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University of Thi-Qar/College of Science



Effect of Optical Feedback and External Optical Injection on Chaos in QD-LED

A thesis

Submitted to the Committee of College of Science, University of Thi-
Qar in partial fulfillment of the requirements for the degree of Master
science in Physics

By

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(B.Sc. 2016)

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والله بما تعملون خبير))

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بأخلاقيات البحث العلمي



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نتعهد بالتقيد التام بما جاء في مضمون كتاب وزارة التعليم العالي والبحث
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Effect of Optical Feedback and External
Optical Injection on Chaos in QD-LED

وبخلافه نتحمل نحن الموقعون أدناه المسؤولية القانونية حال وجود ما
يخالف مضمون الكتاب أعلاه أو ما ينافي أخلاقيات البحث العلمي.

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أحد الدوافع السلمية بقوة فكرية وأفقها لحقوق الفكرية للآخرين، لذا يجب أن تتطوّر الجهود مع تضام السلمية لإيجاد المخرج أهمية فعلى لمصلحة لعلها في كلياتها والحد من رهبا.

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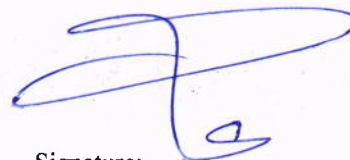
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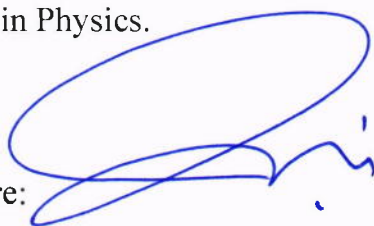
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Supervisor Certification

I certify that this thesis entitled " **Effect of Optical Feedback and External Optical Injection on chaos in QD-LED**" is prepared by (**Hussein Awad Zamzoom**) under my supervision at the College of Science of Thi-Qar University in partial fulfillment of the requirements for the Degree of Master of Science in Physics.

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Hussein

Dedication

To the fountain of patience and optimism and hope to each of the following in the presence of Allah and his messenger, my mother dear, to the big heart my father dear. To those who have demonstrated to me what is the most beautiful of my brother's life. To the people who paved our way of science and knowledge All our teachers distinguished. To the taste of the most beautiful moments with my friends.

Hussein

2018

List of abbreviations

<i>Attribute</i>	<i>Definition</i>
DCM	Direct current modulation
EM	Electro magnetic
FFT	Fast Fourier transformation
FOF	Filtered optical feedback
ISI	Inter-spike intervals
LD	Laser diode
LED	Light emitting diode
MOCVD	Metalorganic chemical vapor diction
MMO	Mixed-mode oscillations
MBE	Molecular beam epitaxy
OFB	Optical feedback
OFBS	Optical feedback strength
OI	Optical injection
OEFB	Optoelectronic feedback
OLED	Organic light emitting diode
PD	Photo diode
QD	Quantum dot
QD-LED	Quantum dot light emitting diode
QD _s	Quantum dots
QW	Quantum well
QW _i	Quantum wire
RO _s	Relaxation oscillations
SL	Semiconductor laser
SHC	Shilnikov homoclinic chaos
WL	Wetting layer

List of symbols

<i>Symbol</i>	<i>Description</i>
$\Delta\omega$	Angular frequency detuning
ω_m	Angular frequency of master system
ω_s	Angular frequency of slave system
ω_o	Angular solitary frequency
δ_o	Bias current
δ_{om}	Bias current of master system
δ_{os}	Bias current of slave system
γ_c	Capture rate from WL into empty dot
τ	Delayed time which is taken optical phase
q	Dipole moment of the QD
W	Einstein coefficient
e	Elementary charge
k, k_g	Feedback coefficient
η	Feedback strength
ω_g	Frequency of the grating mirror
r_{inj}	Injection ratio
α	Linewidth enhancement factor
$\gamma_{r_{QD}}$	Non-radiative decay rate of the number carrier in QD
$\gamma_{r_{WL}}$	Non-radiative decay rate of the number carrier in WL
n_{QD}, y	Number of electron in QDs
n_{WL}, z	Number of electron in WL
γ_s	Output coupling rate of photons in the optical mode
$\varphi, \emptyset$	Phase
φ_τ	Phase delayed

s, x	Photon number
$\hbar$	Plank's constant
c	Speed of light in vacuum
R_{sp}	Spontaneous emission
ϵ_{bg}	Static relative permittivity of the background medium
k_{inj}	The injection coefficient
I	The injection current
τ_{in}	The round trip time of light in the laser cavity as interduced before
N_d, a	Total number of QD_s
ϵ_0	Vacuum permittivity

M.Sc publications

Parts of this work are published in the following Journals and conference:

- [1] Hussein B. Al Hussein, and Hussein A. Al Rekabie" *Optical Injection Locking in Quantum Dot Light Emitting Diode.* " **Journal of Applied Physics & Nanotechnology**, 2018, Vol. 1 • Issue 1 • pp 1-5
- [2] Hussein B. Al Hussein, and Hussein A. Al Rekabie" *Controlling of the Quantum Dot LED Dynamics with a Small Optical Feedback Strength.* " accepted for publication in **Journal of Applied Nonlinear Dynamics**.
- [3] H. Al Hussein, and H. Al Rekabie, " *influence optical injection locking in Quantum Dot Light Emitting Diodes,*" **ICNAMA 2018**, 6th international scientific conference for nanotechnology and advanced materials and their applications 2-3 May, 2018, Baghdad, Iraq.
- [4] Hussein B. Al Hussein, and Hussein A. Al Rekabie" *Selecting Dynamics of the Quantum Dot Light Emitting Diode with a Small Optical Feedback Strength.*" accepted for publication in **Journal of Chaos, Solitons and Fractals: the interdisciplinary journal of Nonlinear Science, and Nonequilibrium and Complex Phenomena**, Elsevier.

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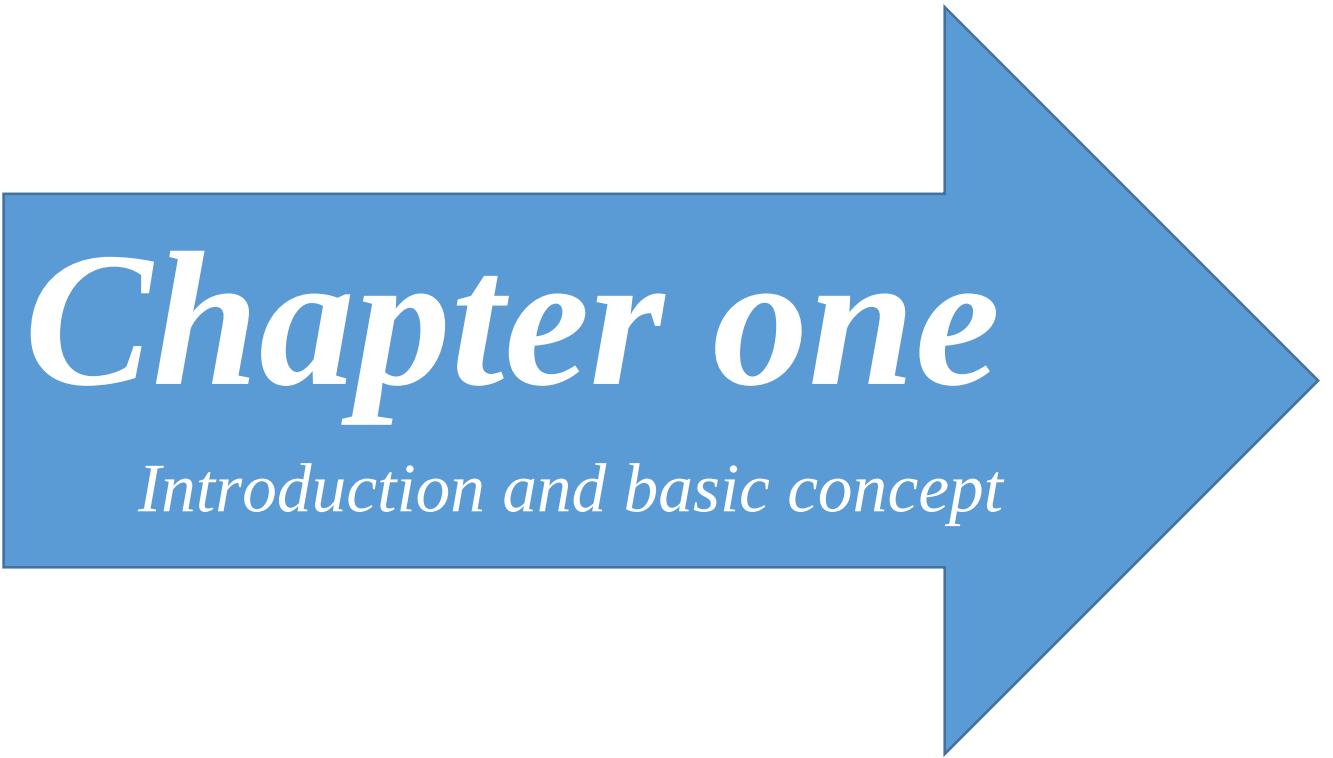
Abstract

In this thesis, the complexed dynamics of semiconductor quantum dot light emitting diode (QD-LED) under optical feedback (OFB) and optical injection locking (OI) effects were studied. We study the existence of chaotic sequences in the dynamics of QD-LED and the corresponding time series, Inter- Spike Intervals (ISI), Fast Fourier Transformation (FFT), and attractor.

We have studied theoretically the dynamics in QD-LED with small optical feedback. The bifurcations of these dynamics is fully determined by the increasing the optical feedback strength (OFBS). Our results show that small OFBS (less than 0.03) lead to a good controlling of selecting QD-LED dynamics. The increasing of the delay time (τ) leads to increase both of them of the double period and the chaos. Otherwise, the increasing of the bias current (δ_o) leads to disappear of the above regions. Adding the grating mirror as a special technique to suppress unwanted frequencies, there is existence of a number of important states transition between periodic and chaotic. Delayed feedback and turn -on dynamics are studied. Results appeared a clear effecting of delay time just with large value of the bias current (The effecting change of τ on the behavior of photons at small values of bias current ($\delta_o = 0.013$) shows a very predictable in dynamics of systems) while the turn-on dynamics of the QD-LED structure show damping relaxation oscillations, phase shift appears with speedy threshold of first pulsing and the dynamic range is incomparable in most cases have examined. When studying the linewidth enhancement factor shows the dynamic starts from the state of the period to chaos. A small amount of displacement beginning chaos to the left with increased OFBS, when the τ increase there is greater displacement appeared than

before, and at default value of the delay time one shows a special case is called the mixed modes pattern.

In this work, we study a QD-LED subject to optical injection which induces an instability in slave system. Frequency detuning, bias current and the optical injection ratio are studied. Results show a chaotic behavior via time series, attractor and bifurcation diagram. Phase-locking state is observed when both the master and slave systems work at the same frequency $\Delta\omega = 0$. We also show two cases, damping with disappearance and increasing the output signal capacity by increasing the optical injection ratio. Injection-locking and stability states also were observed. The boundaries of qualitatively appears different dynamics in the plane of the injection parameters (the detuning and the injected ratio) when we study the transition mode phenomena. Additionally, results show two modes dynamics with two parameters (injection ratio and bias current) effect.



Chapter one

Introduction and basic concept

1.1 Introduction

For nearly three decades after the formulation of the term "chaos", chaotic phenomena and chaotic behavior were observed in many natural and model systems in physics, chemistry, biology, ecology, etc [1].

Irregular spiking sequences in biological, chemical and electronic systems have been observed as a result of multiple time dynamics. In fact, a variety of natural systems that show this behavior (neurons, cardiac tissues, and chemical reactions) can be described in a mathematical way by slow and rapid variables associated with each other (slow- fast systems). Chaotic spiking system can be understood in terms of chaotic excitability, where the small chaotic background causes sudden mutations in an irregular but specific sequence [2].

High-dimensional systems can support more varied and complex dynamics, such as periodicity and irregular bursting. Here, the irregular spikes are the result of the complex chain of complexity, as results to the presence of a purely deterministic origin (chaotic spiking) [3]. Chaos model allows us to understand the inherent characteristics of natural systems and communication. Chaotic systems are inevitable dynamic systems that exhibit irregular random behavior. An attractive sample of chaos is taken in the temporal space by an infinite number of unstable periodic orbits [4].

Two pathways of the chaos system diverge from each other after some time (so-called sensitive dependence on initial conditions). A chaotic system must necessarily be non-linear, which called, can say, a non-linear mathematical model. An important consequence of system instability is the high sensitivity of input changes (work control). This means that small changes in inputs may result in significant differences in system behavior [5].

Chaos controlling, or control of chaotic systems, is the boundary between control theory and the theory of dynamic systems that examines when and how to control systems that exhibit irregular chaotic behavior [1].

These phenomena can be understood in terms of a typical model known as Shilnikov Homoclinic Chaos (SHC) [3]. SHC, initially observed in chemical and laser experiments, shows striking similarities with the electric spike that travel on animal neurons. More generally, chemo-based stimulants that control the biological clocks that control live rhythms, such as heart pacemaker, hormone production, metabolism, etc., exhibit rhythmic trains of ripple with irregular repetition. These rhythms can't be reduced to two-dimensional dynamics, but rather the case of synthetic clocks that rely on stable limit cycles [5,6].

1.2 Logistic Difference Equation

The logistic difference equation, or logistics map, is a model commonly used to introduce chaos, although simple, and presents major chaotic concepts [7]. In general, the relation:

$$X_{n+1} = rX_n \quad (1.1)$$

is a model of growth. This says X changes from one-time period, n , to the next, $n+1$, according to r (real and positive parameter). If r is greater than one, the X becomes larger with a consecutive iteration, if r is less than one, X is diminished. If r is put to be larger than one, initial with: ($n=1$), when $X=16$, ($X_1=16$), and for $r=1.5$, to each (n), X is increased by 50%. So $n=2, 3, 4, 5, \dots$ etc, X have magnitudes (24, 36, 54, ...). Here X is growing exponentially. We have a linear model that produces unlimited growth as shown in Fig. (1.1)

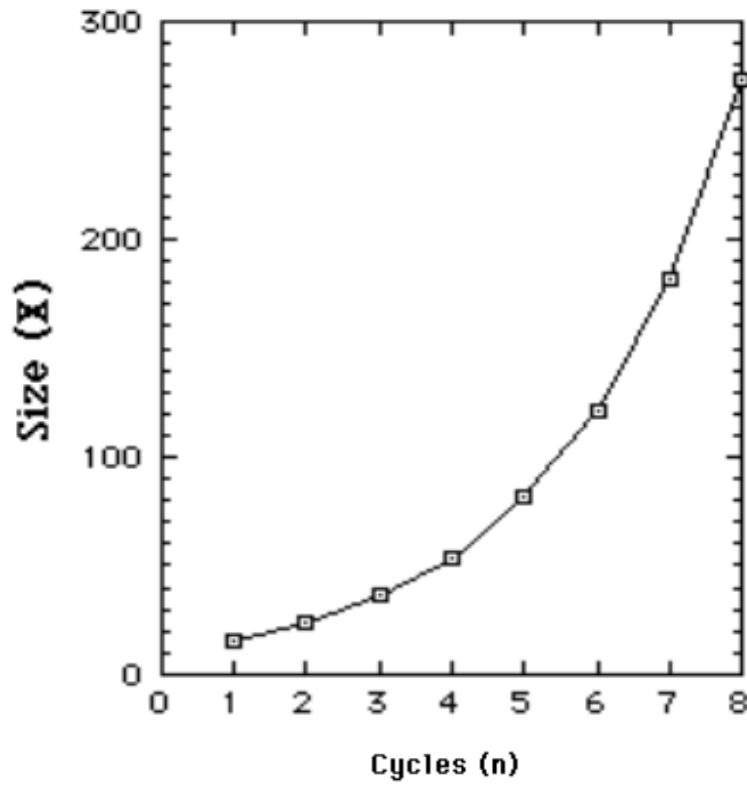


Fig. (1.1): The linear model [7].

this figure shows a linear model that produces unlimited growth. The logistics map inhibits unlimited growth by discouraging growth as an additional term $(1 - X_n)$ whenever a high level is achieved. The growth scale (X) is also measured so that the maximum value of X is converted to 1. Thus, the new form is:

$$X_{n+1} = rX_n(1 - X_n) \quad (1.2)$$

the term $(1 - X_n)$ inhibits growth since X is close to 1, $(1 - X_n)$ is close to 0. By plotting X_{n+1} vs X_n , we see that we have a nonlinear relationship. Limited growth model. X_{n+1} vs X_n , $r = 3$, as in Fig. (1.2).

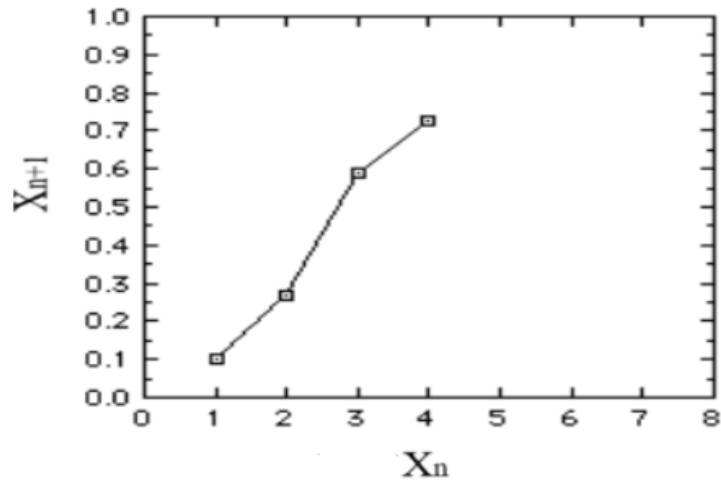


Fig. (1.2): Performance of the Logistic map for $r = 3$, $x_1 = .1$, iterated to give x_2 , x_3 , and x_4 [7].

It turns out that the logistic map is depending on its control factor r and Fig. (1.3) shows when r is less than 1.

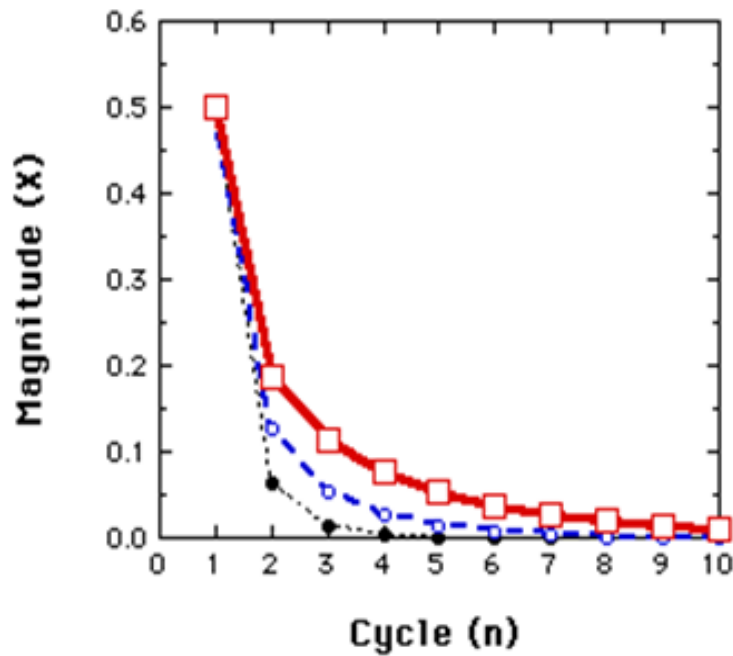


Fig. (1.3): Performance of the Logistic map for $r = 0.25$, 0.50 , and 0.75 . In all cases $x_1 = 0.5$ [7].

As long as r is less than 1, X goes toward 0. This illustrates a one-point attractor. When r is between 1 and 3, the behavior as shown in Fig. (1.4).

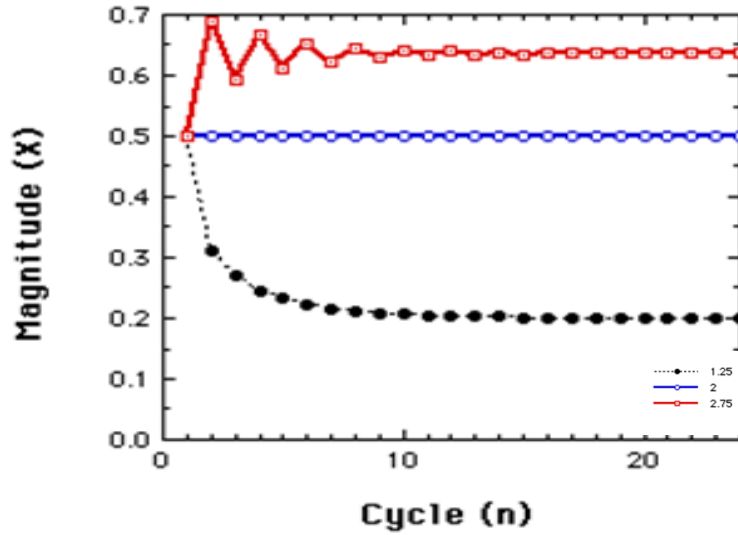


Fig. (1.4): Performance of the Logistic map for $r=1.25$, 2.00 , and 2.75 . In all cases $x_1=0.5$ [7].

Now, regardless, of the starting value, we have non-zero one point attractors a Fig. (1.5) shows a periodic state when r is larger than 3.

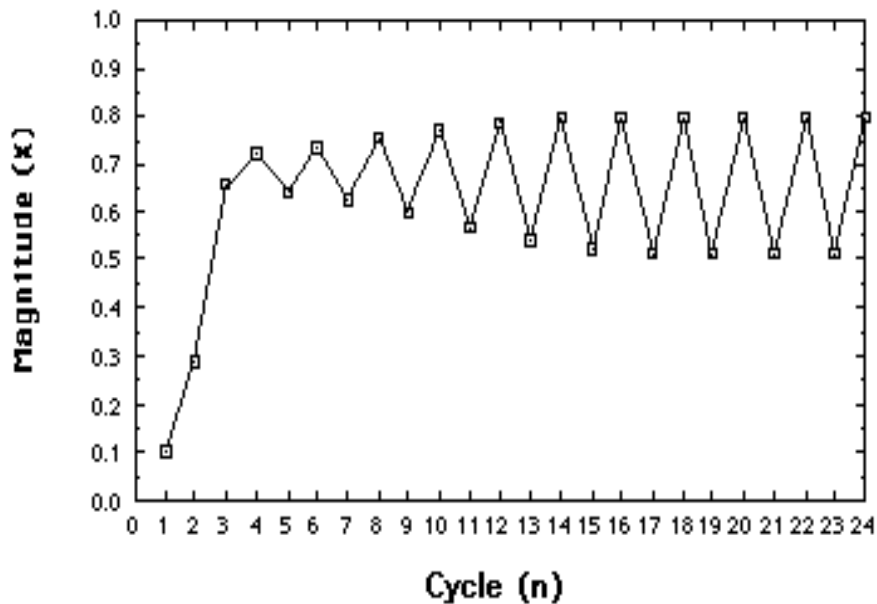


Fig. (1.5): Behavior of the Logistic map for $r=3.2$ [7].

Moving just beyond $r = 3$, the system settles down to alternating between two points. when $r = 3.54$ a period doubling shown in Fig. (1.6). And at $r = 3.99$, Fig. (1.7) shows a chaotic behavior.

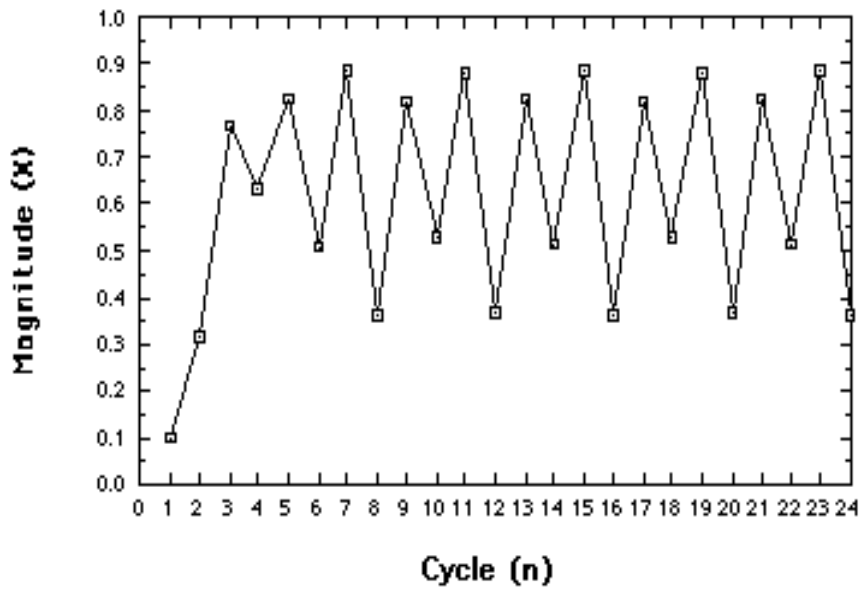


Fig. (1.6): Behavior of the Logistic map for $r = 3.54$ [7].

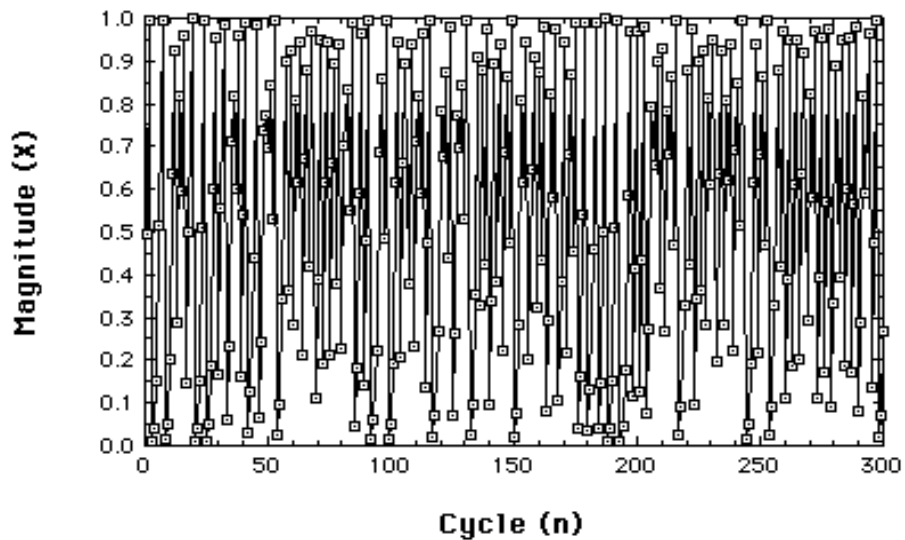


Fig. (1.7): Chaotic behavior of the Logistic map at $r = 3.99$ [7].

1.3 Definitions of Chaos

Chaos can be defined by more than one definition. In fact, within the framework of science so far there is no agreement on the status of the identification of the chaotic dynamic system [1].

Flake spoke in the definition of chaos as an Irregular motion of a dynamical system. It is an inevitable sensitivity to initial conditions, and cannot be predicted in the long term with anything less than infinite and perfect representation of analog values [4].

Another definition of Williams in which chaos is a long-term, unorganized evolution that meets certain specific mathematical standards and occurs in a nonlinear system. Lorenz then came up with another definition that included chaos as the property that characterizes the dynamic system in which most orbits appear to be sensitive [8]. It can also be known as chaos, a type of motion that suddenly occurs and is generated by deterministic differential equations, and rules that generate chaos called chaotic dynamic systems, and the space used to describe the system is often called phase space [9]. The most accurate definition of anarchy is complete disorder and unpredictability in the end [10, 11]. In most definitions, chaotic processes are treated as solutions for linear or nonlinear differences, characterized by local instability and global boundaries [12].

Chaos is a difficult task [13], a feature inherent in many nonlinear physical systems. In particular, the transition from the system to chaos occurs with the global, without regard to the physical properties of the systems. Anaphylaxis occurs in the optics, in the laser or in nonlinear optical devices. These systems, simple to construct in both the construction and the mathematics they describe, provide excellent opportunities to investigate these nonlinear phenomena as well as modern technological innovation. [14]. The chaotic behavior of a dynamic system contains (a) a very large (infinite) number of

attractors and (b) very sensitive to initial conditions [7]. The sensitivity to the initial conditions is that every point in the system approaches arbitrarily from other points in very different future paths. In this way, the arbitrary little disturbance of the current path may lead to a different behavior from the past [15]. The necessary conditions for chaos ($n > 2$, nonlinear, bounded trajectories, continuous-time systems) [8].

1.3.1 Attractor

An attractor is a set of values over time which the system moves to phase space, or iterations, which at least be three-dimensional. The collectors are based on dimensions such as the number of variables that affect their system [10]. The chaotic attractive samples are densely placed in the phase area for an infinite number of unstable periodic orbits [4]. The following Fig.(1.8) shows a range of potential attractors [16]. The attractors can either be: (a) Fixed point, which is fixed constant output, (b) cycle limit, a periodic oscillation, (c) torus, which represents the semi-periodic output power and chaos, which represent the output of energy fluctuates randomly.

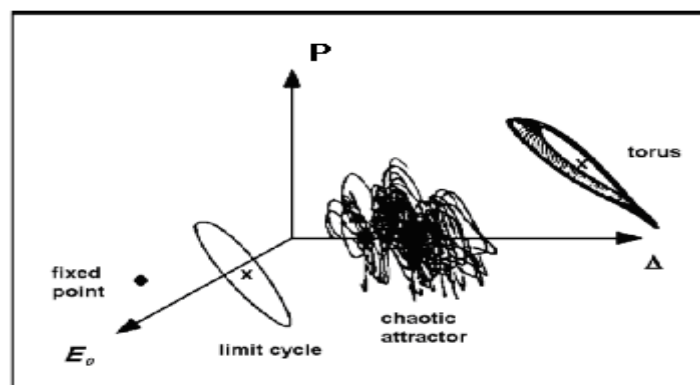


Fig. (1.8): Schematic of attractors [16]

We can call a function point that does not change under certain transformations with a fixed point. The attractor, which is periodically referred to as the reduction cycle, is also called the limit cycle, which is carried out

periodically through a sequence of cases. A torus, is an attractant composed of independent oscillations n , and is drawn in the phase space [7]. A strange attractor, is an attractor which it has non-integer dimension, or the dynamics on it are chaotic.

Lorenz attractor, is a butterfly-shaped strange attractor. It came from a meteorological model developed by Edward Lorenz in 1963 with three equations and three variables. It was one of the first strange attractors studied [7].

The system of differential equations involved only two nonlinear terms and it was given by [17]:

$$\begin{aligned}\dot{x} &= u(y - x) \\ \dot{y} &= Dx - y - xz \\ \dot{z} &= xy - qz\end{aligned}\tag{1.3}$$

where u , D , and q are positive parameters and, moreover, the solution curves were displayed through two different initial conditions: $P_1 = (0, 2, 0)$ and $P_2 = (0, -2, 0)$ when the parameters are: $\sigma = 10$, $b = 8/3$, and $r = 28$. These are the original parameters that led to the discovery by Lorenz. You can see how both solutions begin in a very different way, but in the end they have the same fate, and both seem to lean around a pair of points, alternating with the times they are surrounded. This is the first important fact about the Lorenz system that states all nonequilibrium solutions tend to end up in the same complex group, the so-called Lorenz attraction. $\sigma > b + 1$, as in Fig. (1.9) [17]

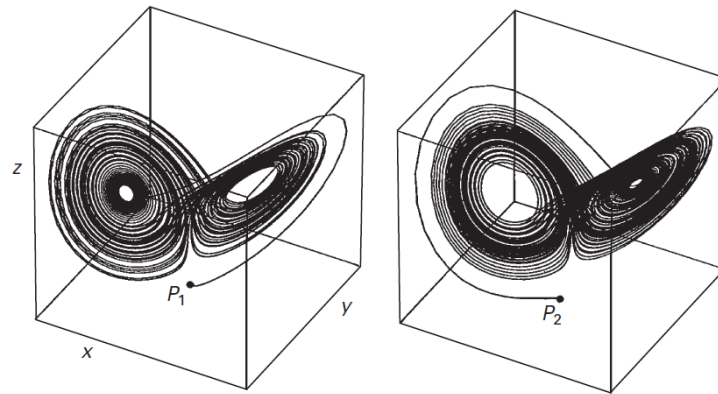


Fig. (1.9): The Lorenz attractor with two solutions at initial conditions, $P_1 = (0, 2, 0)$ and $P_2 = (0, -2, 0)$ [17].

The Rossler system is a three-dimensional system similar in many respects to the Lorenz system. It was given before [17]:

$$\begin{aligned}\dot{x} &= -y - z \\ \dot{y} &= x + ay \\ \dot{z} &= b + z(x - c)\end{aligned}\tag{1.4}$$

where a , b , and c are real parameters, Fig. (1.10) shows Rossler system solution.

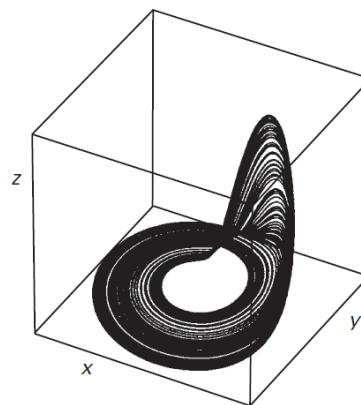


Fig. (1.10): The Rossler attractor [17].

For simplicity, the case where $a = 1/4$, $b = 1$, and c ranges from 0 to 7, with the Rossler system, it is difficult to prove specific results about this system.

A chaotic attractor, is a trajectory in the phase space of chaotic variables and is frequently used of the analysis of chaotic oscillations [18]. Since the laser output power at a stable oscillation is constant, the attractor is a fixed point in the phase space of the output power and the carrier density. A period-1 signal, as the case in Fig. (1.11 (a)), is a closed loop. The attractor of a period-2 oscillation is a double-loop as shown in Fig. (1.11 (b)) [18]

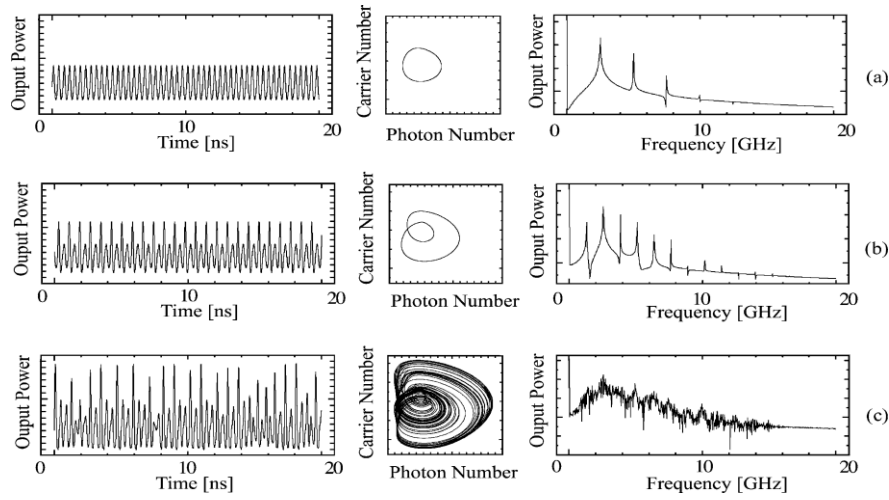


Fig. (1.11): Numerically calculated time series (left row), attractors (middle row), and power spectra (right row) for different feedback ratios [18].

The chaotic attractor behaves in a rather different way from fixed state or periodic oscillations. At chaotic oscillations, the state goes around points within the closed compact space in the attractor, it never visits the same point in the space. The trajectory crosses in the attractor in Fig. (1.11(c)). The chaotic trajectory goes around in a multi-dimensional space and never crosses in such a space. A chaotic attractor is quite different from other periodic oscillations and looks very strange. Therefore, it is sometimes called a strange attractor.

1.3.2 Bifurcation Diagram

A bifurcation is a period doubling, a change from an n -point to a $2n$ -point attractor, which occurs when the control parameter is changed. It is a qualitative change in the behavior (attractor) of a dynamic system associated with a change in control parameter (a control parameter, is a parameter in the equations of a dynamic system), if control parameters are allowed to change, the dynamic system would also change, changes beyond certain values can lead to bifurcations [7].

Mathematically, the term (bifurcation) refers to the (splitting) of equilibrium solutions in a family of vector fields [19]. The object of bifurcation theory is to study the changes that maps undergo as periodic point structure [20]. In particular, fixed points can be created or destroyed, or their stability can change. These qualitative changes in the dynamics are called bifurcations [19].

The plot of a bifurcation diagram is used to investigate chaotic evolutions for the change of a certain parameter. It is obtained from a time series by sampling and plotting local peaks and valleys of the waveform for a parameter change [18], as shown in Fig. (1.12) [7].

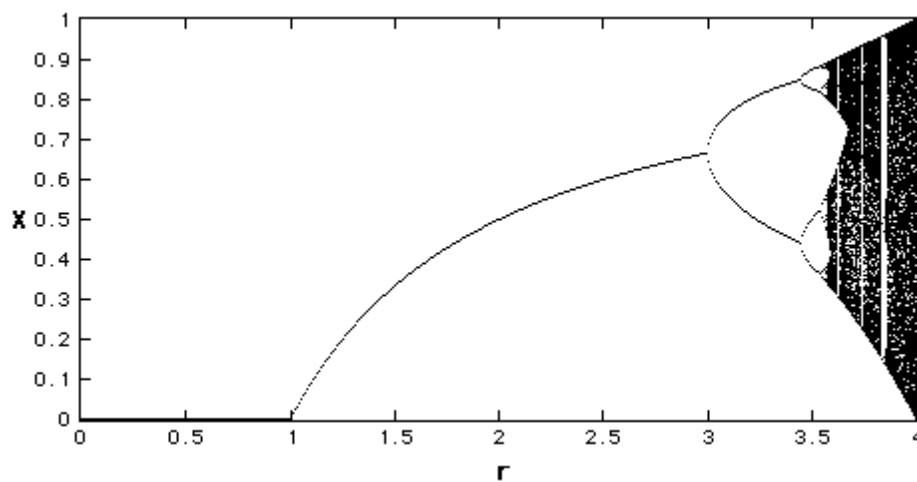


Fig. (1.12): Shows the bifurcation diagram of the logistic map, r along the x -axis between 0 and 4 [7].

when r is less than one there is no periodic point, all the points are plotted at zero. Zero is the one-point attractor for r less than one. For r between 1 and 3, we still have one-point attractors, but the 'attracted' value of x increases as r increases, at least to $r=3$. Bifurcations occur at $r=3$, $r=3.45$, 3.54 , 3.564 , 3.569 (approximately), etc., until just beyond 3.57 , where the system is chaotic.

The bifurcation sequence chaos of a semiconductor laser (SL) subject to delayed incoherent feedback was examined experimentally and numerically by Solorio et al [21]. While a bifurcation diagram for a SL with external optical feedback (OPB) was studied by Pieroux and Mandel [22].

