APPLICATION OF THE "DOUBLE PULSE" METHOD FOR THE SUPPRESSION OF THERMAL WAVES IN A SEMICONDUCTOR INJECTION LASER

V. A. Semenyuk and T. V. Pilipenko UDC 621.375.826

A theoretical foundation is given for the feasibility of eliminating unwanted temperature peaks in the active zone of a pulsed injection laser by the input of a prepulse.

Single-frequency lasing must be maintained when semiconductor injection lasers (IL's) are used in spectroscopy, heterodyning, optical amplification, and coherent optical communications [1-4]. The main cause of wavelength shift and spreading of the spectral emission band is a variation of the temperature in the active zone of the IL. Consequently, the demand for high radiation stability calls for effective thermostatting. For example, coherent optical communications require a temperature instability of ±0.001°C or less [1, 4].

Two factors are responsible for temperature variations in the active zone: fluctuations of the temperature of the medium and variation of the pump current. Temperature fluctuations of the medium can be compensated by thermoelectric coolers [5-7]. Periodic current fluctuations in pulsed IL's generate high-frequency thermal waves, which tend to spread the spectral band and promote multimode lasing. These unwanted effects cannot be eliminated by any kind of external thermal action, because the time constant of the attached thermoregulators is many times the thermal relaxation time for the IL [8].

The dynamic thermal characteristics of semiconductor IL's have been investigated in several papers [2, 9-11]. Aspects of frequency stabilization using thermoelectric cooling, electrical heating, and pump current control have also been studied [3, 4, 9]. A "double pulse" method has been discussed [12] as a means of creating a dynamic temperature waveguide in the active zone. In the present article we give a theoretical foundation for the possibility of employing this method to suppress thermal waves in a laser diode.

This possibility is supported by the following considerations. During the pumping period the temperature of the active zone increases to a certain final value T_f. The basic concept of dynamic thermostatting is to "drive up" the temperature of the active zone to a level close to T_f by means of a prepulse prior to the start of pumping. The subsequent input of the pump pulse then no longer raises the temperature appreciably. The prepulse can be a directly transmitted pulse with an amplitude not exceeding the threshold, or it can be negative pulse sent through a reverse-biased pn junction.

The time variation of the temperature of the active zone in the pumping period depends on the temperature distribution in the laser at the start of the pulse. This distribution, in turn, depends one-to-one on the power q_1 and duration t_1 of the prepulse. It is important to find values of q_1 and t_1 that correspond to the highest possible temperature stability of the pn junction during the pumping period. This problem is solved below.

The following assumptions are used in forming the thermal model of an IL: All the power developed in the IL is concentrated in the plane of a strip pn junction of width 2b and depth h from the thermostatted surface (Fig. 1); the double heterostructure (DH) laser is regarded as a homogeneous semiinfinite block with parameters typical of the bounding

Technological Institute of the Refrigeration Industry, Odessa. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 57, No. 1, pp. 140-145, July, 1989. Original article submitted April 13, 1988.

0022-0841/89/5701-0847$12.50

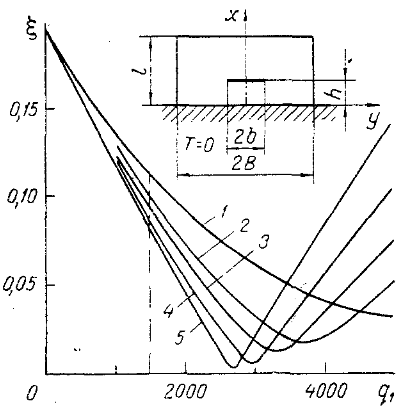

Fig. 1

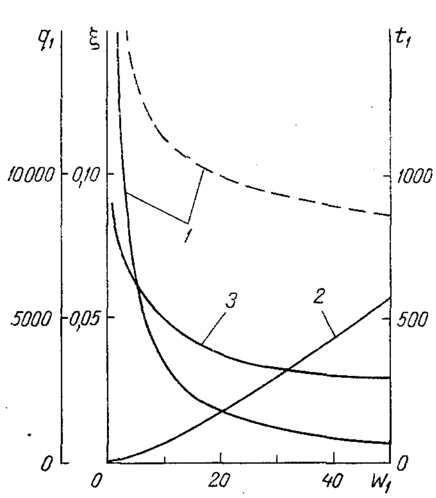

Fig. 2

Fig. 1. Temperature instability ξ, K, of the emitting strip vs prepulse power q_1, W/cm^2, for several values of the prepulse energy W_1 ($j = 2j_t$, $t_2 = 100$ nsec, $\Delta t = 0$). 1) $W_1 = 10$ nJ; 2) 20; 3) 30; 4) 50; 5) 100 nJ.

