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Attractor selection in semiconductor laser chaos generated by optoelectronic feedback

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Abstract: In this paper, an experimental and numerical study for the evolution of the non-linear dynamics of semiconductor laser has been done under two conditions, when the dc bias current of Semiconductor laser is varied, and when the feedback strength is varied. These dynamics were analyzed by time series and their extracted(FFT) power spectrums, phase diagrams (attractors),inter-spike intervals(ISI), these measurements enhanced by bifurcation diagram which explained the chaotic regimes. The stability states using different control parameters have been demonstrated. The role of control parameters of laser such as: dc bias current and feedback strength is proved in spiking generation and chaos control in the laser output.

Key words: chaos, optoelectronic feedback, control, attractor

Introduction:

The problem of controlling chaos in a physical system, that is to vary the state of the system from the chaotic behavior to a periodic time dependence which is predictable has attracted attention. Control of chaos indicates to a process in which a tiny perturbation is applied to a chaotic system, in order to sense a desirable (chaotic, periodic, or stationary) behavior. We cannot predict the future of chaotic evolutions ,because of a small deviation of the initial condition in a nonlinear system results in a completely different solution of the system output .However ,chaos can be controllable[1].With a view to control the behavior of dynamical system, there are two qualitatively various approaches. The first approach depends on the feedback, While the second approach does not use feedback and stabilizes the chaotic oscillations by direct controls .The first approach is usually called chaos control, and the second approach is called chaos suppression without feedback. Both techniques may be accomplished utilizing parameter or force techniques. The utilizing of feedback has a certain advantage, since in most cases feedback control lead up to the required result: a preselected saddle limit cycle is stabilized and the system thus achieve the required motion. However, this method is active just if the image point is near the selected cycle on the other hand there are additional controls are required[2].In 1990,Ott,Grebogi and Yorke, published the first paper to indicate that chaos could be advantageous in achieving control objectives [3].The fundamental idea is that tiny perturbations can be artificially incorporated either to retain large system stable (stabilization) or to direct a large chaotic system into a desired state(control)[4].Chaos control point to purposefully manipulating chaotic dynamical behaviors of some complex nonlinear systems [5].

The first chaos control method was proposed by (Ott-Grebogi-Yorke) currently known as the OGY method ,this is a discrete technique ,while the continuous methods are exemplified by so known delayed feedback control proposed by Pyragas[6].

Semiconductor lasers can be described by the field equation and the population inversion (carrier density) equation. The destabilization of semiconductor lasers can be easily done by the introduction of external perturbations. The most common perturbations are optical injection, optical feedback and optoelectronic feedback. Optoelectronic feedback is a way for obtaining incoherent feedback by the injection current of the laser and it is effective method for external control for the spectral characteristics of the semiconductor lasers[7]. 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 delay usually arises simply by the propagation time around the feedback loop[8].

A chaotic attractor may be explained as the trajectory lies in the phase space of the chaotic variables and is frequently used for the analysis of the chaotic oscillations, and the bifurcation diagram is defined as the diagram which is used to explore the chaotic evolutions or the changes of a particular parameter[9].The implementing for some cases of nonlinear dynamics and the instabilities of semiconductor laser can be execute utilizing Fast Fourier Transform(FFT).

Experimental work and discussion

The experimental setup for semiconductor laser with optoelectronic feedback in order to study the nonlinear dynamics of the laser is schematically shown in figure(1). We consider a closed- loop optical system, consisting of a semiconductor laser with AC-coupled nonlinear optoelectronic feedback. The output laser light is sent to a photo detector through an optical fiber producing an electrical signal. The generated electrical signal is subsequently amplified by a variable amplifier, and then added to the bias current of SL by using a mixer. A fiber-coupled semiconductor laser source (hp / Agilent model 8150A optical signal source) has been used in the experimental work, this source provides an optical power with a wavelength of 850nm over a continuous and power range is from 1nW to 2mW.

