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High repetition rate, V^{3+}:YAG crystal Q-switched diode pumped Nd lasers

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The high repetition rate passively Q-switched neodymium host lasers operating at 1 µm wavelength pumped by a 10-W fibre-coupled diode laser are presented. As a passive Q-switch the V^{3+}:YAG crystal was applied. The V^{3+}:YAG parameters were determined in spectroscopic and saturable transmission experiments. A numerical model taking into account short recovery time of V^{3+}:YAG ~5 ns and excited state absorption was used to analyse such a laser. The thermal lensing magnitude and performance were determined in free running experiments for two Nd:YAG rods of different quality and Nd:YLF crystal. The smooth Q-switched pulses with repetition rates of 40–200 kHz were obtained in short linear cavities of a length less than 11 cm. The highest average power of 1.4 W with slope efficiency of 20% was demonstrated in Nd:YAG laser. Long pulse durations of hundreds ns and low pulse energy of a few µJ (up to 24 µJ in the best case) were caused by low value of the ratio of the absorption cross section of V^{3+}:YAG to emission cross section of Nd:YAG. The much higher pulse energy of 70 µJ with pulse duration of 80 ns was obtained in lower gain Nd:YLF laser in a cavity of 140 mm length with internal lens of 50 mm focal length.

Keywords: diode pumped lasers, passive Q-switching.

1. Introduction

The high repetition rate, kW peak power, compact, pulsed, near infrared lasers operating at 1 µm wavelength are required in a wide range of applications including environment sensing, laser marking, telecommunication, medical diagnostics, measurement techniques, range finding, frequency conversion, OPO and Raman laser pumps, etc. The simplest and the most efficient lasers emitting in this spectral range are neodymium (Nd) host lasers pumped by diode lasers. The best hosts with respect to maximum cw output power are Nd:YAG [1,2], Nd:YLF [1–3], $Nd:YVO_4$ [1,2,4] crystals, however, efficient output at 1 µm was demonstrated in Nd:SFAP [5], $Nd:GdVO_4$ [6], and Nd:KGW [7] lasers as well.

The efficient and low cost method of Q-switching in this wavelength range is till now the subject of interest and intensive research. Electro-optic or acousto-optic Q-switches usually applied in bulk high gain lasers are difficult to use in compact diode pumped microlasers. Application of semiconductor Fabry–Perot saturable absorbers (SESAM) (see Refs. 8 and 9) as passive Q-switches is feasible for such type of lasers, however, it is limited to a relatively low energy and peak power because of their low damage threshold. One of the newest and promising method of Q-switching is application of saturable photonic quantum dot crystal [10] as a passive Q-switch. Such a device can be designed for any spectral range, however, its technology is nowadays at the early stage of development.

The simplest approach is Q-switching by means of a bulk saturable absorber. The best, to our knowledge, passive Q-switch for such a wavelength range is Cr^{4+}:YAG crystal [11], although several other saturable absorbers as

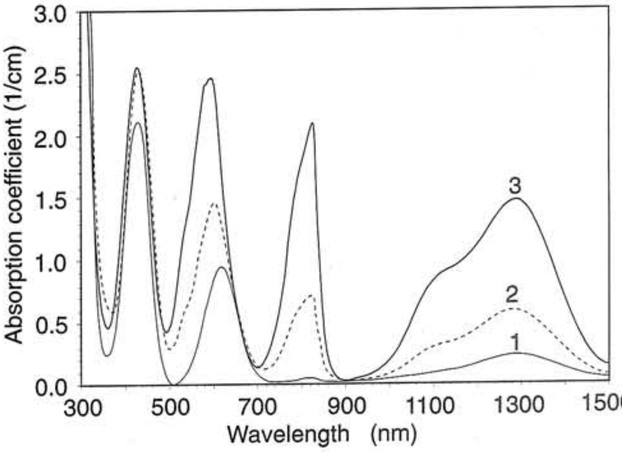

Fig. 1. Three absorption curves for the different stages of crystal „improvement"; 1 – crystal "as grown", 2 and 3 – after two thermo-reduction processes in a solid phase.

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Cr^{4+}:forsterite, Cr^{4+}:GGG [12] or V^{3+}:YAG [13] are also feasible. The relatively new material V^{3+}:YAG crystal [14–19] exhibits saturable absorption in a wide spectral range. The Q-switching and mode locking with V^{3+}:YAG crystals were demonstrated at 1.064 μm wavelength, at first in lamp pumped lasers [15]. The first investigations on diode pumped V^{3+}:YAG passively Q-switched laser were carried out by Malyarevich *et al.* [18] in 1998. The parameters of V^{3+}:YAG crystals are compared with Cr^{4+}:YAG ones in Table 1.

The aim of this work was to examine such type of a crystal for Q-switching of Nd lasers pumped by 10 W fibre-coupled diode laser. In Section 2, the analysis and characterisation of V^{3+}:YAG crystal is presented. The estimation of influence of the excited state absorption (ESA) and a short (comparable to cavity round trip time) recovery time on performance of such a laser was given in Section 3. In Section 4, we have examined two active media (Nd:YAG, Nd:YLF) in free running and passively Q-switched lasers. In the last Section, the conclusions were drawn.

2. Characterisation of V^{3+}:YAG crystal

A spectrum of absorption of vanadium ions doped YAG crystals was examined for the first time in 1971 by Weber and Riseberg [20]. They found four bands of significantly different intensities, in the absorption spectrum within the range of 300–1400 nm, that were classified according to a valence of absorbing ion and its position in a lattice. In a lattice of garnet crystal, vanadium can have all its valences V^{5+}, V^{4+}, V^{3+}, and V^{2+}. As it was shown in Refs. 14, 18, and 19, only the band originating from V^{3+} and V^{4+} ions has been evidenced in experiments.

