# Intensity self-pulsations in injection laser with thin-film nonlinear-refractive element

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## ABSTRACT

An estimation of conditions of regime of lasing self-oscillations arising in cw-pumped injection laser due to light field spectrum linewidth broadening is carried out at assumption of the sub-micrometer planar nonlinear film presence in the laser cavity.

**Keywords:** lasing dynamics, amplitude and phase self-modulation, light field spectrum linewidth broadening

## 1. INTRODUCTION

The lasers emiting continuous trains of short pulses, find application in laser metrology, in modern devices of information transfer. Reception of stable series of contrast light pulses in a range subnano- and picosecond durations demands application of high laser technologies. Planar semiconductor structures as passive $Q$-modulators since recent time are used as elements of the solid-state lasers generating supershort pulses (SSP) in regimes of mode-locking. It is known also, that a number of solid-state lasers at excitation of relaxation oscillations is capable to generate regular trains of enough short pulses [1]. Rather insignificant external modulation of a level of pumping or cavity $Q$-factor is necessary [2]. Action of saturated $Q$-shutters on the basis of semiconductor structures was modelled and in details analyzed for the description of a physical situation in cavities the continuous solid-state lasers radiating SSP [3,4].

A large variety of both regular and stochastic self-modulation structures observed in the radiation of solid-state lasers is attributed to the phase self-modulation (PSM) effect on the process of induced emission in laser cavities [1]. Connection of fluctuations of amplitude and a phase of the generated field, causing PSM, is peculiar to a lot of laser media [5] and is caused by a resonant nonlinear refraction. In the case of injection laser the similar nonlinear refraction in a substance of an active layer in the frequency region of exciton resonance or interband absorption acquires the "giant" character [6]. This connection plays a special role in systems with a phase-sensitive feedback (FB). Its mechanism, as a whole, is a little bit distinct from the reasons causing amplitude-phase connection in the laser substance, considered in two-level approach. That mechanism, however, is qualitatively taken into account at assumption of field spectrum linewidth broadening factor ($\alpha$ – factor), which characterizes relative change of refraction parameter and absorption coefficient depending on change of density of free carriers. The consequences of PSM, related to the non-inertial phase deviations with respect to the carrier concentration, were studied in sufficient detail in the case of systems with external FB [7–9]. The time pattern of emission of an injection laser may exhibit qualitative variations depending on the FB parameters and the pump current, even in the case when the external resonator contains only a reflector, rather than special dispersion or modulation devices.

## 2. MODEL AND BASIC EQUATIONS

It would be of interest to consider a dynamic model of the laser where thin layers of substance with active absorption on the frequencies close to the lasing frequency are in addition included in FB system. As is known, the presence of a thin resonant polarizable film with a thickness smaller than the radiation wavelength may strongly affect the optical properties of the interface. Thin resonant layer transmission it appears sensitive not only to intensity, but also to a phase of an external light field [10, 11]. Under these conditions, the FB efficiency is related to the intrinsic nonlinearity of refraction in active element and the related frequency deviations of the lasing mode field. Thin-film planar elements

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parallel to the exit edge of laser elements may serve as nonlinear *Q*-modulators of a special kind. Their additional feature is the phase sensibility. Therefore, it would be quite expedient to model the nontrivial dynamics of solid-state laser emission, with an allowance for the self-modulation effects in the systems employing such elements. Let us consider a thin nonlinear layer deposited directly onto an end face of a laser element. For conditions of the resonant interaction an absorption in a film depends on a difference of population levels of a transition, which is saturated due to a power supplied via the external (lasing) field. The nonlinear refraction of a gain medium or a planar layer in frequency region of an optical resonance can be considered, being based on so-called generalized two-level scheme. Using this assumption, we may relatively simply take into account a contribution to the total polarizability from the transitions adjacent to the main (resonant). The corresponding deviations of the refractive index are directly connected to a resonant change in the aforementioned population difference, i.e. with the account of the α – factor.

