Frequency Dynamics of Gain-Switched Injection-Locked Semiconductor Lasers

J. Dellunde, M. C. Torrent, J. M. Sancho, and M. San Miguel

***Abstract*— The frequency dynamics of gain-switched single-mode semiconductor lasers subject to optical injection is investigated. The requirements for low time jitter and reduced frequency chirp operation are studied as a function of the frequency mismatch between the master and slave lasers. Suppression of the power overshoot, typical during gain-switched operation, can be achieved for selected frequency detunings.**

***Index Terms*— Chirp modulation, injection-locked oscillators, semiconductor lasers, timing jitter.**

I. Introduction

GAIN-SWITCHED pulses from single-mode semiconductor lasers are used in a variety of applications. In optical communication systems working at high bit rates, narrow-band spectra under fast current modulation and low time jitter at the detection end are required [1]. Several mechanisms have been designed to provide such characteristics, including mode-locking to an external cavity [2], optoelectronic feedback [3], self-seeding [4], and optical injection [5], [6]. Optical narrow-band injection, usually from a similar master laser, seems to be the most promising technique for controlled low-jitter single-frequency pulse generation from laser diodes. While good performance of the injection-locked lasers at moderate injection levels was early demonstrated [7]–[9], only more recently the possibility of injecting a considerable amount of light into the active region of the laser structure has allowed to obtain extremely high repetition rates in the pulsed operation, with narrow spectra and wide eye openings [10]–[13].

The frequency dynamics during the turn-on of a solitary semiconductor laser was considered in [14], [15]. In that case, the evolution of carrier and photon populations is decoupled from the phase evolution. The instantaneous frequency follows the carrier dynamics through the linewidth enhancement factor α, responsible for both the linewidth broadening which appears in steady-state operation and the frequency chirp observed during current modulation of the laser diode. The dynamics of an optically injected semiconductor laser is far more complex than that of a free-running laser, because the relevant variables intensity, phase, and carrier number are nonlinearly coupled. Instabilities can occur even when the master and slave frequencies are perfectly matched, due to the depressed carrier number induced by optical injection. The dc biased slave laser exhibits several behaviors depending on the injection level and the frequency mismatch between the two lasers, including steady states [16], periodic self-oscillations [17], chaotic output [18]–[20], low-frequency fluctuations [21], four-wave mixing, and frequency conversion [22], among others. The steady state, in which the slave laser is frequency-locked to the master laser, has received particular attention [16], [23], [24]. Injection-locking phenomena in semiconductor lasers are currently under active research [25]–[27] due to their potential applications.

Our aim is to provide a framework where the frequency dynamics of the optically injected laser can be elucidated, in the strong dynamical conditions following the laser switch-on. Attention is focused on the ability of the slave laser to lock at the master frequency. The paper is organized as follows. In Section II, a transient potential for the field components is introduced which is useful to understand the frequency dynamics during the first stages of the light intensity build-up. The relaxation of the slave output to a possible steady state and the conditions for which the power overshoot and the frequency chirp can be efficiently suppressed are studied. The timing information is analyzed in Section III, where strong links between the turn-on time statistics and the frequency dynamics appear. Finally, some general conclusions are drawn in Section IV.

II. Frequency Dynamics

Under optical injection, some amount of the output power launched from a master laser enters the cavity of the slave laser at the laser facet with reflectivity R_2. When a single-mode semiconductor laser is considered, the field rate equations for the amplitude of the optical field and the carrier number in the active region of the slave are [28]

$$\frac{dE}{dt} = \frac{1+i\alpha}{2}\left[\frac{g(N(t)-N_0)}{1+s|E(t)|^2} - \gamma\right]E(t) + k_m E_m e^{i\Delta\omega t} + \sqrt{2\beta N(t)}\xi(t) \quad (1)$$

$$\frac{dN}{dt} = C - \gamma_e N(t) - \frac{g(N(t)-N_0)}{1+s|E(t)|^2}|E(t)|^2. \quad (2)$$

The optical field $E(t)$ is normalized in such a way that $|E(t)|^2$ gives the photon number inside the laser cavity. Typical

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TABLE I
SEMICONDUCTOR LASER PARAMETERS

