THE EFFECT OF DELAY TIME ON THE SYNCHRONIZATION OF QUANTUM DOT SEMICONDUCTOR LASER WITH OPTICAL FEEDBACK

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The present study includes a synchronization study on the modelling of rate equations and a study of the dynamics of a quantum dot semiconductor laser (QDSL). The dynamics of a quantum dot semiconductor laser depend on several factors including the delay time, as studied in this research via visual feedback, and by relying on practical results. A systematic study of communications for two quantum dots, the transmitter and receiver, and the possibility of synchronization between them, and a study of the relationship between the photon density, time, and the probability of filling the charge carriers over time. For different delay times $(\tau = 249 to 260 step 0.1)$ and the pump current ratios $(J_{T,R} = 1.5J_{th})$ and line width enhancement factor ($(\alpha_{T,R} = 3.5)$ are proven.

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1. Introduction

Semiconductor lasers have been one of the most successful technological developments of the last century. Since their first demonstration in 1962 [1], this type of quantum dot semiconductor laser has been examined in numerous practical and theoretical studies to determine the best ways in which it can work and the different conditions under which it can be operated to respond to the desires of researchers and workers in different applications at the same time [2]. These lasers have been used in many physical applications and can be described by the use of differential equations [3].

The accompanying visual feedback reflection (FEO) has been included in the theoretical model for the purposes of detecting its effects on the laser output in theory according to various numerical solutions in order to achieve the best rehabilitation for the laser output must be provided with a pumping gap of shape and engineering and local specifications that lead to higher pumping capacity for the effective medium [4].

Semiconductor lasers have experienced tremendous improvements in terms of their performance and reliability, which has led to them becoming a well-established and indispensable technology for a large variety of applications [5,6]. The QD laser was first proposed by Dingle and Henry in 1976 [7]. Their approach was based on the application of the size quantization concept to the semiconductor gain medium that had previously led to the successful development of QW lasers [8]. In 1982, Arkawa *et al.* published the first theoretical treatment of three-dimensional confined QD lasers and, thanks to the discrete nature of the density of states, they predicted a lower temperature sensitivity of the threshold current [9]. The first injection laser based on self-assembled QD was realised in 1994 [10].

Some of the desirable attributes of semiconductor dot lasers are their low threshold currents, high output power and efficiency, temperature-independent operation, large modulation bandwidth, and negligible chirp. Many of these characteristics are determined by the density of states and electronic properties of the gain medium [11,12]. Chaotic optical communication has potential applications in secured communications [13]. The widespread use of lasers in science and technology supports the general interest in problems of laser dynamics as fixed frequency bands

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are of high and low intensity in addition to generating giant pulses that are in great demand for modern medicine, electronics, military equipment, and data processing systems [14]. Optical feedback is defined as the return of a portion of the laser output to its emission zone in the active region [15].

In (2012), Uchida and co-workers studied a scheme of reverse feeding systems for semiconductor lasers and the effects of reverse feeding on the short and long outer bore, coherent interactivity, and non-coherent interactions [16]. In the same year, B. A. Ghalib and co-workers presented an analytical study on the properties of inclusion in Nanoi quantum dot semiconductor lasers operating under the influence of visual feedback [17]. In 2018, the path of a sudden change in the phenomenon of the chaos of semiconductor lasers under the influence of feedback was studied by Wish and co-workers; their study proved that the semi-periodic path, when increasing the electrical current depends on the external cavity, works to fix both the frequency, intensity, voltage difference, and the distance between the optical [18] In the same year Zhao the recognition under different feedback coefficients [19]. In 2019 Shoma Ohara and co-workers conducted a numerical study of the synchronization dependent on the kinetics of two interconnected semiconductor lasers with asymmetric feedback [20]. In 2019, the researcher, Rajaa, studied the photoelectric feeding method at different delay times, demonstrating that the strength of the reverse feed needs to be known to determine regions of stability areas and instability [21].

2. Rate equation for a Quantum Dot Laser:

In QD semiconductor devices, the carriers are first injected into a wetting layer before being captured in a dot at a capture rate that depends strongly on the dot population. The rate equations method includes a set of at least three coupled equations; the carrier density (N), photon density (E), and the occupation probability (ρ). These are given in equations (1-3) below [22]. For rate equations that commonly describe carrier dynamics of QD materials see Ref. [23].

