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DYNAMICS OF SEMICONDUCTOR INJECTION LASERS

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I. INTRODUCTION

SINCE the discovery of the spike structure of a radiation pulse from a ruby laser,[1] much attention has been directed toward theoretical and experimental investigations of the dynamic processes in various types of laser. Various dynamic operating conditions were discovered and investigated: "hard" excitation;[2] spatial and time locking of a large number of various oscillation modes;[3] pulsations of the radiation associated with nonlinear absorption;[4] de-excitation of the active medium in lasers, etc. Investigations of the dynamics of laser emission have made it possible to produce: single-mode lasers; lasers emitting light pulses of 30–1 nsec duration and 1–100 GW power;[5–7] lasers emitting light pulses of 100–1 nsec duration and of 10^2–10^3 GW power.[3, 8] Various dynamic conditions were found in investigations of the amplification of short light pulses in nonlinear amplifiers.[6, 7]

Important results have also been obtained in investigations of the dynamics of the emission from semiconductor lasers. Again, "hard" excitation of a laser was observed,[9] the locking of various oscillation modes was achieved,[10] and a complex spike structure of radiation pulses was observed.[11, 12] Investigations were made of the interaction effects in optically coupled semiconductor diodes, of spectral (selective) and total quenching effects,[13–16] and of the time characteristics of injection lasers.[17, 18] Regular ultrashort light pulses were generated using a semiconductor laser excited nonuniformly across the p–n junction area,[12, 19] and the locking of the spikes by modulation of the exciting current was achieved.[20]

Although many papers have been published on the theory of various dynamic conditions, a rigorous quantitative analysis of the problem, based on the solution of strongly nonlinear equations with a large number of degrees of freedom, has not yet been carried out. Nevertheless, the solution of nonlinear equations with two degrees of freedom has made it possible to determine the conditions of stability of these solutions, the existence of limit cycles, etc.[4, 21–23] For a uniformly broadened line the majority of the dynamic conditions may be described by means of the rate equations.

Theoretical investigations have shown that the spectral line emitted by semiconductors should be regarded as uniformly broadened and that, in the case of heavily doped gallium arsenide and other semiconductors, the saturation of the absorption or amplification can be described completely by a change in the position of the quasi-Fermi level in the conduction band.[24, 25] This approach is valid if the radiative recombination time of electrons is longer than the electron–electron interaction time, whose order of magnitude is 10^{-12}–10^{-13} sec.[26]

Investigations of the dynamics of the radiation from semiconductor injection lasers are of considerable interest, both from the point of view of understanding the physical processes taking place in such lasers and from the point of view of the possibility of constructing, from semiconductor lasers, ultrafast logical elements for optical computers.

The use of semiconductor lasers as fast elements for computers[27] is promising because of the small linear size of lasers (the high gain in semiconductors, reaching a few thousand cm^{-1}, makes it possible to construct semiconductor lasers of few microns in size[28]), the high efficiency of direct conversion of the electric current energy into coherent radiation, and the fast response (in the limit, the operating time of such elements is governed only by the transit time through the active medium of the laser and may be as short as 10^{-12}–10^{-13} sec).

Because of the high frequency of optical oscillations ($\sim 10^{14}$ Hz), optical computers have a potentially wide transmission band and, consequently, a potentially high data processing rate. The development of extremely fast electronic circuits meets with considerable difficulties, associated with the presence of stray inductances and capacitances, which are present in all electronic circuits. The level of interference, due to electrical coupling, increases as the speed of operation rises.[29, 30] The use of optical coupling between elements should avoid the difficulties encountered in electronic circuits. Using optical devices, one should be able to process data in parallel and have a fairly high fan-out coefficient at the output.

Logical elements for optical computers can be made from optically coupled lasers. The operation of such elements is based on the following effects: the switching-on and quenching of radiation in the interaction of diodes, "hard" self-excitation, generation of regular optical spikes, etc. The achievement of good optical coupling between elements in optical systems is difficult because the active region in semiconductor injection lasers is only a few microns thick.[31–33]

In recent years, considerable success has been achieved in the development of fast-response radiation detectors (the photoresponse time may be shorter than 10^{-10} sec). Therefore, it is attractive to consider logical elements consisting of laser diodes and radiation detectors coupled to laser diodes both optically and electrically.[34] Such structures simplify considerably the realization of optical coupling between elements because the receiving area of radiation detector is usually considerably larger than the area of the active region in the semiconductor diode.

The present review is concerned with the results of theoretical and experimental investigations of the radiation dynamics of laser diodes and optically coupled double diodes. In the last chapter of the review, we shall describe the circuits of some logical elements, based on laser diodes as well as on lasers and photodiodes.

II. PRINCIPLE OF OPERATION OF THE GALLIUM ARSENIDE SEMICONDUCTOR INJECTION LASER

The method of excitation of semiconductor lasers by the injection of minority carriers was first suggested in [35]. The principle of the operation of a semiconductor diode, when used as coherent radiation sources, depends on the recombination radiation generated after the excitation of electrons and holes in a semiconductor by the passage of a current through the p–n junction in the forward direction. The passage of the current in the forward direction injects minority carriers in the region adjoining the p–n junction. Since the electron mobility in gallium arsenide is higher than the hole mobility, the excess electrons recombine with holes in a layer—adjoining the p-type region—whose thickness is governed by the diffusion length of electrons and amounts to a few microns. If a degenerate material is present at least on one side of the p–n junction, an increase in the injection level produces eventually a population inversion of energy levels between which carriers recombine, giving rise to photons whose energy is close to the forbidden band width.

The condition for population inversion for transitions which produce photons of energy $\hbar\omega$ is given by the inequality

$$F_n - F_p \gg \hbar\omega, \tag{1}$$

where F_n and F_p are, respectively, the quasi-Fermi levels of electrons and holes in the region where the laser radiation is generated. In order to generate coherent radiation we must achieve not only stimulated radiation conditions but the gain associated with the stimulated transitions must be greater than the total losses.

The threshold condition for the generation of radiation in a Fabry–Perot type resonator is:

$$\sqrt{R_1R_2}\exp[(g-\varkappa)L] = 1, \tag{2}$$

where R_1 and R_2 are the coefficients of reflection from the resonator faces; g is the gain; κ is the absorption coefficient; L is the resonator length.

The main losses in semiconductor lasers are those due to reflection from the ends of the resonator, the diffraction losses due to the thinness of the active region, and the losses associated with the absorption of radiation by free carriers and defects.

Experimental and theoretical investigations have demonstrated that radiative recombination is the result of electron transitions from energy levels of donor impurities (density-of-states "tails") to levels in an acceptor band. In the population inversion case, the gain is given by the following expression: [38] *

$$g(\omega) \propto \sum [f_c(E) - f_v(E-\hbar\omega)]\,\rho_c(E)\,\rho_v(E-\hbar\omega); \tag{3}$$

Here, $f_c(E)$ and $f_V(E)$ are the electron distribution functions; $\rho_c(E)$ and $\rho_V(E)$ are the energy densities of states in the conduction and valence bands, respectively. The summation is carried out over all energies which obey the law of conservation of energy. Because of their large effective mass, the holes are concentrated in a narrow energy band and, therefore, the position of the hole quasi-Fermi level may be assumed to be constant so that the function $f_V(E)$ may be assumed to be constant. It follows that the gain is governed by the density of energy levels near the bottom of the conduction band and by the population of these levels. The available experimental data (the current-voltage characteristics, the shift of the spontaneous radiation maximum with increasing current, the frequency dependence of the gain, etc.) show that the density of states near the bottom of the conduction band is given by

$$\rho_c(E) \sim \exp\left(\frac{E}{E_0}\right), \tag{4}$$

where the parameter E_0 depends on the concentration of donor impurities.

It follows from Eq. (4) that, when the value of E_0 is increased, the density-of-states function increases also, but more slowly; therefore, in the temperature range defined by $kT < E_0$, the quasi-Fermi level F_c falls slowly with increasing temperature and, consequently, the threshold current density also increases slowly with temperature. Experiments show that the parameter E_0 depends on the technique used to prepare the p–n junction. For diffused diodes, this parameter is $E_0 \approx kT$ at T = 77°K and, therefore, the threshold current density of such diodes increases (approximately as $T^{3/2} - T^3$) with increasing temperature.[37] The value of E_0 for diodes prepared by the epitaxial method is considerably higher than the value for diffused diodes,[38] and, therefore, the threshold current density increases more slowly with rising temperature. The threshold current density epitaxial diodes at room temperature is approximately a third of that for diffused diodes; moreover, the threshold current of epitaxial diodes is independent of temperature in a wider temperature range than the threshold current of diffused diodes[39] (Fig. 1). The weak dependence of the threshold current density of epitaxial diodes promises the possibility of continuous laser emission at room temperature.

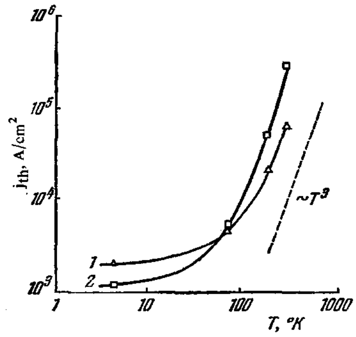

FIG. 1. Temperature dependence of the threshold current density for various types of injection laser: [40] 1) a diode prepared by liquid epitaxy and heat treatment; 2) diffused diode laser; $N_d = 5 \times 10^{18}$ cm^{-3}.

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*The expression for the gain was obtained in [24,25] taking into account the saturation effect. It was shown that at high radiation intensities the gain is inversely proportional to the radiation intensity.

Dyment and D'Asaro[41] reported continuous emission by a gallium arsenide semiconductor laser working at 200° K.

It is known[42] that the gain g increases linearly with increase of the injection current density j;

$$g=\beta j, \tag{5}$$

where β is the coefficient of proportionality.

It follows from Eqs. (2) and (5) that j_{th} is of the form

$$j_{\text{th}}=\frac{\varkappa}{\beta}+\frac{\ln\left(\frac{1}{R_1R_2}\right)}{2\beta L}. \tag{6}$$

It is clear from the above expression that j_{th} is inversely proportional to L.[42, 43] It was reported in [43] that the minimum value of j_{th} at 77° K was close to 300 A/cm^2 for resonators of the Fabry–Perot type. For better samples, the values of κ and β were:

$$\varkappa=10\ \text{cm}^{-1}\quad \beta=3{,}2\cdot 10^{-2}\ \text{cm/A}^{-1}.$$

The coherent radiation output power of a semiconductor laser is given by[43]

$$P=\frac{\hbar\omega}{eU_0}\Theta w\,(P_{\text{el}}-U_0I_{\text{th}}), \tag{7}$$

where P_{el} is the electrical power supplied to the p–n junction; $\hbar\omega$ is the photon energy; U_0 is the external voltage across the p–n junction; Θ is the radiative quantum yield; w is the fraction of the radiation emerging through the faces of the resonator; I_{th} is the threshold current; e is the electron charge.

The efficiency of a semiconductor laser, calculated taking into account the electrical power loss in the resistance R_s in series with the p–n junction, is given by

$$\eta=\frac{P}{P_{\text{el}}+I^2R_s}. \tag{8}$$

Investigations of the threshold and power characteristics of gallium arsenide lasers have demonstrated that the efficiency of conversion of the electrical power into light is close to unity and that the main source of losses is the absorption (or scattering) in the resonator medium. The highest reported value of the differential efficiency, dP/dP_{el}, is about 0.7.

Values of the p–n junction efficiency, P/P_{el}, of the order of 0.5 have been reached; the corresponding laser efficiency is 25%. It has been demonstrated that the maximum laser efficiency can be 50–60% for diodes with resonators about 300 μ long.[43]

III. TIME CHARACTERISTICS OF SEMICONDUCTOR INJECTION LASERS

The conduction and valence bands, as well as impurity levels, are distorted by the presence of a high concentration of impurities in the active region of a semiconductor laser. Nevertheless, calculations carried out for ideal bands and impurities can describe quite satisfactorily, in the quantitative sense, the optical transitions taking place in a semiconductor laser. Assuming "band–band" and "conduction band–shallow acceptor levels" transitions, we can calculate the electron lifetime in the case of spontaneous radiative recombination.[44] Since the interband matrix element of the momentum operator, which occurs in the expression for the carrier lifetime, can be determined from the value of the direct optical absorption or from the value of the effective mass, we can calculate directly the spontaneous electron lifetime for optical transitions between the conduction band and shallow acceptor levels, which, according to [44], is inversely proportional to the number of uncompensated holes P_A:

$$\tau_{\text{sp}}=\frac{1}{0.43\cdot 10^{-9}P_{\text{a}}\ (\text{sec}^{-1}\ \text{cm}^3)}, \tag{9}$$

where τ_{sp} is the spontaneous electron lifetime; P_a is the concentration of zinc in the active region.

