Turk J Phys
35 (2011) , 153 – 160.

doi:10.3906/fiz-1008-22

Strong optical injection locked semiconductor laser for high bit rate chaotic optical communications

Muzahim Ibrahim AZAWE and Ragaad Habib SAIED
Department of Physics, College of Education, Mosul University, Mosul-IRAQ
e-mail: Muzahim_935@yahoo.com

Received: 30.08.2010

Abstract

We present in this article how strong optical injection can produce chaotic dynamics in the output of the semiconductor laser that is preferable for perfect encrypted optical communication networks. Significant increase in the relaxation resonance frequency was found implying higher degree of enhancement in modulation bandwidth. Numerical investigations under the condition of strong optical injection locking of the slave laser shows that instabilities in the photon number was observed and had settled down after a time of in the order of carrier lifetime. The model presented can be used to extract the characteristic parameters of the injection locking for detuning of the system. Optimum value of nonlinear gain and linewidth enhancement factor were found to have an impact on the chaotic dynamics of the slave laser. A layout for optical communication network using Optisystem 7.0 simulation software with slave laser as a transmitter undergoing strong optical injection locking will be illustrated for high bit rate. Chaos at high modulation frequency in the output power of the slave had been established in the simulations predicting the validity of the model for secure optical communications.

Key Words: Injection locking, laser diode, optical communications, chaos

1. Introduction

Strong optical injection locking of semiconductor lasers can provide an excellent transmitter for high-speed optical communication and a candidate for chaotic signals. 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 [1]. Other improvements of the semiconductor laser by optical injection locking had been reported, these improvements include, increasing modulation bandwidth and reducing chirp [2–6], a high gain of 20-dB with small signal modulation below resonance frequency [7], the control of filamentations in broad-area semiconductor lasers [8], antiphase dynamics in an optically injected two-mode laser diode, that was a specially engineered Fabry-Pérot laser designed to support two primary modes with a large terahertz frequency spacing [9]. 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 [10]. An optical carrier wave generated by a chaotic laser is used to encode a message for optical fiber transmission system [11]. Chaos synchronization configuration could lead to spectrally efficient chaos-based optical encryption and decryption of multiple data streams [12].

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 [13].

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 objective of this research.

This paper investigates numerically the possibility of improving the modulation characteristics of semiconductor laser by strong optical injection through bandwidth-enhancement and chirp reduction. Moreover, the chaotic behavior of the laser transmitter operating in the injection locking regime had been recognized at a rate of 10 GHz. A lot of research results reported the strong optical injection, a new chaos associated with the optical injection locking will be presented. The chaos of the transmitter will be demonstrated to be dependent on the well-known parameters of the optical injection.

2. Theoretical analysis

Rate equations of the injection locking and numerical simulations is presented and discussed in this section.

Rate of equations of semiconductor lasers with injection locking are given by [14]:

$$\frac{dA_s(t)}{dt} = \frac{1}{2}G_n\left\{n(t) - n_{th}\right\}\left\{1 - \varepsilon_s\left|A_s\right|^2\right\}A_s(t) + \frac{\kappa_{inj}}{\tau_{in}}A_m(t)\,cos\psi(t) \tag{1}$$

$$\frac{d\psi(t)}{dt} = \frac{1}{2}\alpha G_n\left\{n(t) - n_{th}\right\}1 - \varepsilon_s\left|A_s\right|^2 - \frac{\kappa_{inj}}{\tau_{in}}\frac{A_m(t)}{A_s(t)}sin\psi(t) - \Delta\omega \tag{2}$$

$$\frac{dn(t)}{dt} = \frac{J}{ed} - \frac{n(t)}{\tau_s} - G_n\left\{n(t) - n_o\right\}1 - \varepsilon_s\left|A_s\right|^2 A_s^2(t) \tag{3}$$

$$\psi(t) = \varphi(t) - \Delta\omega t \tag{4}$$

$$\Delta\omega = 2\pi\Delta\nu = \omega_m - \omega_s \tag{5}$$

where $\Delta\omega$ is the detuning between the angular frequencies ω_m and ω_s, for the master and slave lasers, respectively. κ_{inj} is the injection coefficient, and τ_{in} is the roundtrip time of light in the laser cavity. $A_m(t)$ and $A_s(t)$ are the field amplitudes for the master and slave lasers, $n(t)$ is the carrier density, and $\psi(t)$ is the phase. G_n is the gain, ε_s is the coefficient of gain saturation, α is the linewidth enhancement factor, J is the injection current, and $d$is the active region thickness.