It was stated, that saturable absorption of V^{3+}:YAG occurs for the wavelengths of 1340, 1064, 780, and 747 nm. From the point of view of passive Q-switching the crucial parameters of saturable absorbers are the ground state absorption (GSA) cross section σ_{GSA}, ratio of the ESA to GSA cross section defined as $\beta = \sigma_{ESA}/\sigma_{GSA}$ and the recovery time τ. Additionally, the level of a parasitic absorption can influence performance of such a modulator, increasing the total cavity losses δ. A comparison of the properties of V^{3+}YAG to Cr^{4+}:YAG absorbers is given in Table 1.

For V^{3+}:YAG crystal the most controversy is connected with a recovery time. At first, it was stated from the spectroscopic measurements in Ref. 14 that it is about 5 ns. Malyarevich *et al.* showed in Ref. 18, applying the probe beam of pulse duration of 15 ps, that recovery time is about 22 ns.

The level of parasitic non-saturable losses depends on technology of growth and thermo-chemical treatment of V^{3+}:YAG samples. Here, the main task consists in increase in V^{3+}:YAG concentration with simultaneous decrease in parasitic absorption. V^{3+}:YAG crystals with V^{3+} ions concentration of about $(1.0–1.5)\times10^{18}cm^{-3}$ have been obtained by means of the Czochralski method at the Institute of Technology of Electronic Materials in Warsaw [19]. During a crystallisation process, as a result of introduction of vanadium atoms dopants into $Y_3Al_5O_{12}$ structure, V^{3+} ions substitute Al^{3+} in the octahedral or tetrahedral lattice points. During the crystal growth only a small part of vanadium atoms is introduced into a crystal structure as V^{3+} ions in tetrahedral positions, the other ones are still at different positions or at the higher charge state V^{4+} and V^{5+}. Receiving the vanadium ions of V^{3+} valency, which will be in the desired points of YAG structure, can be possible as a result of the complex reactions in a solid-state phase. These reactions occur during the process of a multi-stage crystal burning in the reducing atmosphere and in a vacuum [19].

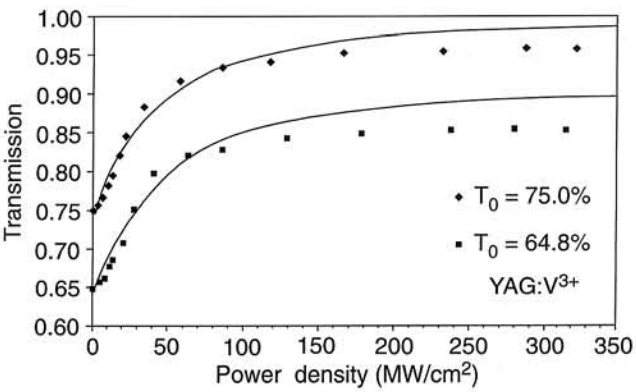

Fig. 2. *LambertW* function applied for approximation of measurement results of transmission as a function of power density of incident laser radiation obtained for V^{3+}:YAG non-linear absorbers for wavelength 1064 nm.

Table 1. Spectroscopic data of V^{3+}:YAG and Cr^{4+}:YAG crystals for wavelengths 1.064 and 1.3 μm.

Crystal	Cr^{4+}:YAG	V^{3+}:YAG
Absorption cross section at 1.06 μm ($10^{-19}cm^2$)	30	25
Absorption cross section at 1.34 μm ($10^{-19}cm^2$)	n.a.	72
Recovery time (ns)	3600	5 [14]/22 [18]
ESA to GSA cross section ratio at 1.064 μm	0.1	0.05
ESA to GSA cross section ratio at 1.3 μm	n.a.	0.1

Investigations on the parameters of V^{3+}:YAG crystals of various V^{3+} ions concentrations were carried out on the basis of analysis of bleaching process dynamics (Fig. 2). If the relaxation time of an absorber $\tau << t_n$, where t_n is the duration of a diagnostic pulse, an absorber is of "fast" type and the dependence of the saturable transmission T(I) describes the equation formulated by Keyes [21] and Hercher [22]

$$(1-T)^{-1}\ln\frac{T}{T_0}=\frac{I}{I_S}, \tag{1}$$

where T_0 is the initial transmission (for small signals), I is the power density of incident radiation, I_S is the power density of saturation determined as

$$I_S=\frac{h\nu}{2\sigma\tau}, \tag{2}$$

where τ is the lifetime of excited absorber, σ is the absorption cross-section, h is the Planck's constant, ν is the laser frequency

Relationship (1) can be solved numerically or analytically using special *LambertW* ≡ W(x) function [23–25], which is defined as a solution of equation

$$W(x)\exp[W(x)]=x. \tag{3}$$

Analytical solution of Eq. (1) is given by

$$T=\frac{I_S}{I}\,LambertW\left(T_0\frac{I}{I_S}\exp\left(\frac{I}{I_S}\right)\right). \tag{4}$$

The changes of transmission of the examined samples as a function of power density of passing radiation emitted by a monopulsed Nd^{3+}:YAG laser were determined in experiments. A power density of diagnostic pulse (t_n = 10 ns) was changed within the range 5–400 MW/cm^2. Figure 2 presents the example of application of *LambertW* function for approximation of measurement data of transmission dependence as a function of power density of incident laser radiation wavelength of 1064 nm obtained for V^{3+}:YAG samples of the initial transmission of 64.8% and 75%.

From the above experimental results (Fig. 2), applying approximation method with *LambertW* function, the value of power density of saturation $I_s = 7.5 \pm 2$ MW/cm^2 was determined. Such a value is in well accordance with the spectroscopic data of the absorption coefficient (see Fig. 1) and the data given in Refs. 17 and 18.

