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Chaos Generation Utilizing Optical Feedback Technique with Modern Applications

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Abstract. This overview summarizes the physical interpretation of chaos phenomenon and the most fundamental principles of Laser chaos generation by using optical feedback technique, the significant characteristics of deterministic chaos technique are mentioned with the moves from ordered state to the chaotic state. The description of the semiconductor lasers used to generate this phenomenon is studied with the multiple instances of laser performance before and after reaching chaos. The most important contemporary applications of chaos are in secure communication and Secure transmission digital images. The first section in your paper

Keywords: chaos, nonlinear, attractor, bifurcation, secure communication.

1. Nonlinear dynamics (chaos)

Chaos theory, is the area as is observed in mathematics and physics used in imitation of describing the behavior regarding dynamical systems which are distinctly sensitive in conformity with preliminary state of the system "i.e. just small perturbation in initial condition leads to significantly varying behavior", also referred to as butterfly effect. This means that long term prediction is impossible even the system is deterministic, also known as "deterministic chaos" [1].

Chaos is a native characteristic concerning many nonlinear systems. Minutely, the transition from order to disorder occurs with universality, irrespective of physical properties of the systems [2].

The mathematical foundations of chaos were presented by poincaré in his study on bifurcation theory [3]. The first dynamic system for generating chaos was made by Edward Lorenz and commenced by Haken in 1975 when he proved the mathematical isomorphism between the Maxwell-Bloch equations "which describes the dynamics of the electric field, the mean polarization of the atoms and the population inversion", and the Lorenz equations for atmospheric convective flow [4].

Since the work of Haken, much attention has been dedicated to the nonlinear dynamics of lasers in general, and laser diodes in particular. An example of a dynamical system (in which time is continuous) is a system of N first- order differential equations: [5].

$$\frac{dx(t)}{dt} = f[x(t)] \qquad (1)$$

where x is an N-dimensional vector and t is time**.** Also, it is usual to refer to a continuous time dynamical system as a flow for a discrete integer-valued [6].

$$X_{n+1} = M(X_n) \qquad (2)$$

where $X_n=(x_n^{(1)}, x_n^{(2)},..,x_n^{(N)})$ given the initial condition x_o, The space $(x^{(1)},x^{(2)},x^{(3)},...)$ is denoted by the phase space, and the system follows a path in space while it evolves with the time is called the orbit or "trajectory". $(x_0,x_1,x_{2,.})$ is the orbit of the discrete time system, a chaotic system represents a special kind of non-linear systems, characterized by its chaotic behavior. There are two indispensable conditions for chaotic motion to take place: (1) the associated phase space of the system must be at least three dimensional, (2) the equation of motion contains a non-linear time period to that amount couples numerous of the variables. The chaotic conduct is determined among realistic functions on deep fields, such namely engineering, biology and economics [7]. Chaos has been proven in accordance with remain useful into a variety of disciplines, such as information processing, the collapse forbidding of power systems, the circuits and devices of high performance, and mixing of liquids using lower power consumption [8].

2. Routes to chaos

In the previous two decades, the concept of chaos hold made an important progress towards raising our appreciation regarding some transitions from an ordinary to chaotic state, which execute keep observed within laboratory experiments [9]. The most important property of deterministic chaos is "Bifurcation" and " route (scenario) to chaos" which means a transition from steady state to chaos state through periodic and quasi-periodic states, at varying one of the parameters of the system. There are three kinds of familiar bifurcations and scenarios to chaos which are featured for many dynamical systems including laser systems. These kinds of scenarios to chaos state can be utilized to show the existence of inevitably chaos in laser systems [10]. These three types of bifurcations and scenarios to chaos are:

2.1. Period-Doubling route to chaos

The chaos theory specializes in studying of the paths from simple until up to complex dynamics, the period-doubling route must be treated as a featured route to chaos state in physical systems [11]. This scenario to chaos initiates from the steady state and after that it transfers to chaos through a series of a period-2m oscillation, where m is a positive integer, as shown in figure (1a). The scenario is correlated with the sub-harmonic bifurcation. This route can be found in many of laser experiments, simulations, continuous-time dynamical systems and discrete systems. Furthermore, this scenario is also named as "Feigenbaum scenario to chaos" [12].

