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COUPLED LONGITUDINAL MODE PULSING IN SEMICONDUCTOR LASERS

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A theory of interaction among the longitudinal modes in a laser made of highly dispersive material is outlined and used to interpret a spontaneous pulsing of the laser intensity at a frequency two orders of magnitude lower than the mode separation, shown to occur in GaAs lasers. Power coupling among the modes in the presence of spontaneous or forced microwave modulation of the population inversion is also explained.

In this communication, we outline a theory which demonstrates that the interaction among the longitudinal modes of a semiconductor laser can lead to a spontaneous pulsing of the laser intensity at a frequency two orders of magnitude lower than the separation of adjacent longitudinal modes. In this new phenomenon, which is unique to lasers in materials with high dispersion, the pulsing is produced by the excitation of the well-known resonance[1] of the laser by combination tones[2] present in the polarization of the active medium. In addition, the experimental observation of coupled multimode pulsing at microwave rates in GaAs injection lasers is reported and interpreted in terms of this theory. The observation of power coupling among the longitudinal modes and a broadening of the oscillation spectrum of the laser is explained in terms of the interaction of the combination tones with the spontaneously induced modulation of the population inversion.

Interaction among the longitudinal modes of a laser can arise because the polarization of the active medium induced by the electromagnetic field acts as the source for every mode. In the second-quantized description of the semiconductor laser first used extensively by Haug,[3] such interaction appears through terms of the form $(l_1 \neq l_2)$

$$B_{l_1}^{+} B_{l_2} \exp[i(\Omega_{l_1} - \Omega_{l_2})t](N_c - N_v) M_{vc}^{l_1} M_{vc}^{l_2 *} \quad (1)$$

which appear in the equations of motion for the photon number of each mode and for the population of each state of the electron field. In the above, B_l is the slowly varying amplitude and phase function of the lth mode whose frequency is denoted by Ω_l. The number operator for each state c of the upper band is denoted by N_c, while N_v is the analogous operator for the state v of the lower band. The matrix element M_{vc}^{l} for the optical transition from state c to state v has been derived previously[4] for semiconductor lasers with well-defined transverse mode distributions.

Direct iteration of the equations of motion indicates that $(N_c - N_v)$ contains a component which varies in time at the frequency $\Delta_{34} \equiv \Omega_{l_3} - \Omega_{l_4}$ and in space as $\cos[(q_3 - q_4)\pi z/L]$, where q_i is the longitudinal-mode integer of mode l_i, z is the axial direction in the laser, and L is the length of the laser. Spatial variations of this kind[5] are not leveled by diffusion since the carriers cannot move a distance $L/2|q_3 - q_4|$ (~200 μm for adjacent modes) in a time comparable with $2\pi/\Delta_{34}$

(~10 psec for adjacent modes). In the interaction of Eq. (1), this component produces a nonvanishing contribution with frequency $\Delta \equiv \Delta_{34}-\Delta_{12}$ for pairs of longitudinal modes satisfying the condition $q_3-q_4=\pm(q_1-q_2)$. Because of the dispersion which exists in semiconductor lasers, it is clear that $\Delta \neq 0$ even when this condition is satisfied by selecting three adjacent longitudinal modes.

The magnitude of Δ is determined by the value and derivative of the "equivalent" index of refraction $\bar{n}_e \equiv n + \nu dn/d\nu$, where n is the refractive index and ν is the optical frequency. For example, in GaAs lasers we can estimate $\Delta/2\pi$ from the refractive-index data of Marple[6] at a value of $\bar{n}_e$ determined from the laser spectra.[7] This leads to a frequency on the order of 1 GHz, which places Δ in the vicinity of the spiking frequency ω_R of these lasers.[8] Hence for certain ranges of pumping current and temperature, the combination tone described above can excite the "spiking" resonance of the laser and lead to a deep modulation of both the laser intensity and the population inversion. The detailed calculations for this phenomenon will be published shortly.

A sustained microwave modulation of the output intensity of continuously operating GaAs junction lasers has recently been reported.[9] In the experiments to be reported here, we have observed that such a modulation is actually a multimode pulsing of the laser intensity in which the longitudinal modes of the laser are strongly coupled. We interpret these observations in terms of the resonance excitation described above.

The laser spectrum was observed with a grating spectrometer of 0.1-Å resolution (approximately 4 GHz at 8400 Å). Simultaneously the laser intensity was monitored with a high-speed photodiode coupled into a microwave spectrum analyzer.[9] In addition the fine structure of each laser mode was observed with a grating spectrometer in series with a pressure-scanned plano-Fabry-Perot interferometer (FPI). The free spectral range of the FPI was 15 GHz and its finesse was greater than 100.

