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Chaotic Dynamics of Semiconductor Lasers for Secure Optical Communication

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1. Introduction

Strong optical injection locking of semiconductor lasers can give an output of chaotic behavior which makes them an attractive transmitter for high speed secure optical communication. Data secure and high transmission rates are the most demanded issues in communication network. Optical injection, chaos synchronization of semiconductor lasers had been studied theoretically and experimentally for a decade [1,2], due their durability and very vast progressing technology. The effects of optical injection locking mainly have two aspects: one is to improve the characteristics of the slave and the other is to synchronize the master and the slave. In the former, the locking is able to improve the properties of the slave laser such as a single wavelength emission, high side mode suppression ratio (SMSR), and narrow linewidth. While in the latter, the synchronization of the master and slave in a wavelength, phase and chaos state had led the injection locking to broad applications in the coherent communications. Other improvements of the semiconductor laser by optical injection locking had been reported, these improvements include, increasing modulation bandwidth and reducing chirp [3,4], a high gain of 20-dB with small signal modulation below resonance frequency [5]. Bistability had been reported when a two color Fabry-Perot laser was subjected to optical injection in both modes and could be the basis for an all optical memory element with switching times below 500 ps [6]. The generalized synchronization of chaos based on phenomenon of injection locking characteristics of semiconductor laser and signal amplification in nonlinear systems is an application for secure data transmissions and communications [6,8].

In order to determine in which conditions (optical power, wavelength of the injected signal) the Fabry-Perot laser diode (FP-LD) is locked, it is essential to map the operating regimes on a chart defined by the two parameters, injected power and detuning which corresponds to the difference between the wavelengths of the injected signal and the one of a specific mode

of FP-LD that is submitted to optical injection, it is so-called injection map, which is well known for a single-mode laser [9,10].

The maximum available modulation frequency of the laser is in the vicinity of the relaxation oscillation frequency. Optical injection can enhance the relaxation oscillation frequency of the slave laser, and hence the bandwidth. So we would expect higher-speed transmitter for optical communication. On the other hand, a laser with controlled chaos could be obtained. The bandwidth-enhancement of the semiconductor laser by optical injection as well as a chaotic transmitter is the major objective.

This chapter will focus on the improvements of semiconductor lasers by the optical injection locking regimes and its applications for secure optical communication networks. The injection locked semiconductor laser, utilizing such applications, noise properties are of vital importance especially, the relative intensity noise (RIN). The aspects of noise influence on the dynamical operation of the laser with injection locking will be emphasized. The deployment of such a high bandwidth and chaotic carrier transmitter will be feasible without extra protection afforded by other means.

2. Basic concepts of injection locking

Rate equations of the injection locking are given below. Optical injection eventually introduces an extra degree of freedom, and due to the low facet reflectivity of the semiconductor, and perturbation from outside will alter the gain of the laser and may induce nonlinear dynamics. As a point of view, this nonlinear dynamics may be a candidate to chaotic system. The illustration of optical injection is shown in figure 1. A master laser, optically isolated from the slave laser, will inject its single-frequency output into the active region of the slave laser. This optical injection has a variety of effects on the operating characteristics of the slave laser that will be discussed here.



Figure 1. Schematic of optical injection.

The optical injection when it has to be in the locking range, the master and slave lasers have to be precisely identical and have the same oscillation frequencies. The frequency detuning must be within several GHz [11]. Once the appropriate conditions of frequency detuning and the optical injection strength have been achieved, a synchronization state of the two lasers is reached. Optical injection locking will be reached under these conditions, i.e., when the slave laser is forced to oscillate at the injected signal frequency from the master laser and is locked to its phase.

The operating principles of semiconductor laser are similar to those of any other laser system, except the linewidth enhancement factor, which arises because the real refractive

index in the active laser medium varies with changing carrier density. The injected carrier-induced refractive index change is associated with the change in the gain, the differential gain. This factor plays an important role in the optical injection regimes of semiconductor lasers. Strong optical injection is usually used in the rate equations so that the impact of the noise and the spontaneous emission rate coupled to the lasing mode are negligible [12].

The rate equations of strong optical injection locking are [13]:

$$\frac{dP(t)}{dt} = \left\{ G(N) - \frac{1}{\tau_p} \right\} P(t) + 2\tau_{in} \sqrt{P(t)P_{inj}} \cos(\phi_i(t) - \phi(t)) \quad (1)$$

$$\frac{d\phi(t)}{dt} = \omega_o(N) - \omega_{inj} - \frac{\alpha}{2} \left(G(N) - \frac{1}{\tau_p} \right) + \tau_{in} \sqrt{\frac{P_{inj}}{P(t)}} \sin(\phi_i(t) - \phi(t)) \quad (2)$$

$$\frac{dN(t)}{dt} = J - \frac{N(t)}{\tau_{sp}} - G(N)P(t) \quad (3)$$

where $\omega_o(N)$ is the angular optical frequency (carrier dependent) of the slave laser, ω_{inj} is of the injected signal, P_{inj} is the injected signal power, $G(N)$ is the carrier dependent gain, τ_{sp} is the carrier lifetime, α is the linewidth enhancement factor, J is the injection current, and $(\phi_i(t) - \phi(t))$ is the phase difference between the injected and the free-running laser fields.

The frequency detuning between the master and slave lasers is defined as $2\pi\Delta f = (\omega_{inj} - \omega_o)$

The injection ratio is defined as the ratio of optical powers of the master and free-running slave laser inside the slave laser cavity $\frac{P_{inj}}{P}$.