There are many different bifurcations: saddle-node, Hopf, period doubling, torus... [8, 23]. The saddle- node bifurcation, is the basic mechanism by which fixed points are created and destroyed, as a parameter is varied. For example, the system $\dot{x} = r + x^2$, where (r) is a parameter, there are two fixed points , one stable and one unstable, as shown in Fig. (1.13) [12].

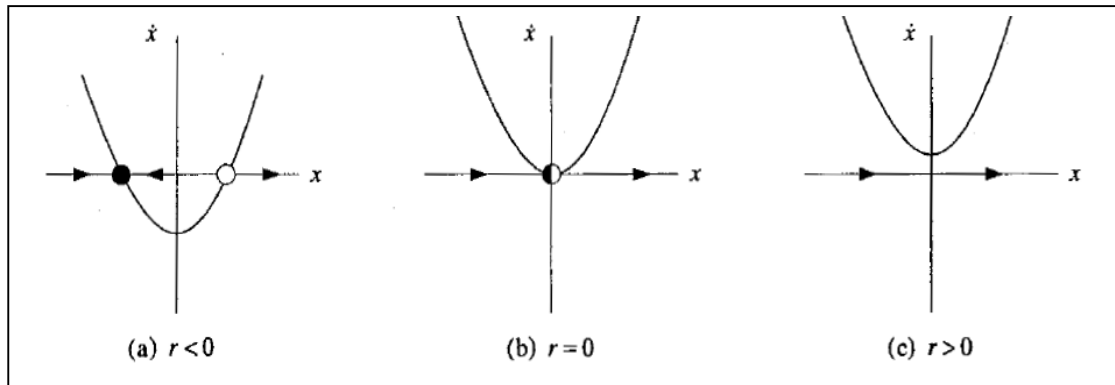


Fig. (1.13): Saddle-node bifurcation as r varied [12].

As $r < 0$, the parabola moves up and the two fixed points move toward each other. when $r = 0$, the fixed points coalesce into a half-stable fixed point at $x = 0$, the bifurcation occurred here. At $r > 0$, this type of fixed point vanishes and there are no fixed points at all.

The flip (or period-doubling) bifurcation occurs when a reversing orientation period point of p changes from attracting to repelling or vice-versa [23], as in Fig. (1.12).

Although these types of bifurcations also occur, but the Hopf bifurcation is the most typical of these, that is for higher dimensional systems. The simplest example of Hopf bifurcation is the system [20].

$$\begin{aligned}\dot{r} &= \mu r - r^3 \\ \dot{\theta} &= \omega + br^2\end{aligned}\tag{1.5}$$

where μ a parameter controls the stability of fixed point at the origin, ω gives the frequency of infinitesimal oscillations, and b a positive parameter determines the dependence of frequency on amplitude for larger amplitude oscillations, as in Fig. (1.14) [20].

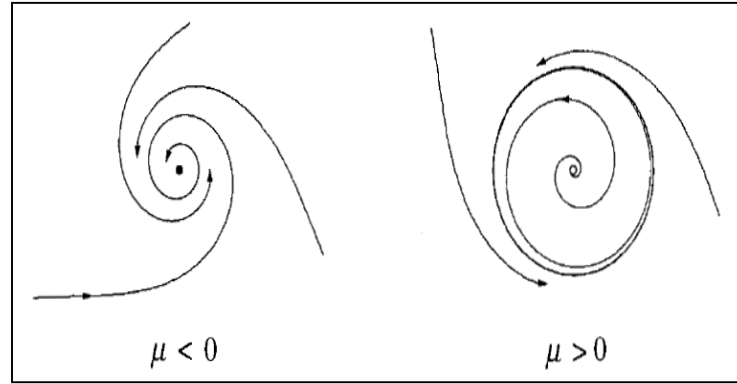


Fig. (1.14): The Hopf bifurcation, when the parameter μ is varied [20].

when $\mu < 0$, the origin $r = 0$ is stable spiral whose sense of rotation depends on the sign of ω . For $\mu = 0$ the origin is still a stable spiral, though a very weak one. Finally, for $\mu > 0$, there is unstable spiral at the origin and a stable circle at $r = \sqrt{\mu}$. The Hopf bifurcation can be supercritical or subcritical depending on the length of the delay and the pumping of the laser above threshold [10].

The relation between the bifurcation and chaos is given in Fig. (1.15) [24]

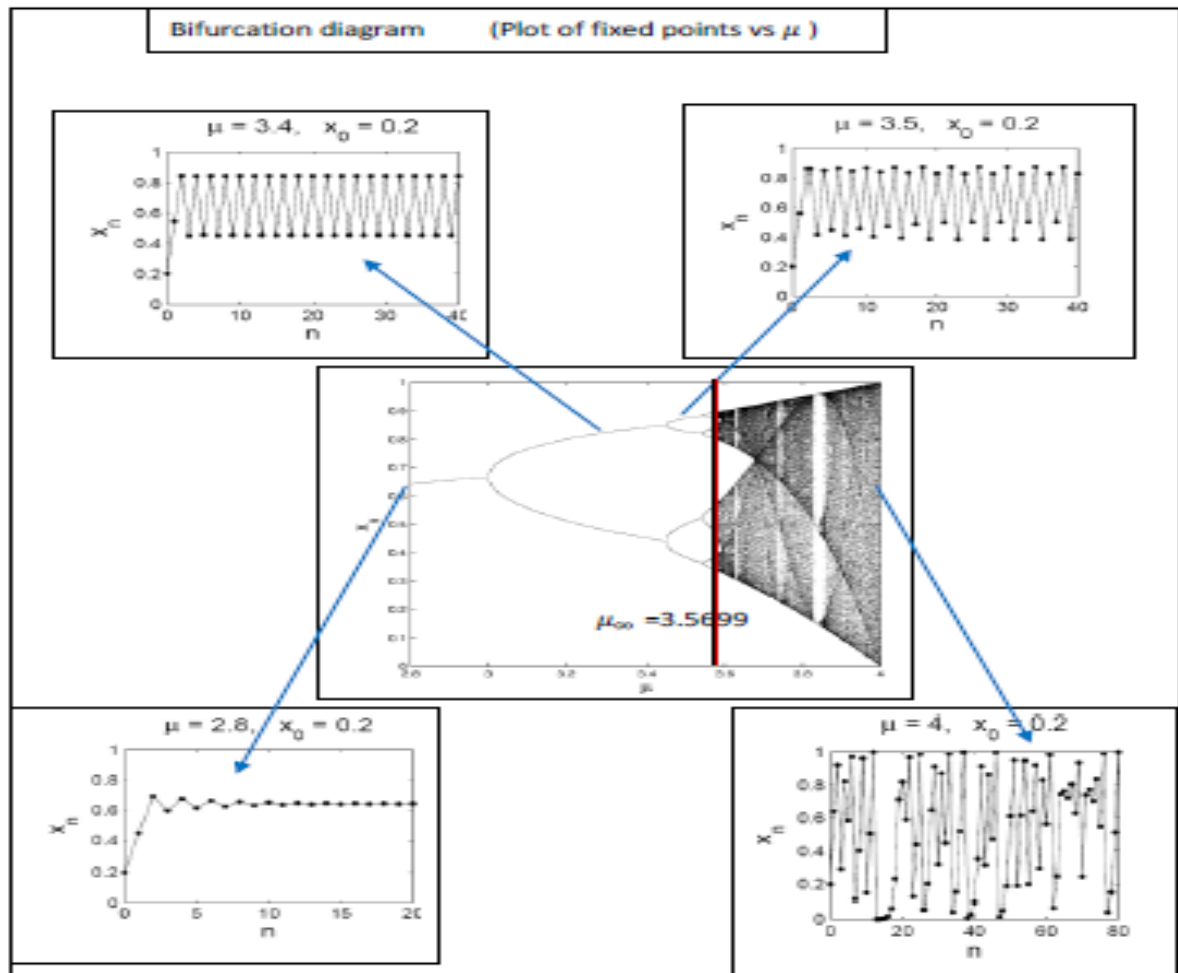


Fig. (1.15): The relation between the Bifurcation and chaos [24].

From Fig. (1.15) a few observations could be built:

- 1) Infinite series of period doublings at pitchfork-like (flip) bifurcations.
- 2) After a point $\mu = 3.5699$, chaos seems to appear.
- 3) Regions where stable periodic cycles exist occur between $\mu=3$ and $\mu=3.5699$.

Bifurcations are important scientifically, they provide models of transitions and instabilities as some control parameter is varied [12]. For example, a Fabry-Perot (FP) cavity is multi-stable if it has more than one equilibrium state, which belongs to the same value of the control parameter. Therefore, there is a critical value of the control parameter σ , for which a qualitative change in the equilibrium states occurs. These geometric arguments lead to the condition for

multi-stability, such that the FP cavity considered stable if $\sigma < \sigma_{cr}$, and multistable if $\sigma > \sigma_{cr}$, as in Fig. (1.16) [25]

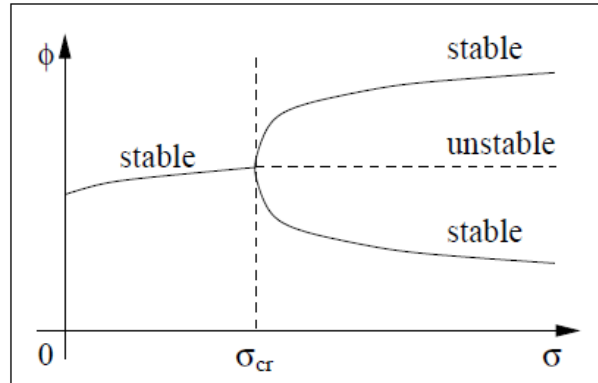


Fig. (1.16): Pitchfork bifurcation [25].

Fig. (1.16) shows that at $\sigma < \sigma_{cr}$, the cavity has only one equilibrium state. If σ is increased reaches the critical point $\sigma = \sigma_{cr}$ the equilibrium state splits into three states, two of the new states are stable and one is unstable. Keep increasing σ at some point another bifurcation occurs and more equilibrium states are created. Such a phenomenon is common in nonlinear physics and is called the pitchfork bifurcation, which is usually referred to as the qualitative transition from regular to chaotic behavior by changing the control parameter [25].

1.3.3 Time Series

Time series is a set of measures of behavior over time [7].

1.3.4 Fast Fourier Transformation FFT

The Fast Fourier Transformation is an older linear tool for examining time series transforms the time domain into a frequency domain, and examines the series for periodicity. The analysis produces a power spectrum and the degree to which each frequency contributes to the series [7].

1.3.5 Distribution of Inter-Spike Intervals (ISI)

The Inter-Spike Intervals is a model for studying the properties of irregular spiking homoclinic chaos, the dynamics of spiking and bursting in a neuron model. ISI mean measures time between consecutive spikes. The discrete distribution of ISI decays exponentially and have peaks located at all natural [27].

1.3.6 Ikeda Scenario

The Ikeda scenario turned out to be a paradigm for the dynamical behavior of delayed-feedback systems under the variation of control parameters [1]. The study of such systems was initiated by Ikeda. The key features of the Ikeda scenario are the occurrence of multistability of periodic or chaotic attractors and the onset of high-dimensional deterministic chaos via attractor merging. Recently, a SL system has been demonstrated to experimentally show the characteristic phenomena of this scenario.

The characterization and modeling of high-dimensional states ($N > 5$) with the help of embedding techniques is a fundamental problem due to the requirements on the amount of data and its precision [28].

1.3.7 Shilnikov Homoclinic Chaos

The geometry of SHC consists of regular orbits in phase space, which repeat themselves with a very small spatial variance. The return period of these orbits is widely fluctuating with very weak correlation between two successive returns [5,29]. Being the most apparent feature, it is convenient to characterize SHC through the statistics of the return intervals. The return map of successive return intervals consists of many branches which cross the fixed point line at a steep angle, so that successive iterations are sparse over the plane rather than

clustered along the diagonal, as it should be for correlated sequences. However, the highly unstable character of the return map makes the SHC extremely vulnerable to noise [6].

The analysis of the local model points to the existence of invariant dynamical structures in the full partial differential equation model are organized about the Shilnikov saddle-node bifurcation [30].

Consider a homoclinic orbit in a three dimensional phase space at a fixed point with a complex pair of unstable eigen values and a real stable eigen value. If there is a homoclinic orbit and also the condition is satisfied, then Silnikov showed that there are horseshoes and thus chaos in the return map defined near the homoclinic orbit [31].

Shilnikov [1969] described a bifurcation involving homoclinic orbits to a non-hyperbolic stationary point [32]. If there are $n \geq 2$ homoclinic orbits to the stationary point, and a parameter is varied so that the stationary point undergoes a saddle-node bifurcation, then on the side of the bifurcation where no stationary points exist locally there is an invariant set on which the dynamics is equivalent to a full shift on n symbols. From Shilnikov's Theorem the system has an infinite number of homoclinic orbits, as in Fig. (1.17) [31].

In slow-fast systems, a Hopf bifurcation can be followed by a period doubling cascade producing a sequence of small-periodic and chaotic excitable attractors, that develops before relaxation oscillations arise. As the mean amplitude of the chaotic attractors grows, some fluctuations of the chaotic background spontaneously triggers excitable spikes in an erratic but deterministic sequence [3].

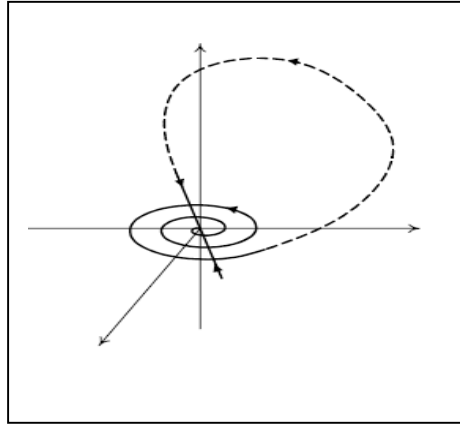


Fig. (1.17): Geometry of Shilnikov chaos [31].

We notice from Fig 1.17 that the behavior of a nonlinear system of differential equations (which have a homoclinic solution to an equilibrium point), the unstable curve leaving the origin. That is eventually returns to the stable plane, this situation of SHC occurs in three dimensional state space [6, 30].

1.4 Semiconductor Devices

Nonlinear dynamics of semiconductor devices are of great interest because of the important of these devices in many significant applications. Chaotic dynamics can be induced in a semiconductor device by increasing its dimension through a proper external perturbation, such as OFB, optical injection (OI), or OEFB [33, 34]. Its intrinsically stable lasers, and can be easily destabilized by the introduction of external perturbations [18].

Within the variety of dynamical regimes observed in semiconductor devices, Laser Diode (LD) or Light Emitting Diode (LED), chaotically spiking attractors play a special role where the typical time series consist of large pulses separated by irregular time intervals in which the system displays small-amplitude chaotic oscillations [35].

Quantum well semiconductor devices use a very thin active region, for example a 20 nm thick layer of GaAs bounded on each side by GaAlAs. The quantum well is a region of minimum potential energy for electrons in the conduction band and holes in the valence band. The reduced threshold injection current in these devices results largely because the very thin quantum well modifies the density of states available to electrons and holes. Recall that these particles have wave-like properties and must satisfy periodic boundary conditions within a box (just like black-body radiation) [36].

Arecchi et al. [37], (1984) investigated laser systems from the viewpoint of the characteristic relaxation times of the three variables and categorized lasers into three classes. According to their classifications, one or two of the relaxation times are in general very fast compared with the other time scales and most lasers are described by the rate equations with one or two variables. Therefore, they are stable systems that are categorized in class A and B lasers. Only class C lasers have the full description of the rate equations with three variables and can show chaotic dynamics. However, class A and B lasers can show chaotic dynamics when one or more degrees of freedom are introduced to the laser systems. Class B lasers are characterized by the rate equations for field and population inversion, and they are easily destabilized by an additional degree of freedom as an external perturbation [18].

In Class B and A laser, the short-timescale quantities can be integrated out effectively reducing the dimensionality of the system as follow:

Class C - 3D, (NH₃, Ne-Xe, infrared He-Ne).

Class B - 2D, (ruby, Nd, CO₂, LDs).

Class A - 1D, (visible He-Ne, Ar, Kr, dye lasers, quantum cascade lasers).

So a SL is a class B laser and it does not show chaotic dynamics, but it is easily destabilized by external disturbances such as external feedback and, as a result, shows chaotic dynamics [37], so that class B lasers themselves cannot exhibit

chaos. But class B lasers easily exhibit instability chaos when one or more degree of freedom is introduced to them.

1.4.1 Comparison semiconductor devices with other laser systems

semiconductor devices have many useful properties that are desirable for applications and in particular in the area of optical communications [38]. The following features distinguish semiconductor devices from other lasers [36]:

- They are build on one chip that contains everything necessary for a laser, his enables semiconductor devices to be easily be inserted in other instruments.
- High efficiency up to 50%, this enables them to be driven by low electrical power compared to other lasers.
- Direct excitation with small electric currents.
- Possibility of direct modulation with applied current.
- Small beam waist low costs due to mass production and high reliability made them a key component in various applications.

However, they also have some disadvantages. They are highly sensitive to temperature. Although this allows wide wavelength tenability, it is unwanted for most applications. Another important unwanted feature is their highly divergent beam [14].

One of the main differences between semiconductor devices and other lasers is low reflectivities of the internal mirrors in the active cavity. It ranges typically only from 10 to 30% of the intensity semiconductor devices. This makes the feedback effects significant in semiconductor devices.

Other difference is a large absolute value of the line width enhancement factor α . The value of $\alpha = 2$ to 6 was reported in SLs, while this value is almost zero in other lasers [13]. These facts lead to interesting due to it has a variety of dynamics different from other lasers [38].

1.4.2 Quantum Dots system

The term quantum dot (QD) is usually used to describe a semiconductor nanocrystal. Nanocrystals are classified by their size (in the range of 1-100 nm). They described as those having, at least one, dimension less than- or equal to- nanosize. QDs, also known as nanocrystals, are a nontraditional type of semiconductor crystals with limitless applications as an enabling material industries [39]. Low dimensional structures include (i) quantum well (QW), where the charge carriers are confined along the growth direction but free in other two directions, (ii) quantum wire (QWi), where the charge carriers are confined in two directions and allow free-carrier motion in only one dimension, and (iii) quantum dots (QD), where the charge carriers are confined in all the three directions, see Fig. (1.18). QW, or QWi confinement gains the electron at least one degree of freedom, but it still gives the electron at least one direction to propagate. On the other hand, today's technology allows us to create QD structures where electron subbands were quantized in all existing degrees of freedom [40]. The QDs, which can also be called artificial atoms, are nanometer-scale structures that selectively hold or release electrons. They consist of few hundred to few millions of atoms.

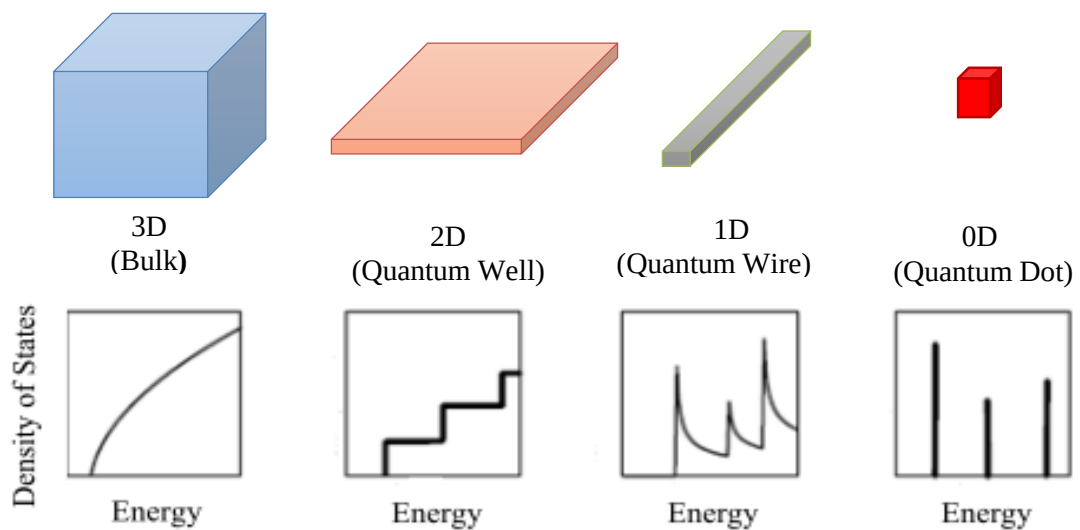


Fig. (1.18): Density of states for charge carriers in structures with different dimensionalities [40].

QDs bridge the gap between the single atoms and the solid state and, because of this, they exhibit a combination of atomic and solid-state properties. Moreover, due to the fact that the size of the semiconductor nanocrystal is small compared with the size of the exciton (electron-hole), charge carriers become spatially confined, which raises their energy (quantum confinement) [41]. Thus, the size and shape-dependent optoelectronic properties are attributed to the quantum confinement effect. Because of this effect, light emission from these particles can be tuned, they show symmetrical and narrow emission spectra and broad absorption spectra. QDs are grown by the self-organized process in a wetting layer (WL), a two-dimensional quantum-well layer. Advanced QD growth techniques, such as molecular beam epitaxy (MBE) and metalorganic chemical vapor deposition (MOCVD), make it possible to manufacture QD structures which were free from surface defects. The crystal growth on a bulk substrate occurs in one of three distinct modes, schematically shown in Fig. (1.19). Thus, QD structure consists of completely quantized subbands in the QDs attached with a two-dimensional WL [40].

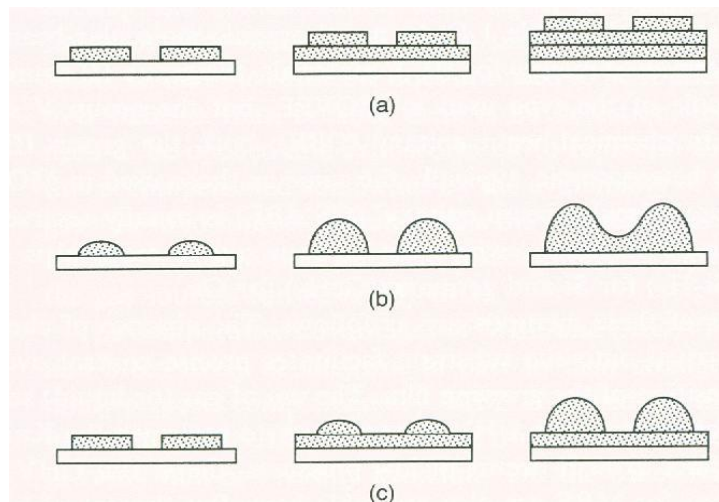


Fig. (1.19): Three types of growth mode on a substrate; (a) Frank-van der Merwe; (b) Volmer-Weber; and (c) Stranski-Krastanow (SK). In the Frank-van der Merwe mode growth proceeds layer by layer [40].

1.4.3 Quantum Dots Light Emitting Diode

Semiconductor quantum dots light emitting diode (QD-LED), as they are often called—are an integral part of modern technology. QD-LED are widely used as incoherent light sources in applications such as lighting and short-distance optical fiber communications. An important performance characteristic of a QD-LED is the output efficiency, i.e., the amount of light extracted from the structure at a given input current. Since higher modulation speed implies a larger information capacity, a high modulation speed is important for short-distance communication applications [42].

Some light sources exhibit intensity and phase fluctuations. These fluctuations are of great importance since they detect errors in optical measurements. Their origin lies in the quantum nature of transition process itself. In fact, every spontaneous emission event in the oscillating mode varying the phase of the electromagnetic field (quantum noise) is responsible for the carrier density variation [43].

1.5 Chaotic spiking in semiconductor devices

In the case no feedback is present, several dynamical behaviors including stable, pulsating and quasi periodic are observed [44]. When a semiconductor device is subjected to one or more perturbations such as OFB, OI, OEFB and optical modulation, it can display rich nonlinear dynamics including chaos [45]. Semiconductor device with feedback is an excellent model for nonlinear optical system which shows chaotic dynamics [46].

One of the characteristics of semiconductor device that is different from other lasers is the direct pump modulation, the disturbance to the injection current is an additional degree of freedom. Therefore, the disturbance due to the injection current induces instabilities in semiconductor devices. It has been proposed that these instabilities are actually a form of deterministic chaos which resulting from the interplay between the many degrees of freedom in the system

[47], and the number of dimensions is equal to the number of initial conditions [8].

1.5.1 The Optical Feedback

The static characteristics of SLs with optical feedback (OFB) can be theoretically investigated with the relations among the reflectivities of internal cavity and external reflector, the gain in a medium, and other static laser parameters. The dynamic characteristics must be described by time dependent equations of the systems. The equations for semiconductor lasers in the presence of OFB are obtained by modifying the rate equations for the solitary laser and the schematic model of a SL with OFB is shown in Fig. (1.20) [1]

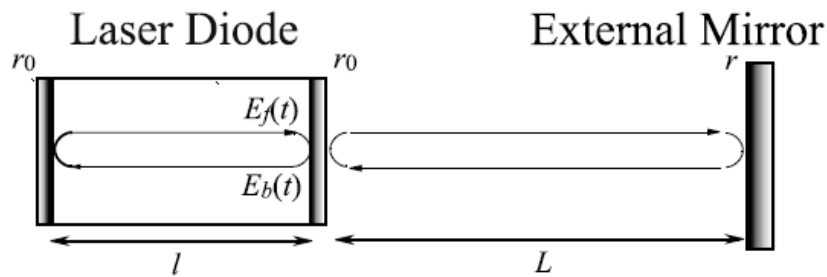


Fig. (1.20) Model of SL with OFB [1].

Fig. (1.20): shows that light from a laser is reflected from an external mirror and feedback into the laser cavity with time delay. Assume that the mirror is positioned within the coherence length of the laser. Also, the laser is assumed to be operated at a single mode, the external feedback effect is added to the equation for the complex field.

Consider the fields propagating forward and backward within the cavity and the extra term added to the laser field from the OFB. The feedback develops an increasingly pronounced spatially periodic modulation.

This periodic modulation introduced small periodic perturbation in the gain coefficient of the laser medium which leads to the fluctuation in the index of

refraction. The relations describing the perturbation in the gain and the index of refraction can be written as [48]:

$$\begin{aligned}\zeta(z) &= \zeta_o + \zeta_1 \cos(2\beta_o z) \\ n(z) &= n_o + n_1 \cos(2\beta_o z)\end{aligned}\tag{1.6}$$

where $\beta_o = \pi/\Lambda$; $\Lambda = \lambda/2$, Λ is grating period, ζ_o and n_o are the static gain and refractive index, ζ_1 and n_1 are constant depends on the level of the injected signal. This fluctuation introduce a modulation in the optical field through the medium, as the level of fluctuation increased above a certain value (threshold value). The electromagnetic wave with a periodic modulation in phase is started, and the wave can be represented as [48]:

$$E(t) = E_o \exp[i\{\omega_o t + \beta \sin(\omega_m t)\}]\tag{1.7}$$

where ω_m is the modulation frequency and β is the modulation index which is given by:

$$\beta = \frac{\Delta\omega}{\omega_m}\tag{1.8}$$

where $\Delta\omega$ is the maximum frequency deviation. Thus the electric field of the propagated Electro Magnetic (EM) wave consists of a carrier wave of frequency ω , subjected to random amplitude and phase modulation, can be written as [49]:

$$E(t) = E_o \exp(-i\omega_o t) a(t) \exp(i\varphi t)\tag{1.9}$$

This formula describe a full dynamical instable state of the laser diode which sometime called the interior crisis [15].

The SLs with OFB have received considerable attention due to their application in optical chaos communication [50].

In chaotic dynamics in SLs with OFB the system generates very fast chaotic signals and it is used as transmitter and receiver in chaotic secure communications since it can construct a very high-speed communication channel [51] and instability in SLs is much enhanced by OFB from an external reflector [48].

1.6 Literature Review

Technical progress in the field of LEDs has been attractive during the last few decades. State-of-the art LEDs are small, rugged, reliable, bright, and efficient. In contrast to many other light sources, LEDs have the potential of converting electricity to light with near-unity efficiency.

The success story of LEDs has not ended but is still in full progress. Great technological advances will surely continue to be made. As a result, it is expected that LEDs will play an increasingly important role as light sources and will become the dominant light source in the future. Followed the demonstration of semiconductor lasers. The first viable LEDs were by-products in this pursuit. During the last 40 years, LEDs have become devices in their own right and today are versatile light sources with a bright future [16].

QD researchers began at the half of nineties of the last century, although earlier prediction that appears in the literature of nanostructures tells that it is only a theoretical insight and experimentally unobtainable. Ledentsov, et al. [52] was the first group that obtains a laser light from QD laser. In our laboratory the work on QD theory began earlier, for example see [53].

M. Kunts et.al. present a progress in the field of QD semiconductor lasers and optical amplifiers with InAs based self-assembled QDs in the active region for optical telecommunication [54]. T.Erneux et.al investigated the electronic structure of cleaved InAs QDs that are embedded in GaAs by means of scanning tunneling spectroscopy at low temperatures [55]. One of the interesting properties of QD lasers respect to the QW counterpart is the possibility of achieving two-state or three -state lasing. It means that lasing starts at low current injection from the GS transition, then with increasing current, the lasing can occur simultaneously also from ES. This effect can be achieved in QD lasers because [56] the carrier density in the states not resonant with the lasing modes, (i.e., upper ES, GS of non-lasing dots) is not clamped at the value of the GS threshold, but it increases with current allowing other longitudinal modes, at the ES lasing transition, to reach the threshold condition [57]. Short pulses and detuning independent at a high carrier density, which are desirable characteristics for optical communications applications was studied in QD [58].

From a dynamical systems point of view, QD lasers are characterized by a time scale separation between the fast photon and the slower carrier subsystem, i.e., they are typical slow-fast systems [59]. As a consequence, their turn-on dynamics shows damped nonlinear intensity oscillations, which are called relaxation oscillations (ROs). The damping of the ROs is a key point in order to understand the stability properties of the laser subject to external perturbations, for instance, optical feedback or optical injection. QW lasers show pronounced, weakly damped ROs, while the ROs of QD lasers are strongly damped [60]. As a result, QD lasers display a higher dynamical stability under optical injection [61] and optical feedback [62].

The present systematic study, by Otto et. al. [57] the complex dynamics of a QD laser subjected to optical feedback from a short external cavity, is an important contribution. This model consists of a Lang-Kobayashi like model for the electric field combined with a microscopically based rate equation system [63]. For a small energy spacing, short lifetimes (large scattering rates) are obtained. They are on the same time scale, or shorter than, the photon lifetime yielding overdamped, very stable devices, which act similar to gas lasers, i.e., typical class A laser. For large energy spacing, long carrier lifetimes on the order of pico-seconds are obtained, which guarantee a clear time-scale separation between the carrier and the photon subsystem (time-scale of femtoseconds) resulting in weakly damped, less stable lasers, whose dynamics is similar to conventional QW lasers, i.e., typical class B lasers. QD lasers lie in-between these two limiting cases and exhibit typical dynamical features of class A and class B lasers [64].

Recently, QD-LED is considered as a next technology after organic light emitting diodes (OLED). Nowadays, it has been studied as a short distances light emitting source, which could provide an alternative for applications such as communication. Because QD-LEDs, have several advantages—such as tunable emission wavelength with changing particle size and narrow emission spectrum (characterized by its full width at half the maximum value) [65].

The OEFB and direct current modulation DCM in QD-LED is done, by Al- Hussein. et al. [66] where both positive and negative OEFB are studied. They found that QD-LED with OEFB is more sensitive to the changes in time delay compared with other SLs. A regular pulsing state, a high period and a quasi-period are observed in the behavior of QD-LED with OEFB. Additionally, mixed-mode oscillations (MMOs) have been observed in this

thesis. At the same year, Al-Husseini et. al. numerically analysed the characteristics and the synchronization of two QD-LED with OEFB in 2015. The systems exhibit broadband chaotic intensity oscillations whose dynamical dimension generally increases with the time delay in the feedback loop (open-loop scheme) [66]. Al-Husseini et al were completed the dynamical attractor analysis demonstrating theoretically the occurrence of complex sequences of chaotic in a QD-LED with filtered optical feedback (FOF) in 2016 [67].

1.7 Aim of thesis

The aim of this thesis is presenting a theoretical model, studying the existence of chaotic in the dynamics of QD-LED with OFB and OI. It reviews the rate equations of QD-LEDs as dimensionless model. Effects of the OFB and IO are discussed as well, and current results for investigations are presented.

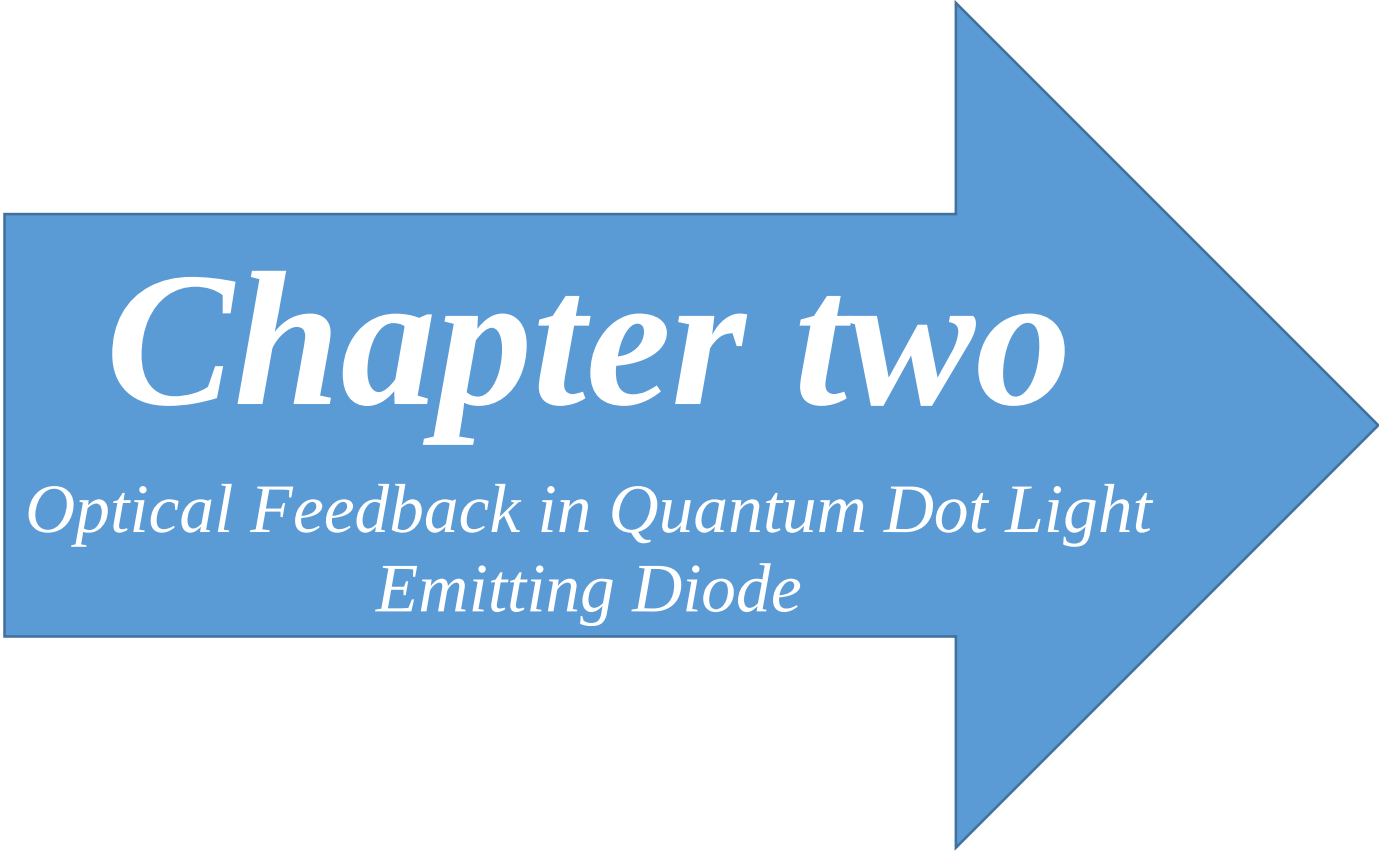
1.8 Thesis Outline

This thesis is organized as follows: In chapter two introducing the field equation with the OFB which that describing our model in the dimensionless differential equations in Section 1.3, study the bifurcation scenarios of the light emitting output that occur by changing the OFBS with the impact of the parameters variation in Section 2.4. Adding the grating mirror as a special technique to suppress unwanted frequencies was discussed in Section 2.5. Delay time, turn-on dynamics and effect of linewidth enhancement factor are studied in Section 2.6, 2.7 and 2.8, respectively.

In chapter three introducing the field equation with the OI (master and slave) describing our model in the dimensionless differential equations in Section 3.2. Study the bifurcation scenarios of the light emitting output that occur by

changing the bias current for the master and slave, and frequency detuning between them. Effect OI, transition mode controlling and locking and two modes dynamics with two parameters effect are studied in Section 3.3, 3.4 and 3.5 respectively the work was concluded.

Chapter four this is includes the conclusions from the theoretical results obtained in this thesis, as well as the suggestions.



Chapter two

*Optical Feedback in Quantum Dot Light
Emitting Diode*

2.1 Introduction

Nonlinear optical properties of the LED attracted the attention of many researchers because of its applications in local encrypted optical communication [65,68] and its use in the generation of random light [69]. However, random disturbances and spikes sudden pointed fluctuations of any structure limitation, typically observed between natural and laboratory systems on a scale, can disturb multiple dynamics and are extremely stable and become a serious barrier when the system is designed for a specific dynamic behavior [70].

The outstanding performance of the self-assembled QD material makes it extremely attractive for use as optical communication systems. It has reduced temperature and independent current threshold and suitable emission in fiber-optic windows. These characteristics, combined with a low-grade and low-spectrum lamination factor, make QD materials extremely attractive to the application of amplifiers or light emitter [71]. The last property is important especially in fiber optical telecom applications. Therefore, a lot of experimental and theoretical work has been done to identify a numerical or other measurable factor that defines a system or sets the conditions of its operation that have the strongest impact on the stability properties of a light emitting subject to optical feedback [72, 73]. In thesis we consider a four-variable rate equation model that combines in a semi-classical approach a Lang-Kobayashi type field equation [71] with the carrier rate equations. We present a nonlinear rate-equation analysis which incorporates the important aspects of electronic transitions. We apply the analysis to propose a rate equations model of three levels states addition the phase equation in dimensionless form that exhibits extremely complicated behaviors of QD-LEDs under optical feedback, taking into account

each of the photon absorption, spontaneous emission and nonradiative recombination processes.

2.2 Optical Feedback Theoretical Model

Nonlinear differential equation system can be used to model the dynamics of the QD-LED. Studying of this system allows theoretically examination of the properties of QD-LEDs, their bifurcation analysis, and their selection attractor. In this work the implementation of the new feedback is provided by the model of QD-LED [74, 75].

