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Synchronization of Chaotic Quantum Dot Light Emitting Diodes under Optical Feedback Effect

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***Abstract*-Chaos synchronization of delayed quantum dot light emitting diode has been studied theortetically which are coupled via the unidirectional and bidirectional. at synchronization of chaotic, The dynamics is identical with delayed optical feedback for those coupling methods. Depending on the coupling parameters and delay time the system exhibits complete synchronization, . Under proper conditions, the receiver quantum dot light emitting diode can be satisfactorily synchronized with the transmitter quantum dot light emitting diode due to the optical feedback effect.**
***Keywords*— quantum dot light emitting diodes, feedback strength, chaos synchronization, control.**

I. Introduction

Networks using the synchronizing in stochastic coupled dynamical systems that show periodic or chaotic behavior are subjects of major interest in a assortment of fields ranging from biology (Feng, 2003;

Jankowski *et al.*, 1995) to semiconductor lasers (Jost and Joy, 2002; Pasemann, 1999) to electronic circuits (Roy and Thornburg, 1994; Al Husseini *et al.*, 2016), such as secure communication and neuroscience. In QD-LED system studying, where control of complex dynamics has evolved over the past years as one of the major problems in nonlinear applied sciences by controlling the chaotic movement converted to a single, regular signal, it is predictable (Al-Naimee *et al.*, 2009; Al Naimee *et al.*, 2015). Here we studied the coupling of two chaotic systems subject to time delayed feedback. The mismatch between the two systems affects the sensitivity of the synchronization of the chaos between them (Al Naimee *et al.*, 2015). Synchronization of the disorder was studied in coupling systems with different ways, here complete synchronization is discussed in the chaos of QD-LED with optical feedback, and this is done by injecting an anarchic signal (Al Husseini *et al.*, 2015). Synchronization is mainly studied in different of states period, double-period, three-period, and chaotic. External reactions are represented by the system of differential equations that describe the dynamics. Consider the conditions in which the equivalence of the transmitter and receiver equation is subject to theoretical phenomena, which are important conditions for the synchronization of complete chaos. This paper is organized as follow: We have achieved perfect synchronization in randomized systems, that introduce the model equations and the optical feedback scheme in Sec. II. Sec. III is devoted to two measures of the stochastic synchronization and we investigated for different coupling schemes of the feedback.

II. QDLED Model with Optical Feedback

Order to model the dynamics of the QDLED with optical feedback we consider a two-section device, consisting of a spontaneous emission section of length that contains the layers of self-organized QDs as active medium, and a feedback section given by a mirror at a distance to the end facet of the QDLED, reflecting light back into the active region. The QD-LED model demonstrates that electrons move from WL to QDs as in Fig. (1), which produce photons as a result of recombination in the active region which were subjected to absorption, spontaneous emission and non-radiative recombination processes (Al Naimee *et al.*, 2015). We can describe the system above using the four rate equations (Al Naimee *et al.*, 2015)

$$\frac{ds}{dt} = -\frac{1}{2}w\,n_{QD} - \frac{\gamma_s}{2}E_{(t)} + wn_{QD}^2 + \frac{k}{\tau_{in}}\sqrt{s_t s_\tau}\cos(w_\circ\tau + \varphi_t - \varphi_\tau) \quad \text{.........(1)}$$

$$\frac{d\varphi}{dt} = \frac{1}{2}\alpha w n_{QD} - \frac{k}{\tau_{in}}\sqrt{s_t/s_\tau}\sin(w_\circ\tau + \varphi_t - \varphi_\tau) \quad \text{...........................(2)}$$

$$\frac{dn_{QD}}{dt} = \gamma_c n_{wl}\left(1 - \frac{n_{QD}}{2N_d}\right) - \gamma_{r_{QD}} - \left(wn_{QD}^2 - wn_{QD}s\right)$$
……………………....(3)

$$\frac{dn_{wl}}{dt} = \frac{J}{e} - \gamma_{r_{wl}} - \gamma_c n_{wl}\left(1 - \frac{n_{QD}}{2N_d}\right)$$
……………...(4)

