Output spectrum of an unlocked optically driven semiconductor laser

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The output of an unlocked optically injected semiconductor laser exhibits a two-sided spectral distribution about its lasing frequency. The experimental results are explained by coupled phase and amplitude modulation and described by a rate-equation analysis.

Injection locking is well known to increase the spectral purity of microwave oscillators.[1] This technique has also been widely investigated with the same goal for semiconductor lasers.[2] In both cases the conditions for achieving a single frequency, i.e., a locked operation, were previously discussed in terms of a locking range.[2–8] However, little attention has yet been paid to the spectral properties in the unlocked case. Nevertheless its investigation is useful in understanding the dynamics of the locking process and more generally the dynamics of the laser gain saturation. For a large frequency mismatch and/or low injection rate, the locking conditions are not fulfilled, and pulsation instability may be observed, especially for injection on the upper-frequency side of the locking range.[4,7,8] For injection on the lower-frequency side, a more stable operation is usually observed. We show that in this case a semiconductor laser exhibits a two-sided spectrum quite similar to that previously observed from a driven tunnel diode oscillator.[9] Although a discussion of this phenomenon in terms of nearly degenerate four-wave mixing was recently suggested,[10] we propose an interpretation in terms of coupled phase and amplitude modulation at the difference between the injected and lasing frequencies and arising from optical excitation of the gain saturated medium. Experimental results are well described by a rate-equation analysis including driving forces to account for optical injection. Moreover, these investigations appear to be an accurate method, free of electrical bandwidth considerations, for studying the relaxation frequency and the associated damping time of the injected laser.

Analysis

The unlocked injected laser is described by the three usual rate equations for the total photon number P, the phase ϕ of the lasing field, and the carrier number N.[11] Supplementary time-dependent driving forces account for the optical driving:

$$\dot{P} = \left(G - \frac{1}{\tau_p}\right)P + f_p(t), \tag{1}$$

$$\dot{\phi} = \frac{\alpha}{2}\left(G - \frac{1}{\tau_p}\right) + f_\phi(t), \tag{2}$$

$$\dot{N} = \frac{I}{e} - GP - \frac{N}{\tau_e}. \tag{3}$$

G is the optical gain, τ_p the photon lifetime, α the phase–amplitude coupling factor introduced by Henry,[11] I the injected current, and τ_e the carrier lifetime. For $\Omega \ll c/2Ln_g$ the driving forces f_p and f_ϕ accounting for optical injection are[5]

$$f_p(t) = 2\bar{P}\rho \cos \Omega t, \qquad f_\phi(t) = \rho \sin \Omega t. \tag{4}$$

Ω is the difference between the injected ω_1 and the lasing frequencies, ω_0, $\bar{P}$ the mean photon number, $\bar{P}_i$ the mean injected photon number, $\rho = (\bar{P}_i/\bar{P})^{1/2}c/2Ln_g$ the normalized injection rate, L the cavity length, and n_g the group index. Spontaneous emission terms and consequent static line broadening are neglected in the following analysis.

In the linear gain approximation, the Fourier analysis of the linearized system [Eqs. (1)–(3)], in terms of small deviations δP, δN, and $\delta\phi$ in P, N, and ϕ from their mean values $\bar{P}$, $\bar{N}$, and $\bar{\phi}$, shows that under optical injection the laser undergoes coupled phase and intensity modulation. The resulting sinusoidal optical phase modulation at frequency $\Omega = x\omega_{R0}$ is found to have an amplitude $R(x)$ given by

$$R(x) = \frac{\rho}{x\omega_{R0}} \times \frac{\{[(1-x^2)^2 + 4\sin^2\delta x^2 - 2\alpha \sin\delta x]^2 + \alpha^2(1-x^2)^2\}^{1/2}}{[(1-x^2) + 4\sin^2\delta x^2]}, \tag{5}$$

with

$$\sin\delta = (\omega_{R0}\tau_R)^{-1}$$

and where

$$\omega_{R0} = \left(\frac{\Gamma A\bar{P}}{\tau_p}\right)^{1/2} \tag{6}$$

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is the relaxation resonance frequency and

$$\tau_R = 2\left(\Gamma A\bar{P} + \frac{1}{\tau_e}\right)^{-1} \quad (7)$$

is the associated damping time.

Γ is the filling factor and A the differential gain. In a first-order analysis, neglecting the direct contribution of intensity modulation to the spectrum, the derivation of the phase-modulation spectrum is then straightforward. For a total output power $\mathcal{P}_o$ and after normalization by the injected power $\mathcal{P}_i$, the power p in the two first-order sidebands is found to be

$$p(\omega_0 \pm \Omega) = \frac{\mathcal{P}_o}{\mathcal{P}_i} J_1^{\,2}(R). \quad (8)$$

With such a definition $p(\omega_0 \pm \Omega)$ appears to be an optical gain of the injected light. $\mathcal{P}_o/\mathcal{P}_i$ is related to the normalized injection rate ρ previously defined by the relation

$$\rho^2 = \tau_p(1 - R)\left[\log\left(\frac{1}{R}\right)\right]^{-1}\left(\frac{c}{2Ln_g}\right)^3\left(\frac{\mathcal{P}_o}{\mathcal{P}_i}\right)^{-1}, \quad (9)$$

where R is the facet reflectivity.

