Australian Journal of Basic and Applied Sciences, 9(33) October 2015, Pages: 417-426

ISSN:1991-8178

Australian Journal of Basic and Applied Sciences

Journal home page: www.ajbasweb.com

Spiking control in semiconductor laser with Ac-coupled optoelectronic feedback

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ARTICLE INFO

Article history:
Received 3 October 2015
Accepted 31 October 2015

Keywords:
Chaos, laser, feedback, control

ABSTRACT

We report both experimentally and numerically the generation of spiking in semiconductor laser (SL) with an ac-coupled optoelectronic delayed feedback. The evolution of nonlinear dynamics of semiconductor lasers with optoelectronic delayed feedback by changing one of the control system parameters (the dc bias current of semiconductor laser, the feedback strength) is investigated. In addition to the period-doubling scenario to chaos which shows the transition of nonlinear dynamics from periodic to quasi-periodic state and eventually to chaotic oscillation state is shown, this paper proved that the application of an external perturbation to this system can eliminate the generated chaos.

To Cite This Article: Hasan Ghassan Abed, Kadhim Abid Hubeatir, Kais A. Al.Naimee, Spiking control in semiconductor laser with Ac-coupled optoelectronic feedback. ***Aust. J. Basic & Appl. Sci.,*** *9(33): 417-426, 2015*

INTRODUCTION

The irregular oscillations for time evolutions in nonlinear dynamical systems are appeared clearly in their outputs as a deterministic manner and it's different from random processes. These oscillations are called dynamical chaos. Chaos may indicate to any state of disorder or confusion (Hilborn, 2000). Dynamic chaos is considered as a very interesting nonlinear phenomenon which has been intensively studied during the last four decades (Pyragas, 1992).

Chaos can be found in miscellaneous fields, such as engineering, physics, biology, chemistry, weather, and climate and even in economics (Aihara, 2002; Ivancevic, 2008). Nonlinear systems can also be observed in optics. Many optical devices and materials, such as the laser, exhibit nonlinear reaction to the optical field and this make it very strong candidates for nonlinear components in chaotic systems (Abdalah, Al-Naimee, Meucci, Al Muslet, & Arecchi, 2010; Jungi Ohtsubo, 2007).

In engineering applications, chaos is usually classified as an unwanted behavior. Therefore, several techniques have been innovated for chaos control, which are required to stabilize fluctuations and chaotic instabilities in many kinds of nonlinear dynamical systems (SchölL, 2001; Uchida, 2012). The first important work by Ott, Grebogi, and Yorke (OGY) in 1990 in which they explained that small time-dependent changes in the control parameter of the system can convert a chaotic motion into a stable periodic motion, and there has been an attracted interest in this technique (SchölL, 2001). In this method, chaos can be avoided by the concept of stabilization of unstable periodic orbits (UPOs) involved within a strange attractor by the application of small perturbations to the nonlinear system by external forces (Pyragas, 1992). The requirements for the necessary information about the attractors and their calculations prevent the application of the OGY algorithm for the control of high-dimensional chaotic systems, in spite of the efforts were made to adjust this method to experimental work to control high dimensional chaotic systems (Jungi Ohtsubo, 2007).

Then, an alternative method is proposed by Pyragas in 1992, which is called the time-delayed feedback. In this method the chaotic system output is divided into two parts: one of them is detected with a delay time that possess an intrinsic time of the period of chaotic attractor and the other emerge normally. Then the difference between the normal output and the delayed output is fed back to one of parameters of the system (SchölL, 2001). The stabilization of the (UPOs) involved within a strange attractor by the application of small perturbations to the nonlinear system by time-delayed feedback, shows an innovative method to eliminate chaos. And this method is easy and helpful for the application to real-world nonlinear dynamical systems (SchölL & Schuster, 2008).

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The semiconductor lasers with delayed feedback have been studied widely in few last years, this is because the rich diversity of nonlinear phenomena they show and also because of their important applications (Bejoy, Rajesh, & Nandakumaran, 2015; Junji Ohtsubo, 1999). The most common perturbations are optical injection, optical feedback and optoelectronic feedback (Uchida, 2012). The latter one is the perturbation that utilized in this paper. Optoelectronic feedback is one of the perturbations that applied to the chaotic systems to convert the chaotic motion into periodic motion and vice versa (Abdalah *et al*., 2010).

The importance of semiconductor laser with optoelectronic delay feedback is in the phase of the laser radiation is a free parameter and for this reason it is not included in the defining of chaotic system dynamics (P. Saboureau, J. P. Foing, 1997). The delay usually arises simply by the propagation time around the feedback loop (J.M. Saucedo Solorio, D.W. Sukow, D. R. Hicks, 2002). The bandwidth of the needed electronics should be very large and flat, since the semiconductor laser chaotic dynamics can extend for tens of gigahertz. If the bandwidth of these electronics does not correspond the speed of the optical intensity fluctuations, the dynamics of the system will be dominated by this bandwidth limitation (S. Tang, 2001; S. Tang, H.F. Chen, 2001). Lasers are usually described by three variables: field, population inversion and polarization of matter, therefore they are utilized for chaotic systems (F.Kh. Abdullaev, S.A. Darmanyan, A.F. Fercher, J. Garnier, C.K. Hitzenberger, J. Ohtsubo, F.G. Omenetto, G. Petite, 2002).