Where

n_{QD} is the number carrier in the QD ground state, n_{wl} is the number carrier in the WL ground state, S is the number of photons in the optical mode, γ_{rQD} is the non-raditive decay rates of the number of carriers in the QD, γ_{rwl} is the non-raditive decay rates of the number of carriers in the WL, J is the injection current, N_d is the number of QDs, e is the electron charge, γ_c is the capture rate from WL into the dot, and γ_s is the output coupling rate of photons in the optical mode. The parameter α is the linewidth enhancement factor, ω_O is the solitary optical mode angular frequency, the parameter K measures the injected field strength. The phase shift of the light during one round trip in the external cavity ($\tau = 2l/c$) is given by $\Theta = \omega_O \tau$, c is the speed of light. The photon number labeled by the subscript τ, S_τ, and therewith $\Theta_{\tau C}$, are the electric field amplitude, and the optical phase taken at the delayed time $(t-\tau)$. The objective here is to provide a qualitative model simulates of experimental results and show the chaotic increase in QD-LED under optical feedback, we rewrite the system Eqs. (1) to rate equations. Defining a new variables by the following:-

X=S , $Y = \frac{W}{\gamma_S} n_{QD}$, Z=$\frac{n_{wl}\gamma_s}{W}$

$\gamma = \frac{\gamma_s}{\gamma_{r_{wl}}}$, $\gamma_1 = \frac{W}{\gamma_s}$,$\gamma_2 = \frac{W}{\gamma_{r_{wl}}}$, $\gamma_3 = \frac{\gamma_{rQD}}{\gamma_{r_{wl}}}$, $\gamma_4 = \frac{\gamma_c}{r_{wl}}$,$N_d \equiv a$, $\delta_\circ = \frac{I}{We}$ and $\acute{t}$=$\gamma_{r_{wl}} t$

after the above conversions become Eqs. (1) as follows:-

$$\dot{x} = \gamma\left(\left(\frac{y^2}{\gamma_1}\right) - x(y+1) + 2\sqrt{x_\tau}x_t\,\eta\cos(w_\circ\tau + \varphi_t - \varphi_\tau)\right)$$
………………(5)

$$\dot{\emptyset} = \frac{1}{2}\alpha y\gamma - \eta\sqrt{x_\tau/x_t}\sin(w_\circ\tau + \varphi_t - \varphi_\tau)$$
……… ………..……………(6)

$$\dot{y} = \gamma_2 z\left(\gamma_1 - \frac{y}{2a}\right) - y(\gamma_3 + \gamma y) + \gamma_2 xy$$
………… ………….…………(7)

$$\dot{z} = \gamma_4\left(\delta_\circ - z + \frac{yz}{2\gamma_1 a}\right) - z$$
…………..………………………………………(8)

Above, the upper "point" (̇) refers to the derivative for (t). The symbol $(\delta_\circ)$ refers to the bias current. Where

$\acute{t} = \gamma_{r_{wl}}\tau$ and $\eta = \frac{K}{\gamma_{r_{wl}}\tau_{in}}$

Next, four associated equations are necessary for QD-LED with optical observations and unstable fluctuations and chaotic dynamics appear in their production forces on four equations associated. In the numerical simulation, Runge-Kutta algorithm was used from the fourth rank in Berkeley Madonna program.

III. Chaos Synchronization of Delay-Coupled QD LED

In this section, we investigate the theoretical treatment for chaos synchronization in the two QD LEDs that are delay-coupled to each other with a coupling delay and additionally receive self-feedback. The basic coupling scheme is depicted in Fig 2. The rate equations for the transmitter and receiver QDLEDs are written by the same equations as those for the model discussed in section .II except for the light transmission term in the receiver rate equations.

The rate equations for the transmitter and the receiver QDLED read where subscript 1 represents the transmitter and subscript 2 represents the receiver QDLED.

