.

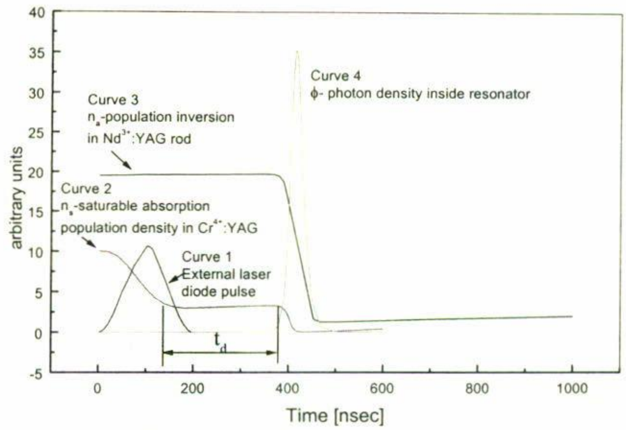

FIGURE 3. Schematic representation of the timing for external control of the passive Q-switch.

A typical solution of Eqs. (1)–(5) is shown in Fig. 3. Let's consider that the initial transmission of the Q-switch is high enough to prevent the laser oscillation. Nevertheless, when an external laser pulse (curve 1) is incident on the Q-switch, decreases of the n_s saturable absorption population (curve 2) results. The new value n_s' for saturable population density, which will be used in Eqs. (2) and (3), allows now starting laser oscillation (curve 4) in the laser resonator. First, the increase of initial transmissivity allows the photon flux to increase in the laser resonator. That will produce a larger increase of the passive Q-switch transmission and the laser oscillations start bleaching the Q-switch up to its final transmissivity. In this way an external small energy diode laser pulse can control the Q-switch operation in the high power Nd:YAG laser CW pumped. The laser pulse is produced after a delay time, t_d, required for laser pulse to build-up, delay that depends, generally, on the population inversion. In addition, an external pulse of high energy will permit laser oscillations for a large range of pumping level.

Two aspects of this Q-switch method are worth to be discussed. First, if the initial transmissivity is increased in a controlable volume of the Q-switch located around the optical axis, only the laser modes which have the gain higher than losses will oscillate. That means the TEM_{00} operation can be performed following the described procedure. Further, because the initial loss inserted by Q-switch is high, the laser pulses are produced only when the external control pulse is incident on the passive Q-switch. That means the threshold level for laser oscillation can be externally controlled. Second, the repetition rate of the Q-switch pulse is under control by changing the laser diode repetition rate. Here, for a given pumping rate w_p, this repetition rate is controlable until a maximum value that results from Eq. (6). Evidently, increases of repetition rate will diminish the laser pulse energy.

The model has one restriction: because of the laser pulse build-up time, which in our case is larger than 200 nsec, the passive Q-switch should sustain the intermediate transmission level longer than this value. A large lifetime on excited level is an advantage here.

3.3. External control by AO Q-switch

As already was mentioned an acoustooptic modulator (AOM) can not produce an extinction rate of 100% for every pumping level and any repetition rate. At a high pumping level the laser requires a minimal repetition rate in order to avoid the continuous laser emission between pulses [2]. By the other hand a passive Q-switch will produce laser pulses which have a repetition rate that depends on the pumping power [20, 21]. That means the energy per pulse cannot be increased when the pumping power is increased. Also, for a passively Q-switched system, the laser emission has a large jitter that is inconvenient during some applications.

Coupling an acoustooptic modulator with a passive Q-switch crystal, which work together in the same resonator will eliminate these disadvantages. Now, because the cumulated losses inside of the resonator are large enough to prevent laser oscillations at the highest pumping level, the laser emission will appear only when the AOM is commanded.

The energy per pulse will be higher than in the case of each Q-switch working alone. The numerical solution of the rate equation gives a pulse energy a little bit higher for the new system. One can determine the minimal pumping level in order to allow laser emission; this level depends very much on the initial transmission of the saturable absorber.

4. Experimental results

4.1. External control by laser pulse

The Cr^{4+}:YAG crystal with a small signal transmissivity of 85% was used to verify the idea presented in Sec. 3.1. The experimental set-up is presented in Fig. 4a. A RK5720 Power Ratiometer and a RJ7100 Energymeter measured the laser output power and laser pulse energy, respectively. The pulse duration was measured by a PBX-65 photodiode with 2 ns risetime and a LeCroy 9450 oscilloscope. Using a CCD camera system, we made the measurements on beam quality. The external pulse wavelength was 1.064 μm. In our scheme the external laser pulse doesn't pass through the Nd:YAG laser crystal so there is no injection seeding phenomenon. We used this wavelength because of the experimental facility, but diode laser which emits at 980 nm was already used to pump Cr^{4+}:YAG laser [17]. Then, a combination of Cr^{4+}:YAG and a diode laser as in Fig. 4b can provide a small, reliable and flexible Q-switch system.

