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# Effect Of Time Delay On The Synchronization In Quantum Cascade Lasers With Negative Optoelectronics Feedback

***Murtadha J. Edam, Hussein H. Waried[1]***

[1]*Physics Department, Sciences College, Thi-Qar University, Thi-Qar, Iraq.*

**Abstract:**

In this paper, synchronization is theoretically investigated in two quantum cascade semiconductor lasers coupled with delayed negative optoelectronic feedback under effect of time delay. Synchronization quality and the influence of times delay mismatches on synchronization performances are investigated. The results indicate that the complete synchronization can be realized under suitable system parameters. Such as, the delay time of the transmitter, the delay time of the receiver, and transmission time have a significant impact on the synchronization quality. Calculations indicate that the correlation coefficient can be enhanced by similar delay times.

**Keywords:** Quantum Cascade lasers, Synchronization, delay time, negative optoelectronic feedback.

**Introduction**

Since 1990, when chaos synchronization (CS) was achieved for first time, the CS was a widely investigated topic of research due to its importance in many potential applications including spread spectrum communications and secure communications [1]. In CS between two nonlinear systems, an output from one of the variables as a subsystem in a transmitter is sent to a receiver. This may lead to chaotic synchronization between the transmitter and receiver systems. One of the most well-known examples of chaotic laser system is a semiconductor laser subjected to optical feedback, optoelectronic feedback [2-16], or optical injection [17]. The generated chaotic signal from semiconductor lasers found potential applications in feedback interferometer, secure high-speed long distance communication, optical frequency conversion, and laser chaos based light detection and ranging (LiDAR) [18].

Quantum Cascade Lasers (QCLs) are semiconductor devices capable of emitting radiation in the frequency ranges 1-5 THz and 15-100 THz, respectively [19, 20]. It was invented and first demonstrated in 1994 to by [16] provide compact mid-infrared sources. In contrast to bipolar semiconductor lasers, the light emission takes place due to intersubband optical transitions entirely within the conduction band between quantized states in heterostructure quantum well (QW). Compared to conventional (interband) lasers, QCLs has the following advantages: First, the photon energy that results from an intersubband transition is not dependent on the band gap of a combination of materials in the active region but can be tuned by tailoring the QW thickness. Second, QCLs are designed based on the multistage cascade scheme, allowing one charge carrier leads to the generation of multiple photons, this leads to a high quantum efficiency and therefore very high optical output power since both photon number and carrier number are proportional to stages number. Finally, the Kramers-Kronig transformations dictate that the linewidth enhancement factor (LEF) in an intersubband laser should be much smaller than that of an interband diode laser [19]. Therefore, the ultrafast carrier dynamics and a small LEF have a significant impact on QCLs performance. Their compactness and high performances at room temperature make QCLs privileged sources for applications such as gas spectroscopy, free-space communications or optical countermeasures.

Optoelectronic feedback is one of the perturbations to the injection current that induces instabilities [18]. In contrast with optical feedback, in which the phase sensitivity plays a crucial role in the laser dynamics, one does not need to consider the phase effect in optoelectronic feedback systems where the phase information is once eliminated by a photodetection in the feedback process. There are two categories of optoelectronic feedback, one is positive feedback and the other negative feedback. In negative feedback, the feedback current is deducted from the bias injection current and it induces the sharpening of the relaxation frequency [17]. One of the main causes of laser instability is the amplification of the relaxation frequency under increasing feedback power under the absence of an intrinsic system resonance at the relaxation frequency. Although the dynamics of QCL, either free running or subject to an external optical injection, have been investigated but the characteristics of coupled semiconductor QCLs has received less attention [21-23]. In this study, a theoretical investigation of the synchronization in two coupled QCLs with optoelectronic feedback is presented. Synchronization quality and the influence of times delay mismatches on synchronization are investigated. This paper is organized as follows, system modeling is given in section two. Numerical results are presented in section three. Finally, section four summarizes the main conclusions.

