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Dynamics of a laser with a nonlinear TIR *Q* switch

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***Abstract*. Computer simulation and experimental investigations of the dynamics are carried out for a solid state laser with an intracavity nonlinear reflector. The nonlinearity appears upon the internal reflection of radiation from the interface between a transparent dielectric and an absorbing liquid due to a change in the refractive index of the latter upon its heating by a refracted laser wave. Our calculations reveal the dynamics of the reflection coefficient and the power of the laser radiation taking into account the variation of temperature and pressure in the boundary layer of the liquid. The dependences of the lasing parameters on the parameters of the nonlinear reflector and pumping power are studied theoretically and experimentally. It is shown that a *Q* switch based on the thermal nonlinearity of reflection provides the generation of giant laser pulses whose duration varies from a few hundred nanoseconds to a few nanoseconds. Such a *Q* switch can be fabricated for any spectral region because it is based on a linear absorber rather than on a saturable absorber. Another advantage of this *Q* switch is the absence of residual absorption, which is a characteristic feature of all phototropic *Q* switches.**

Keywords: *nonlinear reflection, total internal reflection, passive Q switch, laser radiation dynamics.*

1. Introduction

The nonlinear internal reflection of radiation at the interface between a transparent dielectric and absorbing liquid was discovered in [1]. This effect is caused by a change in the refractive index of the liquid due to absorption of the refracted wave and heating of the liquid, leading to a decrease in the limiting angle of total internal reflection (TIR). The initial reflectivity may be low, but its value may increase up to unity during the development of lasing, which was used for *Q*-switching of a laser resonator [2].

A modified version of the *Q* switch based on nonlinear TIR, in which the initial reflectivity is lowered due to interference in a thin layer of a weakly absorbing liquid, was proposed in Refs [3, 4]. The basic problems in the theory of TIR of light at the interface with an amplifying medium were considered in book [5]. Despite the fact that nonlinear TIR is used successfully in practice for *Q*-switching of lasers [6, 7] as well as for controlling the laser pulse shape [8, 9], a detailed analysis of the dynamics of processes occurring at the interface between two media during the development of lasing in a resonator has not been carried out so far.

The reason that a laser with an intracavity nonlinearly reflecting mirror is a quite complicated system. To study the dynamics of such a laser, we have to consider simultaneously a number of interrelated processes: heating of the absorbing medium under the action of the refracted part of the lasing wave, pressure increase in the heating region and the resulting change in the refractive index of the liquid medium, a gradual pushing of the refracted wave to the boundary, an increase in the reflectivity at the boundary, the effect of this factor on the development of lasing in the resonator and, conversely, the effect of varying lasing dynamics on all the above-mentioned processes.

It is also necessary to take into account the pressure and temperature relaxation due to the interaction of the boundary liquid layer with the surrounding media. A proper consideration of this factor requires a calculation of the temperature field dynamics in the boundary layer taking into account the heat exchange between the layer being heated, the surrounding liquid layer, and the optical elements in the boundary region. An analytic solution of such a problem is quite complicated in the absence of considerable simplifying assumptions.

In this work, we present the results of computer simulation of the above-mentioned system for a Nd glass laser. The results of experimental verification of the main theoretical dependences are also given.

Fig. 1 shows the scheme of the laser resonator. The active element (*3*) and the reflection prism (*4*) made of a transparent dielectric (glass) are placed between mirrors (*1*) and (*2*). The hypotenuse side of prism (*4*) is in direct contact with a liquid strongly absorbing laser radiation. We performed numerical calculations for a Nd glass, although other laser media can also be considered to the same effect.

