THERMOELASTIC STRESSES ARISING IN LASER MEDIA

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The article examines the thermal model of a laser diode with a heat source of finite thickness and presents the calculation of thermoelastic stress waves arising at the time of the current pulse. It is shown that the decay of the thermoelastic tensile wave in the active region does not exceed 1 nsec; beyond the limits of the active region a compressive wave originates, and the time of its passage is equal to the time of passage of the wave through the active region. The amplitude of the wave attains $4.1 \cdot 10^4$ Pa with a plane heat source, and 1750 Pa when the active region is 10^{-7} m thick.

The calculation of thermoelastic stresses arising within the bulk of a laser diode on account of the temperature gradient was carried out for a thermal model of the laser diode in which the following was taken into account: a) heat is liberated in the active region with infinitely small thickness; b) the temperature gradient is constant on the section of the active region and refrigeration guide; c) on the other side of the active region the temperature is constant. It was found that for (Al, Ga) As-hetero-lasers with thermal resistance of the diode R_t = 12°K/W the compressive stress in the active layer is determined by the dependence $\sigma = -300$ P (kPa), where P is the power liberated in the active layer (W), and with a power of the heat flux P = 0.1 W, the maximal tensile stress at the place of contact of the diode with the refrigeration guide is equal to 255 kPa [1, 2]. For heterolasers operating in contimuous regime such stresses are much lower than the permissible value which is approximately equal to 20 MPa. Pulsed heterolasers operate with a pulse power of 50-150 W. The nonsteady temperature field originating at the time of the current pulse leads to the appearance of thermoelastic stress waves within the bulk of the laser diode [3, 4]; their value is the higher, the shorter these pulses are and the larger their amplitude is.

To estimate the magnitude of the thermoelastic stresses with a nonsteady temperature field, we chose a thermal model of a laser diode with internal heat source situated in the active region with thickness $2x_0$. The heat source, which is due to Joulean losses, heats the bulk of the diode uniformly without inducing any thermoelastic stresses, and it was therefore not included in the calculation.

Since the length of thermodiffusion is $L_d=\sqrt{\pi a t}$, where a is the thermal diffusion coefficient, and during the time of action of the current pulse it is much smaller than the geometric dimensions of the diode, the distance between the active region and the refrigeration guide was assumed to be infinitely large. In the unidimensional case the solution of the equation of heat conduction for a single pulse with constant thermophysical coefficients has the form

$$T(x,\ t)=\frac{jU_n t}{Cx_0}\begin{cases}\left[\mathrm{i}^2\mathrm{erfc}\left(\dfrac{x-x_0}{2\sqrt{at}}\right)-\mathrm{i}^2\mathrm{erfc}\left(\dfrac{x+x_0}{2\sqrt{at}}\right)\right], & x\geqslant x_0;\\ \left[0{,}5-\mathrm{i}^2\mathrm{erfc}\left(\dfrac{x_0-x}{2\sqrt{at}}\right)-\mathrm{i}^2\mathrm{erfc}\left(\dfrac{x+x_0}{2\sqrt{at}}\right)\right], & -x_0\leqslant x\leqslant x_0;\\ \left[\mathrm{i}^2\mathrm{erfc}\left(-\dfrac{x-x_0}{2\sqrt{at}}\right)-\mathrm{i}^2\mathrm{erfc}\left(\dfrac{x_0-x}{2\sqrt{at}}\right)\right], & x\leqslant -x_0,\end{cases} \tag{1}$$

where j is the current density; $U_n = h\nu_\Gamma/e$ is the voltage drop in the region of the P—n junction; $h\nu_\Gamma$ is the energy of a photon of the generated radiation; e is the elementary charge; $U_n/2x_0$ is the electric field intensity, assumed to be constant across the thickness of the active region; C is the volume heat capacity; $i^2\mathrm{erfc}\, z$ is the double integral of the