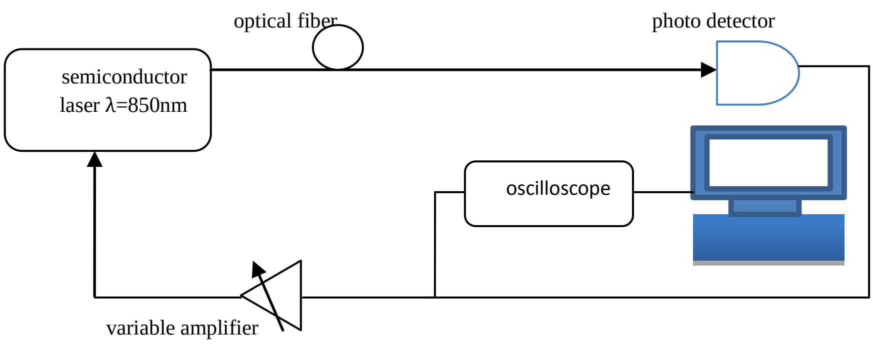

Fig.1: **Sketch of the experimental setup of a semiconductor laser with OEF**

The dynamics of the field density S and the carrier density N is characterized by the rate equations of a single-mode semiconductor laser in which properly appropriately modified by K. A. Al-Naimee et.al[10], in order to include the ac-coupled feedback loop:

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

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

$$\dot{I} = -\gamma_f I + \kappa \dot{S} \qquad (1)$$

where I represents the current of high-pass filtered feedback (before the nonlinear amplifier), I_0 is the bias current, e the electron charge, $f_F(I) \equiv AI/(1+\acute{s} I)$ 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. The first step of experimental work is the variation of the bias current. We accomplished a time series for each observed data set of the generated chaotic signals from each value of the laser diode power which considered as a control parameter of chaotic spiking evolution. In this term, the feedback strength of the system considered constant. Consequently we got the FFT by the analysis of these time series, the phase diagrams represented by the attractors which are plotted by the Ruelle-Takens embedding technique, and inter spike intervals ISI .By the gradual increasing of the value of dc bias current, the oscillations increases in amplitude until they transfer to a periodic state, and eventually arrives to the chaotic spiking state .Figure (2) exhibits a diagram of a certain waveforms, generated by increasing the value of bias current to (3mA),consequently we see that the obtained waveform is stable, this implies that it has the same amplitude height, and the form of the oscillation is semi-sine wave oscillation as shown in figure (2-a). Extra increasing of the value of dc bias current leads to the transition to the chaotic state in the dynamics of semiconductor laser. At the value of dc bias current(14mA)the peaks have different amplitudes and the time intervals are different2(b), The corresponding FFT 2(c) shows many different frequencies, because of different peaks in the time series. The corresponding attractor of this state exhibits various phase-space orbits of different amplitudes(d), and the ISI(e) of the chaotic state.