Parameter	Meaning	Value
g	differential gain	$5.6\ 10^4\ s^{-1}$
γ	losses	$4\ 10^{11}\ s^{-1}$
γ_e	inverse carrier lifetime	$5\ 10^8 s^{-1}$
N_0	transparency value for the carrier number	$6.8\ 10^7$
β	spontaneous emission rate	$1.1\ 10^4 s^{-1}$
α	linewidth enhancement factor	5
s	gain compression factor	$0.7\ 10^{-6}$
τ_L	cavity roundtrip time	$7\ 10^{-12}\ s$
R_2	facet reflectivity	0.32
η_{ext}	coupling losses	1

numerical values assigned to the parameters are listed in Table I. The random spontaneous emission processes are modeled by means of a complex Gaussian white noise term $\xi(t)$ of zero mean and correlation $\langle \xi(t)\xi^*(t')\rangle = 2\delta(t-t')$. We allow for a frequency mismatch between the master laser, with angular frequency ω_m, and the solitary slave laser, with angular frequency ω_s. This frequency mismatch is considered in the field rate equations through the frequency detuning $\Delta\omega = \omega_m - \omega_s$. k_m is the parameter controlling the injection strength. The injected field E_m is affected by power losses arising from filtering, mode matchings, and other effects different to the losses introduced by the laser facet and are considered through the coupling losses parameter η_{ext}, which is always lower than one. The injection strength k_m is then given as

$$k_m = \frac{1}{\tau_L}\,\frac{\sqrt{1-R_2}}{\sqrt{R_2}}\eta_{\text{ext}} \tag{3}$$

where τ_L is the slave cavity round-trip time. Inputs from a far-above-threshold biased master laser are considered, so that E_m can be reasonably taken to be constant. Injected fields with a finite linewidth generally lead to reduced efficiencies [29]. When the phase or amplitude dynamics of the optical field is under study, (1) can be split in two equations. The optical field is written as $E(t) = R(t)e^{i[\Delta\omega t + u(t)]}$ in (1) to give

$$\begin{aligned}\frac{dR}{dt} &= \frac{1}{2}\left[\frac{g(N-N_0)}{1+sR^2} - \gamma\right]R \\ &\quad + k_m E_m\,\cos(u) + \frac{2\beta N}{R} + \sqrt{\beta N}\xi_R(t) \qquad (4)\\ \frac{du}{dt} &= \frac{\alpha}{2}\left[\frac{g(N-N_0)}{1+sR^2} - \gamma\right] \\ &\quad - \Delta\omega - \frac{k_m E_m}{R}\sin(u) + \frac{\sqrt{\beta N}}{R}\xi_u(t). \qquad (5)\end{aligned}$$

$u(t)$ is understood as the residual phase during locked operation, because the frequency component $\Delta\omega$ has been substracted from the field evolution. Amplitude and field noises have zero mean and a time correlation given by $\langle \xi_i(t)\xi_j(t')\rangle = 2\delta_{ij}\delta(t-t')$.

Strong injection is considered, and the particular injection level used in this work is $I_L = (E_m/R_{\text{so}})^2 = 0.04$ (R_{so}^2 is the light intensity of the solitary slave in the on state). The final state depends on the driving current C_{on}, the master field amplitude E_m, and the frequency detuning $\Delta\omega$. Steady states exist inside a locking range given by detunings $|\Delta\omega| < \Delta\omega_L$, where

$$\Delta\omega_L = \frac{k_m E_m}{R_s}\sqrt{1+\alpha^2}. \tag{6}$$

In these steady states, the laser oscillates at the same frequency of the master laser, and the slave laser is said to be *locked*. The steady-state values R_s, u_s, and N_s are obtained by setting to zero the corresponding time derivatives. At low injection currents, only one steady-state solution exists, which is identified as the *off* solution. Three solutions exist in general, two *on* solutions and one off solution. Only one of the two on states is linearly stable. Small perturbations to the steady-state values R_s, N_s, and u_s are considered in order to investigate the linear stability of the solutions. The stability matrix for the solitary laser gives three eigenvalues. One of them, corresponding to the phase perturbations, is zero, and the other two are conjugate complex numbers. For the slave laser, two eigenvalues of the stability matrix, $\lambda_1 = -\Gamma_s + i\Omega_s$ and $\lambda_2 = -\Gamma_s - i\Omega_s$, are conjugate complex numbers. The third eigenvalue, λ_3, is a pure real number. Γ_s is the damping constant of the relaxation oscillations, with angular frequency Ω_s. When Γ_s is positive and λ_3 is negative, the steady state is stable under small perturbations. The ensemble of frequency detunings inside the locking range which lead to stable steady states is called *stable locking range*. The inclusion of gain compression effects in the stability conditions reveals that gain saturation contributes to an increase of the stable locking range, effectively suppressing relaxation oscillations. Additional damping and, as a consequence, further stability can be obtained with a careful selection of the frequency detuning. The criteria for detuning selection are illustrated in Fig. 1. The locking range extends beyond 60 GHz. Negative detunings beyond -35 GHz show negative real parts of the three eigenvalues, leading to stable steady states. The eigenvalues of the solitary laser are included as solid lines. Detunings exceeding -40 GHz lead to damping factors significantly higher than those of the solitary laser.