Using the approximation of non-coherent interaction between the field and atoms in especially thin layer and following the conclusion derived in [10], the dynamics of the optical transmission $\mathrm{T}(t)=|E|^2/E_0^2$ of the surface film as *Q*-modulator can be described by the following expression:

$$\mathrm{T}(t)=\frac{4\eta}{(1+\eta)^2}\Bigg/\left\{\left(1+\frac{\varkappa n}{1+\Delta\omega^2\tau_2^2}\right)^2+\varkappa^2\left[\frac{n\,\Delta\omega\tau_2}{1+\Delta\omega^2\tau_2^2}+\beta_c(n-n_o)\right]^2\right\},$$

$$\frac{dn}{dt}=\frac{1}{\tau_c}\left(n_o-n-\frac{\sigma_l\,n|E|^2}{1+\Delta\omega^2\tau_2^2}\right), \qquad (1)$$

where

$E_0$ and $E$ are values of light field waves, normally incident on a film,
$n$ is the variable of probability of a population difference,
$n_0$ is the initial difference of population ($0 < n_0 \le 1$),
$\eta$ is the refraction parameter of film substance,
$\varkappa$ is the absorption parameter for a center of absorption band,
$\tau_c$ and $\tau_2$ are times of longitudinal and transverse relaxation of resonant transition,
$\Delta\omega$ is the field frequency detuning from the resonance;
$\sigma_l$ is the section of transition (parameter of absorption nonlinearity),
$\beta_l$ is the parameter of a nonlinear refraction proportional to the value of α – the factor for a film substance. In Eq. (1), the term proportional to variation of the differential population $n - n_0$ in the dispersion component of T($t$) reflects the contribution due to the phase shift caused by nonlinear refraction in the film.

In the simplest lasing model, the energy balance between light field and pumped excited medium can be described by usual kinetic equations for the variables of intensity and population inversion (carrier concentration in the laser diode) averaged over the gain element thickness [10]. An allowance for the special physical situation related to the presence of thin layers with saturated absorption and nonlinear refraction on one of the laser element edges leads to some modification of this model. The expression for the variable coefficient of radiative losses (averaged over the laser diode length) will include information about a change of the planar layer transmission depending on the generation power. Then, the laser radiation intensity is considered as the external field intensity in Eq. (1). A change in the film transmission under the action of this field must be also due to variation of the lasing frequency in a nonlinear-refractive medium of the laser diode. The dispersive variation of the transmission in Eq. (1) is assumed to depend on the dimensionless variable of detuning $\Delta = \left(\delta\omega + \frac{d\phi}{dt}\right)\tau_2$, where $\delta\omega$ is the distance (on the frequency scale) between resonances of the laser medium and the planar layer substance; the effective detuning Δ is normalized to the value of reciprocal optical resonance halfwidth in the film $\tau_2^{-1}$ The value of phase derivative $\frac{d\phi}{dt}$ in the lasing field representation $E_g(t) = E_o \exp(i\phi)$ describes nonlinear frequency drift. In the case of cw-pumping, the system of modified kinetic equations is as follows:

$$\frac{dX}{dt} = \frac{1}{\tau_r}\left[Y - \gamma \ln\rho(n)\right] X \quad , \quad \frac{dY}{dt} = \frac{1}{\tau_1}\left(\alpha - Y - XY\right) \quad ,$$

$$\frac{dn}{dt} = \frac{1}{\tau_c}\left[n_o - n - \frac{\sigma\, n\, X}{\rho(n)\left(1+\Delta^2\right)}\right] \quad , \quad \Delta = \left[\delta\omega + \frac{\beta}{\tau}\left(Y-1\right)\right]\tau_2 \quad , \quad (2)$$

$$\rho(n) = \left(1 + \frac{\varkappa n}{1+\Delta^2}\right)^2 + \varkappa^2\left[\frac{\Delta n}{1+\Delta^2} + \beta_c\left(n - n_o\right)\right]^2 ,$$

where

$X = \sigma_g E_0^2$ is intensity of light field, normalized to a level of power of saturation in gain element,