In the above rate equations, a strong optical injection was assumed so that the impact of the noise and the spontaneous emission rate coupled to the lasing mode are negligible [15]. The first two equations, the amplitude and phase arise from the fundamental complex rate equation, and the third equation is the carrier density variation with time [16].

3. Results and discussion

Before solving the rate equation numerically, steady-state solutions of the rate equations were performed in order to find the general condition of optical injection, as

$$|\Delta\omega| \leq \Delta\omega_L = \frac{\sqrt{1+\alpha^2}}{\tau_{in}}\kappa_{inj}\frac{A_m}{A_s} \tag{6}$$

The optical injection locking occurs at frequencies satisfying the above equation, depending on the linewidth enhancement factor α, injection ratio $\frac{A_m}{A_s}$, and the injection coefficient κ_{inj}. This equation, frequency detuning, for a specific case is not possible unless the key parameters such as phase offset, linewidth enhancement factor, and injection ratio can be extracted for that case [16].

The following values for the laser parameters were used in the numerical calculations: wavelength (λ = 1580 nm), injection coefficient ($\kappa_{inj} = 1 \times 10^{11}$), injection ratio (-50 dB), $\alpha = 3\varepsilon_s = 1 \times 10^{-7}$, $\tau_s = 2ns$, $d = 0.1\mu m$ $n_o = 1.16{\times}10^8$ and $n_{th} = 1.68{\times}10^8$ The calculations and numerical simulations were all taken into account the coefficient of gain saturation ε_s, i.e. the nonlinear gain coefficient. Our results will show that the nonlinear gain coefficient will have an impact on the slave dynamics and route to chaos.

Figures 1a–b shows the numerical solutions of the rate equations; the photon number $(= |A_s|^2)$ is shown in Figure 1a, the phase is shown in Figure 1b, and the carrier number is shown in Figure 1c. As can be seen from these Figures, the instabilities in the photon number and carrier numbers will be settled down after a time in the order of the carrier lifetime (nanoseconds). This instability, due to optical injection from the master laser, will have an impact on the dynamical characteristics of the slave laser later on.

Time-series representations of both carrier number and photon number (Figures 1) do not possess any particular pattern and hence the output will be a chaotic system. Consequently, chaotic signals are often characterized as noise. Therefore, this structure makes chaotic signals more difficult to detect. Chaotic systems are nonlinear in nature, which is also a desired feature for communications because of the possibility of increased bandwidth efficiency, which results in encoding more information than linear systems.

Figure 2 shows the 3D-plot of the chaotic behavior of the injected slave laser when the injection ratio was increased to a higher value of (-20 dB), while keeping all the other parameters as given earlier. This chaos will be studied thoroughly when designing the chaotic transmitter for secure optical communications. This optical injection as simple way for generation such a behavior will offer substantial possibility of chaotic communication and also for enhancement modulation bandwidth.

