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Chaos Synchronization of QD Light Emitting Diodes With Optoelectronic Feedback

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Abstract

We theoretically study chaos synchronization of two diodes that emit light using quantum dots (QDLED) which are delay coupled via a closed and open –loop coupling system active relay. While the chaotic systems are synchronized, their dynamics is identical to a single QDLED with delayed optoelectronic feedback for an open –loop system active relay. There is total synchronization in the system depending on the coupling parameters., i.e., the extent of the QDLED's chaos regime under external optoelectronic feedback is evaluated in terms of the chaos synchronization residue and lag diagram for the optimal coupling strength range is debated as well. Under apposite conditions, the headset QDLED can be satisfactorily harmonized with the transmitter QDLED due to the optoelectronic feedback effect.

Index Terms— QDLED, optoelectronic feedback, synchronization residue, control, parameters mismatch, chaos.

I. Introduction

Control of complex dynamics has become one of the key problems in applied nonlinear science over the past few years [1]. By expanding chaos control techniques, especially time-delayed feedback, significant progress has been made among other things in neuroscience. [2 This happens obviously in a variety of biological systems, such as neural nets, where temporal delays are caused by both propagation delays and local neurovascular couplings. [5-3].Furthermore, time-delayed feedback loops may be purposefully used to regulate neurological abnormalities, such as suppressing unwanted neuronal synchronization in Parkinson's disease or epilepsy. [8-6].

One of the disturbances to the injection current in QDLED that causes instabilities is optoelectronic feedback. Phase sensitivity in optical feedback to QDLEDs is critical to the QDLED dynamics [9]. Optoelectronic feedback systems, in contrast to optical feedback, do not require consideration of the phase effect because phase information is removed during the feedback process through a photodetector [19]. The injection current of a laser can be used to consistently and flexibly control its stable or unstable activities. [11] and [12]. The photon number and carrier number in the dot and wetting zone can only be explained by the three equations of the QDLED dynamics with optoelectronic feedback. Consequently, optoelectronic feedback in QDLEDs exhibits distinct dynamics from optical feedback.

There are two types for optoelectronic feedback using the injection current: positive feedback and negative feedback. Their methods for influencing the output's dynamics are dissimilar. When there is negative feedback, the relaxation oscillation becomes sharper and the feedback current is subtracted from the bias injection current [13].

However, the delay-time variation tendency to drive the output into pulsing states because the feedback current is added to the bias injection current.. First, we give a rate-equation analysis that includes all of the important components of electronic transitions in this work. With consideration for both photon reabsorption and nonradiative recombination processes, we use the study to offer a rate equations model of three levels states in dimensionless form that displays incredibly complex behaviors and modulation rate of QDLEDs. Furthermore, we examine two coupled chaotic systems that are affected by optoelectronic feedback that is delayed in time.

II. QDLED model

We will use rate equations to examine QD LED structures. Before being absorbed by the QDs, the electrons in the QD LED system are first pumped into the wetting layer (WL). We take into consideration a system consisting of two electronic levels: upper and lower. The formulas explain the overall number's behavior. n_{QD} of carriers at higher tiers, n_{wl} number of carriers in the WL and photon quantity in the optical mode S, as follows:

$$\dot{S} = An_{QD} - dS - \gamma_s S,$$

$$\dot{n}_{QD} = \gamma_c n_{wl}\left(1 - \frac{n_{QD}}{2Nd}\right) - \gamma_r n_{QD} - \left(An_{QD} - dS\right),$$

$$\dot{n}_{wl} = \frac{J}{e} - \gamma_n n_{wl} - \gamma_c n_{wl}\left(1 - \frac{n_{QD}}{2Nd}\right) \qquad (1)$$

Here, A is the optical mode's spontaneous emission rate, γ_r , γ_n are the rates at which the number of carriers in the upper levels and WL degrade non-radioactively, respectively.; N_d is the is the total number of QDs, and J is the injection current, e is elementary charge, γ_c is the capture rate from WL into an empty dot, and d and γ_s are the rate at which photons are absorbed and coupled out in the optical of mode, separately.