2. Theory

Consider seven radiation fluxes in the laser resonator as shown in Fig. 1. The rate equation for flux 1 has the standard form

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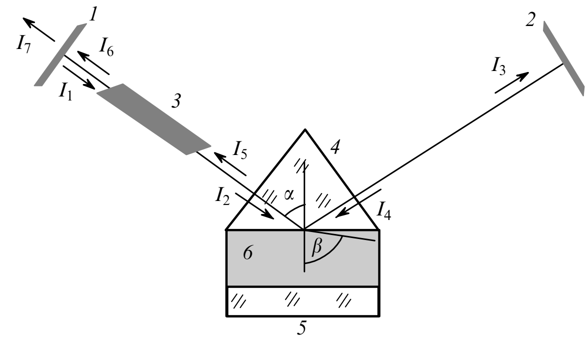

Figure 1. Optical scheme of the laser: (*1, 2*) mirrors; (*3*) laser rod; (*4, 5*) transparent dielectrics; (*6*) absorbing liquid.

$$\frac{\mathrm{d}I_1}{\mathrm{d}t} = \frac{c}{2L}[I_1(a-1) + \varepsilon(a+b)], \tag{1}$$

where I_1 is the radiation intensity corresponding to flux 1; $a = R_1 R_2 T_t^4 R^2 \mathrm{e}^{2kl}$; $b = R_1 \mathrm{e}^{kl}$; R_1 and R_2 are the reflectivities of laser mirrors; k is the gain; l is the length of the active medium; T_t is the transmission of the input and output surfaces of the prism; L is the resonator length; R is the reflectivity at the dielectric–liquid interface; ε is a factor characterising the contribution of the spontaneous emission to the lasing mode; and c is the velocity of light.

The radiation intensity I_7 of the flux emitted by the laser is related to I_1 by the expression

$$I_7 = (1 - R_1)[R_2 T_t^4 R^2 (I_1 + \varepsilon)\mathrm{e}^{kl} + \varepsilon]\mathrm{e}^{kl}. \tag{2}$$

The laser radiation intensity in the liquid just at the interface is

$$I_{\mathrm{in}} = (I_2 + I_4)(1 - R)\gamma, \tag{3}$$

where

$$I_2 = T_t(I_1 + \varepsilon)\mathrm{e}^{kl}, \quad I_4 = R_2 T_t^3 R(I_1 + \varepsilon)\mathrm{e}^{kl} \tag{4}$$

are two laser fluxes inside the prism that are incident on the interface (see Fig. 1); and

$$\gamma = \frac{\cos\alpha}{\cos\beta} \tag{5}$$

is the factor describing the beam compression in the liquid due to refraction. The interference of the fields with intensities I_2 and I_4 is neglected, which is justified for an Nd glass laser having a broad lasing spectrum.

Taking into account the four-level diagram of the laser medium under study, we can write the rate equation for the upper laser level 3 in the form

$$\frac{\mathrm{d}N_3}{\mathrm{d}t} = (1 - N_3)\tau B_p U_p - N_3(\tau B_L U_L + 1), \tag{6}$$

where τ is the lifetime of the upper laser level; $B_p U_p$ is the probability of excitation by pumping; $B_L U_L$ is the induced emission probability; B_p and B_L are the Einstein coefficients;

$$U_L = \frac{n_L(I_1 + I_5)}{c} \tag{7}$$

is the laser radiation energy density in the active medium, which is determined by the sum of the intensities I_1 and I_5 of the counterpropagating fluxes incident on the medium;

$$I_5 = \frac{a(I_1 + \varepsilon) + \varepsilon}{R_1} \tag{8}$$

is the laser radiation intensity in the active medium; n_L is the refractive index of the active medium; and

$$U_p = U_0 \exp\left[-\frac{(t - 2t_p)^2}{t_p^2}\right] \tag{9}$$

is the Gaussian pump pulse. In Eqn (6) we have taken into account the fact that the quantum efficiency of the transition from level 4 to level 3 is close to unity for Nd^{3+} in glass.

A characteristic feature of such a laser system is the presence of nonlinear reflection with coefficient R in the resonator. According to the Fresnel formulas, the reflection coefficients for two orthogonal polarisations are

$$R_{\parallel} = \left[\frac{\tan(\alpha - \beta)}{\tan(\alpha + \beta)}\right]^2, \quad R_{\perp} = \left[\frac{\sin(\alpha - \beta)}{\sin(\alpha + \beta)}\right]^2. \tag{10}$$

where

$$\beta = \arcsin\frac{n\sin\alpha}{n_0 + \Delta n}; \tag{11}$$

n and n_0 are the refractive indices of the dielectric and the liquid, respectively; and Δn is the change in the refractive index of the liquid at the interface due to heating caused by the absorption of the refracted laser wave.