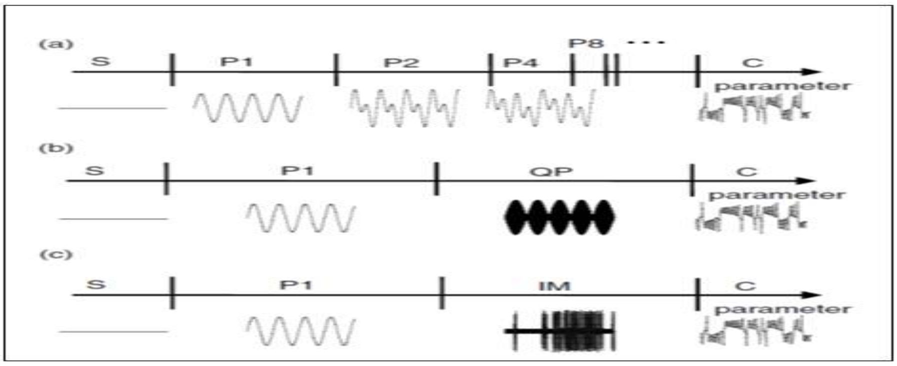

Figure 1. Plots of scenarios to chaos state when a certain parameters of the system are varied. (a) Period-doubling state , (b) quasi-periodicity state and (c) Intermittency state.; where S, is a steady state; P1,is a period-1; P2, is a period-2; P4, is a period-4; P8, is a period-8; C, is chaos; QP, is a quasi-periodicity; and IM, is an intermittency [8].

2.2. Quasi-periodicity route to chaos.

This state of affairs initiates from steady state, after that there is a transition to chaos through, a period-1 and a quasi-periodic oscillation. The oscillations on quasi-periodic may be specified by pay attention to the frequency spectrum which contain two frequencies with non-measurable ratio [13]. A suitable description of quasi periodic motion is "toroidal motion" [14]. When the bifurcation parameter is varied, consequently there is a presence of a nonlinear interaction between the two frequencies yields to break the quasi-periodic attractor and finally constructs the chaotic attractor [15], figure (2).

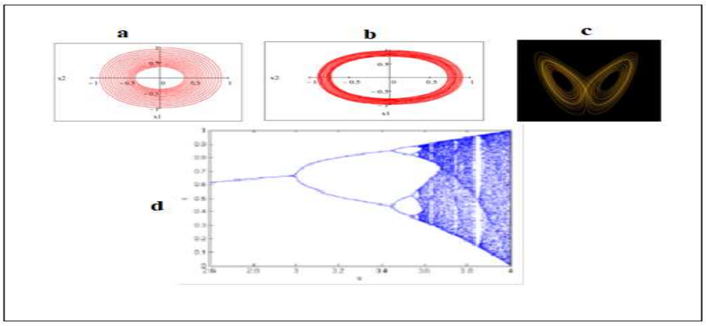

Figure (2). (a) Strong nonlinearity, the phase portrait orbits in the chaotic state, (b) periodic attractor, (c) butterfly effect (d) Logistic mapping bifurcation graph [16].

This scenario to chaos is ordinary spotted in laser systems including external perturbation and modulation due to the presence of a nonlinear interaction between the relaxation oscillation frequency and modulation frequency to produce the chaotic instabilities. This scenario is additionally denoted by the "Ruelle–Takens–Newhouse route to chaos". It must be mentioned here that this type of scenario is correlated with "Hopf bifurcation"[17].