The Einstein relation indicates that for a three-level atomic system with a homogeneously expanded transition [14]

$$d = \Gamma A n_o \qquad (2)$$

where Γ is the confinement factor and n_o is the lower level occupation number. The spontaneous emission coefficient and the absorption coefficient have the same line form in this situation. Both the lower and the upper levels can be inhomogenously widened for genuine material systems, such semiconductors or organic emitters. To find the correct relationship between absorption and spontaneous emission spectra, population distributions at the lower and upper levels must be carefully considered. [15]. The energy arrangement of the QDLED is revealed in Fig.1.

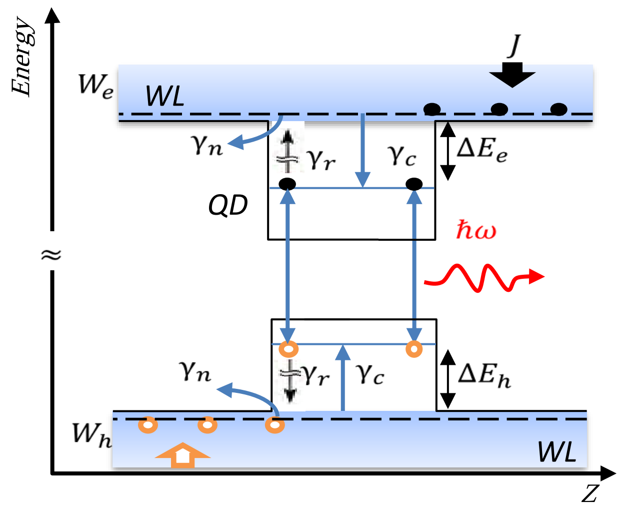


Figure .1 Energy diagram showing the two recombination methods for the active layer QD LED that were taken into consideration in this work: reabsorption recombination processes and radiative and non-radiative recombination via deep level.

The model of optoelectronic feedback in QDLEDs is the same as that treated as the direct current modulation discussed in our recently works. Fig.2 demonstrates an optoelectronic feedback schematic design in a QDLED. The light produced by a QDLED is picked up by a photodetector, and the photocurrent it finds is supplied back via a bias Tee circuit. Depending on the polarity of the amplifier's output in the circuit, the feedback could be either negative or positive. The modulation in optoelectronic feedback is not for the complex field but for the population through the disturbance to the injection current. Therefore, we use the rate equation of the photon number instead of the complex amplitude. Using (1) and (2), the rate equations for the optoelectronic feedback system is written by

$$S^{\square} = -dS - \gamma_s S + An$$

$$\dot{n}_{QD} = \gamma_c n_{wl}(1-\frac{n_{QD}}{2N_d}) - \gamma_r n_{QD} - (An - dS)$$

$$\dot{n}_{wl} = \frac{J}{e}(1+\frac{kS(t-\tau)}{S_o}) - \gamma_n n_{wl} - \gamma_c n_{wl}(1-\frac{n_{QD}}{2N_d}) \qquad (3)$$

Where ξ is the feedback strength. When k is positive, the system provides positive feedback; when k is negative, it provides negative input. This also applies to the photon number's steady state value. τ is the feedback time, which takes into account the detector's and the electronic circuits' time reactions.

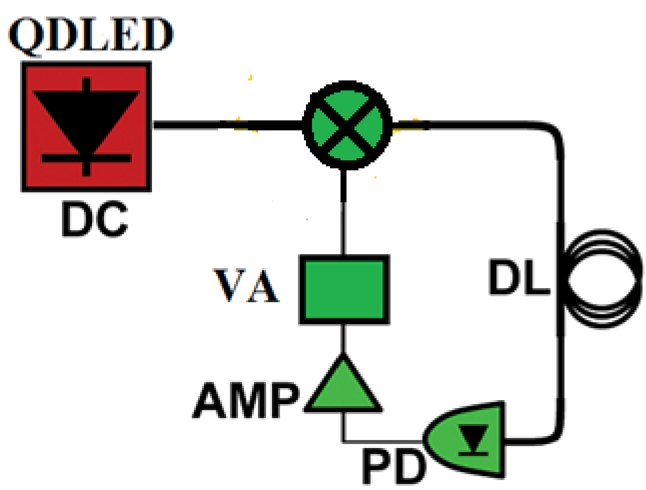


Figure.: 2. The optoelectronic feedback system schematic diagram. Quantum dot light emitting diode (QDLED); photodiode (PD); variable attenuator (VA); optical delay line (DL). Because the maxing is external to the output, there is nonlinearity.

