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Synchronization Dynamics of Quantum Dot Semiconductor Lasers with Optical Feedback by Closed Loop System

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Abstract: In this research, a systematic study on synchronization dynamics of quantum dot semiconductor lasers with optical feedback by close-loop system. The time delay of the feedback has been chosen in order to provide suitable condition for intermittent dynamics. The effect of long and short external cavity of QDSL on synchronization in a closed-loop system are studied under an enhancement factor of (α = 3.5)value by solving the set of 6-rate equation.

Key words: Close-loop system, quantum dot, semiconductor laser, optical feedback, linewidth enhancement factor, intermittent

INTRODUCTION

Control of chaotic synchronization in different dynamical systems has more interest attracted with potential applications on private communication (Husseini, 2016). Synchronization phenomena in Quantum Dot (QD) semiconductor laser chaotic has a good subject of interesting by sensitive with optical feedback and discrete energy for materials and low linewidth enhancement factor. This has motivated many studies with expected benefits including elimination of lasers (Al Husseini *et al*., 2016).

Transmitter and receiver systems have optical feedback loops and this configuration is called a closed-loop system. On other word, 2 time delay on receiver laser. When another transmitter and receiver systems, receiver system does not have a feedback loop, transmitter laser have time delay coupling with receiver laser this asymmetric system is called an open-loop system. The 2 above system must have output a chaotic signal (Ahlers *et al*., 1998). Very small semiconductor particles with (2-10 nm) are called Quantum Dots (QDs) by confined electron and holes in all spatial dimensions (Demchenko, 2008). The idea of chaos synchronization between 2 nonlinear systems was proposed by Pecora and Carroll (1990). They used a Lorenz system with 3 variables for the demonstration. Low threshold current density, high characteristic temperature and small Linewidth Enhancement Factor (LEF) is the characteristic of Quantum Dot Semiconductor Laser (QDSL) (Al-Husseini *et al*., 2009). Therefore, the synchronization scheme is called complete chaos synchronization and itis distinguished from generalized synchronization of chaotic oscillations (Al-Khursan *et al*., 2012). Quantum Dot (QD) nanostructures used on telecommunication applications due to the carrier confinement in three dimensions (Huyet *et al*., 2004; Viktorov *et al*., 2007). Optical feedback is the carrier dynamics to be affects the output of QD laser (Ohtsubo, 2002) also optical injection (Ghalib *et al*., 2013). When used with optoelectronic feedback circuits, QDSLs are more sensitive to time delay changes than other SLs (Ghalib *et al*., 2013). The 2 different origins of synchronization in nonlinear delay differential systems, complete and generalized chaos synchronization. When receiver outputs a synchronized waveform immediately after it receives the transmitter signal, therefore, there is a time lag between the 2 outputs, this system called generalized synchronization. Another type of chaos synchronization accrue when time lag is less than the signal transmission between the transmitter and receiver systems (Ghalib *et al*., 2012).

MATERIALS AND METHODS

Rate equation of quantum dot laser: In QD semiconductor devices, the carriers are first injected into a wetting layer before being captured into a dot at a capture rate that depends strongly on the dot population. The rate equations method, includes a set of at least 3 coupled equations; carrier density (N),

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photon density (E) and the other for the occupation probability (ρ). They are given in Eq. 1-3 (Sugawara *et al*., 1997; Uskov *et al*., 1998). Thus, rate equations that commonly describe carrier dynamics of QD materials read (O'Brien *et al*., 2004):

$$\frac{dE_{(T,\ R)}}{dt}=E_{(T,\ R)}\left(-\frac{1}{2t_s}+\frac{g_o\upsilon}{2}\left(2\rho_{(T,\ R)}-1\right)\right)+ \frac{\gamma}{2}E_{(T,\ R)}\left(t-\tau_{(T,\ R)}\right)+R_{sp} \tag{1}$$

$$\frac{d\rho_{(T,\ R)}}{dt}=-t_n\rho_{(T,\ R)}-g_o\left(2\rho_{(T,\ R)}-1\right)\left|E_{(T,\ R)}\right|^2+ CN^2_{(T,\ R)}\left(1-\rho_{(T,\ R)}\right) \tag{2}$$

$$\frac{dN_{(T,\ R)}}{dt}=J_{(T,\ R)}-\frac{N_{(T,\ R)}}{t_d}-2n_dCN^2_{(T,\ R)}\left(1-\rho_{(T,\ R)}\right) \tag{3}$$

Table 1: Parameters used in the calculation for QDSEL (O'Brien *et al*., 2004)