Figure 5 presents typical variations of the control signal by curve 1 and laser output pulse by curve 2. The laser pulses build-up time is $\sim 1\,\mu$s and depends on the pumping level. Then the Cr^{4+}:YAG crystal, which has 3.5 μs saturable level lifetime, is suitable for this purpose; meantime same experiments on LiF:F_2^- crystals failed because of its shorter lifetime of saturable level. The pulse duration was 328 nsec. On the same figure the laser pulse was expanded (curve 3) in order to show the temporal mode structure. The spatial hole burning in the passive absorber, which has a relaxation time of 3.5 μs, explaines this temporal behaviour. By changing the pumping power, pulses with controllable energy between 1 and 11 mJ were obtained. The repetition rate, which is given by the repetition rate of the external pulses, was limited to 10 Hz by the thermal effects in Cr^{4+}:YAG. A proper cooling system for

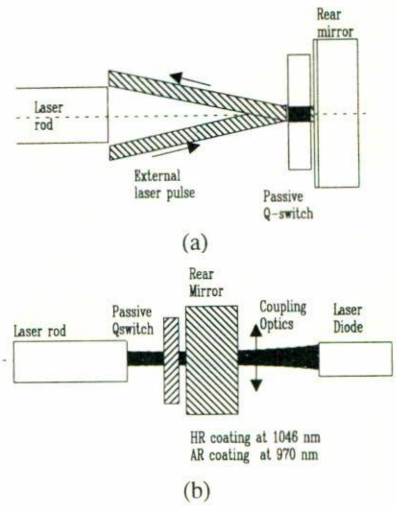

FIGURE 4. (a) The experimental setup for external control of the passive Q-switch by an external laser pulse of 1.064 μm wavelength. (b) This scheme is simplified by using a diode laser (970 nm wavelength).

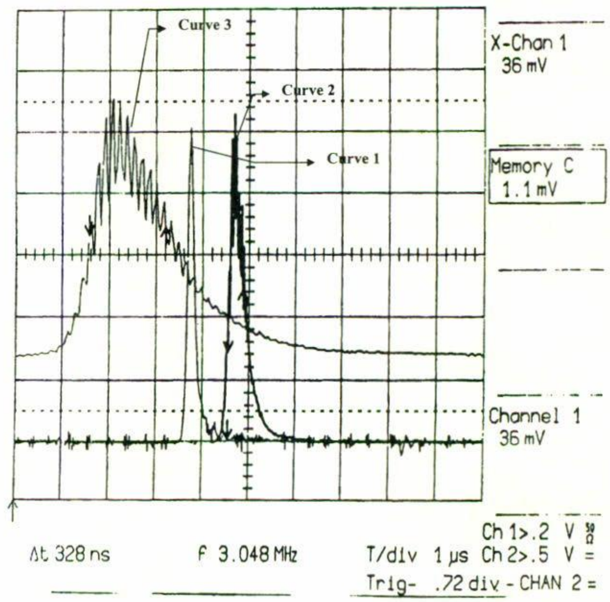

FIGURE 5. Variations of the external laser pulse (curve 1) and the output laser pulse (curve 2) in a passively Q-switch laser. Curve 3 shows the output pulse at an expanded scale. The arrows on the curve 3 indicate the FWHM which is of 328 ns.

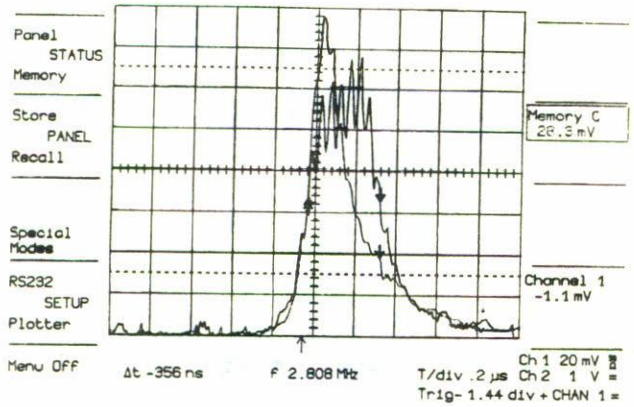

FIGURE 6. Typical output laser pulse fluctuations in CW pumped, passively Q-switch Nd:YAG laser.

for the Q-switch will increases this value. The minimum external pulse fluence that still switch the laser was 0.13 J/cm^2, which in our case means 1 mJ pulse energy on 1 mm spot size.