To obtain the efficient Q-switched pulses for such "fast" saturable absorber the ratio α of absorption to the emission cross section of gain medium should be much greater (>10) than in a case of Cr^{4+}:YAG "slow" absorber. Such a condition is fulfilled only for few Nd doped active media operating at 1 µm wavelength (see Table 2).

Table 2. Parameters of neodymium doped gain crystals at wavelength 1 µm. σ_{em} is the emission cross section, τ is the fluorescence lifetime of upper level, κ is the thermal conductivity, σ_{GSA} *is the GSA cross section of* V^{3+}*:YAG at 1.06 µm* (25×10^{-19}cm^2).

Gain media	$\sigma_{em}10^{19}$ (cm^2)	τ (µs)	κ (W/K/m)	$\alpha = \sigma_{GSA}/\sigma_{em}$
Nd:YAG	3.5	230	14	7.1
Nd:GGG	2.9	200	12	8.6
Nd:YAP	2.4	148	11	10.4
Nd:YLF	2.1	570	8	11.9
Nd:YVO_4	15.6	100	5.1	1.6
Nd:$GdVO_4$	7.6	94	11.7	3.3
Nd:SFAP	5	220	2	5.0
Nd:KGW	3.7	120	3.8	6.8
Nd:YAB	10	60	4	2.5
Nd:BEL	1.5	106	16	16.7
Nd:LSB	1.3	145	3	19.2

3. Modelling of passively Q-switched laser

The main difference of V^{3+}:YAG crystal comparing to typical passive Q-switches (as Cr^{4+}:YAG) is much shorter recovery time. As it was mentioned in Section 2, the inconsistency in evaluation of the recovery time of V^{3+}:YAG exists (5 ns in Ref. 14, 22 ns in Ref. 18). For longer cavities of several dozens of cm this value can be comparable to round trip time. In such a case the commonly used approximation of "slow" Q-switch (Refs. 26 and 27) is not valid yet. Thus, we decided to model such a passively Q-switched laser and examine numerically its performance. Our numerical model gives the same results for "slow" Q-switches as classical models (see Refs. 26 and 27) for which the analytical solutions for pulse energy and pulse duration were found. We have assumed small (in a roundtrip scale) changes of internal flux and occupations of the excited levels. Moreover, the effects of spatial variations of pump and mode beams and diffusion of inversion density are omitted. We included the effect of ESA, with the given, very short (1 ns) relaxation time of II excited level of Q-switch, into the model. The effects of depletion of ground state of gain medium and Auger's energy transfer up-conversion (ETU) [28,29] were included as well. Thus, after some normalisation with respect to cavity round trip time and population of a ground state of Q-switch we have started with the following set of four ordinary differential equations (usually called rate equation set) describing temporal phenomena in such a laser

$$
\begin{aligned}
\frac{d\Phi}{dt} &= [a_1 n_1 + a_0(1-(1-\beta)n_2 - n_3) - \delta - \rho]\Phi, \\
\frac{dn_1}{dt} &= -a_2 n_1 \Phi + P_p(N - n_1) - \frac{n_1}{\tau_0} - a_{Ag} n_1^2, \\
\frac{dn_2}{dt} &= a_3[1-(1+\beta)n_2 - n_3]\Phi - \frac{n_2}{\tau_1} + \frac{n_3}{\tau_2}, \\
\frac{dn_3}{dt} &= a_4 b n_2 \Phi - \frac{n_3}{\tau_2},
\end{aligned} \tag{5}
$$

where the independent variable t is the time divided by the cavity round trip time, $t_r = 2l_r/c$, l_r is the cavity length, c is the light velocity, Φ is the internal flux averaged over round trip, n_1 is the relative occupation of II level of active medium, n_2 is the relative occupation of II (I excited state) level of saturable absorber, n_3 is the relative occupation of III (II excited state) level of an absorber. Each relative occupation is normalised to ground state occupation of the absorber $N_{0,sa}$. In Eq. (5), depletion of ground state of active medium is included by pump reducing factor $(N - n_1)$, $N = N_{0,am}/N_{0,sa}$ is the ratio of ground level occupations of the active medium $N_{0,am}$ and the saturable absorber $N_{0,sa}$, $\tau_0 = \tau_{em}/t_r$ is the relative lifetime of II level of active medium, $\tau_1 = \tau_{GSA}/t_r$ is the relative lifetime of I excited level of saturable absorber, $\tau_2 = \tau_{ESA}/t_r$ is the relative lifetime of II excited level of saturable absorber, $\beta = \sigma_{ESA}/\sigma_{GSA}$ is the ratio of absorber ESA to GSA cross sections, P_p is the pumping rate, δ is the logarithmic round trip passive losses of cavity, $\rho = \ln(1 - T_{OC})$ is the transmission loss of output coupler of transmission T_{OC}.

The first coefficient a_0 denotes double pass small signal losses of the saturable absorber as follows

$$a_0 = -2\ln(T_0), \tag{6}$$

where T_0 is the initial transmission of passive Q-switch.