Definition	Symbol	Values	Units
Photon life time	ts	3.4	ps
Carrier life time well	t_n	1	nsec
Electronic charge	q	1.6×10^{-19}	C
Carrier life time dot	t_d	1	nsec
Linewidth enhancement factor	α	2, 4	-
Velocity of light	c	3×10^{8}	msec
Spontaneous recombination factor	β	3×10^{-5}	-
Group velocity	v_g	7.14×10^{9}	cm/sec
Confinement factor	Γ	0.03	-
Photon decay rate	γ_p	5×10^{11}	sec^{-1}
Number of carrier at transparency	N_{tr}	1.8×10^{18}	cm^{-3}
Effective gain factor	g_0	$0.414*10^{-16}$	
Density of quantum dot	N_d	$2*10^{14}$	cm^{-3}

Where:

$N_{(T,\ R)}$ = The carrier density in the well for transmitter and receiver lasers

$E_{(T,\ R)}$ = The complex amplitude of the electric field for transmitter and receiver lasers

$\rho_{(T,\ R)}$ = The occupation probability in a dot for transmitter and receiver lasers

t_s = The photon lifetime

t_n and t_d = The carrier life time in the well and the dot

N_d = The two-dimensional density of dots

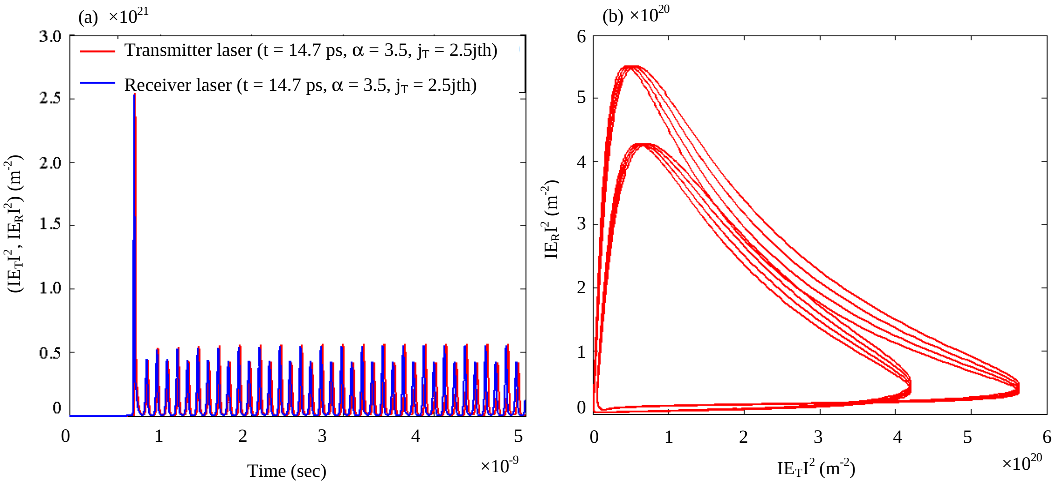
$J_{(T,\ R)}$ = The pump

The γ and τ describe the feedback level and delay time. The $\tau = 2L/c$ is the round trip time of light with in the external cavity (L) and c velocity of light (Uskov *et al*., 1998). C is auger carrier capture rate (O'Brien *et al*., 2004) (Table 1).

In this research we analyze theoretically, closed-loop system consist of 2 type of synchronization as complete and general for transmitter and receiver quantum dot semiconductor lasers with optical feedback. Same 2 laser on linewidth enhancement factor (equal to 4), current, time delay and different on time delay between two lasers τ_c.

RESULTS AND DISCUSSION

The account both photon density, occupation probability, carrier number and attractor using the 4th-order runge-kutta numerical method and MATLAB (Fig. 1-3). Figure 1a shows the photon density of (QDSL) as a function of time when $\alpha = 3.5$, ($\tau = 14.7$ nsec) photon