The static state of the slave laser can be found from solving the steady solutions in the above equations by setting the time derivatives to zero and this will lead to the state of locking frequency within the master-slave frequency detuning. This static locking range is:

$$-\frac{1}{2\pi\tau_{in}} \sqrt{\frac{P_{inj}}{P}} \sqrt{1 + \alpha^2} < \Delta f < \frac{1}{2\pi\tau_{in}} \sqrt{\frac{P_{inj}}{P}} \quad (4)$$

Equation (4) gives the locking range of the slave laser and is increased with the injection ratio and is also inversely proportional to the slave laser cavity round-trip time τ_{in} . The locking frequencies depend strongly on the linewidth enhancement factor. Figure 2 shows the locking range of the slave laser. Asymmetric locking range is obvious from the graph. This can be interpreted as; the locking properties depend on the gain profile of the slave laser supporting many longitudinal modes, and when injection occurs at frequency close to the side mode instead of the free-running dominant mode of the slave laser. Now, gain is carrier density dependent, and refractive index also depends on carrier density in the active region which results in this asymmetry in the locking curve.

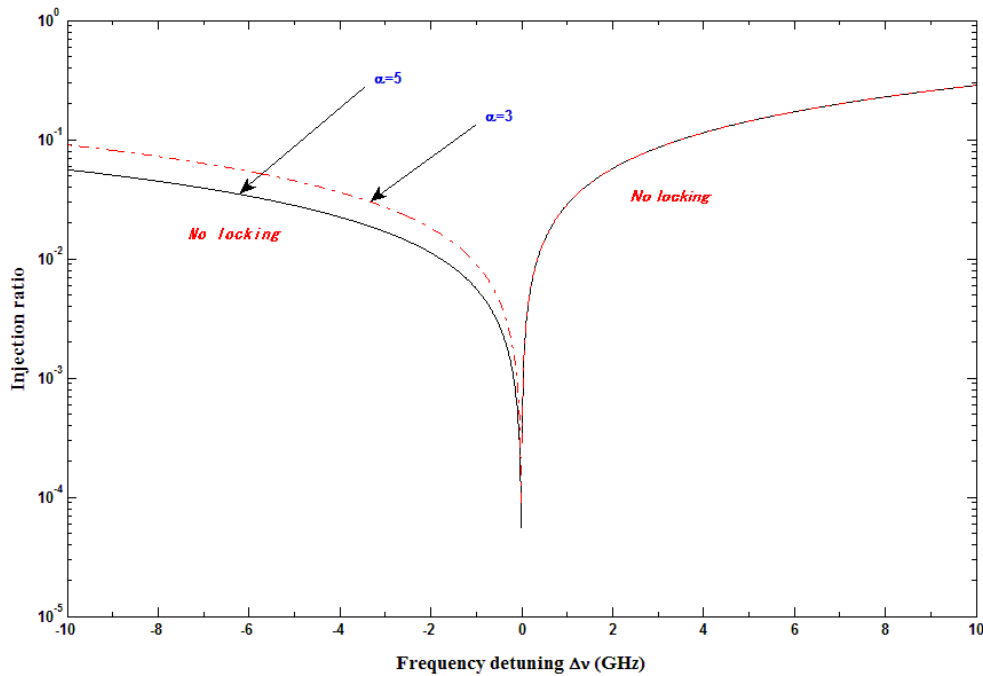


Figure 2. Locking characteristics of the slave laser showing the stable (locking) and unlocking regions for two values of linewidth enhancement factor.

3. Bandwidth enhancement by injection locking

The bandwidth of semiconductor laser is limited by the relaxation oscillation frequency. When a small-signal transient response is applied to rate equations of semiconductor laser as a step increment in the injection current and solved analytically, we will observe that the photon and electron numbers approach asymptotically to a new steady-state after an evanescent oscillation frequency (called relaxation) and with high damping factor. The relaxation oscillation frequency depends on the laser structure and the operation conditions. Any expression of the relaxation oscillation will show that it depends on the differential gain and the volume density of the injection current, as well as the photon lifetime. We will show the power dependence of the relaxation oscillations and the dependence on differential gain, while neglecting the gain saturation (intensity dependence) for simplicity in this monograph.

The frequency response of the intensity modulation of the laser describes the transfer of the modulation from current to optical power output. Figure 3 shows the frequency response of the semiconductor laser with and without strong optical injection. The response is flat in the low-frequency region and with a peak in the vicinity of the relaxation oscillation frequency. The response shows a rapid decrease for frequencies above the relaxation frequency. This means that the maximum frequency response of the laser when directly modulated is limited by the relaxation oscillation frequency.

Strong optical injection, as shown in figure 3, will shift the relaxation oscillation (RO) frequency (cutoff frequency) of the semiconductor to higher values depending on the

operating conditions of the laser. This shift due to optical injection is effective for enhancing the modulation characteristics of semiconductor lasers. The shift is more obvious when plotted as a function of injection strength, as in figure 4. The laser was biased above threshold at $1.6 J_{th}$ and frequency detuning was of -7.962 GHz. The cutoff frequency can be said to be proportional to the injection strength, and hence modulation response of the laser can be enhanced due to strong optical injection [16].