In order to calculate Δn, we should consider the change in temperature as well as pressure of the liquid at the interface:

$$\Delta n = \frac{\partial n}{\partial T}\Delta T + \frac{\partial n}{\partial p}\Delta p. \tag{12}$$

The temperature variation was calculated using the thermal conductivity equation

$$\frac{\partial T}{\partial t} = \frac{\chi}{\rho c_p}\frac{\partial^2 T}{\partial x^2} + q(x,t)\frac{1}{\rho c_p}, \tag{13}$$

where ρ, χ, and c_p are the density, thermal conductivity, and specific heat of the medium (the variation of these quantities upon a transition from the liquid to the dielectric phase is taken into account); $q(x,t) = k_a I_{\mathrm{in}} \exp(-k_a x/\cos\beta)$ is the specific power of heat release in the liquid at point x characterising the distance from the interface; and k_a is the absorption coefficient of the liquid.

The pressure variation in the liquid is described by the relation

$$\frac{dp}{\mathrm{d}t} = \left(\frac{\partial p}{\partial T}\right)_V \frac{\mathrm{d}T}{\mathrm{d}t} - \Delta p\frac{\upsilon}{h}, \tag{14}$$

where Δp is the pressure excess in the layer over the ambient pressure; υ is the velocity of sound in the liquid; $h = l_0/\cos\beta$ is the effective thickness of the liquid layer near the boundary pumped by a refracted laser beam; and l_0 is the characteristic absorption length of a laser beam in the liquid (a ten-fold decrease in the intensity of light occurs over a length $l_0 = 2.3/k_a$).

The system of equations (1)–(14) completely describes the laser dynamics in the case of nonlinear internal reflection in the laser resonator. The following factors are taken into account in these equations:

– heating of the liquid due to absorption of a refracted wave;

– variation of the liquid temperature caused by heating and heat transfer according to the thermal conductivity mechanism in the liquid and dielectric;

– pressure increase due to heating and pressure decrease due to expansion of the heated liquid layer;

– variation of the laser radiation transmission at the liquid–dielectric interface;

– variation of the angle of refraction and the corresponding laser beam compression in the liquid; and

– variation of reflection at the interface, its effect on laser dynamics, as well as the reciprocal effect of laser dynamics on the thermal processes occurring in the liquid in the vicinity of the interface.

The system of equations (1)–(14) is unlikely to have an exact analytic solution, but a numerical solution can be obtained. We developed a flexible software program using the computational packet Digital Fortran 6, which can be used conveniently for studying the laser dynamics of the above system by varying all the basic parameters. For one computation cycle, the programme provides data about the time variation of the intensity of output laser radiation, the energy density of radiation in the liquid, temperature, pressure, reflectivity at the boundary, as well as the temperature profiles along the normal to the interface at any instant of time. The results are compiled for the entire time scale corresponding to the duration of pumping, as well as on an extended scale for a fragment centred automatically at the radiation pulse peak. The programme also envisages an automatic choice of the optimal integration step for reducing the computation time.

3. Experimental

We used in our experiments a Nd glass laser whose optical scheme is shown in Fig. 1. The laser rod had a size $\varnothing 10 \times 130$ mm, the resonator base was 85 cm, and the reflectivities of the mirrors were 100 % and 60 %. A diaphragm ensuring a decrease in the angular divergence to the diffraction limit was placed in the laser resonator. The input prism (*4*) (see Fig. 1) was made of K8 glass ($n = 1.5063$). A solution of aniline black in benzyl alcohol ($n_0 = 1.4907$) was used as the absorbing liquid. The absorption coefficient of the solution varied in the range 4–20 cm^{-1}. We measured the output energy, recorded the general pattern of the time evolution of laser action and the shape of the giant radiation pulse.