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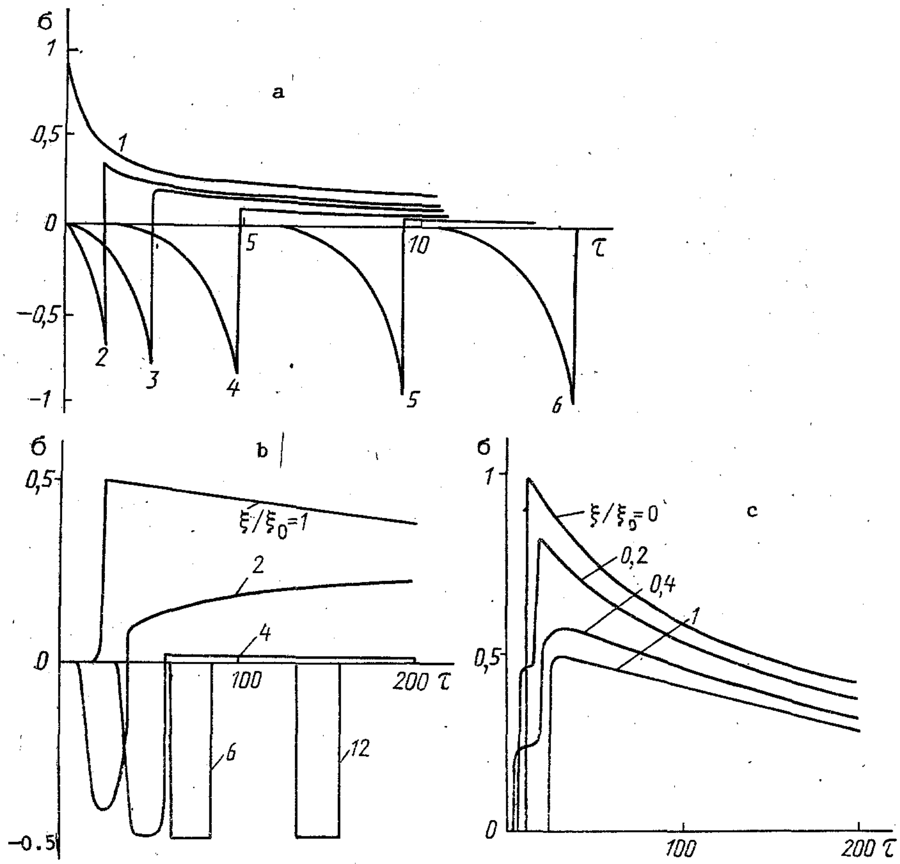

Fig. 1. Dependences of the dimensionless stress σ on the dimensionless time τ: a) with plane heat source for the points ξ = 0; 1.208; 2.415; 4.831: 14.492 (curves 1-6); b) beyond the boundaries of the active region with thickness $2x_0 = 10^{-7}$ m; c) in case of the active region with thickness $2x_0 = 10^{-7}$ m.

function erfc z. The power of the generated radiation was not included in the calculation because the efficiency of a laser diode usually does not exceed 10%.

In dynamic statement of the problem thermoelastic stresses of a longitudinal wave are determined from the solution of the equation [3, 4]

$$\frac{\partial^2\sigma_x}{\partial x^2} - \frac{1}{v^2}\frac{\partial^2\sigma_x}{\partial t^2} = m\rho\frac{\partial^2 T}{\partial t^2}, \tag{2}$$

where $m=\alpha(1+\nu)/(1-\nu)$; $v=[2G(1-\nu)/\rho(1-2\nu)]^{1/2}$ is the speed of the thermoelastic wave, determined by the mechanical properties of the materials; ν is the Poisson ratio; G is the shear modulus; ρ is the density; α is the coefficient of thermal expansion. The initial conditions are:

$$T(x,\ 0)=0;\quad (\sigma_x)_{t=0}=0;\quad \left(\frac{\partial\sigma_x}{\partial t}\right)_{t=0}=0. \tag{3}$$

