Observation of a dip in the spontaneous emission spectrum and a saturation of generation in single-mode semiconductor lasers

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We observed a dip in the spontaneous emission spectrum near the generation frequency. Threshold power for the dip occurrence, its width and dependence of width on intensity all permit us to interpret the effect as the formation of a gap in the electron energy spectrum. Saturation of single-mode generation is observed prior to threshold for occurrence of the second mode. Magnitude of threshold power and its quadratic dependence on photon lifetime in a cavity are in agreement with the kinetic laser theory.

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It was shown earlier[1] that the electron spectrum of a semiconductor in a strong electromagnetic field with quantum energy greater than the width of the forbidden gap, contains a gap which depends on the removal of a degeneracy in the electrons-photon system due to a strong electron-photon coupling. As a result of electron collisions with phonons, holes and charged impurities,[2,3] this gap is destroyed at a certain critical value of the field λ_c, where λ is the gap width proportional to the field amplitude. The critical value of intensity for gap occurrence in a doped GaAs is estimated to be 10^5 W/cm^2. The presence of a gap entails the occurrence in the spontaneous emission spectrum of a dip with a width $\Delta = 2\lambda$ near the generation frequency.[4] A number of experimental data[5,6] support this theory; however, direct investigation of the formation of a gap in the electron energy spectrum has not been attempted herefore. Realization of the experiment at radiation intensities $\sim 10^6$ W/cm^2 was made possible as a result of using an injection semiconductor laser (SL) with a holographic selector[7] in the external cavity because of its high diffraction efficiency and angular dispersion.

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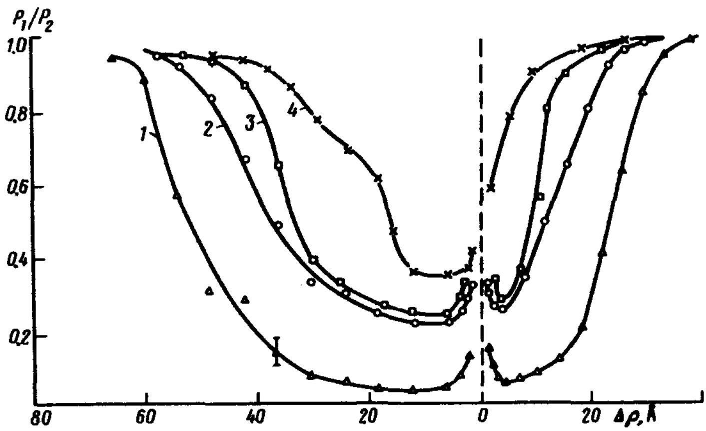

FIG. 1a. Relative size of dip in the spectral envelope of non-laser modes: 1—laser mode intensity $P_0 = 1.8\times10^6$ W/cm²; 2—0.65 P_0; 3—0.46P_0; 4—0.20P_0.

The experiments made use of an injection SL with a strip contact, operating at room temperature in a pulsed mode, and also a SL at liquid nitrogen temperature. Laser diode ends were made completely reflective in order to allow the natural faces of SL and the holographic selector to form a composite selective cavity. The thickness of the holographic selector lattice was 3060 lines/mm and with a diffraction efficiency of 85% at 860 nm wavelength. The external cavity length was 30 cm and the total resolution of the recording channel was 0.7 Å.

Figure 1(a) shows the relative suppression of non-laser (superluminescence) modes at various intensities of a laser mode selected by means of resonant external holographic grating. Here P_2 is the intensity of a non-laser mode without external coupling and P_1, with coupling to the external cavity. The location of a mode to which the external resonator is tuned is indicated in the figure by a vertical dotted line. The frequency difference $\Delta\rho$ in Å is shown to the right and left of this line. All the curves were taken at the same pumping level. Laser mode intensity was varied by the introduction of additional losses into the external resonator.

Figure 1(b–g) shows changes in the spontaneous emission spectra with growth of the pumping current. Shown are spontaneous emisson spectra taken at an angle of 21° to the resonator axis in a 12′ solid angle outside the directional pattern of coherent radiation. The photographs also show the formation of a dip in the spontaneous emission spectrum at intensities above 0.9×10^5 W/cm². The critical field at which a dip occurs and the critical intensity of single-mode generation are of the order of magnitude of the corresponding values given by the strong field theory.[2-4] The theoretical value of a spectral dip at an intensity of 2×10^5 W/cm² is of the order of 10^{12} sec^{-1}. The measured value of the dip halfwidth in $(1\pm0.5)\times10^{12}$ sec^{-1}. Changes in the dip width with generation intensity is proportional, within the measuring error, to field strength in accordance with theory.[1]