The fixed properties of the semiconductor QD-LED can be considered theoretical under optical feedback with relationships between internally processes and external invertebrates, the recombination process in the center, and other fixed parameters. However, the dynamic properties must be described by the system time-dependent equations. QD-LED semiconductor equations can be obtained in the presence of optical feedback easily by modifying the rate equations of the solitary QD-LED. Fig. (2.1) illustrates the schematic model of QD-LED under optical feedback with a conventional external reflection mirror.

The effects of other parameters reflectors such as feedback strength, delay time and grating mirrors will be discussed later. The light of the QD-LED is reflected from the external mirror and feedback into the QD-LED with time delay. We assume that the mirror is placed within a length of hold QD-LED. Also, the QD-LED is supposed to be run in one mode, although this is unlike reality. QD-LED occasionally oscillates in a multimode under certain parameters conditions of the optical feedback even when oscillates at a single mode in a solitary state. The effect of external feedback [72] is added to the

equation of the complex field and the field equation is written in the following equation [66,72],

$$\frac{dE(t)}{dt} = -\frac{1}{2}(1 + i\alpha)Wn_{QD}E(t) - \frac{\gamma_s}{2}E(t) + Esp(t) + \frac{\kappa}{\tau_{in}}E(t-\tau)e^{i\omega_o\tau} \quad (2.1)$$

κ is the feedback coefficient due to the external optical feedback, τ_{in} is the round trip time of light in the cavity, ω_o is the angular oscillation solitary frequency of the QD-LED. The extra term has a delay time τ and the complex field $E(t)$ is described by a delay differential equation and this is the origin of instability and chaotic dynamics in QD-LED and $\alpha \left(\frac{Re\{\chi\}}{Im\{\chi\}} \right)$ is the linewidth enhancement factor which means guide to asymmetric nature of electrons and holes distributions in semiconductor, n_{QD} is the number carrier in the QD ground state, γ_s is the output coupling rate of photons in the optical mode and W is the Einstein coefficient given by $W = \{(|\varrho|^2 \sqrt{\epsilon_{bg}})/(3\pi\epsilon_o\hbar)\}/(\omega/c)^3$ [72]. Where ϵ_{bg} , ϵ_o are the static relative permittivity of background medium and the vacuum permittivity respectively, c is speed of light in vacuum, and ϱ is the dipole moment of QDs, $\hbar$ is Planck's constant, and the frequency ω . The feedback coefficient κ can be calculated from considering the multiple reflection effects of light in the external cavity.

Distributions of carriers population in each of WL and QD are taken into account explicitly in order to determine the acceptable relation between absorption and spontaneous emission spectra. $E_{sp}(t)$ is the stochastic function corresponding to the spontaneous emissions zero-mean random field. This field has the relation of $\langle E_{sp}(t)E^*(t) \rangle = R_{sp}/2$ [76]. Asterisk (*) denotes the complex conjugate. The term R_{sp} is usually used for the effect of spontaneous emission in the photon number equation and is given by [66]

$$R_{sp} = W n_{QD}^2 \quad (2.2)$$

In Fig. (2.1 (a)), we consider the fields to be spread forward and backward within the cavity and add an additional term to the light field of the optical feedback in front of the resonator object.

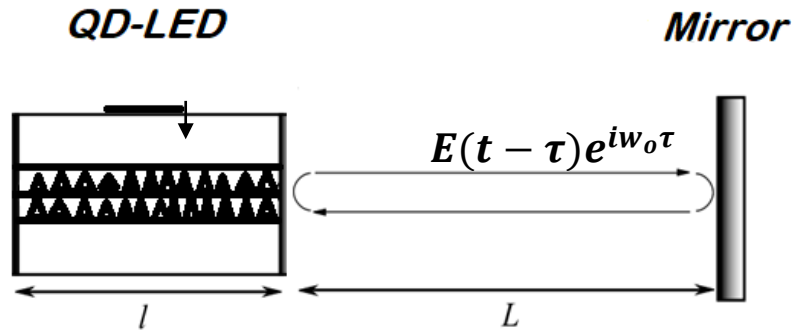


Fig. (2.1 (a)): Schematic setup of the considered QDLED device with optical feedback from a short external cavity.

2.3 Quantum Dots Light Emitting Diode Model

QD-LED model describes the electrons that are injection into WL before they are captured by the QDs firstly, then they exposed to the absorption, spontaneous emission and nonradiative recombination operations. Differential equations describe the dynamic of the number of carrier in the QD ground state n_{QD} , the number of carrier in WL is n_{wl} , after the our transformation to Eq.(2.1) for the number of photon in the optical mode s , [74] and the phase of the electric field ϕ which is the time dependent and plays an important role, since the phase couples with the other variables.

Hence the full model we examine as [66,72],

$$\begin{aligned}
 \frac{ds}{dt} &= -\frac{1}{2}W n_{QD} - \frac{\gamma_s}{2}s_t + Wn_{QD}^2 + \frac{k}{\tau_{in}}\sqrt{s_t s_\tau} \cos(\omega\tau + \varphi_t - \varphi_\tau) \\
 \frac{d\varphi}{dt} &= \frac{1}{2}\alpha W n_{QD} - \frac{k}{\tau_{in}}\sqrt{s_t/s_\tau} \sin(\omega\tau + \varphi_t - \varphi_\tau) \\
 \frac{dn_{QD}}{dt} &= \gamma_c n_{wl} \left(1 - \frac{n_{QD}}{2N_d}\right) - \gamma_{r_{QD}} - (Wn_{QD}^2 - Wn_{QD}s) \\
 \frac{dn_{wl}}{dt} &= \frac{I}{e} - \gamma_{r_{wl}} - \gamma_c n_{wl} \left(1 - \frac{n_{QD}}{2N_d}\right)
 \end{aligned} \tag{2.3}$$

Here, the induced processes of spontaneous emission and absorption in the QDs are modeled by the first and third terms of the first equation in system Eqs. (2.3) [75]. The phase delayed $\varphi_\tau = \omega\tau$, $\gamma_{r_{QD}}$ and $\gamma_{r_{wl}}$ are the non-radiative decay rates of the number of carriers in the QD and WL respectively, and I is the injection current, the other parameters are refer as N_d is the number of QDs, e is the electron charge, γ_c is the capture rate from WL into the dot, as shown in Fig. (2.1 (b))

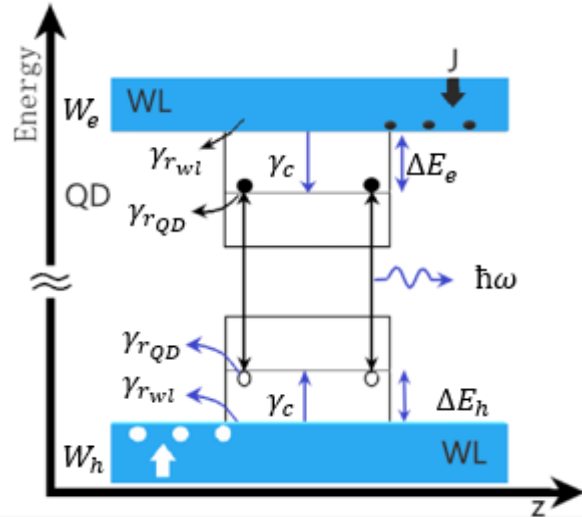


Fig. (2.1 (b)): Energy diagram illustrates the two recombination mechanisms considered in this work of the active layer QDLED; recombination radiative and non-radiative via deep level and reabsorption recombination processes [72].

For that, we rewrite the system Eqs. (2.3) to a set of dimensionless equations. Defining a new variables and dimensionless parameters by the following,

$$x=s, y = \frac{W}{\gamma_s} n_{QD}, z = \frac{n_{wl}\gamma_s}{W}, \gamma = \frac{\gamma_s}{\gamma_{rwl}}, \gamma_1 = \frac{W}{\gamma_s}, \gamma_2 = \frac{W}{\gamma_{rwl}}, \gamma_3 = \frac{\gamma_{rQD}}{\gamma_{rwl}}, \gamma_4 = \frac{\gamma_c}{\gamma_{rwl}}$$

$$N_d \equiv a \text{ and } \delta_\circ = \frac{I}{We}, \text{ and the time scale } \dot{t} = \gamma_{rwl} t.$$

After the our transformation to Eqs.(2.2) the system Eqs.(2.3) can be rewritten in the following:

$$\left. \begin{aligned} \dot{x} &= \gamma \left(\left(\frac{y^2}{\gamma_1} \right) - x(y+1) + 2\sqrt{x_\tau} x_t \eta \cos(\omega_\circ \tau + \varphi_t - \varphi_\tau) \right) \\ \dot{\phi} &= \frac{1}{2} \alpha y \gamma - \eta \sqrt{x_\tau / x_t} \sin(\omega_\circ \tau + \varphi_t - \varphi_\tau) \\ \dot{y} &= \gamma_2 z \left(\gamma_1 - \frac{y}{2a} \right) - y(\gamma_3 + \gamma y) + \gamma_2 x y \\ \dot{z} &= \gamma_4 \left(\delta_\circ - z + \frac{yz}{2\gamma_1 a} \right) - z \end{aligned} \right\} (2.4)$$

here the upper subscript “dot” (·) refers to differentiation with respect to ($\dot{t}$). The bias current is represent by ($\delta_\circ$). Where $t' = \gamma_{rwl} t$ and $\eta = \frac{K}{\gamma_{rwl} \tau_{in}}$.

Then, four coupled equations are essential for QD-LED with optical feedback and they show unstable oscillations and chaotic dynamics in their output powers like three coupled equations in Lorenz systems. In the numerical simulations, the fourth-order Runge-Kutta algorithm. The parameter values used in the simulations are given in Table (2.1), where it can be compared with experimental results in this filed.

Table. 2.1 Numerical parameters used in the simulation unless stated otherwise [66].

Parameters	value	Parameters	value
x_0	0.066	γ_2	0.026
y_0	0.066	γ_3	0.03
z_0	0.99	γ_4	0.078
φ_0	0.0049	α	2
γ	0.158	ω_0	0.008
γ_1	0.049	a	0.891

2.4 Effect of Optical Feedback Strength

When studying the effect of Optical Feedback Strength (OFBS) on this system, is taken for the study of this section, at a small value of bias is equal to $\delta_0 = 0.013$ (at this value when absence of feedback and delay time, the system is in the chaotic state, from the results of the model [78]) and delay time $\tau=0.1$, which is fixed when studying this effect. The plot of a bifurcation diagram is used to investigate chaotic evolutions for the change of the OFBS. A bifurcation diagram is obtained from a time series by sampling and plotting local peaks and valleys of the waveform for the OFBS change.

Fig. (2.2) shows the behavior of a sequential (in order) dynamic from chaotic to a period state with a range of (0-0.03 small feedback regime) for OFBS, when at zero the QD-LED behavior is chaotic and in increasing value of

OFBS to 0.002 it shows the behavior of the 1^2 period state then the chaotic return appears until 0.05 of OFBS.

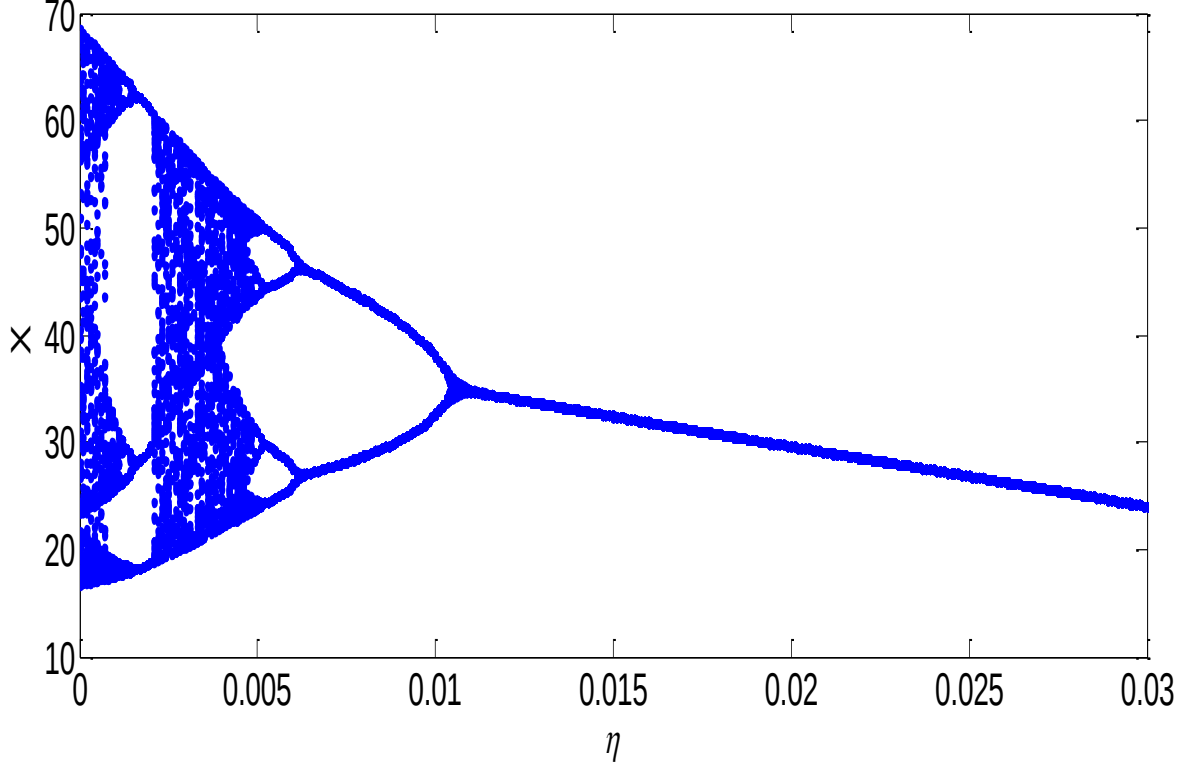
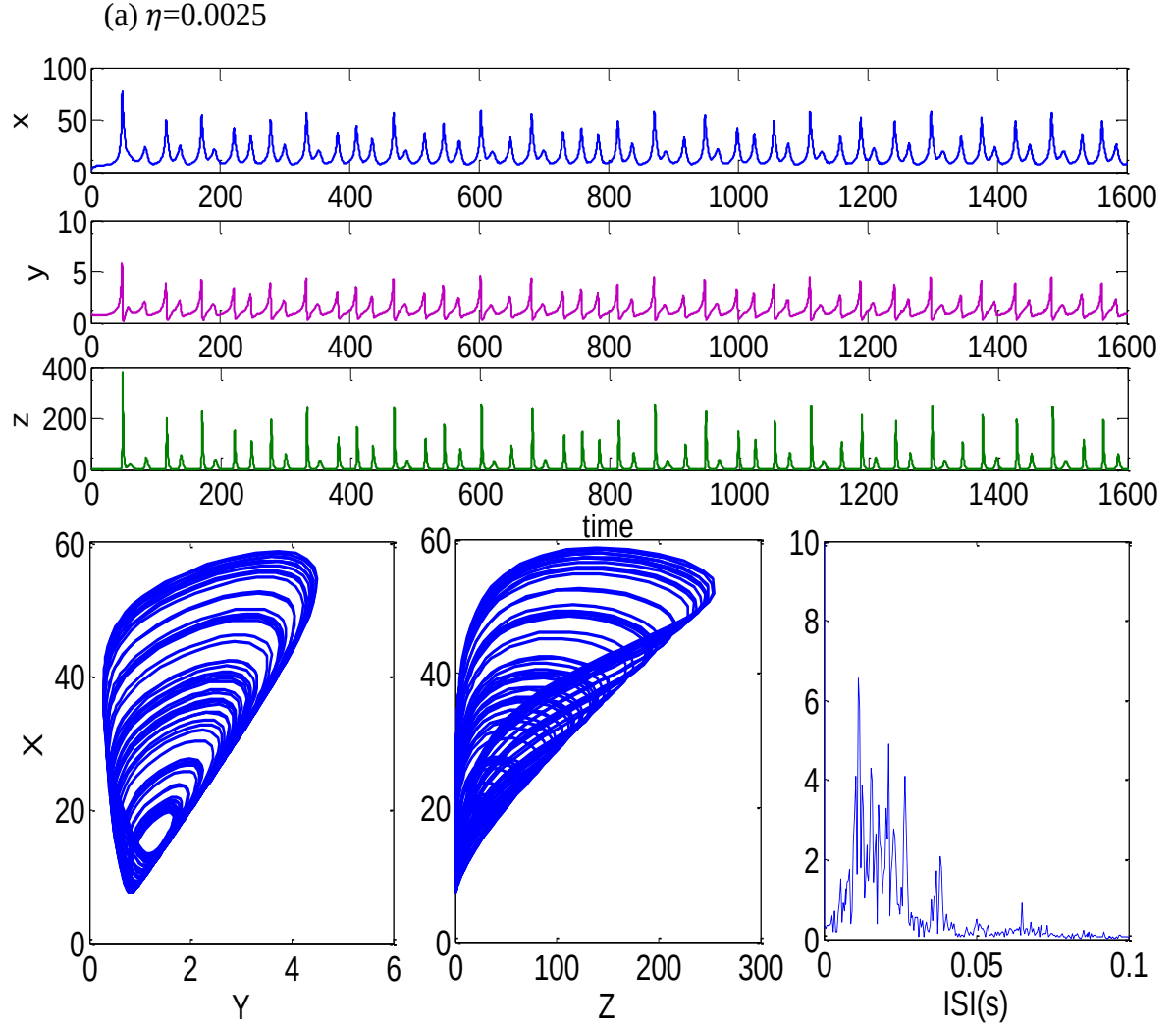


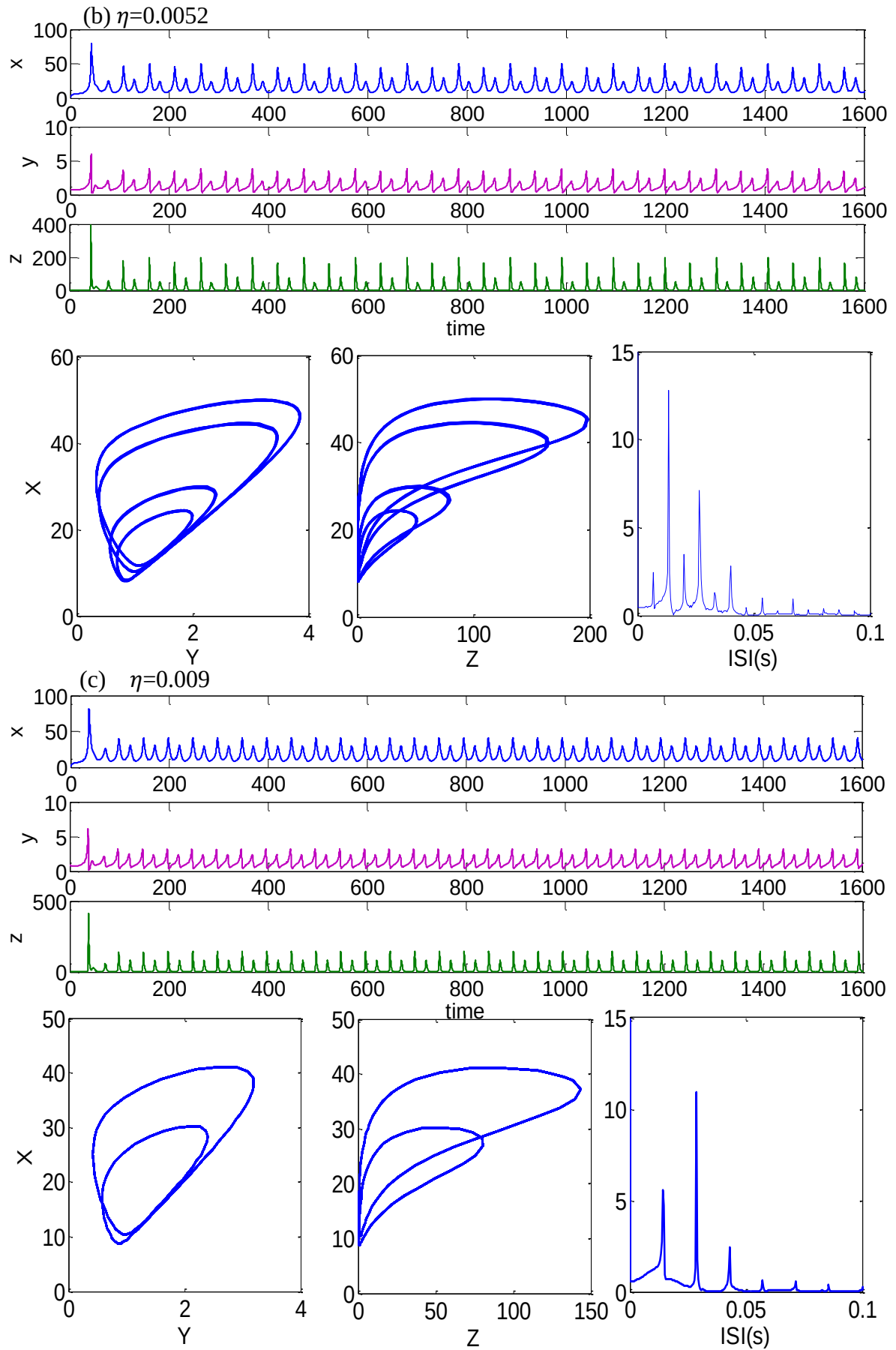
Fig. (2.2): Calculated chaotic bifurcation diagrams of the photon density as a OFBS at a bias injection current of $\delta_o=0.013$ and the external delayed time $\tau=0.1$.

The behavior that is shown in Fig. (2.2), an expected result, due to the significant effect of OFBS on the output power, which is shown by decreasing amplitude with increasing of the OFBS effect. To more explaining the dynamics of Fig. (2.2) as variations of the feedback strength, Fig. (2.3 (a)) shows time series, phase portraits (attractors) of the complex turn-on dynamics for both carrier types and ISI distribution for the chaotic spiking regime at OFBS is equal 0.005. The chaotic spiking state disappear, when we arise the strength of the optical feedback to 0.006 from the output signal the 1^3 period state is observed in Fig. (2.3 (b)). The shape of the attractor and ISI is mainly controlled by the OFBS.

It can be seen that the different dynamics of electrons in QD and WL is related to different configurations of the intersections of the time series as period doubling and period with small-amplitude oscillations as in Fig. (2.3 (c)) and Fig. (2.3 (d)) respectively.



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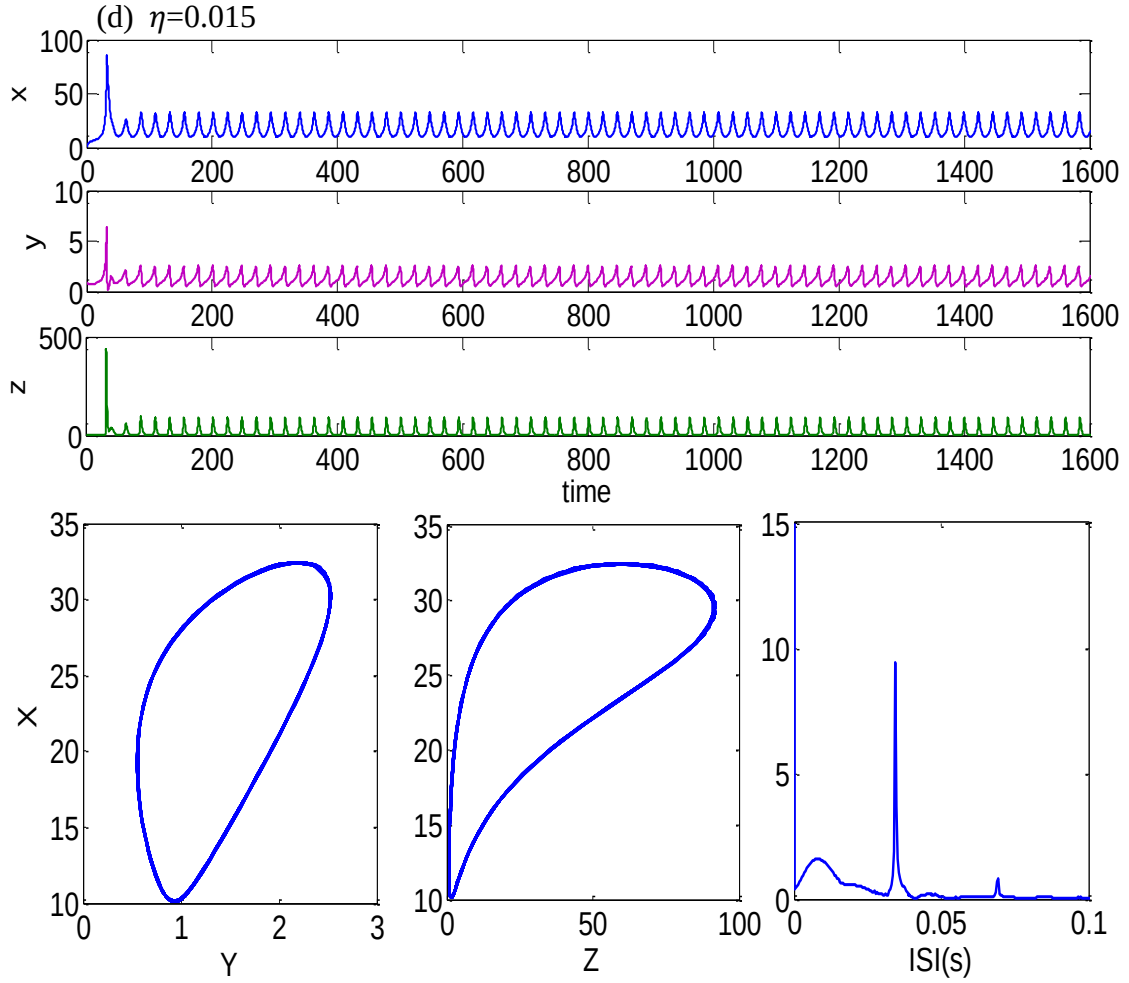


Fig. (2.3): Time series, Phase portraits (attractor) and ISI of the peak series corresponding to bifurcation diagram shown in Fig. (2.2). (a) $\eta = 0.0025$, (b) $\eta = 0.0052$, (c) $\eta = 0.009$, (d) $\eta = 0.015$.

Besides, at different values for τ , as a result, the changing of OFBS value has the effect apparent on the behavior of photons. When the delay time corresponding to the round trip time of light in the external cavity is large enough compared with the coupling rate in cavity, we show the difference dynamics of QD-LED which is distinct. In Fig. (2.4 (a-c)) bifurcations diagram appear chaotic behavior increasing and occupation large range until it exceeds 0.027 of OFBS at $\tau = 10$. But, if the external cavity length becomes large ($\tau > \tau_{in}$) they show return dynamics gradually until it becomes similar to the form in

Fig. (2.2) when the corresponding rate exceeds to $\tau=30$. At the end of the statement, the league was proved periodic of τ by a range of 0.1 to 30, the end of chaotic state in bifurcation Fig. (2.4 (a)) which is at 0.005 of OFBS, while at $\tau=5$ equals the end of the chaotic state to 0.006 until it reaches 0.01 at $\tau=7$, and the end of the cross at $\tau=10$ is 0.027 and then regenerates itself to be the end of the bifurcation at $t=30$ is equal to less than 0.005 of OFBS as Fig. (2.4 (d)).

Other than Fig. (2.5 (a)) shows increasing value of the bias to 0.1 QD-LED (with case of OFBS is equal to zero the behavior of the photons will be double-period), the outer fixed-points have the same stability property as the original fixed-points one call this bifurcation a pitchfork bifurcation because the bifurcation diagram resembles a pitchfork. When OFBS value reach to 0.01, the behavior of photons are forced to periodic, and when we take $\delta_o=0.2$ Fig. (2.5 (b)) the bifurcation still without changing, i.e. bias has a clear effect and greater than the OFBS. Actually, when bias is equal to 0.2 the behavior essentially is periodic, there is no effect of OFBS and for τ . Thus, the effect of (OFBS) is reduced by increase the bias and it is not present at significant values for bias greater than $\delta_o=0.2$. Thus, Bias dominated the course of the photons, in which he turns from chaos to periodicity at a great value. It has the opposite of the above and it is chaos at the same value which is 0.05, while at large values we observe the slightly effect of OFBS.

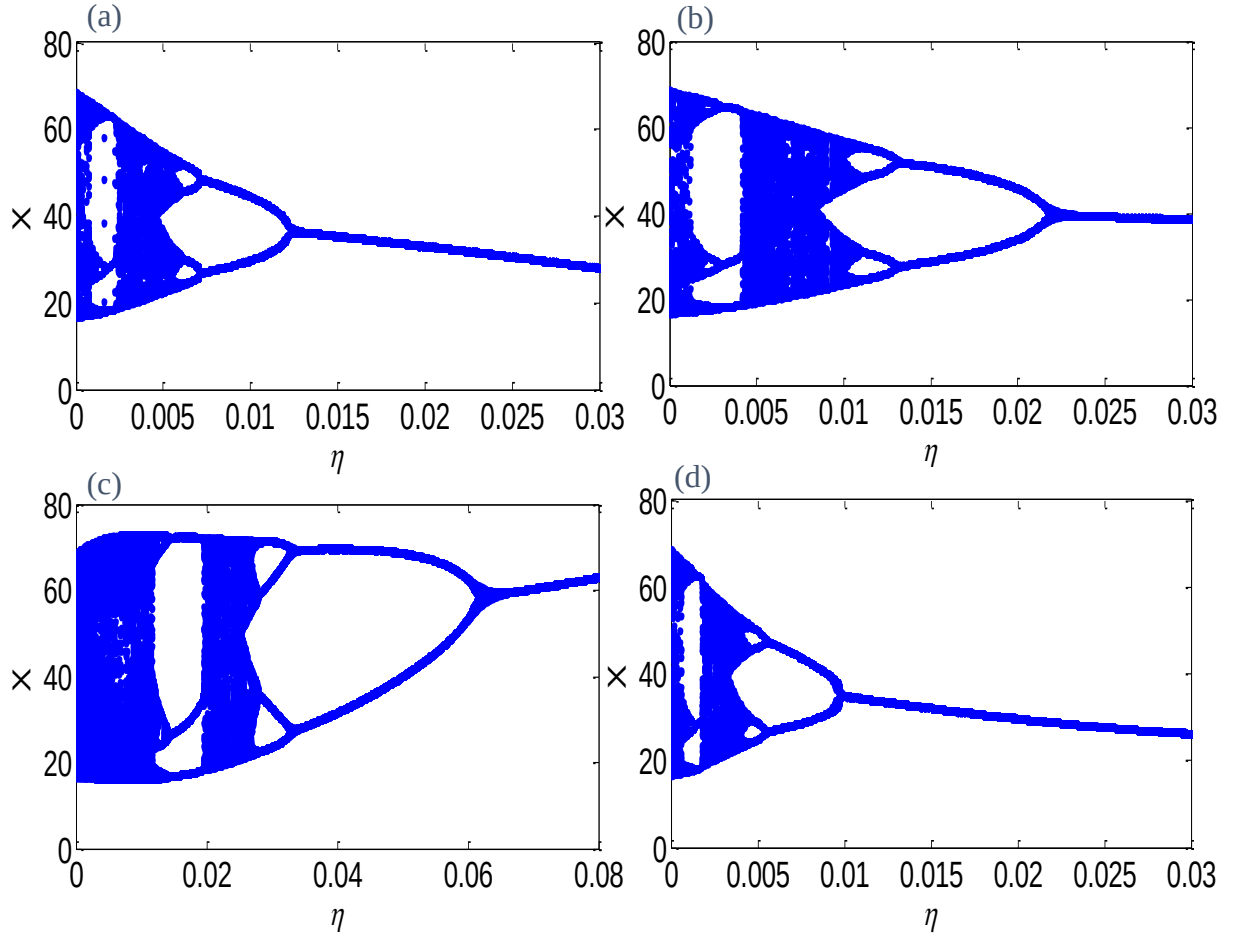


Fig. (2.4): Bifurcation diagrams in the phase space of the photon density as a function of OFBS for QD-LED at a bias injection current of $\delta_0=0.013$. (a) $\tau=5$, (b) $\tau=7$, (c) $\tau=10$ and (d) $\tau=30$.

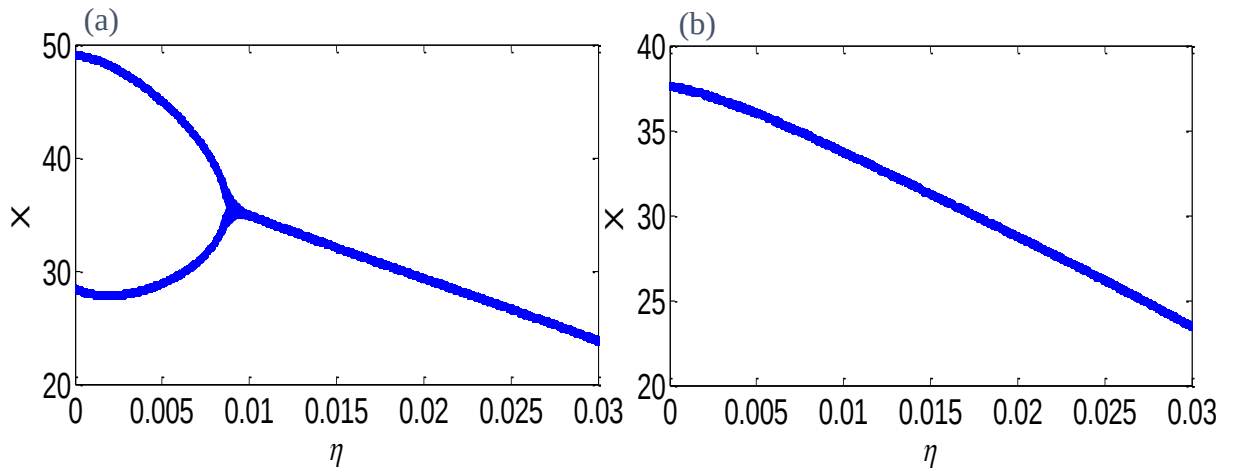


Fig. (2.5): Bifurcation diagrams in the phase space of the photon density as a function of OFBS for QD-LED at delay time $\tau=0.1$ with (a) $\delta_0=0.1$ and (b) $\delta_0=0.3$.

2.5 Dynamics in Quantum Dots Light Emitting Diode with Grating Mirror Feedback

In this section we study the effect of angular frequency on QD-LED system of four dimensionless rate equations, which represent the behavior of photons but now have been added a special technique to suppress unwanted frequencies and we have only received the important frequency to be guided by this technique it is the grating mirror [72] to frequency filter ω_g and the frequency output ω_o required only to study its effect and this technique is the last term which can be write as follows [66,72]:

$$\frac{dE(t)}{dt} = -\frac{1}{2}(1 + i\alpha)Wn_{QD}E(t) - \frac{\gamma_s}{2}E(t) + Esp(t) + \frac{k_g}{\tau_{in}}E(t-\tau) \exp(-i\Delta\omega\tau) \quad (2.5)$$

where $\Delta\omega = (\omega_g - \omega_o)$, after sub stating the value of the complex field, we get the following equations

$$\begin{aligned} \dot{x} &= \gamma \left(\frac{y^2}{\gamma_1} \right) - x(y + 1) + 2\sqrt{x_\tau}x_t \eta \cos(-\Delta\omega\tau) \\ \dot{\emptyset} &= \frac{1}{2}\alpha y \gamma - \eta \sqrt{x_\tau/x_t} \sin(-\Delta\omega\tau) \end{aligned} \quad (2.6)$$

We have obtained a clear and constant dynamic at $\tau = 0.1$, $\delta_0=0.013$ and $\eta = 0.01$ at the frequency of the grating mirror is equal to (0.0001-0.2). Fig. (2.6) shows, in more detail, bifurcation diagram of the grating mirror feedback system, how the dynamics of the photon depends on frequency of the solitary optical mode, a result similar to that in lasers [43]. Begins from the ends to the central solitary optical mode frequency of the grating mirror, there is existence of a number of states, limit cycle, double periodic and 1^3 period then arising from a Hopf bifurcation far from the center. It is worth mentioning that we did not get perfect behavior except using the latest technique.

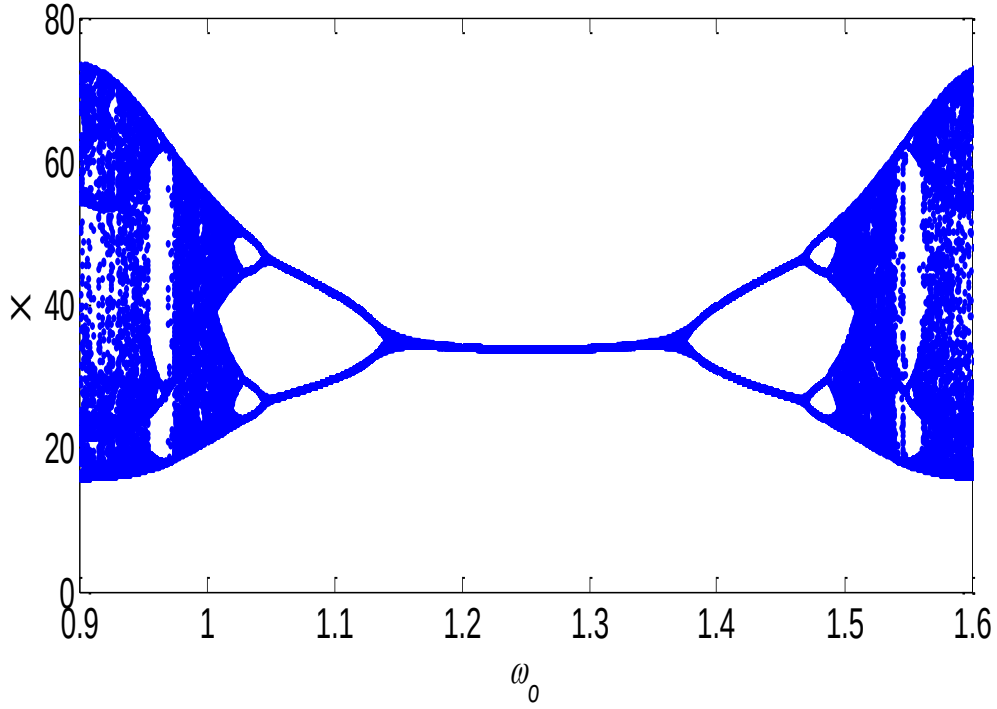


Fig. (2.6): Bifurcation diagrams in the phase space of the photon density as a function of detuning of frequency for QD-LED at delay time $\tau=0.1$ and $\delta o=0.013$.

2.6 Delayed Optical Feedback Control

In the case of the stability of the value of OFBS into the end of the chaos in the bifurcation in first case, we now study the effect of the change τ (delay time) on the behavior of photons at small values of bias ($\delta_o = 0.013$), the results were chaos in the small and large values of delay time $\tau = 0.1 \rightarrow 0.9$ as shown in Fig. (2.7 (a)) This is very predictable in dynamics of laser systems [81], all of this has not changed anything of QD-LED dynamics because of control the bias current on the behavior of photons at OFBS $\eta=0.004$ for $\delta_o = 0.013$.