Under laser emission conditions, when the level population in a semiconductor is inverted, the radiative recombination time is expressed in terms of an effective lifetime[45]

$$\frac{1}{\tau_{\text{eff}}}=\frac{1}{\tau_{\text{sp}}}+\frac{1}{\tau_{\text{las}}}, \tag{10}$$

where τ_{las} is the electron lifetime for stimulated (laser) transitions. This expression, which relates τ_{eff} with τ_{sp} and τ_{las}, means that the spontaneous and stimulated transitions are statistically independent of one another. Using Eq. (10) for τ_{sp} and τ_{las} and the relationship between the spontaneous and stimulated transitions, we can express the value of τ_{eff} as follows:

$$\tau_{\text{eff}}=\frac{\tau_{\text{sp}}}{1+(c^3/8\pi\hbar\omega^3)\,U(\omega)}, \tag{11}$$

where c is the velocity of light; ω is the frequency of emitted photons; $U(\omega)$ is the density of radiation of frequency ω. When the current injection level is increased, the number of emitted photons increases, the value of $U(\omega)$ becomes larger and, as indicated by Eq. (11), the effective lifetime becomes shorter.

On the basis of the value of the electron lifetime we may expect the delay time between the beginning of flow of the injection current and the laser signal to be of the order of 10^{-9} sec or less. Measurements of this delay time were carried out for gallium arsenide lasers operating at liquid-nitrogen temperature.[17] The minimum measured delay time was 0.2 nsec and this value was determined by the time resolution of the detection apparatus. The nature of the dependence of the delay time on the injection current level was used to determine the spontaneous carrier lifetime, which was ~2 nsec. The delay time was found to depend on the value of the spontaneous lifetime and it decreased when the injection current was increased, in accordance with

$$\tau_{\text{d}}=\tau_{\text{sp}}\ln\left[\frac{I}{I-I_{\text{th}}}\right], \tag{12}$$

where τ_d is the delay time between the current and light pulses; τ_{sp} is the spontaneous carrier lifetime; I is the amplitude of the injection current pulse; I_{th} is the threshold value of the current.

The carrier lifetime under the stimulated emission conditions was determined from a change in the leading edge of the light pulse relative to the leading edge of the current pulse.[46] The carrier recombination time was 1.5×10^{-10} sec and it decreased to 5×10^{-11} sec when the current density was increased. The value of τ_{sp}, reported in that paper, was a fraction of a nanosecond, due to the high concentration of the zinc dopant (~10^{19} cm^{-3}).

A method for investigating the time characteristics of of semiconductor lasers was described in [18, 47]; the measurements were made using a device with a time-scanning image converter (the time resolution of the device is 3×10^{-11} sec).[47] The delay time of the light pulses was determined from the delay of the laser emission of a diode relative to a time mark, generated by the leading edge of the voltage pulse, which was taken from a resistor connected in series with the diode; the voltage was applied by means of a calibrated cable to the deflecting plates of the image converter. This method made it possible to determine directly the delay time of the light pulses relative to the current pulses; its accuracy was limited primarily by the time resolution of the device. Various typical gallium arsenide diodes, prepared by the diffusion method and operating at liquid-nitrogen temperature, were investigated. The delay time was measured using two different methods of excitation of a diode: supplying a current pulse directly to an unexcited diode or supplying a current pulse to a diode which had been excited previously by a current pulse from an auxiliary generator, in order to eliminate the delay necessary to reach laser emission conditions. In the first case, the delay time was longer than that in the second and the difference between these times was directly proportional to the p–n junction area of the diode s.[48] The dependence of the value of the delay time of the light pulses on the injection current level and the p–n junction area is shown in Fig. 2. (The dashed curves represent the first case of direct excitation of a diode.) Figure 2 shows that the maximum difference between the delay time τ_d under the direct excitation conditions and the delay time τ_d in the case of diodes which had suffered preliminary excitation was exhibited for the same ratio of the injection and threshold currents, by diodes with the largest area (curves 1 and 1′); that the smallest difference was found for diodes with the smallest area (curves 4 and 4′). These experiments showed that the laser diode response depended on the p–n junction area, the laser excitation conditions, and the value of the injection current. The minimum delay time was $\sim 6 \times 10^{-11}$sec for a current which was 17 times greater than the threshold value.

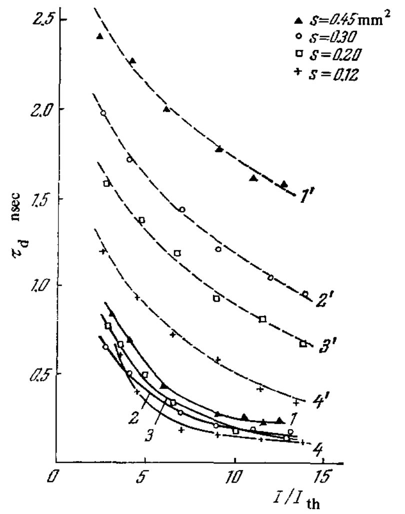

FIG. 2. Dependence of the delay time of light on the ratio of the injection and threshold currents. The dashed curves represent direct excitation of the diode; curves 1-4 and 1′-4′ represent diodes with p-n junction areas of 0.45, 0.30, 0.20, and 0.12 mm², respectively.

The results of measurements of the delay time between the current and light pulses, carried out using the method described in [17], were reported in [49]. However, the nature of the obtained dependence of the delay time on the injection current differed from the dependence reported in [17]. The delay time near the laser threshold was about 3 nsec.

The response of semiconductor lasers was determined in [50] by the method of direct amplitude modulation of the current. However, it is difficult to deduce a quantitative dependence of the response of laser diodes on the injection current from the reported results.

A delay of about 150 nsec between the light and current pulses was reported in [51] for a semiconductor laser operating at room temperature. This delay time was associated with the presence of slow traps in the diode.

IV. INVESTIGATIONS OF DYNAMIC PROCESSES IN SEMICONDUCTOR INJECTION LASERS

In spite of a large number of theoretical and experimental investigations of the dynamics of laser emission, there is as yet no single theory capable of describing the dynamic processes in lasers. Obviously, this is a consequence of the complexity of the problem, which involves the solution of partial differential equations strongly nonlinear in time and space; the solution of this problem even in the single- or two-mode representation is very difficult. Nevertheless, analogies with simple oscillation problems allow us to provide a qualitative as well as a fairly satisfactory quantitative description of the processes taking place in lasers.

The dynamics of emission of radiation by a semiconductor laser with a nonuniformly excited p–n junction area is of great interest.* In such diodes, the average gain for the light transmitted through both parts of the laser may have a maximum in its dependence on the power of the transmitted radiation. This is a consequence of the fact that an emission or absorption line of a semiconductor may be regarded as uniformly broadened, and of the fact that the gain is determined completely by the position of the Fermi level in the conduction band.

A theoretical analysis of dynamic processes in nonuniformly excited semiconductor lasers was carried out in [19, 54] using rate equations. The use of rate equations is justified because the electron–electron collision times are of the order of 10^{-13} sec and, consequently, right down to times of 10^{-12}–10^{-13} sec, the emission line may be regarded as uniformly broadened.[28] The rate equations for a nonuniformly excited semiconductor injection laser are

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*The construction of a semiconductor laser witn nonuniform excitation across the p-n junction area was described in [52,53]. The laser was a double diode, the two parts of which were electrically insulated but had a commom resonator.

$$\left.\begin{aligned}\dot{S}&=\left[V_1(g_1+\gamma g_2)-\frac{1}{\tau_r}\right]S,\\ \dot{n}_1&=\frac{j_1}{d}-\frac{n_1}{\tau}-Sg_1,\\ \dot{n}_2&=\frac{j_2}{d}-\frac{n_2}{\tau}-Sg_2;\end{aligned}\right\} \quad (13)$$

here, S is the density of photons in the resonator; τ_r represents the losses in the resonator; g_1 and g_2 are the gains in parts 1 and 2 of the laser, respectively; V_1 is the relative volume of part 1 (i.e., the volume of part 1 divided by the total volume occupied by the field); $\gamma = V_1/V_2$; the variables n_1 and n_2 represent the electron densities in the two parts of the laser; j_1 and j_2 are the injection current densities; d is the diffusion length; τ is the carrier recombination time.

If we assume that the density of states in the conduction band is $\rho = \rho_0 \exp(E/E_0)$ and that the valence band has a narrow impurity level which can be described by the δ function, we find that the gain in a semiconductor is given by[36]

$$g_i=A\rho_0\exp\left(\frac{E}{E_0}\right)\left[\frac{1}{1+\exp[(E-F_i)/kT]}-\frac{1}{2}\right] \quad (i=1,\,2), \quad (14)$$

where A is a temperature-dependent constant; F_i is the Fermi level of electrons in the conduction band; E is the frequency of the emitted light (expressed in energy units). The number of electrons is related to the Fermi level by the equation

$$n_i=B\rho_0\exp\left(\frac{F_i}{E_0}\right), \quad (15)$$

where the constant B is also temperature-dependent; E_0 is the doping parameter.

For diffused GaAs diodes at liquid-nitrogen temperature, we find that $E_0 \approx kT$ and the Fermi level of electrons is ~kT higher than the emission frequency. Consequently, in a fairly wide range of nonuniform excitation the gain of Eq. (14) can be represented in the form

$$g_i \approx A\rho_0\frac{F_i-E}{4kT}\exp\left(\frac{E}{E_0}\right). \quad (16)$$

Since the emission frequency is governed by the position of a maximum of the total gain, $g_1 + \sqrt{g_2}$, we find that at this maximum

$$\frac{F_1-E}{kT}+\gamma\frac{F_2-E}{kT}=\frac{1+\gamma}{\alpha}, \quad \alpha=\frac{kT}{E_0}. \quad (17)$$

To determine the steady-state conditions, we must know the emission frequency: we easily find from Eqs. (13) and (17) that

$$E=E_0\ln\left(\frac{4\alpha}{A\rho_0V_1\tau_r(1+\gamma)}\right). \quad (18)$$

It must be mentioned that in the approximation represented by Eq. (16) the gain curve has only one maximum and, therefore, there is only one emission frequency. Using Eq. (17) we can find the conditions for the self-excitation of a diode with two electrically insulated parts. For S = 0, we obtain

$$F_1=E_0\ln\left(\frac{j_1\tau}{B\,d\rho_0}\right), \quad F_2=E_0\ln\left(\frac{j_2\tau}{B\,d\rho_0}\right). \quad (19)$$

Substituting these expressions into the first equations of the system (13) and bearing in mind that the gain maximum lies at the frequency

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

we find that the number of photons in the resonator should rise when the following condition is satisfied

$$j_1^{\frac{1}{1+\gamma}}j_2^{\frac{\gamma}{1+\gamma}}>\frac{4B\,d\,\alpha e}{V_1\tau_r A\tau(1+\gamma)}, \quad (20)$$

where e is the base of natural logarithms.

When the self-excitation condition (20) is satisfied, the photon flux is amplified in the resonator and the emission amplitude rises. The Fermi level falls in the amplifying part of the diode and rises in the absorbing part; the total gain may increase with increasing field intensity. Such an increase occurs when the rate of decrease of the absorption coefficient with increasing field in one part of the diode is higher than the rate of decrease of the gain in the other part. In this case, we can excite oscillations in the resonator even when the self-excitation conditions are not initially satisfied. When a certain number of photons is introduced from outside, the total gain may increase so much that it exceeds the losses and steady-state emission conditions are achieved. We can thus have "hard" excitation conditions, i.e., a bistable operation, since (at a given value of the current) there are two stable steady-state conditions.

The condition for the rise of the gain with increasing field intensity

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

can be obtained in the explicit form using the last two equations of the system (13). Invoking the rules for the differentiation of implicit functions, we find that

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

where

$$I_i=\frac{j_1}{j_0}, \quad j_0=\frac{4B\,d\alpha}{AV_1\tau_r\tau(1+\gamma)}=\frac{j_{0\,\mathrm{th}}}{e}.$$

Consequently, the condition for the rise of the gain with increasing field intensity is of the form

$$\frac{\ln I_1}{I_1}+\gamma\frac{\ln I_2}{I_2}<0. \quad (21)$$

From the last two equations of the system (13), which describe the rate of change of the electron density, it is clear that at a frequency E defined by Eq. (20) a gain is obtained only if $j_i > j_0$. However, if $j_i < j_0$, then $(f_i - E)/kT < 0$ at the frequency E and this part of the diode absorbs radiation; consequently, the condition (21) demands that one of the diodes should be absorbing.