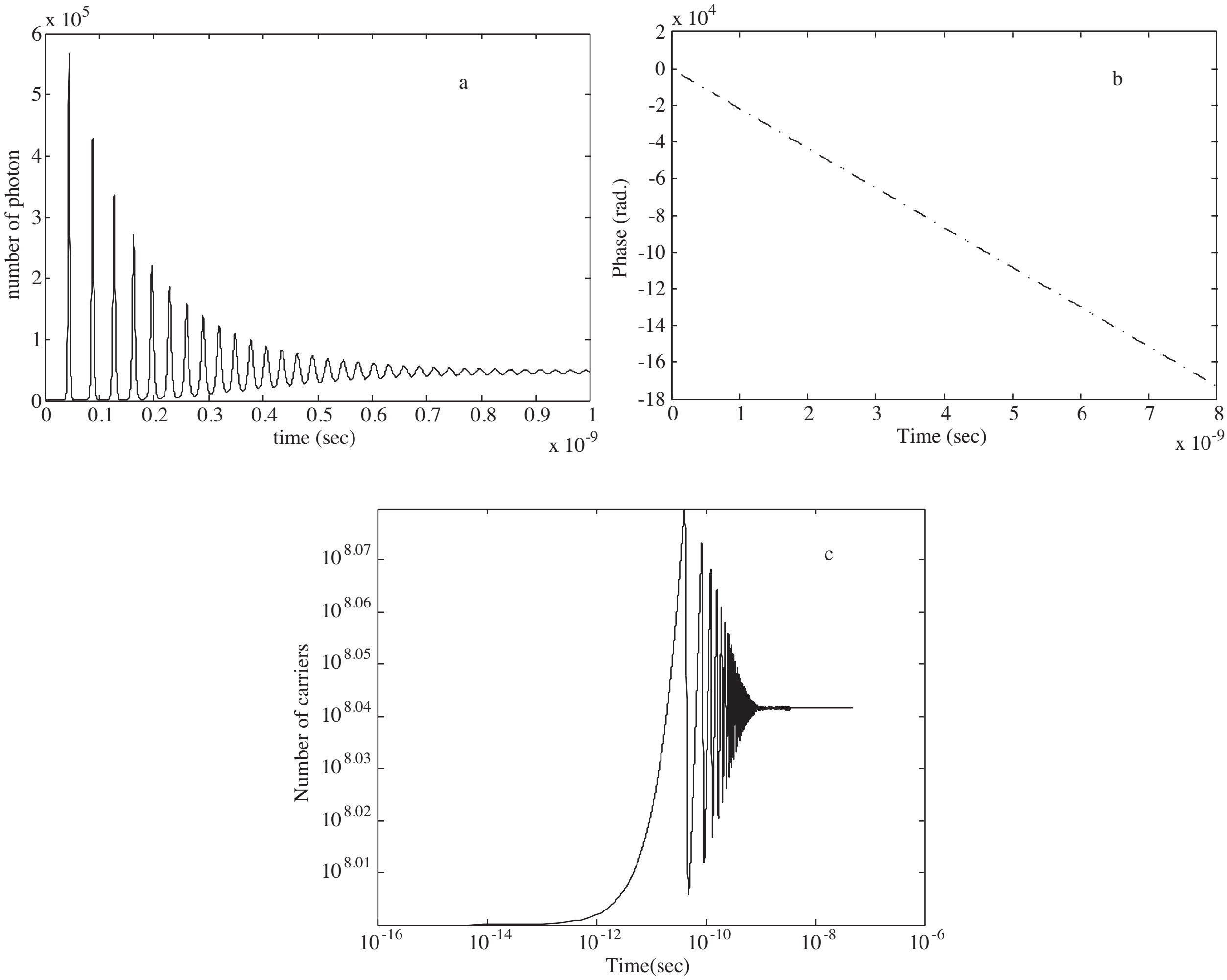

Figure 1. Time series of the rate equations solved numerically for the injected slave laser above threshold ($J = 1.05\,J_{th}$) under the given conditions. (1a) Shows photon number as a function of time, (1b) shows the phase, and (1c) shows carrier number as a function of time.

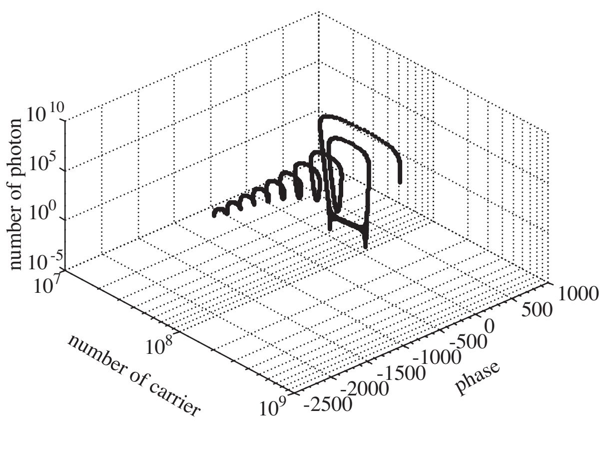

Figure 2. Chaotic behavior of the slave laser under injection with increased injection ratio to (-20 dB), keeping other parameters fixed.