**I. QCLs model**

Fig.1 shows a schematic diagram for a two coupled QCLs implemented with unidirectional optoelectronic coupling [24]. The dashed and solid lines in the figure indicate the electronic paths and the optical paths, respectively. In this setup, the transmitter laser has a negative optoelectronic feedback loop that drives the laser into chaotic pulsing at certain delay times. The feedback may be positive or negative depending on the polarity of the output of the amplifier in the circuit. A beam splitter (BS) is introduced to divide the output of transmitter QCL into two parts. A part of the emitted light from the TQCL is detected by photodetector PD1 and electronically fed back into the bias injection current of the laser taken a time delay $\tau_T$ . On the other hand, the other part of the emitters light is detected by photodetector PD2 and fed into the bias injection current of receiver QCL after a transmission time $\tau_c$. Similarly, RQCL also has an optoelectronic feedback loop with delay time $\tau_R$. At the receiver, the coupled signal from the transmitter, together with the optoelectronic feedback signal from the receiver, are used to drive and synchronize the receiver laser, thus unidirectional coupling of the system is attained

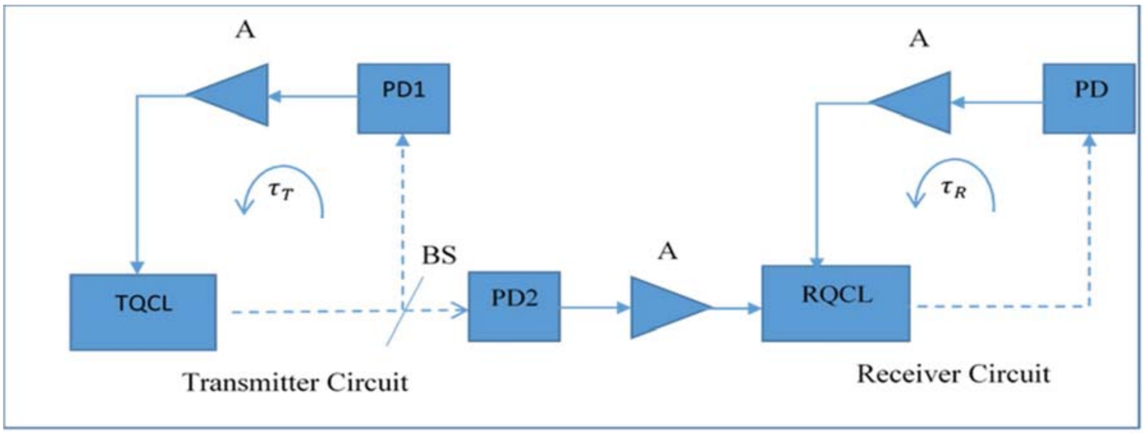


**Fig. 1. Schematic setup of synchronization system** based on optoelectronic negative feedback chaotic quantum cascade lasers. TQCL transmitter laser RQCL: receiver laser; BS: beam splitter; PD: photodetector; A: amplifier [24].

For above proposed scheme and after taking into account the optoelectronic negative feedback for TQCL and the injection from TQCL to RQCL, the model for the two coupled lasers can be expresses by the following rate equation [24-26],

$$\frac{dN_{3,T}}{dt} = \eta\frac{I_{in}}{q}\left(1+\frac{\zeta_T S_T(t-\tau_T) - S_{off,T}}{S_{s,T}}\right) - \frac{N_{3,T}}{\tau_{32}} - \frac{N_{3,T}}{\tau_{31}} - G(N_{3,T}-N_{2,T})S_T \quad (1)$$

$$\frac{dN_{3,R}}{dt} = \eta\frac{I_{in}}{q}\left(1+\frac{\zeta_R S_R(t-\tau_R) + \zeta_{CP} S_T(t-\tau_C) - S_{off,R}}{S_{s,R}}\right) - \frac{N_{3,R}}{\tau_{32}} - \frac{N_{3,R}}{\tau_{31}} - G(N_{3,R}-N_{2,R})S_R \quad (2)$$