Figure 3 shows the dependence of the total relative gain r (defined as the ratio of the gain to the loss level) on the number of photons $\Phi = A\tau S/4B\alpha$ for a diode with $\gamma = 1$. Here, the curves without a prime represent the conditions for an injection current $I_2 = 0.074\ I_{th}$; the curves with a prime correspond to $I_2 = 0.26\ I_{th}$; the current I_1 is regarded as the parameter of these curves: for curves 1 and 1′, the current exceeds the threshold value by 10%; for curves 2 and 2′, the initial gain is equal to the losses; and for curves 3 and 3′, the initial

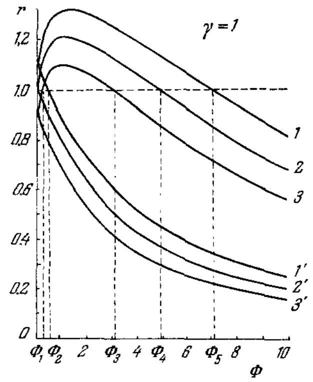

FIG. 3. Saturation effect in a nonuniformly excited semiconductor laser. The abscissa represents a quantity proportional to the density of photons in the resonator and the ordinate gives the ratio of the total gain to the loss level.

gain is 10% lower than the losses. It follows from Fig. 3 that, when $r < 1$ (curves 3 and 3′) and the condition (21) is invalid, there are no steady states (curve 3′). When the condition (21) is satisfied (curve 3), three steady states exist which correspond to $\Phi = 0$, Φ_1, and Φ_3. The state with $\Phi = 0$ is stable when subjected to infinitesimally small perturbations but when a certain number of photons is introduced from outside, emission becomes possible, i.e., the gain exceeds the losses. The state Φ_1 is always unstable since the gain increases with increasing field. Therefore, the diode goes over to the state Φ_3. When the initial gain is equal to the losses ($r = 1$) and the condition (21) is satisfied, steady states are not obtained (there is no emission). When the condition (21) is satisfied, the point Φ_4 corresponds to a steady state. The diode goes over from the $\Phi = 0$ to the Φ_4 state under the influence of infinitesimally weak excitations.

When the initial gain is greater than the losses (curves 1 and 1′) there is only one steady state: either Φ_2, if the condition (21) is not satisfied, or Φ_5 if the condition (21) is satisfied. The problem of the stability of points Φ_2, Φ_3, Φ_4, and Φ_5 requires a special study, such as that carried out in [19]. It is shown in that paper that, under certain conditions, steady states of this type may be unstable and pulsations of the radiation intensity may be observed.

A study of the stability of the steady-state solution yields relationships of the type

$$g_1 \frac{\partial g_1}{\partial n_1} \tau_1 + \gamma g_2 \frac{\partial g_2}{\partial n_2} \tau_2 = -\frac{d(g_1 + \gamma g_2)}{d\Phi} > 0, \tag{22}$$

$$\frac{\tau_1 + \tau_2}{\tau_1^2 \tau_2^2} + G\Phi \left[g_1 \frac{\partial g_1}{\partial n_1} \frac{1}{\tau_1} + g_2 \gamma \frac{\partial g_2}{\partial n_2} \frac{1}{\tau_2} \right] > 0; \tag{23}$$

here, $\tau_i = 1 + (\partial g_i/\partial n_i)\,\Phi$, $G = \tau/\tau_r$. Of these two conditions only one gives rise to self-excitation. In fact, Eq. (22) is identical, including the sign, with the derivative of the total gain with respect to the number of photons; if this derivative is negative, it simply represents the trivial case of instability of the first steady state under "hard" excitation conditions, i.e., an instability of a point such as Φ_1 at which the gain increases with increasing number of photons. The system goes over from the point Φ_1 to a different steady state (the point Φ_3) at which the gain decreases with increasing field. At the point Φ_3, the condition (22) is always satisfied. Violation of the condition (23) means that oscillations of the radiation intensity appear in the system because small deviations from the equilibrium positions increase in magnitude and undamped pulsations of the radiation intensity are established in the system. Since under steady-state conditions

$$g_1 + \gamma g_2 = \frac{1}{V_1 \tau_r} > 0,$$

it follows that the instability condition is satisfied when the gain is negative in the first ($g_1 < 0$) or the second part of the diode, $g_2 < 0$ ($\partial g_i/\partial n_i > 0$), i.e., to establish spiking one part of the diode should absorb and the other should amplify the radiation. An approximate solution of the system of equations (13), corresponding to the points of the Φ_3 type, was obtained in [19]:

$$\left.\begin{aligned} \frac{F_1 - E}{kT} &= \frac{1+\gamma}{\alpha} \frac{j_1 - j_0}{j_1 - j_0 + \gamma(j_2 - j_0)}, \\ \frac{F_2 - E}{kT} &= \frac{1+\gamma}{\alpha} \frac{j_2 - j_0}{j_1 - j_0 + \gamma(j_2 - j_0)}, \\ S &= \frac{V_1 \tau_r}{d} [j_1 - j_0 + \gamma(j_2 - j_0) - j_0(1+\gamma)]. \end{aligned}\right\} \tag{24}$$

It is evident from Eq. (24) that when the density of the injection current in one part is j_0, that part of the diode becomes transparent. The region of existence of the solution of the system (24) is shown in Fig. 4. The solution of the system (24) exists only in a region lying above the threshold line S′S″ (the slope of S′S″ is equal to γ): on the line itself, the number of generated photons is equal to zero. In region I, bounded by the lines $j_1/j_0 = 1$ and S′S″, part 1 of the diode absorbs and part 2 amplifies the radiation; in region II, bounded by the lines $j_2/j_0 = 1$ and S′S″, part 1 amplifies and part 2 absorbs the radiation; in region III, both parts of the diode amplify the radiation.

An approximate instability condition, obtained in [19], is of the form

$$j_1 - j_0 < K_1 (j_2 - j_0), \tag{25}$$

where

$$K_1 = -\frac{1}{2}\left[2\gamma + (1+\gamma)^2 - (1+\gamma)\sqrt{4\gamma + (1+\gamma)^2}\right].$$

The instability condition (25) defines the line P′P″ (Fig. 4) passing through the point (1, 1). Points lying in the region bounded by the lines P′P″ and S′S″ correspond to an unstable steady-state solution (region A). Region B is the spiking region, plotted experimentally. When the ratio of the currents is such that the point (j_1/j_0, j_2/j_0) lies within the instability region, the laser operates under conditions of radiation pulsation. The

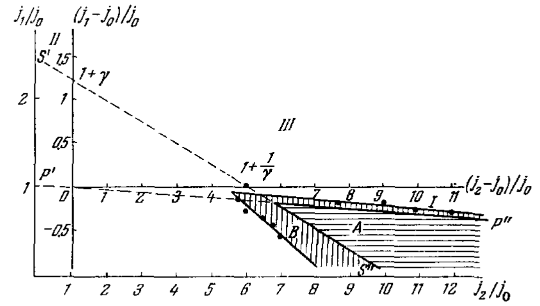

FIG. 4. Range of operation of a nonuniformly excited semiconductor laser under spiking conditions. Region A is the theoretical range and region B is the experimental range.

situation is, in many respects, similar to the case of solid-state lasers with saturable absorbers, but in the case of solid-state lasers we must use a different (easily saturable) substance for a nonlinear absorber, whereas in the case of semiconductor lasers the role of the nonlinear absorber is played by the absorbing part, which is of the same material as the amplifying part of the laser diode. In the case of an unstable steady state, the dynamics of pulsations in semiconductor lasers with nonuniform excitation is, in many respects, similar to the dynamics of emission of periodic pulses by solid-state lasers with nonlinear absorbers.

V. INVESTIGATION OF THE SPIKING OPERATION OF SEMICONDUCTOR LASERS

Investigations of the time dependence of the intensity of radiation of semiconductor lasers, carried out using fast-response radiation detectors, have established that, at a certain value of the injection current, the intensity of radiation of ordinary gallium arsenide injection lasers varies with time. It has been found that a radiation pulse of $10^{-5}-10^{-6}$ sec duration consists of pulses of $10^{-9}-10^{-10}$ sec duration distributed randomly in time.[11, 12] The results of an investigation of the operation of diffused semiconductor lasers, carried out using a time-scanned image converter with a time resolution of 20 nsec, are given in [11]. It was found that when the injection level was increased, the period of these short pulses (spikes) decreased. Some diodes emitted spikes with a period of about 0.5 nsec when the injection current was three times the threshold value. The emission of synchronous spikes from isolated luminous areas of the active region was observed; moreover, diodes with widely separated luminous points also exhibited nonsynchronous radiation with different spiking periods at different points. A theory of the amplitude self-modulation of the radiation of optically pumped lasers,[22, 57] applied to semiconductor lasers in the single-mode approximation, yielded dependences of the duration and period of the spikes on their power. It was assumed by these authors that, in order to compare the calculated and experimental data, it would be necessary to carry out spectral measurements which would give information on the mode composition of the semiconductor laser radiation under spiking conditions.*

An investigation of the dependence of the parameters of the spikes (their repetition frequency and duration) on the injection current and the resonator length was reported in [58]. Diodes with resonators 0.3–1.6 mm long were studied. A time-scanned image converter was used as the detector of the semiconductor laser radiation.

Figure 5 shows the dependence of the period of the spikes on the ratio of the injection and threshold currents for diodes of various lengths (the experimental dependences are shown by continuous curves). It follows from Fig. 5 that the dependence of the average value of the pulsation period on the pumping current is strongest for long diodes (L = 1.6 mm) and weak for short diodes (L = 0.4 mm). When the pumping current is increased the period and duration of spikes in diodes of different length tend to some limit. The scatter of the values of the period and of the duration of the spikes emitted by diodes with long and short resonators is 0.1–0.5 and 0.05–0.2 nsec, respectively. The duration of the spikes represents, in most cases, 0.4–0.6 of the spiking period and depends on the depth of modulation of the radiation, which increases with increasing current and, typically, may reach 80% when the ratio of the injection and threshold currents is 1.5–2. The spiking is observed also at relatively low values (a few percent) of the ratio of the injection and threshold currents but, in this case, the depth of modulation of the radiation is shallow. The reduction in the period and duration of the spikes with increasing injection current can be seen in oscillograms of the radiation from diodes recorded by photographing the screen of an image converter (Figs. 6a and 6b).

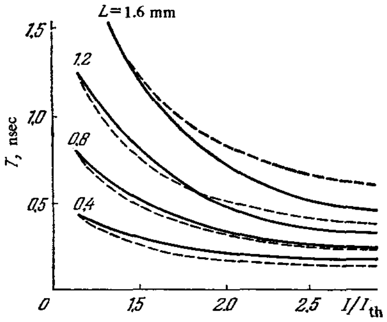

FIG. 5. Dependence of the period of light spikes T on the ratio of the injection and threshold currents I/I_{th} for single diodes with different resonator lengths. The experimental dependences are represented by continuous curves and the theoretical dependences are shown dashed.

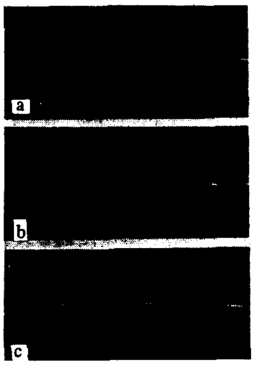

FIG. 6. Oscillograms (a, b) of light spikes emitted by single diodes, recorded from the screen of an image converter for an increasing injection current level; the duration of the scan is ~10 nsec. Oscillogram c shows the structure of the light spikes: the period of the main spikes is ~1.8 nsec and that of the ultrashort spikes is ~5 nsec.

Figure 7 shows the dependence of the spike period on the resonator length at various excitation levels. It follows from Fig. 7 that the dependence is strongest near the threshold and becomes weak when the injection current is 2–3 times higher than the threshold value.

Investigations of the time characteristics of the spikes have established that, in the majority of cases, they are trains of even shorter pulses, i.e., the laser radiation is doubly modulated (Fig. 6c). The repetition frequency of these ultrashort spikes is 10–16 GHz and their duration is at the limit of resolution of the devices used in such measurements and represents typically 0.3–0.5 of the value of the period. The period of these

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*Spiking is also observed in electron-bombarded or optically excited semiconductor lasers [55,56].

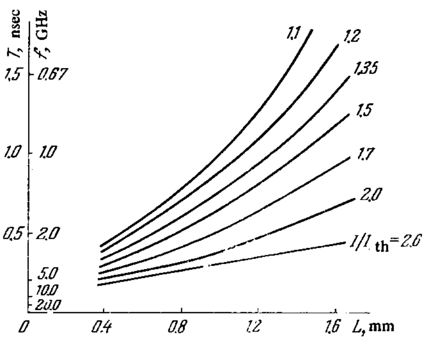


FIG. 7. Dependence of the period of light spikes, emitted by single diodes, on the resonator length. Different curves represent different values of the pumping current.

ultrashort spikes is, in most cases, practically independent of the resonator length; the depth of modulation of the radiation represented by the ultrashort spikes is almost independent of the amplitude of the injection current.