To investigate the modulation charactersitics of the slave laser under strong optical injection by using a modulated current superimposed on bias current and solving the rate equations for small-signal analysis. A detailed analysis for obtaining the modulation response can be found in the lietrature [16, 17]. Based on this analysis, the modulation response function, is defined as

$$|H(\omega)| = \left|\frac{\Delta A_s}{\Delta J}\right|^2 \tag{7}$$

The modulation response as a function of injection coefficient is shown in Figure 3. The influence of the injection coefficient κ_{inj} on the response function is obvious from the graph. With increasing value, the resonance frequency is shifted to higher frequency, giving the system a larger bandwidth for modulation. Hence an improvement in the modulation characteristics of injection locked semiconductor laser had been obtained. A large number of chaotic carriers can be produced easily as a consequence of the sensitive dependence upon initial conditions and parameter variations.

Figure 4 shows the modulation frequency response as a function of modulation frequency and with different power output of the slave laser. The power output of the laser was adjusted by varying the bias current through the laser. The plot illustrates the regions of locking range of the slave laser for increasing its modulation bandwidth.

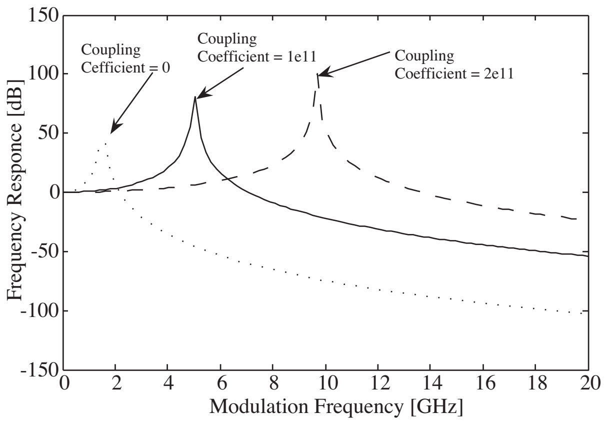

Figure 3. shows the modulation frequency response of the slave laser as a function of modulation frequency for different values of injection coefficient κ_{inj}, and a free-running laser.

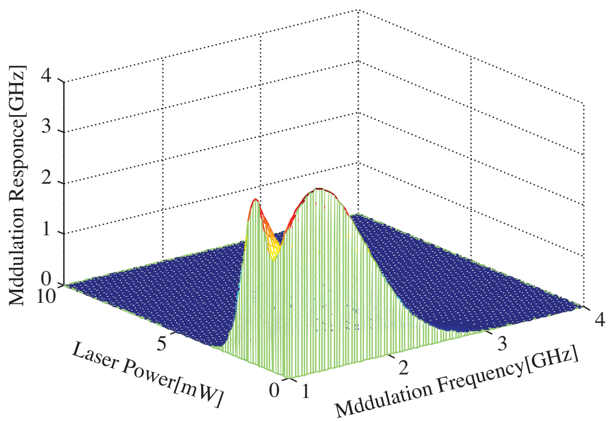

Figure 4. A plot of modulation frequency response as a function of both the modulation frequency and power output of the slave laser.

Regions of chaos synchronization were numerically investigated in the phase space of the frequency detuning. Types of chaos synchronization will be reported for the variations of the frequency detuning and the optical injection rate.

The chaotic dynamics of the slave laser under strong optical injection can be investigated in the unstable locking region (detuning at $\Delta\lambda = .0416$ nm) while varying other important paramaters, i.e., the injection strength from the master to the slave. For injection ratio $\left\{\frac{A_m}{A_s}\right\}$ on the order of 3.82 dB, a chaotic time series given in Figure 5. This chaotic dynamic of slave will further studied with Visual Recurrence Analysis (VRA). In VRA, a one-dimensional time series from a data file is expanded into a higher-dimensional space, in which the dynamics of the underlying generator takes place. This is done using a technique called “delayed coordinate embedding," which recreates a phase space portrait of the dynamical system under study from a single (scalar) time series [17].