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

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

$$\frac{dN_{(T,R)}}{dt} = J_{(T,R)} - \frac{N_{(T,R)}}{t_d} - 2n_d\, CN^2_{(T,R)}(1 - \rho_{(T,R)}) \quad (4)$$

where N$^{(T,R)}$ is the carrier density in the well for the transmitter and receiver lasers, E$^{(T,R)}$ is the complex amplitude of the electric field for the transmitter and receiver lasers, $\rho_{(T,R)}$ is the occupation probability in a dot for transmitter and receiver lasers,; t_s is the photon lifetime; t_n and td are the carrier lifetime in the well and the dot, respectively; N_d is the two-dimensional density of the dots; and $J_{(T,R)}$ is the pump. γ and τ describe the feedback level and delay time, where τ = 2L/c is the round trip time of light within the external cavity (of length L) and c is the velocity of light [15]. C is Auger carrier capture rate [22].

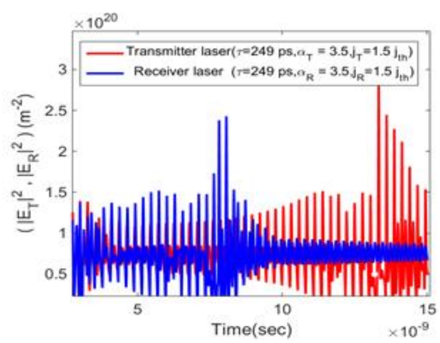
Table 1. Parameters used in the calculation for QDSEL [22].

Definition	Symbol	Value	Units
Photon lifetime	ts	3.4	ps
Carrier lifetime in well	t_n	1	ns
Electronic charge	q	1.6 x10^{-19}	C
Carrier lifetime in dot	t_d	1	ns
Linewidth enhancement factor	α	2 , 4	-
Velocity of light	c	3 x10^{8}	m/sec
Spontaneous recombination factor	β	3 x10^{-5}	-
Group velocity	v_g	7.14 x10^{9}	cm/s
Confinement factor	Γ	0.03	-
Photon decay rate	γ_p	5 x10^{11}	Sec^{-1}
Number of carriers at transparency	N_{tr}	1.8 x10^{18}	cm^{-3}
Effective gain factor	g_0	0.414*10^{-16}	
Density of Quantum Dot	N_d	2*10^{14}	cm^{-3}

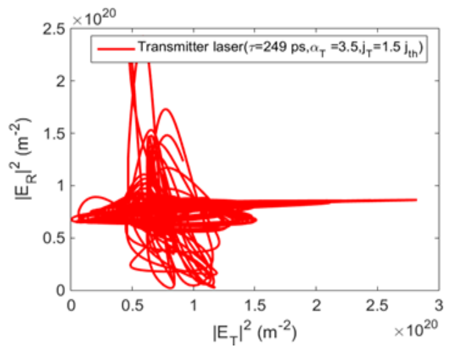
In this work we theoretically analyse a closed -loop system consisting of two types of synchronization as complete and general for transmitter and receiver quantum dot semiconductor lasers with optical feedback.

3. Results and discussion

We find the density of photons that reaches the value (2.79×10^{20}) at the time of (13.33×10^{-9}), while the lowest value of them was (1.26×10^{20}) at the time of (12.2×10^{-9}), then it stabilizes and becomes semi-cyclic.



(a)



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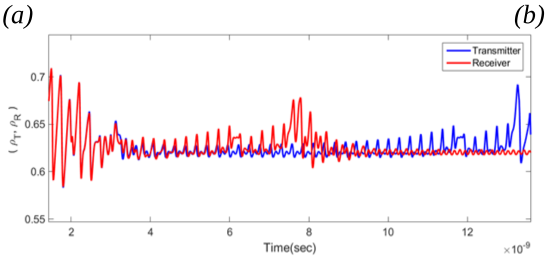


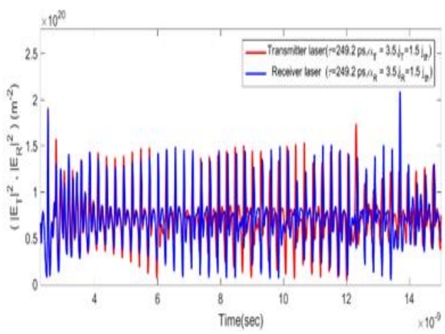
(c)