$$\frac{dN_{2,T,R}}{dt} = \frac{N_{3,T,R}}{\tau_{32}} - \frac{N_{2,T,R}}{\tau_{21}} + G(N_{3,T,R}-N_{2,T,R})S_{T,R} \quad (3)$$

$$\frac{dN_{1,T,R}}{dt} = \frac{N_{3,T,R}}{\tau_{31}} + \frac{N_{2,T,R}}{\tau_{21}} - \frac{N_{1,T,R}}{\tau_{out}} \quad (4)$$

$$\frac{dS_{T,R}}{dt} = ZG(N_{3,T,R} - N_{2,T,R})S_{T,R} - \frac{S_{T,R}}{\tau_p} + \frac{\beta N_{3,T,R}S_{T,R}}{\tau_{32}} + \frac{\beta N_{3,T,R}S_{T,R}}{\tau_{31}} + ZG N_{3,T,R}S_{T,R} \quad (5)$$

The subscripts T and R stand for TQCL and RQCL, respectively. Here I is the pump current, $N_{3,2,1}$ is the carrier numbers in levels 3, 2, 1 respectively, η is the injection efficiency of input current into active region, q is the electron charge, $\tau_p$ is the photon lifetime, S is the photon numbers,G is the gain coefficient ,Z is the number of QCL gain stages, The carrier lifetime of the upper laser level $\tau_{out}$ is the tunneling time of carriers out of level 1 into the subsequent miniband , β is the spontaneous emission factor. $\tau_{31}$, $\tau_{32}$ and $\tau_{21}$ are the phonon scattering times between level 3 and level 1 between level 3 and level 2, and between level 2 and level 1 respectively. Further, $S_{off}$ is the constant offset in the feedback loop, $\zeta_T$ is the coefficient of the transmitter optoelectronic feedback circuit, $\zeta_R$ is the coefficient of the receiver optoelectronic feedback circuit, $\zeta_{CP}$ is the coupling coefficient from the T to the R lasers. $S_s$ is the steady-state value for the photon number. For simplification, the noise factor has been ignored in this model. As in [26], the coupling strength, $c_p$ is introduced to deal with a closed-loop or an open-loop system. The parameter $c_p$ is defined by [24]

$$c_p = 1 - \frac{\zeta_R}{\zeta_{CP} + \zeta_T} \quad (6)$$

After neglecting the nonlinearity effects, the saturation photon density $S_s$ and the threshold injection current $I_{th}$ can be written as [25]:

$$S_s = \frac{1}{\tau_e G(1+\gamma)}\left(\frac{I}{I_{th}} - 1\right) \quad (7)$$

$$I_{th} = \frac{q}{\eta \tau_e \tau_p G(1+\gamma)(1-\delta)} \quad (8)$$

Here $\gamma = \tau_{21}/\tau_{31}$ and $\delta = \tau_{21}/\tau_e(1+\gamma)$, $\tau_e = \tau_{32}^{-1} + \tau_{31}^{-1}$ is the carrier lifetime of the upper laser level. Equations 1-5 were solved numerically to study the dynamics of the carrier densities and photon densities in the T and R lasers. To characterize the quality of synchronization quantitatively, we define a correlation coefficient ρ is used [26]

$$\rho = \frac{\langle [S_T(t) - \langle S_T(t)\rangle][S_R(t) - \langle S_R(t)\rangle]\rangle}{\langle |S_T(t) - \langle S_T(t)\rangle|^2\rangle^{1/2} \langle |S_R(t) - \langle S_R(t)\rangle|^2\rangle^{1/2}} \quad (9)$$

## II. Results and Discussions

To the best of our knowledge, this is the first study to detail the synchronization of unidirectional coupled quantum cascade lasers. The principal target of the simulation is to study the synchronization behavior of coupled quantum cascade lasers giving attention to the role played by the times delay. The results presented here have been evaluated using the rate equations (1) – (9) and the dynamics of the lasers is analyzed for the device parameters in Table I. In [21], similar variation properties among TQCL, and RQCL can be observed, which reveals that the system can realize synchronization. According to [21], the two lasers synchronize with $c_p = 1$ and $\tau_T = \tau_R = \tau_C = 6\,ps$.

