REGULATION OF THE PUMPING CURRENT AS A METHOD FOR CONTROLLING THE TEMPERATURE OF THE ACTIVE REGION OF A PULSED SEMICONDUCTOR LASER

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It is shown theoretically that a constant temperature can be maintained in the active region of a semiconductor injection laser during the period of the radiation pulse by regulating the pumping current.

Single-frequency semiconductor injection lasers (ILs) are finding wide application in spectroscopy, holography, laser ranging, heterodyning, in coherent optical coupling systems, and other objects of quantum electronics, where stability of the radiation frequency is the main requirement [1-4]. It is well known that the frequency of stimulated radiation depends strongly on the temperature of the active region. This makes it necessary to control the temperature of the radiating p–n junction. Thus, for example, for laser amplifiers and coherent optical coupling systems, where frequency stability of the order of 10^{-7} is required for optical heterodyning [5-7], the temperature of the active region must be maintained constant with an accuracy of $\pm 10^{-3}$ K and higher [1, 7].

The problems of temperature control of a continuous wave IL under conditions when the temperature of the surrounding medium changes were studied in [6, 8]. In the case of a pulsed laser the problem of maintaining an average but not instantaneous temperature is usually solved. At the same time, under conditions of pulsed pumping high-frequency temperature waves arise in the active region, and this results in spreading of the spectral band and could cause switching of the predominant modes. Thus for IL based on materials such as GaAs a displacement by the intermodal splitting occurs when the temperature changes by 0.1-1 K [9]; this is comparable with the amplitude of oscillations of the instantaneous temperature of the active region. Thus for a pulsed laser, in addition to maintaining constant the average temperature of the laser diode, there also arises the problem of thermostatic control of the active region during the period of the pumping pulse. In [10] it is shown that optimal control of the temperature of the active region T_a of a pulsed IL can be achieved by applying a preceding cooling pulse from the side of the outer face of the laser diode. In [11] the suppression of heat waves in the active region of the IL in the two-pulse pumping regime was investigated theoretically.

We note that the methods of dynamic thermostatic control studied in [10, 11] do not make it possible to achieve the condition T_a = const exactly. In this connection, in [10, 11] the problems of reducing to a minimum the standard deviation of the function $T_a(t)$ from its average value over the period of the pumping pulse were solved. In reality, however, it is precisely accurate control of the temperature of the active region in the period when the laser is radiating that is of greatest interest. In this paper it is proposed that this problem be solved by using the delay of the stimulated radiation relative to the current pulse combined with regulation of the pumping current in the period of normal lasing. In accordance with this method, a square current pulse, corresponding to a prescribed energy of the radiation pulse, is applied to the laser during the period of the initial delay of lasing. In this case, by the time normal lasing arises the temperature of the active region increases to some value corresponding to the amplitude of the pumping pulse. Then, in order to stabilize the radiation frequency the pumping current must be reduced so that during the entire lasing pulse the temperature of the active region remains constant. In what follows, the method described above is proved mathematically.

The following assumptions were adopted in constructing the thermal model of an IL [11]: The power dissipated in the IL is concentrated in the plane of a flat p-n junction with a width of 2b at a depth h from the surface whose temperature is held constant (Fig. 1a); the double-heterojunction laser is considered to be a uniform semi-infinite solid mass with

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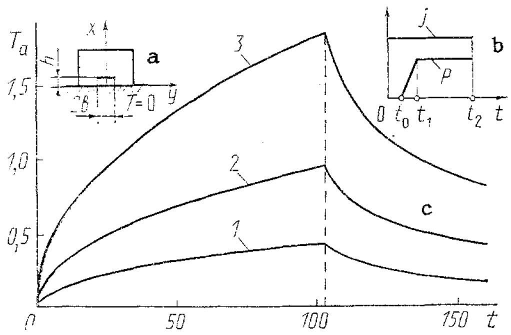

Fig. 1. Geometric model (a), transient characteristic (b), and time-dependence of the temperature of the active region (c) of a semiconductor injection laser: $j = 2j_t$ (1), $5j_t$ (2), and $10j_t$ (3). T_a, K; t, nsec.

parameters characteristic for the bounding layers; the temperature dependence of the physical parameters is neglected; by the time the next pulse is switched on the laser reaches equilibrium with the surrounding medium, whose temperature is taken as the reference point.