Fig. 1 (a),(b) The relationship between the photon density of two lasers (QDSL) with time and synchronization between the transmitter and receiver lasers when $\alpha_{T,R} = 3.5$ *and at* $J_{T,R} = 1.5J_{th}$ *and the delay time* $\tau = 249ps$ *,*

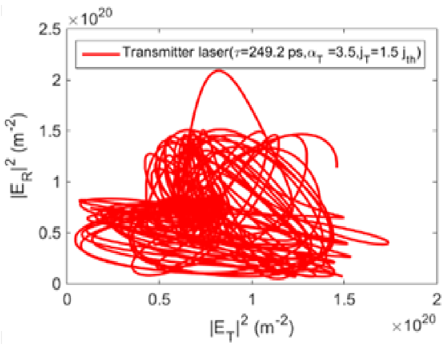
(c) represents the probability relationship between the two lasers where the charge carriers over time is established by both the delay time and current density.

In Fig. 1(b) we find chaos clear and this is important in communication. We also find general synchronization. From the relationship of probability of fullness with time, it is very important to know the accuracy and work of the mathematical model of average equations, and here it becomes clear that the value of the probability of filling does not exceed one and reaches a value (0.83) and stabilizes at (0.62).

It is clear from the figure below that the density of photons fluctuates and its highest value reaches (17.8×10^{20}) at a time (1×10^{-9}) and then this value decreases until it reaches approximately (13.1×10^{20}) and continues with this value for a long time, i.e. it becomes semi-stable. While (b-2) is a chaotic form of chaos. Whereas the probability of filling reaches its highest value is (0.83) and begins to settle in order to reach (0.63).



(a)



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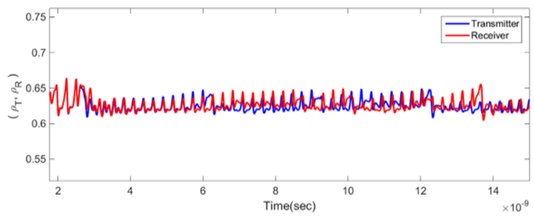


(c)

Fig. 2 (a),(b) The relationship between the photons density of two lasers (QDSL) with time and the synchronization between the transmitter and receiver lasers at $J_{T,R} = 1.5J_{th}, \alpha_{T,R} = 3.5$ *and*

$$\tau_{T,R} = 249.2ps$$

(c) The relationship between the probability of filling with time to the same value of the current density and a factor to enhance the line width.

In the figure below, the density of photons reaches (2.3×10^{20}) and then decreases to reach (1.2×10^{20}) they are unstable oscillatory and that the synchronization is between two lasers in general. In Fig. (c-3) the laser output is stable, and this is due to the possibility of filling and the number of charge carriers also stable.

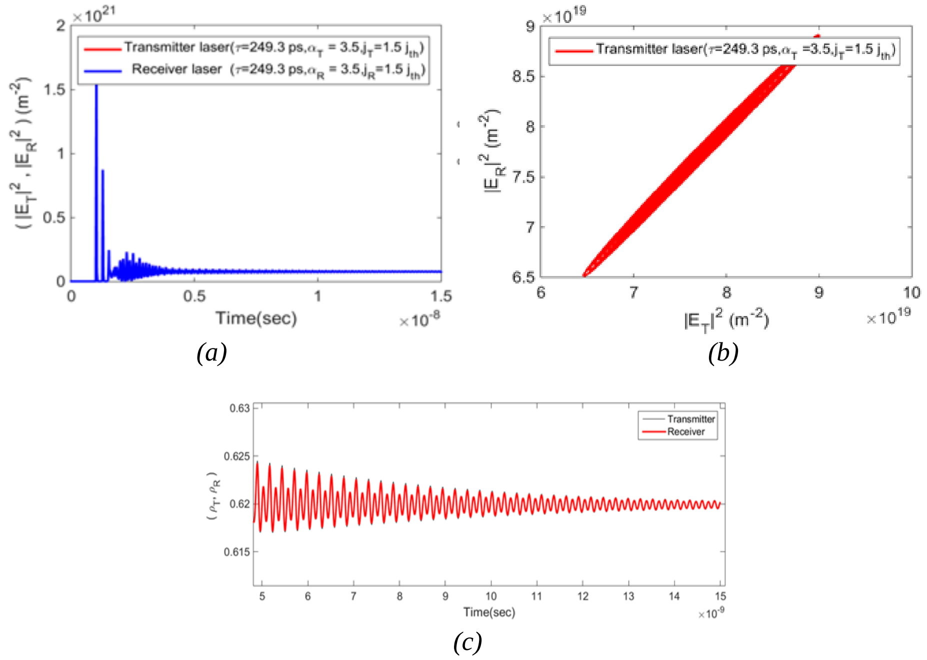


Fig.3 (a),(b) The relationship between the photon density of lasers (QDSL) with time and the synchronization between the transmitter and receiver lasers when $J_{T,R} = 1.5J_{th}, \alpha = 3.5$ *and*

$\tau = 249.3ps$.