In this work, the experimental setup is build to study the generation of spiking oscillations in a semiconductor laser with an ac-coupled optoelectronic delay feedback. The dynamics of single-mode class-B lasers (semiconductor laser), is judged by two linked variables (field density and population inversion) because the polarization term is adiabatically eliminated, evolving with two very different characteristic timescales. The application of optoelectronic feedback establishes a third degree of freedom (and a third timescale), leads to a three-dimensional slow–fast system showing a transition from a periodic spiking sequences to chaotic oscillations as the dc-pumping current of SL and feedback strength is varied. However, in the concept of future experiments that related to synchronization in laser arrays, (SL) appears as a perfect candidate since they permit the fulfillment of a miniaturized chip of units optoelectronically coupled.

Experiment Work and Discussion:

The schematic diagram of the experimental setup is depicted in Fig. 1, in which it is a closed-loop optical system, includes a single-mode semiconductor laser with ac-coupled optoelectronic delay feedback. The output laser beam is sent through an optical fiber to a photodetector, at the photodetector the optical signal is converted to electrical signal. The generated electrical current is proportional to the optical intensity. Then the electrical signal is passed through a variable gain amplifier. After that, this electrical signal is fed back to the injection current of the semiconductor laser.

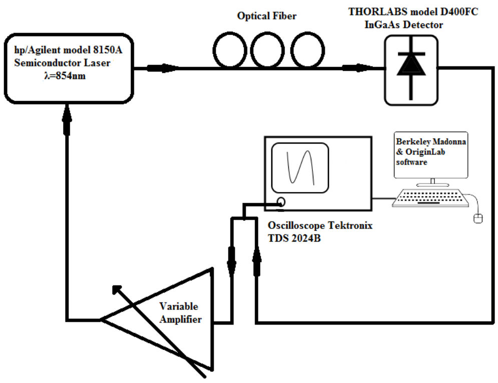


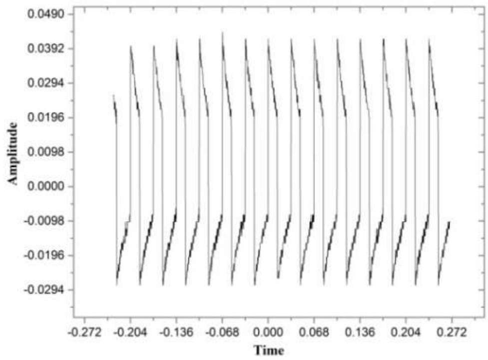
Fig. 1: The diagram of the experimental setup

The amplifier gain is used for determination the feedback strength. The electrical signal in the form of narrow voltage pulses that emerged from the high-pass filter is added to the laser pumping current through a mixer. The laser (hp / Agilent model 8150A optical signal source), which provides an emission with a wavelength of 850 nm and continuous output power of 2mW.

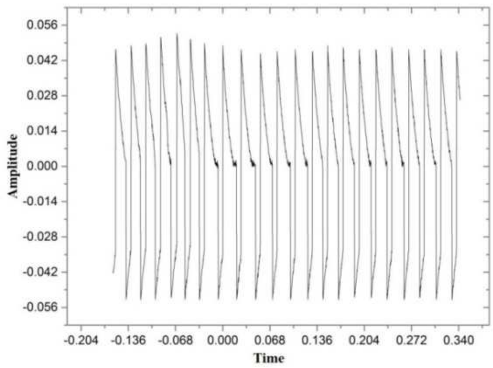
The first experimental part included the following procedure: the net amplifier gain of the entire feedback loop has been fixed and with gradually increasing in the laser dc-pumping current, we observe the dynamical sequence as demonstrated in figures 2(a)-(c) that contains the time series of different dc bias current values. By gradually increasing in the dc pumping current the time series suffers from a transition from a line (at 0mA bias current) to sinusoidal oscillations, this sinusoidal oscillations increases in amplitude gradually until it reach another types of periodicity and finally to chaotic oscillation.

At low current levels (3.5mA), the detected waveform is stable and has semi-sine wave oscillation as illustrated in figure 2(a). Figure 2(b), shows the beginning of the behavior of non regular periodicity, where the time series begins in the quasi-periodic behavior at bias current equals to 6.75mA. Additional increasing in the bias current causes the chaotic oscillation in the SL dynamics, where the peaks have different amplitudes and separated by different time intervals as illustrated in figure 2(c) that contains the time series at bias current equals to 7.75 mA. Figure 2(d) shows the corresponding Fast Fourier Transform (FFT) (i.e. the power of each peaks frequency), where different frequencies which refer to the different peaks in time series at bias current equals to 7.75 mA. The chaotic spiking can be proved by draw the corresponding attractor by the Ruelle–Takens embedding technique (i.e. making appropriate delay), at bias current equals to 7.75mA as shown in figure 2(e).

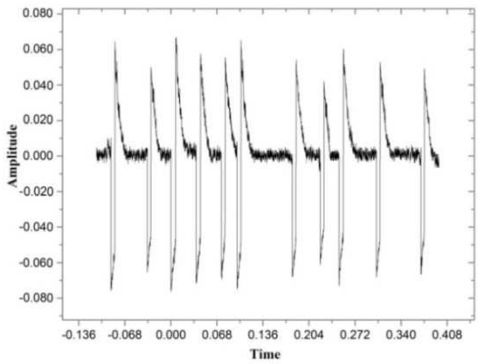
The scenario to chaos is summarized by the bifurcation diagram as illustrated in figure 3. The bifurcation diagram exhibits the intensity of the laser output from peak-to-peak versus the variation of control parameter (dc pumping current of laser source) while the amplifier gain is fixed. The bifurcation diagram is established within slow increase in the control parameter.



