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Optimization of a passively Q-switched Nd:YAG laser with a saturable absorber characterized by excited state absorption (ESA)

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Mathematical description of a passively Q-switched laser and the way it works are presented. Both theoretical and experimental model of this laser have been worked out. Moreover, numerical analysis of saturable absorber influence on laser efficiency was made. It is the saturable absorber characterized by excited state absorption (ESA) that has been taken into account. The optimization procedure points to the optimal circumstances of the laser system considered. The results obtained numerically are in very good agreement with those achieved experimentally.

Keywords: solid state lasers, passive Q-switching, saturable absorber, numerical simulation.

1. Introduction

Q-switching of Nd:YAG lasers is widely applied in scientific research and for practical applications using active or passive devices. Active Q-switching methods (mechanical, electro-optic and acusto-optic) are usually used in Nd:YAG systems to obtain pulses with high repetition rate and high average output power [1]. The technique of active Q-switching is rather complicated but the advantage is that the repetition rate is independent of pumping power. The alternative technique of laser losses switching is the application of a saturable absorber whose transmission changes with the internal laser flux intensity. In this technique, a material with high absorption at the laser wavelength is placed inside the laser resonator and prevents laser oscillation until the population inversion reaches a value exceeding the total optical losses (dissipative losses, saturable absorber losses, transmission losses) inside the laser cavity. As the photon density builds up following achievement of a net positive inversion, passive absorber rapidly bleaches into a high transmission state, thereby Q-switching the laser.

There are some advantages and disadvantages of both passive and active Q-switches. By using an active Q-switch, the repetition rate can be controlled by an external driver, whereas for a passive Q-switch the repetition rate is given by the internal parameters of the laser. The passive Q-switch is initiated by the laser intensity inside the resonator itself. Therefore, this Q-switch is simple – there is no need for drivers but, at the same time, there is reduced flexibility in choosing laser parameters. This means that it is not possible to change the repetition rate for a given input pumping power and absorber transmission. At high depth of modulation the residual losses are also high and therefore the efficiency is low. Other disadvantages of a passive Q-switch are the large build-up of time fluctuations and the intensity instability from pulse to pulse. However, compared with active Q-switching methods, passive techniques that use saturable absorbers can significantly simplify the operation and the alignment, improve the reliability and the compactness, and reduce the costs of laser sources.

Recently, a Cr^{4+}:YAG as a Q-switched element used for Nd:host lasers has attracted considerable attention [2], [3]. It is superior to the traditional Q-switched saturable absorbers (Kodak dyes, celluseacetate thin films or LiF:F_2 crystals, *etc.*) for such reasons as: its excellent thermal and optical properties, large absorption cross-section, high damage threshold and no degradation. Therefore, it is reasonable to believe that Cr^{4+}:YAG is an ideal saturable absorber as passive Q-switch for all high power, high repetition rate solid state lasers.

2. Rate equations for passively Q-switched Nd:YAG lasers

Passive Q-switching is currently the most attractive method of generation of nanosecond and subnanosecond laser pulses. The main characteristics of a Q-switch are as follows: concentration of absorption centers, ground state absorption (GSA) and excited state absorption (ESA) cross-sections, lifetimes of the upper levels. To design the passively Q-switched laser properly we should know all these parameters as well as the potential gain in the lasing medium (LM) and its scatter losses. There are some works [4], [5] where the problem of design and optimization of passively Q-switched lasers with saturable absorbers (SA) exhibiting ESA was solved. However, in these works the solutions were limited to the case of the so-called "slow absorber". In this paper, a detailed analysis of passively Q-switched lasers is made based on the normalized dimensionless rate equations taking into account: ESA and lifetimes of SA levels as well as the magnification in the laser cavity.

The case where a saturable absorber is characterized by only one excited state seldom occurs in nature. In reality, a saturable absorber is usually characterized by more than one excited state to which molecules from ground state are transported. The molecules which are located in excited state can be transported even to higher excited levels (on condition that the energy gap of adjacent excited levels equals the energy of absorption quantum). This situation is depicted in Fig. 1. The parameters marked in this figure are as follows: n_0, n_1, n_2 – population density of the ground state, the first and the second excited states, respectively, σ_{a1} – absorption cross-section from the ground state to the first excited state of SA, σ_{a2} – absorption cross-section from the first to the second excited state of SA, τ_1, τ_2 – lifetime of the first and the second excited states, respectively, α_1, α_2 – deactivation coefficient of SA centers

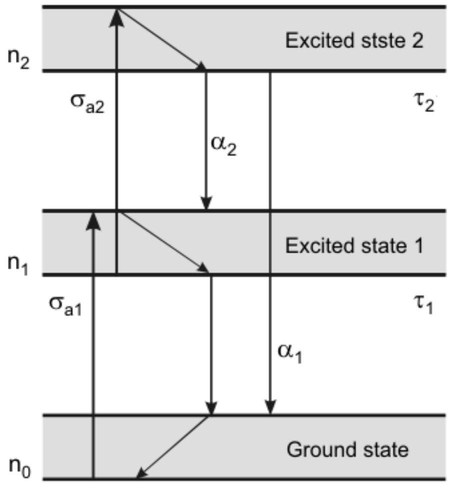

Fig. 1. Energy level diagram of a saturable absorber characterized by ESA.

from the second to the first excited state and to the ground state (the sum of α_1 and α_2 equals one, α_1 V α_2).

