Longitudinal mode spectrum of GaAs injection lasers under high-frequency microwave modulation

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Experimental observations of the lasing spectrum of a single mode semiconductor laser under continuous microwave modulation reveal that the lasing spectrum is apparently locked to a single longitudinal mode for optical modulation depths up to ~80%, beyond which the lasing spectrum becomes multimoded, whose envelope width increases very rapidly with further increase in modulation depth. These results are satisfactorily explained by a theoretical treatment which enables one to predict the dynamic lasing spectrum of a laser from its cw lasing spectra at various output powers.

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The steady state longitudinal mode spectrum of semiconductor lasers has been extensively studied, and major observed features can be understood in terms of modal competition in a common gain reservoir. It was recognized that a laser which oscillates in a single longitudinal mode under cw operation will not remain single moded during turn-on transients and high-frequency modulation. This has been predicted from numerical solutions of the multimode rate equations[1,2] and has been observed by many researchers.[2–9] Previous experiments have shown that when microwave modulation is applied to a single-mode laser, the lasing spectrum will remain single mode unless the optical modulation depth exceeds a certain critical level.[10] There was no systematic experimental study of how that critical level depends on the properties of the laser diode and modulation frequency. This letter addresses these issues and provides an analytical treatment of the phenomenon.

The spectrum of a laser under direct modulation obviously depends on the amount of mode selectivity in the laser, which can be increased by introducing a distributed feedback type,[11] a composite cavity,[12] or a quantum well structure,[13] or by shortening the cavity length.[6–8] In our experiments, we investigate the time-averaged lasing spectrum of lasers of various cavity lengths under high-frequency continuous microwave modulation at various frequencies and modulation depths. The lasers used are index guided lasers with a stable single transverse mode. The cw characteristics of a 120-μm and a 250-μm laser are shown in Figs. 1(a) and 1(b), respectively. The longitudinal mode spectrum becomes essentially single moded at an output power slightly below 1 mW and ~1.3 mW for the shorter and longer lasers, respectively. The fraction of power contained in the dominant lasing mode is higher in the short laser than the long one at all corresponding output power levels. However, it should be mentioned that this is only a general observation, and exceptions where a long laser has a purer longitudinal mode spectrum compared to a short laser do exist. Thus, in high-frequency modulation experiments described below, the comparison is not as much between short and long lasers as between lasers with intrinsically different mode selectivities. All the lasers tested retain their single-mode spectrum unless the optical modulation depth, defined as the ratio of the amplitude to the peak of modulated optical waveform, exceeds a critical level at ~75–90%, depending on the purity of the original cw lasing spectrum. An interesting observation is that, contrary to common belief, this critical modulation depth does not depend on modulation frequency. Results obtained with the lasers in Figs. 1(a) and 1(b) are shown in Figs. 2(a) and 2(b), respectively, which depict the time-averaged spectrum at various modulation depths and frequencies between 1 and 3 GHz. A single-mode spectrum can be maintained in the short laser at a modulation depth up to 90% regardless of modulation frequency; the corresponding level is ~75% for the longer laser. Both lasers are biased at a dc output power of 1.5 mW. However, it can be observed that the width of the individual modes broadens at higher frequencies, although the relative amplitudes of the modes do not change. This arises from fluctuations in the refractive index of the cavity as a result of fluctuation in carrier density. A simple single-mode rate equation analysis shows that under a constant optical modulation depth, the fluctuation in carrier density increases with increasing modulation frequency, and consequently the line broadening effect is more visible at high frequencies.

Extreme care has to be taken in determining the exact value of the optical modulation depth. The drop-off of the photodetector response at high frequencies can be taken into account by precalibrating the photodiode response using picosecond pulse techniques. The excess dc gain present in most photodiodes can be determined as follows: the photodetector output is observed directly in the time domain while modulating the laser at a low frequency (say, a few hundred MHz where the photodiode response is flat) and the rf drive to the laser is increased until clipping occurs at the bottom of the output waveform from the photodiode. This indicates clearly the level corresponding to zero optical power. The excess dc gain over the midband gain of the photodiode can then be accurately determined from the observed dc and rf photocurrents at the point of clipping.