(c) represents the probability of filling at the same value of the threshold current and the line-width enhancement factor.

In figure 4, we note that the highest value of the density of photons Fig.4(a) is (2.4×10^{20}) begins to settle and decreases to reach ($1.40\times10^{20}m^{-2}$) and then stabilizes, while synchronization as shown in Fig. 4 (b) is a general synchronization, that is, there is no complete synchronization here. The probability of filling reaches (0.83) while decreasing to reach (0.63) and then begins to settle, and this is evident in Fig.4 (c).

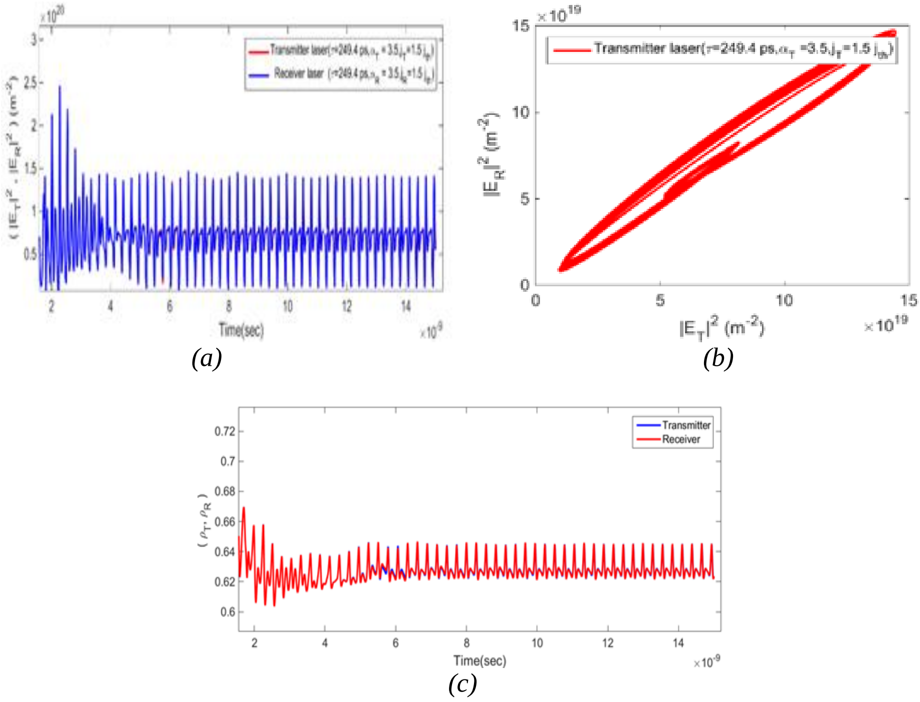
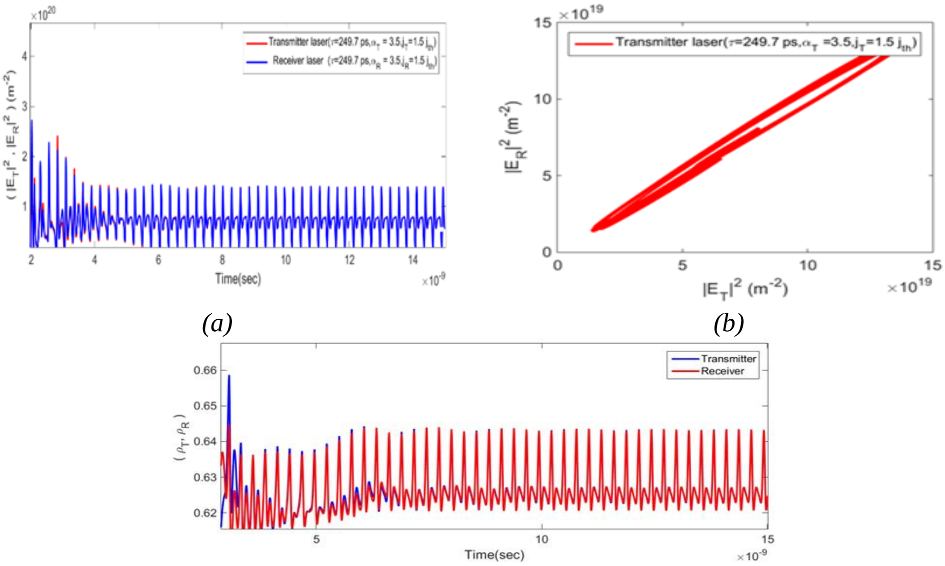