The remaining coefficients a_i are determined as follows

$$
\begin{aligned}
a_1 &= \frac{a_0 l_{am}}{\alpha l_{pq}}, \quad a_2 = \frac{\gamma_{em} a_0 l_{cav}}{\alpha l_{pq}}, \\
a_2 &= \frac{\gamma_{abs} a_0 l_{am}}{l_{pq}}, \quad a_4 = \beta \alpha_3,
\end{aligned} \tag{7}
$$

where $\alpha = m\sigma_{GSA}/\sigma_{em}$ is the ratio of the absorber GSA cross section to emission cross section of active medium multiplied by the mode magnification; $m = A_{am}/A_{sa}$ is the ratio of mode areas in gain medium and saturable absorber; l_{am}, l_{pq} are the lengths of active medium and absorber; γ_{em}, γ_{abs} are the inversion reduction factors of active medium and absorber, respectively. For 4-level scheme lasers and linear cavity we take both reduction factors equal to 1. Length of absorber was determined from initial transmission and given small signal absorption coefficient α_{abs} according to formula $l_{pq} = a_0/2\alpha_{abs}$. Auger's up conversion coefficient a_{AG} is related to, the known in literature, up-conversion rate parameter γ_{ETU} (see Refs. 28 and 29) as follows

$$a_{AG} = \gamma_{ETU} N_{0,sa} t_r. \tag{8}$$

Usually two types of solutions of the rate equations set [Eq. (5)] are analysed:

- "constant pump rate" type. The initial conditions (for t = 0) are the following:

$$
\begin{aligned}
\Phi &= \varepsilon, \\
n_1 &= 0, \\
n_2 &= 0, \\
n_3 &= 0.
\end{aligned} \tag{9}
$$

- "constant initial gain" type. We pose the following initial conditions:

$$
\begin{aligned}
\Phi &= \varepsilon, \\
n_1 &= (a_0 + \delta + \rho)a_1^{-1}, \\
n_2 &= 0 \\
n_3 &= 0
\end{aligned} \tag{10}
$$

where ε denotes the initial noise fluctuation of flux (we take $\varepsilon = 10^{-8}$ for calculations).

The first, more general type enables estimations of pulse energy and duration, repetition period and average power. In such a case the effects of inversion saturation, Auger's ETU can be studied. However, it is much more time consuming in calculations. Moreover, the results (i.e., mode of generation and its parameters) depend on the definite pump rate level. Typical examples of the solutions of I type are given in Fig. 3.

It was found in numerical experiments, that ETU effect can influence performance of Q-switched lasers only for Q-switches of low initial transmissions. The main effect of ETU in such a case consists in elongation of repetition period. The changes of pulse parameters are of the second order. Such result can be explained by a simple model of shortening of gain medium lifetime proposed in Ref. 28. Thus, in the following analysis the ETU effect was neglected.

The "constant gain" type of solution can be treated as a particular case of the first type of solution in which we start calculations from the point where initial gain is equal to cavity losses. Let us note that second relation in Eq. 10 can be rewritten in a well-known form (see Ref. 30)

$$2g_0 l_{am} = a_1 n_1 = a_0 + \delta + \rho. \tag{11}$$

Such approach is appropriate for analysis of optimal coupling, loss mechanisms, etc. Because typical lifetimes of the upper level of an active medium are much longer than the pulse build up and passive Q-switch recovery times, the relaxation term in the rate equation set [Eq. (5)] can be ne-

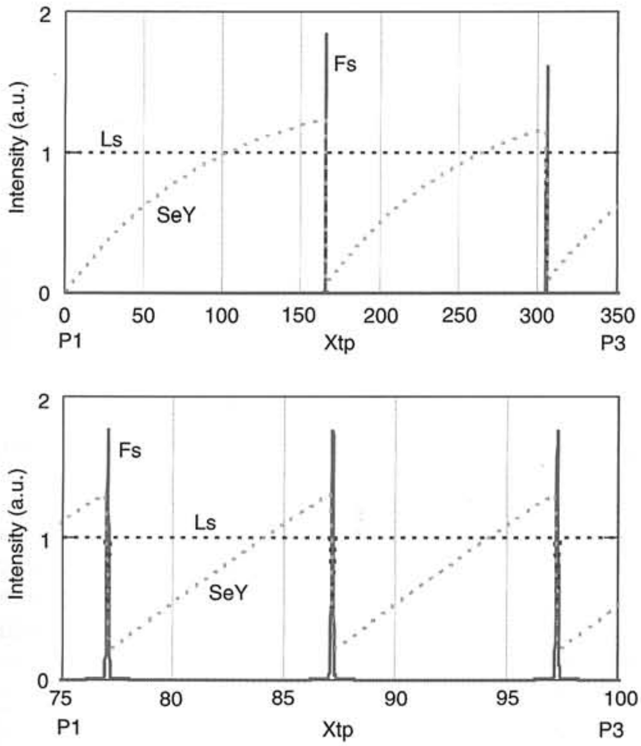

Fig. 3. Q-switching pulse formation in dependence on time, "constant pump rate" case; low $\alpha = 10$ – upper plot, high $\alpha = 100$ – lower plot, internal flux – continuous curves, relative inversion – dashed curves.

glected for "constant gain", whereas it should be considered for "constant pump rate". Let us note, that initial gain value should be determined for definite cavity with passive Q-switch inside. The round trip gain, achievable in cavity without passive Q-switch, can be different (as a rule higher) than the adequate initial gain in the cavity with Q-switch because the passive Q-switch modifies confocal parameter as the results of additional thermal lensing and acts as an amplitude soft diaphragm, lowering M^2 and gain simultaneously.

The absorption to emission cross section ratio α is the crucial parameter in optimisation of laser with "slow" as well as "fast" passive Q-switch. To obtain the same output energy for the given gain and passive losses level, the value of α should be much higher for "fast" Q-switch case comparing to "slow" Q-switch case. For our scope of interest the values of ratio α (see the last column in Table 2) starts from about 2 for $Nd:YVO_4$ laser and achieves about 20 for Nd:LSB.