Fig. 2. Temperature instability t_1, nsec, of the emitting strip (curves 1), optimum duration of the prepulse (curve 2), and optimum power of the prepulse (curve 3) vs prepulse energy W_1, nJ ($j = 2j_t$, $t_2 = 100$ nsec, $\Delta t = 0$). The dashed curve represents the instability for the case of a direct pulse of threshold amplitude.

layers*; the temperature dependence of the physical parameters is ignored; by the time the next prepulse is initiated, the laser is in thermal equilibrium with the surrounding medium, whose temperature is taken as the reference point; the time dependence of the heat-release density is determined by a sequence of two rectangular pulses q_1 and q_2 of duration t_1 and t_2 with a delay time Δt:

$$q(t) = q_1 e(t) - q_1 e(t - t_1) + q_2 e(t - t_1 - \Delta t). \quad (1)$$

Under the stated assumptions, heat transmission in the strip IL is described by the two-dimensional unsteady heat conduction equation

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

$$T(x, y, 0) = 0, \; T(0, y, t) = 0, \; 0 < x < \infty, \; -\infty < y < \infty. \quad (2)$$

Using the Green's function method, we find

$$T(x, y, t) = \frac{1}{4\varkappa\sqrt{\pi}} \sum_{m=1}^{3} g_m \int_{z_m}^{\infty} \frac{1}{z^2} [\exp(-\alpha_1^2 z^2) - \exp(-\alpha_2^2 z^2)] \quad [\mathrm{erf}(\beta_1 z) - \mathrm{erf}(\beta_2 z)]\, dz. \quad (3)$$

We adopt the average temperature of the strip as the thermostatic value:

*It has been shown [13] that the influence of the upper and side boundaries can be disregarded in strip IL's with $b \ll B$ and $h \ll \ell$, even in continuous-wave operation. Consequently, the condition of semiinfinite extent holds up very accurately for short-duration pulse; for durations up to 2 μsec, the dynamic thermal characteristics of a DH laser are determined by the properties of the AlGaAs layers adjacent to the active zone [11].

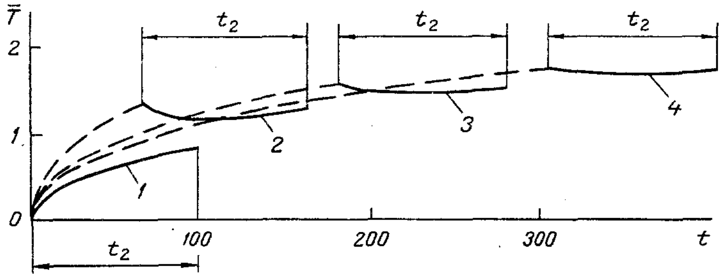

Fig. 3. Dynamics of the temperature $\bar{T}$, K, of the emitting strip during the periods of the prepulse (dashed parts of the curves) and the pump pulse (solid part) for $j = 2j_t$, $t_2 = 100$ nsec, and $\Delta t = 0$. 1) $W_1 = 0$ nJ; 2) 10; 3) 20; 4) 30 nJ.

$$\bar{T}(t) = \frac{1}{2b}\int_{-b}^{b} T(h, y, t)\,dy = \frac{1}{2\varkappa\sqrt{\pi}}\sum_{m=1}^{3} g_m \left\{\frac{1-\exp(-4h^2z_m^2)}{z_m} \times \right.$$
$$\times\left[\operatorname{erf}(2bz_m) - \frac{1-\exp(-4b^2z_m^2)}{2bz_m\sqrt{\pi}}\right] + \frac{2h^2}{b\sqrt{\pi}}[\operatorname{Ei}(-4h^2z_m^2) -$$
$$\left. -\operatorname{Ei}(-4(h^2+b^2)z_m^2)] + 8h^2\int_{z_m}^{\infty}\exp(-4h^2z^2)\operatorname{erf}(2bz)\,dz\right\}. \quad (4)$$

We associate the function $\bar{T}(t)$ with the value averaged over the pump period

$$T_m = \frac{1}{t_2}\int_{t_1+\Delta t}^{t_1+\Delta t+t_2}\bar{T}(t)\,dt. \quad (5)$$