A photodetector receives the light output and converts it to a current. which it is in line with the optical intensity. A delayed positive feedback is produced when The bias current is increased by amplifying the current. By adjusting the distance between the QDLED and the photodetector, one can alter the delay duration. We discover a colorful bifurcation figure as the delay period and feedback intensity are adjusted in The delay differential equations numerical vestiges we have, which explain the dynamics of the optoelectronic feedback QDLED. Generally speaking, chaotic zones are dotted with periodic and quasi-periodic ones, and they are all characterized by the multistability of various attractors, such as limit cycles and fixed points. We discover that the quasi-periodic pathway is when the optoelectronic feedback QDLED enters chaos. This is in good agreement with the findings of the analytical bifurcation analyses of the system-modeling delay differential equations [9].

This work's primary objective is to produce a physical model that qualitatively reproduces the experimental findings and demonstrates that irregular spiking sequences are caused by the optoelectronic feedback of the QDLED. Applying optoelectronic feedback to QDLEDs induces a dramatic change in the photon statistics wherein strong, super-thermal photon bunching is indicative of random intensity fluctuations associated with the spike emission of light, as will be reported in this work. To do so, we rescale the system (2) to a agreed of dimensionless equations as is done more often in the literature [18]-[16]. Establishing new variables and parameters without dimensions by

$$x = S, \quad y = \frac{A}{\gamma_s}(n_{QD} - n_o S),$$

$$w = \frac{n_{wl}\gamma_c}{A}, \quad \gamma_n = \frac{t}{t'},$$

$$\gamma = \frac{\gamma_s}{\gamma_n}, \quad \gamma_1 = \frac{A}{\gamma_n}, \ \gamma_2 = \frac{A}{\gamma_s},$$

$$\gamma_3 = \frac{\gamma_r}{\gamma_n}, \ \gamma_4 = \frac{\gamma_c}{\gamma_n},$$

$$N_d \equiv a, \ n_o \equiv b \ and \ \delta_o = \frac{J}{Ae}$$

Eqs. (1) can be rewritten in the following form

$$x^{\square} = \gamma(y - x),$$

$$y^{\square} = \gamma_1\gamma_2 w\left(1 - \frac{b}{a}x\right) - \gamma_1 y\left(1 + \frac{1}{a}w\right) - b\gamma_1(x - y) - \gamma_3(y + \gamma_2 x),$$

$$w' = \gamma_4 \delta_o \left(1 + \frac{\zeta x_\tau}{x_o}\right) - w\left(1 - \frac{\gamma_4}{a\gamma_2} y\right) - \gamma_4 w\left(1 - \frac{b}{a} x\right) \tag{3}$$

In this case, prime denotes differentiation with regard to (t)′, while δo stands for the bias current.

III. Chaos synchronization in QDLED with Optoelectronic feedback

We talked about optoelectronic feedback's chaotic oscillations in QDLED in section II. Here, we're assuming that optoelectronic feedback is generated chaotically. QDLED showed in Fig. 3. In optoelectronic feedback systems, the rate equations for the carrier and photon number are sufficient for relating the systems. Systems of optoelectronic feedback in QDLEDs possess superior synchronization performance compared to optical feedback. systems. Since the time scale for the carrier number is three figures bigger than that of the photon lifetime [10], Compared to optical feedback systems, optoelectronic feedback systems exhibit distinct differences in the accuracy and performance of chaos synchronization. The following rate equations are written for the photon and carrier number in an optoelectronic feedback transmitter

$$S'_1 = -d_1 S_1 - \Gamma_1 S_1 + A_1 n_1 \tag{4.a}$$

$$n'_{QD1} = \gamma_{c1} n_{wl1}\left(1 - \frac{n_{QD1}}{2N_{d1}}\right) - \gamma_{r1} n_{QD1} - (A_1 n_1 - d_1 S_1) \tag{4.b}$$

$$n'_{wl1} = \frac{J_1}{e}(1 + \zeta_1 S_1(t-\tau)) - \gamma_{n1} n_{wl1} - \gamma_{c1} n_{wl1}\left(1 - \frac{n_{QD1}}{2N_{d1}}\right) \tag{4.c}$$