According to literature reports, there are many saturable absorbers, in which excited state absorption phenomenon occurs. The most common are dielectrics doped with different active ions, such as chromium, vanadium, erbium, cobalt, thulium and many others [6]–[9].

A passive Q-switched laser system with saturable absorber characterized by ESA can be described by four rate equations relating to average power density in a laser cavity J, amplification in a laser medium k, population density of the first and the second excited states (n_1 and n_2, respectively):

$$\frac{\mathrm{d}J(t)}{\mathrm{d}t} = V_R\left\{k(t) - \rho_s - \frac{l_{\mathrm{SA}}}{l_{\mathrm{LM}}}\sigma_{\mathrm{a}1}\left[\Big(N_0 - n_1(t) - n_2(t)\Big) + \frac{\sigma_{a2}}{\sigma_{a1}}n_1(t)\right]\right\}J(t), \tag{1}$$

$$\frac{\mathrm{d}k(t)}{\mathrm{d}t} = \varpi_P\Big[\chi - k(t)\Big] - \frac{k(t)}{\tau_{\mathrm{LM}}} - \frac{k(t)\,J(t)}{E_s}, \tag{2}$$

$$\frac{\mathrm{d}n_1(t)}{\mathrm{d}t} = M^2\frac{J(t)}{E_{s_{a1}}}\left\{\Big[N_0 - n_1(t) - n_2(t)\Big] - \frac{\sigma_{a2}}{\sigma_{a1}}n_1(t)\right\} - \frac{n_1(t)}{\tau_1} + \frac{\alpha_2 n_2(t)}{\tau_2}, \tag{3}$$

$$\frac{\mathrm{d}n_2(t)}{\mathrm{d}t} = M^2\frac{J(t)}{E_{s_{a2}}}n_1(t) - \frac{n_2(t)}{\tau_2}, \tag{4}$$

with initial conditions

$$k(t=0)=k_0, \tag{5}$$

$$J(t=0)=J_0 \tag{6}$$

where: $E_{s_{a1}} = h\nu_s/\sigma_{a1}$ – saturation energy of the nonlinear absorber to the first excited state; $E_{s_{a2}} = h\nu_s/\sigma_{a2}$ – saturation energy of the nonlinear absorber to the second excited state; $E_s = h\nu_s/\sigma_e$ – saturation energy of the laser medium (the energy that can be stored in LM); $N_0 = n_0 + n_1 + n_2$ – total population density of SA absorbing centers; $h\nu_s$ – photon energy; ω_p – pumping speed of the active medium; M – enlargement of an internal beam in a laser cavity (the ratio of cross-sectional area of a beam in SA to cross-sectional area of a beam in LM); l_{LM} and l_{SA} are the lengths of LM and SA, respectively; χ – theoretical maximum gain which can be obtained in LM ($\chi = n_0\sigma_{\mathrm{e}}$); σ_e – emission cross-section of LM; $V_R = c(l_{\mathrm{LM}}/L_{\mathrm{opt}})$ – the speed of light in the resonator (L_{opt} – optical length of the resonator); τ_{LM} – fluorescence lifetime of LM; ρ_s – coefficient of static losses, which include dissipative and transmission losses (ρ_d and ρ_t, respectively).

To describe the Q-switched laser we used a point model. This model is good enough for passive Q-switching. The analysis and solution of the rate equations presented above allow us to depict the dynamics of laser generation in the system discussed.

3. Normalized rate equations for passively Q-switched Nd:YAG lasers

The mathematical description of a passively Q-switched solid-state laser, given in the previous section, includes functions and parameters whose values are dimensional and absolute. This makes more detailed physical interpretation of these equations difficult and permits them to be solved only for specific cases. Obtaining the quantitative information, typical of analytical solution of the problem discussed, is impossible in this case. Therefore, the rate Eqs. (1)–(4) should be transformed into a form in which their functions and parameters will have relative values, linked with certain material constants or laser system features. This guarantees formulation of more general conclusions related to a laser with saturable absorber as a passive switch and allows its optimization.

In the analysis proposed the laser energy balance was taken into account. Depending on $M^2\delta_1$ parameter, being normalized pumping speed of a saturable absorber, the changes of energy generated in a laser with its division between energy emitted on static and dynamic losses were examined. The initial gain and different relations of static and dynamic losses in a laser cavity were changeable.