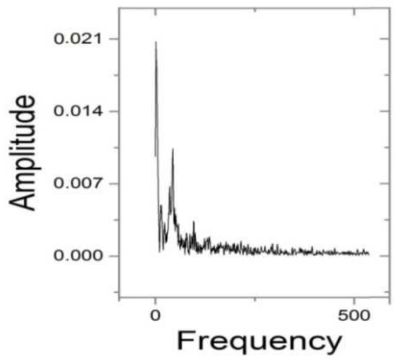
(a)



(b)



(c)



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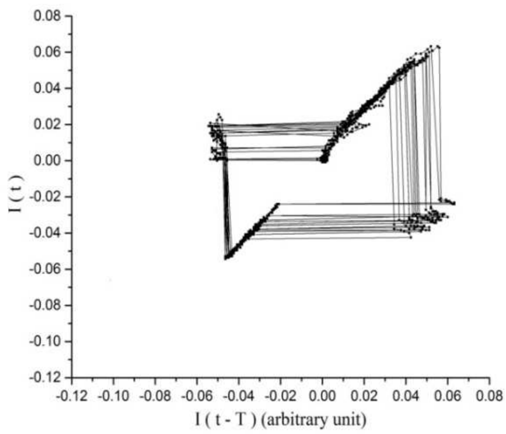


(e)

Fig. 2: The experimental time series at dc-pumping current values. (a) 3.5 mA, (b) 6.75mA, (c) 7.75 mA. (d) The Fast Fourier Transform (FFT) of the corresponding time series at 7.75mA, (e) the attractor corresponding to time series at 7.75mA.

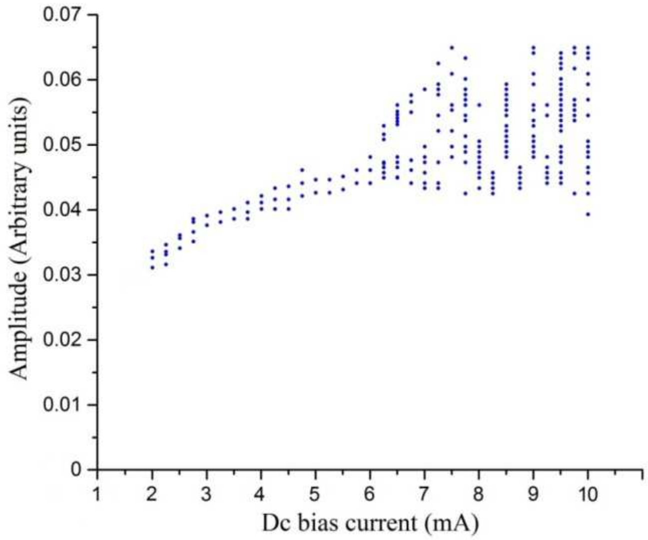
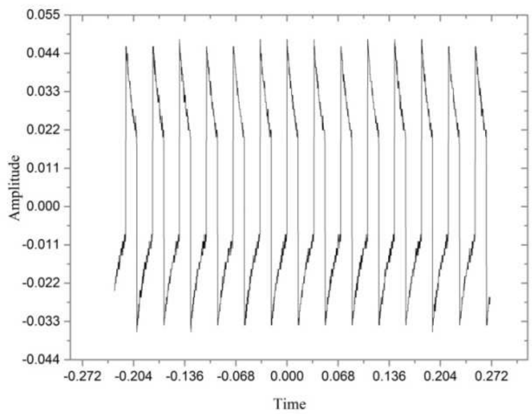


Fig. 3: The bifurcation diagram obtained by the variation of dc pumping current of semiconductor laser.

In Figure 3, the first region from (2-6) mA, the dynamics of semiconductor laser (SL) is in the form of periodic motion then by gradually increasing in the dc pumping current from (6.25-7.25) mA, the quasi-periodic behavior begins to appear, then any more increasing in pumping current from (7.5-10) mA, it demonstrates the chaotic oscillation. The scenario which is shown in figure 3 is called period-doubling route to chaos and sometimes it is also called the Feigenbaum scenario (Uchida, 2012).

This scenario to chaos begins firstly from the steady state or the stability case of the system, then a transition to chaos through a period-1 oscillation, …, a period-2m oscillation where m is a positive integer. This scenario can be noticed in many of laser experiments, simulations, continuous-time dynamical systems and discrete systems.

While the second experimental part included the following procedure: where the bias current of semiconductor laser has been fixed and with gradually increasing in the net amplifier gain of the entire feedback loop (feedback strength), we observe the dynamical sequence as demonstrated in figures 4(a)-(c) that contains the time series of different feedback strength values. In figure 4(a), the sketch of the time series within this sequence is demonstrated when the amplifier gain equals to 0.9, and then the displayed waveform is stable and has semi-sine wave oscillation. In figure 4(b), the start of non regular periodicity behavior is appeared; therefore the time series begins in the quasi-periodic behavior at amplifier gain equals to 1.03. Further increasing in the feedback strength causes the semiconductor laser to outputs chaotic dynamics, where the peaks have different amplitudes and separated by unequal time intervals as shown in figure 4(c), that contains the time series at feedback strength equals to 1.12. Figures 4(d) and (e) shows the corresponding (FFT) and attractor, at feedback strength equals to 1.12, respectively.