4.2. External control by an AO Q-switch

The experimental results on a CW pumped Nd:YAG laser that was Q-switched by (i) a passively Q-switch and (ii) a combination of passively Q-switch with an acoustooptic modulator are presented in this section. Three crystals of Cr^{4+}:YAG with small signal transmission between 83% and 90.5% and saturation transmission of 98% to 98.5% were investigated. A Nd:YAG rod with 4 mm diameter and 100 mm length was pumped by a flash lamp in a diffuse pumping cavity (SPECTRON laser head). The flat-flat symmetric resonator with 0.5 m length was used.

The input power threshold for the passive Q-switch laser operation was found to be $\sim$ 3.5 kW. By using the Cr^{4+}:YAG with the small signal transmission of 90.5% up to 40 W average output laser power was obtained. The laser pulses repetition rate increased from 1.5 to 12 kHz by increasing the pump power from 3.5 kW to 6 kW. Pulse width was 150 nsec and it had 13% variations from the average value that remaines relatively constant when pumping power increases. Typical pulse to pulse variation for the same input power is presented in Fig. 6. Increasing the pump power resulted in smoothing of the pulses and fluctuations decreasing.

The far field intensity distributions for passive Q-switch at pump powers of 3.7 kW and 5.1 kW are shown in Figs. 7a and Fig. 7b, respectively. An increasing in the number of transversal modes by pumping power increasing is observed. The beam parameter product changes from 5.42 mm x mrad corresponding to the 3.7 kW pump power to 6.3 mm x mrad corresponding to the 5.1 kW pump power. The time fluctuations between two Q-switched pulses were in the range 10–35 μs and increased by increasing the input power.

In order to eliminate these fluctuations an AO Q-switch was added into the resonator. Figure 7c shows the far field distribution for this case corresponding to a pump power of 5.1 kW. The beam parameter product was 6.9 mm x mrad and it increased because the modes with higher order are allowed to oscillate when the higher inversion population is achieved. In this configuration the stability became better than 1% and Fig. 8, which shows two pulses superimposed, proves that. Three LiF:F_2^- probes with the small signal transmission of 85.7%, 87.3% and 89.3% and a final transmission of 94.5%, 94.2% and 95% were also considered. However, the LiF:F_2^- crystals were working well only at low repetition rate. The nonsaturable absorption of 5% for Li:F_2^-, larger than that of Cr:YAG that was 1.5%, led to crystal heating. Compared with Cr:YAG, a higher working temperature resulted for Li:F_2^- at high repetition rates that could destroy the saturable absorption phenomenon.

(a) (b) (c)

FIGURE 7. Far field distribution of the laser intensity for the passively Q-switch laser at a pump power of (a) 3.7 kW and (b) 5.1 kW. (c) Inserting an AOM in resonator the beam distribution resulted at 5.1 kW pump power.

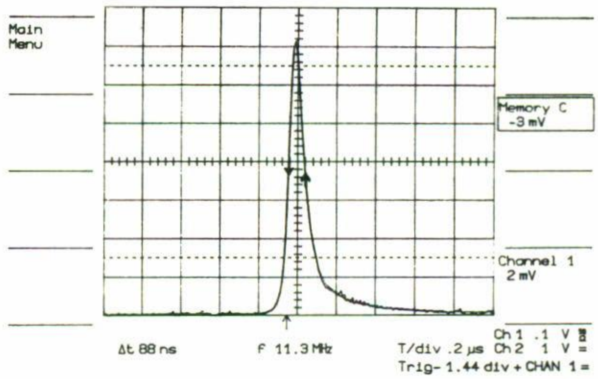

FIGURE 8. Two output laser pulses were superimposed to prove a very good stability in the case of the pasivelly Q-switch that works together with an acoustooptical modulator.

The peak power *versus* input power for the combination of AOM with two different Cr^{4+}:YAG crystals is presented in Fig. 9. Also, Fig 10 shows the pulse width *versus* input power for various combinations of Q-switching. The shortest pulse width is the same for AOM and AOM + passively Q-switch. However, for certain range of repetition rate the AOM cannot assure 100% loss modulation in the resonator. Then a CW emission was measured and the pulse energy, which is presented in Figs. 11 and 12, diminish correspondingly.

The power scaling of this system was demonstrated in a two Nd:YAG rod resonator. Over 180 W average output

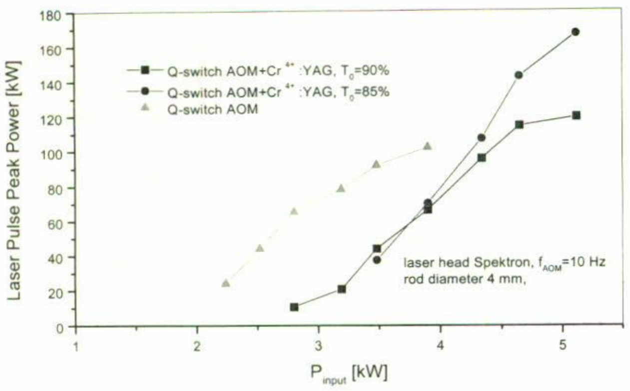

FIGURE 9. The laser peak power as a function of pump power at two values of the Cr^{4+}:YAG initial transmissivity.