In connection with foregoing, the following normalized and dimensionless quantities are introduced (Tab. 1).

Introduction of constants defined in Tab. 1 modifies the Eqs. (1)–(4) to the following form:

$$\frac{\mathrm{d}I}{\mathrm{d}T} = l_{\mathrm{LM}}\chi\left\{K - R_S - \Gamma_{\mathrm{SA}}\left[(1 - N_1 - N_2) + \delta N_1\right]\right\}I, \tag{7}$$

$$\frac{\mathrm{d}K}{\mathrm{d}T} = W_p(1 - K) - \frac{K}{T_{\mathrm{LM}}} - KI, \tag{8}$$

$$\frac{\mathrm{d}N_1}{\mathrm{d}T} = M^2 I\delta_1\left[(1 - N_1 - N_2) - \delta N_1\right] - \frac{N_1}{T_1} + \frac{\alpha N_2}{T_2}, \tag{9}$$

T a b l e 1. Definitions of normalized constants and variables.

Constant	Symbol	Definition
Normalized power density in the laser cavity	I	$\frac{JL_{opt}}{E_S c}$
Normalized gain of LM	K	$\frac{k}{\chi}$
Normalized population of the first excited state of SA	N_1	$\frac{n_1}{N_0}$
Normalized population of the second excited state of SA	N_2	$\frac{n_2}{N_0}$
Normalized fluorescence lifetime of LM	T_{LM}	$\frac{\tau_{\mathrm{LM}}c}{L_{\mathrm{opt}}}$
Normalized lifetime of the first excited state of SA	T_1	$\frac{\tau_1 c}{L_{\mathrm{opt}}}$
Normalized lifetime of the second excited state of SA	T_2	$\frac{\tau_2 c}{L_{\mathrm{opt}}}$
Normalized pumping speed of LM	W_p	$\frac{\varpi_p L_{\mathrm{opt}}}{c}$
Normalized static losses of the laser cavity	R_S	$\frac{\rho_s}{\chi}$
Normalized initial dynamic losses of the laser cavity related to SA	Γ_{SA}	$\frac{\gamma_{\mathrm{SA}}}{\chi}$
Normalized transmission losses of the laser cavity	R_T	$\frac{\rho_t}{\chi}$
Normalized dissipative losses of the laser cavity	R_D	$\frac{\rho_d}{\chi}$

$$\frac{dN_2}{dT} = M^2 I\delta_1 \delta N_1 - \frac{N_2}{T_2}, \tag{10}$$

with initial conditions:

$$I(0) = \frac{\chi l_{\mathrm{LM}}}{T_{\mathrm{LM}}}(R_S + \Gamma_{\mathrm{SA}})\frac{\Omega}{4\pi}, \tag{11}$$

$$K_{\mathrm{OA}}(0) = R_S + \Gamma_{\mathrm{NA}}, \tag{12}$$

$$N_1(0) = 0, \tag{13}$$

$$N_2(0) = 0, \tag{14}$$

where:

$$\delta = \frac{\sigma_{a2}}{\sigma_{a1}}, \tag{15}$$

$$\delta_1 = \frac{\sigma_{a2}}{\sigma_e}, \tag{16}$$

$$\gamma_{\mathrm{SA}} = \frac{l_{\mathrm{SA}} N_0 \sigma_{a1}}{l_{\mathrm{LM}}}, \tag{17}$$

Ω – solid angle of a laser generation.

Using the rate Eqs. (7)–(10) we can find expression describing the values of energy in a laser with a saturable absorber. It can be output energy, energy scattered on static, dynamic losses of a laser cavity or energy stored in a laser medium.

As results from the principle of operation of the laser considered, during its pumping process, the energy is stored in it as long as the gain reaches the static losses and initial dynamic losses delivered by saturable absorber. After the generation threshold overflow, the gain in LM increases due to still working pump, however this increase is usually insignificant. Therefore, it can be assumed that energy stored in a laser medium corresponds to the state where the gain equals the initial cavity losses. Hence, the energy stored in 1 cm^2 of LM cross-section surface can be given by:

$$E_{\mathrm{stored}} = k\,E\,l_{\mathrm{LM}}. \tag{18}$$

Linking this expression with saturation energy of LM we obtain the normalized stored energy

$$E_{\text{stored}}^{N} = \frac{E_{\text{stored}}}{E_S} = \chi\, l_{\text{LM}}(R_S + \Gamma_{\text{SA}}). \tag{19}$$

After crossing the generation threshold in LM ($T = 0$) the lasing begins and continues until the laser medium saturates ($T = T_k$). The power generated is distributed on static and dynamic losses and can be described by:

$$E_{\text{stat}} = \rho_S\, l_{\text{LM}} \int_0^{t_k} J \mathrm{d}t, \tag{20}$$

$$E_{\text{dyn}} = l_{\text{LM}} \int_0^{t_k} J(t) \rho_D(t) \mathrm{d}t. \tag{21}$$

