Spiking Generation and Synchronization in Semiconductor Laser By Means of Optical Feedback

NASRALDIEN, A. EASHAG SAEED  
Physics Dept, College of Education  
Nyala University, Nyala, Sudan

A. M. AWADELGIED  
Karary University  
Khartoum Sudan  
Beisha University  
Saudi Arabia

S.F. ABDALAH  
CNR-Istituto Nazionali di Ottica  
Largo E. Fermi 6,50125, Firenze, Italy

K.A. AL NAIMEE  
CNR-Istituto Nazionali di Ottica  
Largo E. Fermi 6,50125, Firenze, Italy  
Department of physics, College of Science  
University of Baghdad, Baghdad, Iraq

Abstract: Nonlinear dynamics of a semiconductor laser subjected optical feedback observed numerically. The investigation performed based on numerical simulation of Lang-Kobayashi time delay rate equations over wide range of optical feedback strength. The results show that under small, moderate and high optical feedback strength semiconductor laser output power goes different dynamical regimes involving steady state, periodic, mixed modes and chaotic spiking. These dynamics analyzed by time series and their FFT power spectrum with phase space trajectory. The bifurcation diagram is drawn as a function of optical feedback strength. Chaos synchronization in unidirectional coupling scheme numerically presented.

Keywords: Semiconductor Laser Nonlinear Dynamics; Time Delay Optical Feedback; Synchronization;

I. INTRODUCTION

Since idea of laser brought by the Einstein’s concept of stimulated emission; semiconductor laser has bound applications in an increasing number of areas. These usages arisen due to several of their advantageous attributes. They are small in size, inexpensive, low power current sources, directly modulated for both digital and analog photonic communication and very high efficient. In addition to, Semiconductor lasers dynamics are very sensitive to external perturbations as a nonlinear interaction of the light with laser medium which can be utilized to stabilize or destabilize semiconductor laser dynamics. These perturbations have been widely studied involving optical delay feedback from distant mirror or optical fiber loop mirror [1], phase-conjugate feedback [2], opto-electronic feedback [3], opto-electronic feedback and modulation [4][5], optical injection [6]. These complex behaviors are used in great applications such as secure optical communication [7], chaotic lidars, random number generation and neural science [8]. These dynamics of semiconductor lasers are formulated by nonlinear differential equations. Depending on the types of optical feedback, optical feedback strength, external cavity length and injection current [9], many nonlinear dynamical phenomena are observed, such as multistability [10], instability, selfpulsation [11] and coherence collapse. The output power displays steady state, quasi-periodic and irregular oscillations separated by different time intervals with sudden dropouts. A SL subjected to delay optical feedback, opto-electronic feedback or coupling exhibit Chaos synchronization phenomena which have been widely studied in different research activities in recent years numerically and experimentally for its potential applications in physical, biological, ecology physiological [12] and communication systems. In optical communication, chaos synchronization can be classified in to two categories according to the way of connection between the two systems, namely: the unidirectional coupling [13] and the mutual coupling [14]. Different operation mechanisms have been studied such as Complete or identical synchronization, when the differences of states variables of synchronized systems with different initial values converge to zero [15], generalized synchronization (GS)[16], lag and phase synchronization (FS)[17].

In this work we investigate the effect of optical feedback strength in the dynamics of semiconductor laser using the model of coupled time delay differential equations for the electric field which give the intensity by its square and the carrier density is the population inversion. Chaos synchronization in unidirectional coupling SL also numerically investigated. The model is referred to Lang and Kobayashi [18] equations by adding time delay term.

