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# *INVESTIGATION OF INJECTION LASERS WITH INHOMOGENEOUS EXCITATION*

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The threshold characteristics of a semiconductor laser consisting of two electrically isolated diodes in a common resonator are investigated experimentally and theoretically. The watt-ampere characteristics of such a laser are studied. Experimental dna theoretical work is performed to determine the conditions of hard excitation regime.

THE investigation of the emission dynamics in semiconductor lasers is of interest since it helps clarify the physical processes occurring in such lasers. The dynamics was studied in lasers consisting of two electically isolated diodes joined in a common resonator[1-9]. This system allows us to observe the dynamic processes in a large range of pump inhomogeneity variation. A special feature of semiconductor lasers with nonhomogeneous pumping is the strong dependence of their generation threshold on the nonlinear losses in the resonator. Figure 1 shows the experimental threshold characteristics (dashed curves) of the semiconductor laser consisting of two electrically isolated sections in a common resonator. The ratios of currents in the corresponding sections of the diode to the injection current in the homogeneous excitation regime are laid off along the axes. According to Fig. 1, the threshold injection current is minimum[2] at homogeneous excitation. In the lower branch of the threshold characteristic $J_1 > J_2$ and in the upper branch $J_2 > J_1$. A hard excitation regime is possible when the current ratios assume appropriate values.

A theoretical analysis can be based on the velocity equations. The use of the rate equations is justified since the electron-electron collision time $\sim 10^{-13}$ sec and up to $\sim 10^{-12}$ sec the emission line can be considered as homogeneously broadened[10]. Rate equations for semiconductor lasers with nonhomogeneous injection density have the form[8]

$$\dot{S} = \left[ V_1(g_1 + \gamma g_2) - \frac{1}{\tau_p} \right] S,$$

$$\dot{n}_1 = \frac{j_1}{d} - \frac{n_1}{\tau} - Sg_1, \quad \dot{n}_2 = \frac{j_2}{d} - \frac{n_2}{\tau} - Sg_2. \tag{1}$$

Here S is the photon density in the resonator, $\tau_p$ is photon lifetime in the resonator, $g_1$ and $g_2$ are gains in the two sections of the diode, $V_1$ is the volume of one part of the diode relative to the total volume occupied by the field, $\gamma = V_2/V_1$, the variables $n_1$ and $n_2$ denote electron density, $j_1$ and $j_2$ are injection current densities, d is diffusion length, and $\tau$ is carrier recombination time.

If we assume that the density of states in the conduction band varies as $\rho = \rho_0 \exp(E/E_0)$ and the valence band contains a narrow impurity level that can be described by the $\delta$-function then the gain in the semiconductor has the form

$$g_i = A\rho_0 \exp\frac{E}{E_0} \left\{ \frac{1}{1 + \exp[(E - F_i)/kT]} - \frac{1}{2} \right\}, \quad i = 1, 2, \tag{2}$$

where A is a constant depending on temperature, $F_i$ is the Fermi level for electrons in the conduction band, and E is the energy of a quantum of amplified light. The number of electrons is related to the Fermi level by the expression

$$n_i = B\rho_0 \exp(F_i / E_0),$$

where the constant B also depends on temperature and $E_0$ is a doping parameter.

The excess of the Fermi level over the generation quantum energy is usually not too large in relation to kT and according to computation when $kT \sim E_0$ eq. (2) can be written in the form

$$g_i \approx A\rho_0 \frac{F_i - E}{4kT} \exp\frac{E}{E_0} \tag{3}$$

within a sufficiently broad range of excitation inhomogeneity.

Since the generation frequency is determined by the position of the total gain maximum we find that at the maximum gain

$$\frac{F_1 - E}{kT} + \gamma \frac{F_2 - E}{kT} = \frac{1 + \gamma}{\alpha},$$

$$\alpha = \frac{kT}{E_0}. \tag{4}$$

In the case of diffusion diodes at nitrogen temperature $\alpha \sim 1$. The excitation conditions of a split diode can be found with the aid of (4). For S = 0

$$F_1 = E_0 \ln \frac{j_1 \tau}{Bd\rho_0}, \quad F_2 = E_0 \ln \frac{j_2 \tau}{Bd\rho_0}.$$

