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Modeling of synchronization in quantum dot semiconductor lasers

Basim Abdullattif Ghalib [a], Sabri J. Al-Obaidi [b], Amin H. Al-Khursan [c,*]

[a] Laser Physics Department, Science College for Women, Babylon University, Hilla, Iraq
[b] Physics Department, Science College, Al-Mustansiriya University, Baghdad, Iraq
[c] Nassiriya Nanotechnology Research Laboratory (NNRL), Science College, Thi-Qar University, Al-Muntazah, Nassiriya 00964, Iraq

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Chaos synchronization between two quantum dot (QD) semiconductor lasers with optical feedback and optical injection is modeled by the rate equations model including wetting layer, ground state and excited state. Three systems are discussed: open-loop, closed-loop and mutual-coupling. For each case, both generalized and complete synchronization are discussed. Additionally, optically injected QD laser systems are also discussed. Two QD lasers with the same and different parameters are used. Best synchronization is obtained for the cases of open-loop and injected systems. Electron and hole occupations in the QD ground and excited states are contributes in the chaotic behavior.

1. Introduction

Chaos is a complex periodic time-evolution of a deterministic nonlinear systems. The hallmark of chaos is its extreme sensitivity to perturbations [1]. Physically, when a laser beam is reflected back from an external mirror into its cavity, a semiconductor laser (SL) produces a chaotic signal [2]. Since its demonstration, chaos synchronization becomes of fundamental scientific interest in nonlinear dynamics [3], it is not self-evident. A fraction of the output from one of the chaotic systems (chaotic transmitter) is sent to the another system (chaotic receiver). Then, the receiver output synchronizes with the transmitter signal under appropriate parameter conditions [4]. Chaos synchronization is a real surprise, since we cannot expect the same output even for the same two chaotic systems as far as the two systems are isolated from each other [5]. Chaos synchronization gets a wide attention and puzzlement. It is extensively studied in the context of different subjects such as mechanics, electronic circuits, laser dynamics and biological and chemical systems. Besides these fields, it gets a great importance in the applications of secure communications because of its use as information carriers, their ability to generate chaos in high dimensions, and their nonlinear properties [6]. Most of these works are concentrated on semiconductor lasers (SLs) since they are very important in the field of optical communications [1,7].

Chaos synchronization, have two different origins of synchronization in nonlinear delay differential systems, they are: complete and generalized chaos synchronization. In generalized chaos synchronization, the receiver outputs a synchronized waveform immediately after it receives the transmitter signal, therefore there is a time lag between the two outputs. On the other hand, a synchronous chaotic signal in the receiver is generated in advance to receiving the transmitter signal for complete chaos synchronization. The time lag in the complete chaos synchronization is less than the signal transmission between the transmitter and receiver systems [8].

The use of quantum dot (QD) nanostructures in the active region of SLs is increased in this decade. They are an excellent candidates for high speed data and telecommunication applications due to the carrier confinement in three dimensions which results in a high gain and low threshold current. They demonstrates reduced sensitivity to optical feedback compared with bulk and quantum well lasers due to their near-zero linewidth enhancement factor. This makes it possible to design low-cost directly modulated SLs without optical isolators [9,10]. The carrier dynamics is known to be affects the output of QD laser under optical feedback [11] and optical injection [12] crucially. When used with opto-electronic feedback circuits, QD SLs are more sensitive to time delay changes than other SLs [13].

Chaos synchronization in the low-dimensional nanostructures is not investigated yet. Due to these best characteristics of QD SLs, it is beneficial to study its applicability in chaotic optical communications. This work studies the synchronization between two chaotic QD lasers. First we describe the structure of QD active region in Section 2. The structures used in chaos synchronization are described in Section 3. The model for synchronization in QD

* Corresponding author. Tel.: +96 478 13809600.
E-mail address: ameen_2all@yahoo.com (A.H. Al-Khursan).

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lasers with optical feedback is states in Section 4, while the results of QD laser with optical feedback are states in Section 5. A model for synchronized QD lasers with optical injection is states in Section 6, while its results are states in Section 7. The conclusions are drown in Section 8.