2.3. *Intermittency route to chaos.*
This scenario has been described by regular motion (periodic oscillation) known as "Laminar phase", which is intermittency threw into disorder by a short burst of irregular behavior, figure (1c). After a burst, the system goes back to the regular case until the next event take place [18]. The duration of disorderly phases is rightly regular as well as weak dependence on the control variable, but while the control variable is increased, then the duration of laminar phases decreased, then ultimately the laminar phases melt away in order to be a completely chaotic state. This route to chaos state is correlated through a saddle-node, Hopf, and sub harmonic bifurcations. The intermittency scenario is also named as "the Pomeau–Manneville scenario to chaos" [19].

3. Chaos generating by optical feedback technique
The Optical feedback provision is delayed-feedback sensitive to the phase self-sustaining rule in which all three known scenarios, which are, period doubling, quasi-periodicity, and passing by the intermittency to chaos state, can be found [20]. The optical feedback seemed initially as a "perturbing effect" due to the unwanted reflections on an optical channel. The feedback can be come from the mirrors ends of the laser cavity, figure (3), or by the reflections of the other optical elements of the system [21].

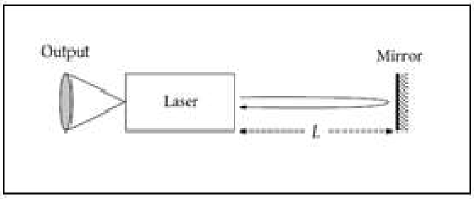

Figure 3. Shows a laser exposed to optical feedback [20].

The optical feedback technique may roil the equipoise of the carrier-photon interaction in the laser cavity, also it can stimulate the laser instability .For this case, the temporal dynamics specified with two predominate components for the frequency: the external cavity frequency and the relaxation oscillation frequency.

The external cavity frequency is the contrary regarding the spherical outing concerning propagation of laser light inside the laser cavity, and it relies upon concerning the distance separating between the laser cavity facet and the external mirror of the laser. The magnitude involving the relaxation oscillation frequency value is proportional with the regarding normalized pump monitoring square root and divided by a value of the life time of the carrier and the photo lifetime. The draw-back of the optical feedback is that feedback can insert a sustained relaxation frequency [22].

The semiconductor lasers are quite sensitive to external optical light. Even with a small external reflections and perturbations may supply a sufficient reason that can give rise to an unstable operating behavior [23]. The pay attention to the interest in the semiconductor dynamics (which subject to optical feedback) is because of the wide laser applications in secure communications utilizing synchronization in chaotic systems[24] such as, imaging, sensing, fiber-optic communications and spectroscopy.[25], Figure (4).

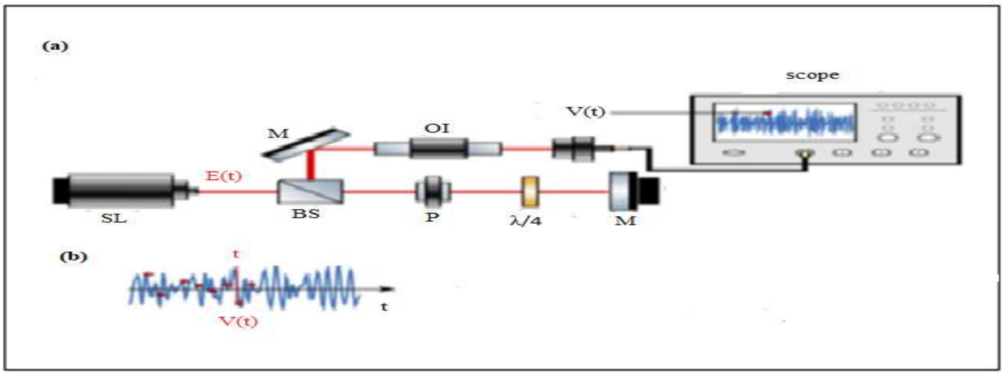

Figure (4). (a) A chaotic regulation including an external-cavity SL. The intensity I(t) is detected with the aid of the photodiode and transformed into voltage V(t). (b) Digitization along 8-bit obviousness then subsampling over the voltage time series [26].