In Fig. (2.7 (b)) and for large value of the bias current $\delta_o = 0.1$ and OFBS at $\eta=0.004$ the presence delay time effecting is shown. The effect of delay forces the system to enter the state of chaos immediately and the system

“waits” until delay time close to 0.17 to be comes the double periodic orbit and only then synchronize with an external oscillation.

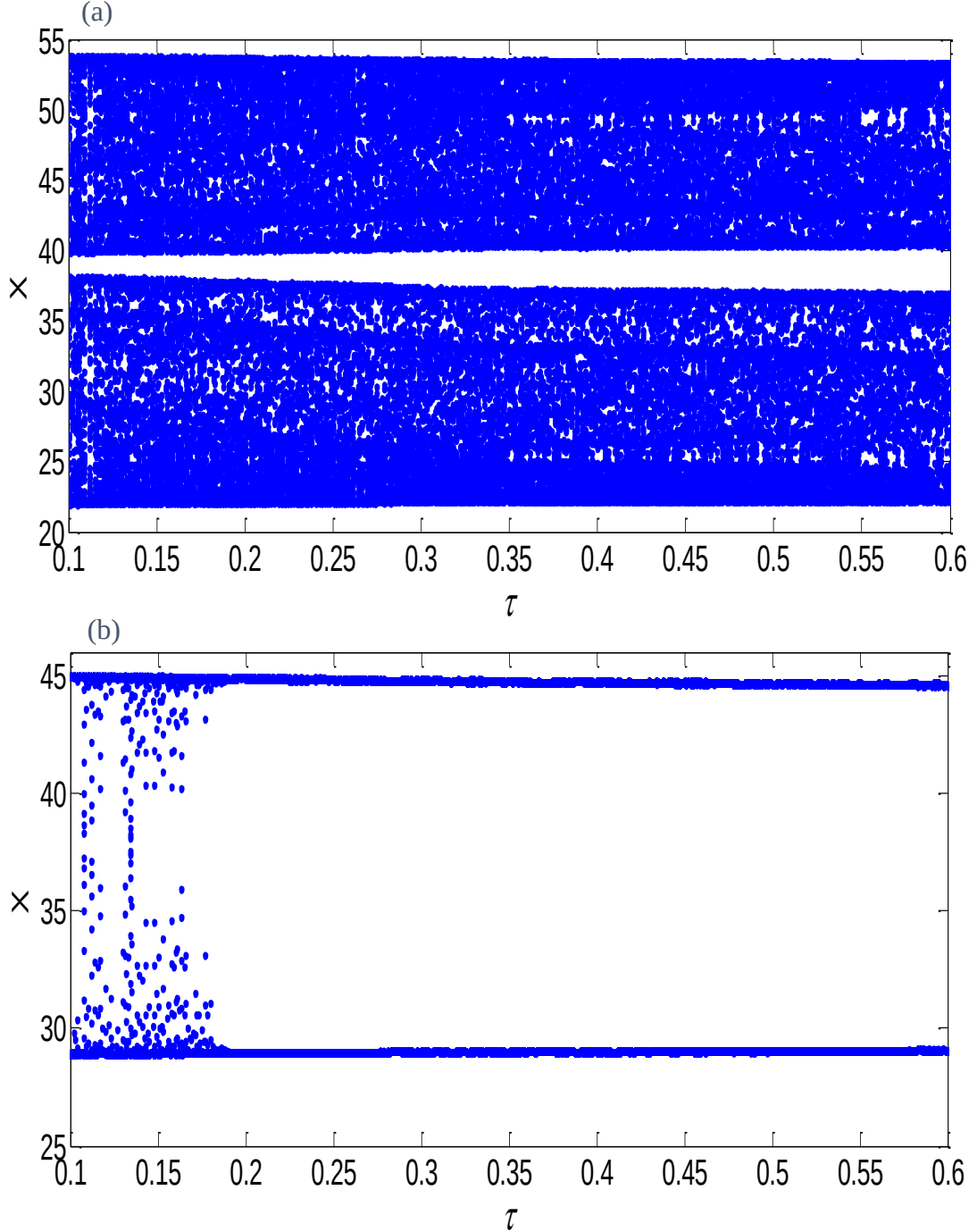


Fig. (2.7): bifurcation diagrams of the photon number S (normalized to x) vs. delay time τ at
 (a) OFBS $\eta=0.004$ and $\delta_o = 0.013$. (b) $\eta=0.005$ and $\delta_o = 0.1$.

2.7 Turn-On Dynamics of the Quantum Dots Light Emitting Diode

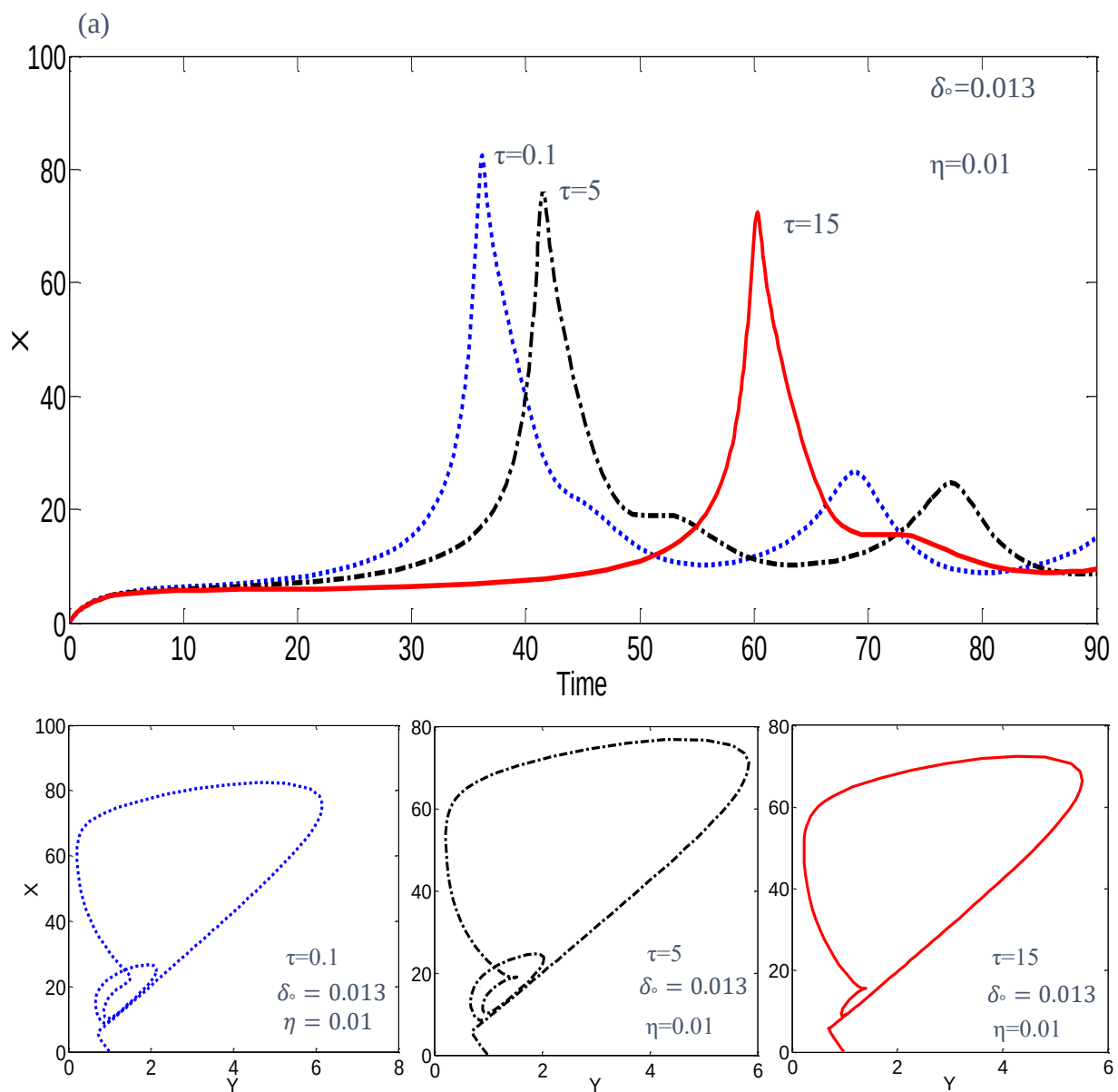
Further insight into the electron dynamics can be gained by studying the functional dependence of the behaviors upon the pump current, OFBS and delay time. Curves in Fig. (2.8 (a)) for $\tau = 0.1$, $\tau = 5$ and $\tau = 15$, respectively, and their attractors show the slow damping of the dynamic range. The solid-red line that corresponds to large value of delay time $\tau = 15$, which shows an exponential decay of the photon density to its chaotic state value. The phase shift appears with delay threshold of first pulsing and the dynamic range is incomparable.

The turn-on dynamic of the QD structure in Fig. (2.8 (b)) and their attractors show relaxation oscillations that are more strongly damped than in the two above cases of slowly damped and it can clear observable at $\eta = 0.04$. This case is called reference as it resembles the behavior found in common QD laser experiments [77] It was investigated in previous dynamical studies of the QD laser with optical feedback [78,79]. In Fig. (2.8 (b)) we consider change the OFBS values of the QD-LED the phase shift appears with speedy threshold of first pulsing and the dynamic range is incomparable.

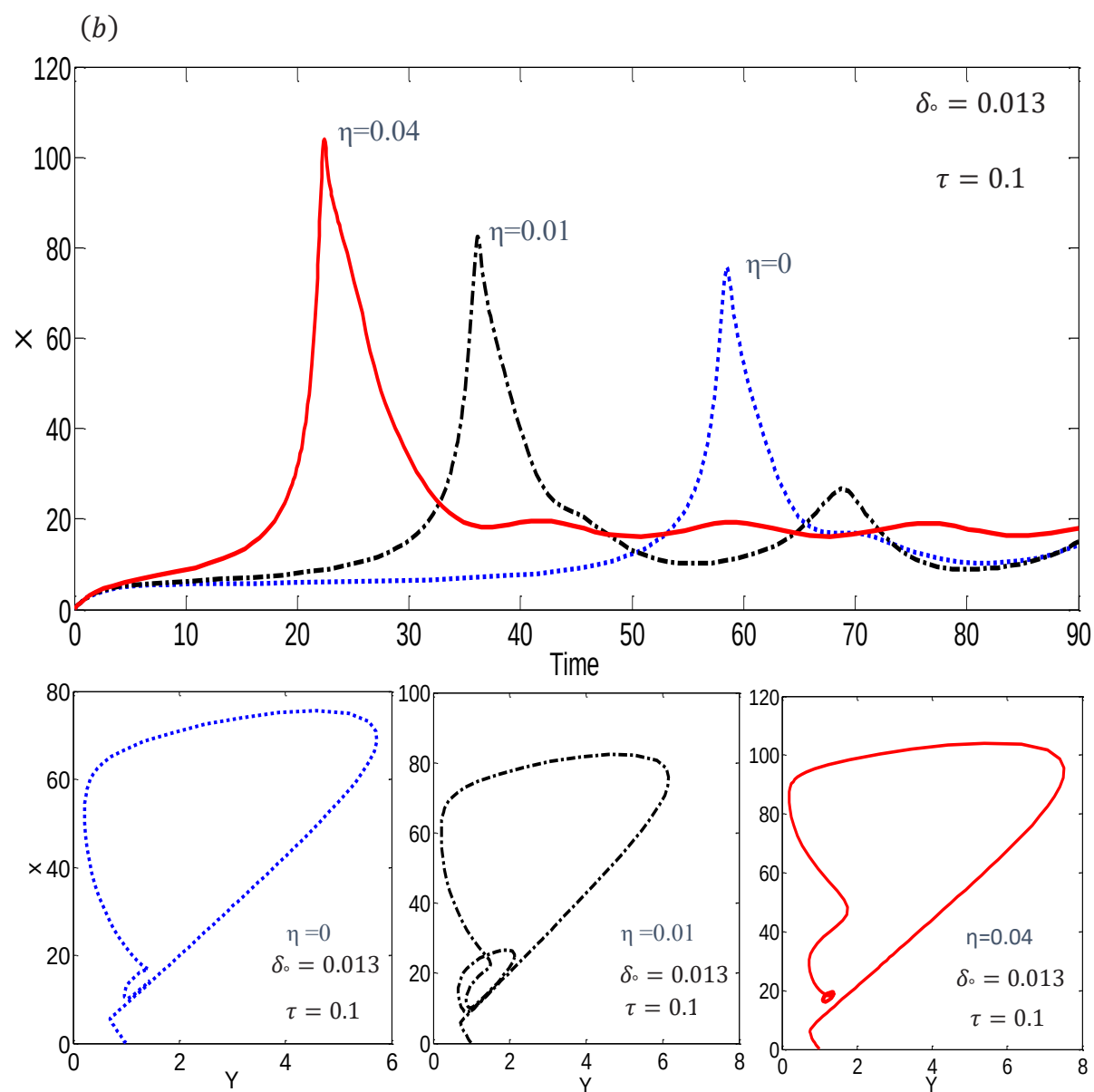
As explained before, this is similar the characteristical turn-on behavior of a class A laser [79]. Hence, this QD structure is labeled fast because short carrier lifetimes imply fast carrier exchange between QD and QW.

Note from following figure that the damping of the relaxation oscillations and the phase shift increases with increase both of OFBS and delay time while from Fig. (2.8 (c)) we can show turn-on transients of the electron dynamics for three different values of bias (increasing the pump current from $\delta_o = 0.013$ to $\delta_o = 0.3$) and fixed both values of $\tau=0.1$ and $\eta=0.01$, decreasing amplitudes are visible in Fig. (2.8 (c)) and their attractors due to the changes in the electron

transition between two layers in this structure. As can be seen for Fig. (2.8 (c)), the phase shift disappears and the dynamic range is incomparable.



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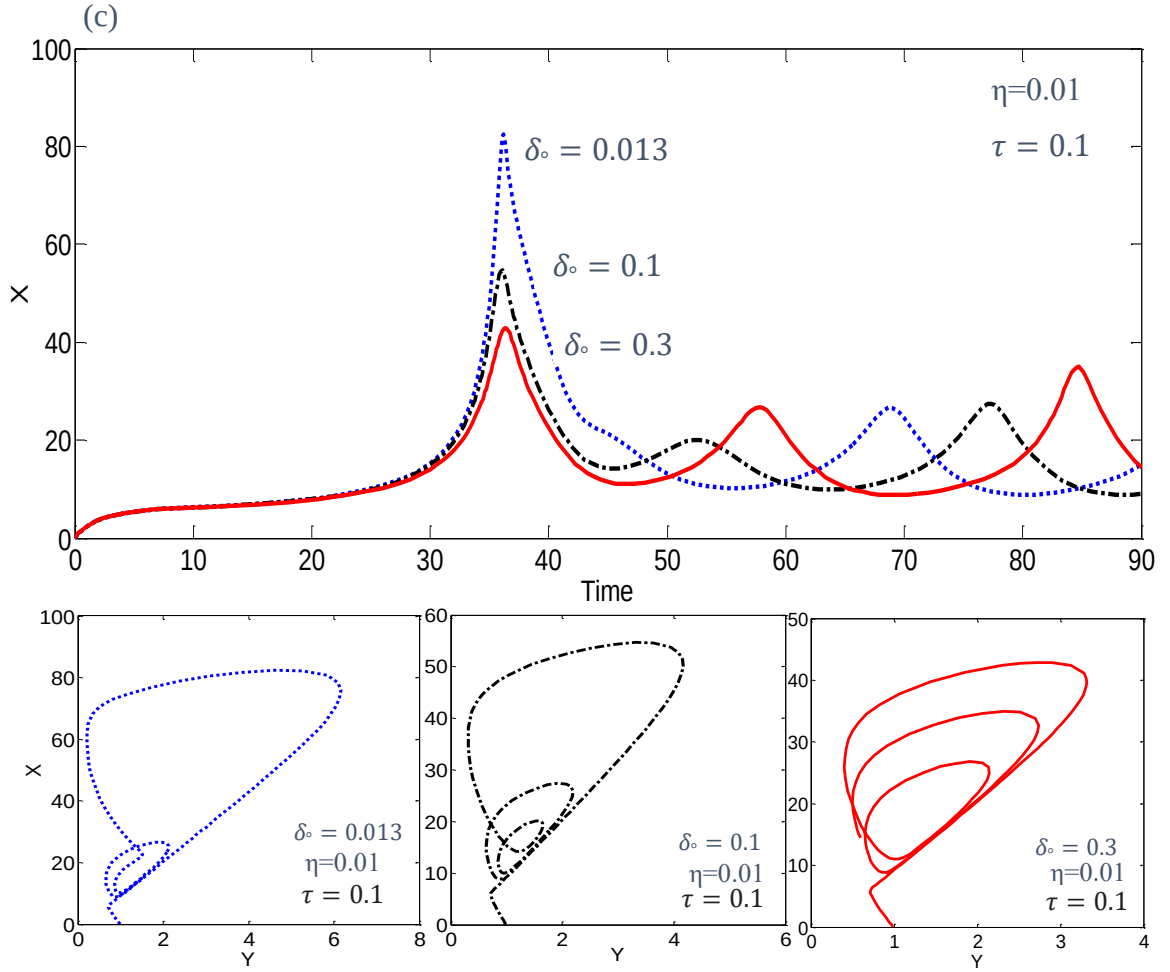


Fig. (2.8): Turn-on dynamics of the QD –LED with optical feedback. In (a) the pump current and OFBS are kept constant at $\delta_0 = 0.013$, $\eta=0.01$ respectively, and delay time is changed. (b) the pump current and delay time are kept constant at $\delta_0 = 0.013$, $\tau=0.1$ respectively, and OFBS is changed. (c) the delay time and OFBS are kept constant at $\tau = 0.1$ and $\eta=0.01$ respectively, and pump current is changed. In agreement with Table 1.

2.8 Effects of Linewidth Enhancement Factor

The instability of the output is greatly enhanced for larger value of the linewidth enhancement factor α of the semiconductor devices, which plays an important role in the dynamics of these devices.

In this section, we examine the dependence of onset of chaos on the linewidth enhancement factor in the QD-LED under optical feedback effect.

For this aim, and with weak optical feedback strength as discussed in section 2.3 QDLED is realized within the ranges of optical feedback. We first consider a transfer employment due to the linewidth enhancement factor on the QD-LED dynamics. Assuming an external cavity length (delay time), and bias current are constant. Generally, control systems can be satisfied by selecting a certain range of the linewidth enhancement factor of less than 5. In Fig. (2.9) chaotic bifurcation diagrams subjected linewidth enhancement factor at a bias current $\delta_o=0,013$ is calculated, with external cavity length $\tau = 5$ and $\omega_o = -0.008$, where $\eta = 0.01$ in Fig. (2.1 (a)), and $\eta = 0.02$ in Fig. (2.9 (b)), respectively. As it can be seen, the proposed controller effectively dynamic is the linewidth enhancement factor. In Fig. (2.9 (a)) the QD-LED is stable for a linewidth enhancement factor at less than 1.5. This dynamic is called a fixed point. After this value, a behavior appears two points corresponding to the peaks and valleys of the period-2 state. When the linewidth enhancement factor exceeds to 2.6 a period-4 oscillation starts and the output has four states of peaks and valleys. For a further increase of the α , finally chaotic oscillations over the linewidth enhancement factor level of 2.8 until 3.6 then return period state. The evolution such as shown in Fig. (2.9 (a)) is called a period-doubling bifurcation.

Fig. (2.9 (b)) shows another example of α effect at $\eta = 0.02$, where the displacement of chaotic behavior from 2.8 in the previous Fig. to 3.4 with a slight change in overall behavior is observed.

Through the following figure it will be unexpected for us to see clearly the implication of the delay time and bias current on the onset of the chaos. Fig. (2.10 (a)) shows the shift of chaos to the left and start from less than 2 where delay $\tau = 7$ and $\eta=0.01$. When one compare this behavior with in Fig. (2.9 (a)),

we notice that the chaos was beginning at less than 3 at the same value of the η . This situation is repeated in Fig. (2.10 (b)) where the chaos is shift to the left with a slight increase at $\tau=7$. This result measure up to Fig. (2.9 (b)), we notice that the chaos started at 3.5 when the $\tau=5$ for the same η value. This clearly shows that increasing of the delay time leads to increased chaotic at small ranges of linewidth enhancement factor and small delay time leading to receding of chaos at small values of linewidth enhancement factor.

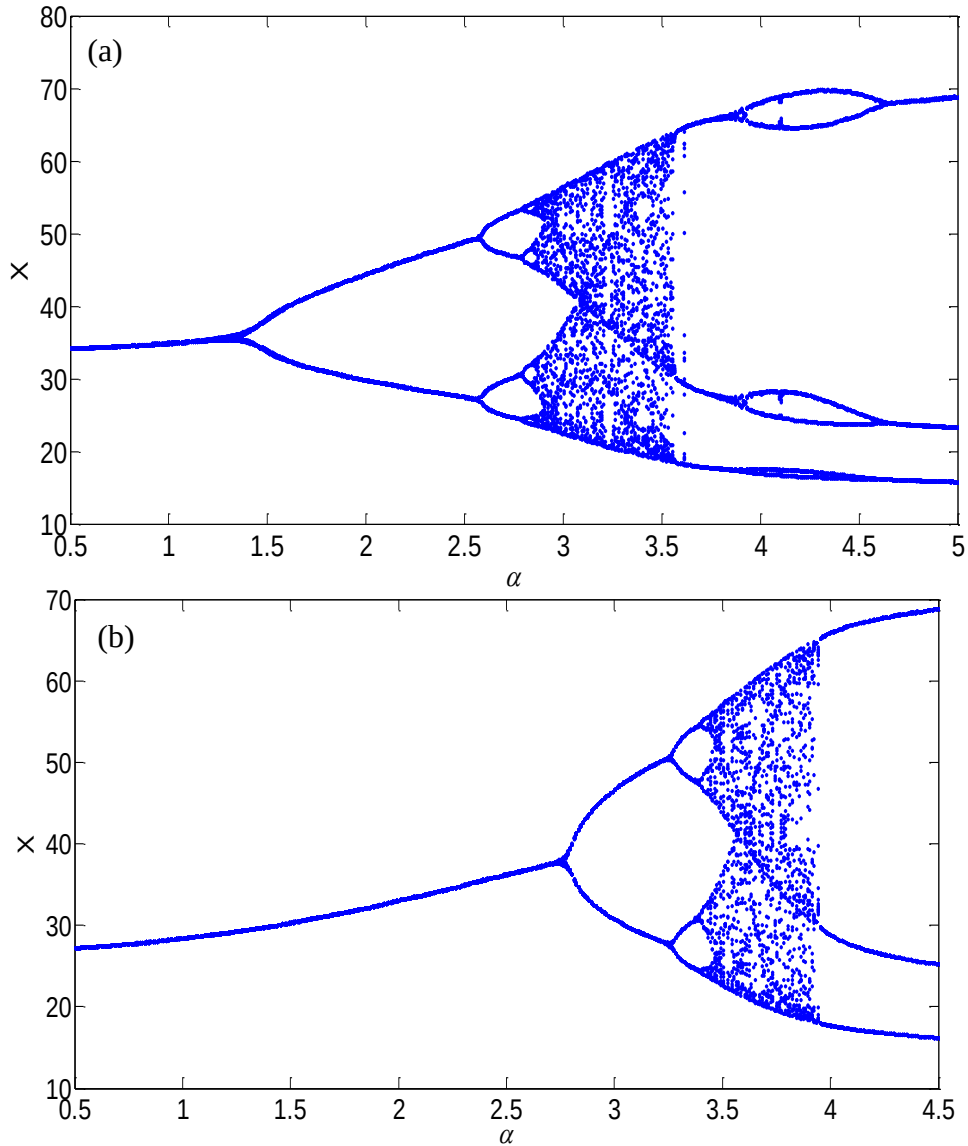


Fig. (2.9): Calculated chaotic bifurcation diagrams subjected linewidth enhancement factor at a bias current of $\delta o=0,013$, the external cavity length of $\tau= 5$ and $w_o=-0.008$. (a) OFBS =0.01, (b)OFBS=0.02.

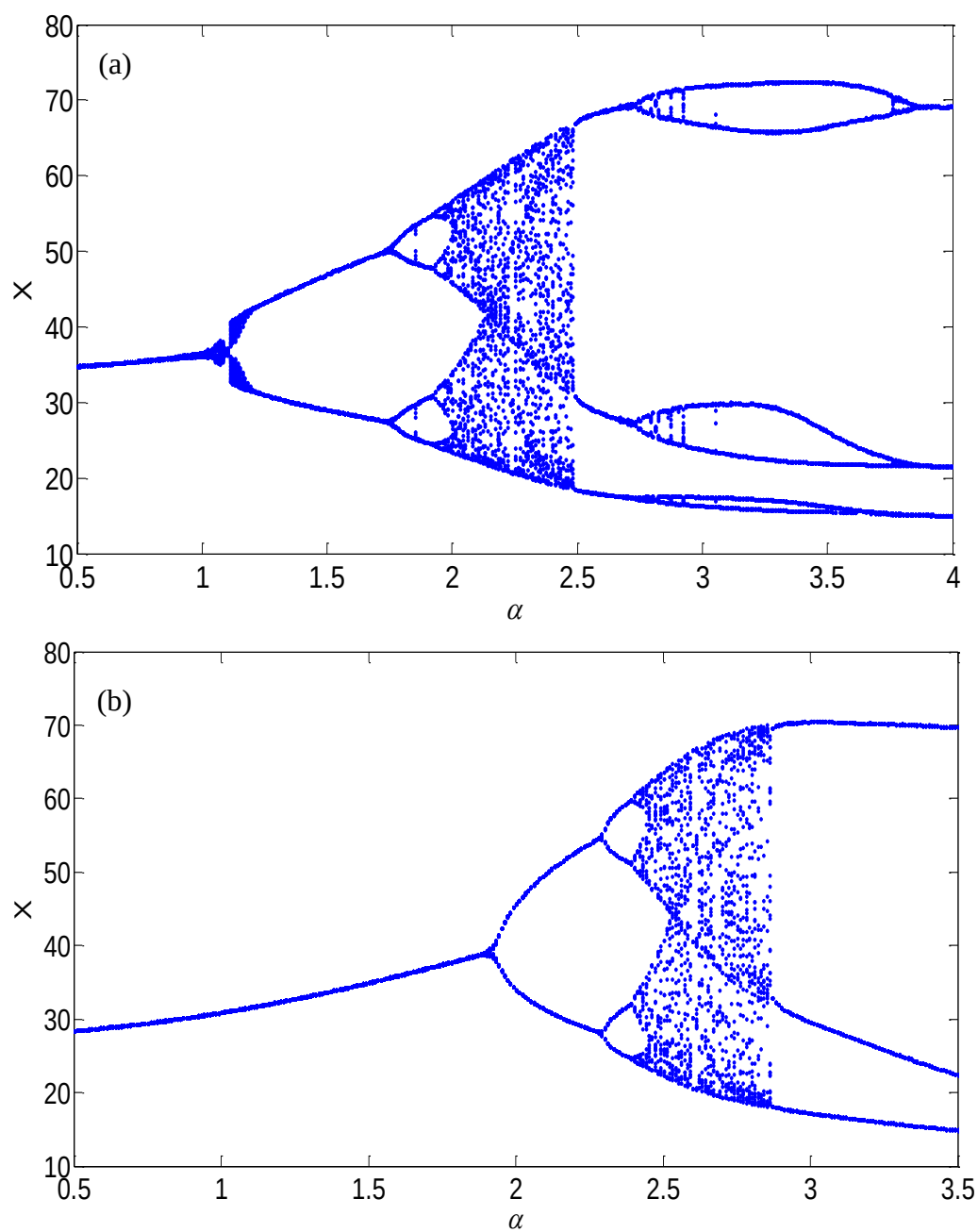


Fig. (2.10): Calculated chaotic bifurcation diagrams subjected linewidth enhancement factor at a bias current of $\delta o=0,013$, the external cavity length of $\tau= 7$ and $w_o=-0.008$. (a) OFBS =0.01, (b)OFBS=0.02.

In Fig. (2.11 (a)), the chaos shifts to the right near 2.7 with the effect of increasing the η despite the high value of the delay. In Fig. (2.11 (b)) we note the displacement of the chaos towards the left beneath 1.4 at increasing continuously of the delay value and a noteworthy increasing in the dynamics of the system.

Fig. (3.12 (a)) when a large delay value is used, we observe shifting the chaos to a value of 2.7 in the direction of the right when η increases. In Fig. (2.12 (b)) with $\eta = 0.03$ the disappearance of the chaos phenomena is observed.

When one continue to increase delay we notice that the chaos arises at narrow linewidth enhancement factor values as in Fig. (2.13 (a)). Once again, the effect of η shows the chaos state is disappeared at $\alpha = 0.04$ as in Fig. (2.13 (b)).

We think that here have focused well on studying the effect of the linewidth enhancement factor on the onset of chaos with two important parameters, τ and η .

From the results above we conclude with general images of increased chaotic behavior of the QDLED system with the breadth of the linewidth enhancement factor. We also noticed the displacement of the beginning of chaos to the left by increasing τ and displacement the chaos to the right by increasing η and chaos disappearing.

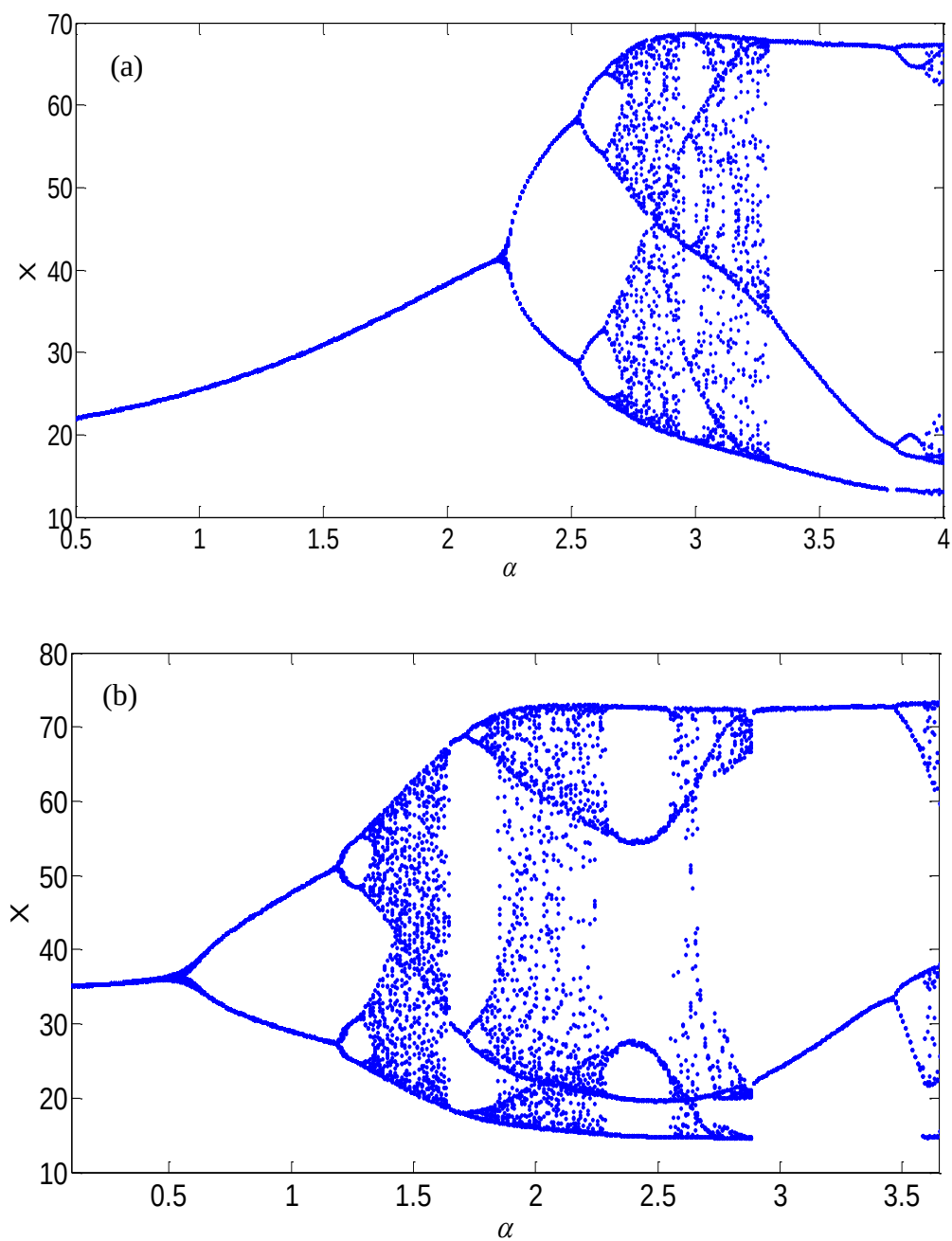


Fig. (2.11): Calculated chaotic bifurcation diagrams subjected linewidth enhancement factor at a bias current of $\delta o = 0.013$, and $w_o = -0.008$. (a) $\text{OFBS} = 0.03$, and the external cavity length of $\tau = 7$ (b) $\text{OFBS} = 0.01$, and the external cavity length of $\tau = 10$.

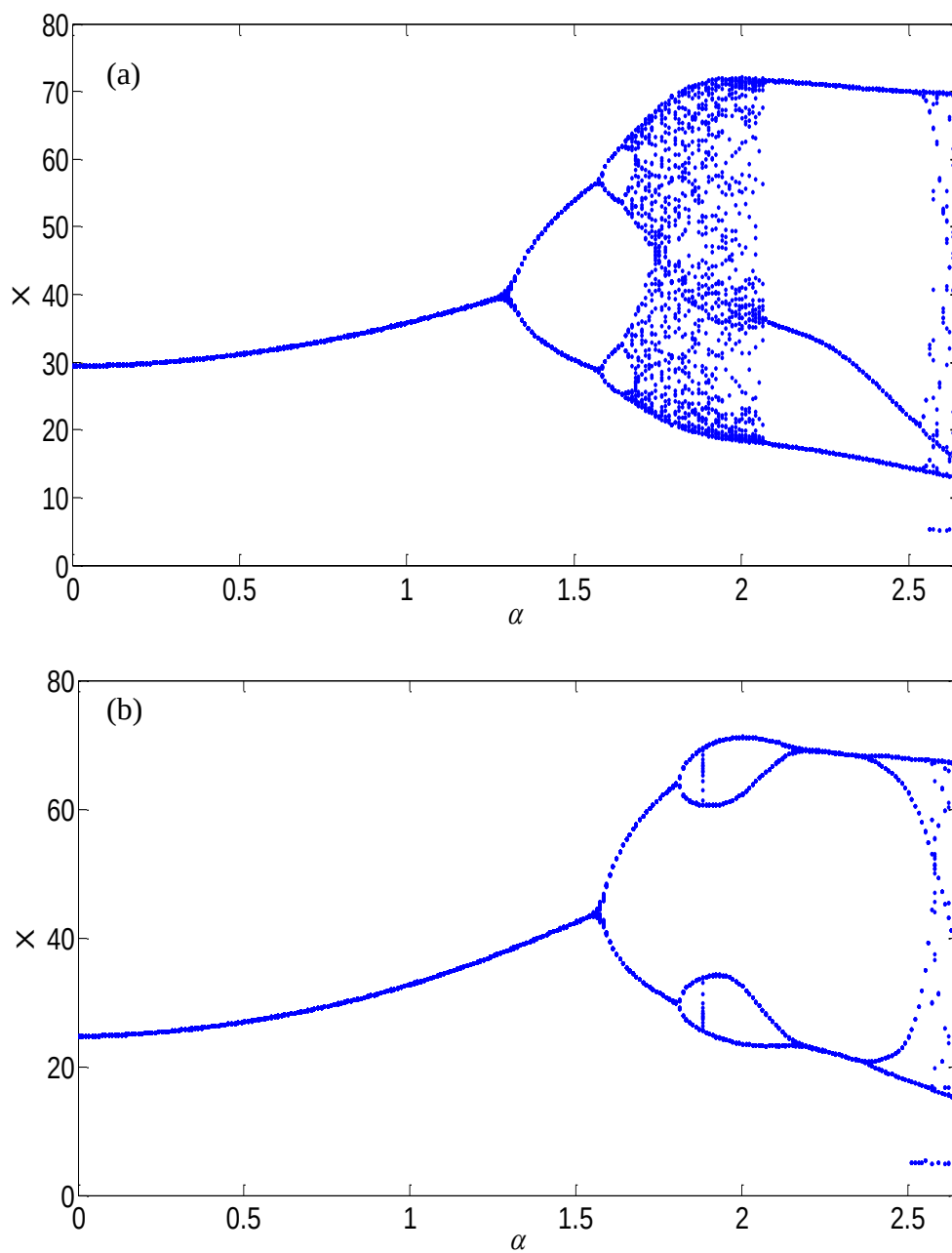


Fig. (2.12): Calculated chaotic bifurcation diagrams subjected linewidth enhancement factor at a bias current of $\delta o=0,013$, $w_o=-0.008$, and the external cavity length of $\tau= 10$
 (a) OFBS =0.02 (b)OFBS=0.03.