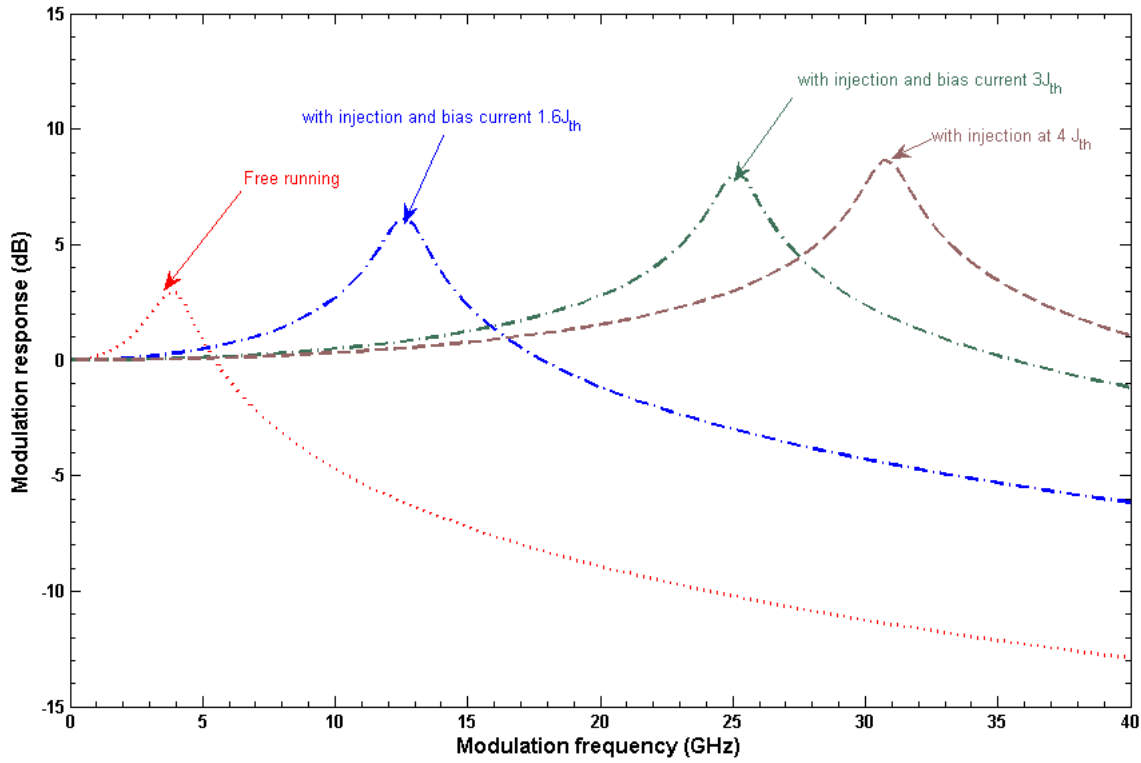


Figure 3. Modulation response of free-running semiconductor laser and with injection-locked laser at different bias currents . Frequency detuning was -7.962 GHz.

Modulation response of the semiconductor laser as being dependent on both the operating conditions and optical injection is illustrated in figure 5. As can be seen from the graph, the shift of RO to a higher frequencies with increasing the injection strength. The strength of RO resonance plays a crucial role in harmonic distortions. It follows that the lasers of having a high RO would result in large harmonic distortions. The resonance peaks can be explained as a result of frequency domain manifestation of the time domain of the optical field of the laser. The fall-off in the modulation response is due to a combination of the intrinsic laser response and the effects due to parasitic elements in the device.

The theory of modulation characteristics of strongly injected semiconductor laser will be stated. Modulation of semiconductor laser had been studied since the invention of this laser and the approach was using the rate equation with noise free and with periodic injection current. Steady-state solutions of the rate equations can be found for constant injection rate. Small fluctuations (first-order perturbations) terms were then added to steady-state as given below. Modulation response when evaluated can be a treated as a direct measure of the rate

at which information can be transmitted (primarily baseband). Modulation bandwidth at any biasing current or optical power is an important for optical communication systems.

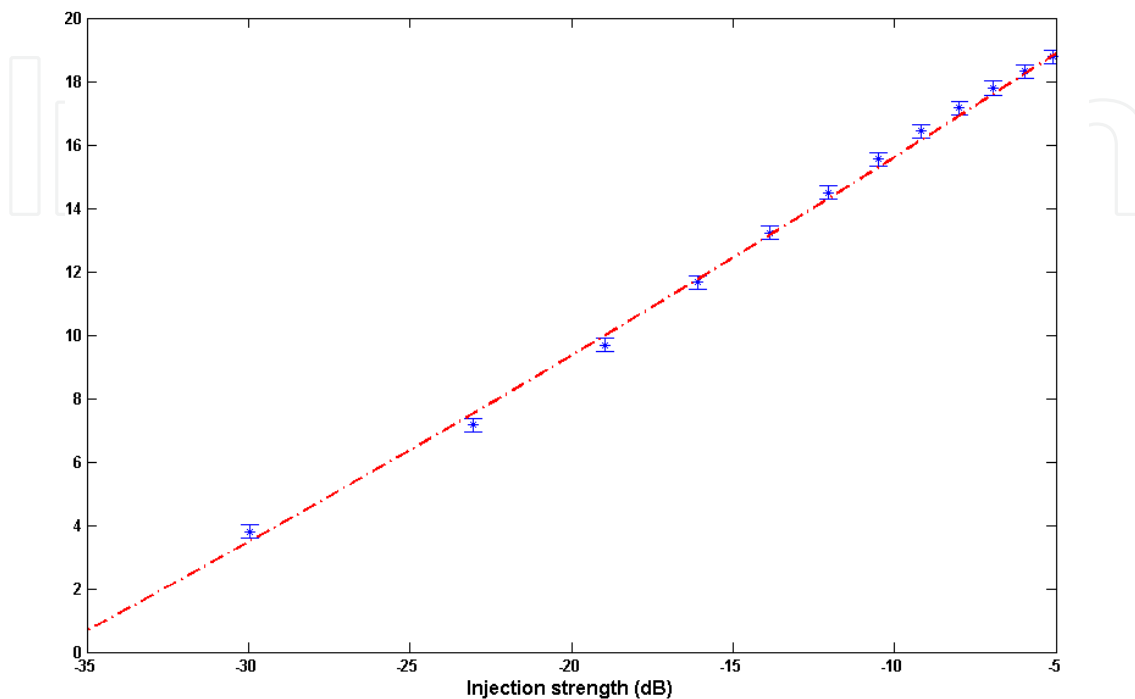


Figure 4. Cutoff frequency dependence on the injection strength of the injection locked semiconductor laser. The solid line is the best fit of the numerical results.

