Relationship Between Carrier-Induced Index Change and Feedback Noise in Diode Lasers

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Abstract—An improved theoretical analysis of single-mode diode laser dynamics reveals that feedback-induced intensity pulsations and frequency modulation are consequences of the carrier-dependent modal refractive index of the laser cavity. A stability criterion based on injection-locking theory indicates that gain-guided diode lasers are more likely to exhibit feedback-induced pulsations than are index-guided devices. Numerical simulation of feedback-induced noise is shown to be in excellent agreement with previously reported experimental data.

I. Introduction

RECENT experimental studies of feedback-induced noise in single-mode diode lasers [1], [2] have revealed that weak feedback can induce the generation of strong submodes in the laser spectrum separated by 1-3 GHz from the primary optical mode (Fig. 1). The asymmetry between the intensity of the upper and lower submodes indicates that the optical feedback is producing both amplitude and frequency modulation of the laser emission. An interesting observation is that, for external cavities longer than several millimeters, the submode frequency is independent of the length of the optical feedback path and increases with increasing laser drive current. Tests on several different types of gain-guided and index-guided single-mode diode lasers revealed that buried heterostructure lasers were the only ones that never exhibited these feedback-induced submodes [3].

The analytical and numerical results reported in this paper indicate that feedback-induced high frequency intensity pulsations and frequency modulation in the emission of single-mode diode lasers are caused by the carrier-dependent modal refractive index of the laser cavity. A simple diode laser stability criterion derived from injection locking theory is used to relate the development of feedback noise to the modal refractive index and modal gain of the diode laser cavity. The stability analysis indicates that gain-guided diode lasers are more likely to exhibit feedback-induced high frequency submodes than are index-guided devices. The experimental observations of feedback-induced submodes in diode laser spectra [1]-[3] are fully explained by including the carrier-dependent modal refractive index in a numerical model of diode laser dynamics.

Manuscript received February 26, 1982; revised May 27, 1982. This work is based in part on a paper presented at the Sixth Topical Meeting on Integrated and Guided Wave Optics, Pacific Grove, CA, January 6-8, 1982.

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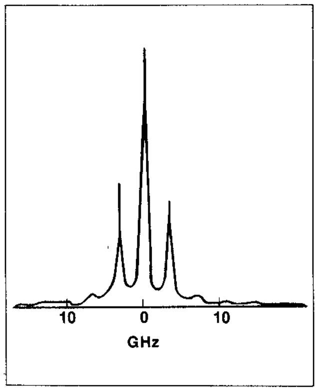

Fig. 1. Observed emission spectrum of CSP diode laser with ≃0.01 percent optical feedback [2]. Drive current is 1.3 times threshold.

II. Analytical Technique and Stability Criterion

The analysis presented here is based on a time-dependent numerical solution of the differential equations that govern the complex optical field and carrier concentration in a single-mode diode laser injected by an external optical signal. The same formalism is used to treat both feedback from an external reflector or injection by an independent optical source. With reference to Fig. 2, the laser optical field $\epsilon(t)$ and injected optical field $\chi(t)$ inside the laser cavity are represented in complex notation as

$$\epsilon(t) = E(t) \exp \{j [\omega_l t + \phi_l(t)]\} \quad (1)$$

and

$$\chi(t) = x(t) \exp \{j [\omega_r t + \phi_r(t)]\} \quad (2)$$

where ω_l, $\phi_l(t)$ are the angular frequency and phase of the laser field, and ω_r, $\phi_r(t)$ are the angular frequency and phase of the externally injected field. The equation that relates $\epsilon(t)$ to $\chi(t)$ is [4], [5]

$$\frac{d\epsilon(t)}{dt} - \left\{ j\omega_N(n) + \frac{1}{2} [G(n) - \tau_p^{-1}] \right\} \epsilon(t) = (2t_p)^{-1} \chi(t) \quad (3)$$

where n is the carrier density, $G(n)$ is the modal gain, and τ_p is the photon lifetime in the laser cavity. The angular optical frequency $\omega_N(n)$ of the Nth longitudinal mode of the laser is determined by the Fabry-Perot resonance relation

$$\omega_N(n) = \frac{N\pi c}{\bar{n}(n) L} \quad (4)$$

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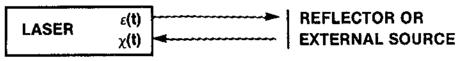

Fig. 2. Diode laser injected by an external optical signal. For external feedback with roundtrip time T, $\chi(t) \sim \epsilon(t - T)$.