The rate equations governing the time evolution of the

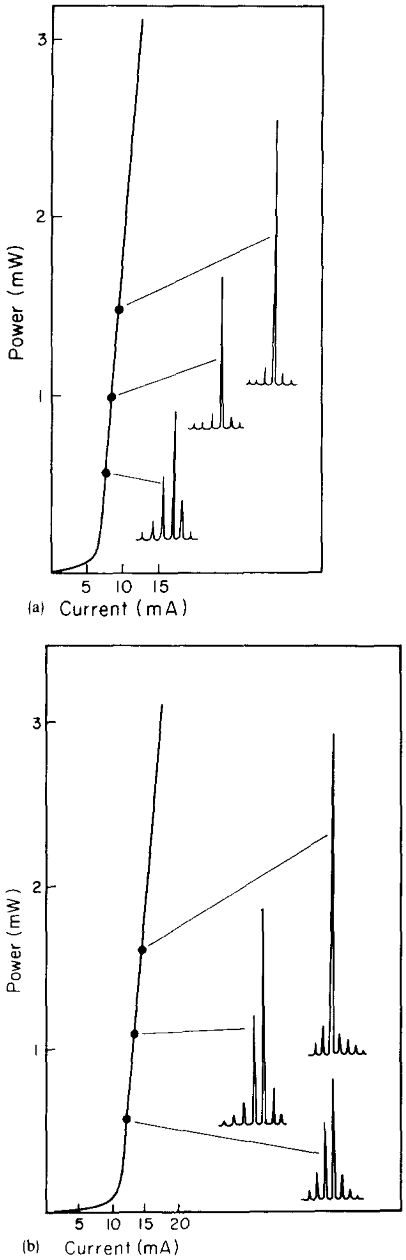

FIG. 1. (a) cw light vs current and spectral characteristics of a GaAs laser whose cavity length is 120 μm and (b) 250 μm.

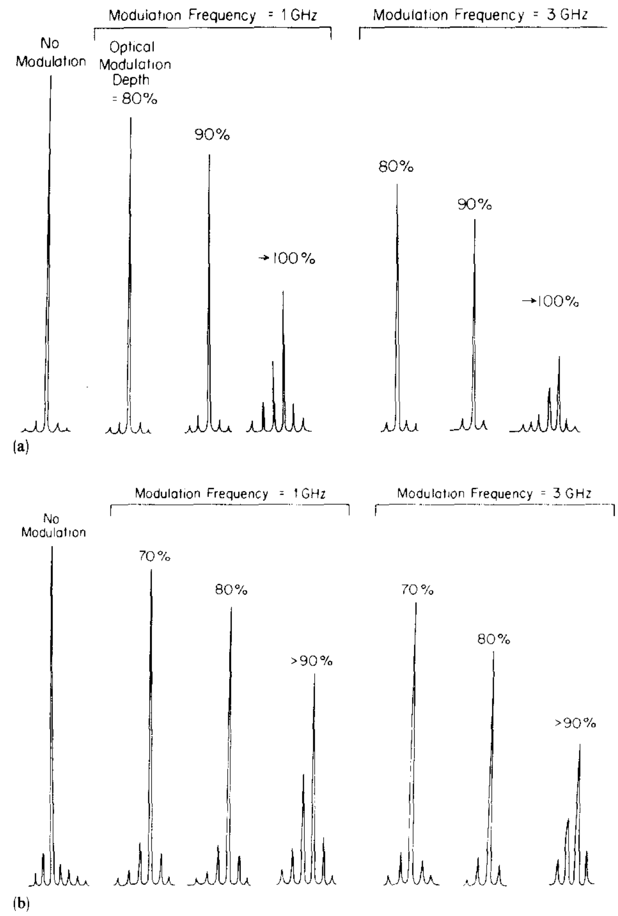

FIG. 2. (a) Observed time-averaged spectrum of the laser shown in Fig. 1(a) under microwave modulation at various optical modulation depths, at modulation frequencies of 1 and 3 GHz. The laser is biased at a dc optical power of 1.5 mW. (b) Same experiment as in (a) but for the laser shown in Fig. 1(b).

number of photons in the ith longitudinal mode read

$$\frac{ds_i}{dt} = \frac{1}{\tau_p}\left[(\Gamma g_i n - 1)s_i + \Gamma \beta_i n\right], \tag{1}$$

where n is the electron density normalized by $1/\alpha\tau_p$, s_i is the photon density in the ith mode normalized by $1/\alpha\tau_s$, α is the optical gain constant, β_i is the spontaneous emission factor for the ith mode, τ_p and τ_s are the photon and spontaneous lifetimes, Γ is the optical confinement factor, and g_i is the Lorentzian gain factor defined as $g_i = 1/(1 + bi^2)$. Let $S = \Sigma s_i$ to be the total photon density summed over all modes, and $a_i = s_i/S$ be the fraction of optical power in the ith mode. The rate equation for a_i is

$$a_i = \frac{\Gamma}{\tau_p}\left(a_i \sum_j (g_i - g_j)a_j - \frac{a}{S}\sum_j \beta_j + \frac{\beta_i}{S}\right) n$$
$$i = -\infty \rightarrow \infty. \tag{2}$$