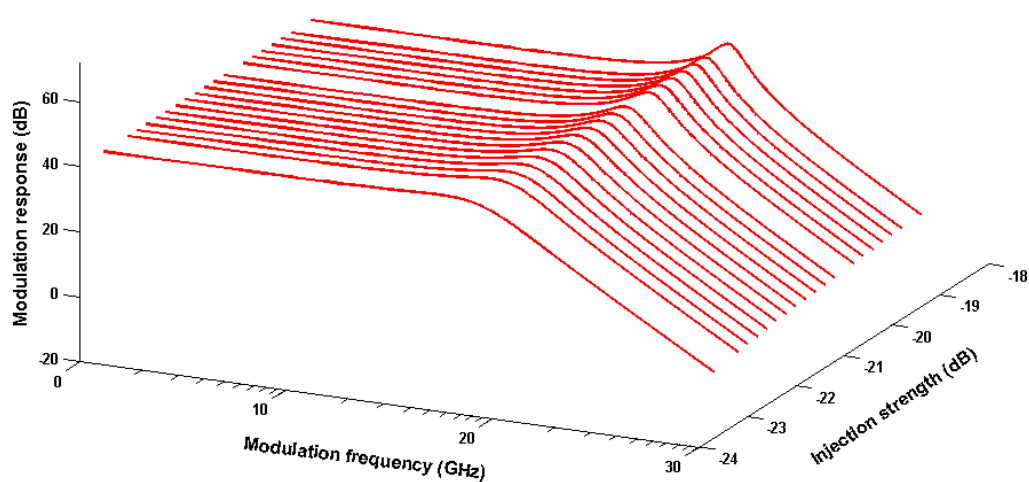


Figure 5. Modulation response of injection locked semiconductor laser as a function of injection strength and modulation frequency. The slave laser was detuned at -7.962 GHz

Single mode rate equations of free-running laser can be regarded as either as a model for purely single-mode operation or as an approximate model for the dynamics of the total photon number. The carrier number N and photon number P can be written as:

$$\frac{dN(t)}{dt} = \text{injected carrier} - \text{spont. emission} - \text{stimulated emission}$$

$$\frac{dP(t)}{dt} = (\text{Gain} - \text{loss}) + \text{spont. term coupled to lasing mode}$$

Now, the two above equations will read as:

$$\frac{dN(t)}{dt} = J(t) - \frac{N}{\tau_{sp}} - G(N, P)P \quad (5)$$

$$\frac{dP(t)}{dt} = \left(G(N, P) - \frac{1}{\tau_p} \right) P + \beta \frac{N}{\tau_{sp}} \quad (6)$$

where the gain $G(N, P)$ can be expressed, assuming linear gain dependence on the carriers, as:

$$G(N, P) = \frac{G_o + G_N(N - N_o)}{1 + \varepsilon P} \quad (7)$$

where G_o is the linear gain, $G_N = \left(\frac{\partial G}{\partial N} \right)_{N=N_o}$ is the differential gain at N_o , and the factor

$1 + \varepsilon P$ accounts for nonlinear gain saturation. The gain saturation becomes important at high photon numbers. The factor ε is called the gain suppression coefficient.

β is the fraction of spontaneous emission coupled to the lasing mode. The steady-state equations can be found by setting $\frac{d}{dt}$ equal to zero.

First-order perturbation is written as:

$$N = \bar{N} + \delta N, \quad |\delta N| \ll \bar{N} \quad (8)$$

$$P = \bar{P} + \delta P, \quad |\delta P| \ll \bar{P} \quad (9)$$

Assuming the gain is a function of the carriers N and photons P , and can be approximated by Taylor expansion around the bias as:

$$G(N, P) = G_o + G_N \delta N + G_P \delta P \quad (10)$$

where G_N is the differential gain, and G_P is the saturation gain.

Substituting Eqs.(8), (9), and (10) into the rate equations (5) & (6) and omitting the small quantities of the second and higher order terms, a differential equations result as:

$$\frac{d}{dt}\delta N = -\left(G_0 + G_p \bar{P}\right)\delta P - \left(G_N \bar{P} + \frac{1}{\tau_p}\right)\delta N \quad (11)$$

$$\frac{d}{dt}\delta P = -\left(\frac{\beta \bar{N}}{\tau_p \bar{P}} - G_p \bar{P}\right)\delta P + \left(G_N \bar{P} + \frac{\beta}{\tau_p}\right)\delta N \quad (12)$$

Eliminating δN from the above equations we get an equation for the modulation in the photon number as:

$$\frac{d^2}{dt^2}\delta P + 2\Gamma \frac{d}{dt}\delta P + \omega_R^2 \delta P = G_N \bar{P} J \quad (13)$$

where the Γ is the damping factor and ω_R is the resonance frequency given as:

$$\omega_R^2 \approx \frac{G_N}{\tau_p} P \quad (14)$$

This resonance frequency is for free-running semiconductor laser, i.e., without optical injection. The modulation response can be found from Eqs. (7) and (8) by assuming an exponential solution for both δP and δN as $(\exp(i\omega t))$, with ω is the modulation frequency. The response is written as:

$$|H(\omega)| = \frac{\omega_R^2}{\left[(\omega_R^2 - \omega^2)^2 + 4\Gamma^2 \omega^2\right]^{1/2}} \quad (15)$$

Now, the resonance frequency and frequency response of semiconductor laser with strong optical injection will be presented.