Fig. 4 (a),(b) The relationship between the photon density with the time and the synchronization between the two lasers when $J_{T,R} = 1.5J_{th}, \alpha = 3.5$ *at* $\tau = 249.4ps$
(c) The relationship between the probability of filling the charge carriers over time with the confirmation of each $J_{T,R}, \alpha, \tau$ *.*

We notice in Fig. 5(a) that the density of photons reaches (17.8×10^{20}), while when the part is enlarged, we find it reaches (2.7×10^{20}) and settles at the value (1.3×10^{20}), and the stability form appears clearly. While the synchronization from what is periodically as in Fig. 5 (b) when increasing the delay time by ($\Delta\tau = 0.1ps$) we find that the density of photons increases in the previous figure by the current by (0.1).Whereas a general semi-cyclic synchronization appears in Fig.5 (b) in the probability of filling, it is almost stable constant at its highest value (0.83). After enlarging a portion of the curve, we find that the highest value of the sphere (0.63).



(a) *(b)*

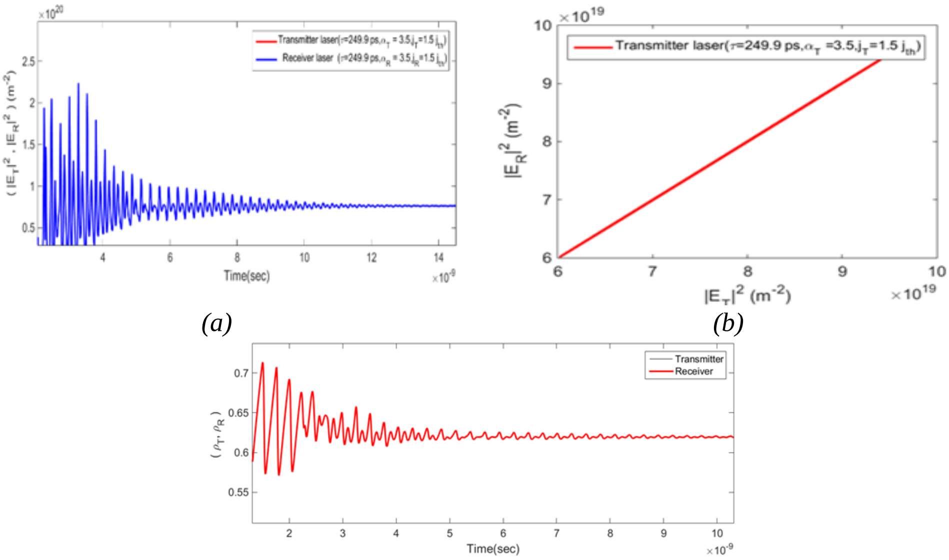
(c)

Fig. 5 (a),(b) Relationship between the laser photons density (QDSL) with time and the synchronization between the transmitter and receiver lasers when $J_{T,R} = 1.5 J_{th}, \alpha = 3.5$ *and*

$\tau_{T,R} = 249.7$.

(c) The relationship between the probability of filling the charge carriers over time with a constant $J_{T,R}, \alpha, \tau$.

Fig. 6(a) shows the density of photons for the two-point semiconductor lasers as a function of time. The highest value of the photon density is)17.8×10^{20}.(It then decreases to 2.02×10^{20} and the beginning is fluctuating, then it stabilizes and the synchronization is a complete synchronization as in (b). The probability takes the highest value (0.71) and is of periodic oscillating shape and then begins to stabilize, meaning there is no disturbance.