Under the assumptions made above, the propagation of heat in a strip injection laser is described by the two-dimensional equation of nonstationary heat conduction

$$\frac{\partial T(x,\ y,\ t)}{\partial t} - a^2\left[\frac{\partial^2 T(x,\ y,\ t)}{\partial x^2} + \frac{\partial^2 T(x,\ y,\ t)}{\partial y^2}\right] = \frac{a^2}{\varkappa}\,\delta(x-h)\,[e(y+b)-e(y-b)]\,q(t),$$

$$T(x,\ y,\ 0) = 0,\ T(0,\ y,\ t) = 0,\ 0 < x < \infty,\ -\infty < y < \infty. \tag{1}$$

In determining the intensity of the heat source q(t) the dynamics of the radiation of the laser and the character of the time dependence of the current must be taken into account. Figure 1b shows an idealized transient characteristic for a laser with a square pumping pulse ($j(t) = \text{const},\ 0 \le t \le t_2$). It is assumed that the stimulated emission is initially delayed with respect to the current pulse by the time t_0 of the order of several nanoseconds [9, 12]. It is also assumed that radiation does not arise instantaneously at the moment $t = t_0$: Under the conditions of constant current the radiation power grows linearly during the time $\delta t = t_1 - t_0$ up to the level of normal lasing.

In accordance with the method proposed for maintaining a constant temperature we shall assume that the pumping current is constant only in the period preceding normal lasing, after which the pump current becomes a decreasing function of time:

$$j(t) = \begin{cases} j_1 = \text{const},\ 0 \leqslant t \leqslant t_1, \\ j_2(t),\ t_1 < t \leqslant t_2. \end{cases} \tag{2}$$

In this case the function q(t) in Eq. (1) assumes the form

$$q(t) = q_0 e(t) - q_0 e(t-t_0) + q_1 e(t-t_0) - q_1 e(t-t_1) + q_2 e(t-t_1) - q_2 e(t-t_2), \tag{3}$$

where

$$q_0 = j_1 V,\ q_1 = j_1 V - \eta_d V (j_1 - j_t)\frac{t-t_0}{\delta t},\ q_2 = j_2(t)\,V - \eta_d V\,(j_2(t) - j_t) \tag{4}$$

is the intensity of the heat source in separate time segments [9].

The problem (1)-(4) was solved by the Green's function method. The corresponding expression for the average temperature of the strip $T_a(t) = \frac{1}{2b}\int\limits_{-b}^{b} T(h,\ y,\ t)\,dy$ with arbitrary function $j_2(t)$ has the form