Integrating and linking these expressions with saturation energy of an active medium we obtain the normalized energy, emitting on static and dynamic losses of a laser cavity:

$$E_{\text{stat}}^{N} = \frac{E_{\text{stat}}}{E_S} = R_S \chi\, l_{\text{LM}} \int_0^{T_k} I \mathrm{d}T, \tag{22}$$

$$E_{\text{dyn}}^{N} = \frac{E_{\text{dyn}}}{E_S} = \Gamma \chi_{\text{SA}}\, l_{\text{LM}} \int_0^{T_k} I(1 - N_1 + \delta N_1 - N_2) \mathrm{d}T. \tag{23}$$

The normalized output energy is given by:

$$E_{\text{out}}^{N} = \frac{E_{\text{out}}}{E_S} = R_T \chi\, l_{\text{LM}} \int_0^{T_k} I \mathrm{d}T. \tag{24}$$

Normalized Eqs. (7)–(10) are the nonlinear system of equations and they do not have trivial analytical solutions. Therefore, they were solved by means of numerical methods.

4. Results of numerical analysis

The whole analysis was conducted in two aspects. In $M^2\delta_1$ parameter domain we looked for the situation where energy necessary to switch dynamic losses would be possibly small while energy emitted on static losses would be the highest. However, in dynamic to static losses ratio domain we looked for the situation when the output energy of the laser would be maximum. To this end, the Eqs. (7)–(10) were integrated and then suitable integrals occurring in Eqs. (22)–(24) were calculated.

The whole calculations were conducted for the following date: $\chi l_{\mathrm{LM}} = 300$, $W_p = 10^{-7}$, $T_{\mathrm{LM}} = 10^4$, $R_s + \Gamma_{\mathrm{SA}} = 0.01$. The participation of dynamic losses Γ_{SA} in the laser cavity was variable and equalled 90%, 80% and 70% of the whole value of initial LM losses. The value of parameter $M^2\delta_1$ was variable in the range from 0 to 100. The normalized lifetimes of SA excited states equalled: $T_1 = 1000$ or 1 and $T_2 = 1$.

Figures 2 and 3 depict the dependence of energy emitted on static (dissipative and

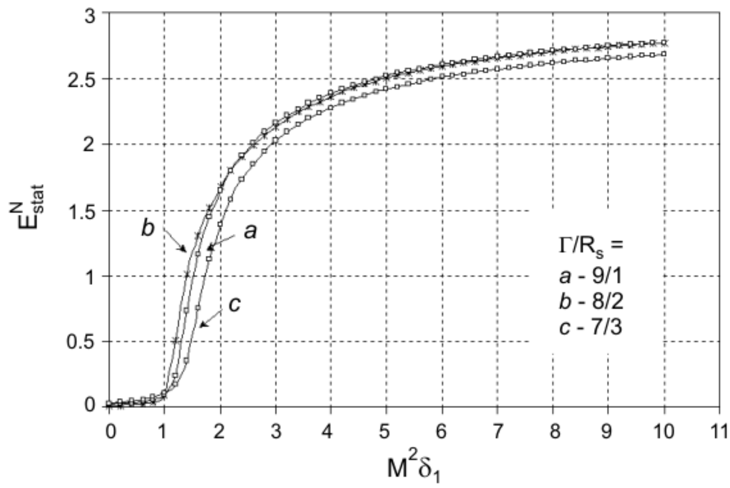

Fig. 2. Normalized energy emitted on static losses of the laser cavity *vs*. $M^2\delta_1$ parameter for SA without ESA ($T_1 = 1000$).

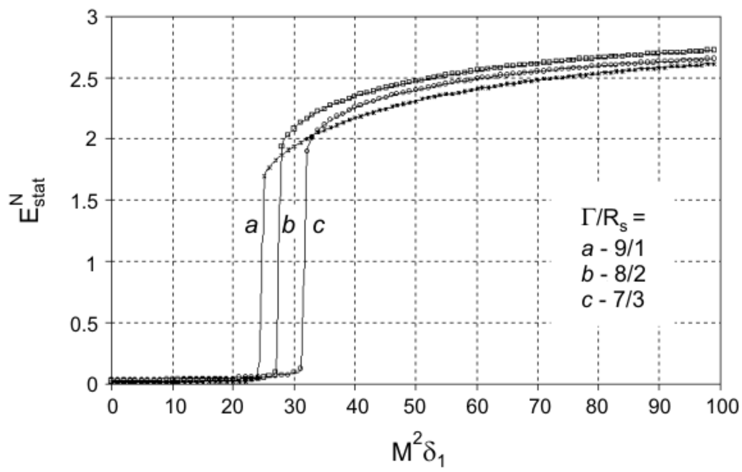

Fig. 3. Normalized energy emitted on static losses of the laser cavity *vs*. $M^2\delta_1$ parameter for SA without ESA ($T_1 = 1$).

transmission) losses as a function of $M^2\delta_1$ for high initial gain and for two different values of time T_1. As one can see, $E^N_{\rm stat}$ always rises along with the increase of $M^2\delta_1$ value. The most explicit changes occur in the range of intermediate values of $M^2\delta_1$, where the greatest changes of $E^N_{\rm stat}$ occur. The high value of $M^2\delta_1$ accompanies the insignificant increment of $E^N_{\rm stat}$. These relations depend on Γ/R_s ratio only to a minimum extent.