3.1. Influence of ESA and round trip time on the output energy

In the first part of numerical analysis we intend to find the difference in performance of Q-switched laser, predicted by our model, with respect to "slow" passively Q-switched laser. Thus, we investigated the influence of the cavity round-trip time t_r and the level of ESA β on the output energy of the laser for the same pumping rate and passive losses. For small β and the cavity round trip time, much shorter than the recovery time of Q switch ($\tau_1 >> 1$), the model gives the same results as analytical solution of a passively Q-switched laser [26].

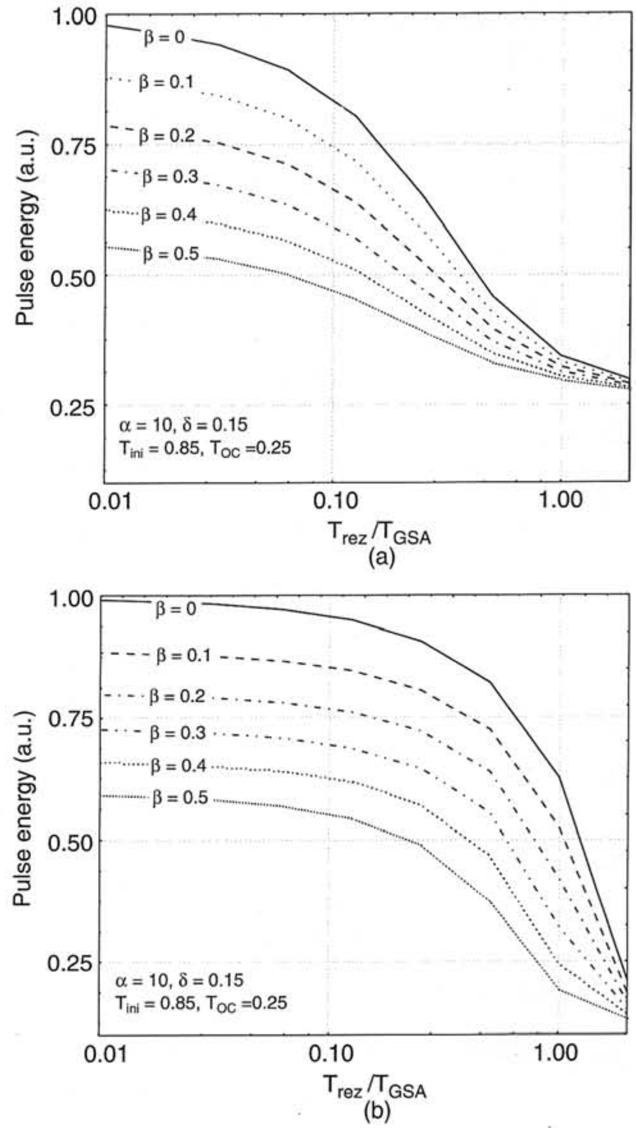

Fig. 4. Normalised pulse energy in dependence on the ratio τ_{GSA}/t_r for several ESA: (a) $T_{ini} = 0.85$, $\rho = 0.15$, $T_{OC} = 0.25$, $\alpha = 10$; (b) $T_{ini} = 0.85$, $\rho = 0.15$, $T_{OC} = 0.25$, $\alpha = 100$.

The difference between the results given by our model (see Fig. 4) and a "slow" Q-switch model increases with increase in β and t_r/τ_{GSA}. For short cavities, the ESA losses influence in the same way as any other type of losses causing drop of the output energy. With increase in roundtrip time the loss mechanism is dominated by a spontaneous decay of I excited level of Q-switch. It results in significant (more than 4–5 times) drop of the output energy, independent on ESA level. With increase in α value, the output energy in long cavities ($t_r/\tau_{GSA} \sim 1$) decreases to the lower level because the relative change of saturable losses is higher in such a case.

3.2. Influence of transmission losses on the output energy

To maximise the output energy in such a laser we should find the appropriate combination of the initial transmission of Q-switch and OC transmission for the given level of cavity losses and initial gain. Because the initial transmission and OC transmission should satisfy the initial condition [Eq. (11)] (gain = passive losses + initial saturable losses) we have only one independent variable, e.g., OC transmission.

The problem of optimisation of such a laser is similar to the problem of optimisation of the laser with "slow" passive Q-switch solved in Refs. 26 and 27. It was shown in numerical simulations that the same value of initial transmission (or OC transmission) maximises the output energy for "fast" as well as for "slow" passive Q-switch (see Fig. 5).

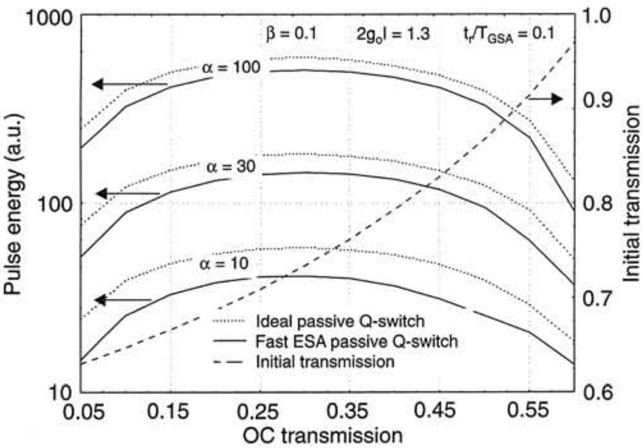

Fig. 5. Dependences of output energy on OC transmission for several values of α.

As it was mentioned earlier, the "constant gain" case is appropriate rather for optimisation purposes. More close to our experimental situation is the case of "constant pump rate". In experiments for different initial transmission of Q-switch we have different values of initial gain, pulse energy, pulse power, and repetition rate. The results of numerical simulation of such a case are shown in Fig. 6.