2. The structure of the quantum dot semiconductor laser

The QD material system used is the self-organized InAs/InGaAs/GaAs QD material system [14] grown by molecular beam epitaxy at NanoSemiconductor GmbH in Germany [15]. A ten-stack QD active region consists of InAs QDs covered with $In_{0.15}Ga_{0.85}As$ as a wetting layer (WL). Each QD layer is estimated to have 5.0×10^{14} cm^{-2} surface density and is separated by GaAs barrier. The structure was processed into a single-mode ridge waveguide. The structure considered here is a Fabry–Perot QD SL. The QD is considered to have a QD ground state (GS) and exited state (ES). The InGaAs WL works as a common carrier reservoir. In order to account for the inhomogeneity of the QD gain medium, it is assumed that the QD carrier relaxation or escape can occurs only among the same group of QDs [14].

Our model recognizes between carriers (electron or hole). First, the carriers are injected in the WL with rate I/q and relax in the dot. The carriers are captured into the ES and then, relaxed from ES to GS. The carriers escape also from the GS back to the ES or from the ES back to the WL. Here, we considers a separate system for electrons and holes. Note that, the model states here is also applicable for other types of SLs after covering some parameters required for their specific characteristics "like field or gain".

3. Systems of SL with optical feedback used for synchronization

Semiconductor lasers with optical feedback have been frequently used for chaotic generators in chaos synchronization [16,17]. In laser systems, a small portion of the output from one of variables (usually the laser output power or the complex field) is sent to the receiver laser instead of sharing common variables. Chaos synchronization is very sensitive to parameter mismatches between the transmitter and receiver systems [16]. Fig. 1 shows a schematic of the chaos synchronization systems. In Fig. 1(a) a unidirectional coupling system in which the receiver laser is isolated from the transmitter laser by an optical isolator. Both the transmitter and receiver systems have an optical feedback loops and this configuration is called a closed-loop system (CLS). In Fig. 1(b), the system is also a unidirectional coupling, but the receiver system does not have a feedback loop. This asymmetric system is called an open-loop system (OLS). The robustness and accuracy of chaos synchronization in the OLS are quite deferent from those in the CLS. However, chaos synchronization is achieved by an injection of a chaotic signal. As a matter of fact, Fig. 1(b) shows a special case of Fig. 1(a) indeed, the system in Fig. 1(a) reduces to the system in Fig. 1(b) when we put the reflectivity of the external reflector equal to zero. We mostly discuss chaos synchronization for the closed-loop configuration of Fig. 1(a), but the OLS is implicitly included in the discussion. Fig. 1(c) is a mutual coupling system. Here, the isolator in Fig. 1(a) is removed. Then, each laser behaves as a transmitter and a receiver. These structures are modeled in the following section and then, they addresses.

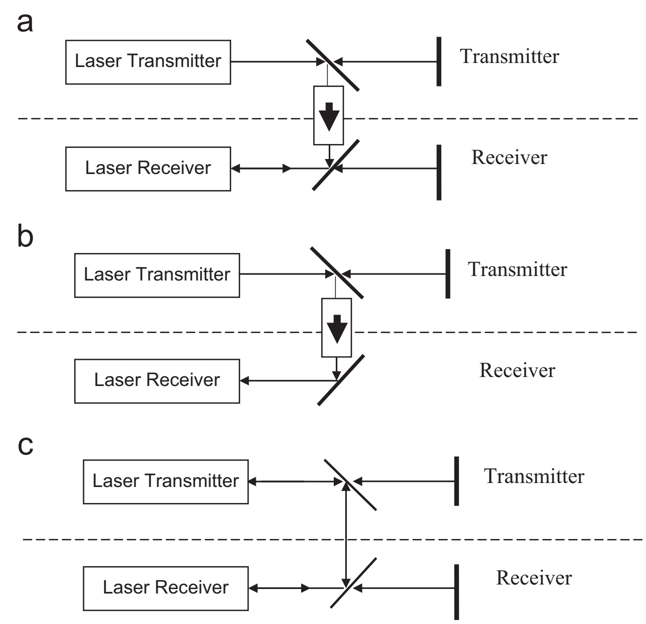

Fig. 1. Schematic diagram of chaos synchronization systems in QDSL with optical feedback. (a) Symmetric unidirectional coupling system (Closed-Loop System), (b) asymmetric unidirectional coupling system (Open-Loop System), and (c) mutual coupling system. For two lasers: transmitter and receiver.