**Table1: Parameter values used for synchronization calculations [24].**

| Symbol | Value | Unit |
|---|---|---|
| η | 0.4 | --- |
| β | $10^{-5}$ | --- |
| G | $1.2\times10^{5}$ | $s^{-1}$ |
| $\tau_p$ | 9.77 | ps |
| $\tau_{32}$ | 2.1 | ps |
| $\tau_{31}$ | 2.6 | ps |
| $\tau_{21}$ | 0.3 | ps |
| $\tau_{out}$ | 0.5 | ps |

Fig. (2) shows the variation of the number of carrier in the transmitter laser as a function of the number of photon in the transmitter laser and Fig. (3) shows the variation of the number of carrier in the receiver laser as a function of the number of photon in the receiver laser. The variation of the number of photon in the receiver laser as a function of the variation the number of photons in the transmitted laser is shown in Fig (4) when $\tau_T = 7ps, \tau_R = 6\,ps$ and $\tau_C = 6\,ps$.

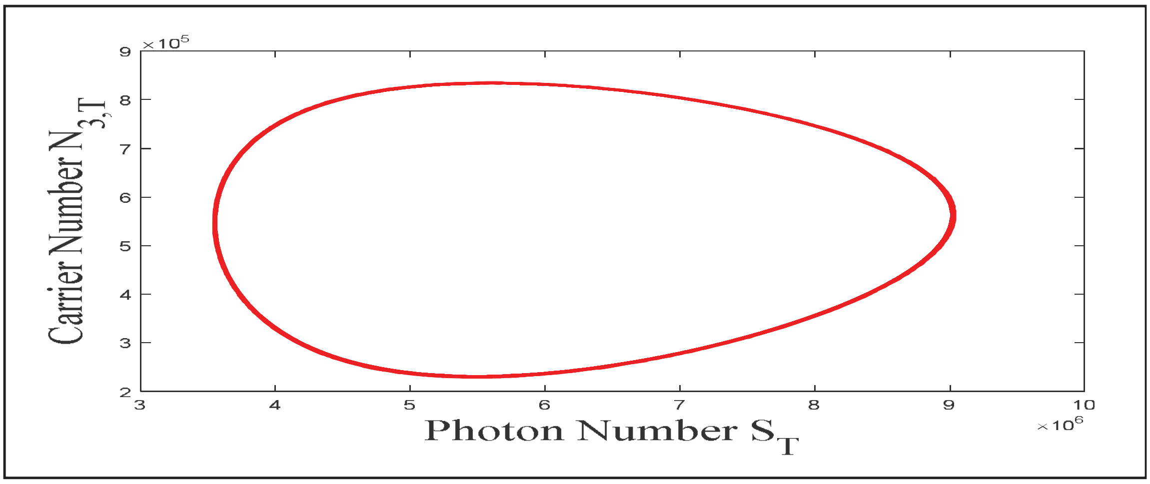


**Fig. 2.** The variation of the number of carriers in the transmitter laser as a function of the variation of number of photons in the transmitter laser when $\tau_T = 7ps, \tau_R = 6\,ps\ \tau_C = 6\,ps$ and ρ = 0.8383