Spectral investigations of the radiation emitted by semiconductor lasers working under spiking conditions show that there is a definite correlation between the emission spectrum and the nature of the spikes. The working conditions under which fairly regular spikes are observed correspond to a spectrum with a small number of axial modes (two or three modes); a wide or multimode spectrum corresponds to random spikes.

Rate equations, developed for semiconductor lasers in the single-mode approximation, were used in [58] to determine the dependence of the spiking period T on the injection current I:

$$T=\sqrt{\frac{\tau\tau_r}{I/I_{\text{th}}-1}}M, \tag{26}$$

where τ is the carrier recombination time; τ_r is the photon lifetime in the resonator; I/I_{th} is the ratio of the injection and threshold currents; M is some quantity which depends weakly on τ, τ_r, and I/I_{th}. It follows from Eq. (26) that, when the resonator length is constant, the spiking period is $T \propto [(I/I_{th}) - 1]^{-1/2}$, which is in good agreement with the experimentally obtained dependence. The curves plotted on the basis of Eq. (26) are shown dashed in Fig. 5. Assuming that the photon lifetime in the resonator is proportional to the resonator length ($\tau_r \propto L$), it follows from Eq. (26) that, when I/I_{th} = const, the spiking period depends on the resonator length: $T \propto \sqrt{L}$. This confirms qualitatively the experimentally observed reduction of the spiking period when the resonator length is reduced. Allowance for nonlinear losses in the resonator, which give rise to undamped pulses with a large modulation depth, alters slightly the dependence of the period Y on the injection level because the observed dependence of the average spiking period on the current agrees quite well with the dependence plotted on the basis of Eq. (26).

Investigations of the spiking of an ordinary semiconductor laser confirm the suggestions put forward in [12, 9] that the main mechanism responsible for the appearance of spikes is the nonlinear absorption of radiation in the active region of the laser. In fact, at low injection levels, when absorbing regions exist in a diode because of the spatial nonuniformity of excitation, the random nature of spikes is less pronounced than at higher injection levels ($I/I_{th} > 1.5$). This may be due to the fact that, when the current is increased, the importance of such absorbing regions decreases and the role of the interaction of various oscillation modes becomes greater.

Nonlinear losses in the active region of a semiconductor laser may also be due to the "spreading" of the radiation along a direction transverse to the laser axis.[59] It was predicted in [60] that such a mechanism could cause undamped self-modulation of the radiation emitted by a semiconductor laser excited by electron bombardment. Calculations carried out in [61] showed that the "spreading" of the field could explain the pulsating nature of the radiation emitted by injection lasers. The existence of a "waveguide" in the active region of a diode imposes definite conditions on the appearance of undamped spikes. It has been shown that undamped pulses appear when

$$\delta\varepsilon_m' < \frac{\zeta^2}{4k^2}; \tag{27}$$

here, $\delta\epsilon_m'$ is the sudden change of the permittivity between the active region and the n-type part of the diode; ζ is a constant representing the half-width of the permittivity curve in the active region; $k = \omega_0/c$, where ω_0 is the frequency of the emitted light. The physical interpretation of this condition is based on the assumption that, under spiking conditions, the field should be able to "leak" out of the active region. Thus, on the basis of this mechanism, undamped spikes should be observed in diodes with a weak dielectric waveguide. The influence of such nonlinear radiation losses on the appearance of spikes should be investigated experimentally.

To obtain clear and regular spikes, investigations of the locking of intrinsic random spikes, generated in an ordinary semiconductor laser, were carried out in [20] using the current from a high-frequency standard-signal generator. The amplitude of the high-frequency current was a few percent of the amplitude of the injection current. When a high-frequency current, whose period was shorter than the separation between single intrinsic pulses, was supplied to a diode operating under irregular spiking conditions, it was possible to lock the spikes by the external current. When the frequency of the current supplied by the signal generator was altered, the spiking frequency changed as well and remained exactly equal to the frequency of the generator current. This spike locking was observed in the frequency range 400–1000 MHz. The locking range depended on the amplitude of the injection current; it shifted in the direction of higher frequencies when the current was increased, and amounted to a few hundred megahertz. Figure 8 shows oscillograms of spikes: the upper oscillogram shows the radiation of a diode with the high-frequency signal generator switched off, while the lower oscillogram shows the operation of the diode supplied simultaneously with the high-frequency and injection currents. It is evident from Fig. 8 that, in the first case, the radiation is of the irregular spike type while, in the second case, regular spikes are observed with a repetition frequency equal to the frequency of the current supplied by the signal generator.

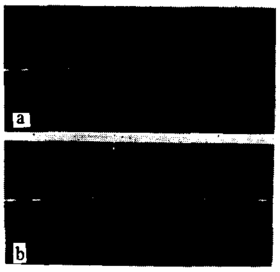


FIG. 8.

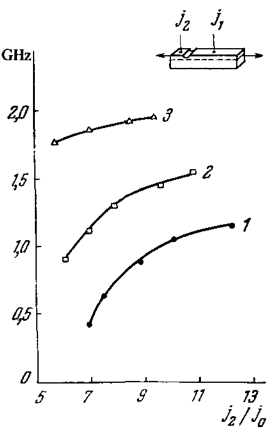


FIG. 9.

FIG. 8. Locking of intrinsic irregular spikes of an ordinary diode by a high-frequency current (680 MHz): a) no high-frequency current; b) high-frequency switched on. In both cases, $I/I_{th} = 1.4$. The ratio of the amplitude of the high-frequency current to the amplitude of the injection current is $I_{hf}/I \approx 0.05$.

FIG. 9. Dependence on the injection current, of the repetition frequency of the light pulses emitted by a diode with a nonuniform injection density; j_0 is the threshold current density in the case of uniform excitation of the diode; j_2 is the injection current density in part 1 of the diode, which is treated as the parameter of the curves.

It was reported in [62] that a single light pulse of ~0.2 nsec duration was emitted when an injection diode was excited with a current pulse of about 2 nsec duration.

Two semiconductor lasers, enclosed in a single resonator, generated regular light pulses with a repetition frequency of the order of a few gigahertz and a pulse duration amounting to a fraction of a nanosecond.[12] In this case, the frequency and duration of the light pulses were practically constant throughout the injection current pulse, whose duration was 10 μsec, and the depth of modulation of the radiation was close to 100%. Such "regular spikes" were observed only when the excitation of a diode was nonuniform across the p–n junction area; for this purpose, one part of the diode was supplied with a current whose density was several times the current density in the other part of the diode. Experiments showed that the frequency and duration of the light pulses depended on the excitation levels in both parts of the diode.

Further investigations of the regular pulsations of the radiation emitted by a nonuniformly excited semiconductor laser were reported in [19]. It was possible to vary smoothly the amplification and the light losses in the resonator by altering the pumping currents because the two independent parts of a diode were placed in a single resonator. Clear spiking was observed when the current density j_2 in the second part of the diode was higher than the threshold density j_0, corresponding to uniform excitation of the semiconductor laser, and the current density j_1 in the first part of the diode was lower than j_0. This indicated that part 2 operated as an amplifier while part 1 acted as an absorber. The dependence of the spike repetition frequency f on the ratio of the current density j_2 to the threshold density j_0 is shown in Fig. 9. Here, the ratio of the current densities j_1/j_0 is the parameter of the curves. The spike duration, under the operating conditions corresponding to curve 1, decreased from 1 to 0.5 nsec when j_2/j_0 was increased; the spike duration changed from 0.2 to 0.1 nsec under the operating conditions corresponding to curve 3. The period and duration of the spikes depended also on the resonator length and became shorter when this length was reduced.[58]

Figure 10 gives the dependences of the period T and duration τ of the regular spikes on the resonator length of a diode, which were obtained using various injection levels. The upper curves correspond to values of the current at which pulsations are observed and the lower curves correspond to currents above which the regular spikes disappear. It follows from Fig. 10 that the range of variation of the period and duration of spikes, considered as a function of the current, is greatest for diodes with the longest resonators, while the shortest spikes are observed for diodes with the shortest resonators. Typical oscillograms of the light pulses emitted by diodes with resonators of different lengths are shown in Fig. 11 for different injection currents.

Thus, using diodes with different resonator lengths and varying the injection level, we can produce regular light pulses (spikes) whose repetition frequency ranges from 3×10^8 to 10^{10} cps, and whose duration is $\sim 10^{-9}-10^{-11}$ sec.

Region B in Fig. 4, representing the operation of a laser under spiking conditions, is plotted for a diode with the ratio of the volumes of its two parts given by $\gamma = 1/4$. The lower line, which is a boundary of region B on the side of low values of j_2, represents the appearance of the regular spikes; the upper line, which is a boundary of region B on the side of high values of j_2, represents the disappearance of the regular spikes. It

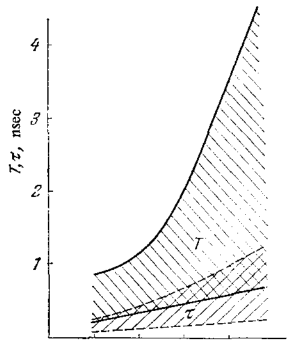


FIG. 10.

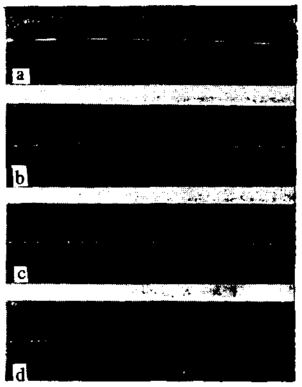


FIG. 11.

FIG. 10. Dependence of the period and duration of regular light spikes on the laser resonator length at various injection levels. The upper curves, denoted by T (continuous and dashed), correspond to currents for which the pulsation conditions are first obtained; the lower curves, denoted by τ, correspond to currents which represent the upper limit for regular spiking.

FIG. 11. Oscillograms of light pulses emitted by a nonuniformly excited diode. Oscillograms a and b represent the radiation emitted by a diode with a resonator 1.5 mm long. Oscillograms c and d represent the radiation of a diode with a resonator 0.6 mm long. The injection current increases from a to b and from c to d, respectively. The duration of the scan is ~10 nsec.

follows from Fig. 4 that the theoretically obtained range of existence of the regular spikes (region A) is in fairly good agreement with the experimental data.

The physical processes occurring in nonuniformly excited semiconductor lasers operating under regular spiking conditions are similar to those in a ruby laser with a saturable absorbing filter. The absorbing part of a diode acts as a nonlinear absorber. Some support for this model is also given in [63].

The locking of the radiation pulses of double diodes was reported in [64]. It was found that when one part of a diode was supplied with square current pulses and the other part with a sinusoidal current, and the amplitudes of the two currents were made approximately equal, spikes were observed whose repetition frequency was equal to the frequency of the alternating current (500 MHz).

VI. OPERATING CHARACTERISTICS OF NONUNIFORMLY EXCITED SEMICONDUCTOR LASERS

In the case of the nonuniform excitation of a double diode (with different current densities in the two parts of the diode), the same excitation level may correspond to two stable optical states (bistable operation).[9, 52] The simplest method for achieving bistable operation is the injection of a current into one part of the diode only. The current is selected so that the diode is close to the laser threshold; the other part of the diode acts as an absorber. In this case, we can have two stable states; one state represents recombination radiation (self-excitation conditions are not satisfied), while the other state represents coherent emission. The coherent-emission state is reached when an additional short pulse of current (or light) is applied to either part of the diode, but the intensity of this pulse must be sufficient to saturate the absorption of light in the diode; this switches the diode to the second stable state.[9] Such a diode may be switched by a short negative current pulse supplied to one of its parts. It was reported in [65] that the application of a triggering current pulse of ~100 nsec duration to a diode operating at T = 80°K switched on this diode, which then emitted coherent radiation for 10 μsec after the end of the triggering pulse; the amplitude of the triggering pulse was less than 1% of the injection current. The total radiation power, integrated over the whole spectrum, emitted in the switched-on state was tens of times higher than the power of the radiation emitted in the switched-off state (Fig. 12). Some diodes operating under bistable conditions produced coherent radiation of about 2 W power from each emitting face. A diode was switched on by the radiation of a second laser. The minimum power of the triggering signal was approximately two orders of magnitude lower than the radiation power of the diode in the switched-on state; the wavelength of the triggering light pulse was shorter than or equal to the wavelength of the radiation emitted by the double diode in the switched-on state. The application of a pulse of light of longer wavelengths switched-off a diode which was in the on state. The quenching efficiency, i.e., the ratio of the reduction in the power of the radiation of the bistable laser to the power of the switching-off signal, was about 10%. Such a low quenching efficiency was evidently due to the fact that the wavelengths of the quenching and quenched lasers differed only slightly (2–3 Å), which resulted in a mutual overlap of the lines and their amplification.