One important result yielded by the kinetic theory of SL was the prediction of

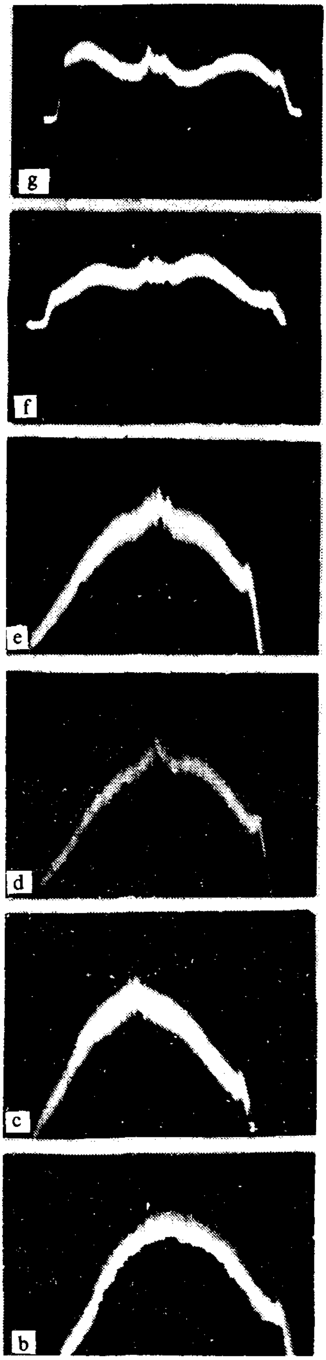

FIG. 1b–g. Spontaneous emission spectra of SL at 21° to the optical axis of resonator. Vertical scale—relative intensity of spectral components. Horizontal scale is 6 Å/div.: b—intensity of coherent radiation $P = 0.02 \times 10^5$ W/cm^2; c—0.8×10^5 W/cm^2; d—0.9×10^5 W/cm^2; e—1.1×10^5 W/cm^2; f—1.5×10^5 W/cm^2; g—2.3×10^5 W/cm^2.

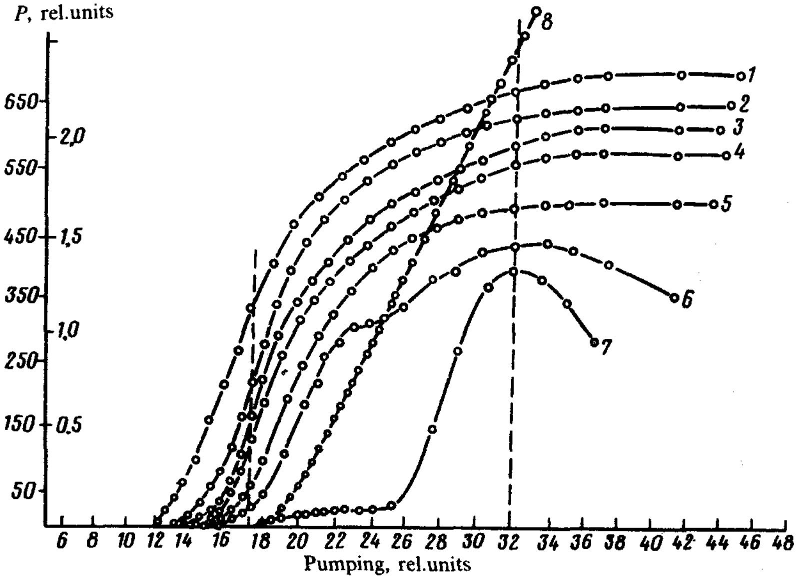

FIG. 2. Watt-ampere mode characteristics of SL with external holographic resonator: 1—without losses in external resonator; 2—filter transmission 0.8, 3—0.68; 4—0.52; 5—0.3; 6—0.13; 7—without external resonator; 8—integral spectral emission power without external resonator.

saturation of single-mode generation at the threshold for occurrence of a second mode.[8,9] Figure 2 shows the dependence of single-mode generation power on the pumping current for various losses in the external cavity. The second mode threshold current is 34 A. Clearly, saturation of generation takes place in the single-mode regime with, the critical power being proportional to the square of photon lifetime in a cavity τ_0 as shown by measurements. The value of critical power, and its dependence on τ_0 may be used, in accordance with the conclusions of the kinetic theory,[9] to emphasize the importance of taking into account the saturation effect—the fundamental nonlinear effect in SL.

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