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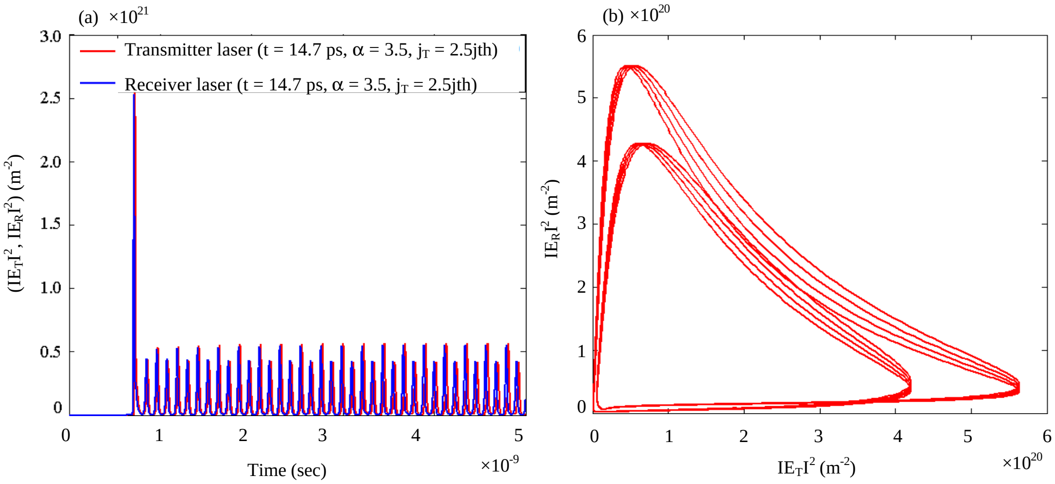
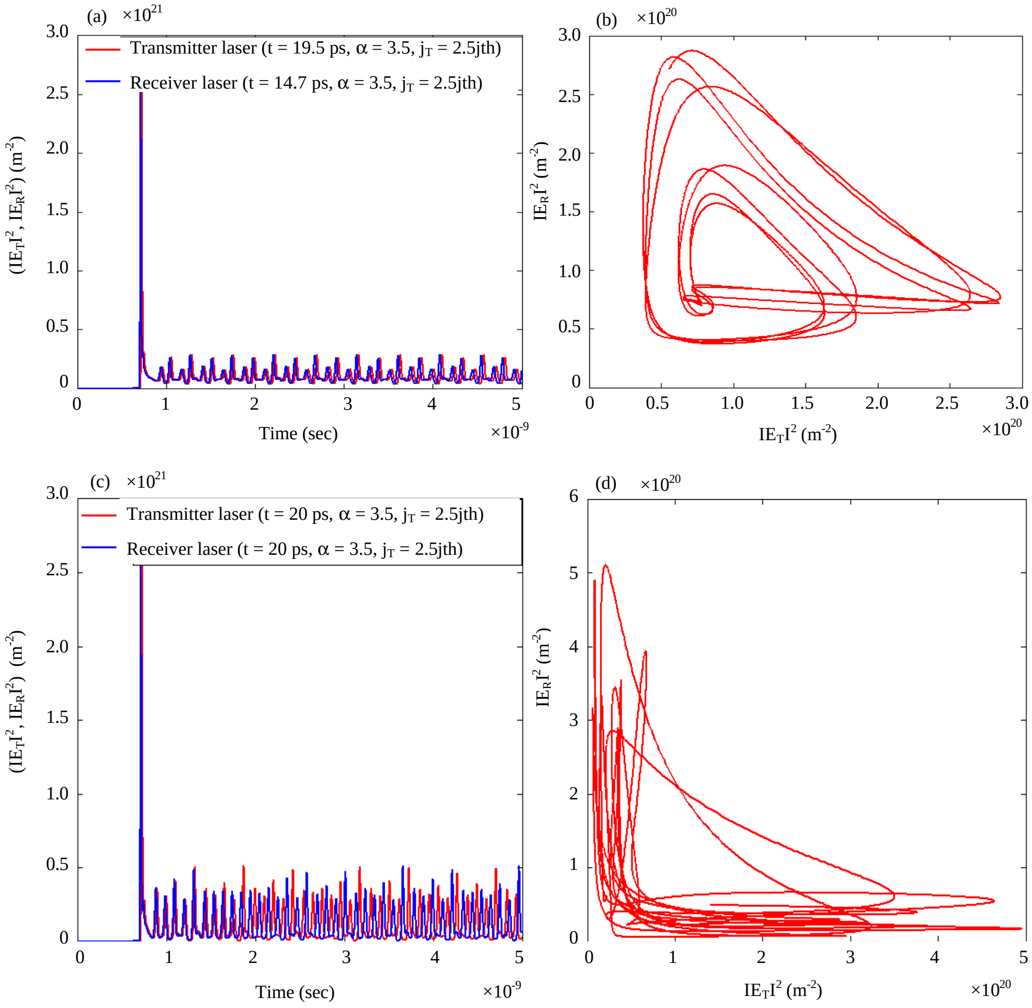