FIG. 12. Oscillogram of the bistable operation of a nonuniformly excited laser. The upper trace represents the current signal (a small switching-on peak can be seen); the lower trace represents the emission of light in the switched-on state.

A feature of a nonuniformly excited double diode is the strong dependence of the laser emission threshold on the magnitude of the nonlinear losses in the resonator. It follows from the condition (20) that the threshold curve, i.e., the curve consisting of points at which the self-excitation conditions are satisfied, is given by the following expression for a diode with $\gamma = 1$

$$I_1 I_2 = \frac{1}{4} I^2_{\text{th}}, \tag{28}$$

where I_1 and I_2 are the currents in the two parts of the diode and I_{th} is the total threshold current in the case of uniform excitation of the diode. The experimental threshold characteristics (dashed curves) and the theoretical dependence (continuous curve) for a semiconductor laser consisting of two equal insulated parts in a single resonator are shown in Fig. 13.

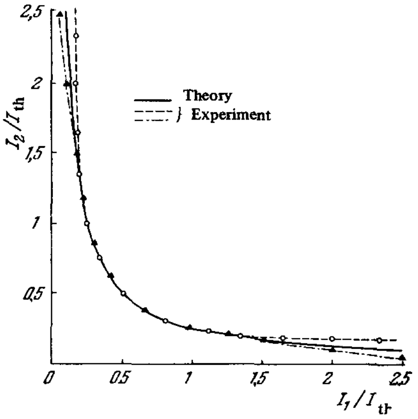


FIG. 13. Experimental and theoretical threshold characteristics of nonuniformly excited lasers for $\gamma = 1$. The dashed and chain curves represent the experimental characteristics for two different diodes.

Figure 14 shows, by dashed lines, typical experimental watt–ampere characteristics of a laser consisting of two identical, electrically insulated, parts under various operating conditions; the parameter of the curves is the degree of nonuniformity of the injection current density in the two parts of the diode. (The experimental curve 1 corresponds to uniform excitation of the laser.)

In the case of nonuniform excitation, when the density of the current in one part of the diode is higher than that in the other (curves 2–5), the slope of the watt–ampere characteristic depends nonlinearly on the current and has its maximum value at the laser threshold; when the injection current is increased, the slope approaches that observed in the case of uniform excitation. When the nonuniformity of the injection current is increased still further, the "hard" excitation conditions are established and coherent emission is achieved in a jump (curves 3–5 in Fig. 14). The slope of the watt–ampere characteristic at the threshold can be calculated using Eqs. (13) and (16). For a small number of photons in the resonator, ΔΦ, the solution of Eq. (13), obtained using Eq. (16), yields

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

Substituting the values thus found in Eq. (17), we find that

$$\frac{I_1\ln I_1}{I_1+\Delta\Phi}+\gamma\frac{I_2\ln I_2}{I_2+\Delta\Phi}=1+\gamma.$$

If $I_2 = I_2^0 + \Delta I_2$ and $I_1 = I_1^0 + \Delta I_1$ and if the point (I_1^0, I_2^0) lies on the threshold curve, i.e.,

$$\ln I_1^0+\gamma\ln I_2^0=\gamma+1,$$

it follows that

$$\Delta\Phi=\left(\frac{\Delta I_1}{I_1^0}+\gamma\frac{\Delta I_2}{I_2^0}\right)\left(\frac{\ln I_1^0}{I_1^0}+\gamma\frac{\ln I_2^0}{I_2^0}\right)^{-1}. \tag{29}$$

The expression (29) defines the slope of the watt–ampere characteristic, i.e., the quantities $(\partial S/\partial f_1)|_{S=0}$ and $(\partial S/\partial f_2)|_{S=0}$ on the threshold curve. The slope of the watt–ampere characteristic increases on approach to the point at which the expression

$$\frac{\ln I_1}{I_1}+\gamma\frac{\ln I_2}{I_2}$$

changes its sign. At the point $I_1^0 = 1.67\,I_{th}$, $I_2^0 = 0.15\,I_{th}$ (i.e., when the total current is 1.82 times larger than the uniform excitation current), the slope becomes infinite and the "hard" excitation conditions are established. It has been found experimentally that the "hard" excitation conditions are obtained when the total injection current is twice the injection current in the uniform excitation case.

The continuous curves in Fig. 14 represent the theoretical watt–ampere characteristics which, as can be seen in the figure, are in good agreement with the experimental curves.

Under some excitation conditions, a diode may have stable states above the coherent emission threshold; these states differ from one another by about 10 Å in their wavelength. When the diode is switched between these coherent emission frequencies, the output power remains practically constant. A theoretical investigation of the conditions for the appearance of two equivalent states above the coherent emission threshold and of their stability conditions is reported in [66]. In the case of uniform excitation, the differential slope of the watt–ampere characteristic of some diodes depends nonlinearly on the current: this may be due to the fact that, in such diodes, there are absorbing regions (due to internal inhomogeneities) and these regions become transparent when the injection current is increased.

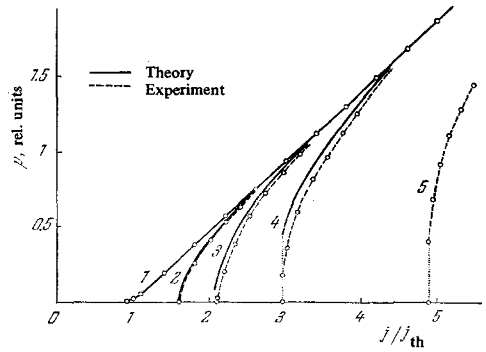


FIG. 14. Family of watt-ampere characteristics of the emission of a nonuniformly excited diode (curve 1 represents the uniform excitation case). The degree of nonuniformity of the excitation increases from curve 2 to curve 5. The continuous curves 2–4 represent theoretically calculated characteristics.

When a sinusoidal voltage is applied to a diode whose watt–ampere characteristic exhibits a sudden change in the slope (AB) and which is in the off state (point A in Fig. 15), such a laser diode generates square light pulses with a repetition frequency equal to the frequency of the sinusoidal signal; the radiation emitted by the diode continuously switches from the on to the off state and back again (a typical oscillogram of such light pulses is shown in Fig. 16).[67] When the amplitude of the injection current is varied, we find we can smoothly vary by a factor of 10, the duration and, consequently, the off-duty factor of the light pulses at a fixed frequency. The rise and decay times of the light pulses are practically independent of the frequency of the sinusoidal signal between 100 kHz and 1 GHz but are governed by the switching time of the diode, which is $\sim 10^{-10}$ sec.

A circuit for a high-frequency generator of light pulses was described in [34]: the generator consists of a laser diode, a quantum light amplifier, and a photoresistor, connected parallel to the diode. The operation of the generator is based on the control of the injection current by means of the photoresistor, which is illuminated by the laser.

The operation of a generator of optical and electrical oscillations was investigated in [68] using a system consisting of a nonuniformly excited laser and a photodiode. A pulse generator supplied the injection current to one part of the diode, while the other part was connected in

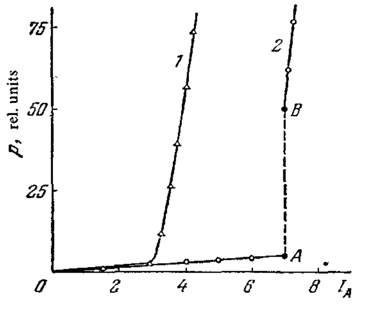


FIG. 15. Watt-ampere characteristics of a semiconductor laser: 1) uniform excitation; 2)nonuniform excitation.

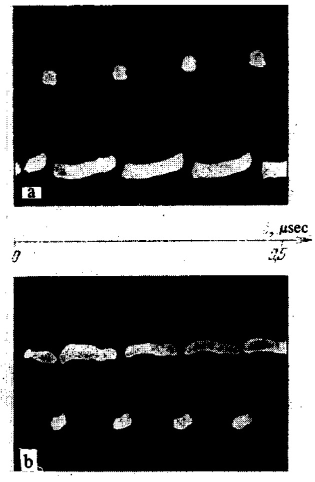


FIG. 16. Oscillograms of square light pulses generated by a semiconductor laser under the "hard" excitation conditions when a small sinusoidal triggering pulse is applied to the laser. $I_a < I_b$ for oscillograms a and b, respectively.

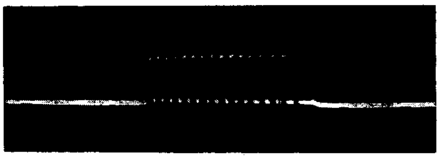


FIG. 17. Oscillogram of light pulses emitted by a laser under the "hard" excitation conditions in the case of opto-electronic coupling with a photodiode. The duration of the scan is ~20 μsec.

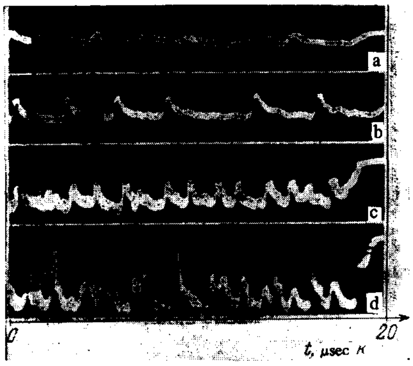


FIG. 18. Dependence of the period and duration of light pulses, emitted by a semiconductor laser with an external mirror, on the injection current level. The length of the common resonator is 35 cm. I_{th} = 2.3 A. The laser threshold is exceeded by 8% in oscillogram a, by 10% in b, by 15% in c, and by 20% in d. The duration of the scan is ~800 nsec.

the photodiode circuit. After switching on the double diode, the photocurrent generated by the laser radiation in the photodiode stopped the laser emission. Consequently, the photocurrent ceased to flow and the laser was switched on again. Figure 17 shows an oscillogram of light pulses, photographed from the screen of an oscillograph. Electrical oscillations of the photocurrent, whose period was identical with the period of the light pulses, were generated simultaneously with the laser radiation. Using photodiodes with a response amounting to a fraction of a nanosecond, an opto-electronic oscillator working in the centimeter range could be constructed. The frequency of this oscillator could be varied in a wide range by altering the response of the negative feedback circuit.

Using positive feedback and a photocurrent amplifier, a gain of ~ 10^5 was obtained for the optical power in such a system.[67]

VII. TIME STRUCTURE OF THE RADIATION OF SEMICONDUCTOR LASERS WITH AN EXTERNAL MIRROR

The time structure of the radiation of an injection laser, coupled optically to an external mirror, was investigated in [65]. The radiation of the laser diode, reflected back from the external mirror, was focused by an optical system on the active region of the laser. The laser emission threshold was reduced by 10–20% when the reflection coefficient of the mirror was ~ 98%.

When the coherent emission threshold of the diode was exceeded slightly, steady-state emission conditions were obtained, i.e., the intensity of the laser radiation did not vary with time. When the injection current was increased further, the intensity of the radiation emitted by the diode coupled to the external mirror began to vary with time: it became a sequence of light pulses whose rise times were much longer than their decay times. The nature and shape of the light pulses depended on the value of the injection current (Fig. 18). When the pumping level was increased, the period and duration of the light pulses became shorter and at the same time the depth of modulation of the radiation increased. Continued increase of the current gave rise to fairly regular spikes with a period proportional to the resonator length. When the current became equal to the threshold value which would apply without the external mirror, the nature of the spikes changed: pulsations became random in shape and intensity. The appearance of these light pulses can be explained by assuming that the steady-state emission by a semiconductor laser can be unstable, i.e., the emission of a diode can be of the spike type.[12, 19] The relaxation nature of the light pulses can be understood on the basis of the following simple considerations. When a diode stops emitting, the rate of decay of the field is governed by the transit time of photons through the resonator formed by the faces of the diode and the external mirror; this is why the decay time of the pulses is short. Since the gain per unit length of such a resonator is very small when the current is only slightly higher than the threshold value, emission starts only after many transits and this is why the rise time of the light pulses is long.

The mode locking effect was observed for the first time in a study of the dynamics of the radiation emitted by a semiconductor laser.[10] The essence of this effect is as follows: owing to the nonlinearity of the active medium, a series of coherent oscillation modes, separated by equal frequency intervals, is generated; because of the interference between these modes, the total radiation is in the form of a sequence of pulses whose period is $2Ln_0/c$ and whose duration is $2Ln_0/mc$, where L is the length of the resonator formed by the diode faces and the mirror, m is the number of locked modes, and n_0 is the refractive index of the medium. This effect is well known for gas and other solid-state lasers.[3, 69–71] A semiconductor laser, coupled optically to an external mirror, makes it possible to increase considerably the number of oscillation modes which can exist in the resonator formed by the diode faces and the mirror. The length of such a resonator was varied from 15 to 75 cm. Since it was known that inclusion of a nonlinear absorber in the resonator increased the number of locked modes, investigations were carried out on double diodes in which one of the parts absorbed radiation nonlinearly. Figure 19 shows an oscillogram of the radiation from a diode under mode-locking conditions. Against a background of relaxation oscillations with a period of 70 nsec, we can see oscillations of the intensity with a period of 5 nsec, corresponding to the separation between neighboring axial modes (the length of the complete resonator was 75 cm). Similar results are obtained also for other lengths of such a resonator. In all the cases, the oscillation period is independent of the ratio of the injection to the threshold current, and agrees quite well with the value 2L/c. Spectral measurements of the radiation from a diode coupled to an external mirror have established that the spectrum is considerably broadened (its half-width is 15 Å), compared with the radiation spectrum of a semiconductor laser without an external mirror. The wide spectrum consists of a large number of modes generated simultaneously in the resonator when an external mirror is used. The 15 Å wide line consists of about 10^3 oscillation modes in the case of a resonator 75 cm long, and the locking of even a small fraction of the total number of modes should give rise to periodic pulsations of the radiation.