In the present section, the interest is concentrated on the relaxation to a steady state following a gain-switch. The laser is initially below threshold with an injection current C_b. The laser is suddenly switched on by means of an increase of the driving current to C_{on}. In our numerical simulations, C_{on} is 2.1 times above its threshold value, C_{th}. Different turn-on situations are analyzed based on the previously described detuning ranges. The nonlinear equations describing the laser switch-on are numerically simulated by means of a first-order Euler algorithm, with an integration time step of 0.01 ps. The bias current is taken to be $C_b = 0.9C_{\text{th}}$. The results are presented in Fig. 2. The intensity, phase, and carrier number time evolutions at detunings of -30 and -60 GHz are included

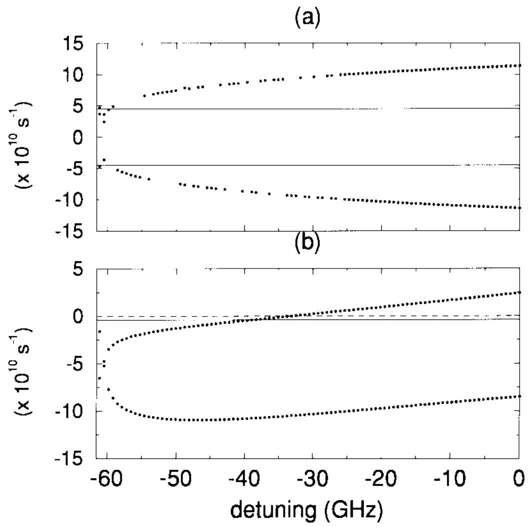

Fig. 1. Eigenvalues of the stability matrix. (a) Imaginary and (b) real parts. The solid lines correspond to the eigenvalues of the solitary laser.

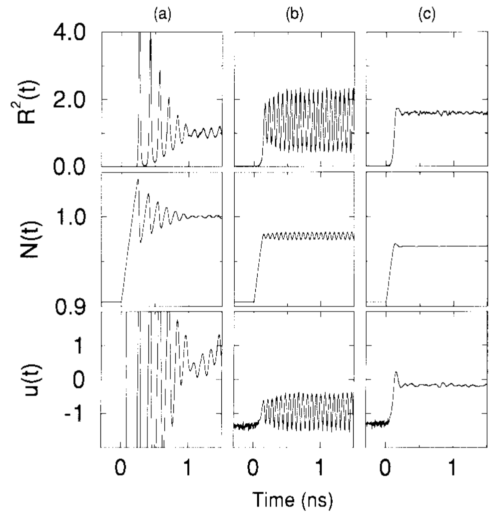

Fig. 2. Time traces of the normalized intensity, normalized carrier number, and field phase after the laser switch-on. (a) Without light injection, (b) with light injection and a detuning of −30 GHz, and (c) with light injection and a detuning of −60 GHz.

and compared to the same evolutions without optical injection. Intensity and carrier number are normalized according to the steady-state values of the free-running slave laser. The solitary laser exhibits large overshoots following the switch-on, with a peak power five times above the steady-state output power. The field phase is rather erratic and displays a fast dynamics up to the final steady state. The injected laser with a frequency detuning of −30 GHz shows periodic oscillations because the chosen detuning lies just outside the stable locking range. The reader will observe, however, that the laser is initially locked before the switch-on time. The off solution is stable for low injection currents. The laser gets unlocked as time goes on because the light intensity grows up, and the locking range is reduced accordingly [see (6)]. With a detuning of −60 GHz, the final state is stable and with a strong damping of any small fluctuation. Strong damping during gain-switched operation is evident as well in Fig. 2(c), where the power overshoot is almost completely suppressed. The frequency dynamics are rather simple in this case. Both initial and final states have well-defined locked phases u_s, different in general to each other. The phase dynamics undergo a smooth transient between the two states, pointing to the fact that the laser is effectively locked. Only a residual instantaneous frequency shift remains as a result of the smooth transient. We stress the fact that a careful examination of the steady states, available by means of standard analytical calculations, is able to predict the more complicated nonlinear dynamics of the laser and the suppression of relaxation oscillations, which involve the numerical simulation of modified stochastic rate equations. The possible suppression of the relaxation oscillations is also shown.