Equation (1) is presented in dimensionless form:

$$\Theta=\begin{cases}\tau\left[\mathrm{i}^2\operatorname{erfc}\left(\dfrac{\xi-\xi_0}{2\sqrt{\tau}}\right)-\mathrm{i}^2\operatorname{erfc}\left(\dfrac{\xi+\xi_0}{2\sqrt{\tau}}\right)\right], & \xi\geqslant\xi_0;\\ \tau\left[0{,}5-\mathrm{i}^2\operatorname{erfc}\left(\dfrac{\xi_0-\xi}{2\sqrt{\tau}}\right)-\mathrm{i}^2\operatorname{erfc}\left(\dfrac{\xi_0+\xi}{2\sqrt{\tau}}\right)\right], & -\xi_0\leqslant\xi\leqslant\xi_0;\\ \tau\left[\mathrm{i}^2\operatorname{erfc}\left(-\dfrac{\xi-\xi_0}{2\sqrt{\tau}}\right)-\mathrm{i}^2\operatorname{erfc}\left(\dfrac{\xi_0-\xi}{2\sqrt{\tau}}\right)\right], & \xi\leqslant-\xi_0,\end{cases} \tag{4}$$

where we introduce the dimensionless variables

$$\tau=\frac{v^2t}{a};\quad \xi=\frac{vx}{a};\quad \xi_0=\frac{vx_0}{a}, \tag{5}$$

$$\Theta=T(x,\ t)\frac{v^2Cx_0}{ajU_n}. \tag{6}$$

In view of this, Eq. (2) assumes the form

$$\frac{\partial^2\sigma}{\partial\xi^2}-\frac{\partial^2\sigma}{\partial\tau^2}=\frac{\partial^2\Theta}{\partial\tau^2}, \tag{7}$$

where the conversion is carried out by the formula

$$\sigma_x=\sigma m\rho\frac{jU_na}{Cd}. \tag{8}$$

Equation (7) has the solution

$$\sigma=\begin{cases}\varphi(\xi+\xi_0,\ \tau)-\varphi(\xi-\xi_0,\ \tau),\ \xi\geqslant\xi_0;\\ \varphi(\xi_0-\xi,\ \tau)+\varphi(\xi_0+\xi,\ \tau),\ -\xi_0\leqslant\xi\leqslant\xi_0;\\ \varphi(-\xi+\xi_0,\ \tau)-\varphi(-\xi-\xi_0,\ \tau),\ \xi\leqslant-\xi_0,\end{cases} \tag{9}$$

$$\varphi(z,\ \tau)=-H(\tau-z)\,[\exp(\tau-z)-1]-\operatorname{erfc}\left(\frac{z}{2\sqrt{\tau}}\right)+0{,}5\times$$
$$\times\left[\exp(\tau-z)\operatorname{erfc}\left(\frac{z-2\tau}{2\sqrt{\tau}}\right)+\exp(\tau+z)\operatorname{erfc}\left(\frac{z+2\tau}{2\sqrt{\tau}}\right)\right], \tag{10}$$

H is Heaviside's function.

With a stepped plane source (ξ = 0) whose heat propagates to both sides, the temperature distribution in dimensionless form is determined by the expression

$$\Theta_{\mathrm{pl}}=\sqrt{\tau}\operatorname{ierfc}\frac{\xi}{2\sqrt{\tau}}. \tag{11}$$

With (11) taken into account, Eq. (7) has the solution

$$\sigma_{\mathrm{pl}}=H(\tau-\xi)\exp(\tau-\xi)-0{,}5\,[\exp(\tau-\xi)\operatorname{erfc}(\xi/2\sqrt{\tau}-\sqrt{\tau})-$$
$$-\exp(\tau+\xi)\operatorname{erfc}(\xi/2\sqrt{\tau}+\sqrt{\tau})]. \tag{12}$$