with N an integer, c the speed of light, L the length of the laser cavity, and $\bar{n}(n)$ the carrier-dependent modal refractive index of the laser cavity. Substituting (1) and (2) into (3) and separating real and imaginary parts yields equations for the phase and amplitude of the optical field in the laser cavity

$$\frac{d\phi_l(t)}{dt} = \omega_N(n) - \omega_l - \frac{x(t)}{E(t)}(2\tau_p)^{-1} \cdot \sin\left[(\omega_l - \omega_r)t + \phi_l(t) - \phi_r(t)\right] \tag{5}$$

$$\frac{dE(t)}{dt} = \frac{1}{2}\left[G(n) - \tau_p^{-1}\right]E(t) + x(t)(2\tau_p)^{-1} \cdot \cos\left[(\omega_l - \omega_r)t + \phi_l(t) - \phi_r(t)\right]. \tag{6}$$

These two equations must be solved in conjunction with the familiar rate equation for the carrier density $n(t)$

$$\frac{dn}{dt} = -\tau_s^{-1}\,n(t) - G(n)\,|E(t)|^2 + \frac{J}{ed} \tag{7}$$

where τ_s is the spontaneous carrier lifetime, J is the injection current density, e is the electronic charge, d is the active layer thickness, and $E(t)$ is normalized such that $|E(t)|^2$ is equal to the photon density in the laser cavity. Equations (5)–(7) are the coupled nonlinear differential equations that express the interaction between the optical field of the diode laser and the optical field of the injected signal. Even though an exact solution for the diode laser dynamics must be found by numerical means, a satisfactory qualitative understanding of feedback-induced intensity pulsations can be provided by extending established injection-locking theory [6] to include the effects of the carrier-dependent modal refractive index in the laser cavity. In order to establish a simple stability criterion involving the carrier-induced index change, the evolution of instability in a diode laser subjected to feedback will be analyzed by considering the closely related case of a free-running diode laser injected by an external optical signal at the center of the locking range. During the first external cavity roundtrip time after a reflected signal returns to the diode laser, the feedback-induced fluctuations in the laser emission are identical to the fluctuations that would be caused by injecting the laser with an independent signal having an optical frequency equal to that of the free-running laser. Numerical results indicate that if self-sustained pulsations are established during this initial time period when the external injection analogy is valid, then they will persist during successive roundtrip periods.

When the injected field amplitude x is much smaller than the field amplitude E_o in the free-running diode laser, setting $E(t) = E_o$ in (5) yields an approximate analytic solution for the phase of the laser field. Analysis based on this weak injection approximation [4], [6] predicts that the optical frequency of the diode laser will lock to the optical frequency of the injected signal if the locking criterion

$$|\omega_N - \omega_r| \leqq (2\tau_p)^{-1}\,K^{1/2} \tag{8}$$

is satisfied, where ω_N is the unperturbed optical angular frequency of the free-running laser, ω_r is the optical angular frequency of the injected signal, and $K = (x/E)^2$ is the ratio between the injected optical power and the laser optical power inside the cavity. The injection locking range is ±400 MHz for a typical diode laser photon lifetime of 2 ps and an injection ratio of 10^{-4}. If the feedback path is long enough to have a Fabry-Perot mode spacing much smaller than the injection locking range, then the steady-state optical field intensity and carrier density in the diode laser subjected to feedback will correspond closely to the case of a diode laser injected by an independent external signal at the center of the locking range. The solution of (5)–(7) reveals that under these conditions the enhanced optical field intensity and reduced carrier density in the injection-locked diode laser are

$$E^2 = E_o^2(1 - K^{1/2})^{-1}\left\{1 + K^{1/2} \cdot \left[\left(1 + n_e\tau_p\frac{dG}{dn}\right)\left(\frac{J}{J_{\text{th}}} - 1\right)\right]^{-1}\right\} \tag{9}$$

and

$$n = n_{\text{th}} - \tau_p^{-1}K^{1/2}\left(\frac{dG}{dn}\right)^{-1} \tag{10}$$

where n_{th} and J_{th} are the carrier density and current density at threshold, respectively.