The locking process during the laser turn-on can be understood by means of a potential for the components of the optical field, valid during the transient. This potential requires the change to a new reference frame $E(t) = G(t)e^{i\phi(t)}$

$$\dot{\phi} = \frac{\alpha}{2} g(N(t) - N_{\rm th}) \tag{7}$$

where $N_{\rm th} = N_0 + \gamma/g$ and $G(t) = G_1(t) + iG_2(t)$. During the transient and before reaching a significant output power, light saturation is not operative and then one can take $s = 0$ in the field rate equations. The nonlinear terms in the carrier evolution equation can be neglected as well. Under these reasonable assumptions, the carrier dynamics can be independently solved to give

$$N(t) = \frac{C_{on}}{\gamma_e} + \frac{1}{\gamma_e}(C_b - C_{on})e^{-\gamma_e t}. \tag{8}$$

Then the time evolution of the field components $G_1(t)$ and $G_2(t)$ can be expressed in terms of the potential

$$\begin{aligned} V(G_1, G_2, t) = &-\tfrac{1}{4} g(N(t) - N_{\rm th})(G_1^2 + G_2^2) \\ &+ k_m E_m(G_1 \cos[\Phi(t)] + G_2 \sin[\Phi(t)]) \end{aligned} \tag{9}$$

with $\dot{\Phi} = \Delta\omega - \dot{\phi}$ and the time evolutions of the field components turn out to be

$$\frac{dG_i}{dt} = -\frac{\partial V(G_1, G_2, t)}{\partial G_i} \tag{10}$$

where $i = 1, 2$. Let's closely examine this last expression. Without optical injection, the extremal values of the potential correspond to a state with a vanishing intensity. Below threshold there is a potential minimum, showing that the laser is stably turned off because of a negative net gain. The stability is lost as time goes on and the carrier number approaches its threshold value, as identified with an increasingly small potential curvature. The transition occurs at the threshold time, when a maximum in the potential appears and the zero-intensity state becomes unstable. At this stage, any fluctuation in the photon population originated from spontaneous emission is able to trigger the laser switch-on. In this case, $\phi(t)$ is nothing else but the instantaneous emission frequency of the solitary laser [30]. It is evident from (7) that the linewidth enhancement factor α linearly couples the frequency to the carrier number.

The previously presented picture completely changes in the presence of optical injection. Stable states with a nonvanishing intensity can appear even below the threshold of the solitary laser. The time at which the instability occurs is shifted with respect to the threshold time of the solitary laser. The most remarkable result is, however, the rotation with time of the potential extrema in the complex (G_1, G_2) plane, with an angular frequency given by $\dot{\Phi} = \Delta\omega - \dot{\phi}$ [see (9)]. The injected field is able to compensate the α-driven frequency shift appreciated in the solitary laser and lock the slave laser emission to the master frequency. In this way, efficient frequency locking even under strong dynamic conditions is predicted. Nevertheless, we point to the fact that noise and phase matchings to the steady states can suppress this perfect locking in some extent.

In what follows, a more systematic study of the locked operation during the whole transient is presented, following the method in [14] in order to get a statistical description of the frequency dynamics. In single-mode lasers, in spite of their single-frequency behavior, a broader spectrum in comparison with the steady-state operation can be measured. This broadening is caused by the carrier-induced frequency shift through the linewidth enhancement factor α. In the gain-switching process, the definition of the field spectrum requires a given time window. The interest is focused on the transient build-up of intensity, so that the final steady state should be avoided when evaluating the spectrum. As a compromise, a time t_f after the first optical pulse of the solitary laser is considered for the time window of the FFT. The transient-averaged field spectrum is then defined as

$$S(w) = \frac{1}{C_s}\int_0^{t_f} \langle E(t)E^*(0)e^{-i\omega t}\rangle \, dt \tag{11}$$

where C_s is a normalization constant giving

$$\int_{-\infty}^{+\infty} |S(w)|^2 \, dw = 1. \tag{12}$$

The normalized field spectrum $S(w)$ allows the calculations of relevant parameters, as the mean frequency

$$\langle\nu\rangle = \int_{-\infty}^{+\infty} \frac{\omega}{2\pi}|S(w)|^2 \, dw \tag{13}$$

and the mean spectrum width

$$\langle\Delta\nu\rangle^2 = \int_{-\infty}^{+\infty} \left(\frac{\omega}{2\pi} - \langle\nu\rangle\right)^2 |S(w)|^2 \, dw. \tag{14}$$