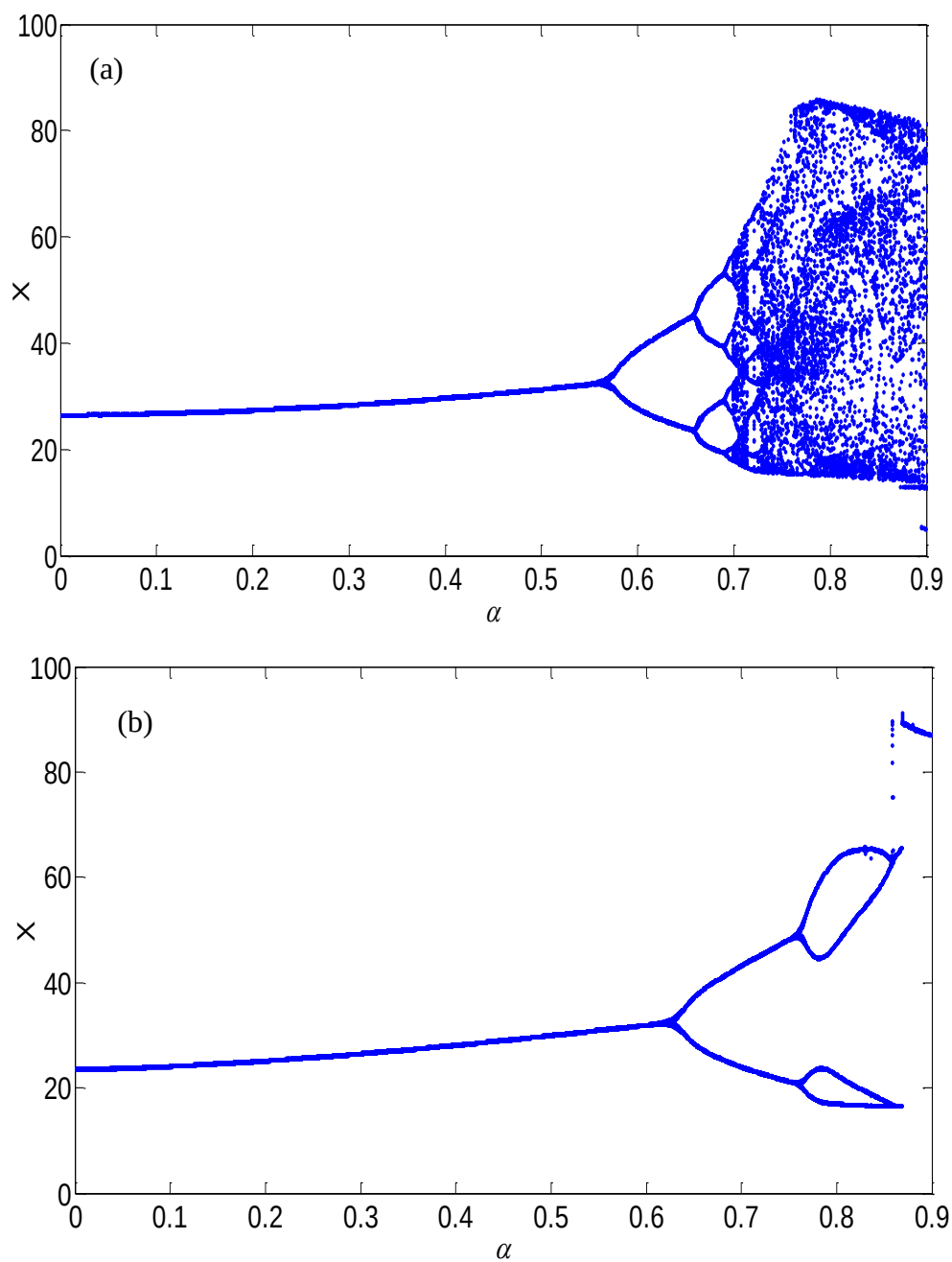


Fig. (2.13): Calculated chaotic bifurcation diagrams subjected linewidth enhancement factor at a bias current of $\delta o = 0.013$, $w o = -0.008$, and the external cavity length of $\tau = 30$ (a) $OFBS = 0.03$ (b) $OFBS = 0.04$.

Different values of α were examined and several dynamics were recorded. Fig. (2.14) represents the mixed modes state, which is one of these are recorded cases at $\delta_o=0.013$, $\omega_o=-0.008$, $\tau = 0.1$ and $\eta =0.01$ [1]. Fig. (2.15) represents the bifurcation diagram calculation along the linewidth values studied in this section. From this figure we see only two peaks, which is exactly the case of mixed mode, which consists of two different modes of amplitude.

Another case was recorded as in Fig. (2.16), where the cascades chaos is shown at $\delta_o=0.013$, $\omega_o=-0.008$, $\tau= 30$ and $\eta =0.02$, where it is a feature characteristic of lasers under the optical feedback.

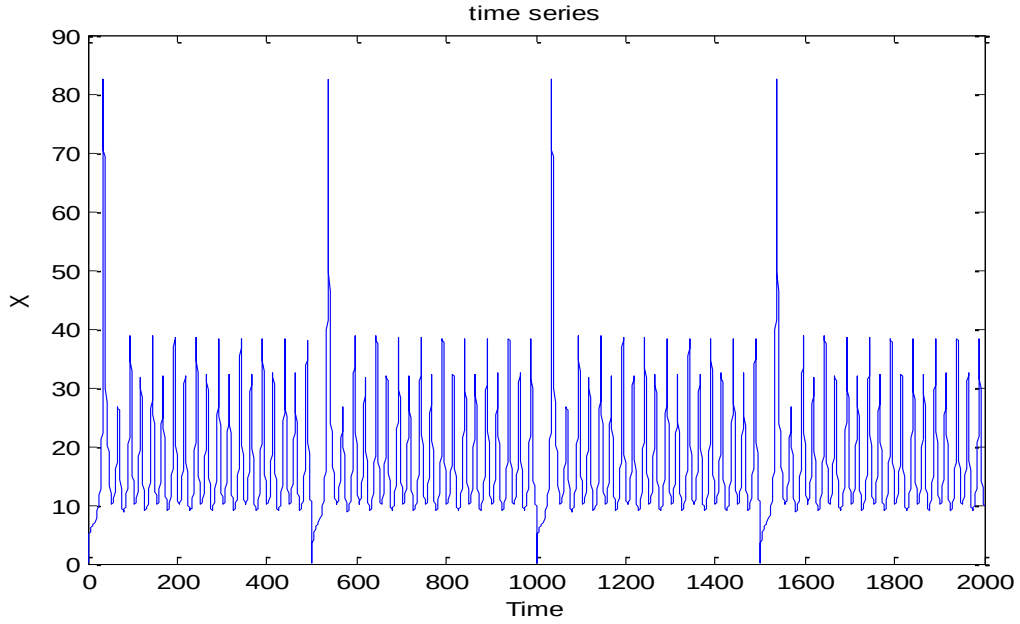


Fig. (2.14): Mixed modes in time series along linewidth enhancement factor values at a bias current of $\delta_o=0.013$, $\omega_o=-0.008$, the external cavity length of $\tau= 0.1$ and OFBS=0.01.

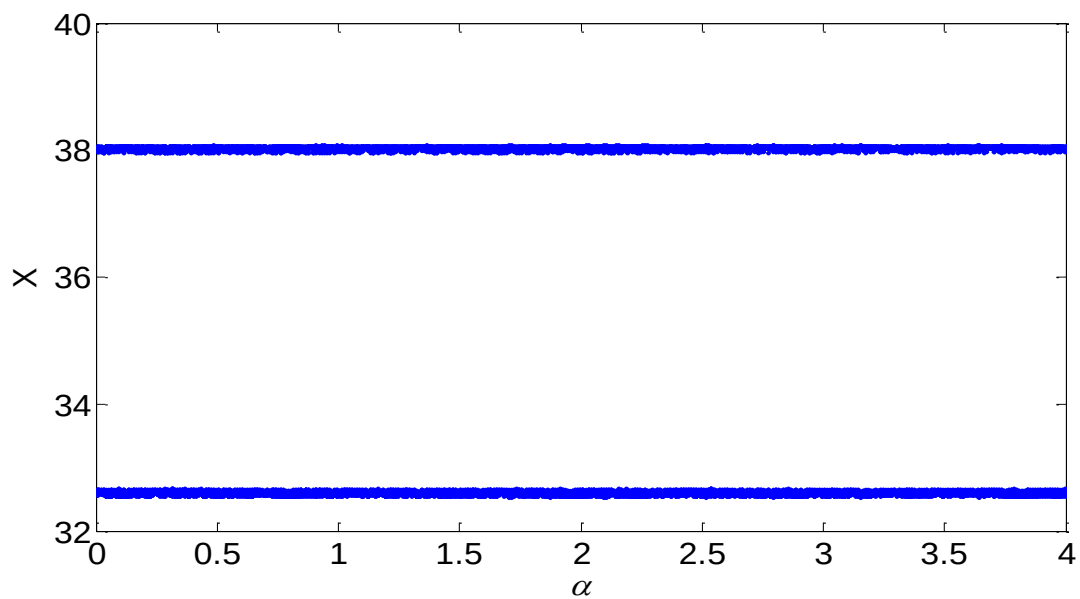


Fig. (2.15): Calculated mixed mode bifurcation diagrams subjected linewidth enhancement factor at a bias current of $\delta o=0,013$, $w_o=-0.008$, the external cavity length of $\tau=0.1$ and OFBS=0.01.

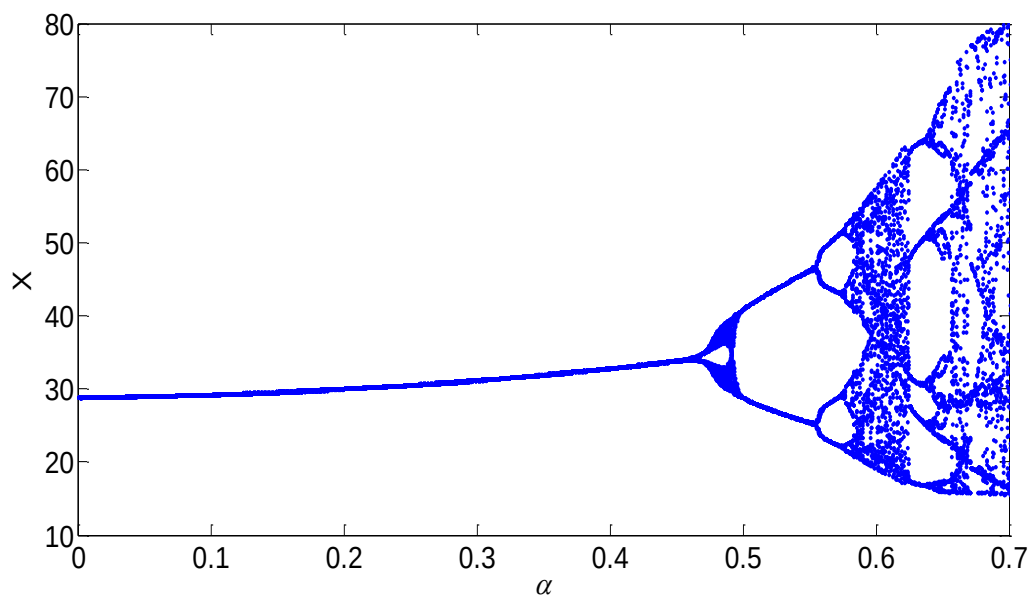
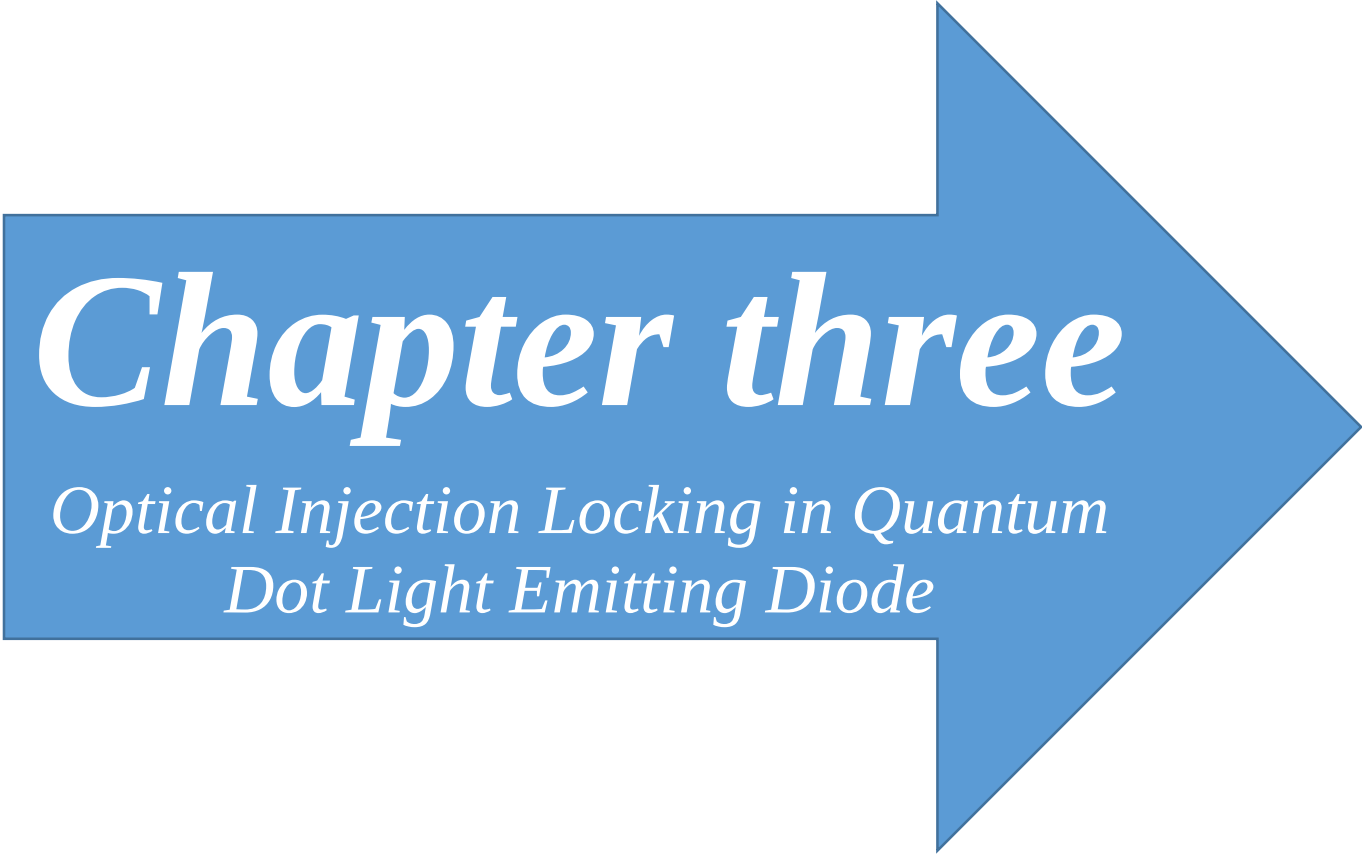


Fig. (2.16): Calculated chaotic bifurcation diagrams subjected linewidth enhancement factor at a bias current of $\delta o=0,013$, $w_o=-0.008$, the external cavity length of $\tau=30$ and OFBS=0.02.



Chapter three

*Optical Injection Locking in Quantum
Dot Light Emitting Diode*

3.1 Introduction

A broad modulation bandwidth is requirement in a wide range of optical communication applications, at the same time as others needs narrowband frequency. Increasing the bandwidth in the direct modulation is used, but the injection locking is shown to do best for the above mentioned requirements [80].

Semiconductor lasers (SLs) exhibit a rich variety of nonlinearities as previous research indicated under optical injection [81], where the SL dynamics was described by the frequency of the optically injected signal added to the slave laser itself. Their difference as known detuning controls the slave system while staying the master one without affecting.

There are many applications depending on the nonlinearity and on the bandwidth controlling of the system. Where, the excitability can be observed in the behavior of a stable dynamical system that pulses exhibit by adding perturbation above threshold as optical injection [82]. Chaos can be seen in the behavior of these nonlinear systems [74].

The outstanding performance of the self-assembled QD material makes it extremely attractive for use as optical communication systems. It has reduced temperature and independent current threshold and suitable emission in fiber-optic windows [82,83]. A limited number of works deals with optical injection in QDs. One of them deals with carrier dynamics in their states [84]. The study of the dynamics in different QD states is important to know the physical parameters controlling them.

Injection-locking is a very useful tool for stabilizing the semiconductor devices, however injection-locked SLs shows a rich variety of dynamics. In this

work and for optical injection locking, two QD-LED are used with almost the same frequencies, see Fig. (3.1), and the frequency detuning between them $\Delta\omega$. Light emitted from the master is injected into the slave system. When the injection locking conditions are satisfied, the frequency of the slave is locked to that of the master. There are two important parameters in injection locking: frequency detuning, $\Delta\omega$, which is the frequency difference between the master and the free-running slave system, and optical injection ratio, r_{inj} , which is a ratio between the injected power from the master and the power of the free-running slave system. The nonlinear differential equation system can be used to model the dynamics of the QD-LED [66]. The study of this system allows theoretical consideration of the properties of QD-LED, analysis of the crossover, and control. In this work an injection is applied from the 3D model of QD-LED [74].

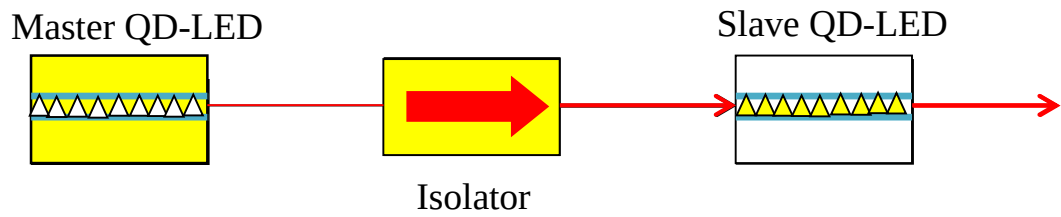


Fig. (3.1): Optical injection system used in QD-LED optically injected

3.2 Quantum Dots Light Emitting Diode Model with Optical Injection

The external optical injection effect is added to the equation of the complex field and the field equation write in the following form [66,72].

$$\frac{dE_s}{dt} = -\frac{1}{2}(1 + i\alpha)Wn_{QD}E_s - \frac{\gamma_s}{2}E_s + E_{sp}(t) + \frac{k_{inj}}{\tau_{in}}E_me^{-i\Delta\omega t} \quad (3.1)$$

Where E_s and E_m are the complex electric fields of the slave and master system, respectively. For the slave LED with QD active region the other parameters are; K_{inj} is the injection coefficient, $\Delta\omega = 2\pi\Delta\nu = \omega_m - \omega_s$ is the detuning between the master and slave systems, ω_m and ω_s , for the master and slave QD-LEDs, respectively.

after the our transformation to Eq.(3.1) for the number of photon in the optical mode in systems master and slave respectively (s_m, s_s), and the phase of the electric field φ_t which is the time dependent phase in the presence of optical injection plays an important role, since the phase couples with the other variables and the four equations for the number of electrons in the QDs (n_{QD}) and in the WL (n_{wl}) can be rewrite:

$$\left. \begin{aligned} \frac{ds_s}{dt} &= Wn_{QD}^2 - s_s W n_{QD} - \gamma_s s_s + \frac{k_{inj}}{\tau_{in}} \sqrt{s_m s_s} \cos \psi_t \\ \frac{d\varphi_s}{dt} &= \frac{1}{2} \alpha W n_{QD} - \frac{k_{inj}}{\tau_{in}} \sqrt{s_m / s_s} \sin(\psi_t - \Delta\omega) \\ \frac{dn_{QD}}{dt} &= \gamma_c n_{wl} \left(1 - \frac{n_{QD}}{2N_d}\right) - \gamma_{r_{QD}} - (Wn_{QD}^2 - Wn_{QD}s) \\ \frac{dn_{wl}}{dt} &= \frac{I}{e} - \gamma_{r_{wl}} - \gamma_c n_{wl} \left(1 - \frac{n_{QD}}{2N_d}\right) \end{aligned} \right\} \quad (3.2)$$

We introduce a phase $\psi_t = \varphi_s - \varphi_m - \Delta\omega$, The system Eqs. (3.2) can be rewritten in the following,

$$\left. \begin{aligned} \dot{x} &= \gamma \left(\left(\frac{y^2}{\gamma_1} \right) - x_s(y+1) + 2r_{inj}\sqrt{x_mx_s} \cos(\psi_t) \right) \\ \dot{\phi} &= \frac{1}{2} \alpha y \gamma - r_{inj}\sqrt{x_m/x_s} \sin(\psi_t - \Delta\omega) \\ \dot{y} &= \gamma_2 z \left(\gamma_1 - \frac{y}{2a} \right) - y(\gamma_3 + \gamma y) + \gamma_2 xy \\ \dot{z} &= \gamma_4 (\delta_0 - z + (yz/2\gamma_1 a)) - z \end{aligned} \right\} \quad (3.3)$$

$$\psi_t = \varphi_t - \Delta\omega t$$

where $r_{inj} = \frac{K_{inj}}{\gamma_{rwl} \tau_{in}}$ and others parameters are defined in chapter two, Here, four coupled equations are essential for QD-LED with optical injection and they show unstable oscillations and chaotic dynamics in their output powers like three coupled equations in Lorenz systems.

3.3 Effect of Optical External Injection

When studying the effect external optical injection of QD-LED for both the master and the slave systems, and as expected, when they work at the same frequency, i.e., $\Delta\omega=0$, one do not obtain a change in the dynamic phenomenon of both the systems as seen in Fig. (3.2 (a)), but there is a large increase in effort compared to the increase of optical external injection r_{inj} and master bias current δ_{om} at a small value of the bias current for slave ($\delta_{os}=0.013$) as seen later.

We will now briefly present examines of bias current effect upon to QD-LED dynamics in both of master and slave systems. In Fig. (3.2 (b)) and in the case of bias current ($\delta_{om}=0.1$) of the master which its corresponding to the periodic state and bias current ($\delta_o=0.013$) of the slave which its corresponding to the chaotic state, the behavior of slave moves to of the double period and when taking the bias current ($\delta_o=0.2$) and ($\delta_o=0.3$ which is not drawn) for the master, the slave be the movements of periodic as seen in Fig. (3.2 (c)). In order to fully demonstrate the frequency detuning effect, a small value is chosen for the difference between the slave and the master frequencies as seen in Fig. (3.3). Fig. (3.3 (a)) shows calculating the effect at the value of 0.013 for the bias current, we observe two things. first, a decrease in the signal capacity, and second, the breadth of the signal width without a phase match. Similar results are obtained when calculating the frequency effect at values 0.1 and 0.2 of the bias current as in Fig. (3.3 (b)) and Fig. (3.3 (c)), respectively. When we compare the two results above, we observe the phase-locking status when they work at the same frequency of the slave and the master, but at a small frequency difference between them we notice the phase spacing and decrease in amplitude.

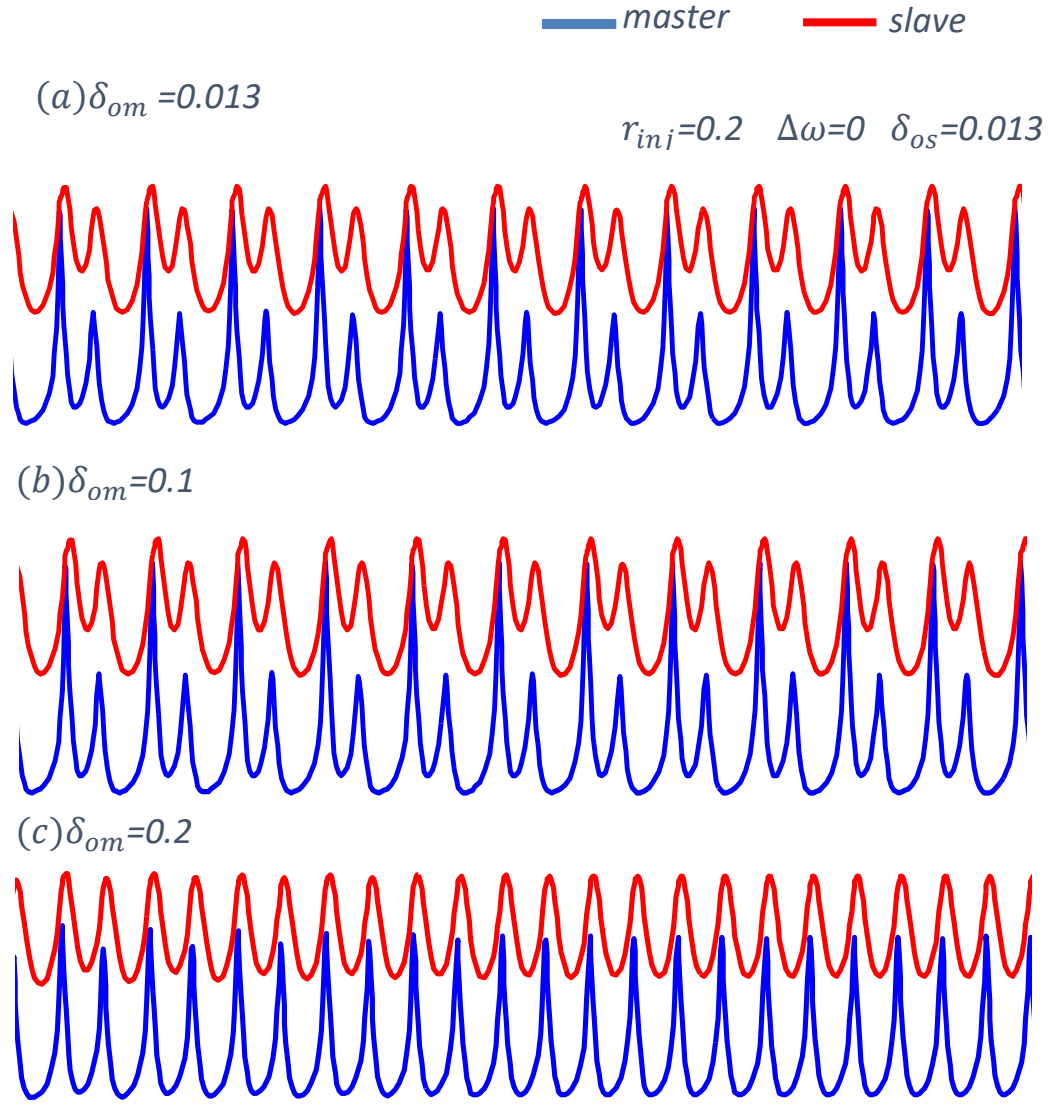


Fig. (3.2): phase locking calculated for the QD-LED model under the condition of bias current changing and $\Delta\omega = 0$, $\delta_{os} = 0.013$ and $r_{inj} = 0.2$: (a) $\delta_{os} = 0.013$, (b) $\delta_{os} = 0.1$ and (c) $\delta_{os} = 0.2$.

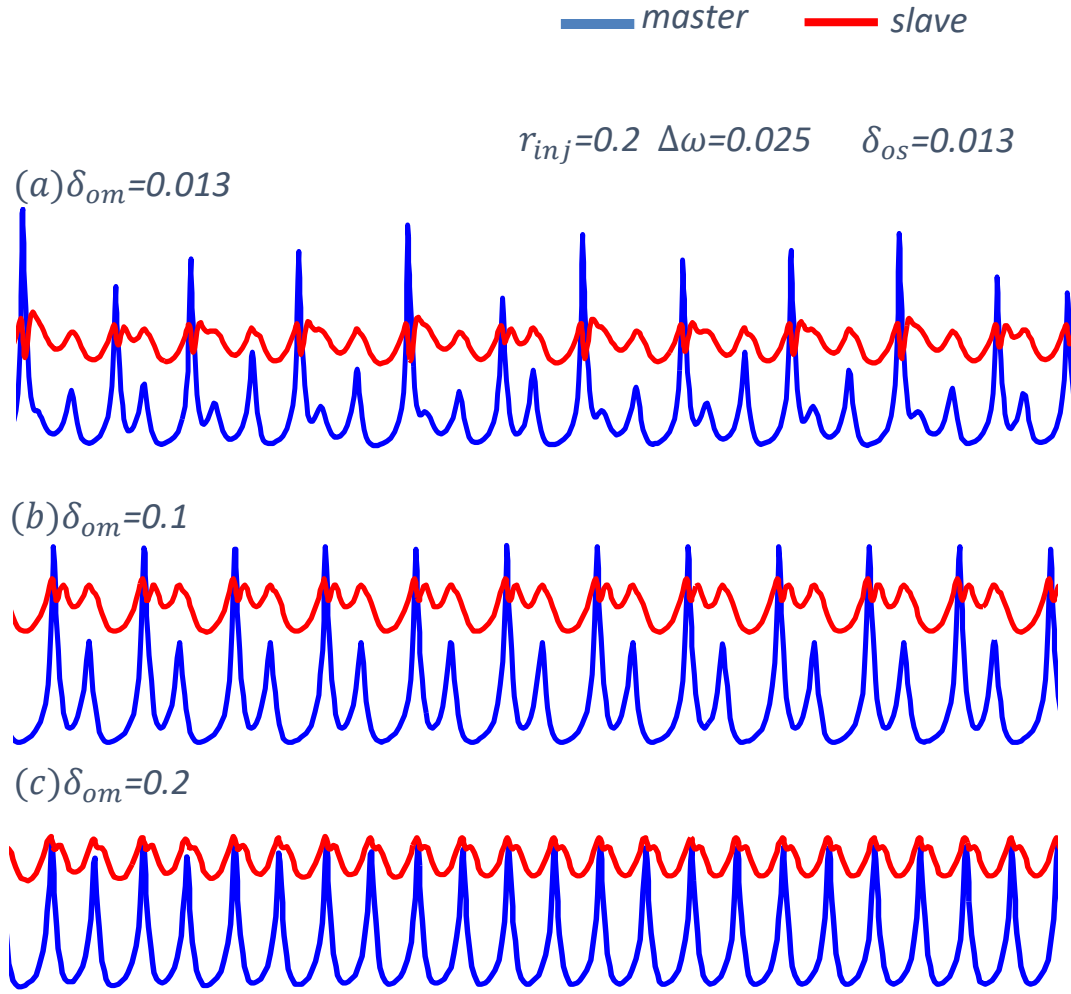


Fig. (3.3): phase locking calculated for the QD-LED model under the condition of bias current changing and $\Delta\omega=0.025$, $\delta_{os}=0.013$ and $r_{inj}=0.2$: (a) $\delta_{os}=0.013$, (b) $\delta_{os}=0.1$ and (c) $\delta_{os}=0.2$.

And contrary to the above of the bias current value between master and slave, one did not have a mutual effect and a result will only be chaos for slave.

From above cases, can be said that the increase of the master's contribution to the slave is more effective at frequency detuning ($\Delta\omega=0$) than the increasing at frequency detuning ($\Delta\omega=0.025$) which forces the behavior of the slave to take the same behavior as the movements of the master.

Now we present effect of frequencies by scanning wide range of the frequency detuning between the master and slave systems as seen in Fig. (3.4). When the bias current is proved to the master ($\delta_o = 0.1$) and the slave ($\delta_o = 0.013$), the dynamic behavior at the injection ($r_{inj} = 0.2$) which is present as bifurcation scenario diagram motions from the chaos at ($\Delta\omega = -0.09$) then follows a period doubling (two cyclic) with frequency detuning from ($\Delta\omega = -0.0875$) to ($\Delta\omega = -0.0775$) then it will be 4 cyclic and when the detuning frequency increases over ($\Delta\omega = -0.076$) the behavior to be of the motility disorder (chaotic state).

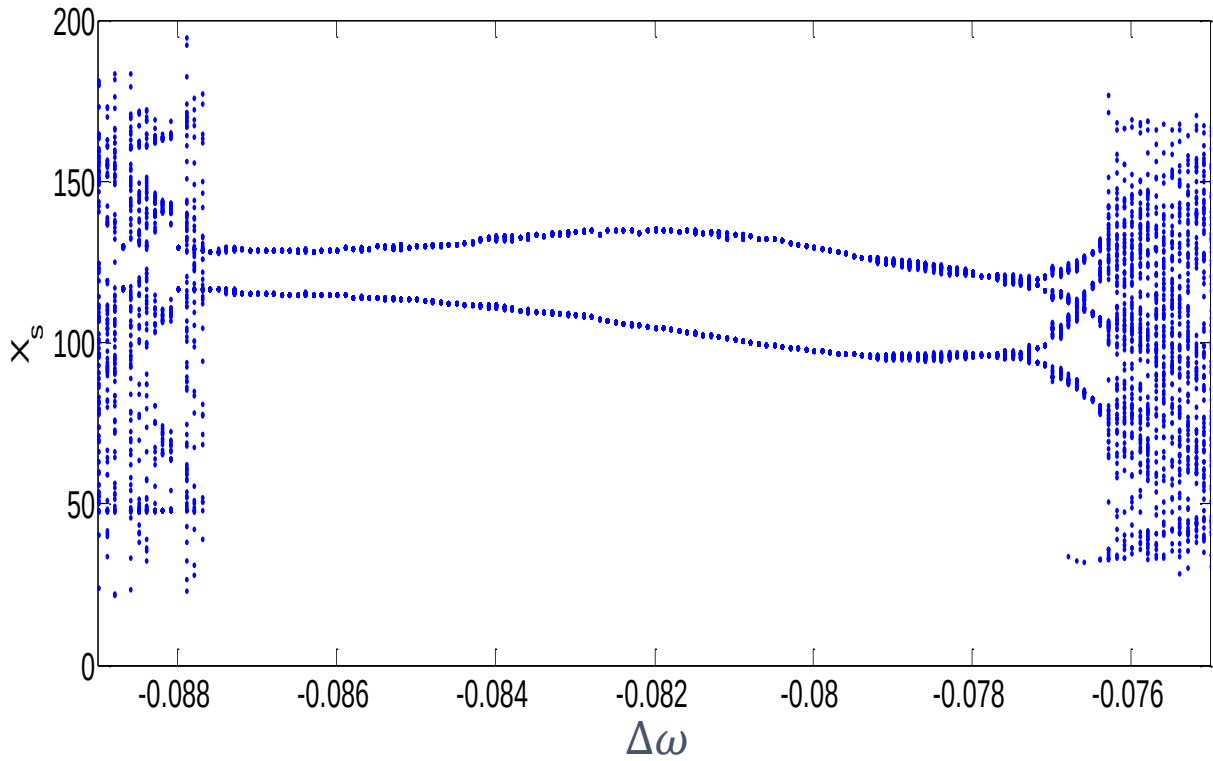


Fig. (3.4): Bifurcation diagram of output photon dependence of detuning when ($\delta_{om} = 0.1$) to master and ($\delta_{os} = 0.013$) to slave, and injection ratio ($r_{inj} = 0.2$).

Fig. (3.5 (a)) shows a new technique of time series appearing several dynamics with different values of detuning, the effect of detuning on the photon output where it becomes ($\Delta\omega = -0.082$, -0.0772 and -0.076), which represent the period doubling, four period and chaotic, respectively. And at all these detuning

the locking is observed. Fig. (3.5 (b)) shows the attractors plotting (x-y phase portraits) of the QD-LED slave system for the same values under discussion in Fig. (3.5 (a)) of the detuning. All Figs. (3.5 (a and b)) corresponding to Fig. (3.4) and the relation between the photon output and detuning with fixed both the injection current and a ratio of optical injection, It is known as bifurcation scenario.

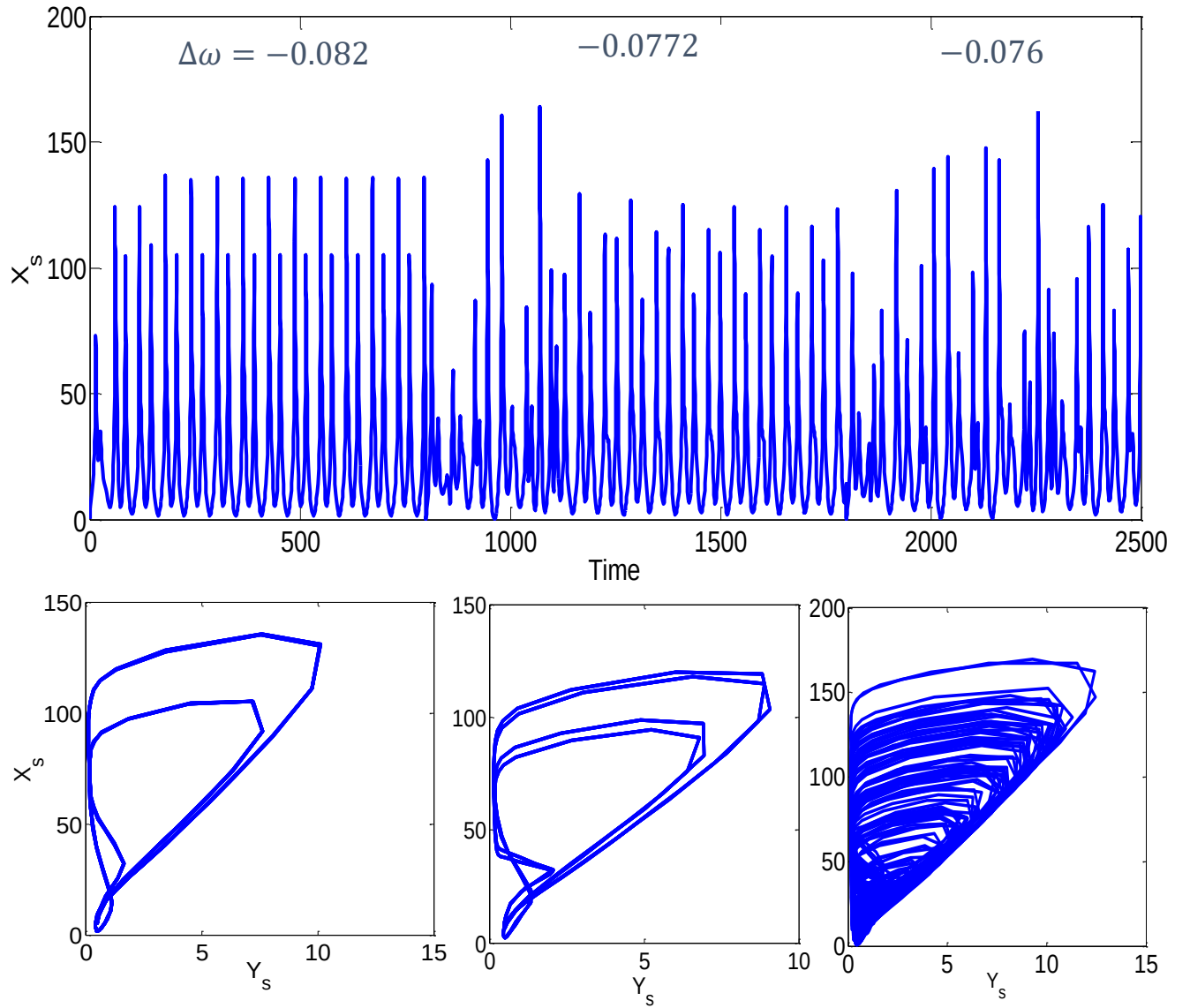


Fig. (3.5): Examples of output photon dynamics for QD-LED slave by using detuning effect.

(a) Time series. (b) attractor, corresponds to bifurcation in Fig. (3.4).

Finally, in Fig. (3.6), we consider an examine of photon output with optical injection ratio. Fig. (3.6) shows different dynamics, and a development in the behavior of the photon from the chaos state, which ends in the value 0.02 of optical injection ratio and then get damping of the signal directly and continue until the value 0.05 of optical injection ratio followed by the case of semi-periodic and later moving upward for the output capacity and continue in the doubling period state.

As we refer in the following Fig. (3.6), is shown several dynamics to QDLED slave at high current compare with ($\delta_o=0.013$) to the master and small detuning frequency at ($\Delta\omega=0.025$) and the other parameters as in Sec II. For illustration we must mention the behavior of QD-LED here is completely different from the behavior of the QD laser under the effect of optical injection, where we have two cases, the first is the damping and disappearance of the slave signal at the value of 0.02 and it is a unique case of the QD-LED behavior, which penetrated the system in previous work when studying the filtered optical feedback [6]. And the second case, increase the output capacity of the slave by increasing the effect of optical injection, which is also a result obtaining for the first time.