It will now be shown that if the carrier-induced change in the natural frequency of the diode laser cavity is large enough, then the presence of optical feedback can cause self-sustained pulsations in the laser emission. An approximate expression for the diode laser natural frequency as a function of the carrier-dependent modal refractive index is derived from (4)

$$\omega_N(n) \cong \omega_o - \frac{\omega_o}{\bar{n}_{\text{th}}}\frac{d\bar{n}}{dn}\Delta n \tag{11}$$

where $\omega_o = \omega_N(n_{\text{th}})$ is the optical angular frequency of the free-running laser and Δn is the difference between n_{th} and the carrier density of the injection-locked laser. The ratio between the carrier-induced change in the modal refractive index and the modal gain can be expressed by the dimensionless factor R, defined as [5]

$$R = \frac{2\omega_o}{\bar{n}_{\text{th}}}\left(\frac{d\bar{n}}{dn}\right)\left(\frac{dG}{dn}\right)^{-1}. \tag{12}$$

Substituting (10) into (11) and making use of (12) yields an expression for $\Delta\omega_N(n)$, the carrier-induced change in the natural frequency of the injection-locked diode laser

$$\Delta\omega_N(n) = R(2\tau_p)^{-1}\,K^{1/2}. \tag{13}$$

It is clear that when $\omega_r = \omega_o$, a consistent steady-state solution of the system (5)–(7) will not exist if $\Delta\omega_N(n)$ exceeds the locking half-bandwidth given by (8). Therefore, if $|R|$ exceeds unity, a diode laser will be potentially unstable with respect to external optical injection at the center of the locking range. Values of R between −0.5 and −3.0 have been previously reported for diode lasers [5], and recent studies at GTE Laboratories have indicated much stronger carrier-induced index changes for gain-guided diode lasers with oxide defined stripes [7].

Fig. 3 contains a schematic representation of self-sustained oscillations caused by injecting a diode laser with an external optical signal at the center of the locking range. When $|R|$ exceeds unity, changes in the carrier density are sufficient to cause the optical frequency of the diode laser to oscillate in and out of the locking range. This modulation of the laser emission frequency is accompanied by strong pulsations in the laser output intensity. It must be emphasized that this pulsation mechanism is a nonlinear injection locking phenomenon that does not depend on the presence of saturable absorbers in the laser cavity [8].

III. Numerical Results

The qualitative stability analysis presented here has been confirmed by numerical solution of the system (5)-(7) using a fifth-order Runge-Kutta algorithm. The modal gain $G(n)$ in (6) and (7) was represented by the linear approximation

$$G(n) = g(n - n_e)$$

with g a proportionally constant and n_e the carrier density at zero gain. The diode laser parameters chosen for these calculations were $\tau_s = 2$ ns, $\tau_p = 2$ ps, $g = 1.4 \times 10^{-6}$ $\text{cm}^3 \cdot \text{s}^{-1}$, and $n_e = 10^{18}$ cm^{-3}. Before proceeding to the exact numerical solution for an example of optical feedback, the case of external injection at the center of the locking band will be examined in order to determine the essential features of the feedback-induced instability. Fig. 4 displays intensity pulsations caused by external injection at the center of the locking band for diode lasers with R values of -0.5, -2.0, and -3.0. In all three cases the diode laser drive current is 30 percent above threshold and the relative intensity of the injected signal is 10^{-4}. As predicted by the stability criterion derived above, the calculated output of the diode laser with $R = -0.5$ is stable with respect to external injection, while the lasers with $|R| > 1.0$ display strong intensity pulsations at a repetition rate of 2.5 GHz. The pulsation frequency is found to be nearly independent of R for values of $|R|$ exceeding unity.

Additional computer calculations indicate that the intensity pulsations are associated with frequency modulation of the laser emission spectrum, in agreement with the qualitative analysis represented by Fig. 3. The frequency modulation has a calculated maximum deviation of 3 GHz, corresponding to an FM modulation index of approximately 1.3. This combination of amplitude and frequency modulation is consistent with the measured diode laser emission spectrum [1] shown in Fig. 1. The magnitude of the observed submodes is primarily a consequence of the relatively large FM modulation index, while the asymmetry in the intensity of the upper and lower submodes results from the combined effect of the amplitude and frequency modulation.

Fig. 5 indicates the variation of the pulsation frequency as a function of drive current for a diode laser with $R = -2.0$, injected at the center of the locking band by an external signal of relative intensity 10^{-4}. As has been observed experimentally [1], [2], the pulsation frequency increases with increasing drive current, from a value of 1.5 GHz for $I = 1.1\, I_{th}$ to a value of 2.5 GHz for $I = 1.3\, I_{th}$. Since the pulsation frequency increases with drive current, but is independent of R, it can be concluded that the frequency of the pulsations is fixed by an intrinsic resonance between the photon and carrier populations in the diode laser. It has previously been established that this resonance is associated with the appearance of relaxation oscillations in pulse modulated diode lasers.