The normalized electron density n is clamped to a value very close to $1/\Gamma$ under steady state operation, and numerical computations have shown that it does not deviate significantly ($<$ parts in 10^2) from that value even during heavy optical transients at high frequencies.[2,9] It is thus very reasonable to take n as $1/\Gamma$ in Eq. (2). This equation can then be solved exactly when the laser has only two modes (or three modes placed symmetrically about the gain peak), and with some approximations when all modes are taken into account. These results will be presented separately. A rough estimate of the time constant involved in spectral transient can be obtained by considering the time evolution equation for the fraction of power in the dominant mode (a_0) and let $\beta \rightarrow 0$, in which case one finds that the characteristic time constant is given by

$$\tau \sim 2\tau_p/\sqrt{b}. \tag{3}$$

Since $b \sim 10^{-4}$ and $\tau_p \sim 2$ ps, τ is of the order of 0.5 ns, which agrees well with experimental observations[4] and numerical results[2,14] for GaAs lasers. Hence, if one modulates a laser at above ~ 1 GHz, the spectrum does not have sufficient time to respond within a modulation cycle and consequently the spectral content will not vary significantly with time. If we assume that the optical output power (and hence the total

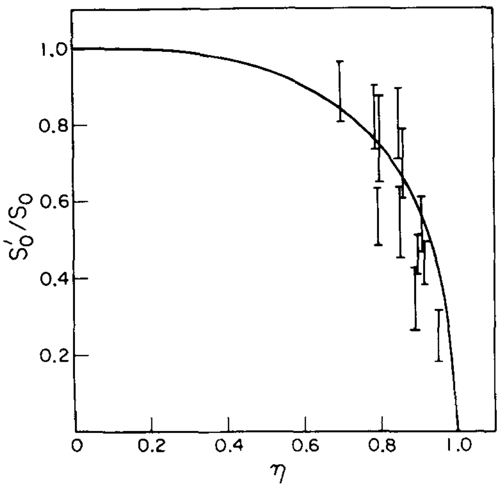

FIG. 3. Plot of S'_0/S_0 vs η. S'_0 is the photon density corresponding to a bias level, at which the laser would emit a longitudinal mode spectrum similar to that when the actual bias level is S_0 and the laser is modulated at high frequencies. The vertical bars are derived from experimental observations of the lasers shown in Figs. 1 and 2, and a few others.

photon density) is

$$S(t) = S_0 + S_1 \cos(\omega t) \tag{4}$$

and we assume that a_0 is constant in time, we can take a time average [defined as $\langle \ \rangle = (1/T)\int_0^T dt$, where $T =$ period of modulation] on both sides of Eq. (2) to give

$$a_i \sum_j (g_i - g_j) a_j - a_i \sum_j \beta_j \left\langle \frac{1}{S(t)} \right\rangle + \beta_i \left\langle \frac{1}{S(t)} \right\rangle = 0. \tag{5}$$

The solution of Eq. (5) is the steady state lasing spectrum of a laser operating cw at a photon density of S'_0, where

$$\frac{1}{S'_0} = \left\langle \frac{1}{S(t)} \right\rangle = (S_0^2 - S_1^2)^{-1/2}. \tag{6}$$

The optical modulation depth η, previously defined as the ratio of the amplitude to the peak of the optical modulated waveform, is $\eta = 2S_1/(S_0 + S_1)$. Thus in terms of modulation depth, the apparent bias power S'_0 is

$$S'_0 = S_0 \frac{2\sqrt{1-\eta}}{2-\eta}. \tag{7}$$

So, when a laser is biased at a certain optical power and being modulated at high frequencies with an optical modulation depth of η, the time-averaged lasing spectrum is equivalent to that of the laser operating cw (without modulation) at a reduced power level of S'_0 as given in Eq. (7). Figure 3 shows a plot of the apparent reduction factor, S'_0/S_0, vs η. The results show that high-frequency modulation has little effect on the lasing spectrum unless the optical modulation depth exceeds ~80%. The points shown on the same plot are obtained from the experimental results of the two lasers described above and a few other lasers. The general agreement with the analysis is good.

If one further increases the microwave drive to the laser beyond the point of 100% optical modulation depth ($S_0 = S_1$), the bottom of the optical waveform will clip. The integral $\langle 1/S(t) \rangle$ becomes very large and consequently S'_0 becomes very small. The spectrum would look like that of a laser below lasing threshold. This is in accord with experimental observations.

The analysis presented above is based on a strictly homogenously broadened gain system and therefore does not take into account of mode jumping and spectral gain suppression.[10] Nevertheless, mode jumping usually (though not always) results from junction heating, and when the modulation frequency is very high, no such thermal effect should occur. Spectral gain suppression is manifested as a decrease in the actual amplitude of the nondominating longitudinal modes as the total optical power is increased, and is usually observed only at fairly high optical power levels. This phenomenon has been explained by considering nonlinear optical properties of the semiconductor material[15] and actually aids the laser in maintaining a single-mode spectrum under high-frequency modulation.

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