The variables z_m and g_m in Eq. (4) depend one-to-one on the prepulse parameters t_1 and q_1, so that each set (t_1, q_1) corresponds to a unique function $\bar{T}(t; t_1, q_1)$ and a unique value of $T_m(t_1, q_1)$. We formulate the following optimal problem: Find a t_1 and a q_1 and the corresponding quantities $\bar{T}(t)$ and T_m from Eqs. (4) and (5) subject to the condition

$$J(t_1, q_1) = \int_{t_1+\Delta t}^{t_1+\Delta t+t_2}[\bar{T}(t; t_1, q_1) - T_m(t_1, q_1)]^2\,dt = \min. \quad (6)$$

This formulation needs to be refined. If the prepulse energy is not limited, problem (6) reduces to the condition $t \to \infty$, $q_1 = q_2$. Thus, only for a prepulse of infinite duration is it possible to attain a constant temperature during the pump period. It is clear, however, that this case is inadmissible from the energy point of view. In order for the optimal problem to have physical significance, an upper bound must be placed on the prepulse energy:

$$t_1q_1S \leqslant W_1 \quad (7)$$

or the duration of the prepulse must be fixed.

Problem (4)-(7) has been solved numerically. An energy balance equation of the form $q_2 = jV - \eta_d V(j - j_t)$ was used to determine q_2 for a given j. Typical initial data for gallium arsenide IL's were used: $j_t = 1000$ A/cm²; V = 1.5 volts; $\eta_d = 0.3$; h = 4 μm; b = 5 μm; L = 300 μm; $a^2 = 0.08$ cm²/sec; $\varkappa = 0.136$ W·cm⁻¹·K⁻¹ [11-14]. The results of the calculations are shown in Figs. 1-4.

The extremal behavior of the temperature instability ξ of the emitting strip as a function of the prepulse power is illustrated in Fig. 1. As q_1 is increased, the value of ξ decreases sharply, attaining a minimum whose depth depends on the energy W_1. It is evident from the figure that the temperature stability of the active zone can be enhanced severalfold by the input of a prepulse, even at low energies (10-30 nJ).

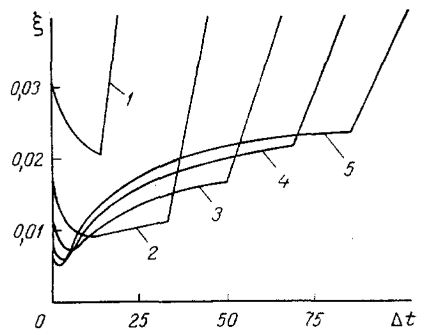

Fig. 4. Temperature instability of the emitting strip vs pump pulse delay time Δt, nsec ($j = 2j_t$, t_2 = 100 nsec). 1) W_1 = 10 nJ; 2) 20; 3) 30; 4) 40; 5) 50.

The most interesting case in practice is a direct prepulse of threshold power ($q_{1t} = j_tV$ = 1500 W/cm²). This power does not satisfy the optimality conditions (Fig. 1). Nonetheless, the instability can be cut in half by means of a direct prepulse, even at an energy of 20 nJ.

Figure 2 shows the optimum parameters t_1, q_1 and the corresponding values of ξ as functions of the energy W_1. As W_1 is increased, the instability ξ decreases until, at W_1 = 50 nJ, it is only $6 \cdot 10^{-3}$ K. Consequently, the double-pulse technique provides an effective dynamic thermostatting method. For threshold-level direct prepulses (dashed curve) an increase in the energy causes ξ to decrease appreciably only in the initial part of the curve, so that the use of direct pulses with energies higher than 20-30 nJ is impractical. We note that the energy of the prepulse must be increased mainly by increasing its duration while simultaneously decreasing the power. Conversely, short-duration high-power pulses must be used at low pulse energies.

Figure 3 shows the time variation of the strip temperature during the periods of the prepulse and the pump pulses for various values of W_1. Also shown for comparison is the function $\bar{T}(t)$ for a single pump pulse; the feasibility of smoothing out the thermal waves in the active zone of the IL by application of the double pulse technique is clearly illustrated in this figure.