Where ξ_1 is the coefficient of the optoelectronic feedback circuit in the transmitter. The rate equations for the receiver QDLED are given by

$$S'_2 = -d_2 S_2 - \Gamma_2 S_2 + A_2 n_2 \tag{5.a}$$

$$n'_{QD2} = \gamma_{c2} n_{wl2}\left(1 - \frac{n_{QD2}}{2N_{d2}}\right) - \gamma_{r2} n_{QD2} - (A_2 n_2 - d_2 S_2) \tag{5.b}$$

$$\dot{n}_{wl2} = \frac{J_2}{e}(1+\zeta_2 S_2(t-\tau)+k_c S_1(t-\tau_c)) - \gamma_{n2} n_{wl2} - \gamma_{c2} n_{wl2}(1-\frac{n_{QD2}}{2N_{d2}}) \quad (5.c)$$

Where ξ_2 is the receiver's optoelectronic feedback circuit's coefficient. and k_c is the coefficient of coupling between the transmitter and the receiver QDLED.

The diagram arrangement of the synchronization theoretical is shown in Fig. 3, where a portion of the chaotic output intensity of the transmitter is detected, amplified, and coupled into the receiver's driving current. The receiver is itself a delayed optoelectronic feedback QDLED.

τ_c

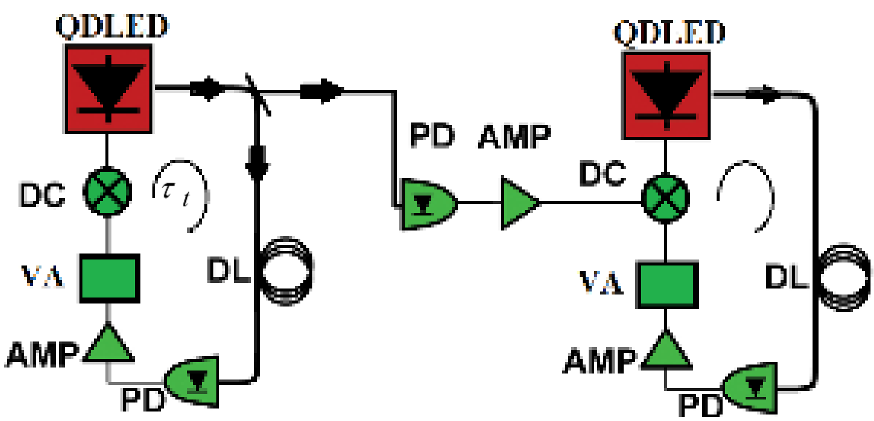


Figure 3. Schematic theoretical setup for the synchronization of Two chaotic systems with optoelectronic feedback that is delayed. τ stands for feedback delay time, τc for transmission time, and QDLED for quantum dot light emitting diode. [11].

As in our model on the synchronization of QDLED, The fraction from the receiver is represented by kc, and we include the factor kc with to show what portion of the total feedback signal strength in the headset comes from the spreader. We refer to a situation as an open loop when there is no feedback signal strength in the receiver (kc = 0). The transmitter and receiver are fully decoupled when kc = 1. The transmission time, or the time it takes for the signal to travel across the open air "channel" and reach the reception system, is shown by the symbol τc. A linked system has a solution when the transmitter and receiver are the same and their dynamical variables are equivalent in time.

In order to attain synchronization, a pair of QDLEDs from the same batch are carefully selected based on their similar properties, and their operating conditions are fine-tuned as shown in Table.1.

Table 1: Unless otherwise indicated, numerical parameters utilized in the simulation [12].