To estimate the modulation response of optically injected semiconductor laser, the rate equations have to be solved again with strong optical injection, a resonance frequency with optical injection formula can be derived as [16]:

$$\omega_{R_{inj}}^2 \approx \omega_R^2 + \left(\frac{1}{\tau_{in}}\right)^2 \left(\frac{P_{inj}}{P}\right) \sin^2 \theta \quad (16)$$

where $\omega_{R_{inj}}$ is the resonance frequency with optical injection, and θ is the is phase difference between the slave laser and the master laser.

With given theoretical analysis above, the transfer function for optically injected laser was obtained and plotted in the above figures. The frequency response of the slave laser with

the highest enhanced resonance frequency can be achieved by optical injection and this found to be more than five times increased as compared to experimental results [17]. The bandwidth accordingly will be increased due to this increase in the frequency response of the slave laser. This enhancement in the bandwidth is dependent on the optical injection parameters and when the slave laser is operated in the stable locking region. Modulation enhancements characteristics of strongly injected slave laser are mainly due to the shift in the resonance frequency have to be understudied thoroughly. The theory of semiconductor laser, as a matter of fact, always simplify the arguments and make assumptions in order to make the an analytical solutions available. Numerical simulations for the laser nowadays can be found in easy used packages in the market. We have analyzed the response of semiconductor laser based on the rate equations and solved numerically. The change in the photon number due to optical injection is not the only source of increasing bandwidth but also the competition between the frequency of dominant mode of the slave laser and the frequency shift induced by strong optical injection. This bandwidth enhanced of slave laser is ultimately a candidate source for optical communications, not due to its enhanced bandwidth but also to its chaotic output as secure transmitter.

4. Chaos by injection locking

The chaotic behavior of the slave laser under strong optical injection will be given in terms of the important parameters of locking regimes which are the frequency detuning and injection ratio. The optical chaos have been observed, as we will see later, and developed through period-doubling, i.e., route-to-chaos. The analysis will show that the chaotic behavior is dependent on the injection strength and frequency detuning. The bandwidth of semiconductor laser will be verified and enhanced by optical injection. The bandwidth of such chaotic laser transmitter is enhanced roughly three times by optical injection compared with the bandwidth when there is no optical injection [14]. Chaotic dynamics and period doubling were observed experimentally in the VCSELs lately [15], in addition to edge emitting lasers.

The differential rate equations (1)-(3) were subjected to numerical solutions using fourth-order Runge-Kutta algorithm with strong optical injection and the chaotic output of the slave laser is shown in figure 6. This output was originated from period-doubling route-to-chaos. This chaotic behavior is optical injection locking parameters dependent, i.e., injection strength, and frequency detuning. This is illustrated in the following diagram.

Figure 7 shows the chaotic dynamics of the slave laser under strong optical injection, with the same parameters as in the previous figure. The chaos is a phenomenon of the generic properties of the extra degree of freedom introduced by the optical injection in rate equations. The scenario of period doubling route-to-chaos was initiated by excitability of the chaotic attractor. This attractor triggers the system in deterministic sequence reaching the chaos. This observation of bifurcation in the laser power output (the response system)

related to the stimulus (the drive) when coupled, synchronization is established. The ability of such synchronizing system offers the opportunity as a chaotic transmitter in optical communications. Any further increase in the injection strength will eventually be an extreme output of chaotic dynamics.

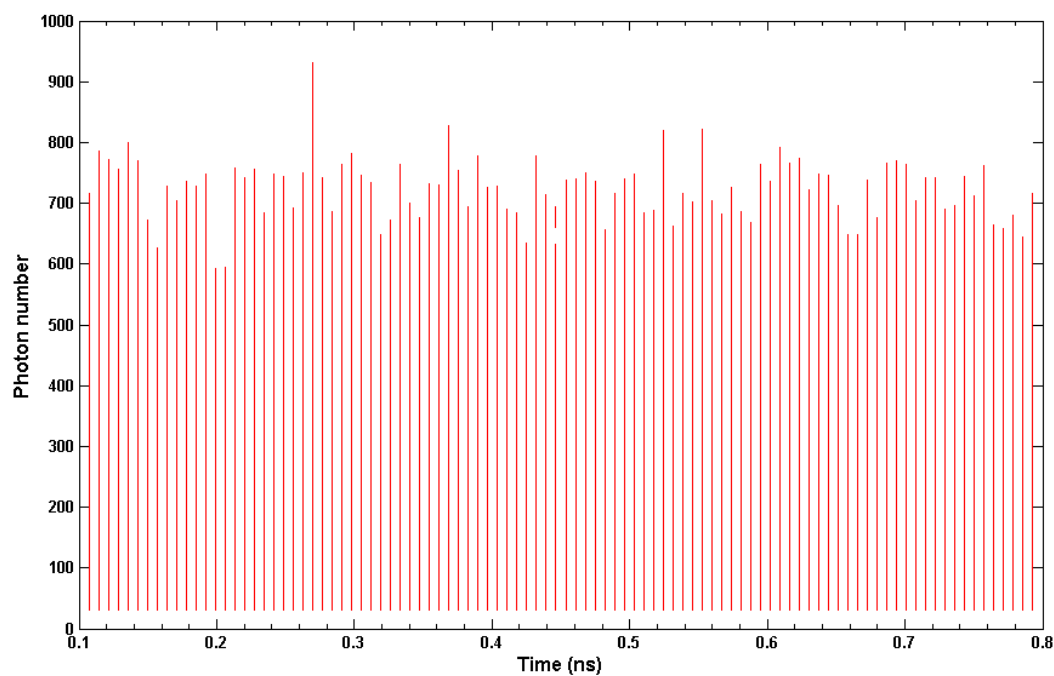


Figure 6. Time series of chaotic photon number of the slave laser at detuning (-7.962 GHz), linewidth enhancement factor ($\alpha=3$), and injection strength (-22 dB).