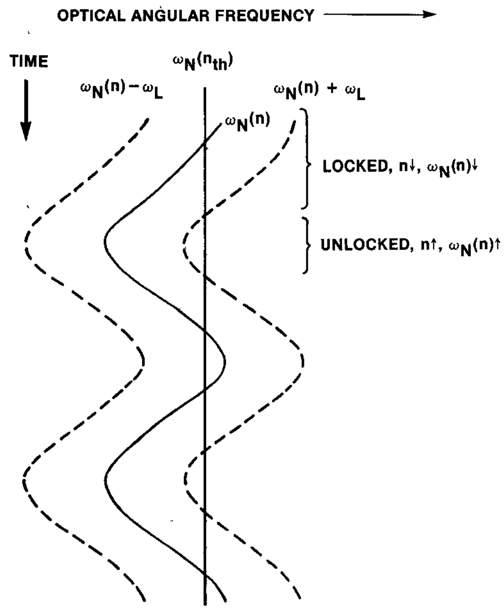

Fig. 3. Self-sustained oscillations for $|R| > 1$ due to external injection at the center of the locking band.

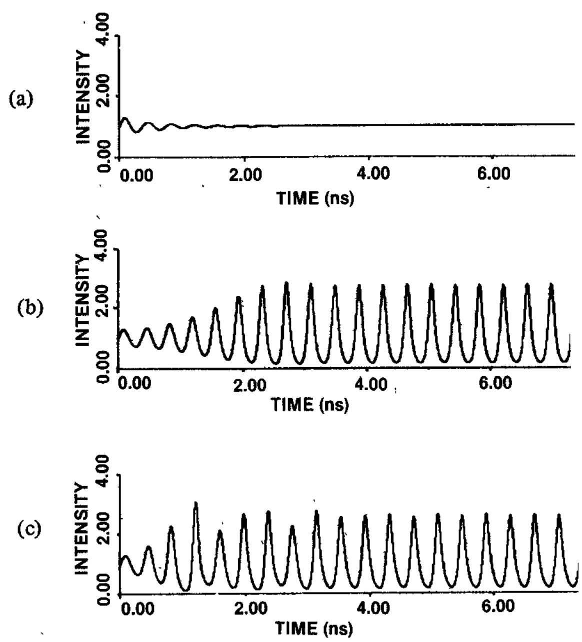

Fig. 4. Intensity pulsations caused by external injection at the center of the locking band, with $K = 10^{-4}$ and $I = 1.3\, I_{th}$. Intensity normalized to that of the free-running laser. (a) $R = -0.5$. (b) $R = -2.0$. (c) $R = -3.0$.

Fig. 6 is a plot of the calculated intensity versus time for a diode laser with $R = -2.0$ coupled to an external cavity of roundtrip length 5 ns and feedback ratio 10^{-4}. In this example, the diode laser is initially in a free-running state and the first reflection from the external cavity reenters the laser at time $t = 5$ ns. Between 5 and 10 ns the laser emission is identical to the results presented in Fig. 5(c) for a diode laser injected at the center of the locking band, and the optical

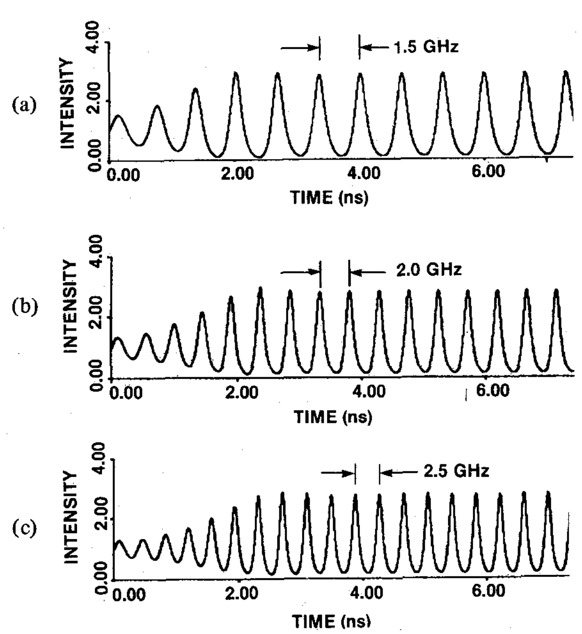

Fig. 5. Pulsation frequency as a function of drive current for $K = 10^{-4}$ and $R = -2.0$. (a) $I = 1.1\,I_{th}$. (b) $I = 1.2\,I_{th}$. (c) $I = 1.3\,I_{th}$.