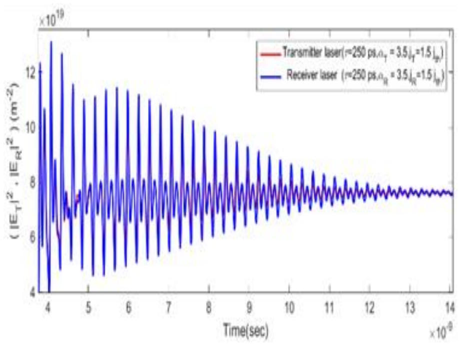
(a) *(b)*

(c)

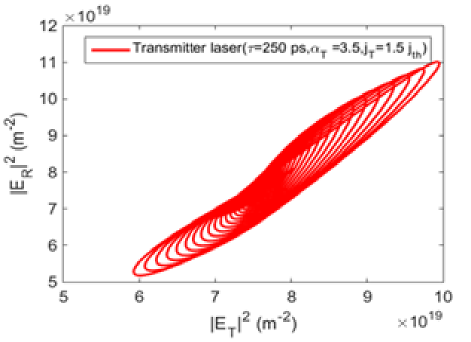
Fig. 6 (a),(b) The relationship between the photons density of two lasers (QDSL) with time and synchronization between the transmitter and receiver at $J_{T,R} = 1.5 J_{th}, \alpha = 3.5$ *and* $\tau_{T,R} = 249.9$.

(c) the relationship between the probability of filling the charge carriers over time with the stability of $J_{T,R}, \alpha, \tau_{T,R}$.

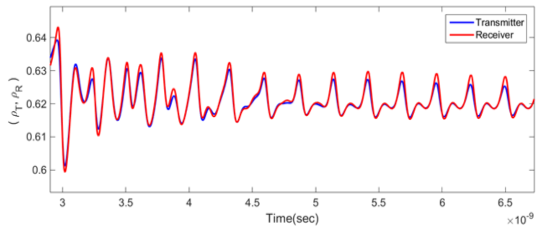
In Fig. 7(a), the density of photons reaches (17.8×10^{20}) and stabilizes at the value (1.2×10^{20}), and the general and periodic synchronization is stable.



(a)



(b)



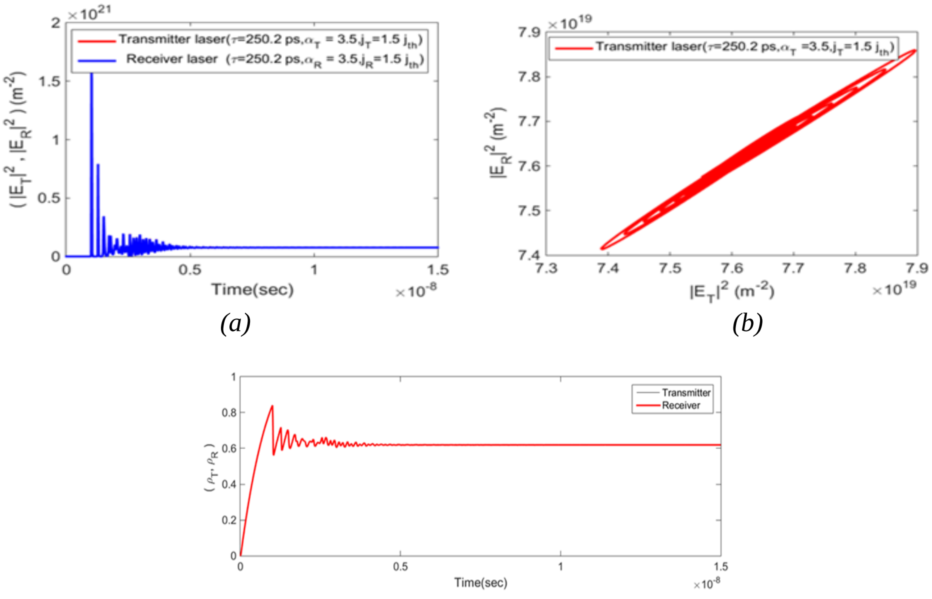
(c)

Fig. 7 (a),(b) The relationship between the laser photons density (QDSL) with time and the synchronization between the transmitter and receiver when $J_{T,R}=1.5J_{th,}\alpha=3.5$ *and* $\tau_{T,R}=250ps$ *.*

(c) shows the probability of filling in time with both lasers with a constant $J_{T,R},\alpha,\tau_{T,R}$ *.*

This is similar to the form Fig. 2(a) and Fig. 6(a), but when enlarging a portion of it, we notice that the density value reaches the highest value at (13.1×10^{20}), and then it decreases to reach (7.5×10^{20}) and exhibits the same stable cyclic behaviour. In the figure for probability, we find its highest value (0.83), and when the part of it is enlarged, it is the highest value (0.643).