$\sigma_g$ is the section of resonant transition in a gain element,

$Y$ is the variable probability of inversion (in relation to a threshold gain level),

$\gamma$ is parameter back to magnitude of threshold loss,

$ln\rho(n)$ is the factor of intensity losses in an absorbing planar layer,

$\tau_r$ is the time of a life of photons in the cavity,

$\alpha$ is the pumping parameter, normalized to threshold level,

$\beta$ and $\tau_1$ are parameter of a nonlinear refraction ($\alpha$ – factor for a laser medium) and a decay time of the inversion,

$\sigma = \sigma_l/\sigma_g$ – the relation of sections of transitions in film and gain element. The self-modulation effect described by Eqs. (2) is determined by a positive feedback existing in the system with planar layer on the laser diode edge. The model also takes into account that the absorption in the layer decreases with an increasing of a lasing power. In addition to a change in the absorption due to saturation, which is traditionally considered in the theory of laser dynamics, Eqs. (2) can be also used to consider the lasing process affected by the deviations in the planar layer absorption related to the frequency drift, that is, the PSM effect.

The system of Eqs. (2) was numerically integrated by the Runge–Kutta method within the framework of the Cauchy problem with the initial conditions corresponding to the lasing threshold [12]. Thus, it was assumed that $y(t = 0) = 1$, $n(t = 0) = n_0 = 1$; the initial intensity was assumed to be extremely small (but nonzero), $X(t = 0) \approx 10^{-5} \ldots 10^{-4}$ ($X(t = 0) << \alpha - 1$), so that the calculations corresponded to the scheme of small signal amplification. The solutions for $X(t)$ were virtually independent of the $X(t = 0)$ value. On the whole, the set of the calculation coefficients for Eqs. (2), including the nonlinear refraction parameters for both media corresponded to characteristics of the *GaAs*-based materials employed in optics and laser physics.

## 3. APPROXIMATION OF MODEL AND ANALYSIS OF LASING INTENSITY STRUCTURE

Special practical interest is usually shown to self-modulation regimes of radiation of trains of contrast nondamping pulses. Indeed, the solutions of Eqs.(2) for $X(t)$, obtained by numerical modeling with a set of parameters corresponding to an injection laser, predict such regimes at rather small values of absorption in a planar layer. Changes of a transparency of a layer induced by a field because of fluctuations of laser intensity also are insignificant.

It allows to consider the simplified model of generation, in which the difference of populations in the film matter without any inertia changes depending on fluctuations of lasing intensity is considered. High-speed parameters of convertibility and section of transition in a film should exceed essentially magnitudes of similar parameters of the gain element substance. The assumption of rather small parameter of active absorption, as a rule, reachable and realized in a film of *Q*-switcher $(\varkappa << 1)$ then enables, using rather simple approximation to reduce above mentioned model (2) to system of two equations:

$$\frac{dX}{dt'} = \frac{1}{\tau}\left\{y + \frac{\gamma}{2}\left[1 - \varphi(X,y)\right]\right\} \cdot X, \quad \varphi(X,y) = -(\sigma X - 2\varkappa)g + \sqrt{\left[1 + (\sigma X - 2\varkappa)g\right]^2 + 8g\varkappa},$$

$$\frac{dy}{dt'} = \alpha - (1 + X)(1 + y), \quad g(y,\Delta_0) = \left[1 + (\Delta_0 + \Delta)^2\right]^{-1}, \quad \Delta = \beta(y - y_n)\tau_2/\tau, \quad \Delta_0 = \delta\omega\tau_2 \quad . \qquad (3)$$

Here $y = Y - 1$ is the variable of inversion deviation, $\tau$ is the decay time of photons in the cavity.

The value of $\tau$, as well as the time $t'$ in system (3), are normalized on magnitude $\tau_1$. Change of $\varphi$ describes the variable loss because of the film bleaching, magnitude of the form - factor $g$ are determined not only $\Delta_0$ – relative detuning of the line centers of gain and absorption, but also $\Delta$ – value of frequency drift of the cavity mode during lasing. That magnitude depends on a resonant variation of inversion ($y_n$ – its initial value) and is proportional to parameter $\beta$, determining phase-amplitude connection.