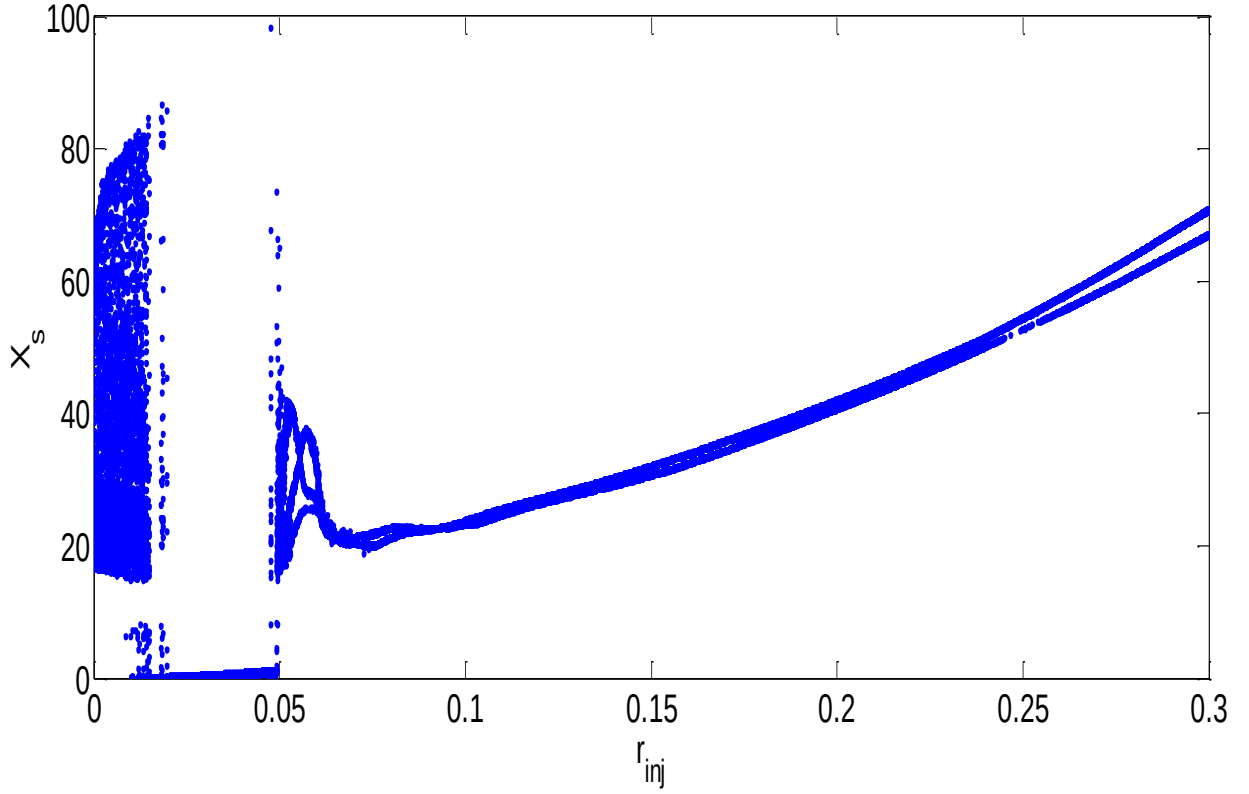


Fig. (3.6): Bifurcation diagram of output photon dependence of optical injection ratio when ($\delta_o = 0.1$) to master and ($\delta_o = 0.013$) to slave, and detuning ($\Delta\omega = 0.025$).

We can illustrate the above figure by the time series and the corresponding attractor plotting. Fig. (3.7 (a)) shows a clear variation of the photon output behavior for cases which they are passes by the effect of changing the optical injection ratio. It should be noted that all these cases get complex dynamic as result the effect of the field strength and the amount of perturbation affecting on the dynamics of the slave. The corresponding attractor shows each case noted that the corresponding attractor of the signal damping state is a line up and a homoclinic attractor with large capacity for corresponding value 0.3 as seen in Fig. (3.7 (b)).

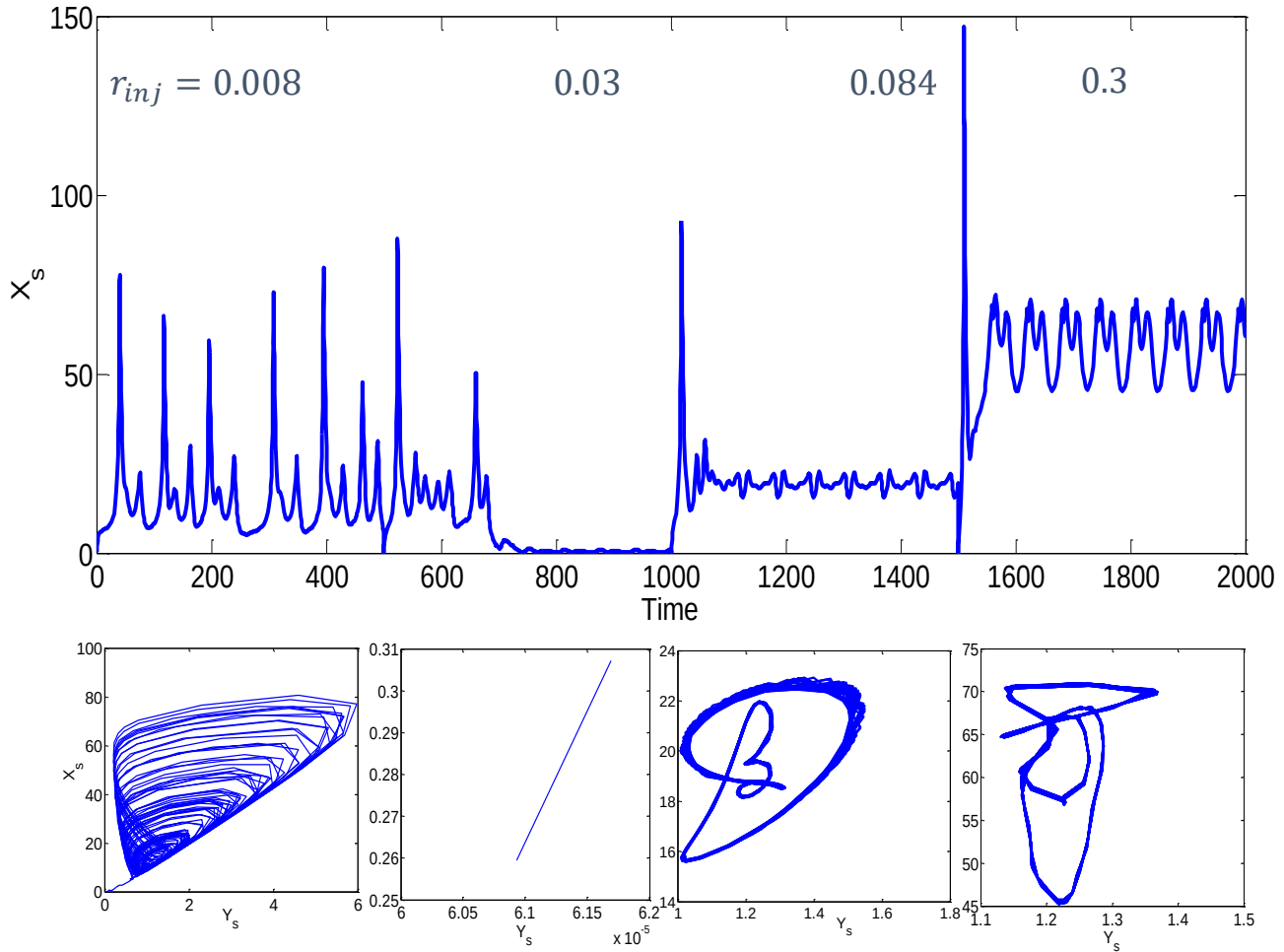


Fig. (3.7): Examples of output photon dynamics for QD-LED slave by using optical injection ratio effect. (a) Time series. (b) attractor, corresponds to bifurcation in Fig. (3.6).

3.4 Transition Mode Controlling and Locking

First we will look for control over the output pattern in the slave system that corresponds to the parameters influencing its behavior. In order to represent the richness of the dynamics in QD-LED with optical injection as a function of bias current for both QD-LED (master and slave systems) at injection coefficient $r_{in}=0.2$, frequency detuning is $\Delta\omega = 0.02$, we show in Fig. (3.8) the boundaries of qualitatively different dynamics in the plane of the injection parameters (the detuning and the injected ratio).

Fig. (3.8 (a)) represents the output of each of the two systems the master (red line) and the slave (blue line) under the influence of the bias current for master $\delta_{om}=0.013$ and for slave $\delta_{os}=0.013$, where the injection ratio is 0.2 and the frequency detuning is 0.02 as mentioned earlier. Note that we have reviewed a small part of the time series of the output so that we can see the behavior more clearly. In this figure, we observe the chaotic behavior of the master and the fast dynamics compared with the semi-periodic and slow-moving behavior in slave. It can be seen that the power of the first pulse reaches to 128 for the slave while it is less than to 80 for the master system. Fig. (3.8 (b)) represents the attractor of both master and slave, which shows the mixed and discordant behavior between the two systems under study.

Fig. (3.8 (c)) shows an increase in the value of the slave bias current to 0.1, while the rest of the other parameters remain unchanged. In this figure, we observe no change in the general behavior, except the first pulse power is reduced to 90 of its value. Fig. (3.8 (c)) shows their corresponding attractors.

Fig. (3.9 (a)) shows behavior when the slave current is equal to 0.2, where there is also no change in general behavior. Again, we observe a continuous decrease in the output power to less than 80 of the value of the first pulse. Fig. (3.9 (b)) also shows no significant change in overall behavior. Fig. (3.9 (c)) shows behavior as double period when the slave current is equal to 0.3, where we also notice that there is no significant change in overall behavior. And the output power continues to decrease to about 70 of the value of the first pulse. Fig. (3.9 (d)) also shows no significant change in overall behavior with persistent inconsistent behavior.

From Fig. (3.8) and Fig. (3.9) we observe absolute control over slave dynamics where general behavior has not changed and this is an important result, where the previous studies have shown the great influence of the bias current on system dynamics without external of perturbation. The above result shows the processes that occur in the active medium of the interaction of fields by optical injection are stronger than the effect of the carriers by the bias current.

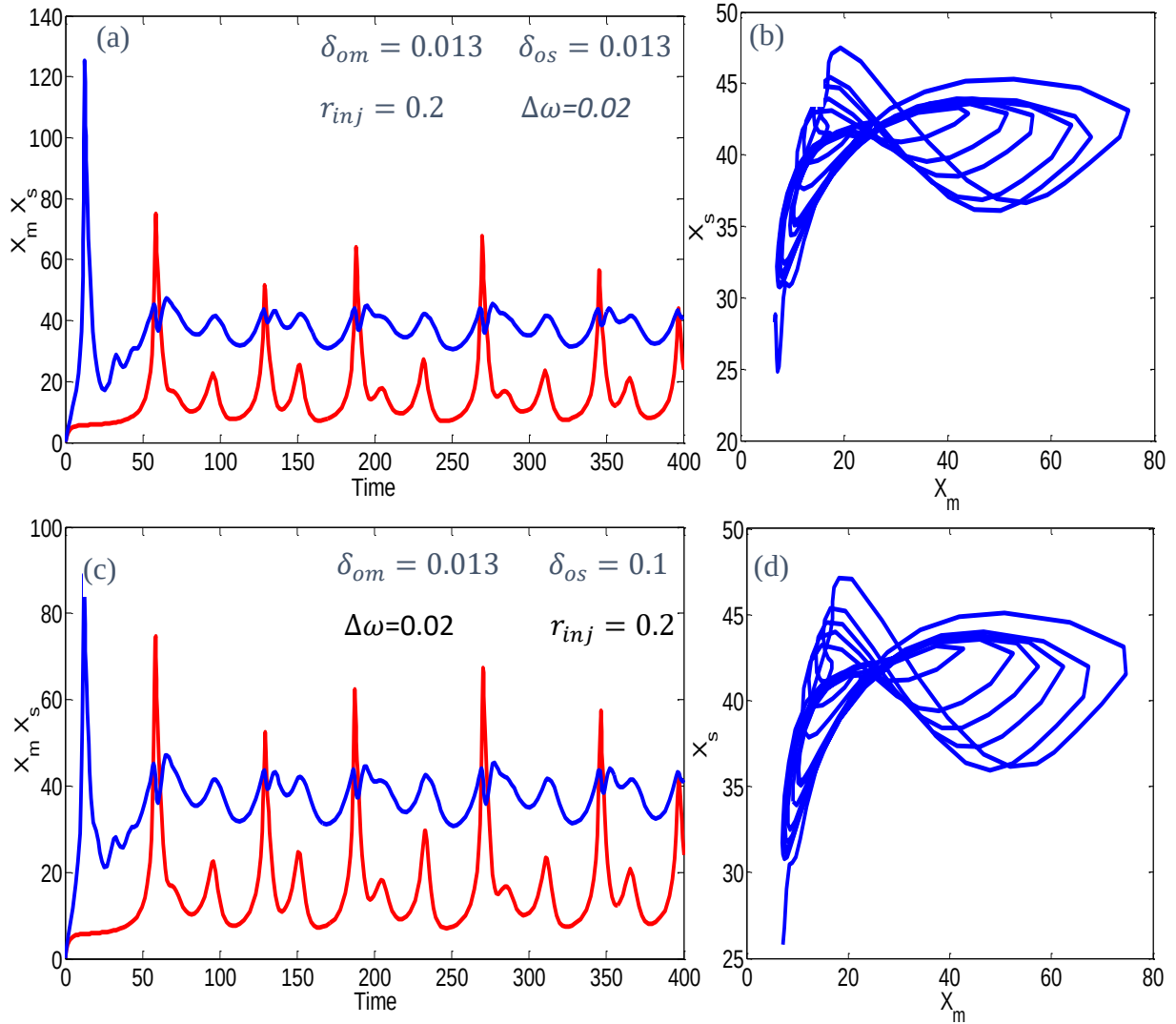


Fig. (3.8): Examples of output photon dynamics for QD-LED master x_m (red line) and slave x_s (blue line) by using bias current effect with fixing values of the detuning $\Delta\omega=0.02$ and the injected ratio $r_{inj}=0.2$. (a) Time series at $\delta_{om}= 0.013$, $\delta_{os}=0.013$ and $\delta_{os}=0.1$ in (c) with their corresponding attractors in (b) and (d).

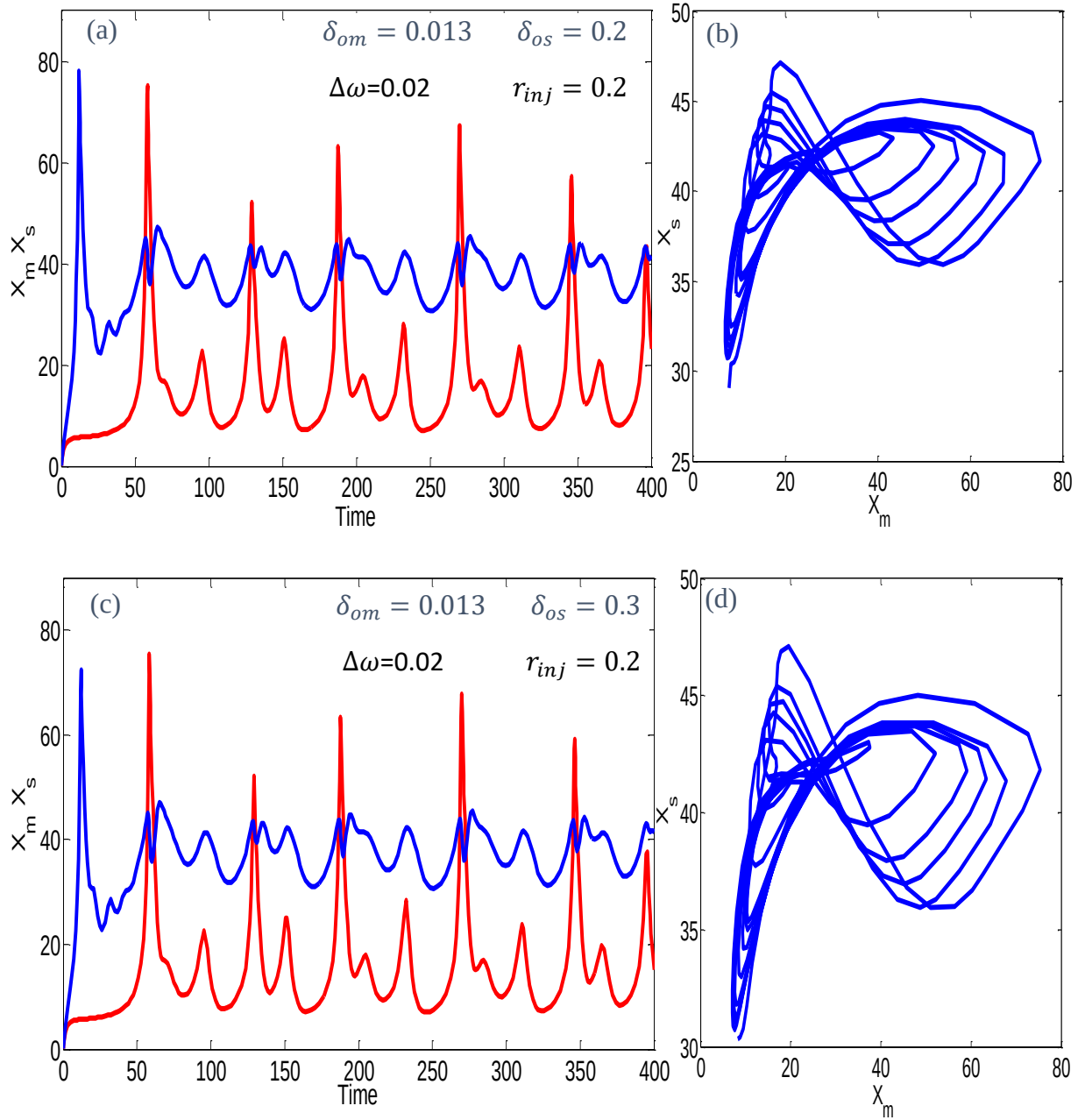


Fig. (3.9): Examples of output photon dynamics for QD-LED master x_m (red line) and slave x_s (blue line) by using bias current effect with fixing values of the detuning $\Delta\omega=0.02$ and the injected ratio $r_{inj}=0.2$. (a) Time series at $\delta_{om}=0.013$, $\delta_{os}=0.2$ and $\delta_{os}=0.3$ in (c) with their corresponding attractors in (b) and (d).

Now we can move to another step where we can determine the period-doubling behavior of the master by selecting the bias current value equal 0.1 comparing with the another parameters are which still without changing. In Fig. (3.10 (a)) and at the bias current $\delta_{os}=0.013$ we notice that the mostly behavior on the slave system is the period-doubling. The fast behavior of slave begins with a pulse of intensity up to 130 while the behavior of the master is slow with the loss of the first pulse completely. The period-doubling behavior shown in Fig. (3.10 (b)) corresponds to the number of circles in the plane. In Fig. (3.10 (c)) we obtain the same behavior as the slave, although the bias value of the current changes to 0.1. Where the fast pulse is reduced to 90. Fig. (3.10 (d)) is consistent with this finding.

The intensity of the signal of the slave decreases to less than 80 at a bias current of 0.2 as in Fig. (3.11 (a)) and to 70 at bias current 0.3 as in Fig. (3.11 (c)) with fix behavior without change. Again the attractor corresponds to the time series in both Fig. (3.11 (b)) and Fig. (3.11d) respectively.

Finally, when we study 0.2 as the value of the bias current of master system, we see full control over the behavior of the slave system with a continuation of general behavior as in Figs. (3.12 (a and c)), and Figs. (3.13 (a and c)) and attractors in Figs. (3.12 (b and d)) and Figs. (3.13 (b and d)).

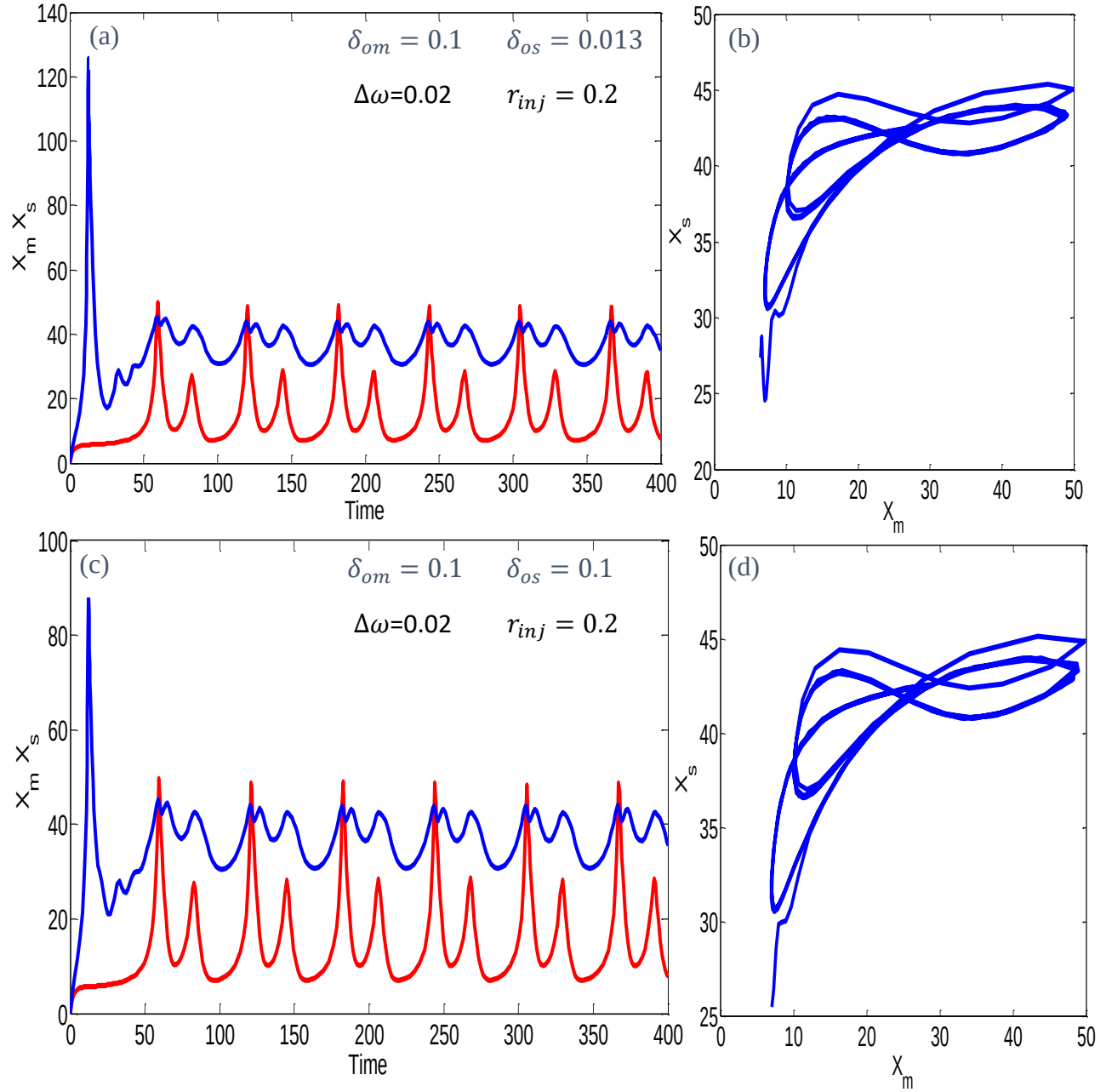


Fig. (3.10): Examples of output photon dynamics for QD-LED master x_m (red line) and slave x_s (blue line) by using bias current effect with fixing values of the detuning $\Delta\omega=0.02$ and the injected ratio $r_{inj}=0.2$. (a) Time series at $\delta_{om}=0.1$, $\delta_{om}=0.013$ and $\delta_{os}=0.1$ in (c) with their corresponding attractors in (b) and (d).

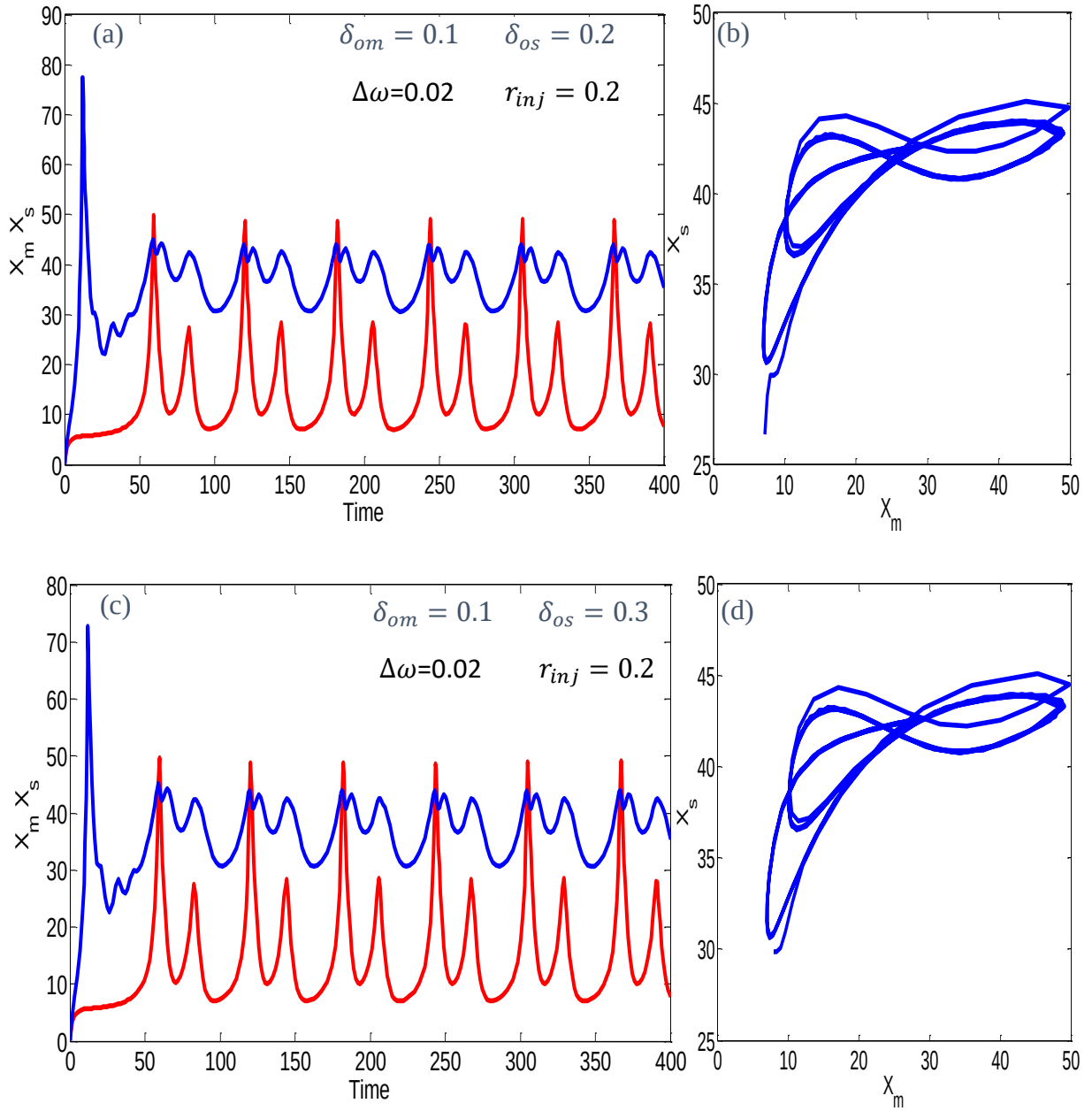


Fig. (3.11): Examples of output photon dynamics for QD-LED master x_m (red line) and slave x_s (blue line) by using bias current effect with fixing values of the detuning $\Delta\omega=0.02$ and the injected ratio $r_{inj}=0.2$. (a) Time series at $\delta_{om}=0.1$, $\delta_{os}=0.2$ and $\delta_{os}=0.3$ in (c) with their corresponding attractors in (b) and (d).

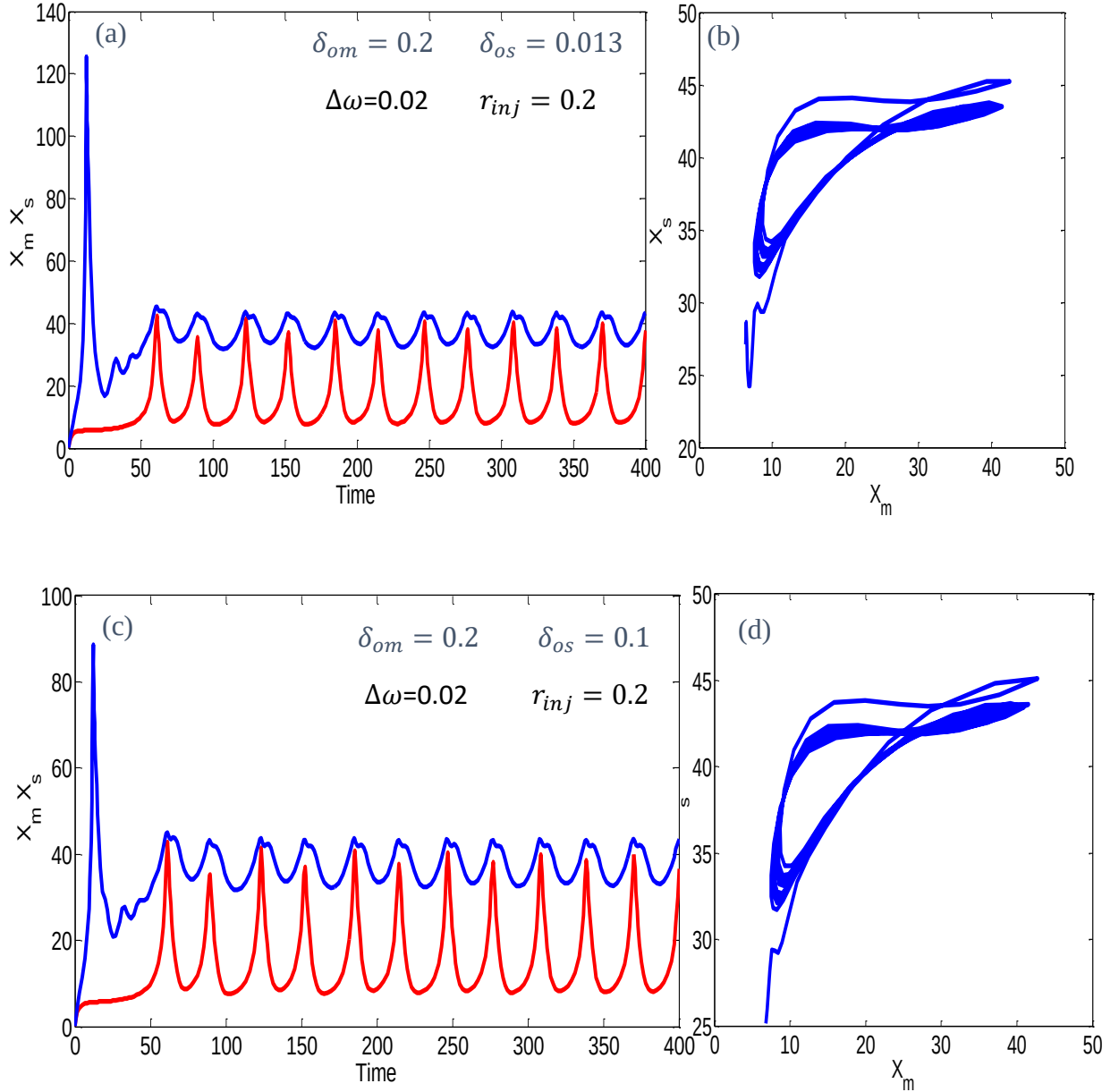


Fig. (3.12): Examples of output photon dynamics for QD-LED master x_m (red line) and slave x_s (blue line) by using bias current effect with fixing values of the detuning $\Delta\omega=0.02$ and the injected ratio $r_{inj}=0.2$. (a) Time series at $\delta_{os}=0.2$, $\delta_{os}=0.013$ and $\delta_{os}=0.1$ in (c) with their corresponding attractors in (b) and (d).

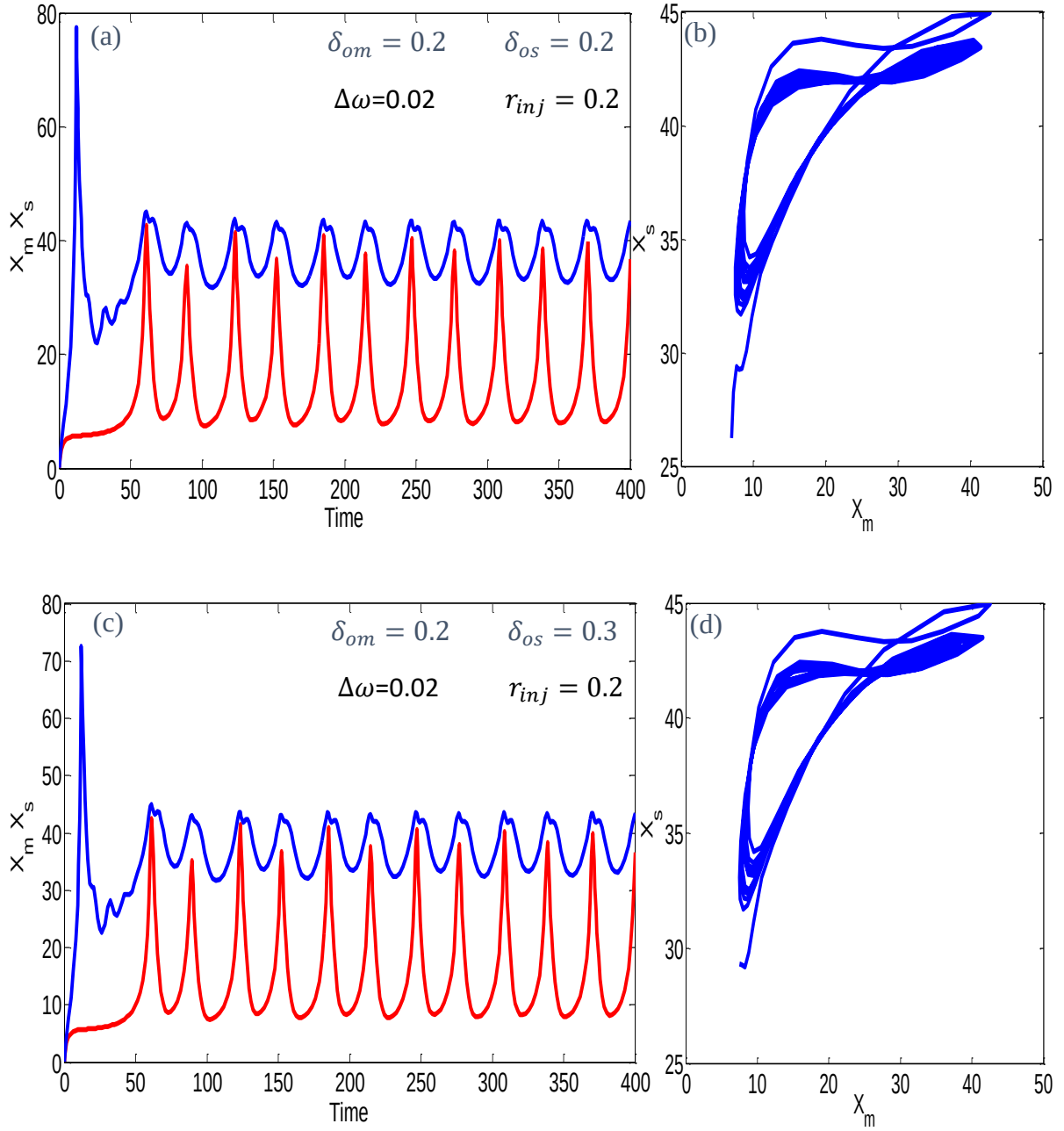


Fig. (3.13): Examples of output photon dynamics for QD-LED master x_m (red line) and slave x_s (blue line) by using bias current effect with fixing values of the detuning $\Delta\omega=0.02$ and the injected ratio $r_{inj}=0.2$. (a) Time series at $\delta_{om} = 0.2$, $\delta_{os}=0.2$ and $\delta_{os}=0.3$ in (c) with their corresponding attractors in (b) and (d).

Second, another phenomenon called optical locking will be studied. The injection locking was known more than 30 years ago in several types of oscillators [85]. Its application for semiconductor devices is of great interest. Indeed, the injection locking was shown to significantly improve the coherence properties of the emitted signal, leading, for example, to a reduction of the mode hopping and mode partition noise, a reduction of the laser linewidth and of the frequency chirping, and an enhancement of the modulation bandwidth.

Fig. (3.14 (a)) represents the time series of both the master and slave signal at the same value for the bias current 0.1 with different values of detuning $\Delta\omega=0$ and small injection ratio $r_{inj}=0.0001$. Here we see the approach of the phase and amplitude of some of them by the effect of injection rate only. Fig. (3.14 (b)) is clearer where we observe symmetry in behavior. To obtain the locking for the optical mode, increase the frequency detuning to 0.1 and also increase the simple in the bias current of both master and slave 0.11 and 0.12 respectively as in Fig. (3.14 (c)). The parity synch is clearly shown in Fig. (3.14 (d)).