The photon and phase equations for the transmitter QDLED in the unidirectional coupling two delayed and the Bidirectional coupling systems read:-

$$\dot{S}_{1(bid)} = -\frac{1}{2}w_1 n_{QD1} - \frac{\gamma_{s1}}{2}E_{(t)} + w_1 n_{QD1}^2 + \frac{k_1}{\tau_{in}}\sqrt{S_{t1}S_{\tau1}}\cos(w_{\circ1}\tau + \varphi_{t1} - \varphi_{\tau1}) + k_c\sqrt{S_{t2}S_{\tau1}}\cos(w_{\circ2}\tau + \varphi_{t1} - \varphi_{\tau2} - (w_{\circ2} - w_{\circ1})t)$$
……………………………….(10)

$$\dot{\varphi}_{1(bid)} = \frac{1}{2}\alpha w_1 n_{QD1} - \frac{k_1}{\tau_{in}}\sqrt{S_{t1}/S_{\tau1}}\sin(w_{\circ1}\tau + \varphi_{t1} - \varphi_{\tau1}) + k_c\sqrt{S_{t2}}/S_{\tau1}\sin(w_{\circ2}\tau + \varphi_{t1} - \varphi_{\tau2} - (w_{\circ2} - w_{\circ1})t)$$
………………………………………………………(11)

And for the receiver QD LED read:-

$$\dot{S}_{2(bid)} = -\frac{1}{2}w_2 n_{QD2} - \frac{\gamma_{s2}}{2}E_{(t)} + w_2 n_{QD2}^2 + \frac{k_2}{\tau_{in}}\sqrt{S_{t2}S_{\tau2}}\cos(w_{\circ2}\tau + \varphi_{t2} - \varphi_{\tau2}) + k_c\sqrt{S_{t1}S_{\tau2}}\cos(w_{\circ1}\tau + \varphi_{t2} - \varphi_{\tau1} - (w_{\circ1} - w_{\circ2})t)$$
……………………………….(12)

$$\varphi'_{2(bid)} = \frac{1}{2}\alpha w_2\, n_{QD2} - \frac{k_2}{\tau_{in}}\sqrt{s_{t2}/s_{\tau 2}}\,\sin(w_{\circ 2}\tau + \varphi_{t2} - \varphi_{\tau 2}) + k_c\sqrt{s_{t1}}/s_{\tau 2} sin(w_{\circ 1}\tau + \varphi_{t2} - \varphi_{\tau 1} - (w_{\circ 1} - w_{\circ 2})t \quad) \ldots\ldots (13)$$

The equations above represent the equation of the field of the Bidirectional coupling systems for the transmitter and for the receiver QD LED. In case the unidirectional coupling two delayed $k_c = 0$ in eq(10), And in a particular case of the unidirectional coupling two delayed $k_2 = 0$ in eq (13) ,this is called the case Unidirectional coupling one delayed system .

Here τ_c is delay-coupled systems with τ is delayed self-feedback. Each connection has a coupling strength k_c and a coupling phase φ . In the equation the last added limit represents the effect of the carrier on the recipient by reverse feedback, represented by Fig. (2), where the chaos synchronization systems in QDLED with optical feedback, (a) unidirectional coupling two delayed systems where each them have self optical feedback. Therefore, even without the optical feedback loop, the QDLEDs can show chaotic oscillations, (b) the external feedback is zero in the receiver system, i.e., k_2= 0, the model reduces to the unidirectional coupling system , and (c) bidirectional coupling two delayed system. In the bidirectional coupling system, each QDLED plays a role for the virtual external mirror to the counterpart QDLED. $(w_{\circ 1} - w_{\circ 2})$ is the angular frequency detuning. The last terms are the effect of the chaotic signal from the other QDLED.

IV. The Results and Discussion

we will study the synchronization of three different cases. A unidirectional coupling two delayed systems represents the first case. Fig. 3 illustrate the state of chaos as a result of the coupling of two systems, although these two systems are in fact two similar systems, but it is known that these systems are sensitive to any external disturbance. Fig. 3 (a) time series plot, initial results where we observe general behavior similarity but without complete synchronization. Fig. 3 (b) correlation plot between the two traces of QD-LEDs coupled, the transmitter and receiver waveforms at delay time τ=369.945, k_1=2e-4, k_2=1e-4, k_c=1.83111e-4, w_{o1}=0.185,w_{o2}=2428 and δ_o=0.0381481.