II. DYNAMICAL MODEL AND METHOD

In the case of a tow -dimensional dynamical system where chaotic dynamics cannot and for small-moderate and strong optical feedback strength; the dynamical model in[15] can be expressed in polar coordinates as:
1-Single semiconductor laser:

\[ \frac{dE}{dt} = \frac{1}{2} (G(t) - 1/\gamma_c) E + (k + \alpha) (E - r) \cos(\omega t - \phi(t) - \phi_0) \]

(2.1)

\[ \frac{d\gamma}{dt} = \frac{1}{2} \left[ G(t) - 1/\gamma_c \right] + (k + \sigma) \left( \frac{E(t)}{E_m} \right) \sin(\omega t + \phi(t) - \phi_0) - \phi(t) \]  

(2.2)

\[ \frac{dN}{dt} = i^c - \gamma_c N - G(t) \left| E(t) \right|^2 . \]  

(2.3)

Where \( E \) stand for electric field amplitude, \( N \) is the carrier density, \( \gamma \) is optical phase .optical gain \( G(t) = \frac{G \left( \frac{E(t)}{E_m} \right)}{1 + \frac{E(t)}{E_0}} \) In numerical simulation matlab we consider the initial conditions and parameters values as \( E , N \) and \( \varphi = 0.01 , 0.1 \) 0.001, photon decay time \( \gamma_2 = 1.93e^{-12} \), carrier decay time \( \gamma_c = 2e^{-9} \), is the gain coefficient \( g = 1.5e4 \), gain saturation coefficient \( s = 5e-7 \), current density injection \( J = 1.5 \), electric charge \( e = 1.6e-19 \), carrier density at transparency \( N_{th} = 1.5e8 \), the linewidth enhancement factor \( \alpha = 3 \), delay time \( \tau = 10e-9 \). Feedback strength \( k = 3.6e11 \), Injection strength \( \sigma = 40 \), Optical angular frequency* delay time \( \omega \tau = 4.9077e6 \), spontaneous emission rate \( \beta = 1.6e3 \), Gaussian noise sources \( X = 1 \).

2-Unidirectional coupled semiconductor lasers:

The systems are described by the same rate Lang and Kobatashi equations.The master is coupled to the slave by its putput power strength while slave laser there is not backward coupling and then we measure their output power as time series.The subscript \( m \) and \( s \) stand for master and slave laser with the same parameters as all, but the difference is at their initial conditions and optical feedback strength as:

**For the Master laser:**

\[ \frac{dE_m}{dt} = \frac{1}{2} (G(t) - 1/\gamma_c) E_m + (k + \alpha) (E_m - r) \cos(\omega t - \phi(t) - \phi_0) \]

(2.4)

\[ \frac{d\gamma_m}{dt} = \frac{1}{2} \left[ G(t) - 1/\gamma_c \right] + (k + \sigma) \left( \frac{E_m(t)}{E_m} \right) \sin(\omega t + \phi(t) - \phi_0) - \phi(t) \]  

(2.5)

\[ \frac{dN_m}{dt} = i^{c_m} - \gamma_c N_m - G_m(t) \left| E(t) \right|^2 . \]  

(2.6)

**For the Slave laser:**

\[ \frac{dE_s}{dt} = \frac{1}{2} (G(t) - 1/\gamma_c) E_s + (k + \alpha) (E_s - r) \cos(\omega t - \phi(t) - \phi_0) + \omega \frac{E_s}{E_s} \]

(2.7)

\[ \frac{d\gamma_s}{dt} = \frac{1}{2} \left[ G(t) - 1/\gamma_c \right] + (k + \sigma) \left( \frac{E_s(t)}{E_m} \right) \sin(\omega t + \phi(t) - \phi_0) - \phi(t) \]  

(2.8)

\[ \frac{dN_s}{dt} = i^{c_s} - \gamma_c N_s - G_s(t) \left| E(t) \right|^2 . \]  

(2.9)

III. RESULTS AND DISCUSSION

Time series analysis of each dynamical regimes for different values of optical feedback strength (km) for the evolution generated signals from semiconductor laser with corresponding power spectrum FFT and phase space portrait by attractor are shown in fig. (a-j).We noticed that from time series figs the generated signals increase their numbers and amplitude power as optical feedback strength increase and suitable evaluated time scales.