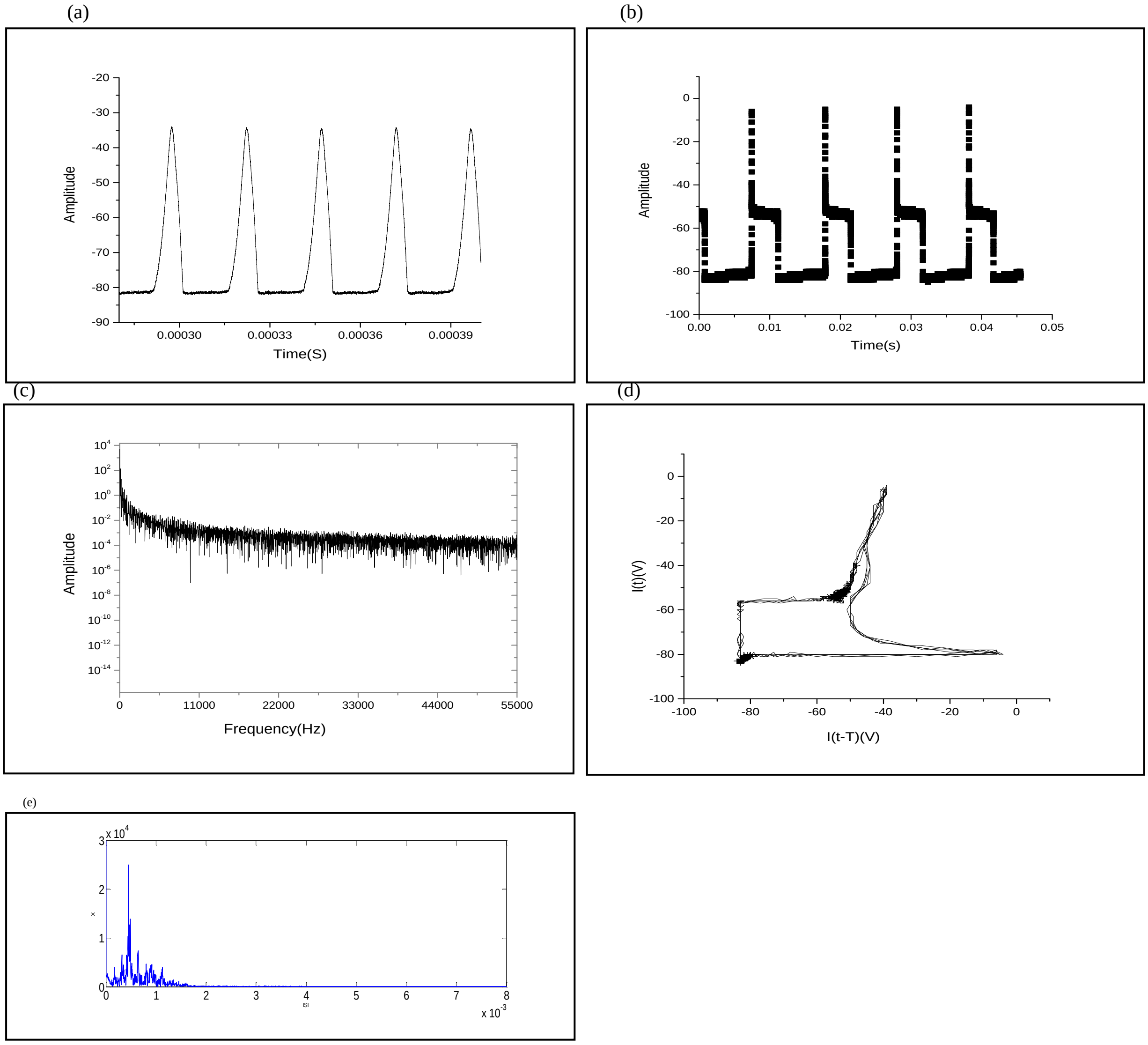

Fig. 2: Experimental time series at bias current values(a)3mA,(b)14mA,(c) the corresponding power spectrum at14mA,((dthe corresponding attractorat 14mA, ,(e) inter spike interval (ISI)at 14mA.

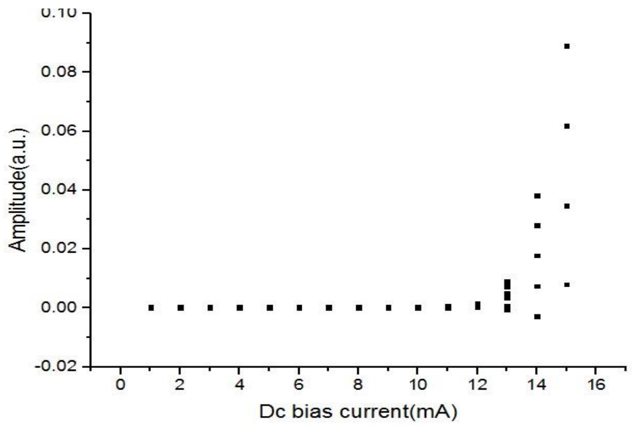

Fig. 3: Bifurcation diagram (output laser intensity vs. dc bias current variation)

The bifurcation diagram which explain the scenario from stable state until reaching to the chaotic state as shown in figure 3. This diagram demonstrates the laser output intensity from peak -to-peak against the change in the dc bias current (as a control parameter). This diagram has been superimposed by the gradual increasing of the values of bias current. The bifurcation diagram is interpreted as follows: the bifurcation diagram includes different regions, the first region is from (1-13)mA, where there are points represent the periodic state in the semiconductor laser dynamics. By more increasing the bias current value (14)mA, the dynamics attains the chaotic state.