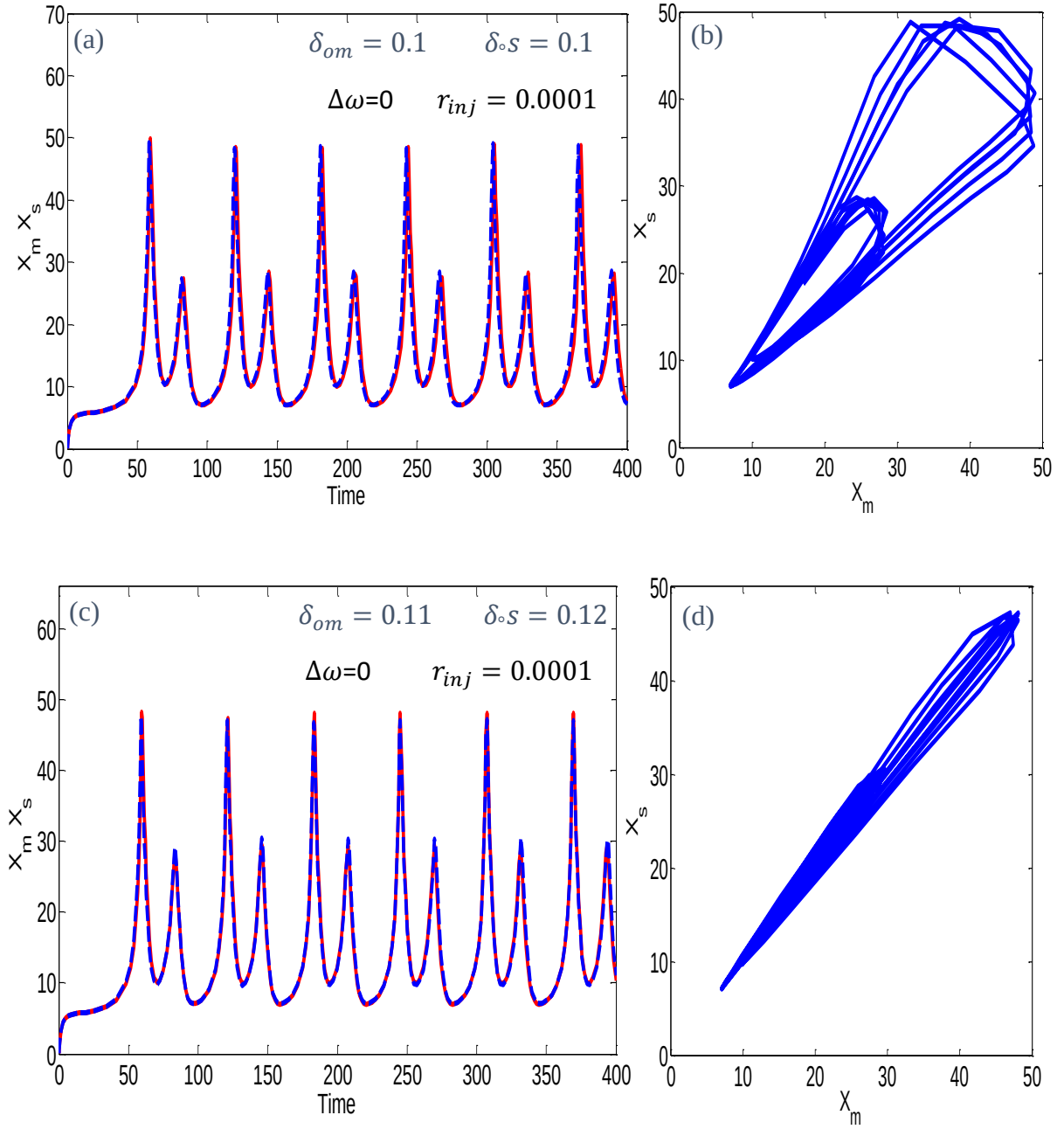
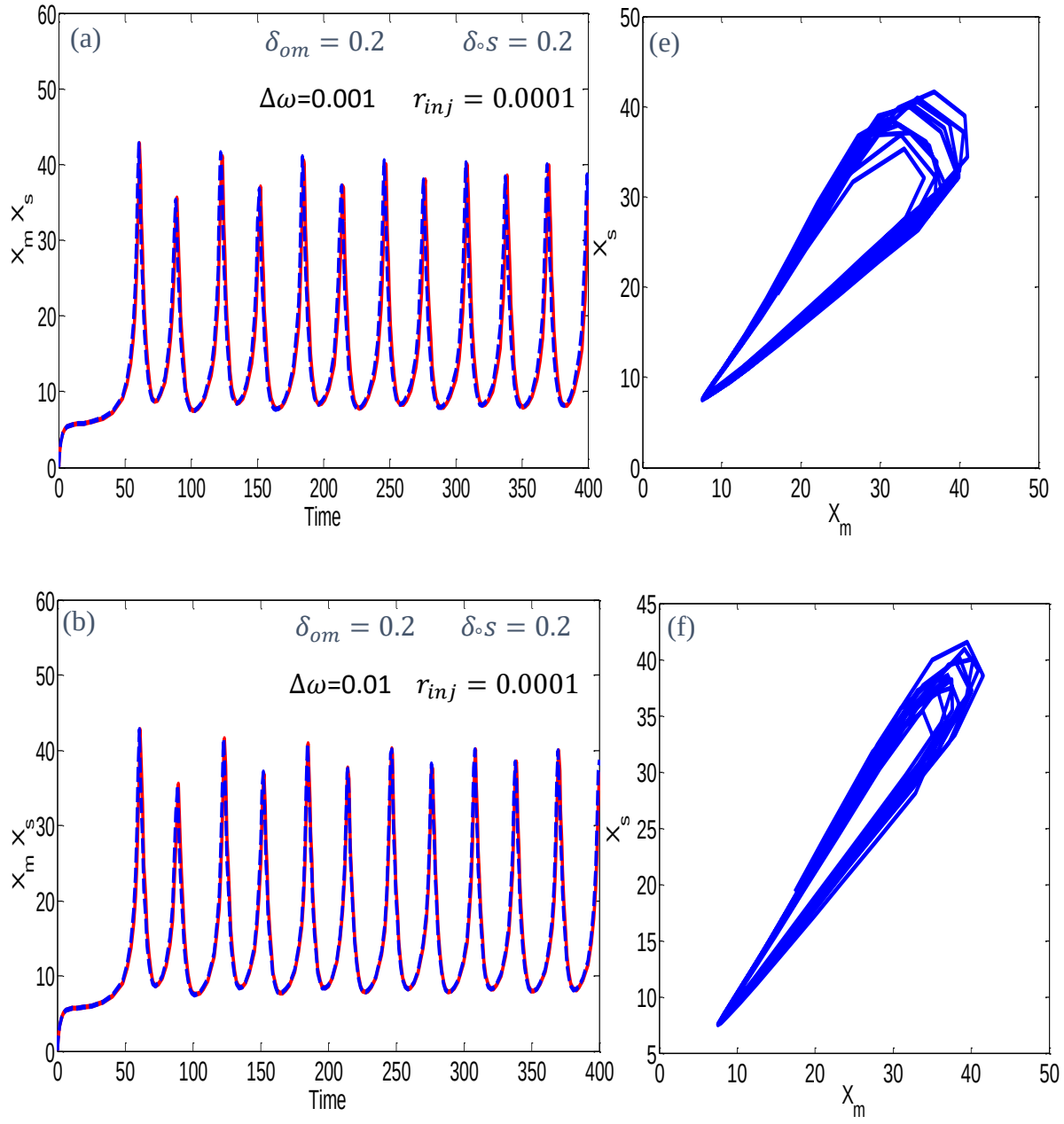


Fig. (3.14): Examples of output photon dynamics for QD-LED slave by using bias, injection ratio and detuning effect to shown looking modes. (a) and (c) Time series. (b) and (d) attractors.

When the value of another bias current which is 0.2 shared by both master and slave we observe the common periodic behavior as in Fig. (3.15 (a)). We obtained this result by choosing the value of the frequency detuning equal to 0.001. Note that the value of the injection ratio (0.0001) will be fixed for the following results. In Figs. (3.15 (b, c and (d)) we see an increase in optical mode locking with increasing frequency detuning from 0.01 to 0.2 where the phase and intensity of the master and slave systems are consistent. The Figs. (3.15 (e, f, g and h)) represent a more useful method in determining the complete synchronization between the two systems where the behavior moves from the symmetry around the default axis (square diameter) as in Fig. (3.15 (e)) and on the diameter as in Fig. (3.15 (h)). In Figs. (3.16 (a and b)) we cannot obtain of locking with 0.3 bias current. and proximately in Figs. (3.17 (a and b)).

We can summarize the dynamics of a QD-LED with optical injection with bias current, frequency detuning and injection ratio effect: Mode control region in which the slave is frequency locked to the master, which corresponds to the “period-doubling state” of the QD-LED system. For locking to occur, two conditions must be satisfied: (i) the detuning between the frequency of the injected field (master) and the slave of the QD-LED should be large enough and (ii) the injected power should not be too large. This is a completely different result of the laser [10] and may be due to the small oscillations relaxation time in the QD-LED.



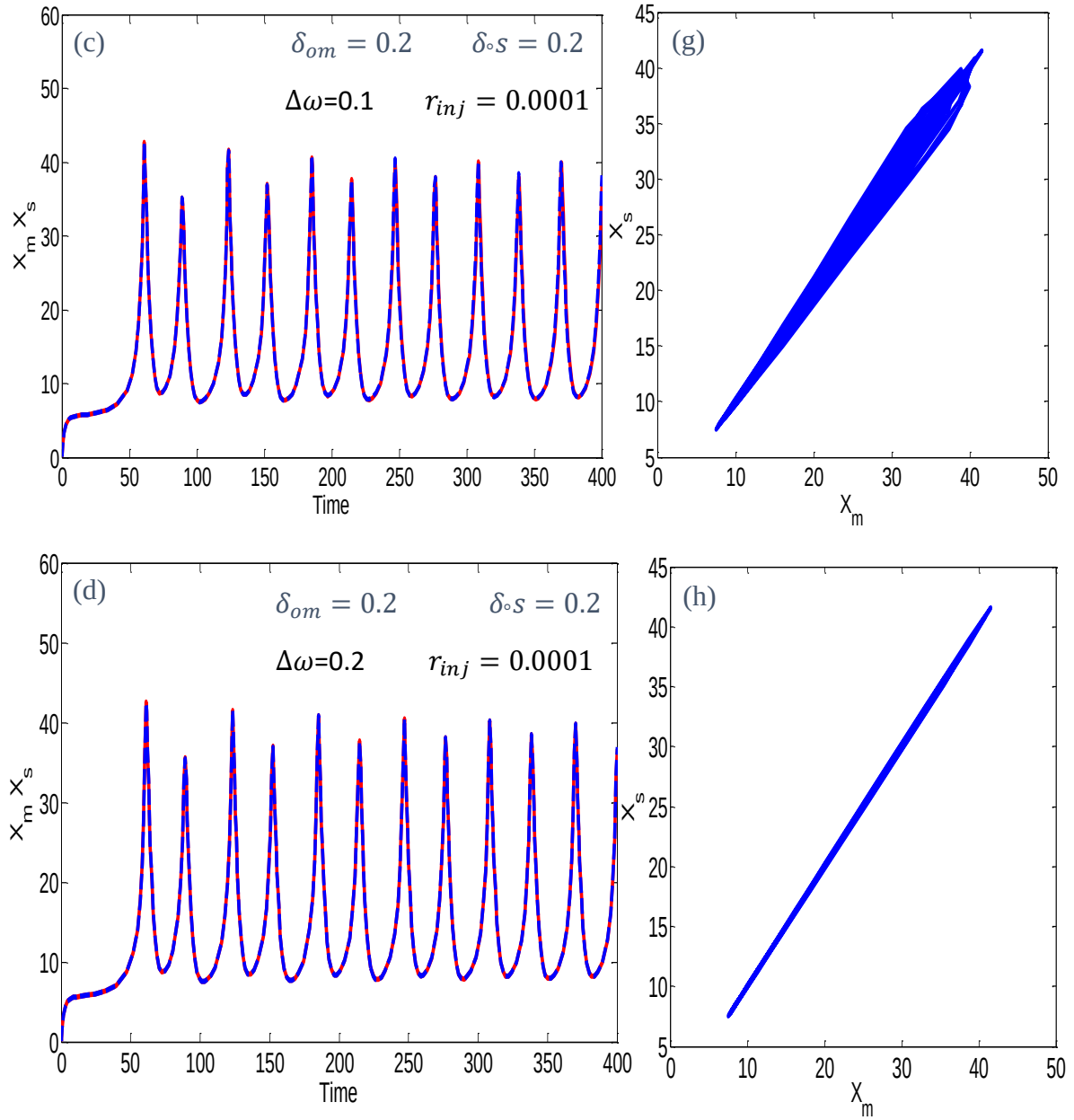


Fig. (3.15): Examples of output photon dynamics for QD-LED slave by using bias, injection ratio and detuning effect to shown looking modes. (a) and (c) Time series. (b) and (d) attractors.

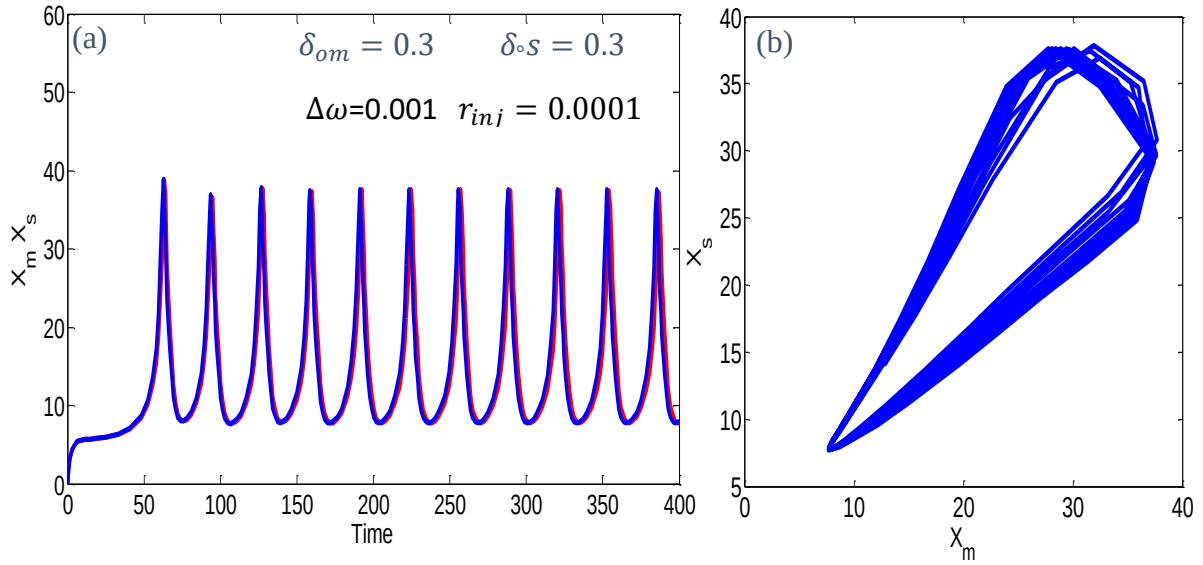


Fig. (3.16): Examples of output photon dynamics for QD-LED slave by using bias, injection ratio and detuning effect to shown looking modes. (a) and (c) Time series. (b) and (d) attractors.

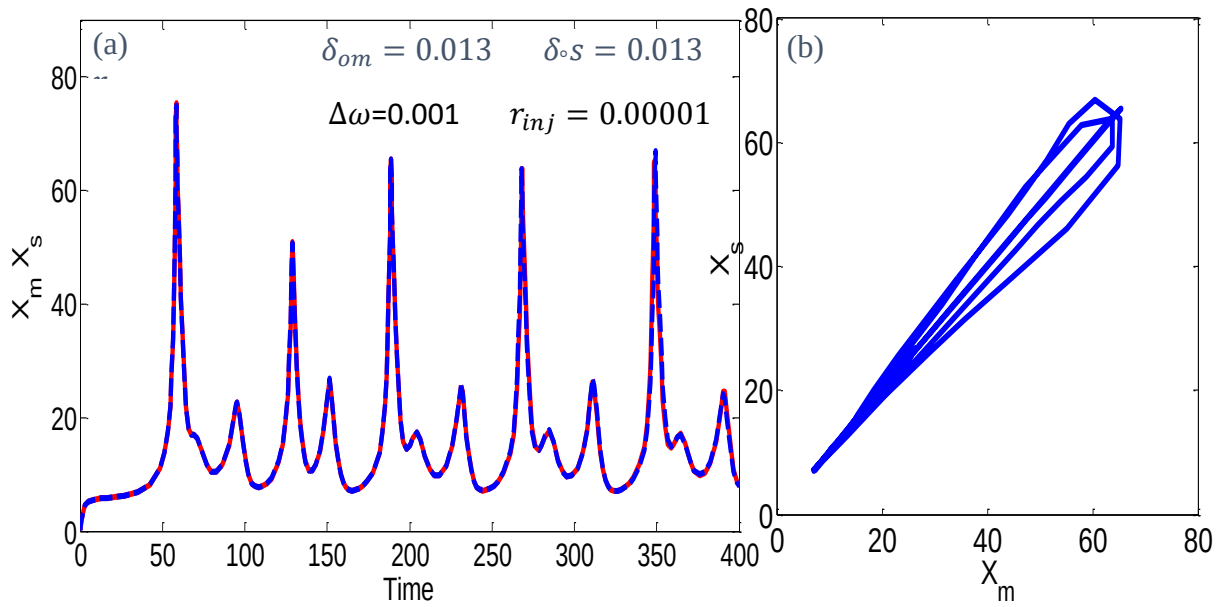


Fig. (3.17): Examples of output photon dynamics for QD-LED slave by using bias, injection ratio and detuning effect to shown looking modes. (a) and (c) Time series. (b) and (d) attractors.

3.5 Two Modes Dynamics with Two Parameters Effect

In the previous sections, we have already introduced the interesting features of QD-LED dynamics with optical injection. The fact that such a LED easily emits multi modes with slightly different frequencies makes it very appealing for the study of mode competition in configurations where the LED is brought into complex nonlinear dynamical scenarios. We have already mentioned the inphase or antiphase dynamics occurring either in chaotic current bias dynamics or in the optical locked dynamics, which are characteristic of optically injection bifurcations. Recently investigations have concerned a so-called two-color laser device, that is, a device that can laser simultaneously on two different modes with possibly quite a large (terahertz) frequency spacing [86–88]. One of the two modes is subject to optical injection and still the laser exhibits a large variety of two-mode inphase and antiphase dynamics including limit cycle, quasi-periodicity and chaos [89].

Here, we shall focus more on the bistable (two modes) properties arising from the mode competition of QD-LED and how they interplay with current bias and injection ratio. We shall introduce our prototype theoretical for the study of the interplay with bistable mode switching: a QD-LED subject to an optical injection and bias current.

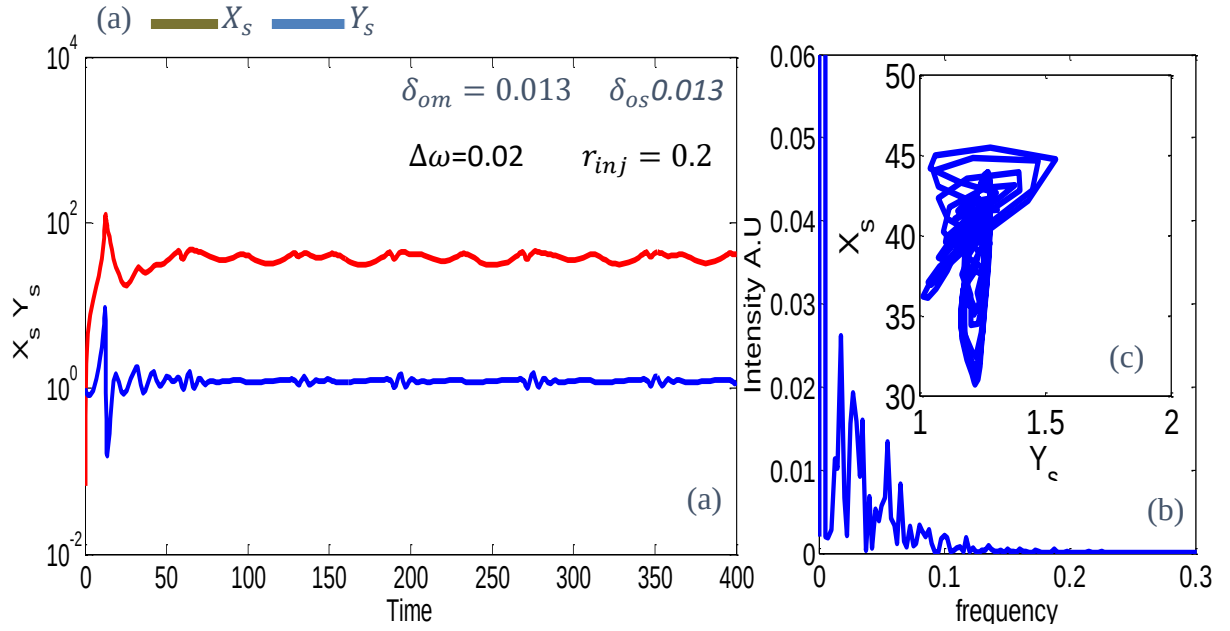
The two modes exhibit by the bias current effects, δ_{om} and δ_{os} , which is depends on the values of the carrier capture and relaxation rates and can be changed by varying the band structure of the QD–QW system, the two modes exhibit also different injection coefficient. These two modes are both high-order transverse modes with approximately the same qualitative features, so the apparent difference is very significative.

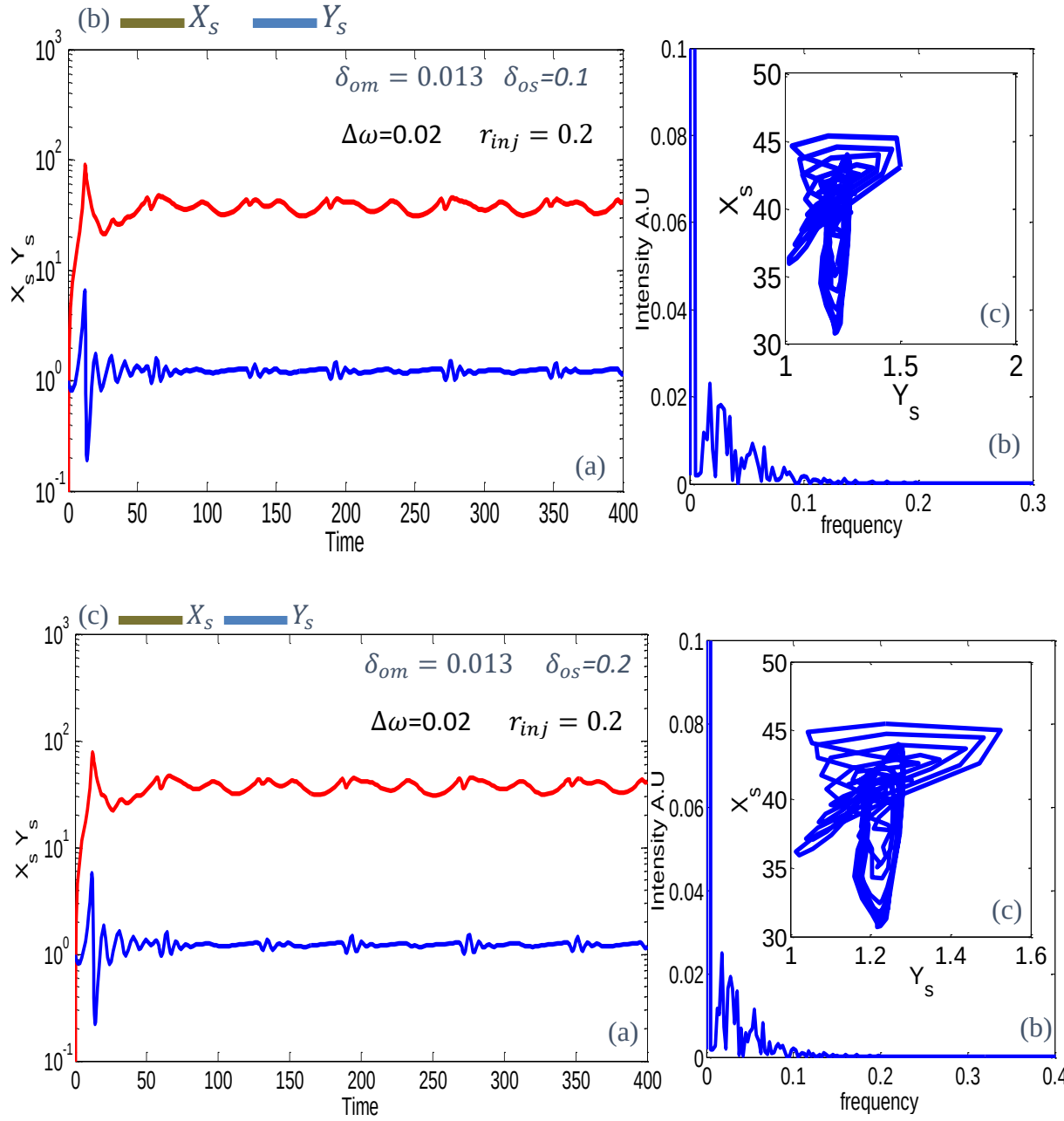
First and in order to represent the dynamics in QD-LED with optical injection under bias current effect, we show in Fig. (3.18) the different dynamics in the two panels of the bias current effect with injection parameters $r_{inj}=0.2$ and the detuning $\Delta\omega=0.02$. In left panel, time traces of total, x_s slave-photon mode intensity (red line), and Y_s slave-carrier mode intensity (blue line). The right panel shows fast Fourier translation (FFT) dynamics in the slave intensity with the subplot illustrates an attractor which is corresponding to a behavior in the time traces.

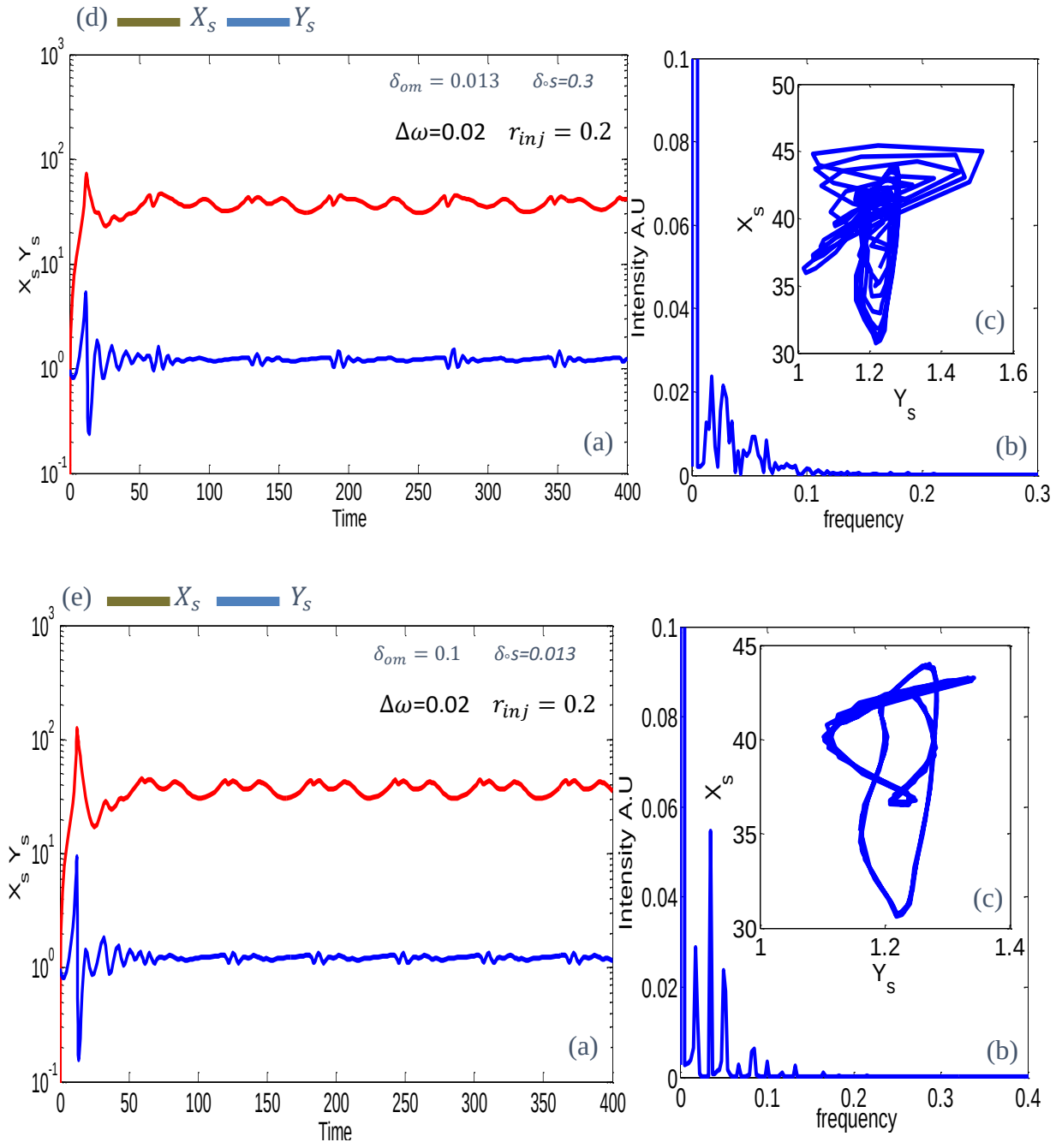
Fig. (3.18 (a)) The time trace shows the logarithmic scale of both photons and charge carriers of the slave system due to the large difference in intensity between them. There are several things that can be observed in addition to the intensity difference of the figure, the behavior of the carriers is slow compared with the fast behavior of the photons, slightly phase dependence, difference in frequency and finally shows the difference of optical mode. In FFT plotting shows chaotic behavior and in the attractor subplot shows the circles be orthogonal in two different planes and this is called homoclinic attractor due to two modes in QD-LED slave are exhibited. In Figs. (3.18 (b, c and d)) we observe that still the same behavior with a much lower pulse through FFT plot, maybe it due to the influence the bias current of the slave. At another value of the master bias current to 0.1 as in Figs. (3.18 (e, f, g and h)), we show the change of dynamic to the quadratic period, with continuous most of the characteristics observed in the previous Figs. From FFT and attractors, behavior can be clearly defined as the number of pulses and circles determines the kind of the dynamic.

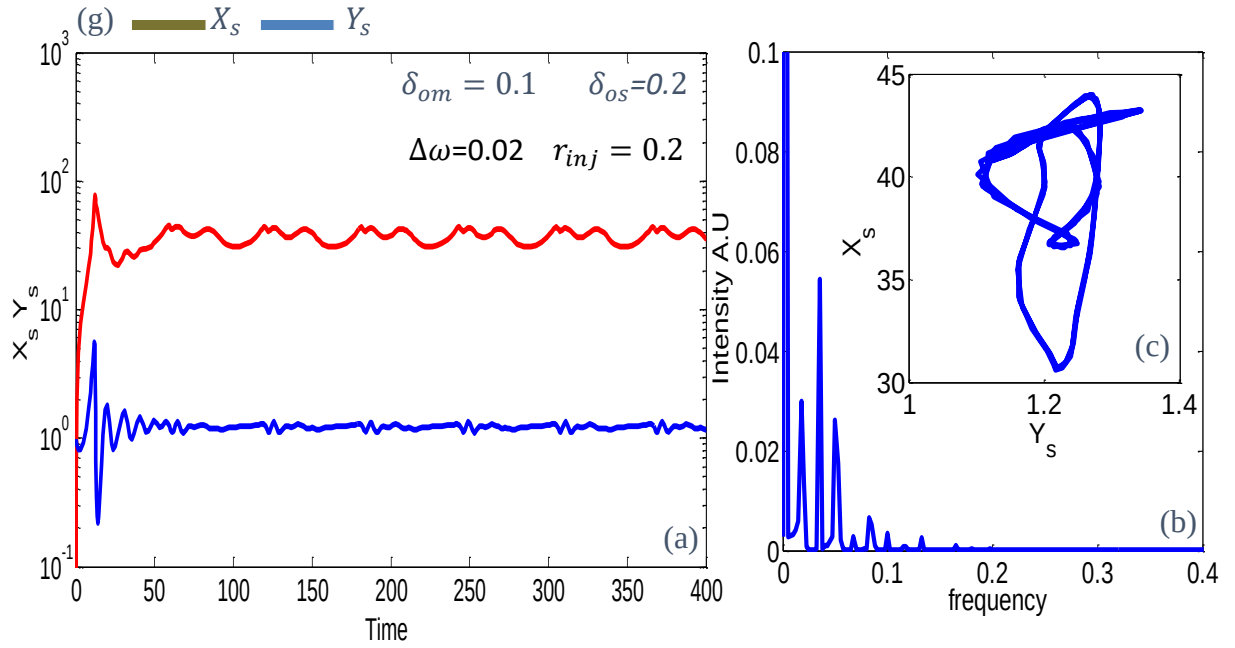
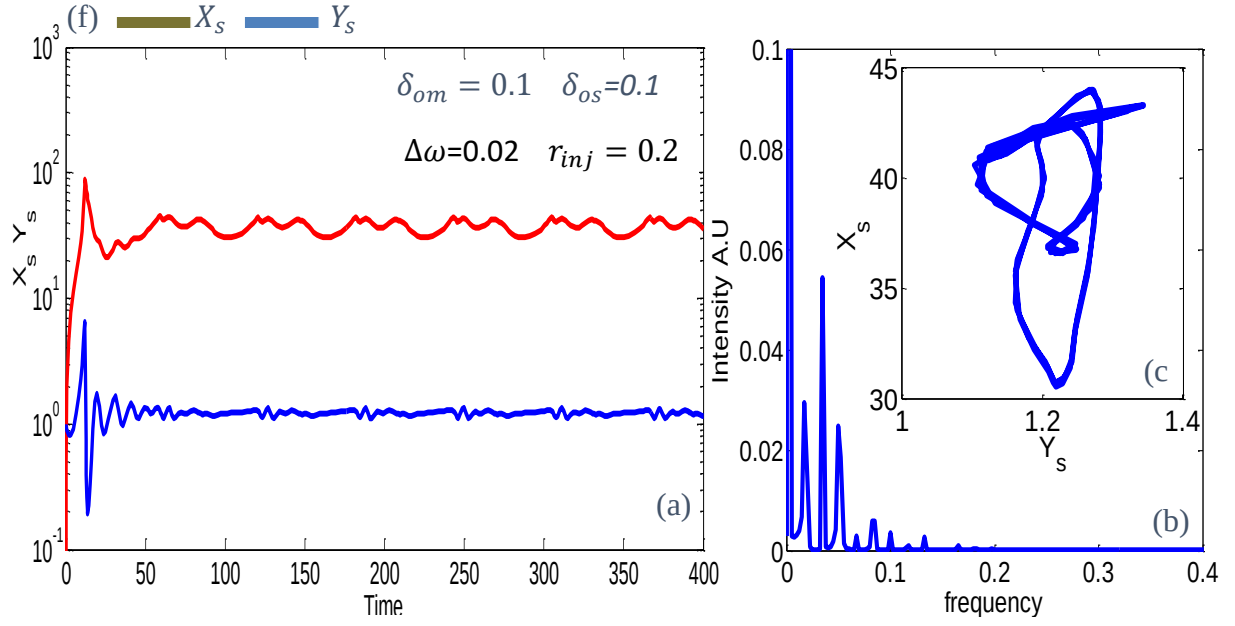
Also, when increasing the bias of the master to 0.2 as in the Figs. (3.18 (i, j, k and l)) and to 0.3 in the Figs. (3.18 (m, n, p and o)) with the increase of the

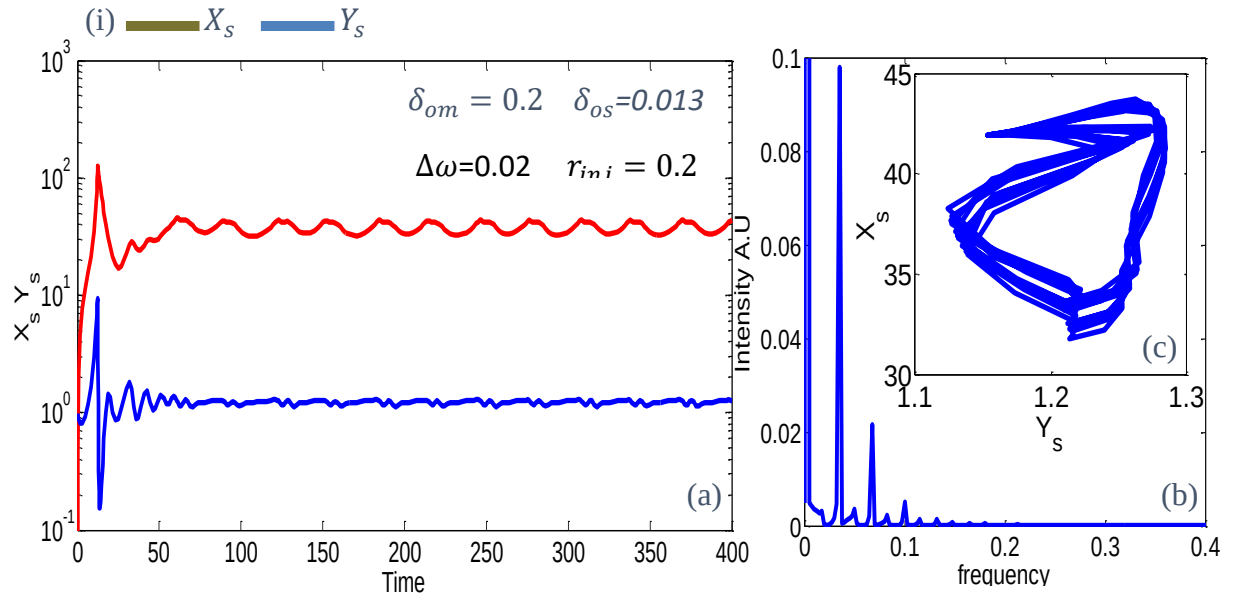
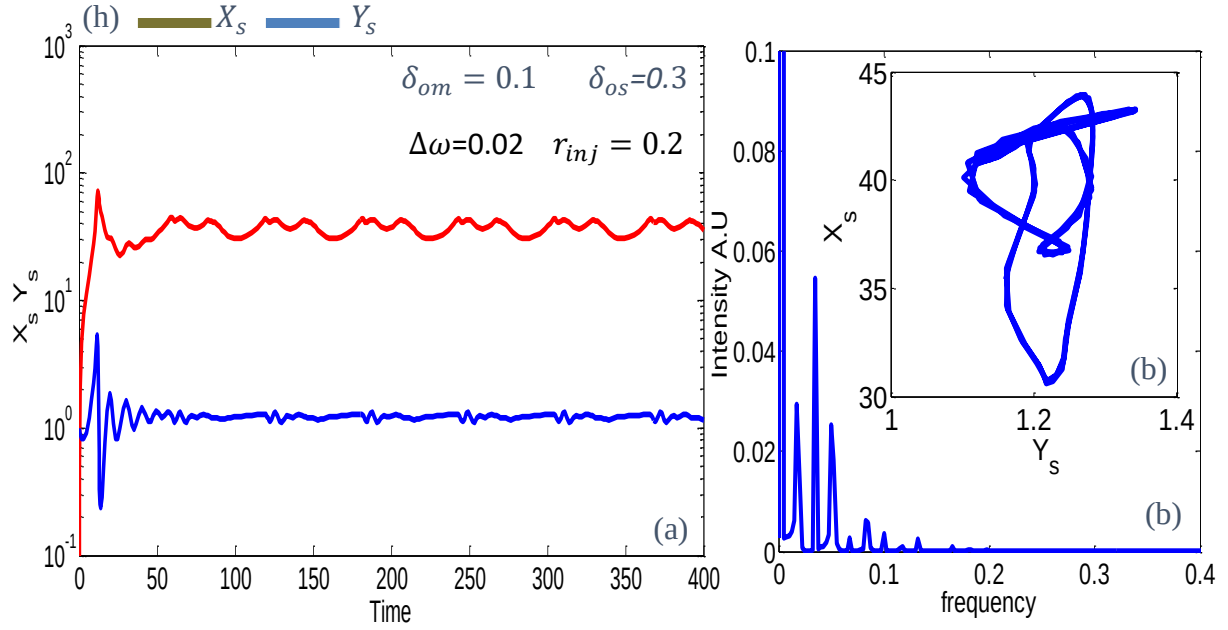
bias of the slave for each value we observe the behavior of the period doubling is dominant and almost disappear phenomenon of the two modes as is evident in the attractor. The large frequency spacing between the output modes makes it possible to investigate the properties of optically injected multimode QD-LED far beyond the approximation of the single-mode QD-LED equations. Among the interesting features, it is worth mentioning a bistability between a photon and a carrier states, that is applied to all-bias values until 0.2, in this value two modes state is ended.