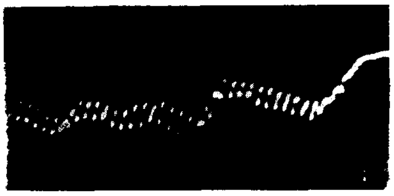


FIG. 19. Oscillogram of the emission of a diode with an external mirror under axial mode-locking conditions. The length of the common resonator is 75 cm. The duration of the scan is ~200 nsec.

When the majority of modes in a semiconductor laser is locked, it is possible to generate ultrashort light pulses of ~ 10^{-12} sec duration with a repetition frequency between 10^8 and 10^{11} Hz.

VIII. INTERACTION OF OPTICALLY COUPLED LASERS

Investigations of the interaction of optically coupled semiconductor lasers have yielded information on several physical processes taking place in injection lasers and have demonstrated, in principle, the possibility of using semiconductor lasers for the construction of optical logical elements. The optical coupling between semiconductor lasers has been investigated in two variants:

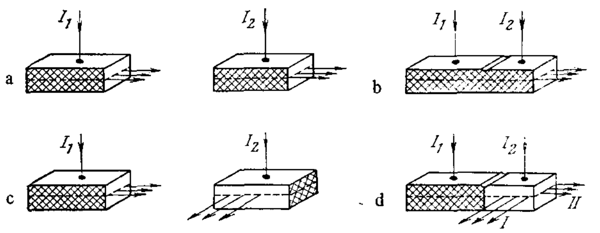


FIG. 20. Various configurations of optically coupled lasers: a) "longitudinal"; b)"longitudinal" in a double diode; c)"transverse"; d)"transverse" in a double diode.

1) "longitudinal," when the direction of radiation from one laser coincides with the direction of radiation from the second laser[14, 72] (Figs. 20a and 20b);

2) "transverse," when the directions of radiation from the lasers are mutually perpendicular[13, 15] (Figs. 20c and 20d).

In both cases, the diodes (in the shape of Fabry–Perot resonators) are aligned in such a way that the planes of their p–n junctions coincide.

In the "longitudinal" position of the diodes, one can investigate the effect of quenching the radiation of one laser by the radiation of the second laser. This quenching effect applies only to the short wavelengths of the radiation from the first laser (the spectral or selective quenching effect) while the long-wavelength radiation of the first laser or of the double resonator, formed by the two lasers, is not quenched and its direction is not affected.

The spectral quenching effect has also been investigated in double laser diodes.[9, 16, 53, 73–75] When a current is supplied to one part of the diode, the laser emits a short-wavelength mode. When a current is supplied to the second part of the diode, during emission from the first part, the short-wavelength radiation is quenched and a stronger long-wavelength mode is produced.

A theoretical analysis of the operation of a system of "longitudinally" oriented diodes (Fig. 20a) is given in [76]. If we assume that the long-wavelength radiation of the quenching laser passes through the active region of the quenched laser, the rate equations for the total number of photons in the quenched and quenching modes and for the electron density are of the form

$$\left.\begin{aligned}\dot{S}_1&=\left[g(E_1)-\frac{1}{\tau_r}\right]S_1,\\ \dot{S}_2&=\frac{S_{20}}{\tau_r}+\left[g(E_2)-\frac{1}{\tau_r}\right]S_2,\\ \dot{n}&=\frac{j}{d}-\frac{n}{\tau}-\frac{S_1}{V}g(E_1)-\frac{S_2}{V}g(E_2);\end{aligned}\right\}\qquad(30)$$

here, S_1, $g(E_1)$, S_2, $g(E_2)$ are the fields (S) and gains (g) at the quenched (E_1) and quenching (E_2) frequencies, respectively; n is the electron density; j is the injection current density; d is the diffusion length of electrons; τ is the recombination time of electrons; V is the volume of the resonator of the quenched diode; S_{20} is the field in the resonator set up by the quenching laser; τ_r represents the radiation losses in the resonator (absorption and scattering, diffraction losses in reflection, etc.). The steady-state solution of the system of equations (30) for the fields S_1 and S_2 is of the form

$$S_1 = V\frac{I-n}{\tau g(E_1)} - \beta_1 S_2, \quad S_2 = \frac{S_{20}}{1-\beta_1}, \tag{31}$$

where

$$I = \frac{j\tau}{d}, \quad \beta_1 = \frac{g(E_2)}{g(E_1)}, \quad g(E_1) = \frac{1}{\tau_r}.$$

It follows from Eq. (31) that the total number of photons in the quenched oscillation modes decreases with increasing S_2, i.e., the quenching effect is a linear function of the quenching power and the reduction in the output power of the quenched laser is independent of the injection current in that laser if the output power of the quenching laser is constant. The quenching efficiency, i.e., the ratio of the reduction in the output power of the quenched laser to the power of the quenching radiation, is governed by the power S_{20} at which the laser emission stops, i.e., S_1 vanishes; the quenching efficiency is equal to $\beta_1/(1-\beta_1)$. The quantity β_1 can be written approximately in the form

$$\beta_1 = \left(1+\frac{\Delta E}{E_0}\right)\exp\left(-\frac{\Delta E}{E_0}\right) \approx 1-\left(\frac{\Delta E}{E_0}\right)^2; \tag{32}$$

here, $\Delta E = E_1 - E_2$.

Consequently, the quenching efficiency is governed by the ratio of the gains at the quenching and quenched frequencies. When the difference between these frequencies (E_1 and E_2) is large, the gain at the quenching frequency is small compared with $g(E_1)$, and the quenching efficiency is low. The quenching efficiency is higher when the frequencies E_1 and E_2 are close to one another.

An analysis of the operation of a semiconductor laser with a nonuniform injection density was carried out in [76,77] assuming that the Fermi levels in the two parts of the diode differed strongly, because the spectral quenching effect was observed experimentally only in the case of nonuniform excitation of the diode. It was found that the reduction in the number of photons at the quenched frequency was governed by the quenching-frequency field. The quenching efficiency increased when the frequencies approached each other, and it then tended to unity.

Since the direction of radiation from a diode does not alter under spectral quenching conditions and the radiation power integrated over the whole spectrum increases, such a diode configuration is not very suitable for logical elements since it would be necessary to use narrow-band interference filters passing only the short-wavelength radiation and absorbing long wavelengths.

The coherent radiation from the first laser in the "transverse" optical coupling configuration is reduced in intensity or stopped altogether by the passage of the radiation from the second laser through the active medium of the first laser (Fig. 20c). In this case, the quenching efficiency reaches only a few percent.[72] The low quenching efficiency of this optical coupling configuration is due to the high losses suffered by the quenching radiation. The losses are caused by the difficulty of achieving exact alignment of the emission regions of the interacting diodes because the thickness of the active region of each semiconductor laser is only a few microns.

The optical coupling between lasers is improved by incorporating two mutually perpendicular lasers within the structure of a single diode[15,16,75,78] (Fig. 20d).

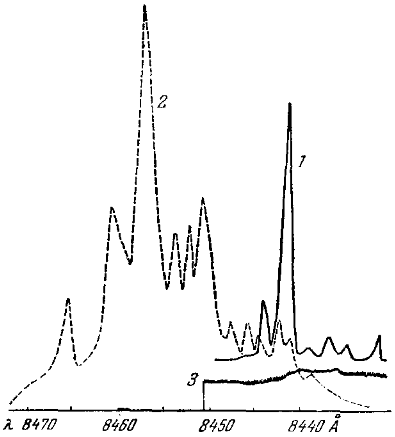


FIG. 21. Total and spectral quenching of the radiation of laser 2 by the radiation of laser 1. Curve 1 represents the emission spectrum of laser 2 when laser 1 is switched off. Curve 2 represents the emission spectrum of the "quenching" laser 1. Curve 3 gives the spectrum of the "quenched" laser 2 (the diode is shown schematically in Fig. 20d).

Thus, both parts of the diode can generate coherent radiation along mutually perpendicular directions. When a current I_2 is supplied to the second part, the diode begins to emit radiation along the direction I, because large losses in part 1 do not permit the operation of the diode along direction II. When currents I_1 and I_2 are supplied simultaneously, the intensity of the radiation of the laser along direction I decreases but the signal along direction II becomes stronger. Further increase of the current I_1 quenches the radiation along direction I. Spectral measurements show that the short-wavelength modes of the radiation I are quenched most effectively by the longer wavelengths of the radiation II. This is explained as follows: when the quenching radiation II consists of longer wavelengths, the Fermi level in the conduction band of the active region of laser 1 falls; this reduces effectively the population inversion of the energy levels corresponding to shorter wavelengths.

Figure 21 shows the emission spectra of coupled lasers 1 and 2. Here, curve 1 represents the radiation spectrum of laser 2 along direction I for a current $I_1 = 0$. Curve 2 represents the spectrum of the quenching radiation along direction II; this radiation quenches the emission along direction I (curve 3). Quenching efficiencies of the order of 50–70% have been reported for lasers whose radiation spectra differ by about 20 Å. A theoretical analysis of the "transverse" optical coupling of two semiconductor lasers (Fig. 20c) shows that the quenching efficiency is given by the expression[76]

$$\eta \sim \frac{\beta_1}{1-\frac{\tau_2}{\tau_1}\beta_1}; \tag{33}$$

here, τ_1 is the lifetime of a photon in the resonator of the quenched diode; τ_2 is the lifetime of a photon during its transit between the lateral faces of the same quenched diode. It follows from Eq. (33) that efficient quenching is obtained when the values of τ_1 and τ_2 do not differ greatly because, if $\beta_1 \approx 1$, a low power level is sufficient for quenching which is due to the regenerative amplification of the external radiation.

The quenching effect for two mutually perpendicular lasers (Fig. 20d) is described quite satisfactorily by the rate equations for the balance of carriers injected into the two parts of the diode and the balance of the interacting fields.[76] The steady-state solutions of the system of such rate equations for the fields S_1 and S_2 are

$$S_1=\frac{V}{\tau}\frac{I_1-n_1}{g_1(E_1)}, \quad S_2=\frac{V_2}{\tau}\frac{I_2-n_2}{g_2(E_2)}-\frac{V_2}{V}\frac{g_2(E_1)}{g_2(F_2)}S_1, \tag{34}$$

where S_1 and S_2 are the fields at the quenching and quenched frequencies; τ is the carrier lifetime; $V = V_1 + V_2$, where V_1 and V_2 are the volumes of parts 1 and 2, respectively; j_1 and j_2 are the densities of the injection currents in parts 1 and 2; n_1 and n_2 are the electron densities and $g_1(E)$ and $g_2(E)$ are the gains in the two parts of the diode. The gain is defined by Eq. (16). It is assumed that $E_1 < E_2$ and $I = j\tau/d$, where d is the diffusion length. It follows from the expression for S_2 that the reduction in the number of photons in the quenched oscillation modes is governed by the number of photons in the quenching modes. The quenching efficiency is given by

$$\eta=\frac{\gamma}{1+\gamma}\frac{\tau_2(1+\ln\tau_1/\tau_2)}{\tau_1}. \tag{35}$$

When the frequencies of the interacting fields are equal ($\tau_1 = \tau_2$), the quenching efficiency is equal to the volume ratio $V_2/(V_1 + V_2)$. The experimentally obtained quenching efficiencies, of the order of 50–70%, show that strong optical coupling between lasers is achieved in the interacting laser configuration where the two parts of the diode have a common resonator.

The interaction time of two optically coupled lasers was determined in [47] using a time-scanned image converter with a time resolution of $\sim 3 \times 10^{-11}$ sec. The diode axis was aligned parallel to the cathode of an image converter onto which the radiation from laser 2 was projected simultaneously with the radiation from laser 1 (this was done by means of a rotating mirror). The interaction time was determined from the delay time separating the moment of cut-off of the radiation from laser 2 and the beginning of emission from the quenching laser 1. At a fixed amplitude of the current I_1, the interaction time increased when the current I_2 was increased; when the amplitude of the current I_2 was kept constant, the interaction time decreased when the current I_1 was increased. The measured interaction time ranged from 3×10^{-10} to 5×10^{-11} sec. The shortest interaction time found in this way was limited by the resolution of the recording apparatus.