(a)

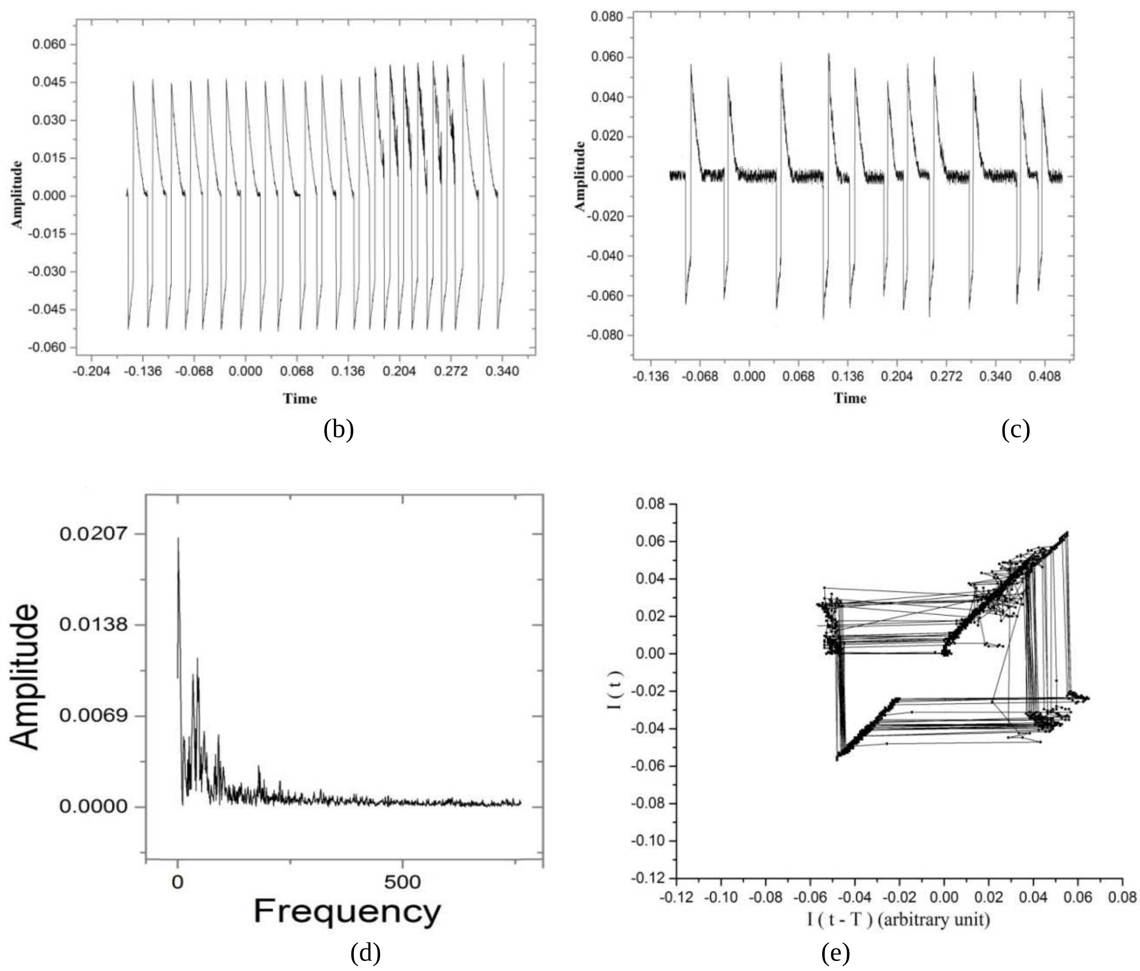


Fig. 4: The experimental time series at feedback strength values. (a) 0.9, (b) 1.03, (c) 1.12. (d) The Fast Fourier Transform (FFT) of the corresponding time series at 1.12, (e) the attractor corresponding to time series at 1.12.

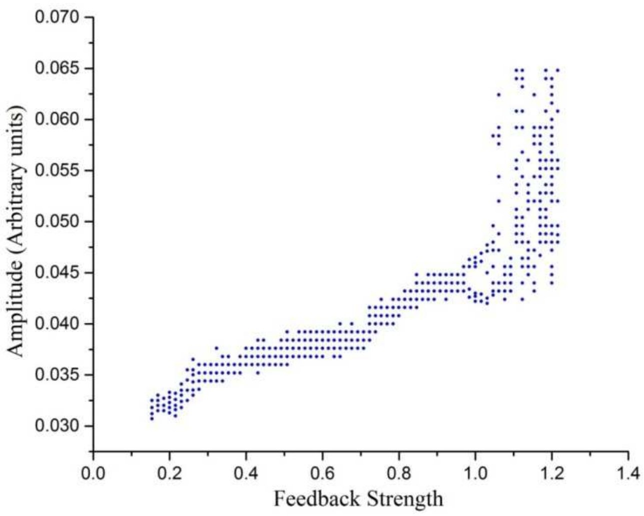


Fig. 5: The bifurcation diagram obtained by the variation of the feedback strength.