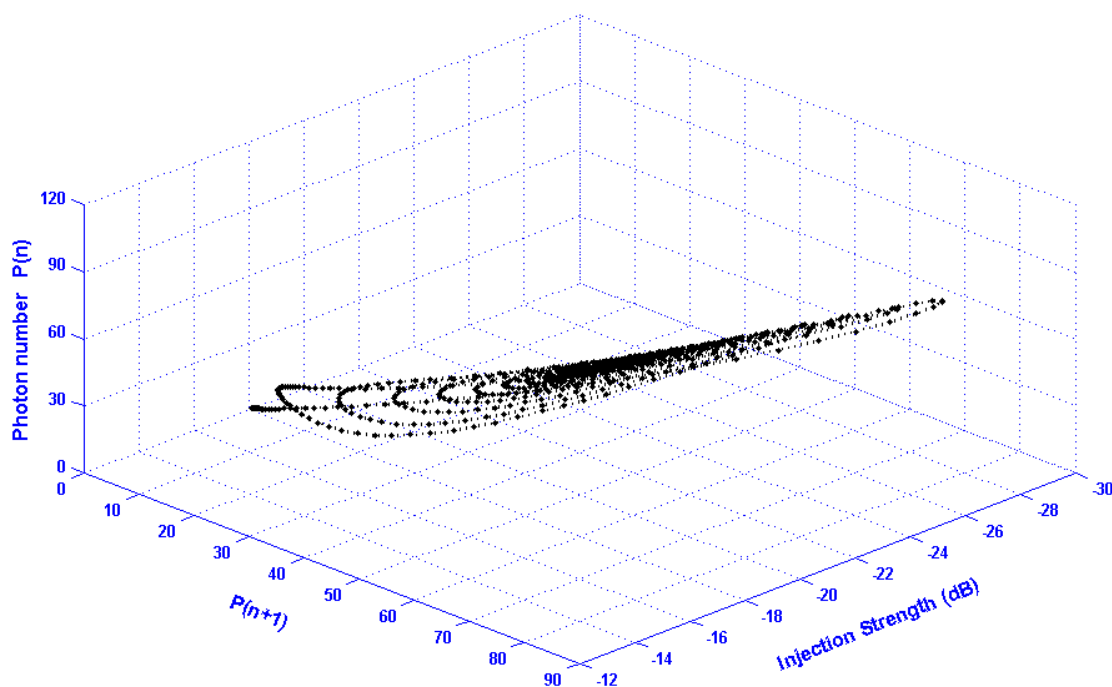


Figure 7. Phase portraits of chaotic output of the slave laser as a function of injection strength.

Injection strength plays a great role in the chaotic behavior of the slave laser through period-doubling route-to-chaos. This chaotic dynamics, when explained by nonlinear bifurcation theory, is established as the relaxation oscillations (RO) become undamped via Hopf bifurcations. This bifurcations originating from the undamped RO for Fabry-Perot lasers, while the enhanced RO damping of quantum dot lasers results in the removal of these chaotic regions [18]. Period doubling in the above figure has predicted the dependence on the injection parameters. Recently, the origin of such periodicity was explained as the beating between two wavelengths, namely, the injected wavelength and the cavity resonance wavelength [19].

The above theoretical results and predictions of chaotic dynamics agree well with the experiments on a qualitative level [20]. Many theoretical and experimental studies revealed the necessity in viewing the dynamics from a broad perspective [21-25].

5. Frequency chirping

Frequency chirping in semiconductor lasers can be suppressed by strong optical injection and hopefully this laser could have better modulation characteristics than free-running laser. As the carrier density increases, resulting from the current injection into the active region will change the refractive index of the region and generate the frequency chirping. This phenomenon can have a considerable limitations on the modulation of semiconductor laser at high bit rate. An important figure-of-merit for chirp is the chirp-to -power ratio (CPR), which is defined as the ratio of lasing frequency deviation to power deviation [26], and is defined as [27]:

$$CPR = \frac{1}{2\pi H(\omega)} \left| \frac{d\theta}{dt} \right| \cong \frac{\omega}{2\pi} \alpha \sqrt{\frac{\omega^2 + (U - V/\alpha)^2}{\omega^2 + (U + V\alpha)^2}} \quad (17)$$

Where

$$U = \frac{1}{\tau_{in}} \left| \frac{P_{inj}}{P} \right| \cos \phi_L \quad (18)$$

$$V = \frac{1}{\tau_{in}} \left| \frac{P_{inj}}{P} \right| \sin \phi_L \quad (19)$$

with ϕ_L is the phase of the intracavity laser field relative to the injection field. This equation provides with the fact that CPR is dependent entirely on the modulation response and the phase. The stated above equations of the injection-locked semiconductor explains the chirp suppression or reduction and its dependence on injection parameters, with this arguments it can optimize the performance of the laser.

Chirp-to-power ratio of injection locked semiconductor at locking range of stable operation and as a function of modulated frequency is shown in figure 8, three different injection strength were taken and for two values of linewidth enhancement factor (α). This factor has influenced the frequency chirping characteristics of the laser under direct current

modulation, since this factor plays great role in the refractive change with injected carriers. This influence can be realized from the relation stated in Eq. (17).

The frequency chirping when considered in the output power of the slave laser, the detuning was assumed to be constant, but it is dependent on the optical input power, hence the CPR has to take into account this dependent. Also, the laser cavity frequency $\omega_o(N)$, is carrier dependent. So the effects of variations in frequency detuning, and laser cavity frequency have to be included in the CPR.