### 3.1 Results of numerical modelling

Computer simulation of the process of formation of field intensity also as in the case of calculation on system (2), was carried out it on the basis of Runge – Kutta method for the scheme of an amplification – during the initial moment of time $t'_0 = 0$ the reaching of a threshold condition of generation $\left(y(t'_0) = y_n = 2\gamma\varkappa/\left(1 + \Delta_0^2\right)\right)$ was supposed at rather small values of intensity $X(t_o) << X_s$ ($X_s$ – equilibrium magnitude of intensity). The system (3) was integrated for the parameters corresponding to injection lasers on basis of *AlGaAs* with a direct current (pumping current with continuous magnitude, determined $\alpha$, changed in variants of calculation within the limits of 1.02 ... 1.72, the parameter of linear loss on value has been fixed – $\gamma = 0.17$; the decay time (average free carriers life time in active layer of laser diode) – $\tau_1 = 1.0 \cdot 10^{-9}$c, then with the account of normalization value of $\tau$ undertook equal $\sim 1.0 \cdot 10^3$, for value of $\tau_2$ was accepted $\sim 1.0 \cdot 10^3$).

The received numerical solutions for $X(t)$ which examples are resulted on Fig. 1, have specified an possibiity of two patterns of generation – transitive, i.e. decaying to an equilibrium level (Fig. 1, *a*, *e*), and self-oscillatory. In the latter case temporal display of the solution describes the periodic sequence of symmetric pulses (Fig. 1, *b-d*, *f*). Fig. 1, *a'-f'* also show a course of trajectories on a phase plane of system (3). Attractor of solutions is accordingly or a point of an equilibrium condition – steady focus (Fig. 1, *a'*, *e'*), or a limiting cycle (Fig. 1, *b'-d'*, *f'*). The transition on a regime of self-oscillations occurs after short (depending on values $X(t'_0)$) of a series of transitive pulsations and it is possible in the certain range of a current level at other parameters (3) fixed on values.

Change of inversion in relation to a gain threshold, and also variations of film *Q*-switcher transmission, thus are rather insignificant – up to several percents. Frequencies of pulses, as one would expect for relaxation series, accrued with an increase in a level of pumping current. At the parameters of injection lasers used in calculation the period of following of pulsations on value concerned to sub-nanosecond range, duration of pulses on a level ½ to intensity maximum had the order from several picoseconds up to tens picoseconds. The period and duration of nonlinear pulsations are critical in relation to current and to a level of absorption in the film *Q*-switcher.

### 3.2 The qualitative analysis of model

On a phase plane transition of solutions to a mode of self-oscillations corresponds to an exit of trajectories on a limiting cycle (Fig. 1, *b-d*, *f*). Points $(X_s, \ y_s)$, adequate to equilibrium conditions with nonzero intensity, are inside the area covered with curves of a limiting cycle. The qualitative studying of stability of solutions near to one of equilibrium conditions enables to determinate that region of parameters of system (3) in which this condition is steady. In case of definition of a condition of self-oscillations in solutions (3) interest represents search of zones of parameters where points $(X_s, \ y_s)$ are characterized as unstable focus. Oscillatory leaving of solution trajectories from a vicinity of a point of balance can mean, that its attractor because of an inevitable saturation of an increase $X(t)$, $y(t)$ is the limiting cycle.

Equations for equilibrium conditions $(X_s, \ y_s)$ follow from singular limits of system (3):

$$\sigma X_s = (y_s + \gamma)\left\{2\varkappa/y_s - 1/\left[\gamma \cdot g(y_s, \Delta_o)\right]\right\}, \quad \alpha = (1 + X_s)(1 + y_s). \quad (4)$$