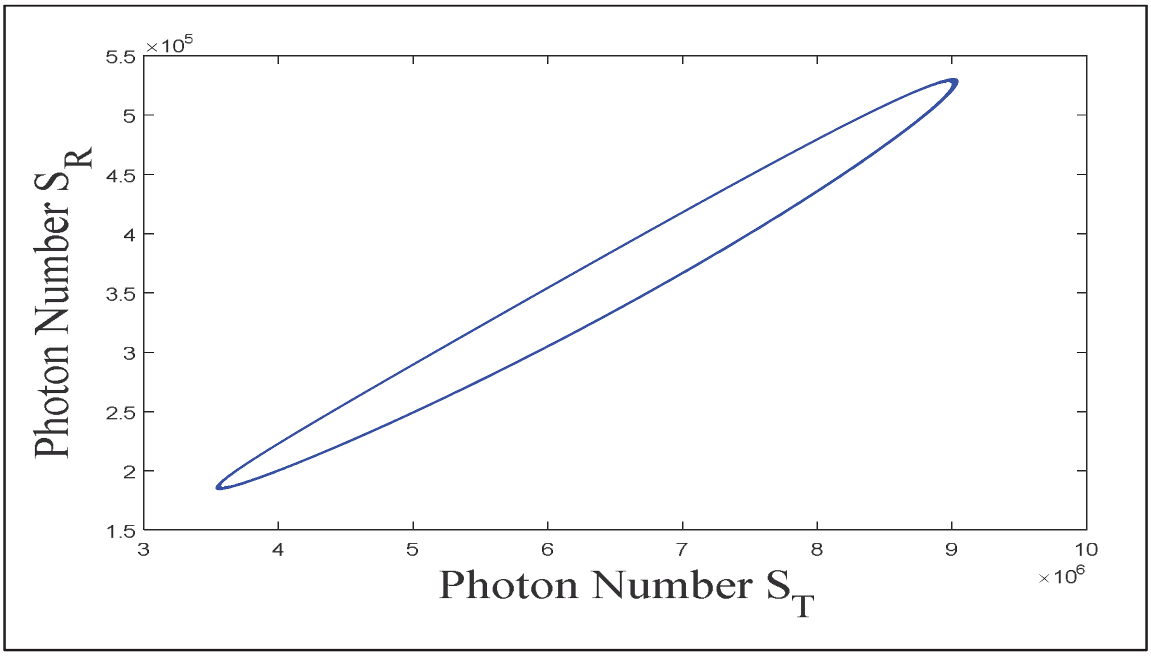


**Fig. 3.** The variation of the number of carriers in the receiver laser as a function of the variation of the number of photons in the receiver laser when $\tau_T = 7ps, \tau_R = 6\ ps\ \tau_C = 6\ ps$ and ρ = 0.8383.

