# RADIO-FREQUENCY INSTABILITY OF A SEMICONDUCTOR LASER WITH INHOMOGENEOUS INJECTION

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An inhomogeneously-injected semiconductor laser (SL) consisting of sections with negative and positive light absorption possesses strong optical nonlinearity that is manifest in complicated dynamics of the SL radiation (self-modulation, synchronization, and other phenomena, cf., e.g., the review [1]). As noted in [2], a semiconductor laser with such an optical nonlinearity is capable of exciting stimulated radio-frequency oscillations in a tank circuit connected to it.

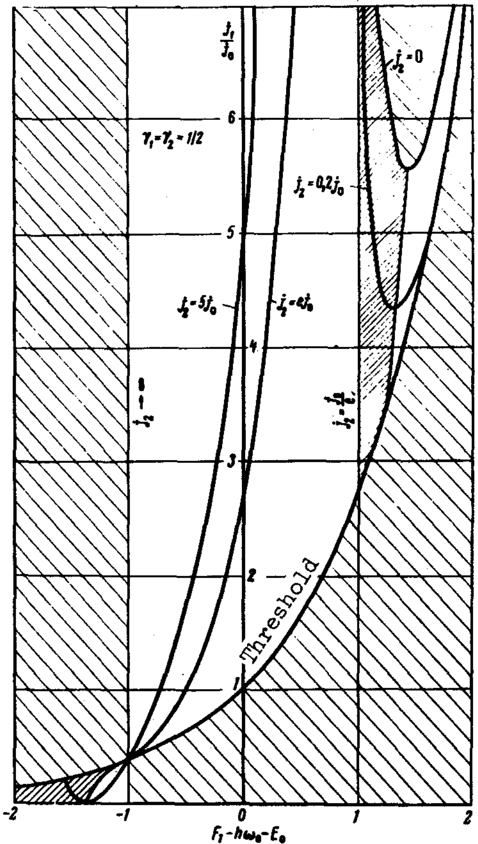

Fig. 1

The gist of the phenomenon is that the pulsations of the optical radiation of the SL with inhomogeneous injection is accompanied by a corresponding motion of the electronic Fermi quasilevels F, and consequently by an alternating emf that causes oscillations to build up in the radio-frequency circuit if the positive feedback is strong enough. If the period of the oscillations greatly exceeds the times of electronic and optical transients in the SL, then it becomes possible, by using the stationary solutions of the rate equations of an SL with inhomogeneous injection (Formula (9) of [3]), to find the decreasing sections of the current-voltage characteristics of the SL from the expression

$$i_1 = \frac{\gamma_2(F_1-\hbar\omega_0)}{\gamma_1(F_1-\hbar\omega_0)-E_0}\left[i_0\exp\left(-\frac{\gamma_1}{\gamma_2}\,\frac{F_1-\hbar\omega_0-E_0}{E_0}\right)-i_2\right] + i_0\exp\left(\frac{F_1-\hbar\omega_0-E_0}{E_0}\right) \qquad (1)$$

which connects the injection current densities $j_1$ and $j_2$ on the SL sections with relative length $\gamma_1$ and $\gamma_2$ ($\gamma_1 + \gamma_2 = 1$) and the Fermi quasilevel $F_1$ on one of the sections (here $\hbar\omega_0$ is the energy of the photons emitted by the SL, $E_0$ is the doping parameter,

$$i_0 = \frac{2e}{\pi^2}\,\frac{\epsilon d E_0 a}{c^2\hbar^3\eta}\,(a\beta)(\hbar\omega_0)^2 = \text{const}$$

$\varepsilon$ is the electron charge, e = 2.73, d is the diffusion length, $\alpha$ the SL loss coefficient, $(a\beta)$ the temperature factor, c velocity of light in the semiconductor, and $\eta$ the quantum efficiency of the injection). The stationary solutions (1) were obtained in [3] in the single-mode approximation, as applied to gallium arsenide, for the radiative transitions between a narrow acceptor level and the exponential "tail" at the bottom of the conduction band.

An idea of the form of the corresponding current-voltage characteristics of a junction biased in the forward direction can be gained from the $j_1(F_1)$ curves plotted in accordance with (1) with $j_2$ as a parameter. These plots show that negative resistance occurs in two regions of the diagrams (with dense cross-hatching). The regions where $dj_1/dF_1 < 0$ are bounded for $j_1 > j_2$ (positive values of the argument) by the curves

$$i_1 = i_0 \exp \frac{F_1 - \hbar\omega_0 - E_0}{E_0};$$

$$\left.\frac{F_1 - \hbar\omega_0}{E_0}\right|_{i_2 = \frac{i_0}{e}} = \frac{1}{\gamma_1};$$

$$\left. i_1 \right|_{i_2 = 0} = i_0 \left[ 1 + \gamma_2 \frac{F_1 - \hbar\omega_0}{\gamma_1 F_1 - \gamma_1 \hbar\omega_0 - E_0} \exp\left( - \frac{F_1 - \hbar\omega_0 - E_0}{\gamma_2 E_0} \right) \right] \exp\left( \frac{F_1 - \hbar\omega_0 - E_0}{E_0} \right)$$

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$$i_1 = i_0 \left\{ \frac{\gamma_1}{E_0^2} (F_1 - \hbar\omega_0)^2 \left[ 1 - \exp\left( - \frac{F_1 - \hbar\omega_0 - E_0}{\gamma_2 E_0} \right) \right] - \right.$$
$$\left. - \frac{F_1 - \hbar\omega_0 - E_0}{E_0} \right\} \exp\left( \frac{F_1 - \hbar\omega_0 - E_0}{E_0} \right),$$

and for $j_1 < j_2$ (negative values of the argument) by the curves $j_1 = 0$;

$$i_1 = i_0 \exp\left( \frac{F_1 - \hbar\omega_0 - E_0}{E_0} \right)$$

and the last curve of the preceding case.