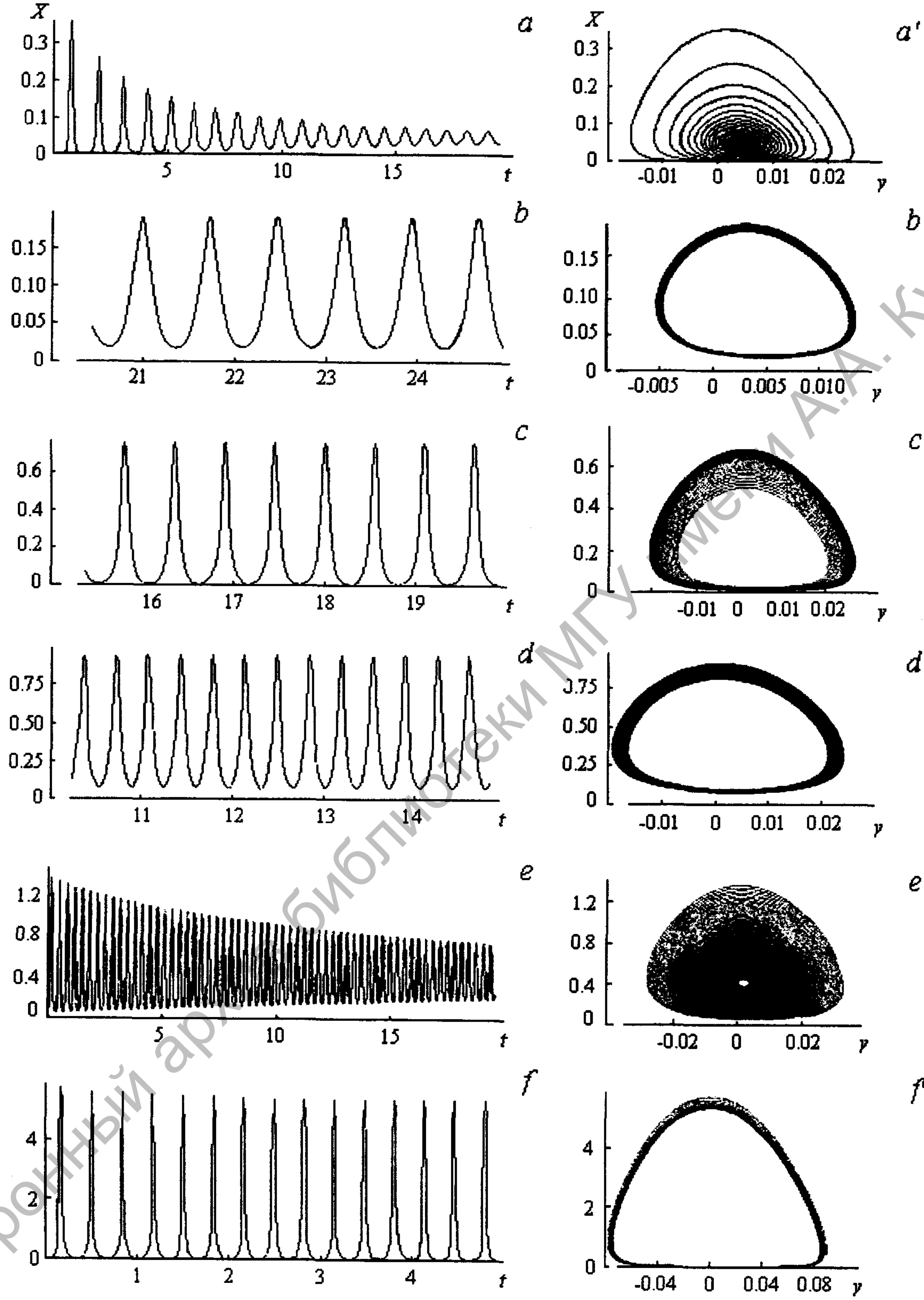


Figure 1: Dynamics of intensity and phase trajectories at $\alpha = 1.05$ (*a*), 1.08 (*b*), 1.17 (*c*), 1.35 (*d*), 1.40 (*e*), 1.70 (*f*), $\varkappa = 0.033$ (*a-e*), 0.05 (*f*), $\Delta_0 = -1.0$ (*a-e*), 0 (*f*), $\sigma = 10$, $\beta = 5.0$ (time scale – in nanoseconds).