Fig. a show that the dynamics of optical output power grows to maximum peak and then down to steady state at very week optical feedback strength (3e-9s^-1) and its corresponding FFT spectrum dynamic. Fig. (b, c and f) illustrate transition from semistady state to 4 and 6 periodic oscillations associated with four peaks at four different frequencies and one of them is very high power at frequency 1.8e7Hz. Fig. g For optical feedback strength level 3.6e8 where output power shows mixed mode oscillations (small and large amplitude separated by irregular time interval) with four main high peaks at different frequencies [19]. Fig. h reveal laser output power transited from moderate to chaotic state with clear spectral peaks at frequency 1.02e7Hz which is close to low frequency oscillation for optical feedback strength around 3.6e9 to 3.6e10 Fig. (E, j and i) complex behavior of laser output power with high chaotic state and clear spectral peaks at different frequencies closed to low frequency oscillation, these large and small spikes separated by irregular time interval are associated with mixed mode and multi homoclinic orbits to saddle focus with its phase space trajectory. As all we note that oscillation frequencies decrease by increasing optical feedback strength. Fig. (l and z) represent the phase space trajectory of for laser output power versus carrier density as multi spiral orbits grows exponentially which reveal chaotic behavior.

The whole evolutions of semiconductor laser dynamics from periodic at low optical feedback strength and periodic doubling with increasing amplitude, to high chaotic state with increasing amplitude exponentially by increasing optical feedback strength are illustrated at bifurcation diagram in fig. r[20].

Fig. s. Describe independent time series for the output power of two coupled systems operated at different initial conditions and optical feedback strength constants are set as \( k_1 = 3.6e11 \) and \( k_2 = 3.6e11 \) and coupling injection factor \( R = 0.06 \) Fig. t. Shows no linear correlation between the spikes of chaotic lasers, but fig.u. explain that there is partially linear relation between the time of spikes of two chaotic oscillators, which mean that two oscillators are partially synchronized at the place of spikes. By contrast fig. v. present the identical and dependent time series for the output power of two coupled semiconductor lasers operated at optical feedback strength constants are set as \( k_1 = k_2 \) and coupling injection factor \( R = 0.0 \) Fig.t shows the prove of identical synchronization where a linear relation between spikes and time of spikes of two lasers exist.
Fig. a The time series of the laser output power and its corresponding FFT spectrum. When the optical feedback strength is 36e-9ns⁻¹.

Fig. b The time series of the laser output power and its corresponding FFT spectrum. When the optical feedback strength is 36e-8ns⁻¹.

Fig. c The time series of the laser output power and its corresponding FFT spectrum. When the optical feedback strength is 36e-7ns⁻¹ and 36e-6ns⁻¹.

Fig. f The time series of the laser output power and its corresponding FFT spectrum. When the optical feedback strength is 36e-3ns⁻¹.

Fig. g The time series of the laser output power and its corresponding FFT spectrum. When the optical feedback strength is 36e-2ns⁻¹.

Fig. h The time series of the laser output power and its corresponding FFT spectrum. When the optical feedback strength is 36e-1ns⁻¹.
Fig. 1 The time series of the laser output power and its corresponding FFT spectrum. When the optical feedback strength is $36\text{ns}^{-1}$.

Fig. 2 The phase space trajectory for the dynamics of optical output power versus carrier density.

$(k=36e^{-7}\text{ns}^{-1})$.

Fig. 3 The phase space trajectory for the dynamics of optical output power versus carrier density, it grows to oscillate at maximum peaks and the down to periodic state at optical feedback strength $(k=36\text{ns}^{-1})$.

Fig. 4 The corresponding Attractor in two and three dimension for phase space trajectory When the optical feedback strength $360\text{ns}^{-1}$

Fig. 5 The time series of the laser output power and its corresponding FFT spectrum. When the optical feedback strength is $360\text{ns}^{-1}$

Fig. 6 Bifurcation diagram of high chaotic peaks generated as a function of optical feedback strength.
In conclusion, we have studies and discussed the evolution of semiconductor laser nonlinear dynamics over wide range of optical feedback strength and its coupling in chaos synchronization, different dynamical regimes from steady state to high chaotic spiking with their FFT spectrum and phase space trajectory. Mixed mode and broadband spectra increases with increasing optical feedback strength. We observe Evolutions of dynamics from periodic and periodic doubling with increasing amplitude, to high chaotic state with growing amplitude exponentially obtained by bifurcation diagram. Also demonstrated that the complexity system depend highly on time scales of evaluated time series output power. The obtained results have shown that in future chaos synchronization of semiconductor lasers is good devices for network synchronization.

V. REFERENCES