4. Rate equations system for chaos synchronization in QD SL with optical feedback

For complete chaos synchronization, where the optical feedback for transmitter and receiver lasers exists, i.e., the external mirror for the receiver laser is also exists with a receiver delay time ($\tau_R \neq 0$). In this case, the rate equations system for the QD SLs are written as follows:

$$\frac{dE_T}{dt} = -\frac{E_T}{2\tau_{s,T}} + \frac{1}{2}E_T(1+i\alpha)\Gamma g_{G,T}\upsilon_g\left(\rho^e_{G,T}+\rho^h_{G,T}-1\right) + \frac{k_T}{\tau_{in,T}}E_T(t-\tau_T)\,e^{-(i\omega_{o,T}\tau)} + R_{spT} \tag{1}$$

$$\frac{dE_R}{dt} = -\frac{E_R}{2\tau_{s,R}} + \frac{1}{2}E_R(1+i\alpha)\Gamma g_{G,R}\upsilon_g\left(\rho^e_{G,R}+\rho^h_{G,R}-1\right) + \frac{k_R}{\tau_{in,R}}E_R(t-\tau_R)\,e^{-(i\omega_{o,R}\tau)} + \frac{k_{cp}}{\tau_{in,R}}E_R(t-\tau_c)\,e^{-(i\omega_{o,R}\tau_c)}e^{(i\Delta\omega\ t)} + R_{sp,R} \tag{2}$$

$$\frac{d\rho^{e,h}_{G,T,R}}{dt} = -\frac{\rho^{e,h}_{G,T,R}}{\tau^{e,h}_{r,G}} - \frac{1}{N_Q}g_{G,T,R}\upsilon_g\left(\rho^e_{G,T,R}+\rho^h_{G,T,R}-1\right)|E_{T,R}|^2 + \frac{\rho^{e,h}_{E,T,R}\left(1-\rho^{e,h}_{G,T,R}\right)}{\tau^{e,h}_{c,E}} - \frac{\rho^{e,h}_{G,T,R}\left(1-\rho^{e,h}_{E,T,R}\right)}{\tau^{e,h}_{e,G}} \tag{3}$$

$$\frac{d\rho^{e,h}_{E,T,R}}{dt} = -\frac{\rho^{e,h}_{E,T,R}}{\tau^{e,h}_{r,E}} - \frac{\rho^{e,h}_{E,T,R}\left(1-\rho^{e,h}_{G,T,R}\right)}{\tau^{e,h}_{c,E}} + \frac{\rho^{e,h}_{G,T,R}\left(1-\rho^{e,h}_{E,T,R}\right)}{\tau^{e,h}_{e,G}} - \frac{\rho^{e,h}_{E,T,R}}{\tau^{e,h}_{e,E}} + \frac{N^{e,h}_{W,T,R}\left(1-\rho^{e,h}_{E,T,R}\right)}{\tau^{e,h}_{c,W}NQ} \tag{4}$$

$$\frac{dN^{e,h}_{W,T,R}}{dt} = \frac{J_{c1,c3,c2,c4}}{q} + \frac{\rho^{e,h}_{E,T,R}NQ}{\tau^{e,h}_{e,E}} - \frac{N^{e,h}_{W,T,R}\left(1-\rho^{e}_{E,T}\right)}{\tau^{e,h}_{c,w}} - \frac{N^{e,h}_{W,T,R}}{\tau^{e,h}_{r,w}} \tag{5}$$

where E_T, E_R are the complex amplitudes of electric field in the QD GS for transmitter and receiver lasers, respectively. $\tau_{s,T}$, $\tau_{s,R}$ are the photon lifetime for transmitter and receiver lasers.