$\langle\Delta\nu\rangle$ is the dynamic equivalent of the linewidth in steady-state operation. It is usually called *mean frequency chirp* or simply *chirp*. In our numerical simulations, the time window of the FFT is set to $t_f = 280$ ps and the averages are taken over 10^4 turn-on events. We say that the laser is dynamically locked when the slave mean frequency is the same as the master frequency and the chirp is significantly lower than the solitary laser chirp. Both criteria have to be met to elucidate the transient frequency locking. The range of detunings giving rise to transient locking define the *dynamical locking range*. Similar definitions of the dynamical

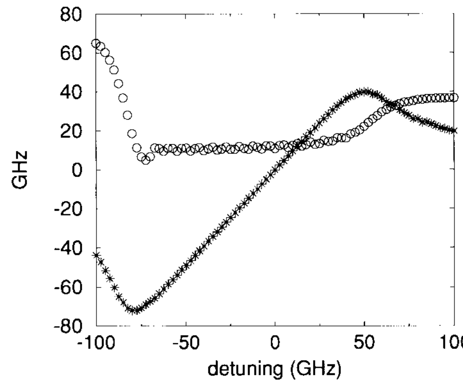

Fig. 3. Mean frequency (stars) and mean frequency chirp (circles) as a function of the frequency detuning.

locking range were reported in previous works [12] for current modulated laser diodes. Some results are presented in Fig. 3. Frequency locking is identified as a straight line in the mean frequency versus detuning curve. In the chirp versus detuning curve, a plateau is observed, with a chirp as low as 10 GHz (the solitary laser chirp value is around 40 GHz). In the present example, the dynamical locking range goes approximately from -70 to 30 GHz. As in steady-state operation, this locking range is asymmetric and favorable to negative detunings. The low carrier population, induced by a high intensity level, leads to a preferred emission at reduced frequencies. The reader will appreciate that the dynamical locking range is broader than the stable locking range (about 25 GHz). This remarkable fact is a result of the whole turn-on process, which include stages of low intensity and thus allows wide locking regimes [see (6)].

III. Jitter and Dynamical Locking

In this section, the turn-on time statistics is analyzed in terms of the results obtained in Section II on the frequency dynamics. In the solitary laser, the turn-on is triggered by spontaneous emission random events, which lead to an important dispersion of turn-on times and to a broadening of the corresponding probability density function (PDF). The variance in the PDF of turn-on times can be considerably reduced when the turn-on process is triggered by a deterministic seed instead of the random noise. This reduction of jitter in the presence of a weak optical field was analytically studied in [5]. The results were reported as a function of the frequency detuning between the master and the slave lasers. For large detunings, both the mean turn-on time and the time jitter turned out to be the same as for the solitary laser, while small values of the detuning parameter led to reduced values of that quantities. The lower values corresponded to a master laser completely tuned to the slave emission frequency, and symmetrical detunings around the zero value gave the same results for the PDF of turn-on times. Experimental verification of this behavior as a function of the frequency detuning has been reported in agreement with the theoretical results [31], [32]. Additional experimental observations were a linear increase in the SMSR and pulse broadening, specially noticeable at high injection levels.

Under strong injection conditions the analytical approximations in [5] lose their validity. An alternative method was

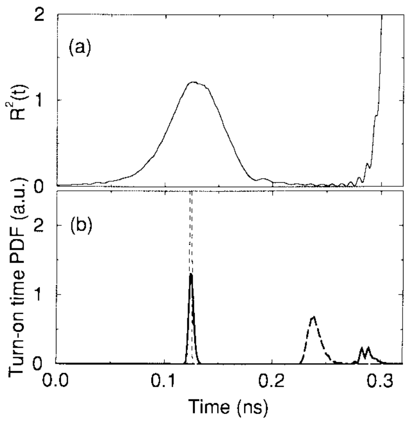

Fig. 4. (a) Time trace of the normalized intensity after the gain-switching using a detuning of −70 GHz, outside the locking range. (b) PDF of turn-on times for the solitary laser (long dashed line), and optically injected lasers with detunings of −60 GHz (short dashed line) and −70 GHz (solid line).

developed in [33] for lasers with a simpler dynamics (class-A), but the more complex dynamics present in semiconductor lasers prevents its direct implementation. Nonlinear effects arise in the turn-on of the optically injected slave laser when large frequency detunings are forced. A typical example is depicted in Fig. 4(a), where a relatively high-peak-power prepulse appears before the final optical pulse has developed. A detuning of −70 GHz has been used just outside the negative side of the locking range, and the nonlinear effects are enhanced accordingly. As we mentioned in Section II, if a detuning value inside the stable locking range is selected, a smooth transient occurs and prepulses are avoided.