Let us note that for the both cases the output energy approximately linearly increases with the ratio α. Moreover, for the short cavities ($t_r << \tau_{GSA}$), the influence of ESA (non zero value of β) is approximately the same as an additional level of passive losses. Thus, we can conclude that the predictions of analytical model of optimisation of a passively Q-switched laser can be also applied for "fast" Q-switches with ESA losses, however, limited to the rather short cavities.

4. Passive Q-switching experiments

All experiments of passive Q-switching were carried out in linear cavities (Fig. 7). As a pump unit, 10 W fibre coupled diode (FCD) SDL 3950 P was used. The pump wavelength was controlled by thermoelectric cooler (TEC). The pump

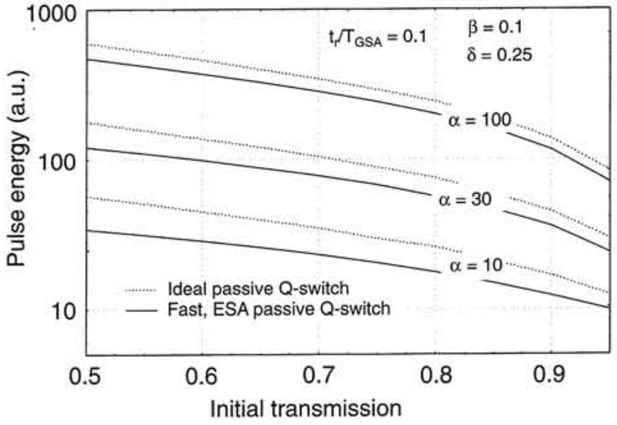

Fig. 6. Dependences of output energy on initial transmission of passive Q-switch for several values of α.

beam, after passing through the coupling optics (CO), was focused in the laser crystal (LC) to waist of 600-μm diameter. To exploit an effect of geometrical magnification the saturable absorbers (SA) were located in the vicinity of the flat output coupler (OC).

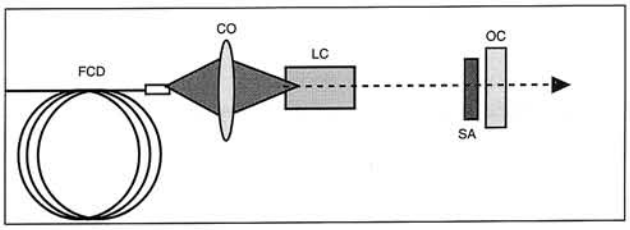

Fig. 7. Scheme of end-pumped passively Q-switched laser.

We have checked three gain crystals (Nd:YAG, Nd:YLF and Nd:YVO_4) in free running as well as passive Q-switching experiments. Although quite efficient Q-switching was achieved in a case of vanadate laser applying Cr^{4+}:YAG as a modulator, the same regime of operation was not achieved with V^{3+}:YAG. We concluded, according to a numerical modelling given in Section 3 that the reason was too small cross section ratio α for a pair (V^{3+}:YAG , Nd:YVO_4).

4.1. Free running experiments

The best results, but markedly different comparing to our experience with Cr^{4+}:YAG absorbers, were obtained for Nd:YAG lasers. In the first part of the experiments we have optimised the cavity parameters in a free running mode. It was found in theoretical analysis [31] and confirmed in numerous experiments that for high pump power densities performance of end-pumped laser is determined by pump induced diffraction losses. To minimise this effect the proper size of pump volume and the cavity length should be found. Two Nd:YAG rods with nominal 1% at dopant level were investigated. The both crystals were wrapped with indium foil and held in the same water-cooled copper heat sink. Their parameters and results of free running performance were summarised in Table 3.

Table 3. Parameters of Nd:YAG lasers in a free running mode.

Rod No	Size	Thermal lensing at 12 W of pump	Maximum output power (W)	Slope efficiency (%)	Round trip gain at 12 W of pump
1	ϕ 4×10 mm	16 D	4.1	43	0.85
2	ϕ 3×5 mm	8 D	4.7	47	1

It was found that for a pump beam of 12 W of incident power the thermal lensing optical power was about 16 D for rod No 1 and only 8 D for rod No 2. Because performance of thermal contacts of both rods was similar, such large difference in thermal lensing magnitude is caused mainly by the difference in pumping efficiency. We suppose that the first rod has much higher "dead site" concentration causing decrease in laser performance and huge increase in thermal lensing. However, as it will be shown further, these properties can be advantageous for passive Q-switching. For the better case (rod No 2), the cavity passive losses were 0.026 and an available round trip gain for the maximum pump power of 12 W was $2g_0l \cong 1$. The M^2 of such a laser, operating in a free running mode, was about 4 (for the cavity length of 35 mm). Increasing cavity length to more than 70 mm, TEM_{00} beam with the output power of 4 W was achieved. Moreover, due to shortening of the Rayleigh range, the magnification of the mode areas between SA location and laser crystals increased. For the Nd:YAG rod No 1 the maximum output power was 4.1 W for a short cavity. Despite much stronger thermal lensing of 16 D in this case, also satisfactory TEM_{00} output beam (~3 W) in a cavity of 70 mm length was obtained.

4.2. Passive Q-switching experiments for Nd:YAG lasers

As a result of thermal lensing effect the mode magnification m increases with a pump power. Thus, the different conditions of passive Q-switching occur for different pump power values. The results of measurements for the Nd:YAG rod No. 1 were shown in Figs. 8 and 9 and for the second one in Figs. 10 and 11.