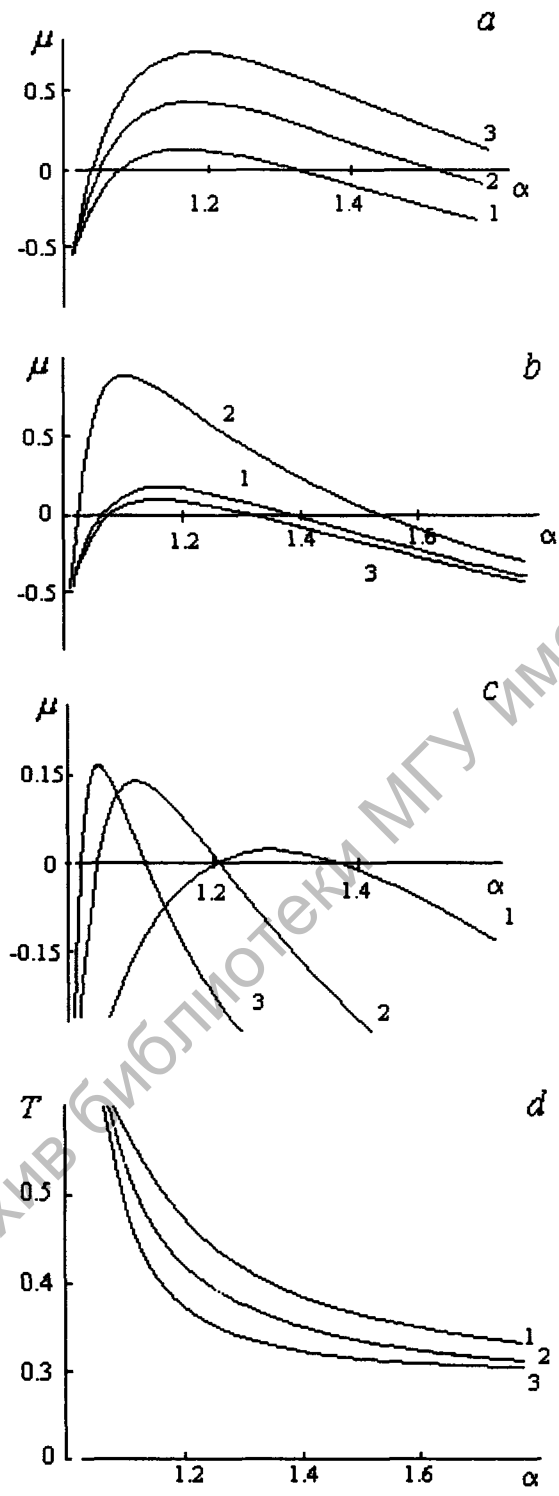


Figure 2: A material part $\lambda$ and a period $T$ depending on the pumping parameter $\alpha$ at $\varkappa = 0.03$ (curve 1), 0.04 (2), 0.05 (3), $\Delta_0 = -1.0$, $\sigma = 10$ (*a*), $\sigma = 5.0$(1), 20 (2), 50 (3), $\varkappa = 0.035$, $\Delta_0 = -1.0$ (*b*), $\Delta_0 = -1.0$ (1), 0.0 (2), 1.0 (3), $\varkappa = 0.035$, $\sigma = 10$ (*c, d*), $\beta = 5.0$ (*a,d*), 2.5 (*b,c*).