In Figures 4 and 5 the dependence of energy emitted on dynamic losses *vs.*

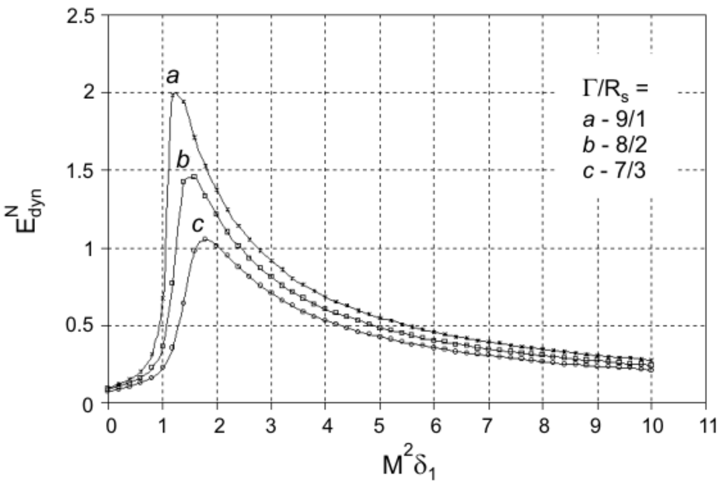

Fig. 4. Normalized energy emitted on dynamic losses of the laser cavity *vs.* $M^2\delta_1$ parameter for SA without ESA (T_1 = 1000).

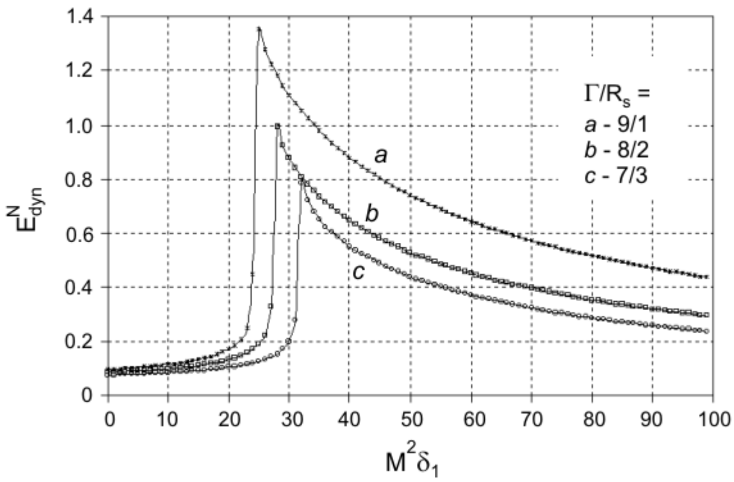

Fig. 5. Normalized energy emitted on dynamic losses of the laser cavity *vs.* $M^2\delta_1$ parameter for SA without ESA (T_1 = 1).

parameter $M^2\delta_1$ is presented. What can be quantitatively determined from this diagram is the energy which is necessary to saturate the SA. There is a clear maximum of the energy absorbed by SA – as far as effective laser losses switching is concerned, this range is the most relevant. Along with the increase of Γ/R_s ratio the maximum of E^N_{dyn} shifts towards the lowest values of $M^2\delta_1$ and the value of this maximum decreases. It determines the necessity of using saturable absorbers characterized by higher absorption cross-section or it forces us to make an artificial modification of $M^2\delta_1$ parameter by using higher enlargements M of a generated laser beam.

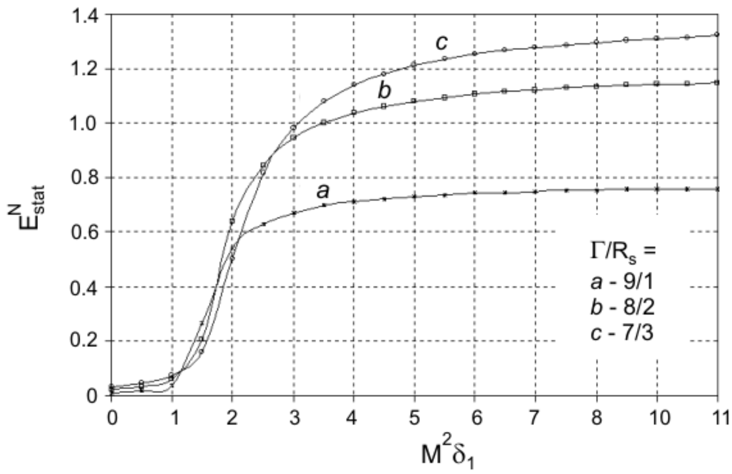

Fig. 6. Normalized energy emitted on static losses of the laser cavity *vs*. $M^2\delta_1$ parameter for SA with ESA (T_1 = 1000, T_2 = 1, δ = 0.2).