Frequency chirping had been decreased with increasing injection strength and with lowered value of linewidth enhancement factor. The simulation reveals the dramatic influence of injection locking on the frequency chirping characteristics. Dynamical properties have been found, experimentally lately [28], to depend on the injection strength through the evolution of the optical and electrical spectral distribution. Substantial reduction in frequency chirping was observed in the direct modulation injection-locked laser, and this reduction was much more pronounced at low modulation frequency in experiment [29].

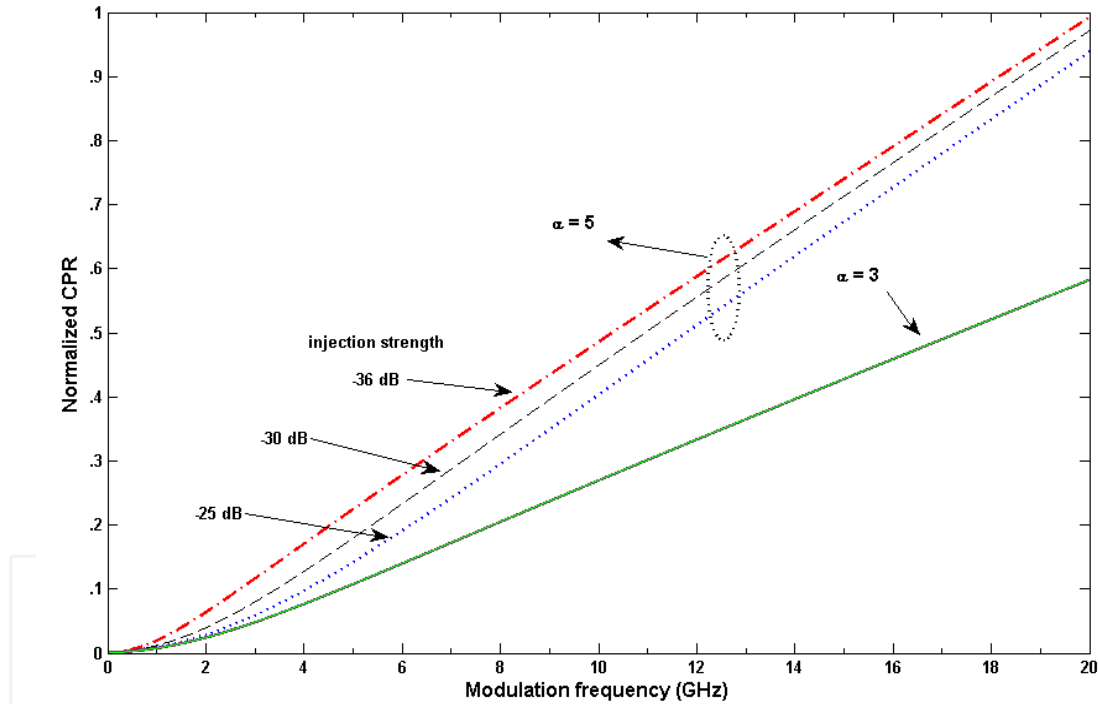


Figure 8. Frequency chirping characteristics of injection locked semiconductor showing its dependence on injection strength and linewidth enhancement factor.

6. Relative intensity noise

The relative intensity noise (RIN), intrinsic noise inherited in the device due to spontaneous emission noise, is of major importance for optical communication systems, whereas low RIN is needed to achieve high signal-to-noise ratio (SNR). It is observed that RIN shows a peak near the relaxation oscillation frequency and this would be related to the bandwidth of the laser [30]. If the injection locked slave laser could show a suppression in the spectrum of the

RIN near the resonance and more damping due to the increase of injection strength, more enhancement in bandwidth will be realized. Experimentally has verified the enhancement bandwidth of sampled grating distributed Bragg reflector laser (SG-DBR), lower of intensity noise and higher resonance frequency due to strong optical injection [31]. The dependence of RIN on both bias current and detuning have been studied [32].

The fluctuations in the power spectrum $\Theta_p(\omega)$ can be defined as:

$$\Theta_p(\omega) = \langle |\Delta \tilde{P}(\omega)|^2 \rangle \quad (20)$$

This, by normalization with $(\bar{P})^2$, would give the relative intensity noise spectrum:

$$RIN = \frac{\Theta_p(\omega)}{(\bar{P})^2} \quad (21)$$

The relative intensity noise spectrum, RIN, for free-running laser and with strong optical injection is shown in figure 9. With injection locking, the noise peak was shifted to a higher frequency.