Linearization of system (3) in a vicinity of balance points allows to formulate the characteristic polynom for relative $\lambda$ – factor in a parameter of exponential solutions of linearized system (3) analogue. In case the point of balance $(X_s, \; y_s)$ represents the focus, the received quadratic should possess in a complex - connected roots $\lambda_{1,2} = \mu/2 \pm i\sqrt{-D}$. Expression for a material part of roots and a discriminant of the characteristic equation:

$$\mu = -1 - X_s + \frac{1}{\tau}\frac{\sigma\gamma X_s y_s}{\gamma(\sigma X_s - 2\varkappa) + (2y_s + \gamma)/g(y_s, \Delta_o)},$$

$$D = \frac{1}{4}\left[1 + X_s + \frac{\sigma\gamma X_s y_s/\tau}{\gamma(\sigma X_s - 2\varkappa) + (2y_s + \gamma)/g(y_s, \Delta_o)}\right]^2 - X_s\frac{1 + y_s}{\tau}\left\{1 + 2\beta\frac{\tau_2}{\tau}\frac{\gamma y_s(\sigma X_s - 2\varkappa)[\Delta_o + \Delta(y_s)]}{\gamma(\sigma X_s - 2\varkappa) + (2y_s + \gamma)/g(y_s, \Delta_o)}\right\}, \quad (5)$$

together with Eqs. (4) can be based criterion of instability of behavior of trajectories in a vicinity of an equilibrium condition $(X_s, \; y_s)$. Really, the point of balance appears unstable focus if $\mu > 0$, $D < 0$. Such instability corresponds to the periodic solution of linearized equations with frequency $\Omega = \sqrt{-D}$, the initial system (3) is characterized by oscillatory solutions for $X(t)$ and $y(t)$, which can adjust to a limiting cycle.

Basing on of calculation of (4) and (5) it was convenient to search for a range of possible regular solutions on a scale of dependence $\mu$, $D$ on the pumping parameter $\alpha$ at the fixed values of other coefficients of system (3). In this case it is possible to accept $y_s$ as non-negative linearly increasing parameter and formally to consider it as argument of functions $\mu(y_s)$, $\Omega(y_s)$, together with $X_s(y_s)$ and $\alpha(y_s)$. Results of parametrical calculation of dependence of a material part of roots of the characteristic equation and the normalized magnitude of period $T = 2\pi/\Omega$ upon pumping current parameter $\alpha$ are demonstrated on Fig. 2. Near to a balance point and the behavior of solutions (3) adequate to a mode of self-oscillations, it is necessary to expect unstable behavior of trajectories in the limited area of values $\alpha$, which basically reached in injection lasers.

Let's assume, that this range corresponds to a zone of a nonlinear resonance in which the level of modulation of losses due to variations thin-film *Q*-switcher transmission is optimum. The sizes and position of a zone on a scale $\alpha$ show a criticality in relation to values of non-saturated absorption $\varkappa$, to distinction of sections of transitions in an active layer and in modulating film substance, to value of the frequency detuning of line centers (Fig. 2, *a-c*). Comparison of the data of numerical simulation (Fig. 1, *a-f*) with results of the qualitative analysis (the curve 2 Fig. 2, *c*) specifies, that the estimation of range of stability enables to define critical points $\alpha$. Under these values of current factor there is "occurrence" or "disappearance" of a self-oscillatory regime in time displays of solutions (3). The period of a steady limiting cycle, by these displays, appears close to values *T*, which received on estimation $\Omega$ basing on (4), (5) (Fig. 2, *d*).

## 4. CONCLUSIONS

Application of a passive modulating element on the basis of thin films of semiconductor used in optics in the cavity of the solid-state laser can cause an arising of a regime of self-oscillations in output radiation. Such element represents the phase-sensitive component in a laser FB. Result is the generation of regular series of enough short pulses without the use of external modulating devices. Occurrence of self-modulating changes in temporal structure of injection laser radiation at a presence in the external cavity of a thin-film active element on the basis of semiconductor were observed in [13].

The estimation of the phenomenon is above carried out for parameters of injection lasers. These calculation results have an obvious generality and can be used in case of other solid-state laser media. For example, corresponding simulation of similar self-induced process in lasers based on *Nd:YAG*, which generation and nonlinear parameters were estimated on the data [14], has specified a possibility of an arising of a self-pulsation modes with duration up to several nanoseconds. The essential factor with which this occurrence of regular pulsations is stimulated is light field spectrum linewidth broadening. Change of a pumping current level and non-saturated absorption in a modulating element in the certain range can be used for control of time parameters of output intensity pulsations.

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