Since the spiking frequency ω_R and the dispersion are functions of the temperature T and the injection current I,[8] coincidence of Δ and ω_R occurs only over limited ranges of these variables.[10] Outside this region of T and I, the mode spectrum of a typical diode consists of a few independent, narrow longitudinal modes with normal transverse-mode structure,[7] as shown in Fig. 1(a). While no modulation of the laser intensity can be

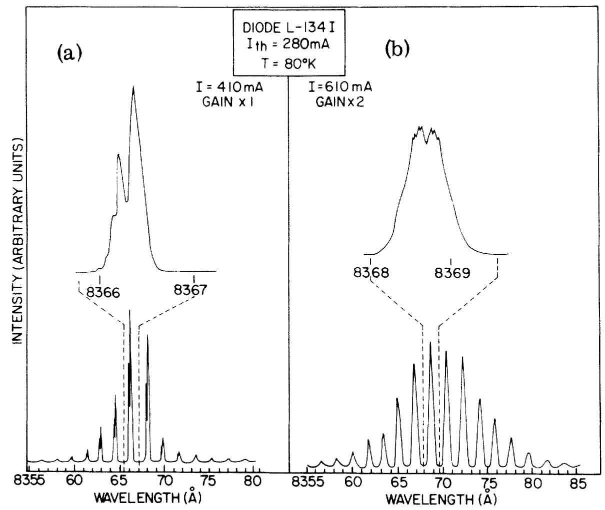

FIG. 1. (a) Normal, uncoupled-mode spectrum of a stripe-geometry GaAs junction laser. The expanded view shows one longitudinal-mode group with several transverse modes along the junction plane. (b) Spontaneously coupled spectrum of the same laser at 1.5 GHz. The expanded view shows a longitudinal mode broadened by the large number of unresolved harmonics of the pulsing frequency.

detected with the photodiode, the FPI scans reveal very small sidebands on each laser mode. As the current and/or temperature is varied so as to bring ω_R and Δ closer to resonance, the laser intensity begins to show an increasingly strong modulation while the high-resolution FPI scans show an increasing number of large sidebands whose amplitude distribution indicates both amplitude and phase modulation. Simultaneously more longitudinal modes appear with amplitudes lying under a smoothly varying bell-shaped envelope [Fig. 1(b)] centered about the wavelength at which the dispersion provides a value for Δ closest to ω_R. The considerable broadening of each longitudinal mode shown in Fig. 1(b) is due to the large number of harmonics of ω_R that cannot be resolved by the spectrometer, while the increase in the number of modes indicates the reaction of the modulation in the population inversion back on the laser modes. The reaction is effective since when a mode Ω_{q_i} is modulated at the frequency Δ, generating sidebands at $\Omega_{q_i}\pm\Delta$, a combination tone (at $2\Omega_{q_i+1}-[\Omega_{q_i}+\Delta]$) is produced at the frequency (Ω_{q_i+2}) of a natural laser mode. This leads directly to power sharing among every three consecutive modes. The coupling among the modes is further confirmed by a large reduction of low-frequency noise in the amplitude of each mode[11] and by the fact that the modes retain their relative amplitudes over a range of currents.

In the range of currents for which ω_R and Δ are equal, the amplitude of the intensity oscillation becomes quite large and the ring structure of the FPI suddenly becomes blurred. This blurring indicates a decrease of the coherence time by orders of magnitude to less than 200 psec and is a result of the modulation depth reaching 100% with a consequent loss of phase information as laser action ceases after each pulse.

Increases in the injection current beyond the point where $\omega_R \approx \Delta$ eventually lead to a breakup of the stable multimode spectrum. One or two of the longitudinal modes begin to dominate and the spectrum again becomes similar to that shown in Fig. 1(a). At the same time, the oscillation in the laser intensity decreases in amplitude and eventually disappears. If the current is now decreased, the reverse behavior occurs but with some hysteresis, in which the modes remain coupled beyond the current at which coupling first appeared. This indicates that the modulation of the population inversion tends to stabilize itself through its reaction on the laser modes.

Since the power coupling described above depends only on modulation of the population inversion at the frequency Δ, it should occur whether this modulation is spontaneous or forced. This was confirmed by externally modulating the injection current of a laser in a region of T and I where oscillations do not occur spontaneously. The laser spectra as observed with the spectrometer (Fig. 2) or with the FPI are very similar to those described above for the spontaneous modulation. Again the point at which the modulation becomes 100% can be clearly observed with the FPI. It should be noted that the frequency of the external signal in Fig. 2 is about 65 times smaller than the separation of adjacent longitudinal modes. In this experiment, the amount of microwave power required depends on the proximity of Δ to the resonance frequency ω_R and can be from a fraction of a milliwatt to nearly a watt.