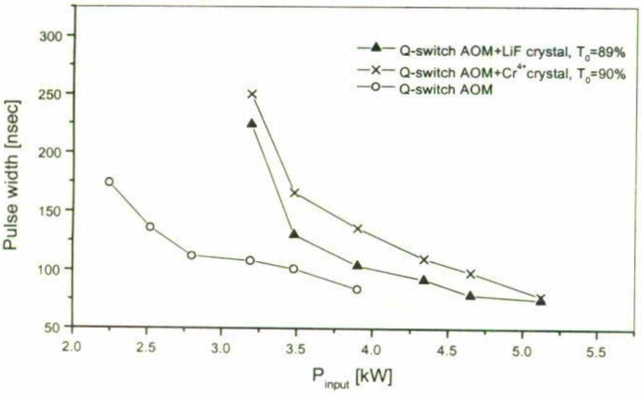

FIGURE 10. Pulse width as a function of pump power when the Cr:YAG and LiF crystals were used.

power was obtained at 15.3 kW input power, when the Cr^{4+}:YAG crystal of 90.5% initial transmission was used. Further, inserting the AO Q-switch into the Nd:YAG laser resonator together with Cr^{4+}:YAG Q-switch, insignificant decreases of the output power were obtained. The pulse to pulse stability was very good and the pulse energy was increased at lower frequency.

5. Conclusion

The concept of "passive-active" Q-switch method, developed for two directions, was presented theoretically and proved experimentally. The control of the small signal transmission by a laser diode eliminate the main disadvantage of the passive Q-switch: the repetition rate fluctuations.

The applications field for this method seems to be large. The complicated and expensive electrooptical Q-switches used in laser range finders can be replaced by simpler de-

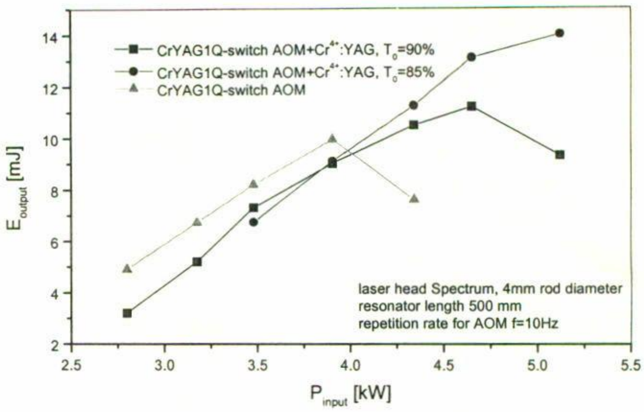

FIGURE 11. Laser pulse energy as a function of pumping power at two different values for initial transmission (90% and 85%) of Cr:YAG passive Q-switch.

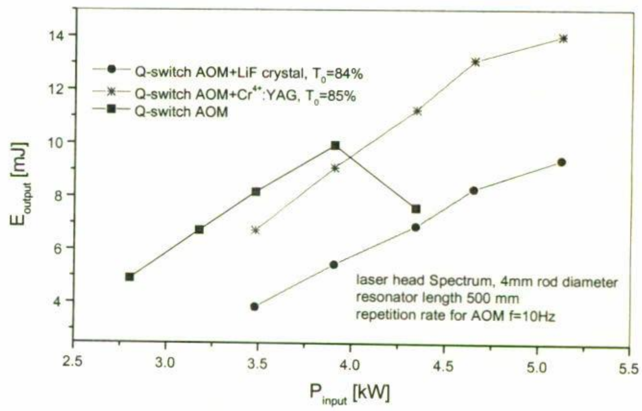

FIGURE 12. Laser pulse energy as a function of pump power for Q-switching by an AOM, a combination of AOM and Cr:YAG crystal of 85% initial transmission and a combination of AOM and LiF crystal of 84% initial transmission.

vices. Also for applications as laser scribing where the repetition rate is necessarily to be kept constant this Q-switch method should be a cheaper alternative to AOM Qswitches.

The second method of the external control, which is passive Q-switch+AOM presents the advantage of increasing the laser pulse energy for high power-high repetition rate Nd:YAG CW pumped laser. The experimental results obtained with the Cr^{4+}:YAG crystal used as passive and active-passive Q-switch in Nd:YAG lasers are described.

The average laser output power over 180 W was obtained in two rod CW Nd:YAG laser passive Q-switched by Cr^{4+}:YAG. The output power can be scaled to the kW range by using a long Cr^{4+}:YAG crystal with low density of phototropic Cr^{4+} ions that is more suitable for cooling. The intensity stability of the laser pulse is very good.

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