Coupling factor is a factor influencing synchronization applications between coupling systems. Fig. 4 (a) represents the bifurcation diagram and it illustrates very well the effect of optical feedback strength on the behavior of the receiver system because of the one-way connection. Several areas show synchronization cases, especially before reaching (0.000185). Fig. 4(b) full synchronization state represents in time series plot of the status of the chaos. It is worth noting here that the synchronization status was achieved at a significant value of the delay time, the input signals of each QDLED should interfere in such a way that each QDLED receives the same input signal, relative to its own phase. This is a different kind of controlling the synchronization phenomenon. Correlation plot between the two traces shown in Fig. 4(c) corresponding with result in Fig. 4(b) where τ=624.683 and k_c=1.836e-4.

The second case investigated in this study represents the correlation of two systems in the one-way coupling method. But in a different state from the first case where the first system has an optical feedback while the other is without this feedback. The diagram of bifurcation shown in Fig. 5(a) represents the scenario of behavior of both the transmitter and receiver system under the influence of this type of coupling, where only three complete synchronization zones can be specified: 0.000103, 0.000135 and 0.000148, respectively. Fig. 5(b) shows the exact synchronization between the output signals of the two associated systems at 0.000148 of the coupling factor value. The correlation traces of the two systems shows the state of complete synchronization as shown in Fig. 5(c) and corresponds to the result in the previous figure. The third and final case in this study is bidirectional coupling with optical feedback. The mutual effect, which is clearly demonstrated by the plotting of the bifurcation scenario, and although it is difficult to control such a correlation, good results were obtained in several regions for complete synchronization, as shown in Fig. 6(a). Fig. 6(b) represents the time series of the output power of the two systems. Fig. 6(c) shows the synchronization between the two traces and the appearance of a small area of symmetry at the end of the path.

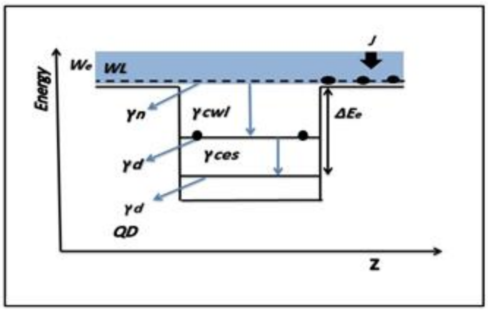

Fig. (1):- Energy diagram illustrating of the two recombination mechanisms considered in this work of conduction band of the active layer QD LED; recombination radiative and non-radiative via deep level and reabsorption recombination processes.

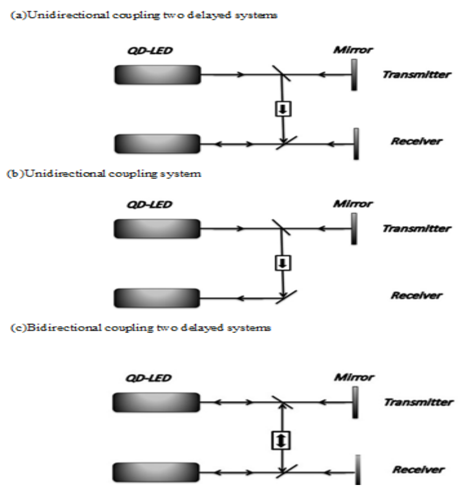

Fig. 2. Schematic diagram of chaos synchronization systems in QDLED with optical feedback. a. unidirectional coupling two delayed systems, b. unidirectional coupling system, and c. Bidirectional coupling two delayed system.

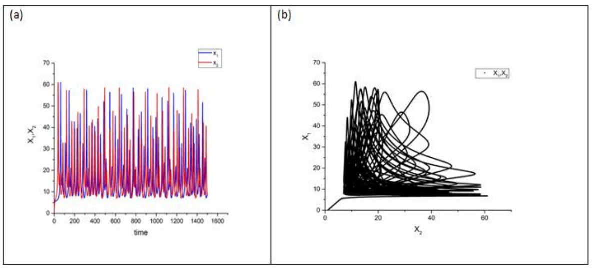

Fig. 3. (a) time series and (b) correlation traces of two QD-LEDs coupled as unidirectional two delayed systems at τ=369.945, k_1=2e^{-4}, k_2=1e^{-4}, k_c=1.83111e^{-4}, w_{o1}=0.185,w_{o2}=2428 and δ_o=0.0381481