Substituting these expressions into the first equations of (1) and considering that gain is maximum for quanta

$$E = \frac{F_1}{1 + \gamma} + \frac{\gamma}{1 + \gamma} F_2 - E_0,$$

we find that the number of photons in the resonator grows if

$$j_1^{1/(1+\gamma)} j_2^{\gamma/(1+\gamma)} > \frac{4eBd\alpha}{V_1 \tau_p A \tau (1 + \gamma)} = j_{0\,\mathrm{th}}, \tag{5}$$

Here e is the base of natural logarithms. The threshold curve, i.e., the curve in the $(J_1, J_2)$ plane whose points satisfy the excitation conditions, has the form

$$J_1^{1/(1+\gamma)} J_2^{\gamma/(1+\gamma)} = \mathrm{const}.$$

For a diode with $\gamma = 1$ the curve has the form

$$J_1 J_2 = {}^1/_4 J^2_{\mathrm{th}},$$

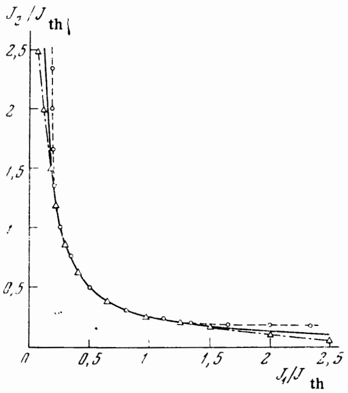

FIG. 1. Experimental (dashed) and theoretical (solid) threshold curves.

where $J_1$ and $J_2$ are injection currents into the two sections of the diode and $J_{th}$ is the total threshold current in homogeneous excitation regime.

In Fig. 1 the solid line denotes the theoretical threshold curve and dashed lines denote experimental curves obtained for two different diodes. The deviation of the theoretical from the experimental curves can be explained in the following manner. According to (2) when $(F - E)/kT \gtrsim 2$ gain (or absorption) at fixed frequency weakly depends on the position of the Fermi level and therefore, beginning with some small value of $J_2$ for example, the theoretical threshold curve should be almost parallel to the $J_1$ axis in accordance with the upper experimental curve. This can be readily obtained by "joining" (3) to a suitable approximation of (2). The deviation from the lower experimental curve is due to current leakage across the slot of the split diode. To determine stationary states we must know the generation frequency $(E/h)$; we readily find from (1) and (4) that

$$E = E_0 \ln \frac{4\alpha}{A\rho_0 V_1\tau_p(1+\gamma)}. \tag{6}$$

If the excitation conditions (5) are satisfied, photons in the resonator are amplified and the generation amplitude increases. Fermi level drops in the amplifier section and rises in the absorber section; consequently if both sections amplified in the beginning, the total gain of both sections decreases and the stationary amplitude of generation is determined by the saturation effect. However, if one of the sections acts as an absorber, the total gain can increase with the field. This can occur when the rate of absorption decrease in one section exceeds the rate of gain decrease in the other section. Oscillation can obviously be excited in the resonator in this case even if the excitation conditions were not satisfied in the beginning. If a number of photons is introduced from the outside, the gain may increase to the point where it exceeds losses and a stationary generation regime is possible. Consequently a hard generation regime can be achieved. This can also be called a bistable regime since two stable stationary states exist with the given values of currents.

The condition for increasing gain with increasing field

$$\frac{d}{dS}\Big|_{S=0}(g_1 + \gamma g_2) > 0$$

can be obtained explicitly using the last two equations of (1). Employing the rules of differentiating implicit functions we find that

$$\frac{dg_i}{dS}\Big|_{S=0} = -\frac{A\tau}{4B\alpha V_1\tau_p(1+\gamma)}\frac{\ln I_i}{I_i}, \qquad i = 1, 2,$$

where

$$I_i = \frac{j_i}{j_0}, \qquad j_0 = \frac{4Bd\alpha}{AV_1\tau_p\tau(1+\gamma)} = \frac{j_{0\,th}}{e}.$$