4. Results and discussion

Figs 2a and b show the theoretical and experimental time dependences of the intensity of output laser radiation for an angle of incidence at the dielectric–liquid interface $\alpha > \alpha_{lim}$, where α_{lim} is the initial limiting TIR angle. In this case, the reflection coefficient R at the interface is equal to unity at the very beginning and does not change during lasing, i.e., the Q factor of the resonator remains constant and the laser operates in the free-running mode. In the computational version, we observe the intensity oscillations at the initial stage, followed by a transition to the quasi-stationary lasing mode. In the experiment, random pulsations of radiation, which are characteristic of a solid-state laser with a flat resonator, are observed over the entire lasing period.

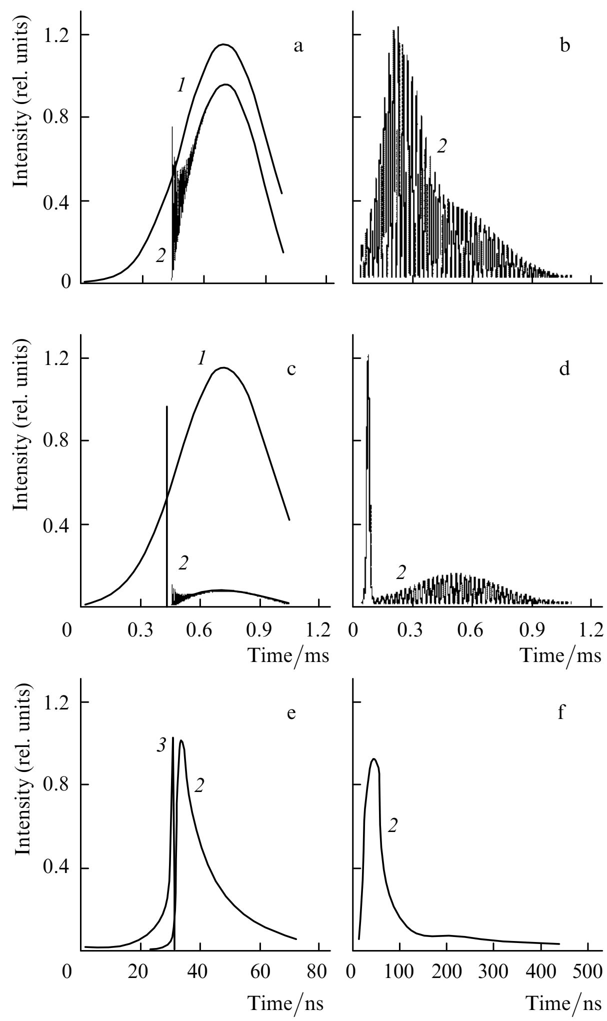

Figure 2. Theoretical (a, c, e) and experimental (b, d, f) time dependences of radiation intensity of a laser with a nonlinear TIR Q switch for angles of incidence of radiation on the interface between two media $\alpha > \alpha_{lim}$ (a, b) and $\alpha < \alpha_{lim}$ (c–f): (*1*) pump pulse, (*2*) lasing pulse, (*3*) radiation intensity in the liquid at the interface.

The dependences shown in Figs 2c–f correspond to the case when the angle of incidence of radiation at the interface is smaller than the initial limiting TIR angle by $\Delta\alpha = 10'$. Both theory and experiment reveal a radical variation of the lasing mode upon a transition to the range of angles $\alpha < \alpha_{lim}$: instead of the free-running mode, a single-pulse mode is observed. One can see from Figs 2c and d that only one single pulse is developed during the growth of the entire pumping pulse, and this may be followed by a free-running mode of a much lower intensity. Figs 2e and f show a single pulse with an enhanced time resolution. The energy of a single pulse generated with a given passive Q switch attained values up to 1 J in the experiments.

