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ON THE POSSIBILITY OF COHERENT EFFECTS IN THE CONDITIONS OF GENERATION OF ULTRASHORT PULSES BY LASER ON QUANTUM DOTS

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1. Introduction

It is known [1] that the experimental realization of coherent radiation of injection semiconductor lasers' medium is an extremely complicated problem. This circumstance is connected with obvious difficulties of hard conditions' realization for pulse generation of particles and requirement, that the time duration of a pulse τ_0 is small in comparison with relaxation time of polarization τ_2. The study of coherent effects of interaction of light with substance is based on Bloch equations, and the times τ_1 and τ_2 of relaxation, which are included in these equations are considered independent from the field. Note that τ_1 is defined as the lifetime of population's inversion, moreover $\tau_1 >> \tau_2 \approx 10^{-13}$ s. At the same time in the strong field, when the Rabi frequency $\Omega = \mu E/\hbar$ (μ and E are value of dipole moment for optical transition and the amplitude of the light field), becomes comparable with the characteristic frequency of one of the channels of relaxation, the corresponding channel is suppressed [2], and as a consequence the coherent condition $\tau_0 < \tau_2(\mathrm{E})$ is satisfied. It is necessary to note that the Rabi frequency is equal to speed, with which transitions between the levels are coherently excited.

It is known that a generation of light in the regime of coherent radiation of two-level medium in its pure occurrence is a coherent radiation ensemble of particles with endless times τ_1 and τ_2, the amplitude of vector of particle's polarization P changing according to the law

$$P \sim \sin\frac{\mu}{\hbar}\int_{-\infty}^{t} E(t)dt.$$

Subject to size of the corner ("square of momentum")

$$\Psi = \frac{\mu}{\hbar}\int_{-\infty}^{t} Edt$$

particles either absorb or radiate photons resonant to crossover frequency and the medium may radiate even not being inverted.

In work [1] the use of a new version of Q-switched semiconductor laser has allowed to obtain for the density of power 10^8 W/cm^2 (the case of generation of a strong field) and $\Omega\tau_2 \approx 1$ at duration 5ps of pulses.

On the other hand, it is known [3] that the low-dimensional structures are likely to play a major role in the next generation of opto- and nanoelectronic devices. This is approved by the revelation of many nonlinear effects in heterostructures with quantum dots (QD), which take place in relatively lowered fields [4]. Such renormalization of concept of a strong field is generally connected with δ-figurative spectrum of density of states and the oscillator's gigantic strength of optical transitions to unit volume of QD. Moreover, the experimental studies have shown [5] that the lasers on vertically connected QD demonstrate much more optical amplification and their amplification's saturation is absent until of short lengths of the resonator. This will give an opportunity to save a coefficient of absorption of the nonlinear absorber on a high level, having avoided its enlightenment by spontaneous radiation. In order to continue recent progress in the nanoelectronic devices, the well known physical effects relevant to the development of these devices need to be studied.

In this paper we present the results of theoretical investigation of coherent radiation of QD laser's medium, when $\tau_0 > \tau_2(0)$.

2. Theory

In order to estimate the possibility of revelation of coherent effects, we study a simple model of laser.

Suppose that the active region of the QD laser along the axis of the resonator consists of three parts - two amplifying light and one nonlinear absorbing, located between them. Dynamics of radiation will be investigated on model of the QD laser, which is described by the following system of the Maxwell-Bloch equations for homogenously broadened line of radiation.

$$\frac{dF}{d\theta} = -F + \alpha\upsilon, \tag{1a}$$

$$\frac{d\upsilon}{d\theta} = -\beta\upsilon + wF, \tag{1b}$$

$$\frac{du}{d\theta} = -\beta u, \tag{1c}$$

$$\frac{dw}{d\theta} = -F\upsilon. \tag{1d}$$

Here $F = \frac{\mu\tau_{ph}}{\hbar}E,\ \theta = \frac{t}{\tau_{ph}},\ \beta = \frac{\tau_{ph}}{\tau_2(E)},\ \alpha = \frac{\tau_{ph}\eta}{w_0\tau_2(0)}$, where

$$\eta = \frac{2\pi\omega\mu^2\tau_2(0)\tau_{ph}}{\hbar n^2} w_0 N \quad (2)$$

is a parameter of inversion's excess above the threshold value. It defines the modulator's efficiency; τ_{ph} is the lifetime of photon in the resonator. n is the refraction index of medium around QD; ω is the frequency of generation; N is the density of QD, υ and u are the active and reactive parts of dipole moment of QD, w is the inversion for single QD. The inversion for a single QD is defined as the ratio of a number of QD, filled with excitons, to their total number; $w_0 = w\ (t = 0)$ is an initial inversion when the Q-switched is on.

In spite of relative simplicity of system of equations (1a-1d) its full analysis is possible only numerically.

Before passing to the results of analysis of the numerical solution (1a-1d) it should be noted that in structures with QD there takes place a stabilization of exciton in space, and, as a result of that, oscillator strength is fully concentrated on the transition between the discrete levels of QD. Matrix element will have a huge value, as it depends on recover of the wave functions of the ground state and functions of excite state with electron and a hole in the same quantum dot. So, the condition $\Omega\tau_2(E) \approx 1$ may be carried out in relatively lowered fields $E \approx 10^2 \div 10^3$ V/cm.