In this case the conversion of σ_{pl} is carried out by the formula

$$\sigma_x=\sigma_{\mathrm{pl}}m\rho\frac{jU_nv}{C}. \tag{13}$$

The numerical calculations were carried out for a laser diode based on GaAs with p—n junction with an area of $2\cdot10^{-7}$ m², thickness 10^{-6} m, and distance to the refrigeration guide more than $3\cdot10^{-6}$ m. The parameters of the current pulse are: amplitude I = 50 A, width t_p = 10^{-8} sec, magnitude U_n = 1.5 V. To the value $\sigma_{p\ell}$ = 1 there corresponds $4.11\cdot10^4$ Pa (E = 10^{11} Pa; ν = 0.3; G = $3.7\cdot10^{10}$ Pa, α = $5.4\cdot10^{-6}$ °K⁻¹, C = $1.73\cdot10^6$ J/m³; a = $2.72\cdot10^{-5}$ m²/sec, ρ = $3\cdot10^3$ kg/m³); magnitude $\sigma(\xi,\ \tau)$ = 1 is, respectively, $2\xi_0$ times smaller (in our case $2\xi_0$ = 233). To values τ = 1 there corresponds the time t = $0.63\cdot10^{-12}$ sec, and to ξ = 1 the distance x = $4.1\cdot10^{-9}$ m.

Figure 1a shows the dependence of the dimensionless stress $\sigma_{p\ell}$ on the dimensionless time τ for different distances ξ from the plane heat source. For the given model of the diode, at the instant when the current pulse is switched on, in the plane ξ = 0 there is a jump of the tensile stress from 0 to 1 which within the time 10^{-11} sec ($\tau = 15$) practically drops to zero (see Fig. 1a). Such a jump of the stress at the initial instant is due to the fact that the heating temperature of the plane $\xi = 0$ is proportional to the square root of the time, and the differential equation (2) contains the second derivative with respect to time. For the other planes of the diode the compressive stress increases from 0 to the maximal value, which does not exceed -1. At the instant of arrival of the thermoelastic tensile wave from the active region ($\tau = \xi$) the stress changes jumpwise by unity, and with $\tau = \xi > 15$ the compressive stress wave tends to the Dirac's unit delta function (see Fig. 1a). With the specified parameters of the pulse, the arising stresses are $\simeq 4 \cdot 10^4$ Pa, which is much less than the permissible value.

Inside the active region the thermoelastic tensile stresses gradually decrease from the center, where the maximal value is $\sigma_{max} = 1$, to the edge of the active region ($\sigma_{max} = 0.5$) (see Fig. 1c). Here we find two smooth jumps of the stress. The first jump corresponds to the tensile wave induced by the arrival of the thermoelastic stress wave from the near edge of the active region, the second jump corresponds to the more distant edge. For the center of the active region both jumps occur simultaneously. The tensile wave reaches the edge of the active region after a time equal to the time of passage of the wave through the active region ($\tau = 2\xi_0$), which decays within the time $\tau = 1500$ ($t \simeq 10^{-9}$ sec).

When the thickness of the active region is $2x_0 = 10^{-7}$ m, the amplitude of the thermoelastic stress wave in it assumes the value 1750 Pa; with $2x_0 = 10^{-6}$ m, the amplitude of the wave is equal to 175 Pa.

At first a smoothly increasing compressive wave from nearest layers arrives at the planes lying outside the boundaries of the active region, then the stress smoothly decreases to zero, and at the instant the wave from the distant edge of the active region arrives, it passes into the range of tensile stresses. The time of action of the compressive stress is equal to the time of passage of the thermoelastic wave across the thickness of the active region (see Fig. 1b). With $\xi/\xi_0 \geq 6$ we find only an elastic compressive wave over the entire thickness of the elastic region, and the magnitude of the stress is $\sigma_{max} = -0.5$.

It follows from the calculation that for the given model of the laser diode, which takes the finite dimensions of the active region into account, the stresses due to thermoelastic waves on account of abrupt heat liberation in the active region of the diode are at least two orders of magnitude smaller than the permissible values. At that the time of action of the thermoelastic wave does not exceed 10^{-9} sec. The model of a diode with a plane heat source yields values of stresses more than one order of magnitude too high.

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