To examine the influence of the gradually increasing in the feedback strength (the amplifier gain) on the output dynamics of the semiconductor laser while the bias current was kept constant, the bifurcation diagram was sketched for increment values of A_V as illustrated in figure 5. In Figure 5, the first region at feedback strength range (0.15- 0.96) the dynamics of (SL) is in the form of periodic motion then by gradually increasing in the feedback strength (0.97-1.05), the quasi-periodic behavior begins to appear, then any more increasing in feedback strength in the range (1.06-1.22), it demonstrates the chaotic oscillation.

Therefore the two control parameters (bias current and the amplifier gain of the feedback) are used to display the period-doubling route to chaos. Finally the proper changing in the dc pumping current or the feedback strength within feedback can eliminate the chaotic behavior by pushing the laser oscillation to stay in periodic behavior from the fact that chaos is an undesired phenomenon.

Dynamical Model And Numerical Results With Discussion:

As previously mentioned that the (field density and population inversion) are two linked variables which be used to describe the complete dynamics in our system. These variables have two very different characteristics time-scales. The application of an optoelectronic feedback shows two benefits: firstly, adds a third degree of freedom in our system, secondly, adds a third much slower time-scale. The dynamics of the field density S and the population inversion N is characterized by rate equations of a single-mode semiconductor laser (Weng W. Chow, Stefan W. Koch, 1994) in which properly modified in order to include the ac-coupled optoelectronic feedback:

$$\dot{S} = [\, g\,(N - N_t) - \gamma_0\,]\, S \qquad (1)$$

$$\dot{N} = \frac{I_0 + f_F(I)}{eV} - \gamma_C\, N - g(N - N_t)\, S \qquad (2)$$

$$\dot{I} = -\gamma_f\, I + \kappa\, \dot{S} \qquad (3)$$

where I represents the current of high-pass filtered feedback (before the nonlinear amplifier), I_0 is the bias current, e the electron charge, $f_F(I) \equiv$ *AI/(1+ś I)* is the feedback amplifier function, V is the active layer volume, N_t is the carrier density at transparency , g is the differential gain, , γ_0 is the photon damping and γ_C is population relaxation rate, κ is a coefficient proportional to the photodetector responsivity and γ_f is the cutoff frequency of the high-pass filter.

For analytical and numerical purposes, it is helpful to rewrite equations 1 in dimensionless form. For this purpose, we insert the new variables: $x = \frac{g}{\gamma_C} S, y = \frac{g}{\gamma_0}(N - N_t), \quad w = \frac{g}{\kappa\gamma_C} I - x$ and the time scale $\acute{t} = \gamma_0 t$. where $s = \gamma_C\, \acute{s}\, \kappa/g$ is the saturation coefficient, $\delta_0 = (I_0 - I_t)/(I_{th} - I_t)$ is the bias current, $f(w + x) \equiv \alpha \frac{w+x}{1+s(w+x)}$,$(I_{th} = eV\,\gamma_C(\frac{\gamma_0}{g} + N_t)$ is the current of solitary laser threshold), $\alpha = A\kappa/(eV\gamma_0)$ is the strength of feedback, $\varepsilon = \frac{w_0}{\gamma_0}$ is the bandwidth at resonant frequency w_0 , $\gamma = \frac{\gamma_C}{\gamma_0}$. To more simplifications of dimensionless equations 1, 2 and 3, let $z = w + x$, therefore the above equations can be reformulated as follows:

The rate equations then become (Al-naimee *et al*., 2009)

$$\dot{x} = x(y - 1) \qquad (4a)$$

$$\dot{y} = \gamma\left(\delta_0 - y + \alpha\,\frac{z}{1+sz} - xy\right) \qquad (4b)$$

$$\dot{z} = -\varepsilon\, z + \dot{x} \qquad (4c)$$

where 4a equation represents the photon density of laser source while 4b equation represents the population inversion of carriers and 4c equation represents the effect of feedback. Now the theoretical results have been done by the utilizing of the fourth-order Runge-Kutta integration scheme, and apply the above equations 4(a, b and c) in Berkeley Madonna software version 8.3.18 with time step $dt = 1$.

The entire simulation time chosen depends heavily on the quantity of the temporal scales described by the parameters δ_0 and α where δ_0 represents the bias current and α is the amplifier gain of the feedback (feedback strength). The first numerical part included the following procedure: the feedback strength α has been fixed at (1) and the bias current δ_0 is gradually increased, then the model is programmed with the following parameters $\varepsilon = 2 \times 10^{-5}$, $s = 11$, and $\gamma = 0.001$ and with initial values of parameters x1, y1, and z1 are 0.022, 1, and 0.005 respectively.

It was observed throughout the experiments that when the feedback photocurrent of low level, the laser is oscillated periodically and when the level of the injected photocurrent (in the feedback part) is increased, the time series shows chaotic behavior passing through a quasi-periodic state. The corresponding dynamical sequence of the above procedure is illustrated in figures 6(a)-(c) that contain the time series of different dc bias current of the laser source. The chaotic dynamics appears clearly in figures 6(c), at dc bias current equals to 1.016, where the time series shows various heights in amplitudes and the weight of each peak frequency illustrated by the corresponding FFT in figure 6(d) where many no. of frequencies contributed with different amplitudes. In this case, the corresponding attractor is obtained by draw the relationship between photon density (x1) as y-coordinate and population inversion (y1) as x-coordinate which shows a strange-shaped attractor in phase-space due to various amplitudes.