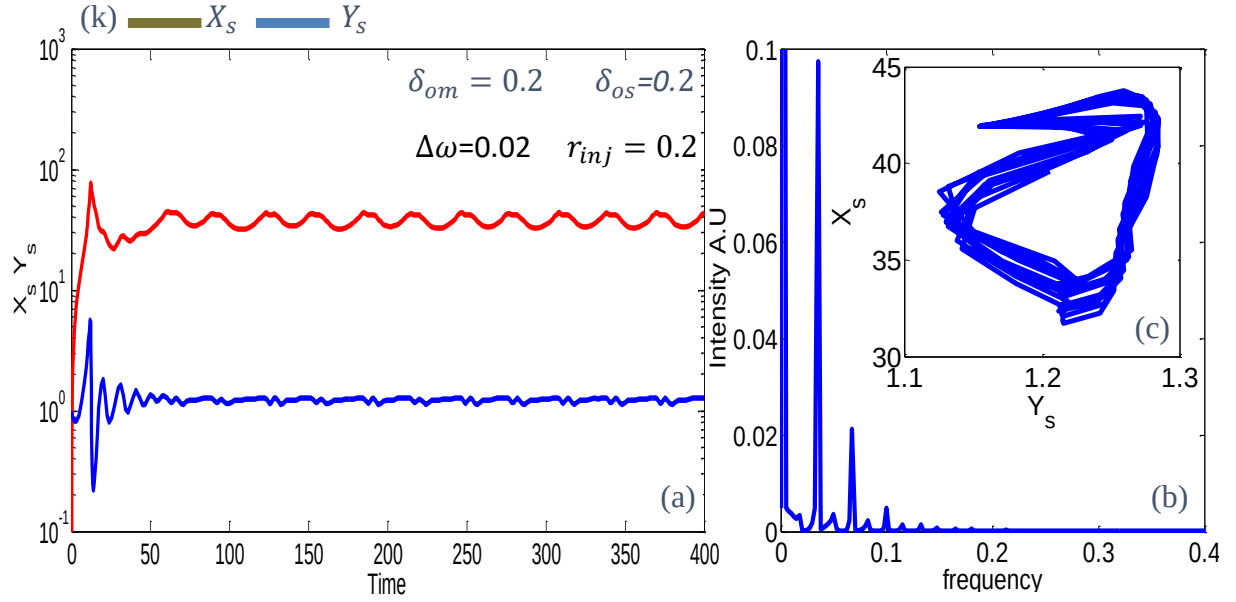
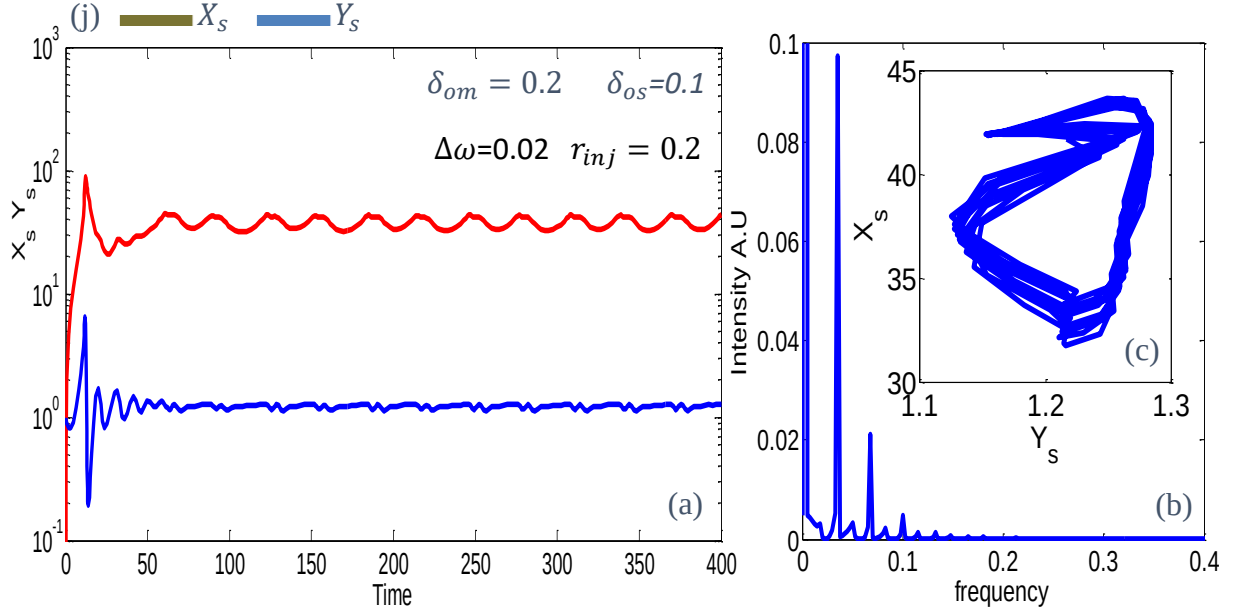


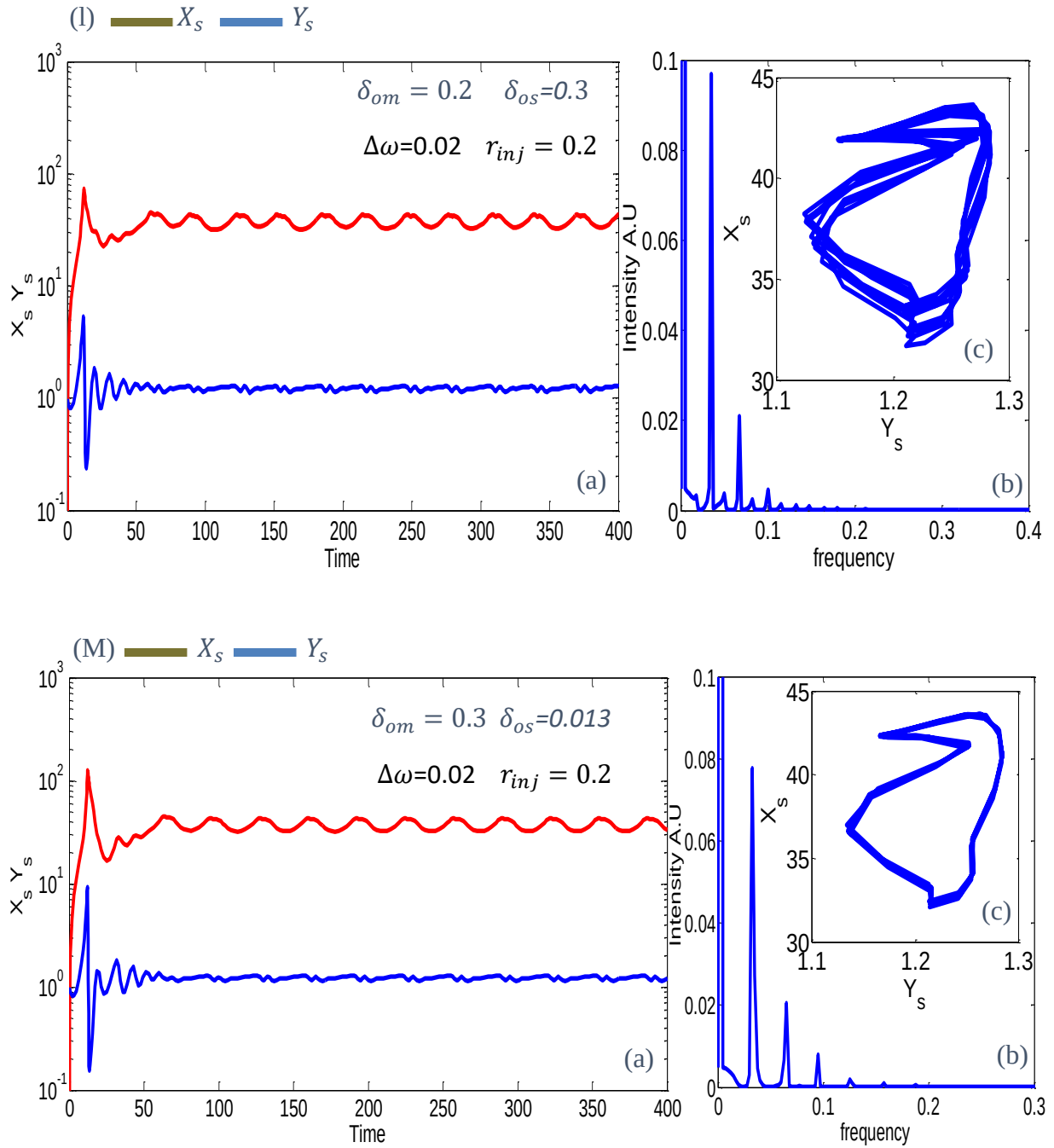


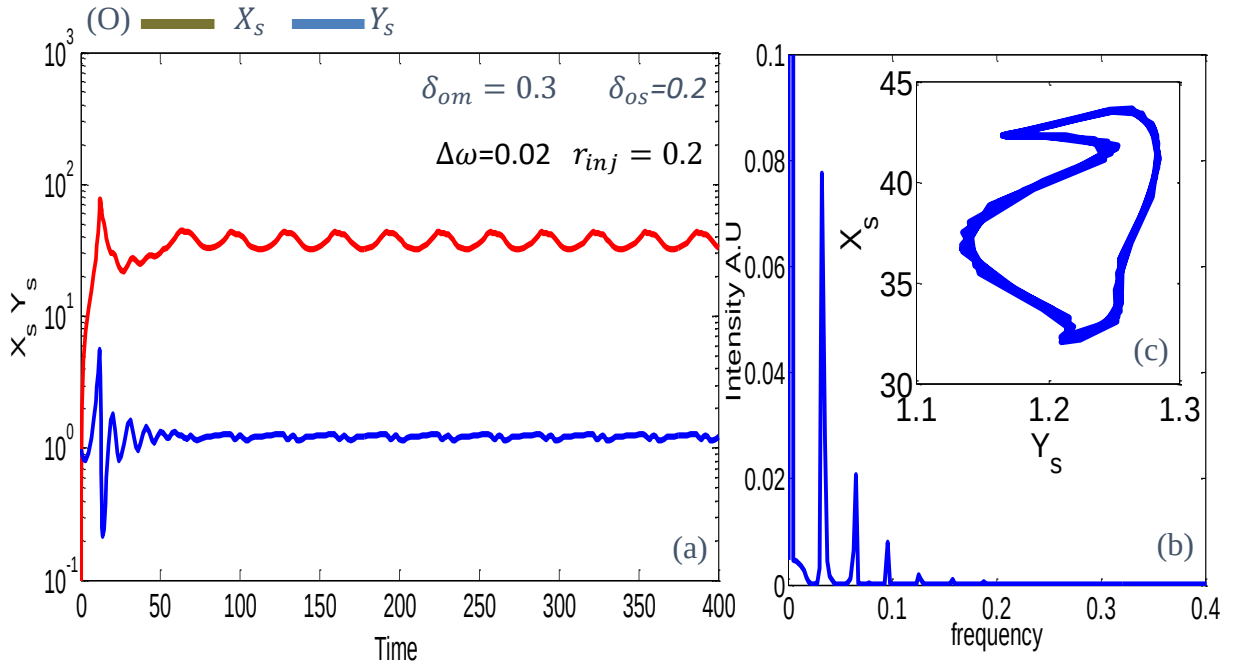
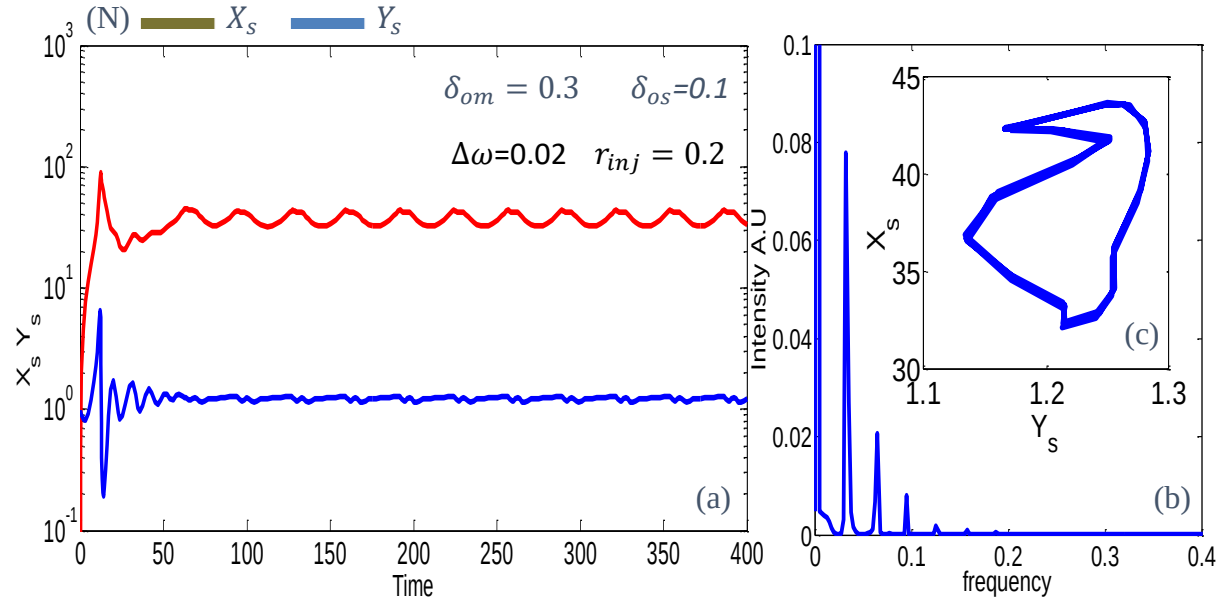












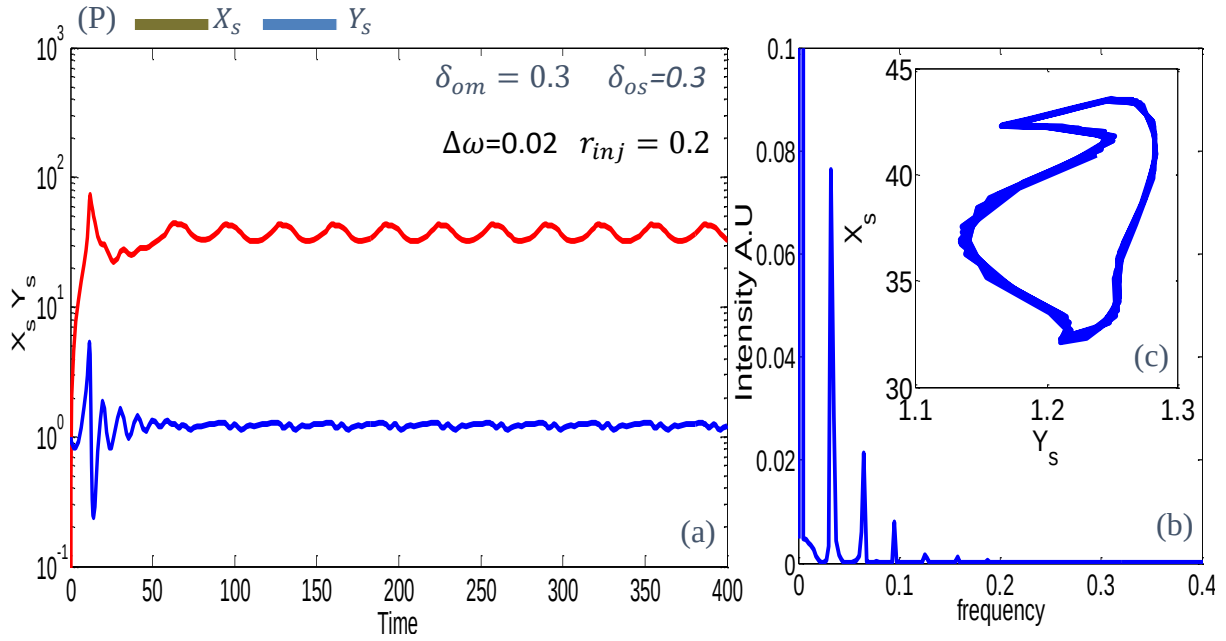


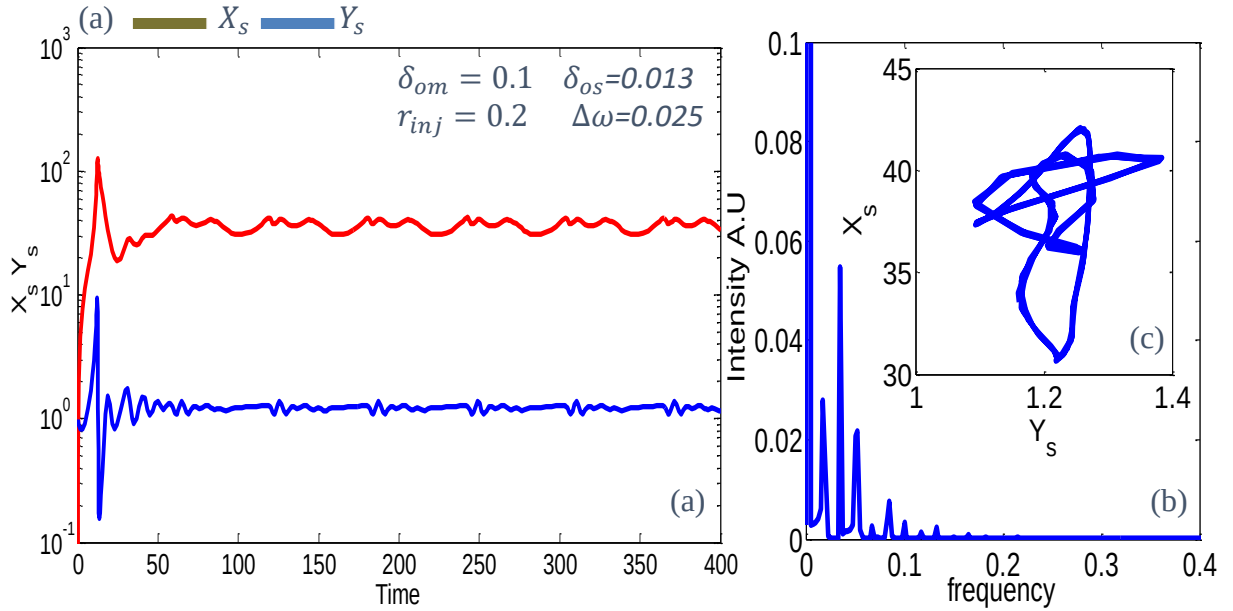
Fig. (3.18): Simulated optically injection dynamics in QD-LED for the different values of bias current. In left panel: time traces of total, x_s slave-photon mode intensity (red line), and Y_s slave-carrier mode intensity (blue line). The right panel shows FFT dynamics in the slave intensity. The subplot illustrates an attractor, however, the two modes fluctuate in anticorrelated dynamics resulting in less frequent dropouts of the total intensity.

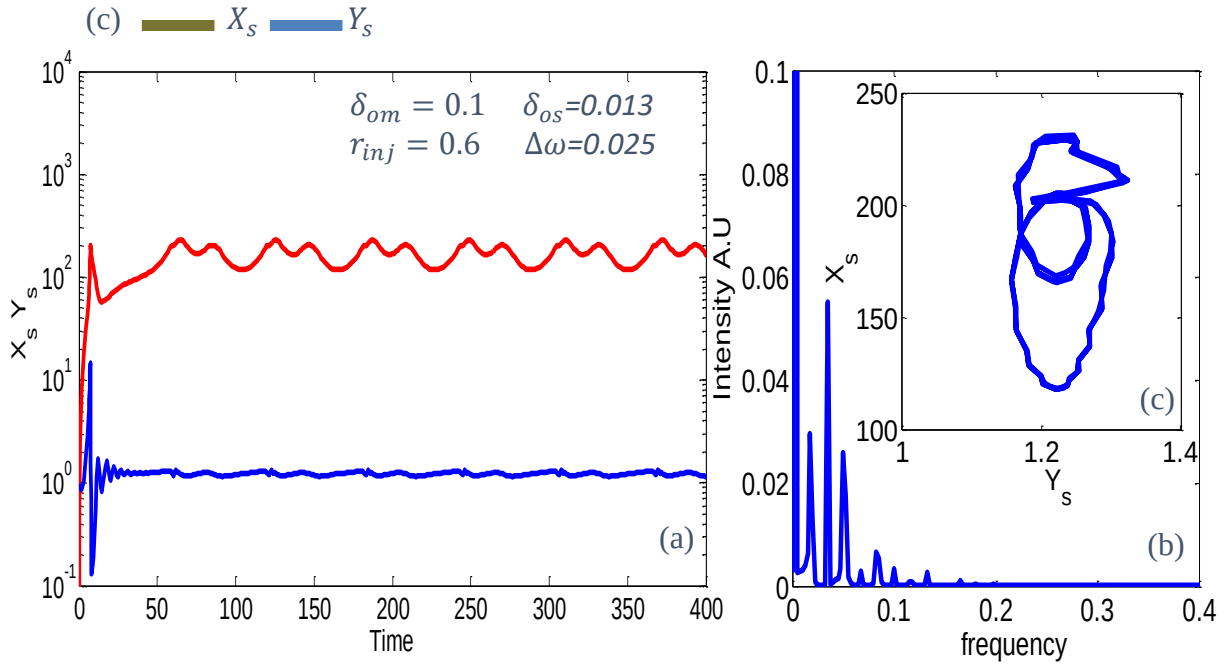
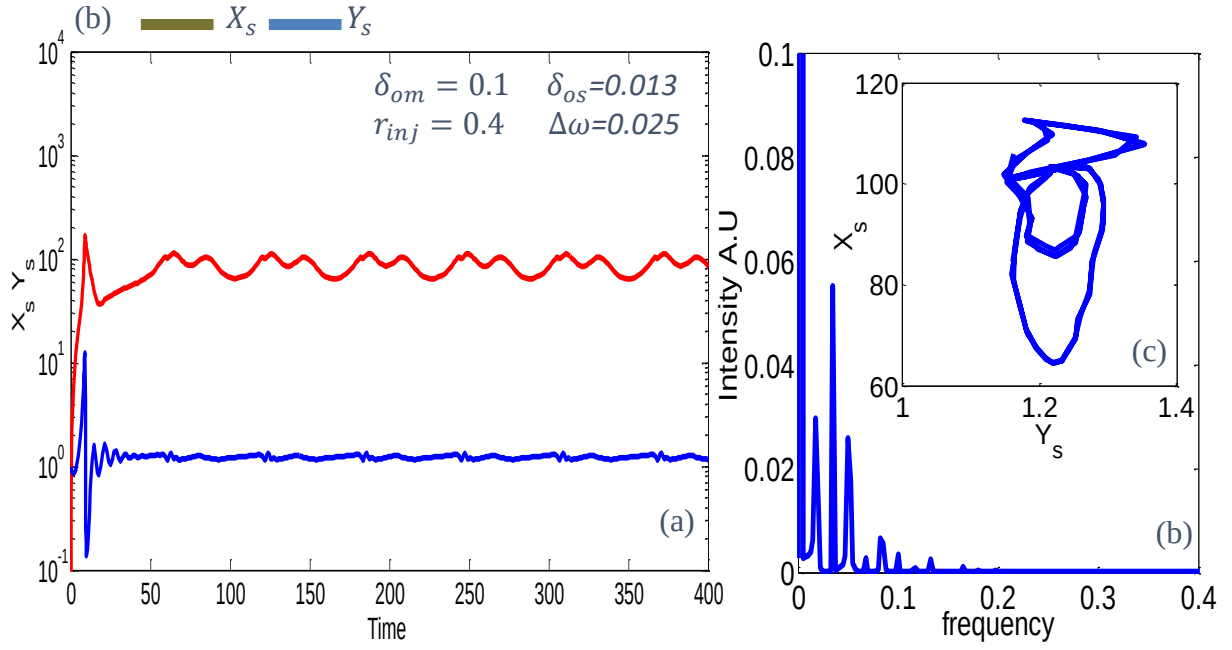
Second, we studied study a two-mode phenomenon with the effect of the ratio of optical injection r_{inj} with the stability value of both bias currents ($\delta_{om}=0.1$, $\delta_{os}=0.013$) and frequency detuning $\Delta\omega=0.025$.

In the following, an increase in the ratio of optical injection to the values of 0.2 as in Fig. (3.19 (a)), 0.4 as in Fig. (3.19 (b)), 0.6 as in Fig. (3.19 (c)), 0.8 as in Fig. (3.19 (d)) and 1 as in Fig. (3.19 (e)) where we observe the periodic behavior of photons and carriers together, but the frequency difference between them helps to the exhibit of the two modes phenomenon. As previously noted,

FFT represents the behavior of the slave photons while the attractor clearly represents both the level of carriers and the level of photons. This phenomenon continues with increase the ratio of optical injection to a large value of it, where we note the beginning of the stability of the mode at the value of 1 as in Fig. (3.1 (e)) or greater.

From this result we note that increasing of the injection ratio causes the stability of the mode and this is contrary to some results (an increase in the injection strength leads to a strong competition between the modes) [90].





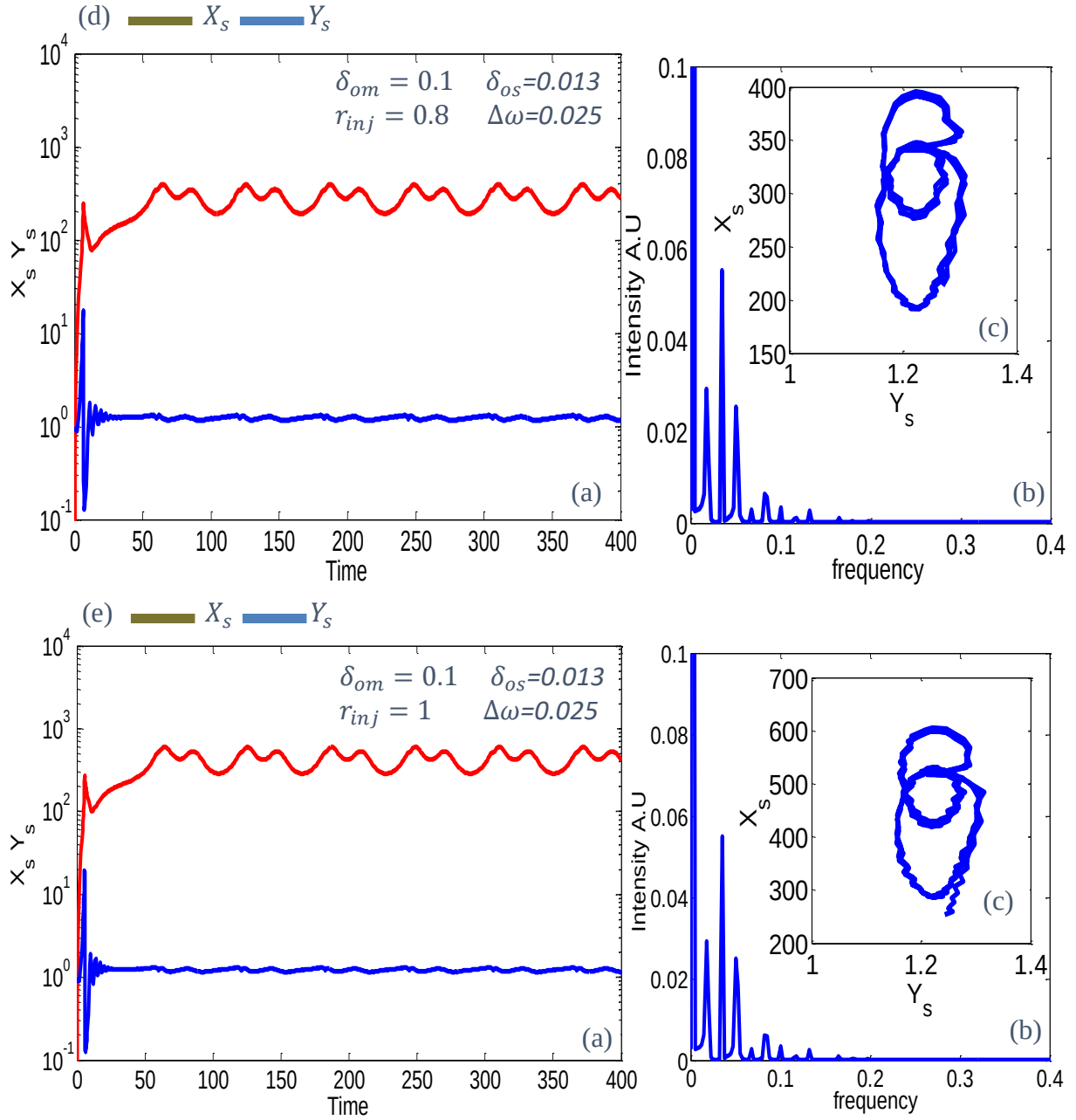


Fig. (3.19): Simulated optically injection dynamics in QD-LED for the different values of injection ratio. In left panel: time traces of total, x_s slave-photon mode intensity (red line), and y_s slave-carrier mode intensity (blue line). The right panel shows FFT dynamics in the slave intensity. The subplot illustrates an attractor, however, the two modes fluctuate in anticorrelated dynamics resulting in less frequent dropouts of the total intensity.



Chapter four

Conclusion and Future Works

4.1 Conclusions

The following findings can be states

1. Dynamic of the photon is a starts from chaos to the periodic state accompanied decreasing in capacity under optical feedback strength effect.
2. Chaos region is shifting to the right side of the delay effect.
3. Increasing the injection current for its default value begins the behavior of the photon from the dabble period to the period only.
4. When studying the angular frequency effect at ($\delta\omega=0.013$, $\tau = 0.1$ and $\eta = 0.01$), we have obtained a clear and constant dynamic.
5. No change in QD-LED dynamics under delay time effect when optical feedback strength is presented. But the effect of delay forces the system immediately enter the state of chaos at large value of the bias current.
6. When examining the exact effect of the delay time on first pulse, the first pulse is shifting to the right side by increasing the delay time and also decrease the amplitude and it is shifted to the left side and also increase the amplitude by increasing the optical feedback and finally the effect of the injection current on the first pulse is only a decrease in amplitude.
7. The linewidth enhancement α factor controller on QD-LED dynamics show that increasing of the delay time leads to increased chaotic at small ranges of α and small delay time leading to receding of chaos at small values of α .
8. There is no effect of the bias current of the master at frequency detuning ($\Delta\omega=0$) and when making the frequency difference between the two systems note there is a slight difference in the behavior.
9. When the bias current is proved to the master ($\delta\omega= 0.1$) and the slave ($\delta\omega = 0.013$), the dynamic behavior at the injection ($r_{inj}= 0.2$) which is present as bifurcation scenario diagram motions from the chaos then follows a period doubling (two cyclic) then it will be 4 cyclic and chaotic state at finally.

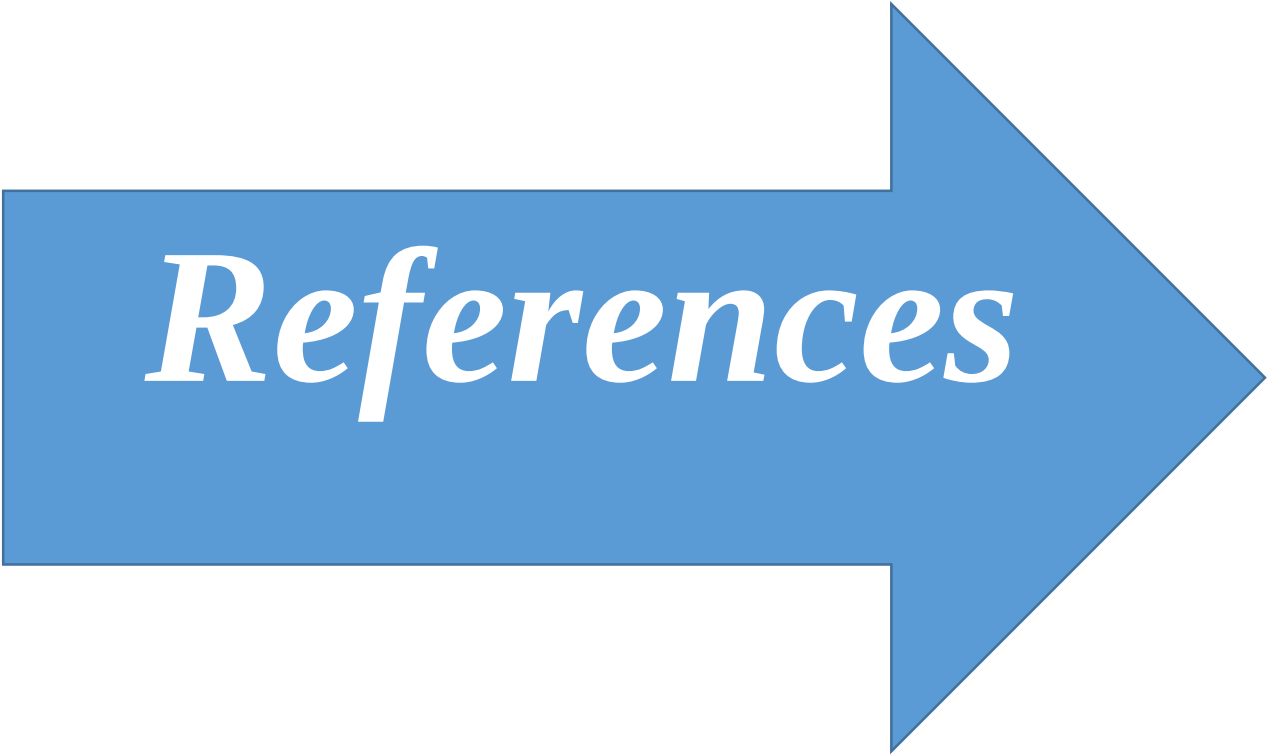
10. When studying the external injection factor r_{inj} , the behavior of QD-LED here is completely different from the behavior of the QD laser, where we have two cases; first it is damping and disappearance of the slave signal. second, increasing the output capacity of the slave.
11. When the frequency difference between the two systems increases in each increment, the lock of the pattern becomes more integrated from the previous until we get a complete lock at the last and other tests in the message board. The binary mode of the slave system is achieved only through the two types of carriers (The number of photons in the QD and ground state Layer Wet).

4.2 Future Works

Regarding the future of the subjects studied here, I consider that the topics of QD-LED dynamics still carrier a lot of surprises to basic nonlinear dynamics research and engineering applications, but especially to the modeling and analysis. I consider that there is a lot of lab for more detailed and physical dynamic studies that can help us to better comprehend issues like:

1. The equilibrium and stability points to order of the requirement and performance of our system, a fundamental issue with important physical applications.
2. Large-Signal response, chaos synchronization in networks of delay-coupled and influence of noise on QD-LED.

Additionally, one can consider the modeling of chaotic behavior in double dot (DD) system using density matrix theory (DMT). Chaos at any system was not modeled by DMT, also DD which have an extremely important applications and demonstrates higher nonlinearity (second harmonics and Kerr effect).



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الخلاصة

في هذه الرسالة، تمت دراسة الحركات المعقدة للثنائي النقطي الكمي الباعث للضوء (QD-LED) في ظل التغذية البصرية العكسية (OFB) وتأثيرات الحقن البصري (OI) ودراسة وجود تعاقب الشواش في حركات QD-LED والسلسلة الزمنية المناظرة، الفترات الزمنية بين التشويك (ISI)، تحويلات فورير السريعة (FFT) والجاذب.

قمنا بدراسة حركات QD-LED نظرياً مع التغذية البصرية العكسية الضعيفة. تم تحديد التشعبات لهذه الحركات بشكل كامل عن طريق زيادة قوة التغذية البصرية العكسية (OFBS). تظهر نتائجنا أن OFBS الصغيرة (أقل من 0.03) تؤدي إلى تحكم جيد في اختيار حركات QD-LED. زيادة وقت التأخير (τ) تؤدي إلى زيادة كل من منطقتي الثنائية الدورية والشواش. خلاف ذلك، تؤدي زيادة الانحياز (δo) إلى اختفاء المناطق المذكورة أعلاه. بالإضافة مرآة الحاجز المشبك كأسلوب خاص لعزل الترددات غير المرغوب فيها، لوحظ وجود عدد من الحالات الهامة حيث الانتقال بين الحالة الدورية والشواش. تم دراسة تأخير التغذية العكسية وحركات التحول. أظهرت النتائج تأثير واضح لزمن التأخير مع قيمة كبيرة من الانحياز فقط (تأثير التغير في τ على سلوك الفوتونات عند القيم الصغيرة للانحياز ($\delta o = 0.013$) أظهر القابلية الكبيرة للتنبؤ في حركات الانظمة) في حين تظهر ان حركات التحول ل QD-LED تخميد تنذبات الاسترخاء، يظهر ازاحة الطور مع عتبة سريعة للنبضة الأولى والنطاق الحركي لا يمكن مقارنته في معظم الحالات التي يتم فحصها. عند دراسة معامل تحسين عرض الخط يظهر أن الحركات تبدأ من حالة الدوري إلى حالة الشواش. تبدأ كمية صغيرة من إزاحة الشواش إلى اليسار مع زيادة OFBS، عندما يزداد زمن التأخير تكون هناك زيادة أكبر في الإزاحة عن قبل، وعند القيمة الافتراضية لوقت التأخير تظهر حالة خاصة تسمى هي حالة الأنماط المختلطة.

وأيضا دراسة موضوع QD-LED مع الحقن البصري الذي يسبب عدم استقرار في نظام slave. تم دراسة فرق تردد، الانحياز ونسبة الحقن البصري. تشير النتائج إلى ظهور سلوك الشواش من خلال السلاسل الزمنية، الجاذب ومخطط التشعب. تلاحظ حالة انغلاق الطور عندما تعمل كل من أنظمة master و slave على نفس التردد $\Delta\omega = 0$. كما نلاحظ حالتين، التخميد مع الاختفاء وزيادة سعة إشارة الخرج عن

طريق زيادة نسبة الحقن البصري. وقد لوحظ أيضا حالات انغلاق الطور والاستقرارية. تظهر حدود النوعية حركات مختلفة في مستوي معاملات الحقن (فرق التردد ونسبة الحقن) عند دراسة ظواهر انتقال النمط. بالإضافة إلى ذلك، تُظهر النتائج ظاهرة ثنائية النمط مع تأثير معاملين (نسبة الحقن وتأثير الانحياز).



جمهورية العراق

وزارة التعليم العالي والبحث العلمي

جامعة ذي قار/كلية العلوم

تأثير التغذية البصرية العكسية والحقن البصري الخارجي على الشواش في الثنائي النقطي الكمي الباعث للضوء

رسالة

مقدمة إلى مجلس كلية العلوم، جامعة ذي قار وهي جزء من متطلبات نيل درجة

الماجستير في علوم الفيزياء

من قبل

حسين عواد زمزوم

(بكالوريوس ٢٠١٦)

بإشراف

أ.م.د حسين برغوث الحسيني

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