The results of measurements of the interaction time of two mutually perpendicular lasers were also reported in [78]. The measured time was ~0.4 nsec and this value was limited by the time resolution threshold of the recording apparatus.

IX. PRINCIPAL LOGICAL ELEMENTS BASED ON SEMICONDUCTOR INJECTION LASERS

Already in the early papers on the subject, it was pointed out that, because of the high gain in semiconductors (reaching a few thousand cm^{-1}), it should be possible to build masers and lasers of very small dimensions, close to the emitted wavelength. The time necessary for the establishment of oscillations in the resonators of such devices should be of the order of 10^{-12}–10^{-13} sec, which opens up the possibility of the microwave-frequency control of oscillations of semiconductor lasers and of constructing ultrafast logical laser elements for computers (cf., for example, [27]).

The existence of two dynamic laser emission conditions—spontaneous and coherent—makes it possible to use lasers to construct optical logical elements of the pulse amplitude type, in which the zero and unity in a binary system are represented by the absence and presence of a coherent signal. In such elements, the information is carried by optical and not electrical signals. Optical logical elements, constructed from semiconductor lasers, are controlled by the processes of nonlinear interaction between the optical signals of different lasers, and between the optical radiation and the easily saturable laser medium.

As pointed out already, the efficiency of this interaction between optically coupled lasers depends strongly on the coupling between them. The quenching efficiency for diodes separated in space (Fig. 20c) is only a few percent and the quantity which limits the efficiency of the interaction is the diffraction divergence of the laser beam along the direction perpendicular to the p–n junction plane. In order to eliminate the diffraction divergence and increase appreciably the quenching efficiency, we must ensure that the distance between the interacting lasers does not exceed d^2/λ, where d is the thickness of the active region and λ is the wavelength of the radiation emitted by a semiconductor laser. In the case of gallium arsenide semiconductor lasers, the thickness of the active region is only a few microns and, therefore, the quantity d^2/λ is less than $10\,\mu$. Moreover, the active regions must be in the same plane. All these conditions present considerable difficulties in the construction of logical schemes from spatially separated lasers.[79] Therefore, it is more promising to consider the use of logical schemes based on lasers enclosed within one structure.

The principal elements of any computer, which carries out logical operations on discrete signals, are the AND, OR, NOT, and nonequivalence (exclusive OR) elements, a dynamic trigger, and others. Using these logical elements, we can construct a functional logical system of any complexity.

We shall consider the operation of some of the possible variants of these elements constructed from semiconductor lasers. Figure 22a shows the scheme of the element AND, which produces a signal at the output side C only when the light pulses arrive simultaneously at the inputs A and B (code signal 1). Such an element is constructed as a semiconductor laser with three electrically insulated parts, enclosed in a common resonator. A constant injection current is supplied to the middle part of the diode (the contact denoted by an asterisk *) and this current produces subthreshold spontaneous radiation (code signal 0). The other two parts of the diode act as nonlinear absorbers in the resonator, because no current is injected into them. When optical signals A and B are applied to such a diode, optical pumping generates carriers which are injected into the absorbing parts, so that they become more transparent and the losses in the resonator decrease until the laser emission threshold is reached. The diode is thus switched into the coherent radiation state, which represents the code signal 1. The injection current level is such that when an optical signal is applied only to the input A or only to the input B, the residual losses in the resonator are sufficiently high to ensure self-excitation conditions so that the device continues to emit spontaneous radiation. The element AND fulfills the logical function of multiplication of the code information signals, because when one set of code signals is applied to the input A and another set of signals is applied to the input B, the resultant information at the output C consists of signals each of which is the result of the logical operation AND on the corresponding pairs of code information signals A and B. The logical element AND can be used as a switch in the transmission channel of binary information and either of the inputs can be used as the control input.

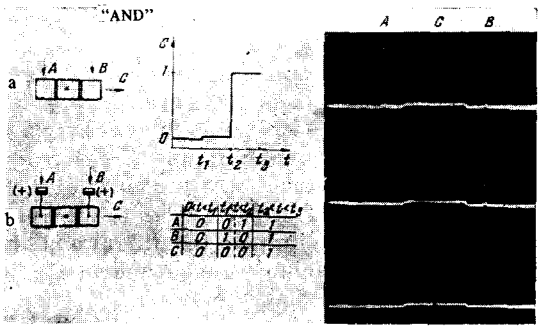


FIG. 22. Logical element AND constructed from semiconductor lasers: a) optical scheme; b) opto-electronic circuit.

The circuit of the element OR with two inputs is shown in Fig. 23a. This element is constructed in the form of a semiconductor laser diode consisting of two insulated parts. Such a diode is excited by an injection current to a level which is close to the coherent emission threshold and it produces the code signal 0. When the code signals 1 are applied simultaneously or at different times to the inputs A and B, the absorbing part becomes transparent and coherent radiation is emitted along the direction C, which corresponds to the code signal 1. In this way, the logical operation of the addition of the input signals A and B is carried out.

A single-input optical inverter, which carries out the operation NOT, can be constructed from a semiconductor diode by enclosing in the same resonator two mutually perpendicular lasers (Fig. 24a).[15, 16] When an injection current is applied to the diode, it emits coherent radiation along the direction C (code signal 1) but no coherent radiation is emitted along the perpendicular direction because of the presence of an absorbing part (the code signal is 0 along the direction A). When an optical signal is applied to the input A of the diode, the passive region becomes transparent and coherent emission is obtained along the direction A (code signal 1); simultaneously, the coherent emission along the direction C is stopped (signal 0). Figure 24b shows a different optical inverter scheme, consisting of one passive and two active parts in the same resonator. The advantage of such an inverter is the lower power of the control signal needed to stop coherent emission along the direction C; this is due to the presence of an amplifying region in the resonator. A diode with transparent resonator faces along the direction A can also be used as an optical inverter.[70]

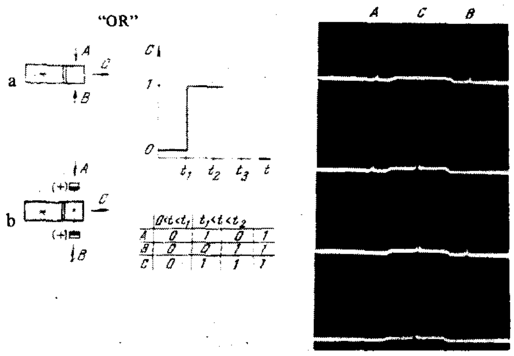


FIG. 23. Logical element OR: a) optical scheme; b) opto-electronic circuit.

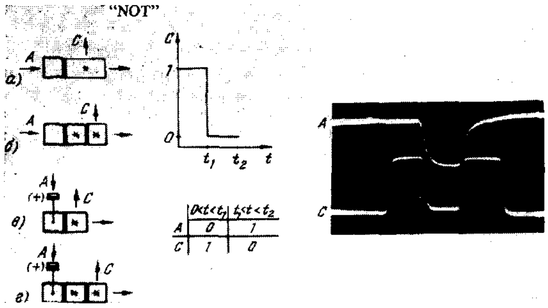
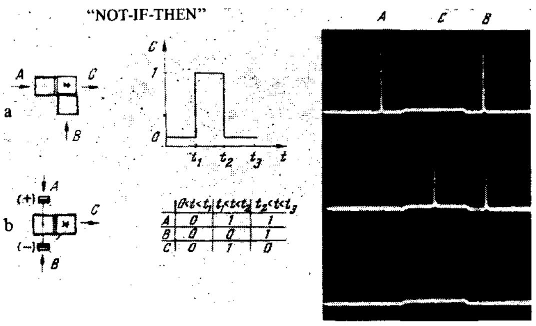


FIG. 24. Inverter (NOT element): a), b) optical schemes; c), d) opto-electronic circuits.

The exclusion element, which represents the logical operation NOT-IF-THEN (Fig. 25a), consists of two mutually perpendicular semiconductor lasers which have a common part to which the injection current is supplied, as well as one passive part each; all parts are electrically insulated from one another. The injection current level is selected so that in the absence of signals 1 at the inputs A and B, the device emits spontaneous radiation along the direction C (signal 0). When the code signal 1 is applied to the input A, the diode begins to emit coherent radiation along the direction C (signal 1), i.e., the element transmits information from A to C without any change. When the signal 1 is applied simultaneously to the inputs B and A, the laser begins to operate along a direction perpendicular to C because of the larger active region in this resonator; therefore, the coherent emission along the direction C is quenched (signal 0). The input B is called the control input because the application of the control signal 1 to this input stops the transmission of information from A to C through the element.

The memory element. Information storage units in computers can be divided into two types: internal or operative memory and external memory. The response of the internal (operative) memory should match the speed of the processing (arithmetic) units. The external memory units are much slower and their response is not directly related to the speed of the fast units of a



	$0<t<t_1$	$t_1<t<t_2$	$t_2<t<t_3$
A	0	1	1
B	0	0	1
C	0	1	0

FIG. 25. Logical exclusion (NOT-IF-THEN) element: a) optical scheme; b) opto-electronic circuit

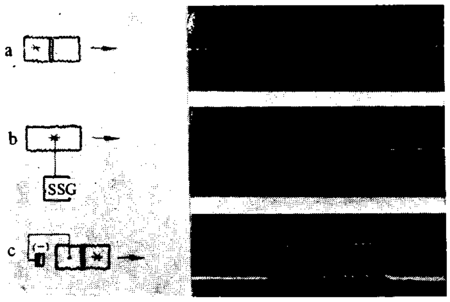


FIG. 26. Optical timing pulse generator: a), b) optical schemes; c) opto-electronic circuit. SSG is a standard signal generator.

computer. A high rate of information processing by semiconductor computers based on semiconductor lasers would require a correspondingly fast internal memory. A logical element, carrying out the memory function, can be in the form of a semiconductor laser with two stable states, one of which is the switched-off state (the spontaneous emission conditions) and the other is the switched-on state (coherent emission conditions). The laser is switched from one state to the other by a low intensity short external optical signal. The time for which the information can be stored in such an element is at present limited to 10 μsec;[65] it is restricted by the thermal conditions of operation of a semiconductor laser. Using bistable elements, working under continuous emission conditions, we can store information for a long time.

An important technical characteristic of a memory unit based on semiconductor lasers is its ability to receive and record information at a speed comparable with the speed of the processing (computing) elements. In the case of laser memory elements, the operation time is limited by the switching time of a bistable diode from one state to another. The measured switching time of such a diode is $\sim 10^{-10}$ sec.[68] A nonuniformly excited semiconductor laser, working under regular spiking conditions, or an ordinary diode synchronized by an external high-frequency signal generator (Figs. 26a and b) can be used as a generator of light pulses, which act as timing signals of all the logical elements in a computing unit so that the elements operate in synchronism. Using diodes of various lengths and by changing the injection current level, the timing frequency of a light pulse generator can be varied from 3×10^8 to 10^{10} Hz and the power of the synchronizing signal from the external generator need be only a few percent of the laser output power.

The dynamic trigger (Fig. 27a) is an element for storing a single code signal. The injection current in laser 1 is selected so that in the absence of the code signal 1 at the input A, spontaneous radiation is emitted along the direction C (signal 0). The injection current and nonlinear losses in laser 2 are selected so as to ensure that its watt–ampere characteristic has two stable states: spontaneous and coherent emission. When the code signal 1 is applied to the input A, laser 2 is switched on and its radiation makes the passive part of the element transparent. The losses in laser 1 are selected so as to ensure operation of this laser under the regular spiking conditions. Consequently, when a single signal 1 is applied to the input A, laser 2 is switched on, its radiation triggers laser 1 which then begins to operate under the regular spiking conditions so that a series of signals 1 appears at the output C, i.e., the trigger becomes a generator of unities. Laser 1 continues to generate light pulses until a control signal 1 is applied to the input B; then, laser 2 is switched off and this stops the generation of pulses by laser 1 so that its output is now equivalent to the code signal zero. Thus, the trigger has two stable states corresponding to 1 and 0. The input A of the trigger is the starting input and the input B is the control input.

The binary half adder is a device for carrying out elementary arithmetical operations on a single digit of a number. The optical adder scheme is shown in Fig. 28a. It is a complex structure, consisting of three electrically insulated lasers, each of which has an active and a passive region. The current injection level in all three lasers is such that, in the absence of the code signal 1 at the inputs A and B, the outputs S and C produce the signal 0. When the signal 1 is applied only to the input A or to the input B, either laser 1 or laser 2 begins to operate and the signal 1 appears at the output S, while the output C produces the signal 0 because of the losses in the resonator of laser 3. When the optical signal 1 is applied simultaneously to the inputs A and B, the losses in the resonator of laser 3 decrease and coherent radiation appears along the direction C (signal 1), while the output S produces the signal 0 because the radiation from laser 3 quenches the radiation from lasers 1 and 2. The wavelength emitted by laser 3 should be no longer than the wavelengths emitted by lasers 1 and 2 in order to ensure high quenching efficiency.