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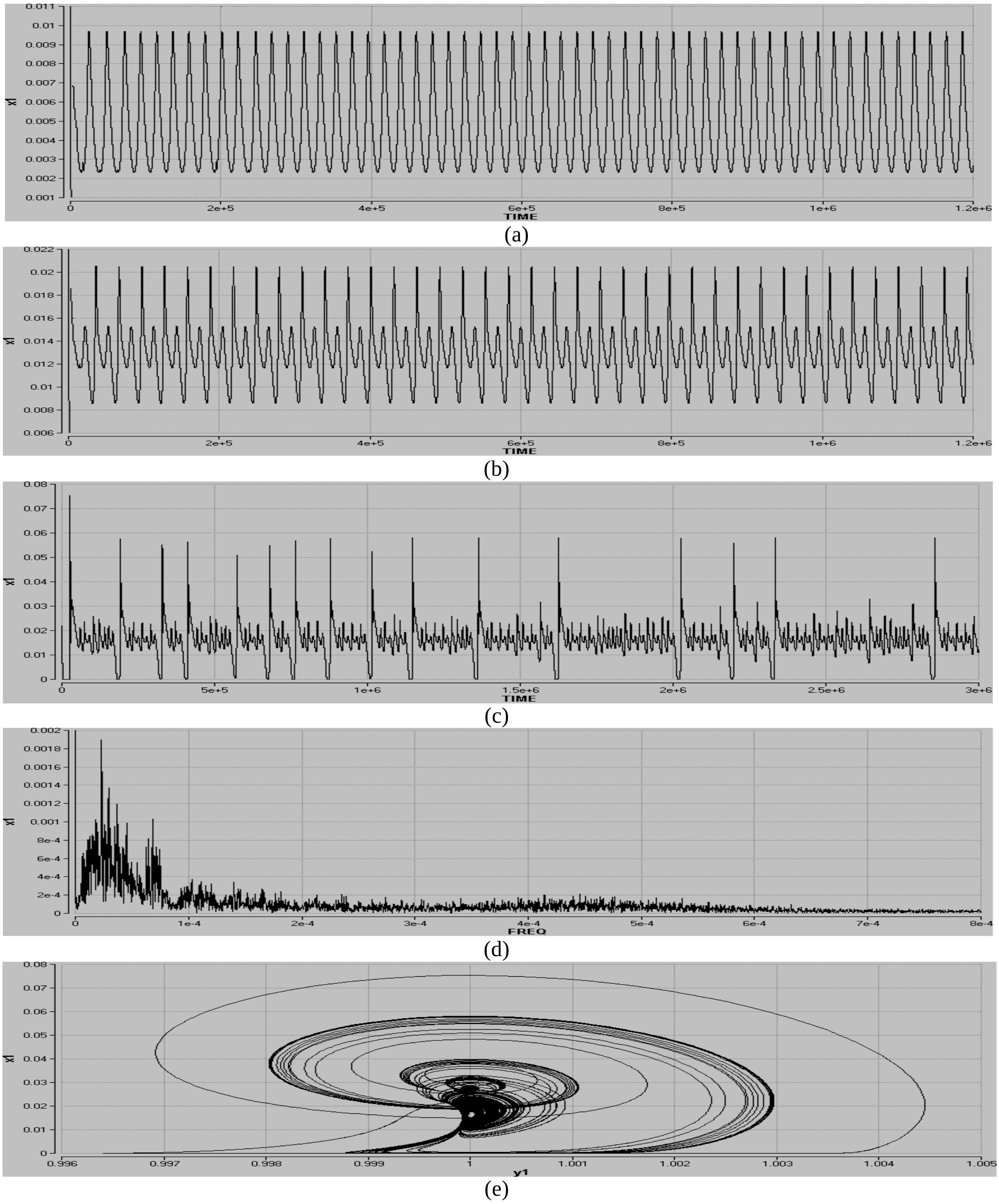


Fig. 6: The numerical time series at dc bias current δ_0 (a) 1.005, (b) 1.013, (c) 1.016, (d) The Fast Fourier Transform (FFT) of the corresponding time series at 1.016, (e) the attractor corresponding to time series at 1.016.

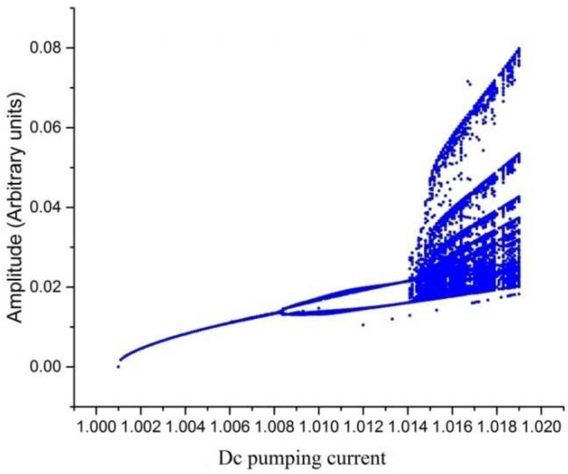
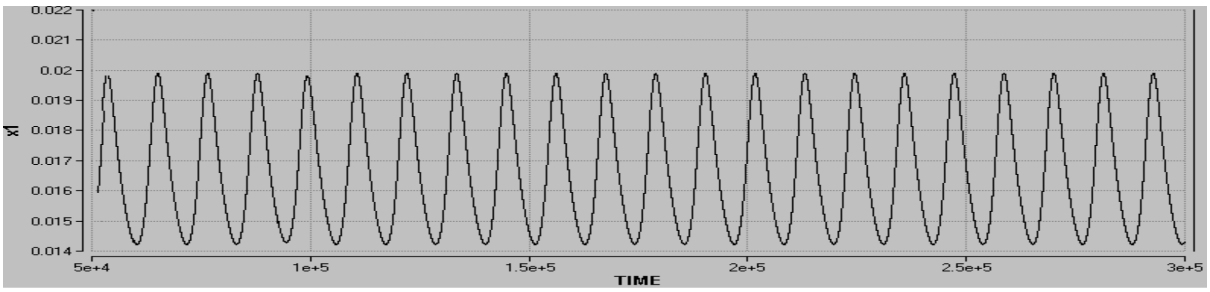