Note that the laser pulse penetrating the liquid (curve *3* in Fig. 2e) differs significantly from the input pulse. After the onset of lasing, the liquid layer is heated quite rapidly, the transmission through the boundary decreases quickly to zero, and the radiation intensity inside the medium decreases sharply. As a result, pulse (*3*) turns out to be much shorter than the output laser pulse. In a typical case, the duration of pulse (*3*) is 1.5 ns, which is an order of magnitude shorter than the output pulse duration. This fact is of considerable practical interest: if a solution of the molecules under investigation is chosen as the absorbing liquid, these molecules will be excited near the interface by a much shorter pulse than the output laser pulse. The peak intensity of pulse (*3*) in Fig. 2e is naturally lower than of the output pulse (*2*), but this difference is comparatively small, and these intensities differ by a factor of just 2 – 5 in typical cases.

The duration of the single lasing pulse depends on the angle of incidence of laser radiation at the interface between the two media or, to be more precise, on the quantity $\Delta\alpha = \alpha_{\lim} - \alpha$ characterising the initial departure of the angle of incidence from the limiting TIR angle. This dependence is especially significant for small angles of deviation $\Delta\alpha$. The experimental and theoretical curves illustrating this dependence are presented in Figs 3a and b. One can see that the single pulse duration varies with $\Delta\alpha$ over a wide range, from hundreds to tens of nanosecond. Calculations show that for large values of the deviation angles $\Delta\alpha$ ($\sim 12°$), the output laser pulse duration may be reduced to 1.5 ns.

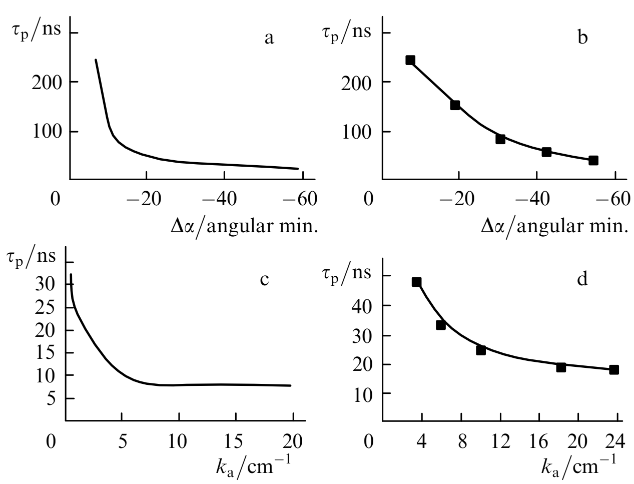

Figure 3. Theoretical (a, c) and experimental (b, d) dependences of the half-width τ_p of a laser single pulse on detuning angle $\Delta\alpha$ (a, b) and the absorption coefficient k_a of the liquid (c, d).

Another factor whose influence must be known before making an appropriate choice of the experimental conditions is the absorption coefficient of the liquid. One can see from Figs 3c and d that the duration of the lasing pulse depends significantly on the absorption coefficient of the liquid only for small values of the absorption coefficient (up to 7 cm^{-1}). Subsequent increase in the absorption coefficient of the liquid does not lead to a significant decrease in the lasing pulse duration. This is due to the fact that the liquid is heated mainly in the period when the laser pulse intensity is quite high, the reflectivity R is close to unity, and hence the angle of refraction is close to 90°; i.e., when the refracted beam is at a grazing angle with the interface. The decrease in the absorption coefficient can be compensated easily by increasing the path length of the beam in the liquid, since the refracted beam in this case grazes along the interface. Moderate requirements imposed on the absorption coefficient considerably simplify the quest for the appropriate liquids for such a nonlinear Q switch, which is an important factor for applications in the IR spectral region.

When a liquid is heated rapidly, its refractive index does not change instantaneously, since the temperature variation of the refractive index during the first instants of time can be compensated by an increase in pressure in the heating region. Fig. 4 shows the pressure dynamics during operation with the passive Q switch under consideration. Fig. 4a shows the time dependence of temperature (curve *1*) and pressure (curve *2*) in a time interval corresponding to the emergence of a single pulse (curve *4*). It can be seen that the pressure relaxes much more rapidly than the temperature. This is also due to the fact that the heating of the liquid mainly occurs at quite high intensities of laser radiation, when the reflectivity at the interface approaches unity. In this case, the refracted beam is at a grazing angle with the interface and the layer being heated is extremely thin, which leads to a sharp decrease in pressure due to an expansion of this layer.