The adder just described can also fulfill the function of the nonequivalence (exclusive OR) element. In this case, the processed information is taken from the output S. When a set of code signals is applied to the input A and another set to the input B, the output S produces the result of the addition (modulo 2) of each pair of input signals. The nonequivalence element can be used also as an inverter of the input signals. When control signals 1 are applied continuously to one of the inputs, the inverter output S produces a code signal which is the reverse of that applied to the other input of the element. Thus, the input signal 1 can be altered to the signal 0 at the output and the converse operation can also be performed.

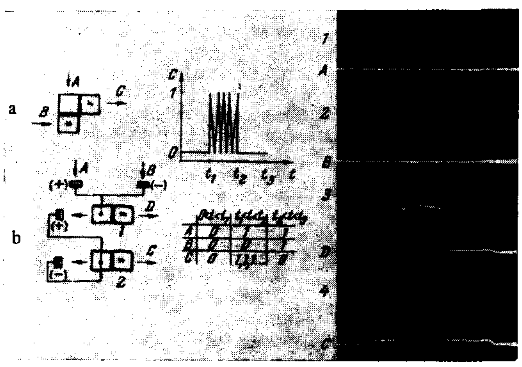
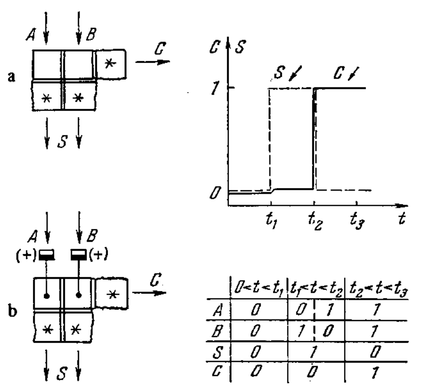


FIG. 27. Dynamic trigger: a) optical scheme; b) opto-electronic circuit.



	$0<t<t_1$	$t_1<t<t_2$	$t_2<t<t_3$
A	0	0 ⁝ 1	1
B	0	1 ⁝ 0	1
S	0	1	0
C	0	0	1

FIG. 28. Adder: a) optical scheme; b) opto-electronic circuit.

X. PRINCIPAL OPTO-ELECTRONIC ELEMENTS OF AN OPTICAL COMPUTER

In ordinary electronic circuits used in computer technology, the information is carried by electrons. Since electronic devices have an internal feedback, satisfactory electrical decoupling between the input and output cannot be achieved, and, moreover, such devices are sensitive to external stray signals and interference.

When opto-electronic elements are used and the various parts of a unit are coupled optically, the deficiencies of electronic circuits, due to stray coupling, can be reduced very appreciably. The strong decoupling obtained in the case of optical coupling is due to the absence of electrical coupling between the input and output of a unit. The equivalent resistance between the source of light and a radiation detector in an opto-electronic element may reach 10^{16} Ω and the equivalent capacitance between them is $\sim 10^{-4}$ pF.[29]

The recent successes in the development and study of the properties of gallium arsenide semiconductor lasers permit us to conclude that these lasers are the most promising as optical radiation sources in opto-electronic units. Radiation detectors available at present have a response time representing a fraction of a nanosecond, a high quantum yield (efficiency), and spectral characteristics suitable for their use in the near infrared and visible range of wavelengths, where most semiconductor injection lasers are operating. Thus, using a gallium arsenide semiconductor laser and a fast-response radiation detector, we can produce the principal opto-electronic logical elements with a response time in the fraction of a nanosecond range.

We shall now consider some possible coupling variants of "laser + photodiode" units which can be used to construct the principal logical elements of an opto-electronic computer.* An investigation of the operation of such opto-electronic logical elements was reported in [81].

Figure 22b shows the circuit of an opto-electronic element which carries out the logical operation AND. In this circuit there are photodiodes at the inputs A and B; these photodiodes transform the optical input signals into electrical signals and they are connected to the passive part of the laser. A current, ensuring subthreshold excitation (the contact denoted by an asterisk), is injected into the active part of the diode. In the absence of the signals 1 at the inputs A and B or in the presence of the signal 1 at only one of the inputs, the device operates under spontaneous emission conditions (signal 0 at the output C). When the signals 1 are applied simultaneously to the inputs A and B, the diode begins to emit laser radiation (signal 1) due to the injection of photocurrents into the passive part of the diode.

The circuit of the OR element is shown in Fig. 23b. In this case, the diode is excited by an injection current to a level close to the coherent emission threshold and, in the absence of the signals 1 at the inputs A and B, it produces the code signal 0 at the output C. When the optical signals 1 are applied simultaneously or at different times to the inputs A and B, coherent emission is observed along the direction C (signal 1).

An opto-electronic inverter circuit can be in the form of the diode shown in Figs. 24c and 24d. The current amplitudes in the separate parts of the diode are such that the diode emits coherent radiation along the direction C (signal 1). When the signal 1 is applied to the input A, the photocurrent makes the passive part of the diode transparent and coherent radiation is emitted along the direction I, which quenches the laser emission along the direction C (signal 0). The inverter can be made from a diode with two or three insulated parts; the variant with three parts is preferred because the presence of a middle amplifying part increases the efficiency of quenching of the radiation along the direction C.

Figure 25b shows the circuit of the exclusion element. The level of the injection current in the active part of a double diode ensures that the diode is operating under spontaneous emission conditions (signal 0). When the optical signal 1 is applied to the input A, the photocurrent from a radiation detector (placed in front of the input) causes the laser to emit coherent radiation: the code signal 1 appears at the output C. Information passes from A to C without any change. When the signal 1 (the control signal) is applied to the input B, a negative photocurrent switches off laser 1 (the code signal 0 appears at the output C).

The opto-electronic multivibrator, shown in Fig. 26c,

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*The principal logical elements can also be made from semiconductor lasers coupled to photoresistors. [34].

is described in [68]. A semiconductor laser, consisting of two insulated parts and having a "hard" watt–ampere characteristic, is used as the light source. An injection current stimulates the laser emission of the diode. The laser radiation falls on a photodiode, is transformed into the photocurrent, which is supplied to the passive part of the laser with a polarity opposite to that of the injection current. This stops the emission of coherent radiation and the final result is the generation, at the output C, of light pulses whose repetition frequency is governed by the switching time of the laser, the photoresponse time of the photodiode, and the distance between the laser and the photodiode. Such a device can be used as an opto-electronic generator of timing pulses.

A laser with a "hard" characteristic, together with two photodiodes connected to the passive part of the laser (one of them is connected to give a positive polarity and the other a negative one), can be used as an opto-electronic memory element. Its circuit is similar to that shown in Fig. 25b. The injection current in the laser ensures that it operates in the first stable state, i.e., emitting spontaneous radiation. When the optical signal 1 is applied from outside to the input A, the laser is switched to the second optical state (coherent radiation emission) and continues to operate in that state until the arrival of a switching-off pulse at the input B of the photodiode, so connected as to give the opposite polarity. The response time of the memory element is governed by the inertia of its components.

An optical dynamic trigger (Fig. 27b) is a combination of the logical memory element and the opto-electronic multivibrator. Currents producing subthreshold emission from lasers (the code signal 0 at the outputs C and D) are injected into the active parts of a double diode. When a single signal 1 is applied to the starting input A, a memory signal appears at the output D (oscillogram 3). The electrical memory signal from the photodiode is injected into the passive part of laser 2 and switches on the diode (laser emission is produced); at the same time, the diode connected as a multivibrator produces a series of signals 1. The generation of the unity signal at the output C (oscillogram 4) continues until the application of a control signal (1) to the control input B; this interrupts the generation of a sequence of the unity signals.

An opto-electronic adder, shown in Fig. 28b, consists of three electrically insulated lasers, each of which has active and passive regions. The injection current to all three lasers produces spontaneous radiation along the directions S and C (signal 0). When the signal 1 is applied to the input A or B, the corresponding laser emits coherent radiation along the direction S. The simultaneous application of light pulses to the inputs A and B produces coherent radiation along the direction C (signal 1) but the laser emission along the direction S stops.

Some semiconductor laser units, which can carry out various logical operations, are described in [82, 83]. The elements are controlled by external electrical pulses. However, as already mentioned, circuits using electrical pulse control have the serious disadvantage of a high electrical interference level. Therefore, the most interesting logical elements are those with optical control.[82]

XI. CONCLUSIONS

The problem of increasing appreciably the performance of computers may be solved either by constructing computers based on new ultrafast elements or by increasing the number of operations carried out in parallel. A high-performance computer, capable of performing 10^9 operations per second, can be produced by joining in parallel 1000 currently available computers capable of about 10^6 operations per second[84] but this method of increasing the performance of computers would increase considerably the complexity of the construction of these machines, increase the bulk of the equipment, and reduce its reliability.

As pointed out earlier, the speed of electronic elements is limited, to a considerable degree, by the properties of electric circuits. The use of optical elements makes it possible to increase the speed of each element separately and to carry out parallel processing of a large amount of information at the same time.

The advantages of semiconductor injection lasers over other optical devices (their speed, efficiency, size, etc.) permit us to draw the immediate conclusion that ultrafast logical elements can be developed using such lasers. The best parameters are exhibited by the gallium arsenide lasers. The currently available lasers have a threshold current density of 10^2 A/cm^2 at liquid-nitrogen temperature and their efficiency reaches 50%. The first examples of lasers were capable of operating continuously only at liquid-helium temperature but continuous operation has already been achieved at $T = 200°K$ and there are grounds for assuming that a semiconductor laser can work also continuously at room temperature. Improvements in the performance of gallium arsenide lasers should follow advances in the technique of their fabrication, in the preparation of more perfect single crystals, and in the development of new methods for making p–n junctions (gas and liquid epitaxy).

The principal logical elements, based on semiconductor lasers and having speeds of the order of 10^{-10} sec, are already available but many technical problems have to be solved first before a computer can be built from these elements. These problems are associated with the manufacture of separate elements in a matrix (for example, the development of the printed circuit techniques for laser diodes), which presents additional requirements in respect of the perfection and uniformity of the original material in large volume. Because of a fairly strong divergence of the radiation emitted by diodes, separate elements must be placed at distances a few microns apart or they must be coupled optically by means of fibers, which presents a difficult technological problem.

The difficulties encountered in purely optical computers would be eliminated, to a considerable degree, by the use of opto-electronic logical elements. The use of a structure consisting of a laser, coupled to a fast-response radiation detector, simplifies considerably the construction of the elements, and imposes less rigorous requirements on the materials and technology, without reducing appreciably the speed of response. However, it does carry the penalty of reducing the possible packing density of the elements. The opportunity of being able to make a preliminary selection of opto-electronic elements in accordance with their parameters and the simpler construction of these elements (compared with the optical elements) should make it possible to start immediately the construction of one-off computers based on these elements.

A comparison is made in [85] of the current required by one switching element in a silicon transistor (with a switching time of ~ 1 nsec) and the current needed by an optical inverter constructed from semiconductor lasers. The switching time of an inverter is assumed to be ~ 1 nsec, which is equal to the spontaneous lifetime of electrons. For this switching time, a laser inverter requires a current (per one switching operation) which is an order of magnitude higher than the current required by a silicon transistor. However, investigations have established that the switching time of a semiconductor-laser inverter is about 10^{-10} sec when the current is twice as high as the threshold value. This means that the current per single switching operation is practically the same for both elements but the speed of the laser inverter is one order of magnitude higher. The various difficulties do not make it possible to produce, at present, an optical general-purpose computer using injection lasers but construction of fairly simple computers for special applications, exploiting all the advantages of the optical logic (compared with electronic circuits), can start now. In such computers, semiconductor lasers can be used to make an internal (operative) memory with a short turn-round time, to process information rapidly in parallel, to construct information input and output units, to produce pattern recognition systems, etc.

Theoretical and experimental investigations of the dynamic processes in semiconductor injection lasers should make it possible to construct practically all the principal logical elements for optical computers with a speed of the order of 10^{-10} sec.

It should be mentioned that so far only the preliminary results have been obtained for the dynamics of the semiconductor laser radiation; they can be understood on the basis of relatively simple representations. Recording apparatus with a time resolution of the order of 10^{-12}–10^{-13} sec is required for future studies of the dynamic processes in semiconductor lasers. These studies should include theoretical and experimental investigations of complex structures consisting of several laser diodes, which would enable us to produce optical logical elements, based on semiconductor lasers, with a speed of the order of 10^{-12}–10^{-13} sec.

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