Fig. 7: The numerical bifurcation diagram of the variation of dc pumping current δ_0. The system parameters are: $\varepsilon = 2 \times 10^{-5}$, $\alpha = 1$, $s = 11$, and $\gamma = 0.001$.

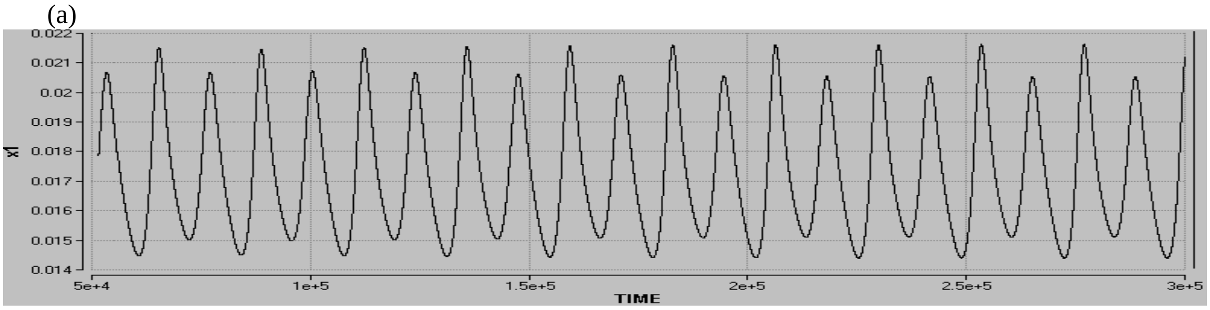
In figure 7, the period-doubling route to chaos is demonstrated in clearly manner, where the steady state appears clearly at current value equals to 1.001 as a single point, then the periodic state begins from (1.0015-1.0082) then by additional increasing in the dc pumping current from (1.0083-1.0146) the quasi-periodic state appear clearly, finally the chaotic state occurs at the values of (1.0147-1.019). Therefore this system undergoes a transition from steady-state, passing through a cascade of period doubling, to chaotic oscillation.

Then the second numerical part included the following procedure: the bias current δ_0 has been fixed at 1.0173 while the feedback strength α is gradually increased, then the model is programmed with the following parameters $\varepsilon = 2 \times 10^{-5}$, $s = 11$, and $\gamma = 0.001$ and with initial values of parameters x1, y1, and z1 are 0.022, 1, and 0.005 respectively. It was observed throughout the experiments that when the feedback strength of low level, the laser is oscillated periodically and when the level of the feedback strength is increased, the time series shows chaotic behavior passing through a quasi periodic state.

The corresponding dynamical sequence of the above procedure is illustrated in figures 8 (a)-(c) that contains the time series of different feedback strength values. The chaotic dynamics appears clearly in figures 8(c), at feedback strength equals to 1.004, where the time series shows various heights of amplitudes and the weight of each peak frequency illustrated by the corresponding FFT in figure 8(d) where many no. of frequencies contributed with different amplitudes. In this case, the corresponding attractor is obtained by draw the relationship between photon density (x1) as y-coordinate and population inversion (y1) as x-coordinate which shows a strange-shaped attractor in phase-space, where many circles with different heights form due to various amplitudes.



(a)



(b)

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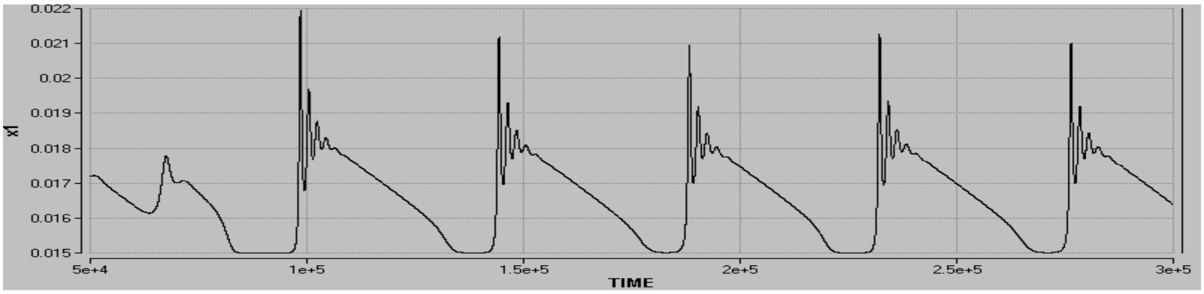
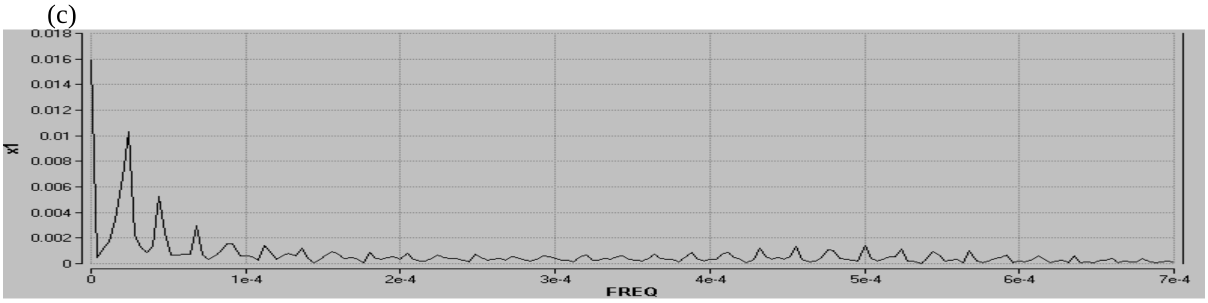