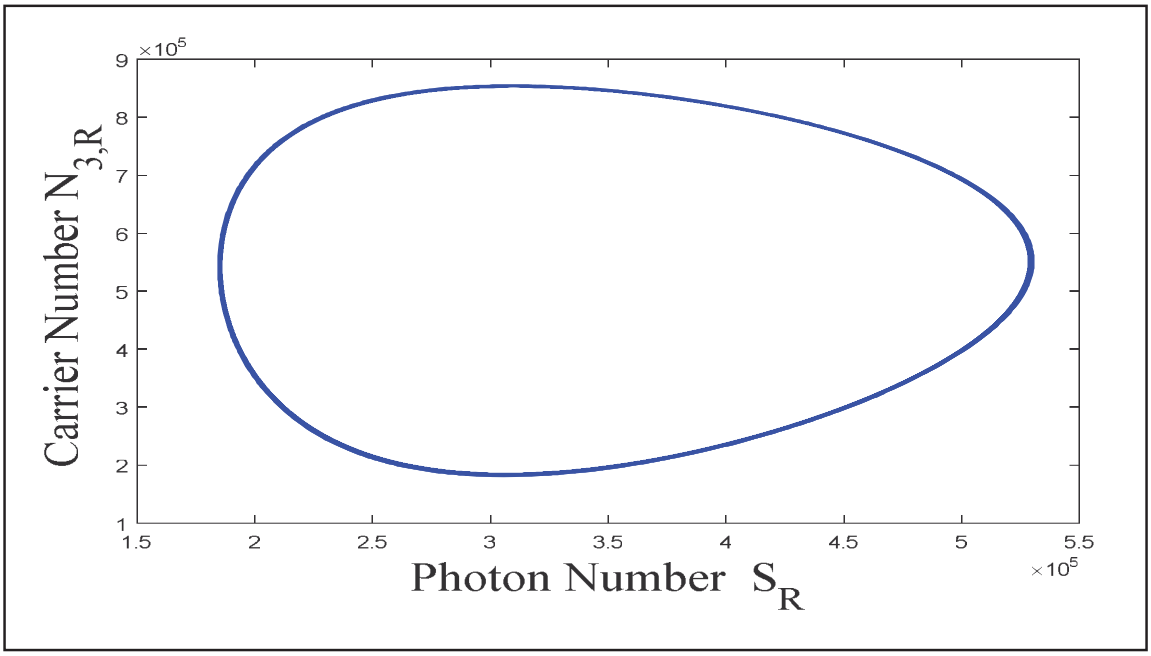


**Fig. 4.** The variation of the number of photons in the receiver laser as a function of the variation of the number of photons in the transmitted laser when $\tau_T = 7ps, \tau_R = 6\ ps\ \tau_C = 6\ ps$ and ρ = 0.8383.

According to the present results, we note that there is a significant variation in the value of ρ where the value changed from ρ =1 to ρ = 0.8383 when the feedback delay time in transmitter laser changed to 7 ps. Fig. (6) shows the variation of the number of carrier in the transmitter laser as a function of the number of photon in the transmitter laser and Fig. (7) shows the variation of the number of carrier in the receiver laser as a function of the number of photon in the receiver laser. The variation of the number of photon in the receiver laser as a function of the variation the number of photons in the transmitted laser is shown in Fig (8) when $\tau_T = 6\,ps, \tau_R = 7\,ps, \tau_C = 6\,ps$ and ρ=0.9964. It is clear that, the decreasing in the correlation coefficient is very small. This is because the coupling strength, $c_p$. When the coupling strength is larger than zero (0) means closed-loop configuration and 1 means open-loop configuration) then the effect of the difference in time delay between the receiver circuit and the transmitter circuit is very weak, while for the same coupling strength when the difference in time delay between the transmitter circuit and receiver circuit is negative leads to deplete the carriers in receiver laser, therefore, the difference in the carrier number between two lasers is very small. This is the same behavior when the transmission time is larger than the time delay in the transmitter circuit and receiver circuit i.e. the difference between the time delay in the transmitter circuit and receiver circuit has small effect in comparison with the transmission time. High synchronization quality requires fast transmission time and short time delay in transmitter laser. The time series of photon number for transmitter and receiver laser are show in fig (5).