4. Dynamics of semiconductor laser with optical feedback

The traits of SL with optical feedback have an attention of many researchers interested in this field since their contrivance [27]. If the semiconductor laser is exposed to optical feedback, utilizing a reflecting surface, that showcase a huge range regarding dynamics, the first effect of optical feedback is on the value of threshold [28]. This effect is illustrated in Figure (5).

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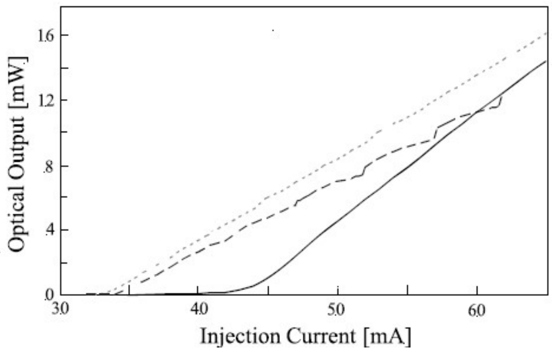

Figure 5. The rigid curve represents the traits for the solitary laser, while the other curves are for semiconductor laser subjected to optical feedback; the threshold current values for this case discount are touching 30%[27].

The laser threshold is reduced utilizing optical feedback because the light re-entering the laser cavity decreases the losses and consequently the threshold current. At the highest feedback, the greatest reduction in the pumping current is gotten [29]. Many nonlinear dynamical phenomena are noticed depending on the feedback strength, such as instability, bi-stability, self-pulsation, and the coherence collapse. The dynamics of the semiconductor laser exposed to optical feedback can be expressed with the "Lang-Kobayashi equations" of complex electric field ε(t) and the carrier population N(t), as follows:[30]

$$\frac{d\varepsilon(t)}{dt} = \frac{1}{2}\,(1+i\alpha)\left[G(N) - \frac{1}{\tau_{\mathrm{p}}}\right]E(t) + \frac{k}{\tau_{\mathrm{in}}}\,E(t-\tau)e^{-\mathrm{i}\Omega\tau} \qquad (3)$$

$$\frac{d(t)}{dt} = RP\,\frac{N(t)}{\tau_{\mathrm{s}}}\,G(N)|E(t)|^2 \qquad (4)$$

$$G(N) = \zeta\,(N(t) - N_t) \qquad (5)$$

Where: E(t) represents the magnitude of slowly varying of the electric field, N(t) is the carrier density, k represents the feedback parameter, ζ is the model gain, Ω is the solitary laser frequency, α is the line width enhancement factor, RP is the pump parameter, τ_s, τ_p are carrier and photon lifetime, τ_{in} is the time of flight in the laser and N_t is the carrier density at transparency. The semiconductor lasers dynamics undergo optical feedback can be classified into five regimes which are [20]:

Regime 1: the feedback is less than 0.01%, very small value of feedback strength and small effect, in this regime the semiconductor laser oscillation line width becomes narrow.

Regime 2: the strength of the feedback is less than 0.1%, small value of feedback strength but not disregarded effects.

Regime 3: the feedback strength is about 0.1%, a narrow region. In this region the mode hopping noise is repressed, therefore the semiconductor laser oscillation line width becomes tight.

Regime 4: the value of feedback strength is moderate. In this region the diversion oscillation frequency will become damped hence the semiconductor laser oscillation line width is broadened. The behavior of the laser in this regime is chaotic.

Regime 5: the value of feedback strength is larger than 10%, the feedback strength within it area is strong. This characterized that the inner and exterior cavities treat as a one cavity therefore the oscillation of the semiconductor laser be in a single mode. In this region the line width is extremely tighten.