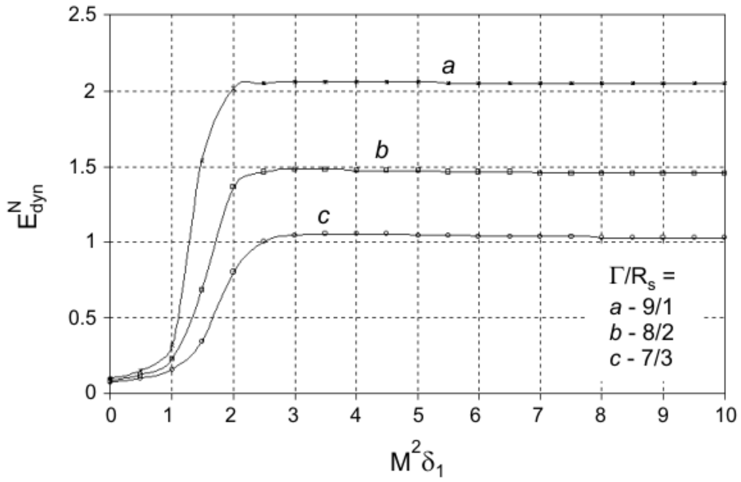

Fig. 7. Normalized energy emitted on static losses of the laser cavity *vs*. $M^2\delta_1$ parameter for SA with ESA (T_1 = 1000, T_2 = 1, δ = 0.2).

The behaviour of a Q-switched laser with SA characterized by ESA is presented in Figs. 6 and 7. It is easy to notice that excited state absorption phenomenon in SA influences negatively laser generation efficiency causing the decrease of energy emitted on static losses and simultaneously increasing the energy which saturates the SA. The differences between $E^N_{\rm stat}$ and $E^N_{\rm dyn}$ *vs.* Γ/R_s ratio are greater than for SA without ESA.

From the diagrams presented above (depending on $M^2\delta_1$ parameter value) we can specify three different working regimes of a passive Q-switched laser:

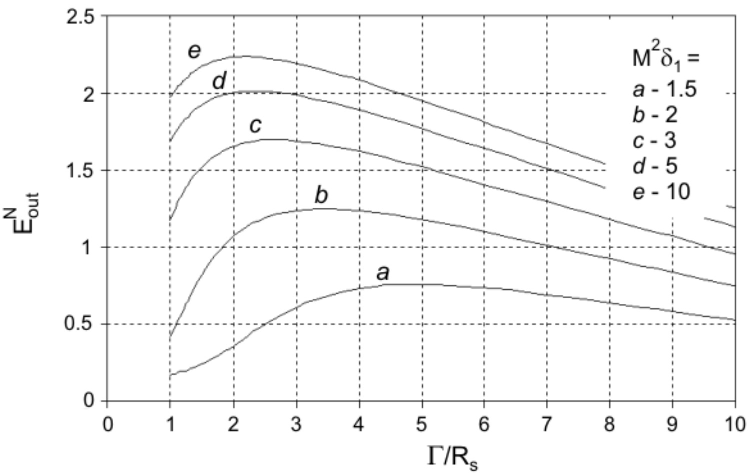

Fig. 8. Normalized output laser energy *vs.* Γ/R_s ratio for the laser with SA without ESA (R_D = 5%, T_1 = 1000).

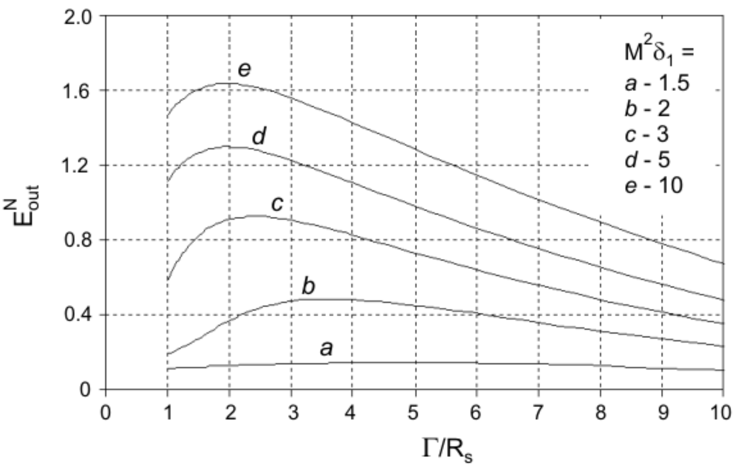

Fig. 9. Normalized output laser energy *vs.* Γ/R_s ratio for the laser with SA characterized by ESA (R_D = 5%, T_1 = 1000, T_2 = 1, δ = 0.2).