The data in Figs. 1-3 correspond to the conditions $j = 2j_t$, t_2 = 100 nsec, and Δt = 0. The dynamic thermostatting efficiency increases significantly with a decrease in j and t_2. For example, ξ can be reduced to 10^{-3} K for $j = 1.3j_t$, t_2 = 50 nsec, and W_1 = 55 nJ.

Interesting data are obtained in the investigation of the influence of the pump pulse delay time (Fig. 4). The ξ(Δt) curves have minima in the interval 2-15 nsec, and the optimum delay time reduces the temperature instability by 2/3 to 1/2. This unexpected result is attributable to the fact that low-energy prepulses of very short duration and high power propagate under nearly adiabatic conditions, giving rise to large temperature gradients. The subsequent termination of the prepulse causes current to flow suddenly out of the active zone and distorts the form of the $\bar{T}(t)$ curve in the initial pump period (see, e.g., curve 2 in Fig. 3). A small delay time of the pump pulse tends to smoothe out this effect, but with a further increase in Δt the stabilizing influence of the prepulse is diminished and is lost almost completely at Δt > 1 μsec. The calculations show that as Δt is increased, the value of q_1 increases rapidly, attaining unrealizable values. Consequently, an additional restriction on the prepulse power is introduced in the computational model. The curves in Fig. 4 correspond to the case in which the prepulse power is limited by the inequality $q_1 \leqslant 10q_{1t}$ where the corner points and ascending parts of the curves correspond to attainment of the upper bound of this inequality.

We now consider the possibility of utilizing the emission delay time to control the temperature of the active medium. The initial delay time of the stimulated emission relative to the current pulse t_d is usually 1-5 nsec [14]. The pump current can be regarded as a direct prepulse with an above-threshold amplitude during this period. Its power is best chosen so as to satisfy the requirement (6) subject to the constraint $t_1 \leqslant t_d$ without exceeding admissible values. The solution of this problem for the conditions t_1 = 4 nsec, $j = 1.5j_t$, t_2 = 50 nsec, Δt = 0, and $q_1 \leqslant 10q_{1t}$ gives the value ξ = 0.047 K. The instability decreases to 0.035 K at Δt = 1.5 nsec. The prepulse energy is only 1.8 nJ. We point out by way of comparison that a threshold-amplitude direct prepulse must have a duration of 790 nsec and an energy of 36 nJ in order to achieve the same instability. Consequently, the initial delay time can be utilized effectively for dynamic thermostatting.

The reported investigations show that the previously indicated [12] suppression of multimode lasing in strip IL's with the input of a prepulse cannot be attributed entirely to the dynamic temperature waveguide. According to calculations for the laser described in [12], the temperature rise at the center of the strip toward the end of the prepulse (100 mA at t_1 = 1 μsec) is 3.8 K. This increment is far below the estimates obtained in the adiabatic heating approximation, and so the expected increase in the refraction index is not attained. Consequently, the suppression of thermal waves in the active zone of an IL with a double-pulse input can play a significant role in the creation of single-frequency lasing, along with optical satellite limiting.

NOTATION

q_1, q_2, heat-release power of prepulse and pump pulse per unit area of strip pn junction; B, b, h, ℓ, dimensions of laser according to Fig. 1; S = 2bL; L, length of cavity; t_1, t_2, durations of prepulse and pump pulse; Δt, delay time of pump pulse; a^2, thermal diffusivity; $\varkappa$, thermal conductivity; T, temperature; x, y, coordinates; t, time; $z_1=\sqrt{4a^2t}$, $z_2=\sqrt{4a^2(t-t_1)}$, $z_3=\sqrt{4a^2(t-t_1-\Delta t)}$; $g_1=q_1e(t)$, $g_2=-q_1e(t-t_1)$, $g_3=q_2e(t-t_1-\Delta t)$; $e(u)$, Heaviside unit function [e(u) = 0 at u < 0, e(u) = 1 at $u\geqslant 0$]; δ(u), Dirac delta function; $\alpha_{1,2} = x \mp h$; $\beta_{1,2} = y \pm b$; $\bar{T}$, average temperature of strip over period of pump pulse; T_m, time-average temperature of strip; J, total quadratic deviation of function $\bar{T}(t)$ from T_m; $\xi = \sqrt{J/t_2}$, temperature instability (mean-square deviation of average temperature of strip from thermostatic temperature); W_1, energy of prepulse; j_t, j, threshold current density and pump current density; V, forward voltage across pn junction; η_d, differential quantum efficiency; t_d, initial delay time of stimulated emission.

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