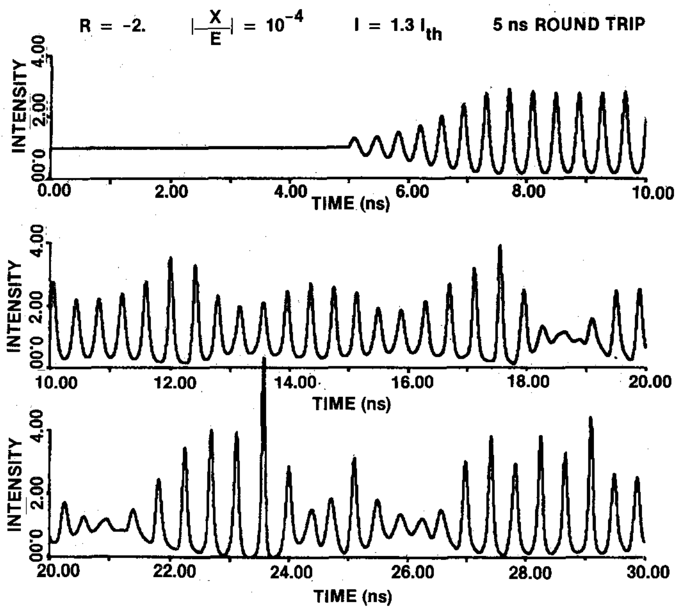

Fig. 6. Feedback-induced intensity pulsations for 5 ns roundtrip time. $K = 10^{-4}$, $R = -2.0$, and $I = 1.3\,I_{th}$.

feedback causes self-sustained pulsations in the laser emission. After 10 ns the calculated response of the cavity coupled laser is complicated by the influence of multiple reflections. The most important feature of the feedback-induced pulsations displayed in Fig. 6 is that harmonics of the roundtrip frequency modulate the depth of the intensity pulsations without changing the pulsation frequency. This calculated behavior is in agreement with observation [1]-[3], and confirms that the frequency of the strong feedback-induced submodes is independent of the length of the external cavity.

Conclusions

It has been demonstrated that feedback-induced amplitude and frequency modulation will occur in diode lasers for which the carrier-induced change in the modal refractive index causes the quantity $|R|$ defined in (12) to exceed unity. Numerical simulation of this feedback noise phenomenon is in excellent agreement with the observations reported in [1]-[3]. Even though accurate independent measurements of R are difficult to obtain, the stability criterion presented does provide an explanation for the absence of feedback-induced submodes in index-guided single-mode lasers. In index-guided devices the longitudinal mode frequencies are determined primarily by the properties of the built-in waveguide, and the carrier-induced change in the refractive index of the active layer results in a relatively small change in the modal refractive index of the laser cavity. For gain-guided diode lasers the absence of a built-in waveguide causes the modal propagation constant to be a stronger function of the carrier-dependent refractive index of the active layer. Index-guided single-mode diode lasers are, therefore, to be preferred for critical applications such as laser gyroscopes and high-speed coherent communications where the presence of feedback-induced submodes would degrade system performance.

References

[1] R. O. Miles, A. Dandridge, A. B. Tveten, H. F. Taylor, and T. G. Giallorenzi, "Feedback-induced lined broadening in cw channel-substrate planar laser diodes," *Appl. Phys. Lett.*, vol. 37, pp. 990–992, Dec. 1980.

[2] A. Dandridge and R. O. Miles, "Spectral characteristics of semiconductor laser diodes coupled to optical fibers," *Electron. Lett.*, vol. 17, pp. 273–274, Apr. 1981.

[3] A. Dandridge, R. O. Miles, A. B. Tveten, and T. G. Giallorenzi, "Noise and spectral properties of single-mode cw diode lasers," in *Tech. Dig. IOOC '81*, Apr. 1981, p. 36.

[4] O. Hirota and Y. Suematsu, "Noise properties of injection lasers due to reflected waves," *IEEE J. Quantum Electron.*, vol. QE-15, pp. 142–149, Mar. 1979.

[5] R. Lang and K. Kobayashi, "External optical feedback effects on semiconductor injection laser properties," *IEEE J. Quantum Electron.*, vol. QE-16, pp. 347–355, Mar. 1980.

[6] R. Adler, "A study of locking phenomena in oscillators," *Proc. IRE*, vol. 34, pp. 351–357, Oct. 1946.

[7] J. S. Manning and R. Olshansky, "Carrier-induced index change in AlGaAs double-heterostructure laser diodes," *Electron. Lett.*, vol. 17, pp. 506–507, July 1981.

[8] R. W. Dixon and W. B. Joyce, "A possible model for sustained oscillations (pulsations) in (Al, Ga)As double-heterostructure lasers," *IEEE J. Quantum Electron.*, vol. QE-15, pp. 470–474, June 1979.

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