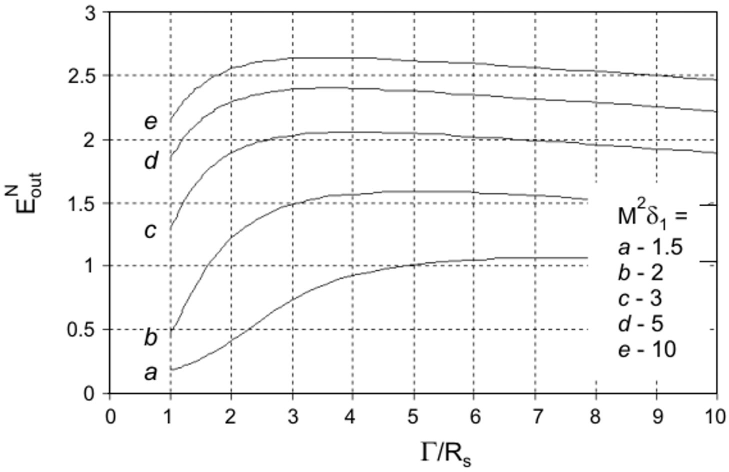

Fig. 10. Normalized output laser energy *vs.* Γ/R_s ratio for the laser with SA without ESA(R_D = 1%, T_1 = 1000).

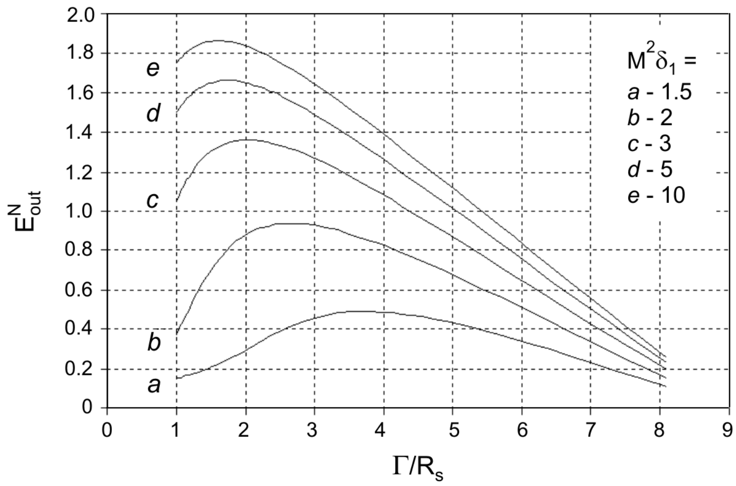

Fig. 11. Normalized output laser energy *vs.* Γ/R_s ratio for the laser with SA without ESA (R_D = 10%, T_1 = 1000).

1. The case where $M^2\delta_1$ W 1. Then we deal with a well designed passively Q-switched laser. The laser medium is strongly saturated. In the case of SA without ESA the small amount of energy stored in the laser cavity is destined for dynamic losses switching. Most of the energy stored is emitted on transmission and dissipative losses. However, as far as a laser with SA characterized by ESA is concerned, the energy saturating SA is constant *vs.* $M^2\delta_1$ parameter value.

2. The case where $M^2\delta_1 < 1$. The gain in LM is weakly saturated and the energy generated is very small. In extreme case, where $M^2\delta_1 \to 0$ (we can interpret it as using an absorber with absorption cross-section close to zero and characterized by some finite transmission – resulting from the concentration of absorbing centers) our laser works in free running regime. The losses introduced by SA are not changeable during the generation and such an absorber cannot be called nonlinear.

3. The case where $M^2\delta_1 > 1$ (where energy changes are the greatest). In this range along with the increase of $M^2\delta_1$ value the gain saturation of LM builds up rapidly, especially for high values of Γ/R_s ratio value. This is caused by absorption saturation of SA. There is an explicit maximum of energy switching the SA, whose location depends on Γ/R_s ratio. This range can be called ineffective Q-modulation.

From the analysis done so far it is not difficult to notice that for a laser with a SA exhibiting ESA as well as a laser with a SA characterized by the lack of ESA phenomenon the relations of energy emitted on static losses R_S change as a function of the ratio of the whole laser losses components. This points to the necessity of optimizing laser transmission losses R_T depending on dissipative losses R_D and $M^2\delta_1$ parameter.