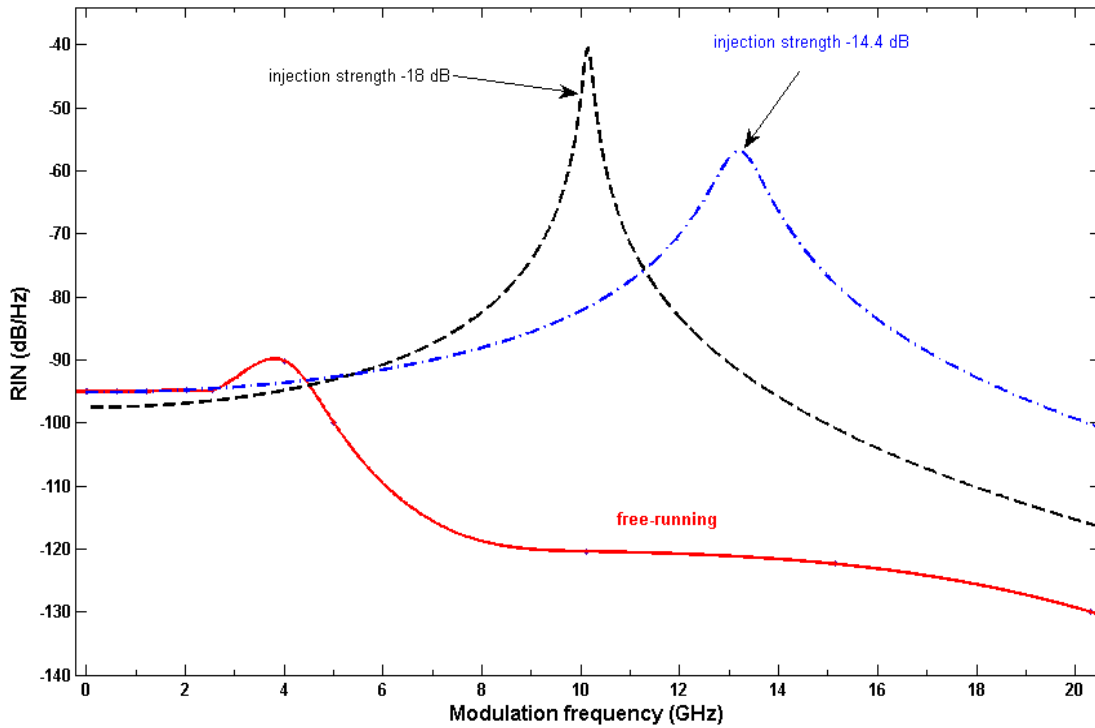


Figure 9. Relative intensity noise spectrum of free-running semiconductor laser and injection-locked for two different injection strengths.

When injection locking was increased from -18 dB to -14.4 dB, the noise peak was shifted from 10 GHz to at least 13 GHz. Hence, injection locking can enhance the bandwidth of optical communication systems. Also, a reduction 14 dB/Hz in RIN had occurred when injection strength was increased at the mentioned values above.

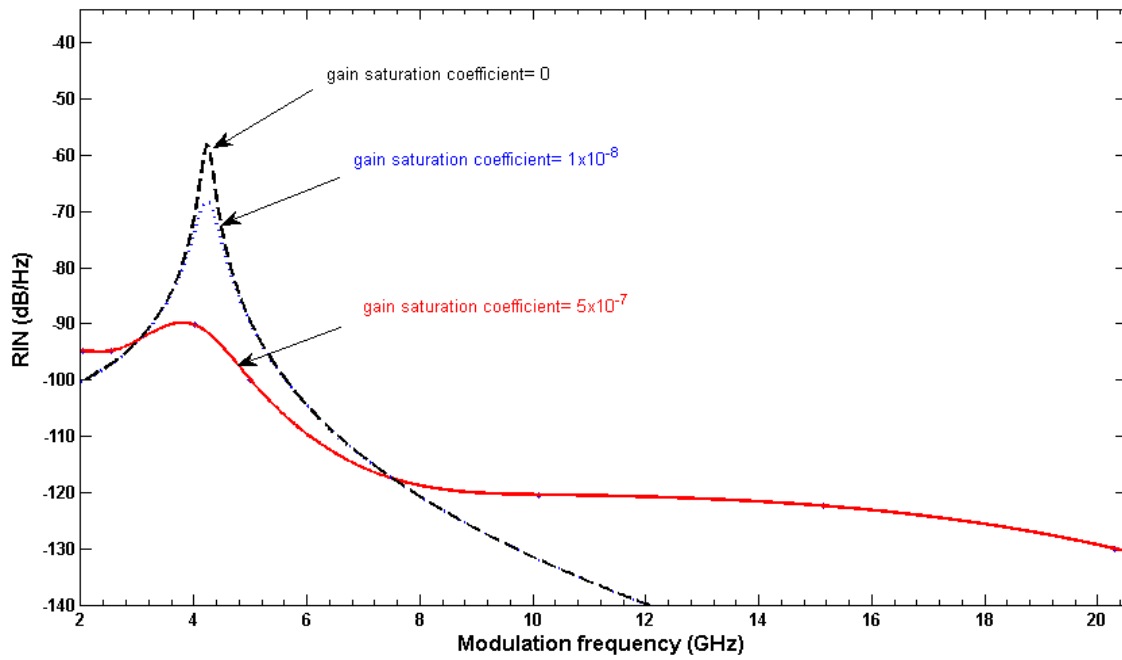


Figure 10. The influence of gain saturation coefficient on the RIN spectrum of semiconductor laser.

To illustrate how gain saturation coefficient can alter the RIN spectrum of the slave laser, figure 10 shows this effect. When the gain saturation coefficient was increased, it is noticed that the RIN spectrum at the resonance peak was suppressed and this can be interpreted as damping due to the gain saturation coefficient. We would expect that the strong injection locking phenomenon may give extra damping of RIN peak in addition to the gain saturation coefficient. This has to be verified experimentally. So, both the methods will exhibit large significant RIN suppression, and meet the demands for higher bit rates and longer optical communication network.

7. Conclusions

This chapter, as I intend to, gave a brief description and theory of strong optical injection and its influence on the characteristics of the slave laser. Secure optical communications can be verified by such operation of the laser. Modulation bandwidth enhancement has been found by numerical simulation of the rate equations. The enhancement was found to be dependent on the injection parameters, frequency detuning and injection strength. Period doubling and relaxation oscillation frequency are the physical mechanisms of bandwidth enhancement by injection locking. Substantial reduction in frequency chirping, and a suppression of 14 dB/Hz in the RIN were observed in the direct modulation injection-locked laser. These characteristics of such a laser are the demands for high bit rate and longer optical communication network. Chaotic dynamics of the slave laser is the challenging candidate for secure optical systems.

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