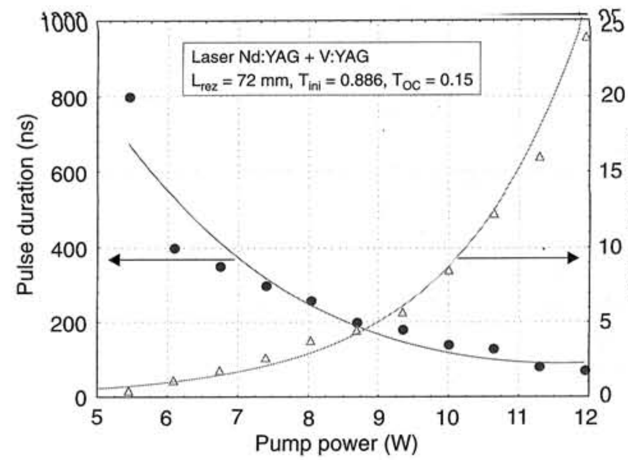

Fig. 9. Pulse energy and pulse duration vs. pump power for passively Q-switched Nd:YAG laser, (rod No 1).

We have used the uncoated samples of V:YAG inclined at a Brewster angle. Such configuration reduces $n_{YAG} = 1.8$ times the parameter α what results in worse performance of Q-switching. Let us notice that for the known initial gain (about 1) much higher initial saturable losses should be feasible. However, we have found that for Q-switches with lower transmissions, the performance of Q-switching was much worse as a result of significant increase in residual (non-saturable) parasitic losses of our modulators.

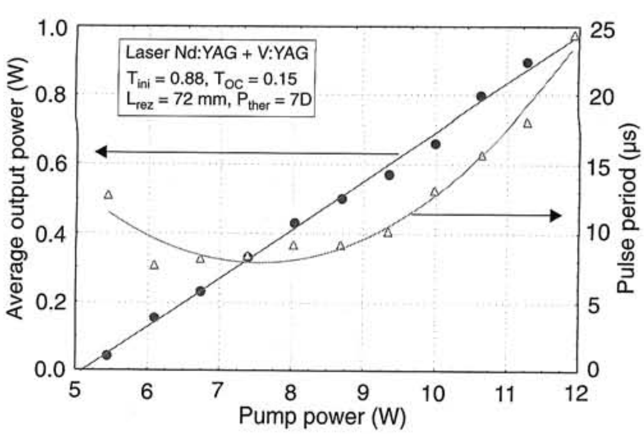

Fig. 8. Average output power and pulse repetition period vs. pump power for passively Q-switched Nd:YAG laser (rod No. 1).

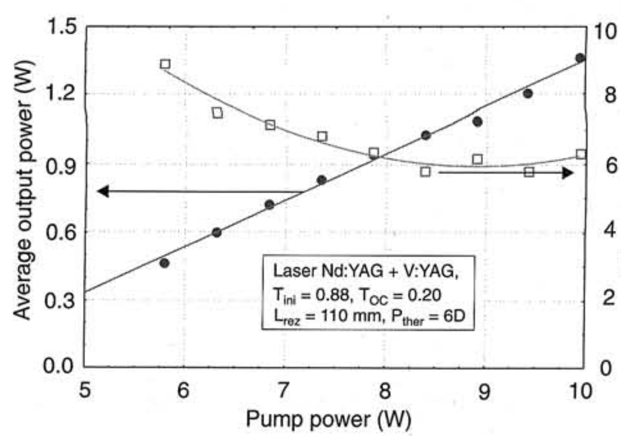

Fig. 10. Average output power and pulse repetition period vs. pump power for passively Q-switched Nd:YAG laser (rod No. 2).

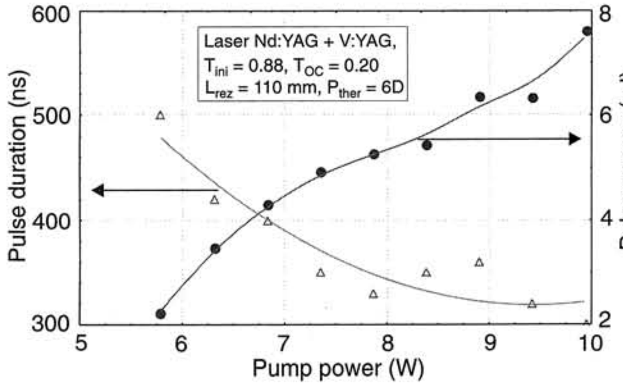

Fig. 11. Pulse energy and pulse duration vs. pump power for passively Q-switched Nd:YAG laser, (rod No 2).

The pulse duration was of a few hundred ns and the repetition rate was of 60–200 kHz for rod No. 2. For rod No. 1 (of stronger thermal lensing) both pulse duration and repetition rate were lower comparing to previous ones. As a rule, the pulse energy increased with pump power for both cases. As it was shown in Figs. 9 and 11, the acceptable pulse energy is achieved for the maximum pump power. Surprisingly, the higher pulse energy (24 µJ) was achieved for rod No 1 in the shorter cavity.

We observed satisfactory stable pulsed generation with temporal jitter less than 10% for the best cases only for high pump power. For the low pump powers, the chaotic generation with much longer pulse duration and temporal jitter >30% was observed as a rule.

These results, markedly different comparing to the well known experience with "slow" saturable absorbers, are caused mainly by changing a magnification factor. We conclude that the parameter α should be greater than 10 for efficient Q-switching with V:YAG.

As it was expected, the output generation was in a fundamental transverse mode. We have checked the longitudinal mode content by means of a Fabry-Perot interferometer (Fig. 12). It was found that each pulse is generated in a single longitudinal mode, similarly as it was observed for Cr^{4+}:YAG Q-switched Nd:YAG diode pumped laser [11,32]. However, the spectrum averaged over several pulses consists of three modes separated on about 17 GHz. Thus, some mechanism of longitudinal mode selection exists.