The laser is transferred to a stable state, a single-period state, a double-period state, a period-6 state, a period-8 state, a period-9 state, a multi-period state, beat phenomenon, etc. Consequently the laser can be out of control to chaos state. So we give a sever road to chaos state, as shown in figure (6).

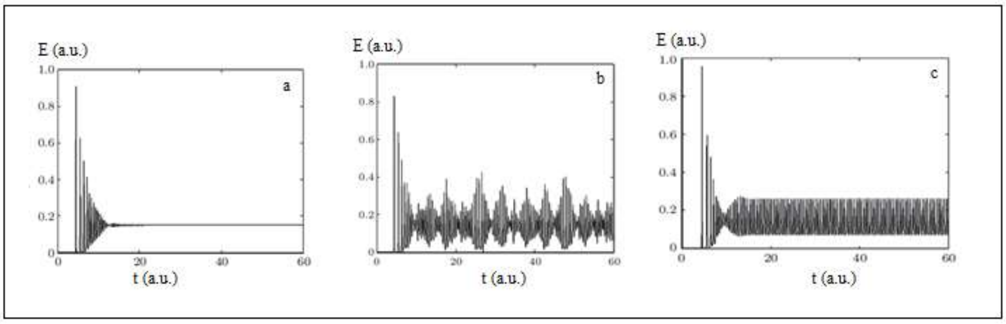

Figure 6. (a); The laser evolvement to a stable state during 30 ns, (b);The laser is periodically oscillated during time 60 ns., (c); The laser pulses is periodically oscillates during time 30 ns [31].

5. Modern applications of chaos theory

Many researchers have investigated the chaotic behavior of several laser systems. In numerous applications of semiconductor lasers subjected to optical feedback the laser active region plays a considerable role in the accomplishment of the system. The most important application of this technique is in secure communication systems by using semiconductor lasers subjected to optical feedback. In optical chaotic secure communication system, the encoding information has been conducted out, the carrier which is in the chaos state is dispatched using traditional potential to the receiver. Then the decoding is accomplished in a real time utilizing a "chaos-synchronization process". The operation principle of chaos in optical communication systems is showed in the figure 7 [32].

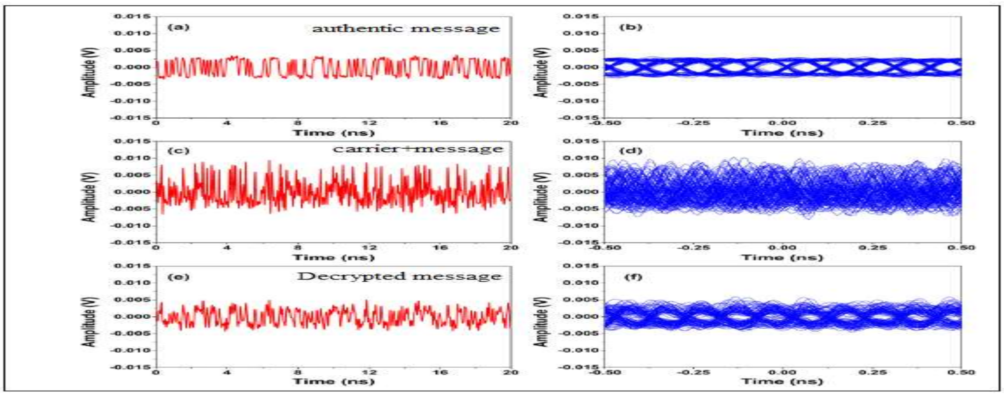

Figure 7. An optical communication system based totally on chaos encryption, with time series for (a), (b) authentic message; (c), (d) chaotic carrier together with message; (e), (f) decrypted message [32].

The main advantages regarding chaos in secure communication systems are: the real-time excessive bit rate in message encoding within the line of transmission, enhanced security, Compatibility along the mounted community infrastructure [20], a good candidate to hide information for satisfying the resonance phenomenon to evaluate secure optical communication [33] and in an Ultra-fast system [34].

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