Parameters	value	meaning
S_{1o}	0.066	initial photon number value of transmitter
n_{QD1o}	0.99	initial carrier number value in QD region of transmitter
n_{wl1o}	0.0049	initial carrier number value in WL region of transmitter
τ_t	2800	transmitter feedback delay time
ζ_t	± 0.05	transmitter feedback strength
S_{2o}	0.022	initial photon number value of receiver
n_{QD2o}	1	initial carrier number value in QD region of receiver
n_{wl2o}	0.01	initial carrier number value in WL region of receiver
τ_r	1800	receiver feedback delay time
ζ_r	± 0.002	receiver feedback strength
τ_c	2800	transmission time
I_o	1.7	bias current

The residue of chaos synchronization in the Fig.4 is as indicated by the subsequent equation [11]:

$$R_{chaos} = \left| \frac{S_1 - S_2}{S_1} \right| \tag{6}$$

Where S_1 and S_2 are the intensities maximum of the sender and recipient QDLED. To discuss Synchronization in a more detailed is by imposition of different cases of feedback that can be determined the values of the negative and positive feedback signal strength for each of the two systems. We discovered statistically that, for kc of about -0.4, this solution is stable and that both the transmitter and the receiver's photon and carrier numbers are synchronized. negative feedback strength for transmitter and receiver (see Fig.4 (a)). We furthermore showed in (Fig. 4(a)) In addition, we demonstrated in (Fig. 4(a)) that the delay time is the parameter mismatch that causes synchronization to be most sensitive, with synchronization residue for differences of up to a few percent for any other parameter.

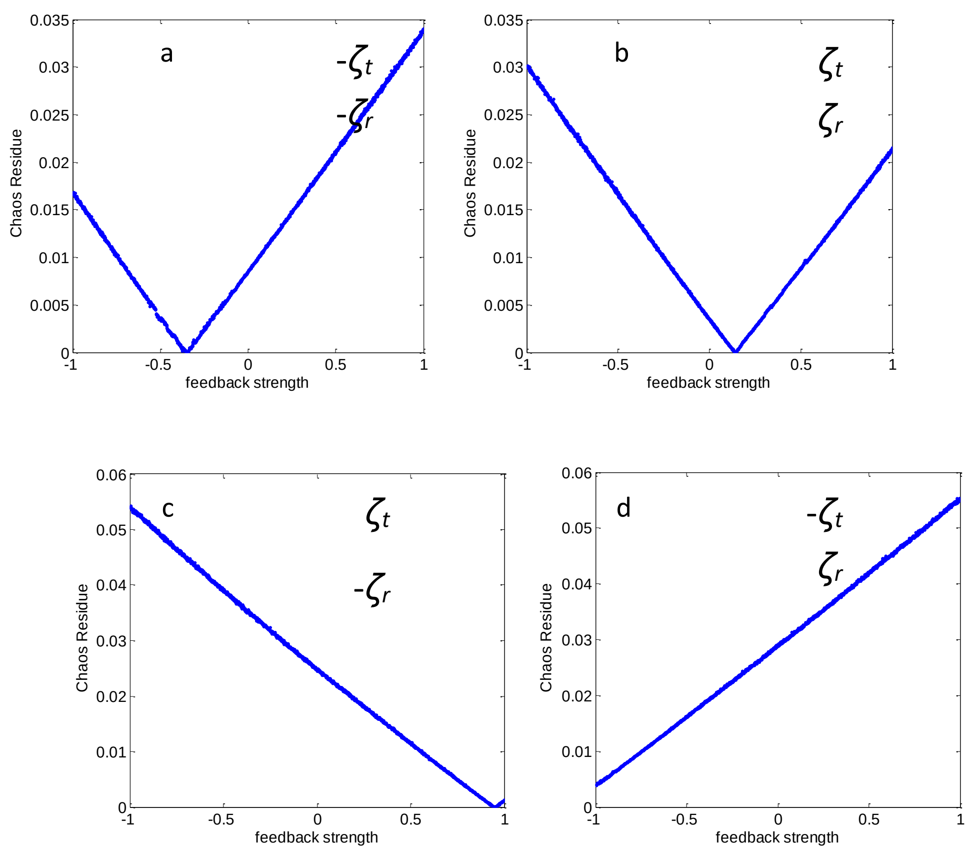
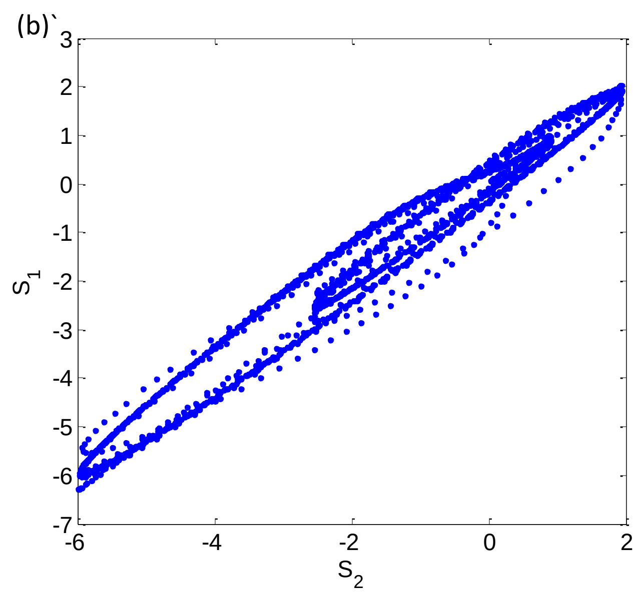