The second important parameter of the experimental work is the feedback strength. In this term the voltage amplification factor Av taken as a feedback strength in order to demonstrate the effect of the optoelectronic feedback in our system. Figure4 demonstrates the bifurcation diagram for the variation of Av versus output intensity. When the value of Av is increased then the dynamics of the system is transfer from single periodic state to the quasi periodic state and after that it reach to the chaotic state at Av =0.98 ,and then the system continue in the chaotic behavior

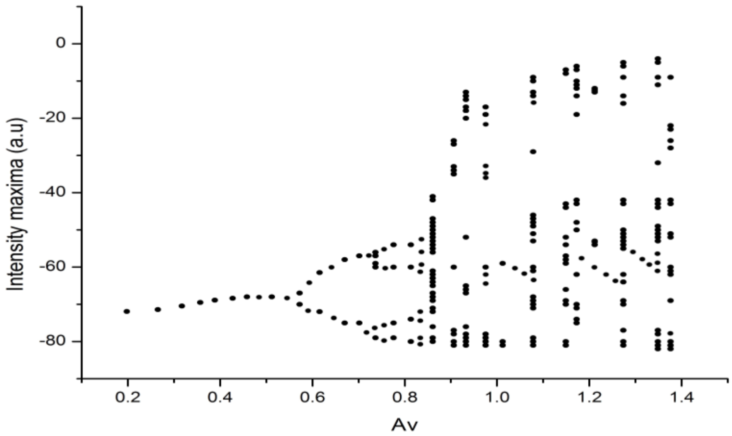

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Fig. 4 : bifurcation diagram for the variation of feedback strength

Numerical results

For the programming the dynamical model ,the Barkely Madonna software version 8.3.18 is used .The analyzing of the dynamical model by the programming. The quantity of the temporal scales which are denoted by the parameters α and δ_o ,where α represents the feedback strength, and δ_o is the bias current ,where these quantities relied upon in choosing the entire simulation time. The utilized parameters are :$s=11,\gamma=1\times10^{-13},\varepsilon=2\times10^{-5}$.The value of initial are:$x_1=0.022,y_1=1,z_1=0.005$.The system passes through different states, such as the transition from steady state to periodic state, and passes through the quasi-periodic state, eventually it is reaches to the chaotic oscillation.

The numerical results includes variation both of the bias current and the feedback strength, at the beginning for the variation of bias current the value of bias current is increased gradually and the change of value of feedback strength remains constant at(α=0.9),and the intensity spectra (photon density spectra)are gained, and the corresponding FFT and the corresponding phase space(attractors).

The dynamical sequence is shown in figure5(a-c),which explain the time series of various values of bias current. The chaotic behavior is obvious in figure(5)(c)at the value of bias current 1.016,which demonstrates various heights in amplitude, figure(5(d) exhibit the corresponding FFT of the chaotic state where different frequencies with different amplitudes. In the chaotic state the corresponding attractor is shown in figure 5(e),it appears as a strange-shaped attractor because of various amplitudes. The corresponding ISI is shown in figure 5(f).