Consequently the condition for gain increase with the field has the form

$$\frac{\ln I_1}{I_1} + \gamma\frac{\ln I_2}{I_2} < 0. \tag{7}$$

The electron density equations show that for E determined by (6) gain is possible only when $j_i > j_0$. On the other hand, when $j_i < j_0$ then $(F_i - E)kT < 0$ and this diode section acts as an absorber; consequently according to (7) one section of the diode must be an absorber. Condition (7) can be rewritten in another form to make a comparison with the excitation condition (5):

$$j_2\left(1 + \ln\frac{j_1}{j_{0\,th}}\right) + \gamma j_1\left(1 + \ln\frac{j_2}{j_{0\,th}}\right) < 0. \tag{8}$$

Figure 2 shows the solution of (8) for a diode with $\gamma = 1$. Condition (8) is satisfied in the dashed region. A threshold curve for $\gamma = 1$ was plotted for the purpose of comparison. When $\gamma = 1$ the threshold curve crosses the boundary of region (7) at the current values of $J_1 = 1.67\ J_{th}$, $J_2 = 0.15\ J_{th}$ and $J_1 = 0.15\ J_{th}$, $J_2 = 1.67\ J_{th}$; the total current here is $1.82\ J_{th}$.

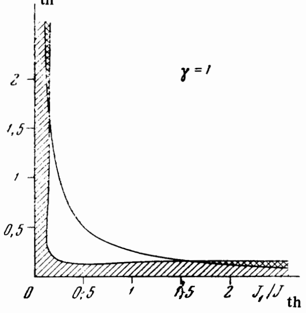

FIG. 2. Threshold characteristic and region (cross-hatched) where condition (7) is valid.

Figure 3 shows total gain K relative to losses as a function of photon number $\Phi = A\tau S/4B\alpha$ for a diode with $\gamma = 1$. Curves 1, 2, 3 in Fig. 3 are obtained with $J_2 = 0.074\ J_{th}$, and curves 1′, 2′, 3′ in Fig. 3 are obtained with $J_2 = 0.26\ J_{th}$. Current $J_1$ was chosen to obtain a 10% excess over threshold in curves 1 and 1′ in Fig. 3, an initial gain equal to losses in curves 2 and 2′, and an initial gain 10% lower than losses in curves 3 and 3′.

Figure 3 makes it simple to analyze the possible operating regimes of a diode with nonhomogeneous excitation. If the initial gain is lower than the losses (curves 3 and 3′) and if (7) is not valid, there are no stationary states (curve 3′). If (7) holds (curve 3), there are three stationary states, $\Phi = 0$, $\Phi_1$, and $\Phi_3$. The state with $\Phi = 0$ is stable against infinitely small perturbations, but if a sufficient number of photons is introduced into the resonator to make the gain larger than the losses, a generation regime is possible. The next state $F_1$ is clearly always unstable since the gain at this point increases with the field, and the diode assumes state $\Phi_3$. If the initial gain is exactly equal to the losses and (7) is not valid, there are no stationary

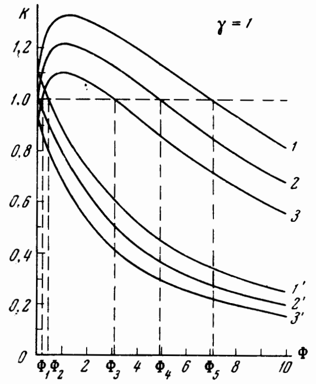

FIG. 3. Total gain K relative to losses as a function of the number of photons in the resonator. $J_2 = 0.074\ J_{th}$ for curves 1, 2, 3; $J_2 = 0.26\ J_{th}$ for curves 1′, 2′, 3′; $J_{th}$ is the total threshold current in homogeneous excitation.

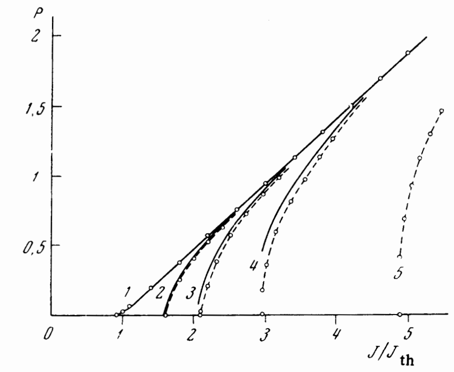

FIG. 4. Experimental (dashed) and theoretical (solid) watt-ampere characteristics of a diode with nonhomogeneous excitation.

states, i.e., there is no generation regime. If (7) is satisfied, stationary state corresponds to the point $\Phi_4$. The diode changes from state $\Phi = 0$ to state $\Phi_4$ because of infinitely small perturbations.

