Dynamic instability of a semiconductor laser at low temperatures

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We investigated the dynamics of the emission of a single-mode injection semiconductor laser at low temperatures. A dynamic instability of the monochromatic regime of generation has been observed and is due to coherent character of the interaction of the radiation with the medium in strong fields.

In the investigation of the equations for a single-mode laser with a homogeneously broadened emission line, it was found that under definite conditions the stationary monochromatic generation regime is unstable.[1,2] The physical meaning of such an instability is connected with the periodic oscillations of the active particles from the upper level to the lower one and back, in the field of a strong electromagnetic wave. The instability exists only when a necessary condition is satisfied, namely that the transmission-line width of the resonator be larger than the width of the emission line of the active medium. The sufficient condition is that the pump power exceed a certain critical value that depends on the ratio of these widths.

For solid-state lasers, the instability discovered in[1,2] is apparently easiest to observe in semiconductor lasers in which, owing to the large gain, the resonator length amounts to hundreds or dozens of microns, and it is possible by the same token to satisfy the conditions under which the resonator bandwidth exceeds the emission-line width.

It has been shown in[3] that the system of equations for the polarization of the field in semiconduction laser

Time scan of laser emission, photographed from the screen of an electron-optical converter at $\beta=\beta_{cr}$. Sweep duration 3 nsec.

is formally analogous to the system of equations for two-level systems with inhomogeneously broadened emission line, where the "inhomogeneous" broadening is determined by the distribution function and by the density of the energy states of the electrons.

The purpose of this study was to investigate the dynamics of a single-mode semiconductor laser under conditions close to the requirements of[1].

To obtain as narrow an emission line as possible, the experiments were performed at liquid-helium temperature.

We used single-channel laser diodes of gallium arsenide with active-region width 5—10 μ [4] and with a resonator length 100—400 μ. The threshold current densities of the diodes were 0.5—2 kA/cm^2 at helium temperature. The injection-current pulse duration was 30—40 nsec at a pulse rise and fall-off time ~5 nsec.

The laser emission from one side of the resonator was registered with the aid of a scanning electron-optical converter of the FÉR-2m type, and on the other side it passed through an external Fabry-Perot etalon and was incident on a high-speed photoelectronic multiplier, the signal from which was fed to a 6LOR-02m oscilloscope. Thus, it was possible to observe simultaneously both the dynamic and the spectral pictures of the lasing.

Measurements of the temperature heating of the active region of the laser by the procedure described in[5] has shown that even at 10—20 fold excess over the lasing threshold the increase of the temperature of the active region did not exceed 1 °K.

An investigation of the amplitude-time structure of the diode emission pulses has shown that at pumps $\beta=I/I_{thr}<\beta_{cr}$ (I is the injection-current amplitude and I_{thr} is the threshold value of the current) the lasers operate in a stationary (spikeless) lasing regime. When a definite excitation level is reached ($\beta=\beta_{cr}$), the lasing picture changes—the laser begins to generate short regular light pulses (see the figure) with large depth of modulation.

The period of the pulsations at the threshold of their production is 150—300 psec for different diodes. With increasing pump, the period decreases. The pulsation duration measured with a photoelectronic FÉR-2m recorder was determined by the time required to damage the device and amounted to approximately 50 psec.

Theoretical calculations performed for a two-level system[6] yield the following expression for the period of the spikes (at $\beta=\beta_{cr}$):

$$T=2\sqrt{c}\sqrt{\frac{T_1T_2}{\beta_{cr}-1}}\,, \tag{1}$$

where c is the parameter of the statistical limit cycle, and T_2 and T_1 are the relaxation times of the off-diagonal and diagonal elements of the density matrix. Inasmuch as $\beta_{cr}=T_2/\tau_p\gg 1$, where τ_p is the photon lifetime in the resonator, it follows that $T=2\sqrt{cT_1\tau_p}$. Although the expression for the period of the pulsations and the instability emission were obtained for a two-level system, one can expect them to remain valid also for a semiconductor laser, if T_2 is taken to mean the coherence-loss time due to all types of collisions.

The time τ_p can be determined from the formula $\tau_p=\{v[(\ln(1/R))/L+\alpha]\}^{-1}$, where v is the velocity of the light in the medium, R is the reflection coefficient, L is the resonator length, and α is the coefficient of non-resonant internal losses. At $R=0.32$, $L=200\ \mu$, $\alpha=20$ cm^{-1}, a spontaneous carrier-recombination time $T_1=10^{-9}$ sec, and $c\approx 9$, we get a pulsation period $T\approx 2.4\times10^{-10}$ sec, which agrees well with the experimentally obtained value. The value of β_{cr} is smaller for longer diodes and increases with increasing temperature, owing to the shortening of the time T_2. These facts agree well with the definition $\beta_{cr}=T_2/\tau_p$. With further increase of the temperature, the dynamic instability disappears.

From (1) we can estimate the time T_2, which turns out under the conditions of our experiment to be $(2-4)\times10^{-11}$ sec, in satisfactory agreement with the values of the electron collision times for the semiconductors of the given type.

The investigations of the spectral characteristics were carried out with the aid of a Fabry-Perot etalon and a spectrometer with a resolution 0.5 Å. It was established that the emission of the investigated semiconductor lasers was single-mode in the entire range of investigated pump values. When intensity pulsations set in, a broadening of the emission line was observed. The half-width of the emission spectrum was estimated with the aid of an etalon with a 5 mm base. The pulsations produced a decrease in the depth of modulation of the etalon transmission peaks, and with further increase of the pump the peaks leveled out completely. An estimate of the duration of the emission pulse from the width of the etalon dispersion region yields $\tau=3\times10^{-11}$ sec. It follows from the theoretical calculations that $\tau\approx T/c\approx 2.7\times10^{-11}$ sec, which agrees with the value obtained with the aid of the Fabry-Perot etalon.

The diode emission power increased linearly with increasing pump. The radiation power density and a spike off-duty factor ~10 was 5×10^6 W/cm^2.

The results serve as an experimental confirmation of the existence of dynamic instability in single-mode lasers; this instability is connected with the effect of coherent interaction of the radiation field with the active medium. The developed method makes it possible to determine the characteristic intraband relaxation times of the carriers and to study the waveform of the gain line of semiconductor lasers at different temperatures.

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