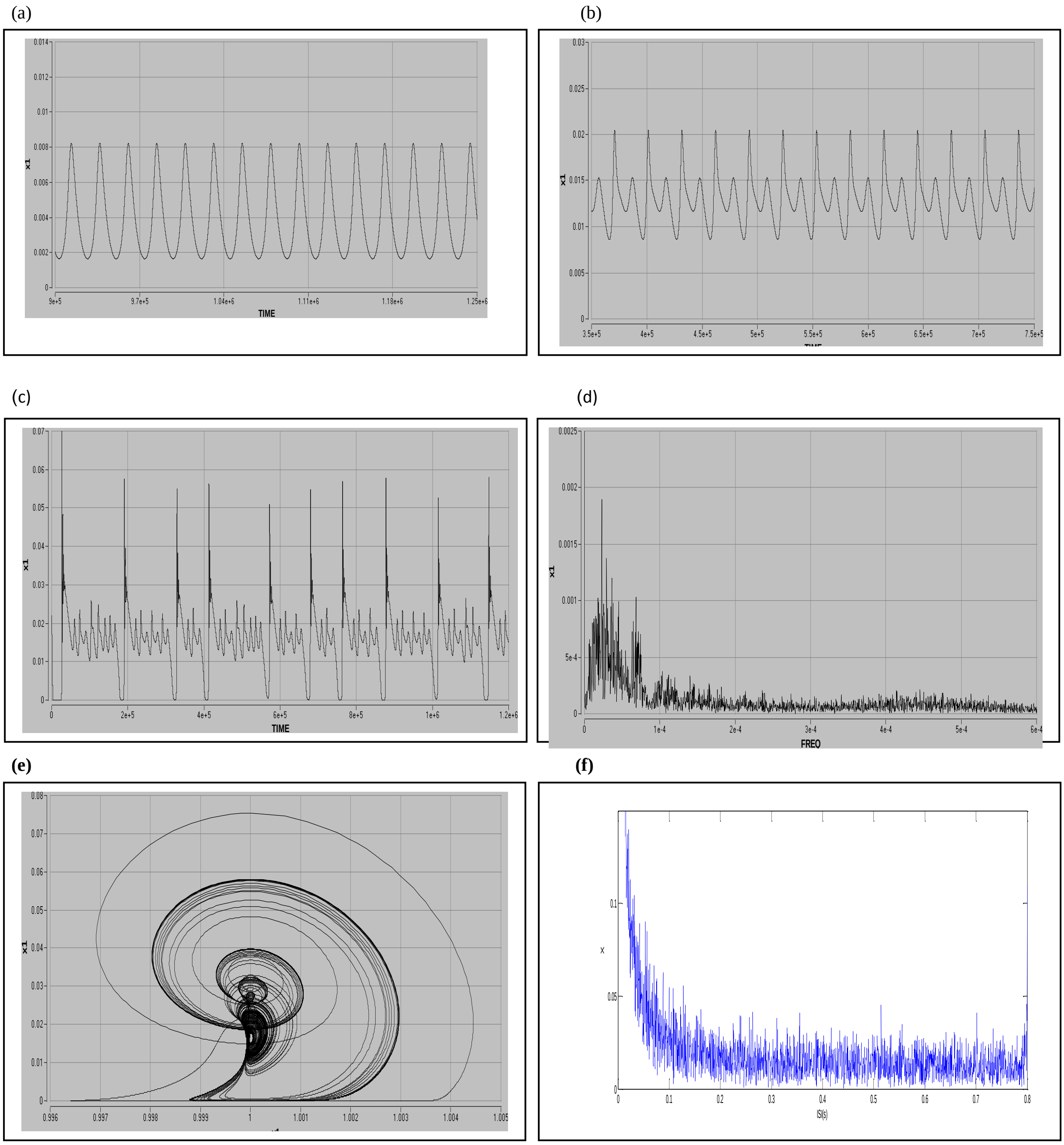

Fig. 5:The numerical time series at bias current values(a)1.004,(b)1.013,(c)1.016,(d)the fast fouriertronformFFTat1.016,(e)the attractor at 1.016,(f)the corresponding ISI.

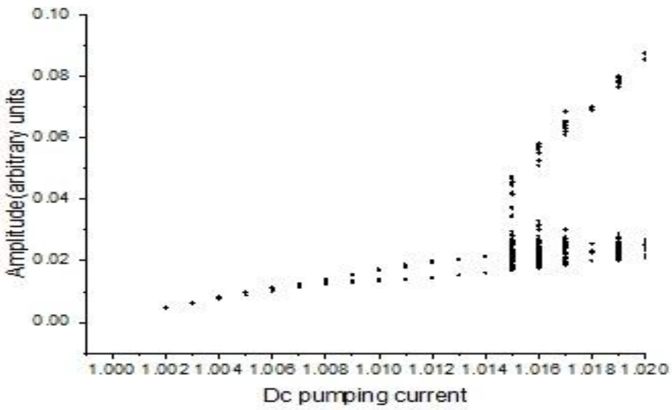

Fig.6:Bifurcation diagram (maxima of photon densities vs. bias current variation)

The bifurcation diagram (peak-to peak- laser intensity versus the dc bias current)is shown in figure (6).This figure refers that for a small values of bias current δ_o, the effect of feedback on the laser dynamics is not evident and the feedback increases lightly the output intensity. By the gradual increasing of the value of bias current from(1.001-1.008)mA, the laser dynamics transform from the stable state to the periodic state. More increase of bias current values from(1.09-1.014)mA, leads that the dynamics of the semiconductor laser attains to quasi-periodic state. The chaotic behavior occurs at the values of bias current from 1.015mA. At the value bias current 1.018, the system go back to the periodic state(MMOs).