Previously, it was shown[4] that at high injection currents laser diodes tend to oscillate simultaneously in two families of modes with different transverse-mode numbers perpendicular to the junction plane. When spontaneous oscillations occur at these currents, one or both of the families may be pulsing depending on the details of the dispersion. In the former case [Fig. 3(a)] an examination with the FPI of each mode in the coupled set indicates a deep pulsing with the consequent loss of coherence, while the uncoupled mode is only weakly modulated due to the modulation of the population inversion. The simultaneous occurrence in the same laser of pulsing and nonpulsing modes further supports the conclusion that the mode interaction is responsible for the pulsing of the laser intensity. In the latter case [Fig. 3(b)], each family appears under its own envelope, with all modes pulsing. This demonstrates that there is little, if any, interaction among modes of different families due to the

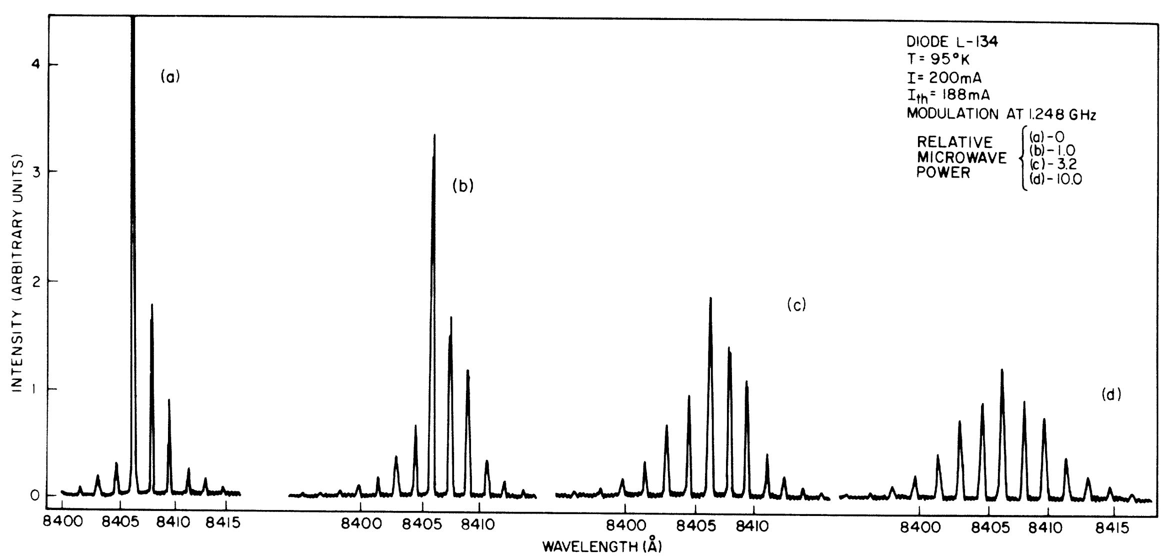

FIG. 2. Longitudinal-mode spectra of a GaAs-junction laser showing mode coupling induced by external modulation of the population inversion in a region where no spontaneous pulsing of the laser intensity occurred.

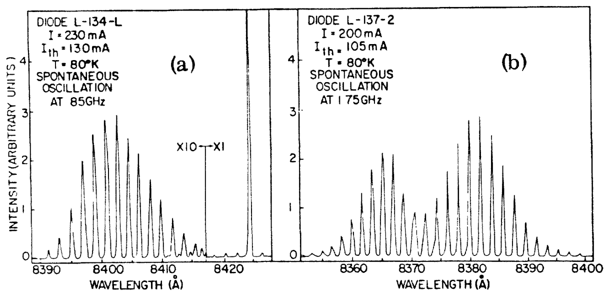

FIG. 3. Longitudinal-mode spectra of GaAs-junction lasers showing simultaneous oscillation in two families of modes. In (a) only one family exhibits the coupled, pulsing behavior, while the single mode at 8424 Å is only weakly modulated; in (b) all modes are pulsing.

orthogonality of modes with different transverse distributions. The difference between the two types of behavior is a result of the variation among diodes in the strength of the dispersion, which determines whether or not Δ for each family is close enough to ω_R for strong coupling to occur. The possibility of having all modes pulsing is greatest for families whose center frequencies are close to each other.

While our experimental observations have been made on GaAs stripe-geometry injection lasers, it is reasonable to expect that similar phenomena can also occur in other semiconductor lasers. However in nonsemiconductor lasers, the dispersion is generally insufficient to produce the effect. In conclusion, we note that the high dispersion, which is of prime importance in the phenomenon described above, is also one factor which greatly hinders spontaneous mode locking of semiconductor lasers.[12]

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COLLECTIVE OSCILLATIONS IN PURE LIQUID BENZENE*

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Measurements of the optical properties of pure liquid benzene in the vacuum ultraviolet are interpreted in terms of a molecular excitation of the π electrons and also collective, volume-plasma oscillations of these same electrons.

Benzene vapor exhibits an intense absorption band in the vacuum ultraviolet[1-4] with a maximum at about 1790 Å. This corresponds[5] to the allowed transition ${}^1A_{1g}{}^- \rightarrow {}^1E_{1u}{}^+$ which is a molecular excitation of the π electrons in the benzene ring.

We have observed this same molecular excitation in pure liquid benzene,[6] shifted slightly in energy by the close proximity of other molecules in the liquid state. In addition our optical data show the existence of volume-plasma oscillations, presumably involving the π electrons acting collec-