Figure. 4.Calculated chaos synchronization residue as a function of feedback strength. Two chaotic system synchronization with four different cases of feedback signal strength in the receiver and transmitter. The parameters are used in Table 1.

Fig. 4(b) displays the numerical findings regarding synchronization with k_c =0 .2, a configuration where the feedback strength in the receiver and transmitter is positive. While synchronization occurs with k_c =0.9 (Fig. 4(c)) or larger (Fig. 4(d)), and this occurs when coupled two chaotic systems with feedback signals strength opposite. The time series in Fig. are compared. 5(a) shows that they are almost identical. Take note that Fig.'s time series. 5(a) are affected by the transmission delay in terms of time τ_c (see Fig. 4) to enhance the synchronization's visual. The association plot Figure. 5(b) is achieved by graphing the output of the transmitter against that of the receiver. The data distribution follows a 45° line, suggesting the same level of synchronization.



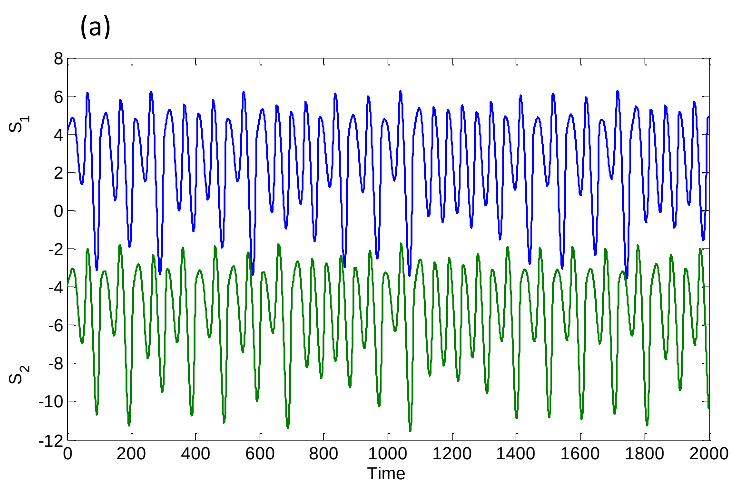


Figure. 5. Same system as in Fig. 4.numerical outcome of the uncontrollably synchronizing kc=-0.4. (a) Time series of transmitter and receiver. (b) Illustration of lag synchronization of the transmitter output vs. the receiver output, the straight line exhibits lag synchronization.

We determine the transmitter and receiver correlation output to quantify the quality of synchronization. When k_c approaches k_c =1 where ζ_t (ζ_r) effectively reaches -1 (0) at a 2100(0) τ_t (τ_r), The system moves toward synchrony with latency. After identifying the transmission time delay 2800 by this similarity function S, lag synchronization can be graphically illustrated directly by plots of S_1 vs. S_2 which is restricted to an almost straight line, as seen in Fig. 6(b). It has demonstrated through numerical means that lag synchronization is rather resilient to perturbations..