The numerical integration of the system (1a-1d), when $\eta = 5$ and more, demonstrates properties typical for coherent interaction between the pulse and medium of QD laser. In the course of pulse duration the amplitude of field's strength makes a series of oscillations crossing zero. Of course, this is a consecutive transition of energy from the substance to a field, and vice versa. The form of laser pulse is similar to the form of light pulse propagating in non-relaxation medium with resonance amplification [6]. Indeed the field of pulse becomes divided into subpulses. In Fig.1 there is presented the dependence of amplitude of the pulse field from the time for the homogeneously broadened line of amplification with $\eta = 8$, $\tau_2 \to \infty$, when $E > E_0 = \hbar/\mu\tau_{ph} = 1$.

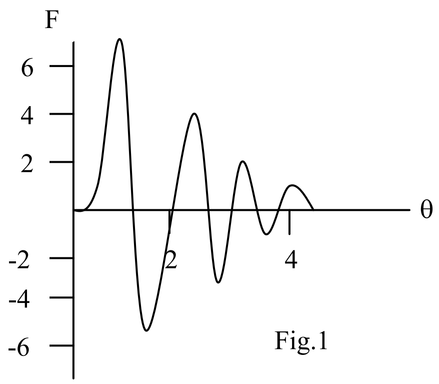

Fig.1

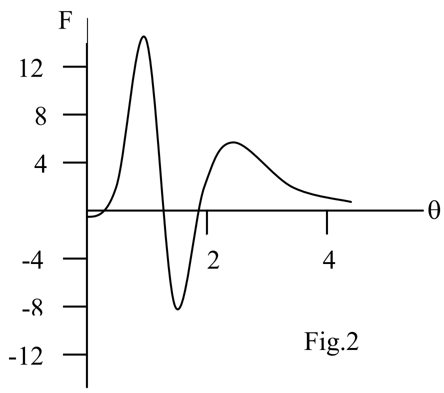

Fig.2

The analytical solution may be found for large η, if in (1) E / τ_{ϕ} and u/τ_2 are neglected, i.e. supposing that the duration of a subpulse is small in comparison with τ_{ph} in the resonator and the relaxation τ_2 is suppressed. Then we find the equation for the area of a subpulse $\Psi = \frac{\mu}{\hbar}\int_{-\infty}^{t} E(t')dt'$, which is

$$\frac{d^2\Psi}{dt^2} - \frac{1}{\tau_0^2}\sin\Psi = 0. \tag{3}$$

This equation is well known in the theory of solitons [7]. If $\tau_0 > 0$, estimations it has the solution in the form of a single stationary pulse

$$E(t) = \frac{2\hbar}{\mu\tau_0}\sec h\frac{t-t_0}{\tau_0}, \quad \tau_0 = \sqrt{\tau_2(0)\tau_{ph}\cdot\eta^{-1}}. \tag{4}$$

When $t = t_0$ the field of a subpulse reaches its maximum: all the energy reserved initially in substance of the laser, is now in the form of an electromagnetic field and according to (2) and (4), the density of energy of a field is expressed as

$$\frac{n^2E^2}{8\pi} = \hbar\omega w_0 N, \quad \tau_0 = \sqrt{\hbar / 2\pi\omega\mu^2 w_0 N}. \tag{5}$$

It is seen that the density of energy of the field grows with the increase in the initial inversion, and the duration of a subpulse decreases. Now we consider a more realistic case, when τ_2 increases with the growth of the field and is limited by the lifetime of photon in the resonator. So, the effective relaxation time of polarization $\tau_2(E)$ may be approximated by the relation of

$$\tau_2(E) = \tau_2(0) + \tau_{ph} th\frac{E}{E_0}. \tag{6}$$

As it is shown in Fig.2, the restriction of the growth of $\tau_2(E)$ leads to the sharp reduction of the number of field oscillations. The fact, that should be paid attention to, is that the coherent interaction of a field with the QD laser medium is saved. The following parameters were chosen for computation: $\tau_2(0) = 10^{-13}$ s, $\tau_{ph} = 3\cdot10^{-12}s$, $\mu = 2\cdot10^{-15}CGSE$, $\eta = 10$, $\tau_2(E) = 3\cdot10^{-12}s$.

Conclusion

The generation of ultrashort pulses by Q-swiched QD semiconduction laser is investigated theoretically. The theoretical treatment of the QD laser dynamics is based on the Maxwell-Bloch equations, taking into consideration homogeneous broadening mechanism and the dependence of the relaxation time of polarization on the amplitude of the pulse electromagnetic field.

The division of a pulse field into subpulses indicates the coherent interaction of a pulse with the laser medium. In the considered problem the basic property of QD laser was the fulfillment of the condition $\Omega\tau_2 \approx 1$ that becomes possible in case of relatively lowered fields. For getting great values of η it is necessary to have structures of QD ensemble with density $N = 10^{12}$ cm^{-2} and more, which is the limit of the technologies' capacity of creating such structures. To our mind, the further increase in the meaning of η may be carried out by means of growth of a number of vertically-stored layers.

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