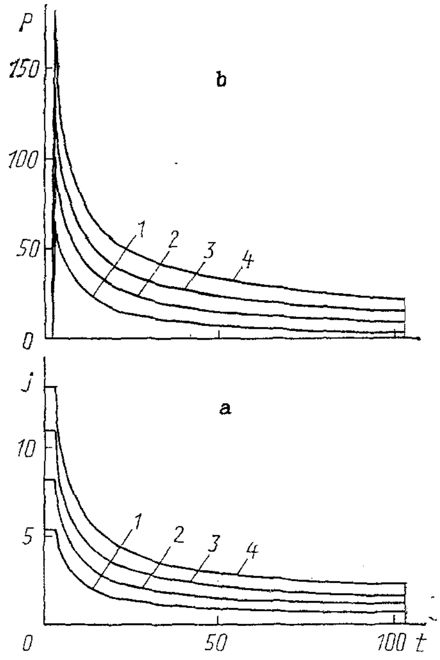

Fig. 2

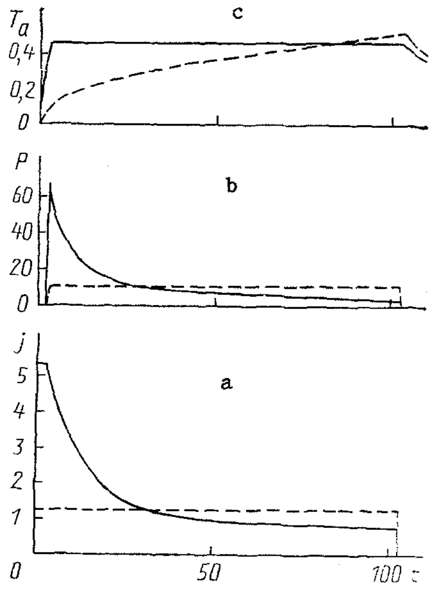

Fig. 3

Fig. 2. Time dependence of the pumping current (a) and radiation power (b) corresponding to the condition of constant temperature of the active region: 1) W_0 = 1 nJ; 2) 2; 3) 3; 4) 4. j, kA/cm²; P, mW.

Fig. 3. Pumping current density (a), the radiation power (b), and the temperature of the active region (c) as a function of time under the condition of contant temperature (solid lines) and with a constant pumping current (dashed lines).

$$T_a(t)=\begin{cases} cq_0\int\limits_0^t K(t-\tau)\,dt, \quad 0\leqslant t\leqslant t_0, \\ c\,[q_0\int\limits_0^{t_0} K(t-\tau)\,dt+\int\limits_{t_0}^{t} q_1(\tau)\,K(t-\tau)\,d\tau], \quad t_0<t\leqslant t_1, \\ c\,[q_0\int\limits_0^{t_0} K(t-\tau)\,d\tau+\int\limits_{t_0}^{t_1} q_1(\tau)\,K(t-\tau)\,d\tau+ \\ +\int\limits_{t_1}^{t} q_2(\tau)\,K(t-\tau)\,d\tau], \quad t_1<t\leqslant t_2, \end{cases} \tag{5}$$

where

$$K(t-\tau)=[1-\exp(-4h^2z^2)]\,\{2bz\,\mathrm{erf}\,(2bz)-\frac{2}{\sqrt{\pi}}[1-\exp(-4b^2z^2)]\}\ ;z=\frac{1}{\sqrt{4a^2(t-\tau)}}. \tag{6}$$

We shall first study the case of a square pumping pulse, when $j_2(t)\equiv j_1$, $t_1 < t \leq t_2$. In this case, all functions on the right hand side of Eq. (5), including q_2, are determined, and the temperature $T_a(t)$ can be calculated at any time. The results of the numerical calculations for different pumping currents are presented in Fig. 1c. In the calculations the initial data typical for gallium-arsenide injection lasers were employed [2, 13]: j_t = 500 A/cm², V = 1.5 V, η_d = 0.3, h = 4 μm, b = 5 μm, L = 300 μm, a^2 = 0.08 cm²/sec, κ = 0.136 W·cm⁻¹·K⁻¹, t_0 = 2 nsec, δt = 1 nsec, Δt = 100 nsec.

It is clear from Fig. 1c that the average temperature of the strip is strongly unstable in time. The heating of the active region toward the end of the radiation pulse ($t = t_2$) increases with the pumping current and is equal to 0.43 K for $j = 2j_t$ and 1.85 K for $j = 10j_t$. This is substantially greater than the range of temperature variations which lead to mode switching in gallium-arsenide lasers.

We now formulate the problem of maintaining a constant temperature. Let, in accordance with Eq. (2), a square pulse with pumping-current density $j = j_1$ be applied to the IL in the period $0 < t \leq t_1$. By the time t_1 the temperature of the active region increases to the value $T_a(t_1)$, determined uniquely by the relation (5). We shall choose a form of the current $j_2(t)$ in the segment $t_1 < t \leq t_2$ such that the average temperature of the strip is constant:

$$T_a(t) = T_a(t_1) = \text{const}, \quad t_1 < t \leqslant t_2. \tag{7}$$

In this case the radiation power

$$P(t) = \eta_d V (j_2(t) - j_t) S \tag{8}$$

becomes a function of time, and the pulse energy is determined uniquely in the form of the integral

$$W = \int_{t_1}^{t_2} P(t)\, dt. \tag{9}$$

Taking a different value of j_1, we obtain a new function $j_2(t)$ and a new energy $W(j_1)$. We shall state the problem of maintaining a constant temperature as follows: Choose a parameter j_1 and a corresponding function $j_2(t)$ so that the condition of constant temperature (7) is satisfied and at the same time a prescribed pulse energy is achieved