The phenomenon in question was observed experimentally in an SL of gallium arsenide constructed by the diffusion technology, with a resistance of about 10 ohms separating the injection regions. The tank circuit connected to the absorbing section of the SL consisted of several turns of wire having an inductance L less than 1 μH, and the intrinsic capacitance of the SL (Fig. 2). Figure 3a shows an oscillogram of the optical radiation of the SL, modulated by the 12-MHz oscillations excited by it in the tank circuit. The linear dependence of the reciprocal of the frequency squared $1/f^2$ on the inductance L (Fig. 2 - two samples) is evidence of the stimulated character of the oscillations excited in the tank circuit. The intrinsic SL capacitance, according to the data of these experiments, is approximately 2000 pF, amounting to several microfarads per square centimeter of junction.

The 250 MHz electric oscillations in a circuit made up of a segment of short-circuited cable with wave resistance 25 ohms, and the laser-emission pulsations synchronous with these oscillations, registered by the procedure of [4], are shown in oscillograms 3b and 3c respectively. Attention is called to the nonsinusoidal char-

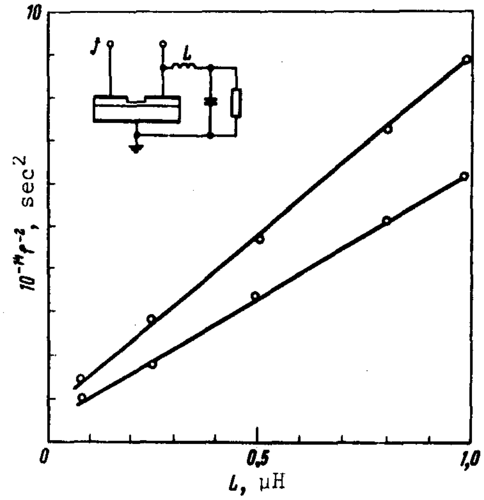

Fig. 2

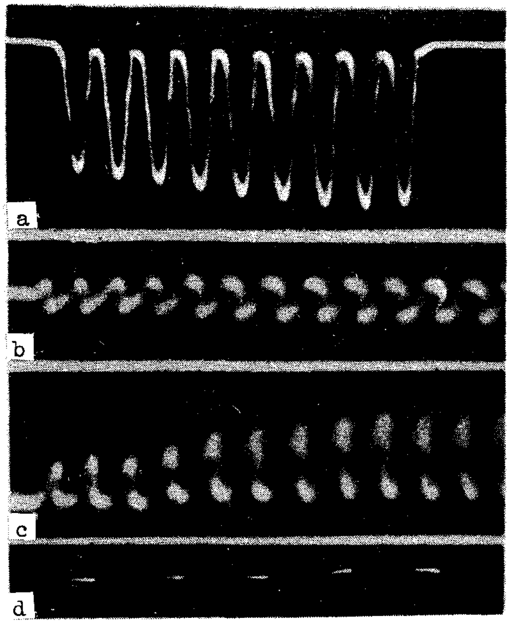

Fig. 3

acter of the electric oscillations, indicating that many harmonic components that are phased with one another, the presence of which had been noted in [2], are simultaneously excited in the circuit with distributed reactances.

The optical pulsations caused by the self-oscillations of the highest frequency ($f \approx 1000$ MHz) in a circuit made up of a cable segment 5 cm long, were registered with a scanning electron-optical converter (Fig. 3d). In all cases, the optical and electric pulsations were produced only when the radio-frequency circuit was connected to the SL.

To increase the frequency f, it is necessary to use waveguide oscillating systems with distributed interaction and to produce synchronism between the slowed-down electromagnetic wave and the electronic perturbation in an SL with periodically alternating injection sections [2], which can also be represented in the form of a superposition of traveling waves. Optical-pulsation frequencies up to $10^5$ MHz were registered in similar lasers operating in the mode locking regime, and the frequency can be expected to be increased by one more order of magnitude. Thus, the upper frequency limit of the observed phenomenon lies apparently in the far infrared.

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[5] V.D. Kurnosov, A.A. Pleshkov, L.A. Rivlin, V.V. Tsvetkov, and V.S. Shildyaev, 9th International Conference on the Physics of Semiconductors, Proc. 1, 550 (1968).

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# OBSERVATION OF REGULAR OSCILLATIONS OF THE TOTAL CROSS SECTION FOR THE EXCITATION OF Ne RESONANCE LINES IN COLLISIONS WITH $Na^+$ IONS

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We investigated the excitation functions of the resonance lines of the Ne atom, Ne 736 Å (I) and 744 Å (II), emitted upon collision of the $Na^+$ ions with Ne atoms

$$Na^+ + Ne \rightarrow Na + Ne^* - 16.85\ eV; -16.67\ eV \tag{1}$$

in the $Na^+$ ion energy interval from 0.2 to 11 keV. The experimental setup and the measurement procedure are described in [1]. In the present investigation we used as the quantum detector an open electron multiplier (VEU-1) with an