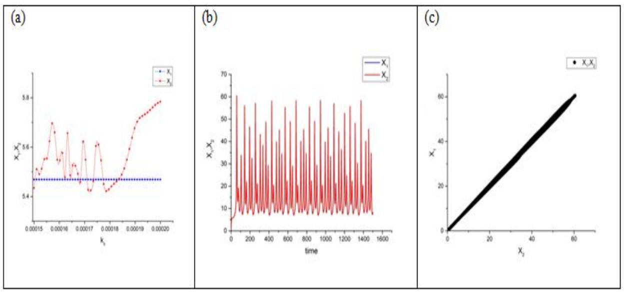

Fig.4 (a) bifurcation diagram (b) time series and (c) correlation traces of two QD-LEDs coupled as unidirectional two delayed systems at τ=624.683, k_1=2e^{-4}, k_2=1e^{-4}, k_c=1.836e^{-4}, w_{o1}=0.0545,w_{o2}=0.0545 and δ_o=0.0396741.

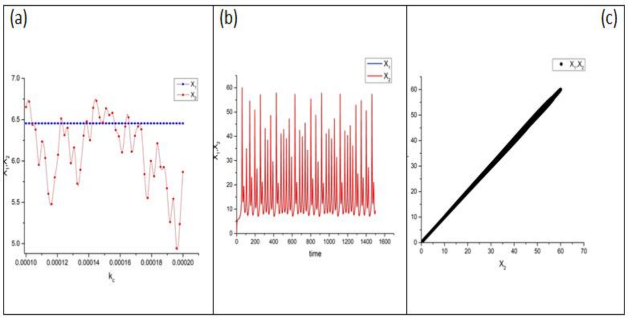

Fig. 5 (a) bifurcation diagram (b) time series and (c) correlation traces of QD-LEDs coupled as unidirectional systems at τ=2003.05, k1=1e-4, k2=0.0032e-4, kc=1.52593e-4, wo1=0.5057,wo2=0.7798 and δo=0.0412

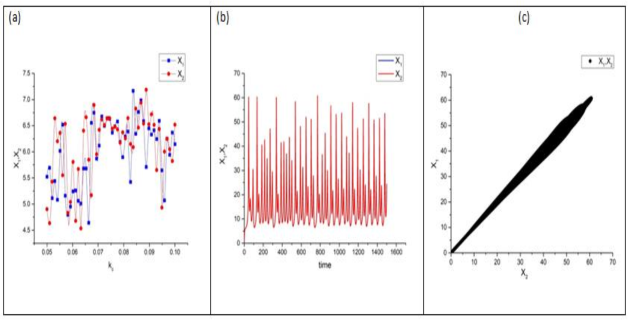

Fig. 6 (a) bifurcation diagram (b) time series and (c) correlation traces of two QD-LEDs coupled as bidirectional two delayed systems at τ=1659.63, k1=2e-4, k2=1e-4, kc=0.09687e-4, wo1=0.4687,wo2=0.4651 and δo=0.0396741.

V. Conclusions

In conclusion, we have discussed chaos synchronization conditions for optical coupled QDLEDs. In all optical coupling, the delay time and the coupling strengths play a crucial role for the synchronizability. The condition of the constant row sum corresponds to specific interference conditions, i.e. the input signals of each QDLED should interfere in such a way that each QDLED receives the same input signal, relative to its own phase. This corresponds to the existence of an identical synchronization manifold. Through interference, the phases may compensate for mismatches in the increasing of delay time. This is a different kind of controlling the synchronization phenomenon as reported. This approach allows controlling the parameter mismatch between the coupled units, what usually occurs in the theoretical methods. Here, the interaction of the optical units has been reached through adjustment of the system states whereas the injection current is kept fixed. Moreover, we have realized theoretical synchronization in terms of the bifurcation diagram and correlation traces of the response times, measured between interacting QDLEDs units. The results revealed the possibility of obtaining multiple synchronization cases to be used in applications of these structures in communications.

VI. REFERENCES

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