$$W(j_1) = W_0. \tag{10}$$

We now determine the function $j_2(t)$ corresponding to the condition of constant temperature. Using the relation (7), together with Eq. (5), we arrive at a Volterra integral equation of the first kind for the function sought $j_2(t)$:

$$\int_{t_1}^{t} q_2[j_2(\tau)]\, K(t-\tau)\, d\tau = f(t), \quad t_1 < t \leqslant t_2, \tag{11}$$

where

$$f(t) = q_0 \int_0^{t_0} K(t_1-\tau)\, d\tau + \int_{t_0}^{t_1} q_1(\tau) K(t_1-\tau)\, d\tau - q_0 \int_0^{t_0} K(t-\tau)\, d\tau - \int_{t_0}^{t_1} q_1(\tau) K(t-\tau)\, d\tau. \tag{12}$$

As follows from Eq. (6), the kernel $K(t - \tau)$ of the integral equation (11) is discontinuous on the diagonal $t = \tau$. To eliminate this singularity we transform Eq. (11) into an equivalent Volterra equation of the second kind [14]:

$$q_2(t) + \frac{\int_{t_1}^{t} [q_2(\tau) - q_2(t)]\, K(t-\tau)\, d\tau}{\int_{t_1}^{t} K(t-\tau)\, d\tau} = \frac{f(t)}{\int_{t_1}^{t} K(t-\tau)\, d\tau}. \tag{13}$$

Now the difference $q_2(\tau)-q_2(t)$ vanishes on the diagonal and the indicated singularity vanishes.

The equation (13) was solved numerically by the method of quadratures [14]. The parameter j_1, satisfying Eq. (10), was found by the method of Newtonian iterations. The values of j_1 and the function $j_2(t)$ were found for different pulse energies W_0.* The computational results are presented in Figs. 2 and 3.

*Investigations of the integral equation (13) in the limit $t \to t_1$ showed that the function $q(t)$ must be continuous at the point $t = t_1$, i.e., $q_2(t_1) = q_1(t_1)$, and therefore $j_2(t_1) = j_1$.

It is obvious from Fig. 2 that at the moment t_1 the pumping current and correspondingly the radiation power must be relatively high. Thus for a pump energy of only 1 nJ $j_1 = 10j_t$. Then, according to the condition of constant temperature, the current and radiation power decrease in time, and in addition the curves are steepest in the first 10 nsec. This circumstance must be taken into account when this method of maintaining a constant temperature is employed.

The solid lines in Fig. 3 show as a function of time the pumping current density, the radiation power, and the temperature of the IL strip with $W_0 = 1$ nJ. The dashed lines show these quantities as a function of time under conditions of constant current, corresponding to the prescribed pulse energy. One can see from the figure that for j = const the range of variation of the temperature of the active region is equal to 0.51 K, while an optimal choice of the function $j_2(t)$ makes it possible to maintain constant the temperature of the radiating strip.

Thus control of the pumping current can be an effective method for stabilizing the frequency of the laser radiation.

NOTATION

b and h, dimensions of the laser in accordance with Fig. 1a; S = 2bL; L, length of the resonator; T, temperature; x and y, coordinates; t, time; a^2, thermal diffusivity; κ, thermal conductivity; $\delta(u)$, a Dirac δ-function; e(u), Heaviside unit step function (e(u) = 0 for u < 0 and e(u) = 1 for u ≥ 0); t_0, delay time of the radiation pulse with respect to the pumping pulse; t_1, moment of onset of normal lasing; t_2, width of the pumping pulse; $\Delta\delta = t_1 - t_0$, radiation front; $\Delta t = t_2 - t_1$, width of the radiation pulse; T_a) mean integral temperature of the radiating strip; j_t and j, threshold current density and the pumping current density; j_1, initial value of the pumping current density; $j_2(t)$, punping current density in period of normal lasing; $C = a^2/(2\kappa\sqrt{\pi b})$; η_α, differential quantum efficiency; V, direct voltage drop across the p–n junction; and W, energy of the radiation pulse.

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