4.3. Passive Q-switching experiments for Nd:YLF laser

Our fibre coupled diode laser was not destined to Nd:YLF pumping thus, lower absorption efficiency, higher threshold, and lower overlapping efficiency were achieved in such a laser comparing to Nd:YAG one. To match a pump wavelength to an absorption peak of Nd:YLF (~806 nm), the low TEC temperature of 1–3°C was required. To stabilise pump generation for such a low temperature we should cool it very intensively using TEC. We have found that only for quasi-cw regime of pumping, with the duty factor less than 50%, it was possible to obtain a required pump wavelength for the maximum pump current.

Because of negative thermal dispersion of Nd:YLF crystal, the additional internal lens of 50 mm focal length was inserted into the cavity. The Nd:YLF rod of 8×15 mm sizes was aligned in such a way that due to linear polarisation, enforced by V:YAG sample inclined at a Brewster angle, the generation at 1047 nm wavelength was achieved. Moreover, because of bad quality of Nd:YLF crystal and its much lower thermal conductivity, the high thermal aberrations occurred.

The results of passive Q-switching examination in Nd:YLF laser were presented in Figs. 13 and 14. The performance of Nd:YLF laser in free running as well as passive Q-switching regimes were much worse comparing to Nd:YAG ones.

5. Conclusions

The uncoated, inclined at Brewster angle, passive Q-switches, made of V^{3+}:YAG crystal grown in the Institute of Electronic Materials Technology were used in the experiments. Two different Nd:YAG rods with higher and lower thermal lensing were used as active media. As a

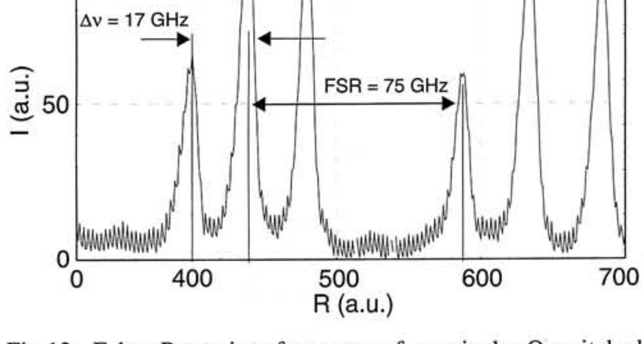

Fig.12. Fabry-Perot interferogram of passively Q-switched generation of Nd:YAG laser.

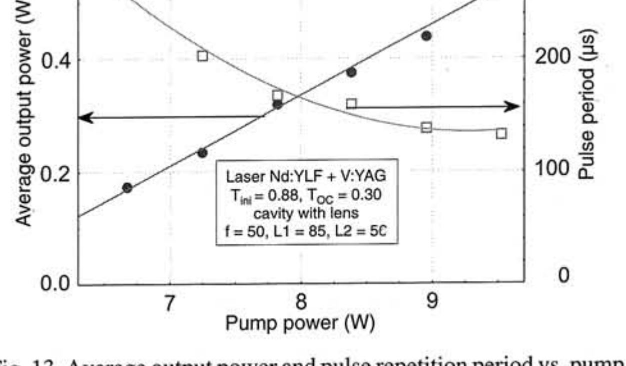

Fig. 13. Average output power and pulse repetition period vs. pump power for passively Q-switched Nd:YLF laser.

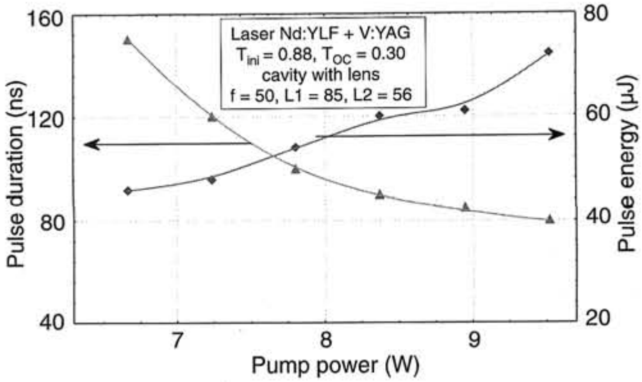

Fig. 14. Pulse energy and pulse duration vs. pump power for passively Q-switched Nd:YLF laser.

pump, 10 W fibre coupled diode SDL 3450-P5 was applied. We designed cavity consisting of Nd crystal wrapped with the indium foil and mounted in water-cooled copper heat sink and passive Q-switch located in the vicinity of a flat output coupler.

We have found in numerical modelling and verified in the experiments that the parameter α should be higher than 10. This parameter, for the pair of (V^{3+}:YAG, Nd^{3+}:YAG), is about 7, thus, we obtained long pulses with low energies. Nevertheless, in such a laser with a Nd:YAG rod of lower thermal lensing of 8 D, about 1.4 W of averaged output power was obtained with a slope efficiency 20%. Pulse energy were a few μJ, pulse duration a few hundred ns, and repetition rates of above 100 kHz, respectively. For the Nd:YAG rod of higher thermal lensing (about 16 D for maximum pump power), the mode magnification m significantly increased, resulting in quite well parameters of the pulses (24 μJ pulse energy and less than 100 ns pulse duration). However, the lower output power of 1 W, with the slope efficiency of 14%, were obtained because of higher intrinsic losses of this gain medium.

For comparison we have carried out the same experiments for Nd:YLF laser, for which the parameter $\alpha = 12$. In this case, a cavity with internal lens was applied because of negative thermal dispersion of Nd:YLF refractive index for s-polarisation (i.e., 1047 nm line). We observed true passive Q-switched regime with higher pulse energy and much lower repetition rates < 10 kHz in this laser. The highest pulse energy was 70 μJ, but only 0.5 W of the average output power was obtained in this case because of bad quality of Nd:YLF rod.

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