The solid lines in Fig. 1 show the calculated normalized power in the two first-order sidebands as a function of the frequency departure of the injected field from the carrier in the experimental conditions of the next section and with the following values of the laser parameters: $\tau_p = 1.7$ psec, $\tau_e = 2.2$ nsec, $\Gamma A = 2600$ sec^{-1}, $L = 300$ μm, $n_g = 4.3$, $R = 0.3$, and $\alpha = 5.4$.

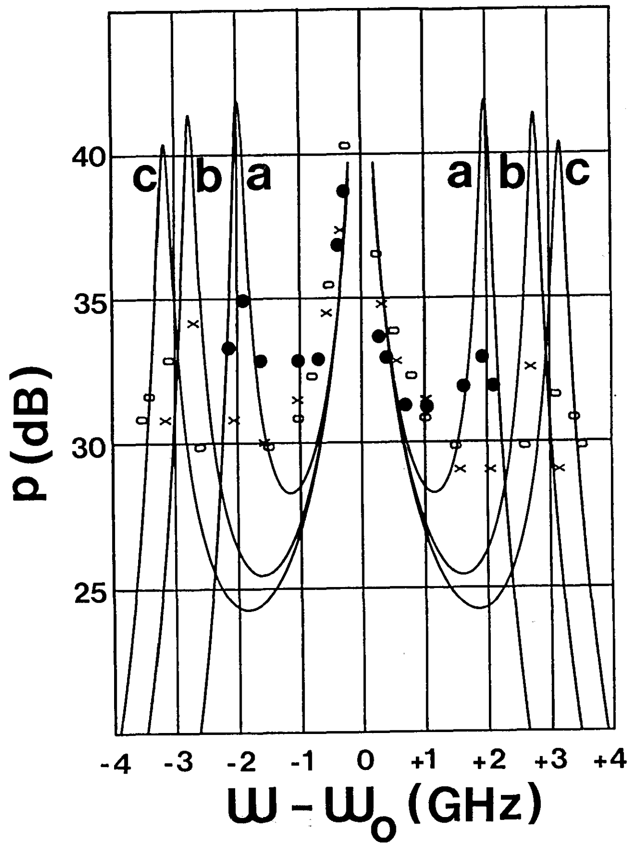

Fig. 1. Measured and calculated normalized power p (in decibels) in the two first-order sidebands versus the frequency departure (in gigahertz) of the injection field from the carrier. The injection level is $P_i = 0.07$ μW, and the power output level is $\mathcal{P}_o = 3.4$ mW (● and a), 6.6 mW (× and b), and 8.7 mW (○ and c).

Experiment

The experiment uses two Hitachi HPL 1400 (GaAl)As channeled substrate planar lasers.[10] The temperature and injection current of each were stabilized within 0.01°C and 10 μA, respectively. The frequency difference Ω is obtained from the locking state by detuning the driver laser toward the shorter frequencies. An optical isolator avoids mutual injection. The injected laser output spectrum is analyzed by a scanning Fabry–Perot interferometer.

We show in Fig. 1 the measured normalized power in the two first-order sidebands as a function of frequency departure from the carrier for a given injection level $\mathbf{P}_i = 0.07$ μW and various values of the total output power $\mathbf{P}_o = 3.4$, 6.6, 8.7 mW. Because of the locking phenomena it is not possible to observe the sidebands nearest the carrier, i.e., within the locking bandwidth.

Discussion

Taking into account the precision of the measurements, the experimental data closely fit the analysis far from the resonance frequencies, the values of which are also well described by Eq. (6). However, two major discrepancies are observed. First, as observed from transient studies of the photon number P in pulse current operation, the damping appears to be stronger than that derived from Eq. (7). This anomalously strong damping of the relaxation oscillations has been universally observed in transient studies of semiconductor lasers under pulse modulation. Various explanations have been proposed for its interpretation, such as spontaneous emission, nonlinear absorption, and gain saturation associated with spectral hole burning.[11–13] The unlocked injected laser spectrum studies appear to be a tool for investigating the relaxation frequency and its associated damping time. Because they directly involve the optical spectrum they are free of electrical bandwidth considerations. The observed sidebands are several orders of magnitude greater than those resulting from the spontaneous emission excitation of the laser medium.[14] The second major discrepancy concerns the asymmetry of the observed spectrum. The simultaneous intensity-modulation contribution to the laser spectrum has been evoked to interpret the low level of the right-hand sideband obtained from the spontaneous emission excitation of the laser.[14] A detailed analysis including both the contributions of the coupled phase and intensity modulation on the field spectrum will be published elsewhere.

Conclusion

We have shown that an unlocked optically injected semiconductor laser exhibits a two-sided spectral distribution about the lasing frequency. Such a spectral distribution is well interpreted by an optically driven phase modulation at the difference frequency between the injected and lasing fields. Unlocked injected laser spectrum observation appears to be an accurate tool free of electrical-circuit considerations for investigating the dynamics of gain saturation.

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