In Fig. 8 (a), the density of photons reaches 17.7×10^{20} and is very close to the result in Fig.2(a), Fig.6(a) and Fig 7(a). This then decreases to 0.9×10^{20} and settles. Synchronicity is almost complete, which is useful for studying inclusion. The probability portion has the same value as in the previous figures and the current shape, and it settles at the same values as in the previous forms, namely 0.63.



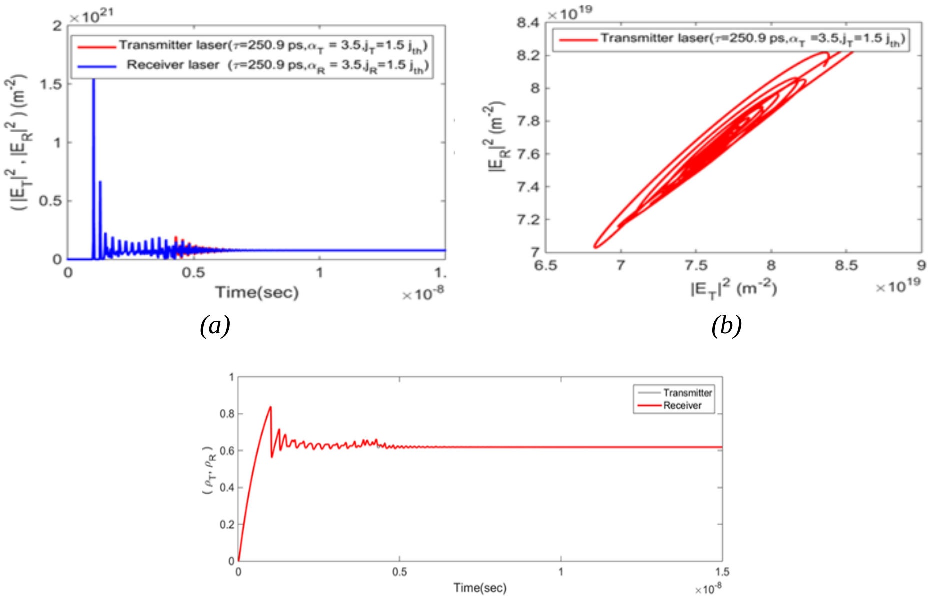
(a) (b)

(c)

Fig. 8 (a),(b) The relationship between the photons density of two lasers (QDSL) with time and synchronization when $J_{T,R} = 1.5 J_{th,} \alpha = 3.5$ *and* $\tau_{T,R} = 250.2 ps$.

(c) The probability of filling in time with both lasers with a constant $J_{T,R}, \alpha, \tau_{T,R}$.

The density of photons reaches 17.8×10^{20} and is similar to the previous forms. The type of synchronization is complete. Also, the probability of filling takes the same values as the previous figures in relation to the highest value.



(a) (b)

(c)

Fig. 9(a),(b) Relationship between the photons density of two lasers (QDSL) with time and the synchronization when $J_{T,R} = 1.5 J_{th,}, \alpha = 3.5$ *and* $\tau_{T,R} = 250.9 ps$.

(c) Probability of filling in time with both lasers with a constant ($J_{T,R}, \alpha, \tau_{T,R}$ *).*

Table. 2 The table shows the delay and synchronization time values.

Time delay	Photon density	Type of synchronization
249	Chaotic	No synchronization
249.2	Different quasi periodic	No synchronization
249.3	Chaotic	General
249.4	Quasi-periodic	General
249.6	periodic	General
249.7	periodic	general
249.9	Semi-stable	Compact
250	Multi –periotic	Multi
250.2	Multi-period	Multi general
250.3	Chaotic	complete
250.9	chaotic	No signal

4. Conclusion

When drawing the relationship between the photon density of the transmitting and receiving lasers and different values of delay times ($\tau_{T,R} = 249, 249.2, 249.3, 249.4, 249.5, 249.6, 249.7, 249.9, 250, 250.2, 250.9$) there appears an association between the output of the lasers and this is due to the choice of parameters that are completely similar in both lasers. As the relationship is a straight line that indicates the equality of the photon density values for the two lasers. As for the relationship with the probability of filling the charge carriers of both lasers, it is a random relationship resulting from the probability of filling which does not reach one. We also find two types of complete and general synchronization.

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