In Fig. 6 (a) we find that a mismatch of more than or less than a few percent causes the synchronization quality to rapidly decline. For chaotic synchronization and communication using this delayed optoelectronic feedback system, kc=1 is the recommended configuration since it exhibits the highest quality synchronization and does not have the delay time mismatch issue.

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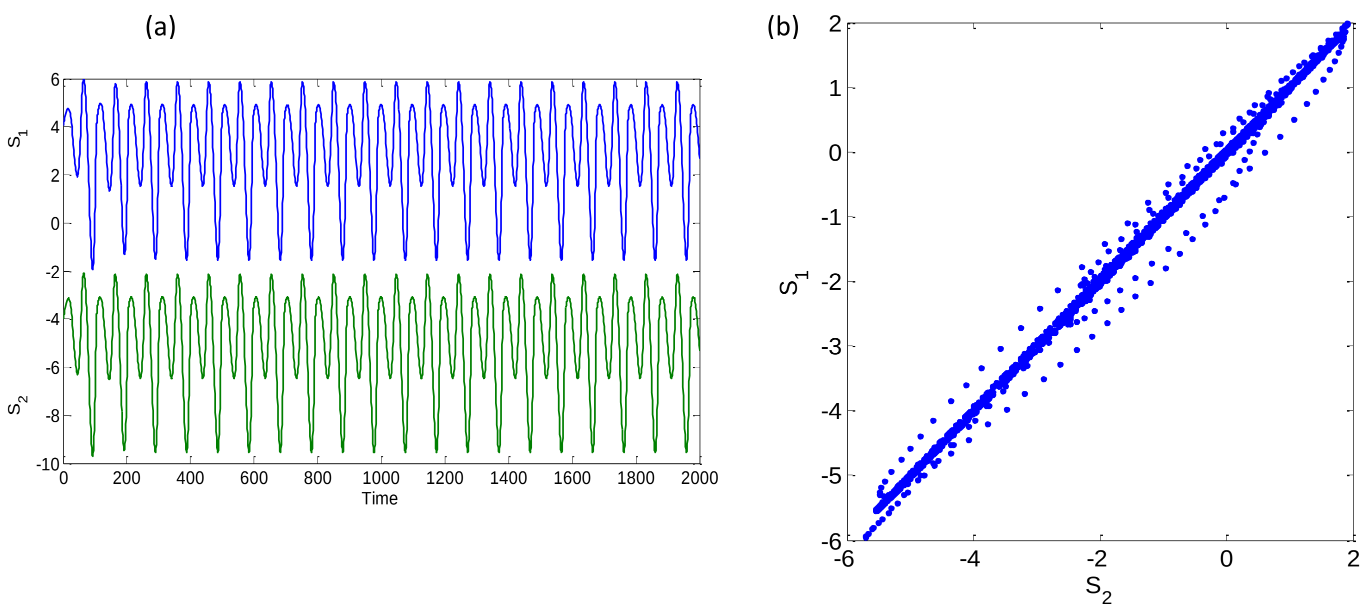

Figure. 6. Numerical result of chaotic synchronization with k_c=-1. (a) Time series of transmitter and receiver. (b) Illustration of lag synchronization of the transmitter output vs. the receiver output at open loop configuration with I_o=1.03.

IV. Conclusion

In conclusion, we have discussed chaos synchronization conditions for optoelectronic coupled QDLEDs. an alternative method of managing the stated synchronization problem. Unlike theoretical methods, this methodology enables the control of parameter mismatch between the connected components. In this case, the phase effect is disregarded and the optoelectronic units' interaction is achieved by adjusting the system states. Moreover, we have realized theoretical synchronization in terms of the chaos synchronization residue and lag of the reaction times, calculated between communicating QDLEDs units. From both the chaos synchronization residue and lag have been evaluated what revealed the positive and negative effect in its value as the coupling strength was modulated.

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