The formation of these prepulses can be a source of large variances in the PDF of turn-on times if the reference intensity is chosen to lie near the prepulse intensity peak. This effect is illustrated in Fig. 4(b), where the PDF is shown to be double-peaked. On the contrary, choices of the frequency detuning inside the stable locking range give rise to a lower time jitter than for the solitary laser. The long tail in the PDF of turn-on times typical of semiconductor lasers without optical injection, the consequence of a turn-on triggered by noise, completely disappear when a master laser is used to seed the slave. Strong optical injection forces the laser to reach the reference intensity before the carrier number has crossed its threshold value, so that the performance of the slave laser is similar to that of a semiconductor optical amplifier.

Nonlinear effects can also be appreciated at lower values of the injection level $(I_L = 0.001)$. The results concerning the mean turn-on time and time jitter are in Fig. 5 as a function of the frequency detuning, at different reference intensities. The modified rate equations have been numerically solved and averaged over 10^4 turn-on events. The frequency detuning that gives a minimum in the mean turn-on time curve is generally shifted to negative detunings. Considerable reductions in the time jitter values, up to 80% those of the solitary laser, can be achieved by selecting positive detunings.

The choice of several reference intensities gives significantly different turn-on time PDF's. This is a known effect also present in class-A lasers subject to strong light injection [33] and is a consequence of the nonexponential growth of the

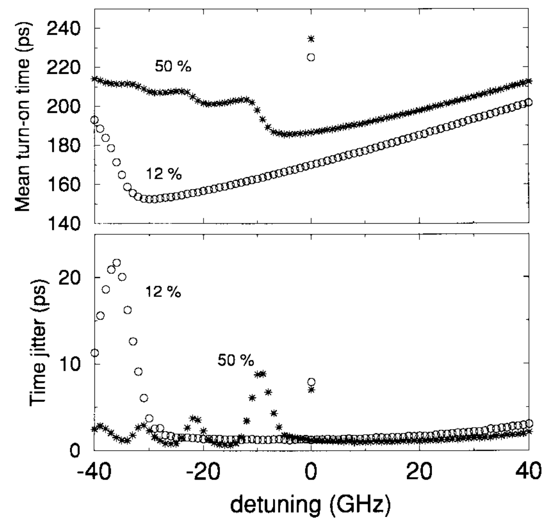

Fig. 5. Mean turn-on time (above) and time jitter (below) at two reference intensities $(I_L = 0.001)$. The percentages refer to the steady-state intensity of the solitary laser. Separate points at zero detuning correspond to the values of the solitary slave laser.

light intensity during the laser turn-on. Peaks in the time jitter appear at selected detunings. In these turn-on events, the light intensity crosses its reference value with an almost vanishing time slope, leading to a higher dispersion of turn-on times driven by noise-induced fluctuations.

IV. Conclusion

The frequency dynamics of optically injected single-mode semiconductor lasers has been studied during the laser turn-on. A transient potential for the components of the optical field has been introduced which qualitatively describe the transient locking process. A simple linear stability analysis provides relevant information to characterize the relaxation of the gain-switched laser to a steady-state. Transient-locked operation is appreciated inside a dynamical locking range of detunings where the mean frequency of the slave laser is that of the master laser. The mean frequency chirp can be as low as a 75% its numerical value in the free-running slave laser. This dynamical locking range is broader than the stable locking range. In addition, relaxation oscillations in the laser turn-on can be selectively suppressed.

The optically injected laser operates as a low time jitter source. A 80% reduction in the numerical value of jitter can be achieved if carefully selected values of frequency detuning and reference level are used. In order to obtain the above-mentioned performance, the master laser must be biased above threshold in CW operation.

These conclusions are of practical importance when injection-locked lasers are used as light sources in intensity-modulated communication systems, where the direct detection requires a low time jitter.

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