The second step of numerical work is that the bias δ_o is considered constant at the value(1.01725) , and the value of the feedback strength α is varied. The values of the other parameters and the initial conditions are the same of the values in the case of the variation of bias current. The dynamical sequence of the this step is exhibited in figure (7)(a-c) which represent the time series at various values of feedback strength. The chaotic dynamics shown obviously in figure (7)(c), where the value of feedback strength equals to0.997 the time series display different heights of amplitudes and the corresponding FFT in figure (7)(d)where there are many no. of frequencies have different amplitudes. The corresponding attractor of the chaotic state shows a strange-shaped attractor in phase circles with different heights because of different amplitudes is explained in figure (7)(e), while figure(7)(f) shows the corresponding ISI of the chaotic state.

The bifurcation diagram is explained in figure (8),which displays the complete behavior of the numerical system under the effect of the feedback strength. For values of the feedback strength α from(0.981-0.991)mA, the periodic state appears obviously. The system transfer to quasi periodic state at the values of α from(0.992-0.993)mA. The chaotic oscillation state appears in the range of α from(0.994-0.997)mA. eventually the system displays a mixed mode oscillations(MM0s)for the values of α from(0.998-1.005)mA. Consequently this numerical system suffers from aseries of transitions,begins from periodic state, passing through a quasi-periodic state ,and attains to the to chaotic oscillation and eventually it go back tothe periodic state.