(c)



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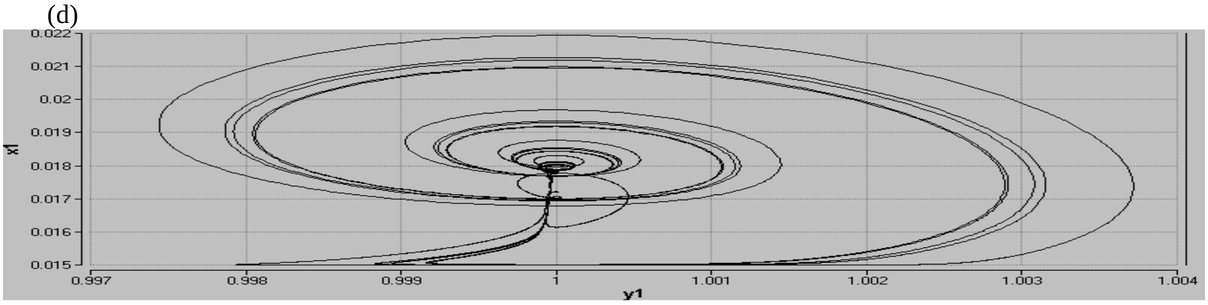

(e)

Fig. 8: The numerical time series at feedback strength α (a) 0.987, (b) 0.992(c) 1.004, (d) The numerical (FFT) of the corresponding time series at 1.004, (e) the numerical attractor corresponding to time series at 1.004.

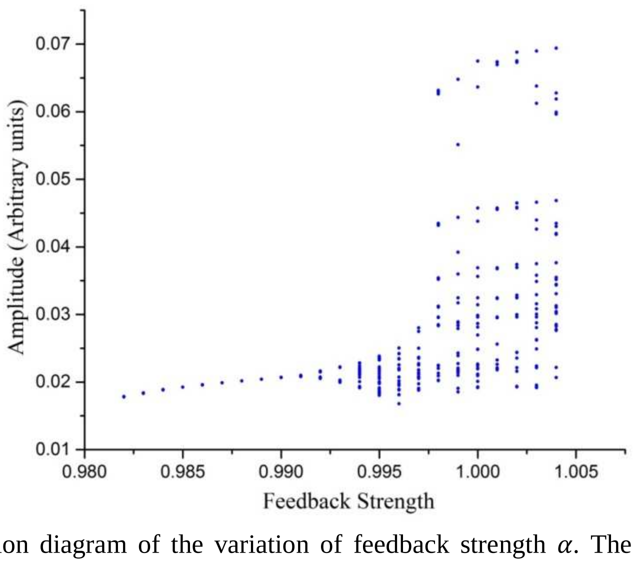

Fig. 9: Theoretical bifurcation diagram of the variation of feedback strength α. The system parameters are: $\varepsilon = 2 \times 10^{-5}$, $\delta_0 = 1.0173$, $s = 11$, and $\gamma = 0.001$.

The period-doubling route to chaos scenario is demonstrated in clearly manner in figure 9, where the periodic state begins from (0.982-0.991) then by increase the feedback strength from (0.992-0.997) the quasi-periodic state appear clearly, finally the chaotic state occurs at the values of (0.998-1.004). The termination of chaos can be achieved numerically also by the appropriate changing in the dc pumping current of the semiconductor laser or the feedback strength to make the system oscillate in a periodic manner.

Conclusions:

In this work, the nonlinear dynamics of SL with the application of optoelectronic delay feedback are demonstrated. The period-doubling route to chaos of the dynamics of SL is investigated both experimentally and theoretically, both when the net gain of feedback loop is fixed with gradually increasing in dc pumping current of SL, and when the dc pumping current is fixed and with gradual increase in the feedback strength, this may cause many variations in the system states stability. This variation in the system parameters can make the process of elimination of dynamic chaos is possible especially in engineering applications where dynamic chaos can affect the system performance and may be causes damaged effects. This means, that the control parameters of laser system such as dc-pumping current and the amplifier gain, play fateful role in the generation of chaotic oscillation in the laser output.

ACKNOWLEDGMENTS

H.G.A. would like to acknowledge the support of laboratories of physics department, college of science, university of Baghdad and would like to thank colleagues for their assistance.

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