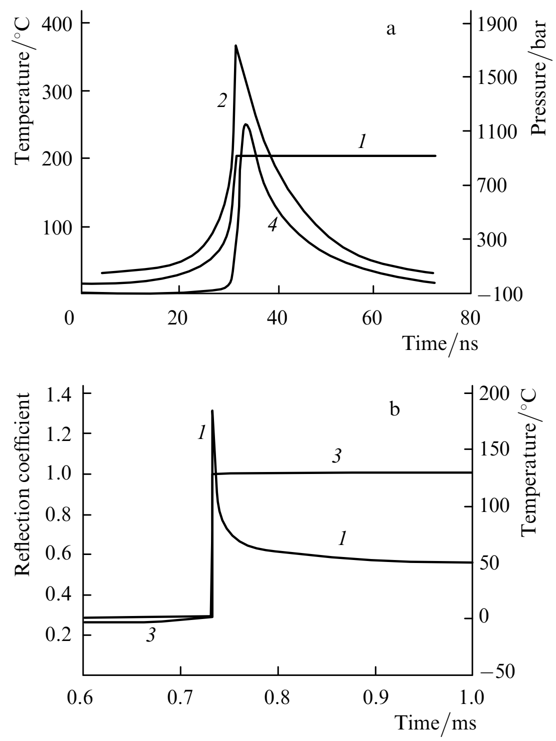

Figure 4. Dynamics of temperature (*1*), pressure (*2*) and reflection coefficient R (*3*), as well as the shape of a laser single pulse (*4*) in a nonlinear internal reflection laser.

One can see from Fig. 4a that the temperature increases as rapidly as the pressure, but the subsequent cooling of the solution according to the thermal conductivity mechanism occurs much more slowly and is not noticeable on the time scale of Fig. 4a. The dependences in Fig. 4b are presented on a more compressed time scale and show that after the coefficient of reflection at the dielectric – liquid interface attains a value equal to unity (i.e., the transmission through the interface becomes equal to zero), the initial sharp decrease in temperature occurs in a few microseconds, after which the subsequent cooling occurs much more slowly (curve *1* in Fig. 4b). The maximum values of the temperature attained in a thin liquid layer near the interface are quite high and may even exceed the boiling point. However, since such a high temperature prevails only for a few microseconds, the liquid does not start boiling.

Fig. 4b (curve *3*) shows the time dependence of the reflectivity at the interface. One can see that the reflectivity varies over a wide range (from 0.27 to unity in the present case), and this variation occurs extremely rapidly so that curve (*4*) in this time scale has the form of a rectangular step.

We also studied the dependence of the lasing parameter on polarisation of the radiation and the ratio of the refractive indices of the dielectric and the liquid. It was found that the effect of polarisation is not significant: the duration of the generated pulse decreases by 10 % – 15 % upon a transition from the electric vector orientation perpendicular to the plane of incidence to an orientation of the polarisation orthogonal to this plane. The refractive indices of the media in contact do not have a significant effect on the lasing parameters, since the main role is played by the deviation $\Delta\alpha$ of the angle of incidence from the initial limiting angle of total internal reflection. A variation of the refractive indices of the two media over a wide range does not lead to a significant change in the lasing parameters if the incidence angle is varied simultaneously in such a way that the quantity $\Delta\alpha$ remains the same in all cases. This factor, as well as the above-mentioned weak dependence of the Q switch efficiency on the absorption coefficient of the liquid offer a wide range of options of the medium to the experimenter while creating a nonlinear TIR Q switch.

Thus, our calculations which are confirmed in experimental measurements, reveal the dynamics of temperature, pressure and reflectivity in a passive Q switch based on nonlinear TIR, and show that such a switch can be used successfully for obtaining giant laser radiation pulses whose duration can be varied from several hundred nanoseconds to a few nanoseconds. One of the undoubted advantages of such a passive Q switch is that there is no need to use saturable absorbers, and hence it can be employed virtually in any spectral region. Moreover, no residual absorption of any kind is observed in such a Q switch.

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