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Dynamics of a semiconductor laser and time marks*

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Abstract**. The possibility of using relaxation oscillations in a semiconductor laser to obtain time marks is analysed.**

Keywords: *semiconductor laser, relaxation oscillations, time marks.*

At present femtosecond pulses are widely used in laser metrology [1]. The stabilisation of the repetition period of femtosecond pulses with the help of a microwave frequency standard makes it possible to obtain time marks, which can be detected with an accuracy determined by the duration of a single pulse.

The generation of a long train of femtosecond pulses belongs to high laser technologies. Meanwhile, it is well known that, when relaxation oscillations are excited in lasers of class B, they can generate a continuous train of sufficiently short pulses at a comparatively weak modulation of pump current or Q-factor [2]. The duration of such pulses depends on the laser parameters, and the pulse duration of 10^{-12} s is quite accessible for semiconductor lasers. In this case, the accuracy of fixing the time mark is $\sim 10^{-12}$ s. Such an accuracy proves to be sufficient for a number of practical applications.

To elucidate the possibilities of this method for obtaining time marks, consider the standard dynamic model of a semiconductor laser:

$$\frac{\mathrm{d}E}{\mathrm{d}t} = -\frac{1}{2}\left(\frac{1}{\tau_{\mathrm{c}}} + \mathrm{i}\Delta\right)E + \frac{1}{2}g(n)(1+\mathrm{i}\alpha)E,$$
$$\frac{\mathrm{d}n}{\mathrm{d}t} = J - \frac{1}{\tau_{\mathrm{s}}}n - g(n)\frac{|E|^2}{8\pi\hbar\omega}, \tag{1}$$

where τ_{c} is the decay time in the resonator; J is the pump current; τ_{s} is the inversion decay time; $g(n)$ is the form factor; n is the population inversion; Δ is the detuning of the laser frequency from the resonance-transition frequency; and α is the coefficient of amplitude – phase coupling. In the case of a weak Q-modulation described by the expression

$$\frac{1}{\tau_{\mathrm{c}}} = \frac{1}{\tau_{\mathrm{c0}}}(1 + m\cos\Omega t), \tag{2}$$

the laser can be put into the regime of regular relaxation intensity oscillations, as shown in Fig. 1. The period T of these pulsations is determined by the Q-modulation frequency Ω and is equal to $T = 2\pi/\Omega$. If the Q-modulation frequency is specified by a high-frequency microwave standard, then the pulsation period in the laser will be also controlled by this standard.

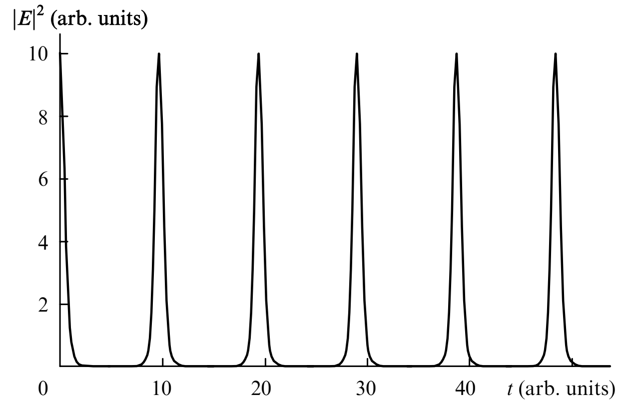

Figure 1. Relaxation pulsations of radiation in a class B laser.

For convenience, we introduce the pulsation 'swing' C as the ratio of the laser radiation intensity to its average value. The analytic theory of relaxation oscillations of laser radiation was developed in papers [3, 4]. According to this theory, the pulsation period is related to their swing by the expression

$$T(C) = \frac{2}{\Omega_0}\left[\sqrt{C} + \frac{2}{\sqrt{C}}\operatorname{arcosh}\left(\frac{C}{2}\right)^{1/2}\right], \tag{3}$$

where

$$\Omega_0 = [(\eta - 1)/(\tau_{\mathrm{s}}\tau_{\mathrm{c0}})]^{1/2} \tag{4}$$

is the frequency of relaxation oscillations; $\eta = J/J_{\mathrm{th}}$; and J_{th} is the threshold current. One can see from expression (3) that the Q-modulation frequency and, hence, the pulsation period determine the swing of pulsations. When the pulsation swing is large enough, we have

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$$C \approx \pi^2 \frac{\Omega_0^2}{\Omega^2}. \tag{5}$$

Intensity pulsations have a large swing when the modulation depth m exceeds a threshold value

$$m_{\rm th} \approx \frac{\eta}{6\pi} \frac{C^2}{\ln C}. \tag{6}$$

It follows from relations (4) and (5) that the pulsation swing is related to the laser parameters as

$$\eta - 1 = \frac{C}{\pi^2} \tau_{\rm s} \tau_{\rm c0} \Omega^2. \tag{7}$$

The stability of the pulsation period should be determined formally only by the stability of a modulating radiation source. However, the presence of spontaneous emission leads both to fluctuations in the intensity of output pulses and in their repetition period. The effect of spontaneous emission is especially strong between the pulses. According to Refs [3, 4], the ratio of the radiation intensity between laser pulses to the average intensity of laser radiation is described by the expression

$$\frac{E_{\rm min}^2}{E_{\rm av}^2} = {\rm e}^{-C/2}. \tag{8}$$

To reduce the effect of fluctuations caused by spontaneous emission, the intensity $E_{\rm min}$ should exceed the intensity of spontaneous emission to one (generated) mode. By using the probability of spontaneous emission in a resonator calculated in Refs [5, 6] and expression (8), we can show that this requirement leads to the condition

$$C < 2 \ln \left(\frac{V E_{\rm sat}^2}{\hbar\omega} \frac{\eta - 1}{\eta} \right), \tag{9}$$

where $E_{\rm sat}$ is the saturating field amplitude and V is the volume of the generated mode. This condition restricts the parameter C in a semiconductor laser:

$$C < 20 - 30. \tag{10}$$

However, the question about the stability of the interval between time marks generated by a semiconductor laser should be finally resolved in experiments.

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