When the initial gain is larger than the losses (curves 1 and 1′ in Fig. 3) there is only a single stationary state: $\Phi_2$ if (7) is not valid, and $\Phi_5$ if (7) holds. The stability of points $\Phi_2$, $\Phi_3$, $\Phi_4$, and $\Phi_5$ was specially investigated in[9]. It was shown there that under definite conditions stationary states of this type can be unstable and emission intensity pulsations occur. A stable limiting cycle then appears in (1).

One of the important characteristics of the diode with nonhomogeneous excitation is the watt-ampere characteristic, i.e., the power emitted by the diode as a function of the injection currents $J_1$ and $J_2$. Analysis of the watt-ampere characteristics showed[3] that the differential slope increases considerably in nonhomogeneous excitation in comparison to the slope obtained with homogeneous excitation.

In Fig. 4, dashed lines denote typical experimental watt-ampere characteristics of a laser consisting of two identical electrically insulated sections operating in different regimes. The parameter of the curves is the degree of inhomogeneity of injection current density in the diode sections. The laser emission power was measured with a silicon photodiode within an angle of 20°. The differential slope of the watt-ampere characteristic of the homogeneously excited laser (curve 1 in Fig. 4) was 0.1–0.25 w/a in the best specimens and was practically constant within a wide range of injection currents. With inhomogeneous excitation when current density in one section is larger than in the other (curves 2–5 in Fig. 4) the differential slope is nonlinear, has a maximum value near threshold, and when the injection current increases the slope asymptotically approaches the differential slope of the Watt-ampere characteristic of the homogeneous excitation case. Further increase of the injection current inhomogeneity over the (p-n)-transition area leads to a so-called hard regime in which coherent emission is established in a jump (curves 3, 4, and 5 in Fig. 4). According to experiments, the slope of the watt-ampere characteristic turns to infinity and the hard excitation regime sets in when the total injection current is twice the current of homogeneous excitation. The theoretical value is 1.81.

In Fig. 4, the solid lines denote theoretical watt-ampere characteristics obtained from (1) and (3). The theoretical curves correctly describe the nature of the watt-ampere characteristics and their slope. As the current flowing to one of the diode sections increases to $(2-3)J_{th}$ the theoretical threshold curve deviates from the experimental threshold curves; thus the theoretical curves in Fig. 4 deviate from the experimental curves 3 and 4. The theoretical slope of the watt-ampere characteristic of the threshold curve can be computed with the aid of (1) and (3). When the number of photons in the resonator is small, $\Delta\Phi = (A\tau/4B\alpha)\Delta S$:

$$\alpha\frac{F_1-E}{kT}=\frac{I_1\ln I_1}{I_1+\Delta\Phi},\qquad \alpha\frac{F_2-E}{kT}=\frac{I_2\ln I_2}{I_2+\Delta\Phi}.$$

If the point $I_1$, $I_2$ lies on the threshold curve the stationary solution (1) for small $\Delta\Phi$ has the form

$$\Delta\Phi=\left(\frac{\Delta I_1}{I_1}+\gamma\frac{\Delta I_2}{I_2}\right)\left(\frac{\ln I_1}{I_1}+\gamma\frac{\ln I_2}{I_2}\right)^{-1}, \tag{9}$$

where $\Delta I_1$ and $\Delta I_2$ are small deviations of currents $I_1$ and $I_2$ from their values taken from the threshold curve. Equation (9) determines the slope of the watt-ampere characteristic, i.e., the quantities $(\partial S/\partial J_1)|_{S=0}$, and $(\partial S/\partial J_2)|_{S=0}$ on the threshold curve. As the point in which $I_1^{-1}\ln I_1 + I_2^{-1}\ln I_2 = 0$ is approached the slope of the watt-ampere characteristic increases; at that point the slope turns to infinity and the hard regime follows.

In conclusion we note that the watt-ampere characteristic has a nonlinear character in some diodes with homogeneous excitation. According to the above discussion, this can be due to the fact that such a diode contains absorbing regions caused by internal inhomogeneities and capable of bleaching with increased injection current. The existence of such inhomogeneities in diodes can be the cause of the undamped emission intensity pulsations in semiconductor lasers.

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