A time series of the kind shown in Figure 5 will be a data file for VRA to plot space plot. Figure 6 illustrates the time series obtained numerically solved from the rate equations using (Runge-Kutta Fourth-order), and after being expanded with the help of VRA. It is noted that the vertical axis and the horizontal axis were replaced compared with the plot in Figure 5.

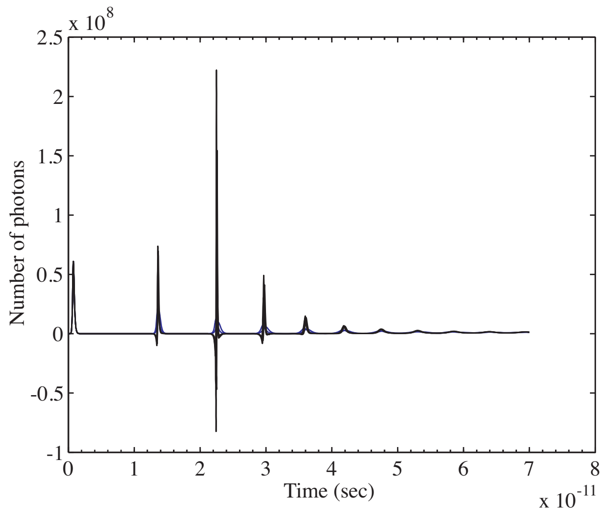

Figure 5. Time series of the rate equation for photon number of the slave with parameters as previous except that the injection ratio was 3.82 dB.

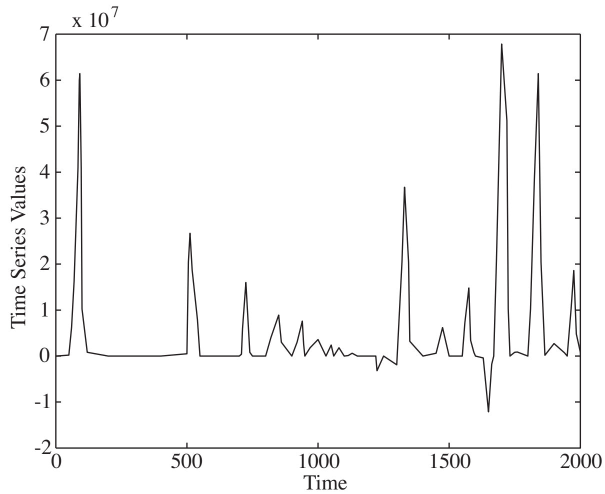

Figure 6. Time series of Figure 5 after being processed with VRA. Notice that the vertical axis and the horizontal axis were replaced compared with the plot in Figure 5.

This time series has to be then processed in order to obtain the space plot. Space plot will illustrate the chaotic attractors for such dynamical system, as in Figure 7. This nonlinear system may have different attractors in the phase plot, if the initial parameters have been varied and will give a different chaotic map. Multistability states in the injection locked semiconductor will have the corresponding number of attractors.

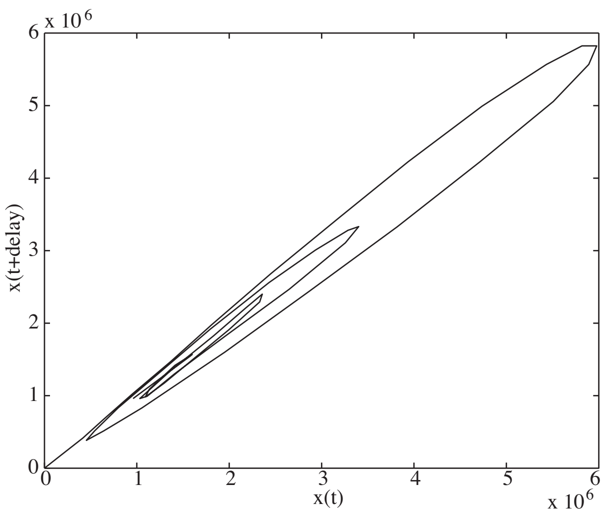

Figure 7. Coexistence of the attractors obtained for the plot of time series of Figure 6 using the VRA software.