Fig. 1: Photon Density of transmitter and receiver (QDSL) as a function of time at various value of time delay: a, c) Chaotic attractor for photon density of transmitter as a function of photon density of receiver (QDSL); b) Chaotic and d) Double quasiperiodic



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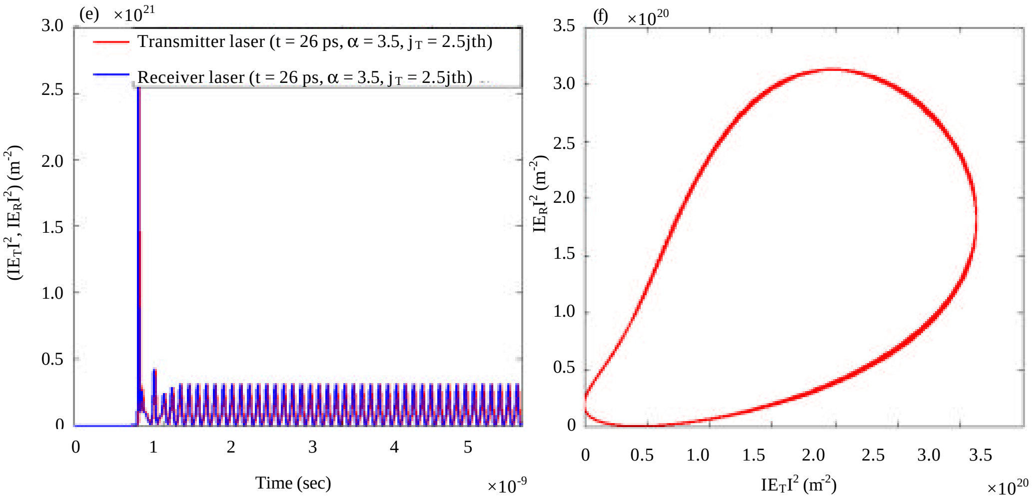
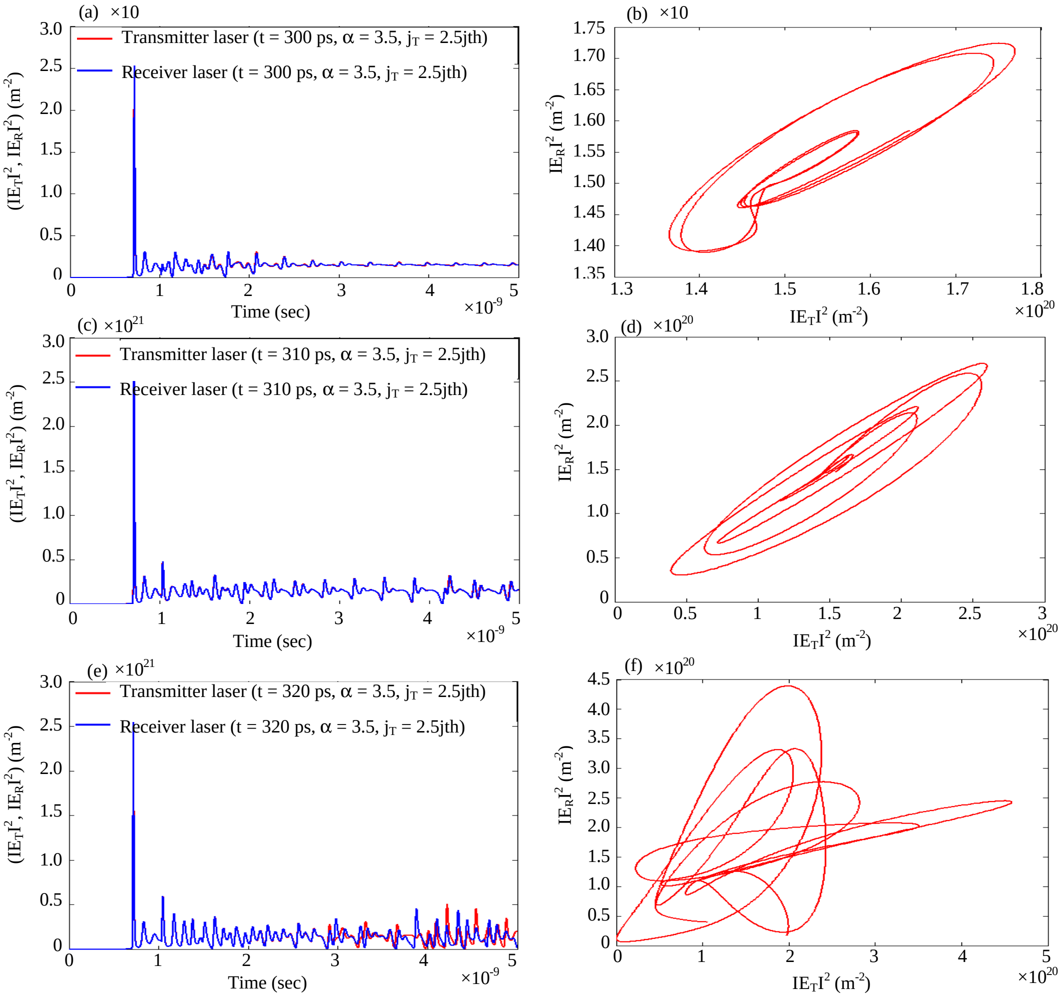