Figures 8–11 present dependences of normalized output laser energy as a function of Γ/R_s ratio. The dissipative losses were assumed at 1%, 5% and 10% of initial gain. On the basis of the characteristic curves presented above we can point to the optimum Γ/R_s ratio for which the output energy is maximum. This maximum is strongly dependent on dissipative losses level, which is obvious ($R_S = R_T + R_D$). The higher value of dissipative losses corresponds to lower laser output energy (Figs. 10 and 11) and the higher value of $M^2\delta_1$ corresponds to higher output energy. Along with the increase of $M^2\delta_1$ the maximum of output energy shifts towards lower values of Γ/R_s ratio, and the level of this maximum increases. The optimal output energy is strongly limited especially from low values of Γ/R_s ratio direction. In this range the slight change of this ratio induces significant changes of output energy. This limitation occurs especially for higher values of dissipative losses (see Fig. 11).

5. Experimental verification of numerical analysis results

In order to confirm the correctness of the numerical analysis conducted in Sec. 4 an experimental passively Q-switched laser set-up was designed. The ϕ4-mm × 3.5' Nd^{3+}:YAG crystal was used as an active medium with both sides antireflection coated at 1060 nm. This crystal was pumped by a ϕ4x30 mm xenon flash lamp and was located in a 92 cm-long plane-plane laser cavity. The rear reflector had nearly total reflection at 1064 nm, and another flat mirror acted as an output coupler with reflectivity of 15% (optimal value for Cr^{+4}:YAG) and 70% (optimal value for Cr^{+4}:GSGG). The pump light was focused by means of a diffusion elliptical cylinder reflector (LM 1520T C300S). In this set-up a ϕ2.25 mm diaphragm was applied, forcing the laser to work in a fundamental transverse mode TEM_{00}. Cr^{+4}:YAG and Cr^{+4}:GSGG crystals, antireflection coated at 1064 nm, were used as passive switches. Applications of two different absorbers aimed to confirm the conclusions formulated earlier. Both Cr^{+4}:YAG and Cr^{+4}:GSGG crystals were characterized by excited state absorption and, what is the most important from experimental point of view, they are also characterized by different value of parameter δ. The Cr^{+4}:YAG absorber was characterized by: $\sigma_a = 2.08\times10^{-18}$ cm^2, $l_{SA} = 0.55$ cm, initial transmission $T_0 = 17\%$, $\delta = 0.098$, $\delta_1 = 3.2$. However, Cr^{+4}:GSGG crystal was characterized by: $\sigma_a = 1.5\times10^{-18}$ cm^2, $l_{SA} = 0.8$ cm, initial transmission $T_0 = 36\%$, $\delta = 0.19$, $\delta_1 = 2.3$. The experimental set-up worked with 1 Hz repetition rate. The Rj–7100 energy meter with Rjp–735 probe and the digital oscilloscope (2040 Tektronix) were used to measure the output energy and the pulse width of the laser pulse, respectively. It was necessary to compare the measurement results obtained with those achieved by applying the numerical calculations. This comparison is presented in Tab. 2.

T a b l e 2. Compatibility comparison of simulation and experimental results.

	Computer simulation		Experimental results	
Saturable absorber	Pulse energy	Pulse width	Pulse energy	Pulse width
Cr^{+4}:YAG	17.73 mJ	15 ns	16.6 mJ	14.4 ns
Cr^{+4}:GSGG	3.26 mJ	30 ns	3.12 mJ	28.3 ns

All pulse characteristics, such as output energy and pulse duration were in very good agreement with those predicted theoretically. Therefore, this allows us to assume that the numerical model proposed is correct and can be applied for different saturable absorbers both with and without ESA phenomenon.

6. Conclusions

The optimization of a passively Q-switched laser with saturable absorber characterized by ESA was considered. A detailed analysis of the passively Q-switched lasers was made based on the normalized dimensionless rate equations considering: ESA and lifetimes of the SA as well as the magnification in the laser cavity. The following conclusions have been drawn from the analysis presented above:

– Efficient generation in a passively Q-switched laser takes place when a saturable absorber is characterized by the absence of ESA;

– In order to maximize the laser output energy the saturable absorber should be characterized by long lifetime of its first excited state as well as high value of the ratio of ground state absorption cross-section of a SA to emission cross-section of an LM. This guarantees high saturation of a laser medium;

– ESA phenomenon decreases the laser generation efficiency. It results from multiple absorption transitions between excited states of an SA. The ESA phenomenon causes: the decrease of energy emitted on static (dissipative and transmission) losses of a laser cavity, the increase of energy level which is necessary to "switch" saturable absorber, and the fall of laser medium gain saturation;

– The level of energy emitted on the whole laser cavity losses depends on the ratio of its particular components. This relation occurs especially in the case of a SA characterized by ESA.

Apart from theoretical analysis an experimental Q-switched laser set-up was designed. Cr^{+4}:YAG and Cr^{+4}:GSGG crystals were used as passive switches. They were characterized by different values of the ratio of its absorption cross-sections δ. The theoretical and experimental results obtained are in very good agreement and thereby they are very useful in designing of such lasers.

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