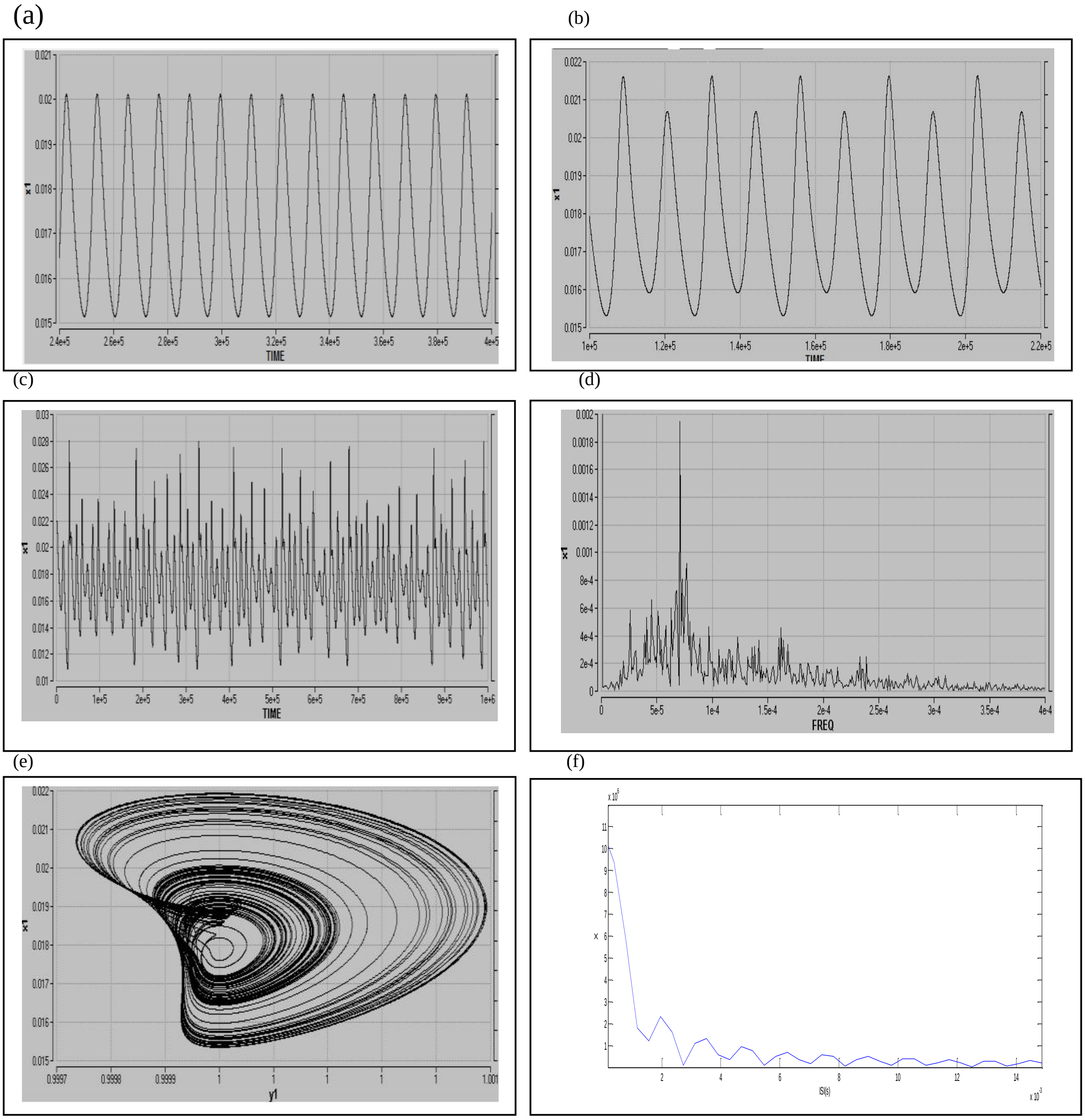

Fig.7: The numerical time series for various values of feedback strength (a)0.988,(b)0.992,(c)0.997,(d)FFT at the chaotic state,(e) the corresponding attractor of the chaotic state(0.997),(f) ISI at the chaotic state.

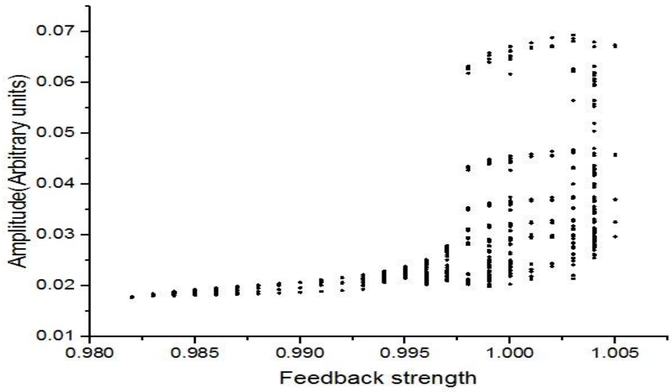

Fig.8: Bifurcation diagram (maxima of photon densities vs. feedback strength variation).

Conclusions:

We have studied experimentally and numerically the chaotic signals generated in semiconductor laser with optoelectronic feedback, we have controlled the chaotic regimes by the laser's bias current and feedback strength. We have analyzed the effects of bias current and feedback strength on time series, extracted power spectrum(FFT) of the time series, attractors, and the inter-spike intervals(ISI) showed the changes of inter-spike duration of optoelectronic chaotic spiking with laser diode power. The period-doubling route to chaos in the dynamics of SL is verified both experimentally and numerically. When the feedback strength is fixed with progressively increasing in dc pumping current of SL, there are many variations in the system states stability. The same behavior (the period-doubling route to chaos) is also obtained when the bias current is fixed with gradually increasing in feedback strength (amplifier gain of the feedback). The variation in the system parameters can make the process of control of dynamic chaos possible in various applications such as, in communication systems, therefore the role of control parameters of laser such as: dc bias current and feedback strength is proved in spiking generation and chaos control in the laser output.

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انتخاب الجاذب في شواش ليزر شبه الموصل المتولد بواسطة التغذية الاسترجاعية الكهروبصرية

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الخلاصة:

تم في هذا البحث اجراء دراسة تجريبية ونظرية لتطور الديناميكية غير الخطية لليزر شبه الموصل تحت شرطين هما تغير تيار الانحياز لليزر شبه الموصل وتغير قوة الاسترجاعية .وقد تم تحليل هذه الديناميكيات بواسطة السلاسل الزمنية واطياف القدرة المستخرجة (FFT)،مخططات الطور(الجاذب)،والفواصل بين الارتفاعات(ISI)،وهذه القياسات تعززت بواسطة مخطط التشعب والذي وضح الانظمة الشواشية.وقد توضحت حالات الاستقرار باستخدام معلمات السيطرة المختلفة.تم اثبات دور معلمات السيطرة لليزر مثل:تيار الانحياز وقوة الاسترجاعية في توليد الارتفاعات والسيطرة على الشواش في نتاج الليزر.