Fig. 2: a, c ,e) Photon Density of transmitter and receiver (QDSL) as a function of time at various value of time delayl; b) Irregular quasi periodic; d) Chaotic attractor and f) Periodic attractor synchronization for photon density of transmitter as a function of photon density of receiver (QDSL)



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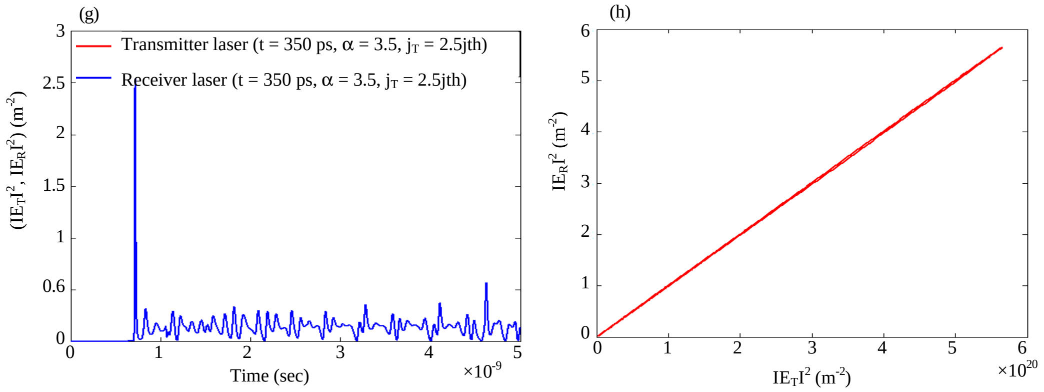

Fig. 3: Photon density of transmitter and receiver (QDSL) as a function of time at various value of time delay: a, c, e, g) Chaotic attractor; b, d, f) Chaotic synchronization for photon density of transmitter as a function of photon density of receiver (QDSL) and h) Complete synchronization

density reach to ($2.8*10^{20}$ m^{-2}) and reduced to a chaotic behavior at steady state. Not periodic behavior for transmitter and receiver of (QDSL) and attractor between photon density of receiver laser and transmitter laser is clearly not periodic with general synchronization in Fig 1b. Figure 1-c time series for photon density of transmitter and receiver (QDSL) laser when $\alpha = 3.5$, ($\tau = 15$ nsec) double quasiperiodic and chaotic quasiperiodic, respectively. Attractor chaotic behavior clearly on Fig. 1b, d double quasiperiodic and chaotic quasiperiodic, respectively when $\alpha = 3.5$, ($\tau = 14.7$ nsec), ($\tau = 15$ nsec), respectively. From Fig. 1a, c notice that change on time delay by 0.3 ps that good results to use on application.

For Fig. 2a-f when time delay ($\tau_{T,R} = 19.5, 20, 26$ ps), irregular quasi periodic relation between photon density of quantum dot semiconductor lasers (transmitter and receiver) and quasigeneral synchronization as in Fig. 2a, b. Chaotic behavior, chaotic synchronization as in Fig. 2b, c, different on time delay equal to 0.5 ps, after (6 ps) photon density is stable with periodic behavior and good general synchronization as in Fig. 2d-e.

For long external cavity length when time delay ($\tau_{T,R} = 300, 310, 320, 350$ ps) for transmitter and receiver QD lasers. A chaotic behavior on all values time delay with no synchronization except when we obtained good complete synchronization. That is good results for application communication as on Fig. 3a-h.

CONCLUSION

The effect of time delay on quantum dot semiconductor lasers with optical feedback dynamics are studied in this search with one value of linewidth enhancement factor (3.5), critical behaviour of chaotic when short external cavity and crisis general synchronization. Long external cavity determine critical behaviour of chaotic and good complete synchronization at.

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