4. Conclusions

Theoretical investigation of strong optical injection locking and its influence on the slave characteristics and the route to chaos for secure optical communication have been performed. Injection locking parameters that affected the laser stability, especially κ_{inj}, had the major influence. Numerical integration of photon number that gives in turn the time evolution of the optical field, was controlled by the bifurcation parameter κ_{inj} through the injected field into the slave laser. The parameter κ_{inj} controls the nature of the output dynamics of the slave laser. The phase of the slave laser had locked onto that of the master laser (phase detuning) giving an extra degree of freedom for instabilities. This dynamical lock of the phase fluctuated through multiple bifurcations as it transitions from a stable regime to periodic oscillations with an increasing number of periods, before lapsing into chaotic oscillations.

We observed a shifting the resonance frequency to a higher frequency, increasing modulation bandwidth by injection locking. The route to chaos have been studied with the aid of VRA package to obtain the space plot for chaotic dynamics of the slave alser.

Optical communication network using Optisystem 7.0 simulation software with slave laser as a transmitter undergoing strong optical injection locking had been studied intensively for high bit rate. Chaos due to the variations in the wavelength detuning and injection current were observed in the output of the slave laser. The results of chaotic injection-locked laser showed that the prediction of the validity of the model for secure optical communications.

References

[1] H. Cai1, X. M. Zhang, A. Q. Liu, B. Liu, M. B. Yu, G. Q. Lo and D. L. Kwong, *J. Micromech. Microeng.*, **20** (2010), 1.

[2] Y. Okajima, S. K. Hwang, and J.M. Liu, *Opt. Commun.*, **219**, (2003), 357.

[3] A. Bhardwaj, S. Ristic, L. A. Johansson, C. Althouse and L. A. Coldren, *Elect. Lett.,* **46**, (2010)363.

[4] X. G. Qiong, W. Z. Mao1, Y. Qi, and L. X. Dong, *Chinese Sci. Bull.*, **54**, (2009), 3643.

[5] Sze-Chun Chan, *IEEE J. Quantum Electron.,* **QE- 46** (2010), 421.

[6] Y. Takiguchi, K. Ohyagi, and J. Ohtsubo, *Opt. Lett.* **28**, (2003), 319.

[7] L. Chrostowski, X. Zhao, C. J. Chang-Hasnain, R. Shau, M. Ortsiefer, and M.-C. Amann, *IEEE Photon. Techn. Lett.*, **18**, (2006), 367.

[8] S. Takimoto, T. Tachikawa, R. Shogenji and J. Ohtsubo*, ibid,* **21**, (2009), 1051.

[9] S. Osborne, A. Amann, K. Buckley, G. Ryan, S. P. Hegarty, G. Huyet, and S. O'Brien, *Phys. Rev.* **A79**, (2009), 023834.

[10] K. Kusumoto and J. Ohtsubo, *IEEE J. Quantum Electron.*, **QE-39**, (2003), 1531.

[11] A. Argyris, D. Syvridis, L. Larger, V. Annovazzi-Lodi, P. Colet, I. Fischer, J. Garcia-Ojavlo, C. R. Mirrasso, L. Pesquera, and K. A. Shore, *Nature,* **438**, (2005), 343.

[12] D. Rontani, A. Locquet, M. Sciamanna, and D. S. Citrin, *Opt Lett.*, **35**, (2010), 2016.

[13] S. Blin, C. Guignard, P. Besnard, R. Gabet, G. M. Stephan, M. Bondiou, *Comptes Rendus Physique Semiconductor lasers*, **4**, (2003), 687.

[14] J. Ohtsubo, *Semiconductor Lasers: Stability, Instability and Chaos*, 2^{nd} ed. Berlin, Germany: Springer-Verlag, 2007, Chap. **6**.

[15] E. K. Lau, H. K. Sung, and M. C. Wu, *IEEE J. Quantum Electron.*, **44**, (2008), 90.

[16] N. A. Naderi, M. Pochet, F. Grillot, N. B. Terry, V. Kovanis, and L. F. Lester, *IEEE J. Select. Topic Quantum Electron.,* **15**, (2009), 563.

[17] *http://home.netcom.com/∼eugenek/download.htm*