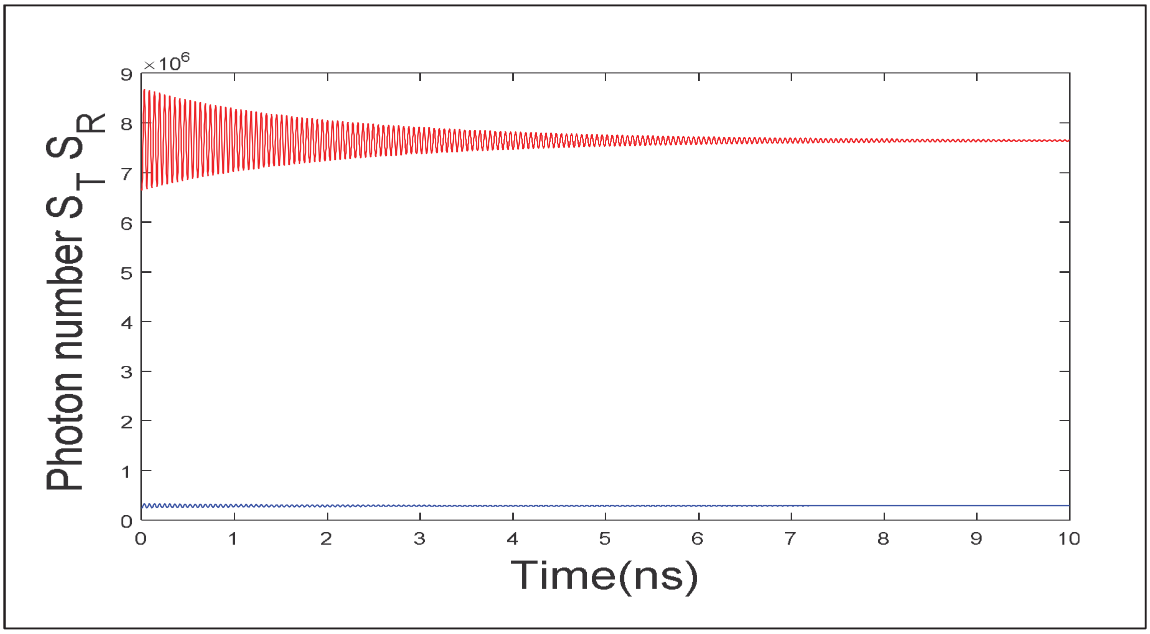


**Fig. 5.** Time variation of photon number for transmitter and receiver laser when $\tau_T = 6ps, \tau_R = 7\,ps$ $\tau_C = 6\,ps$ and ρ=0.9964.

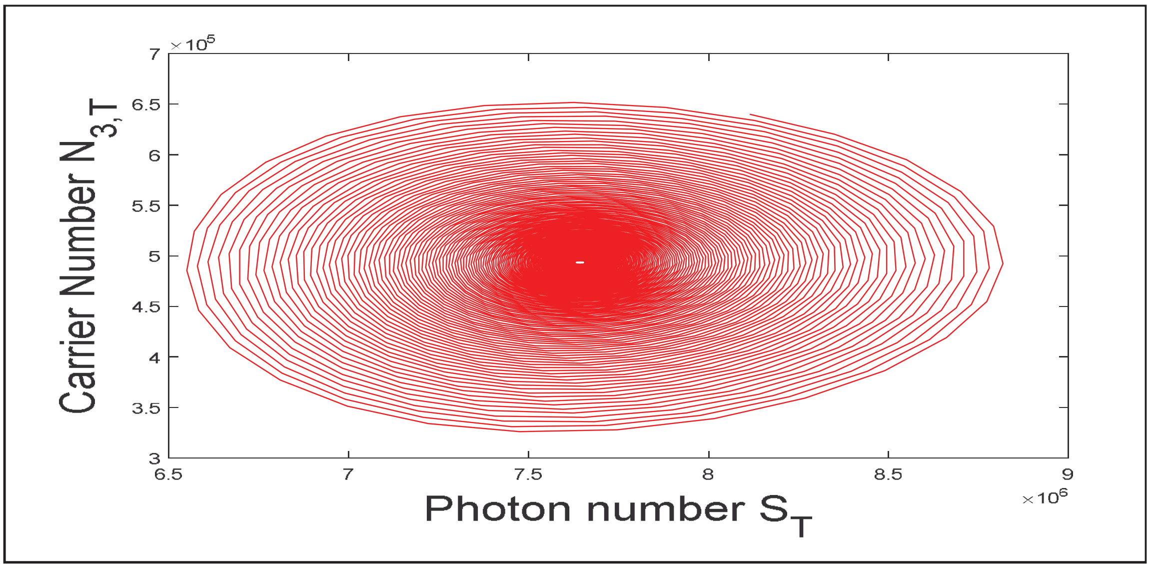


**Fig. 6.** The variation of the number of carriers in the receiver laser as a function of the variation of the number of photons in the receiver laser when $\tau_T = 6ps$, $\tau_R = 7\ ps$ $\tau_C = 6\ ps$ and ρ=0.9964.

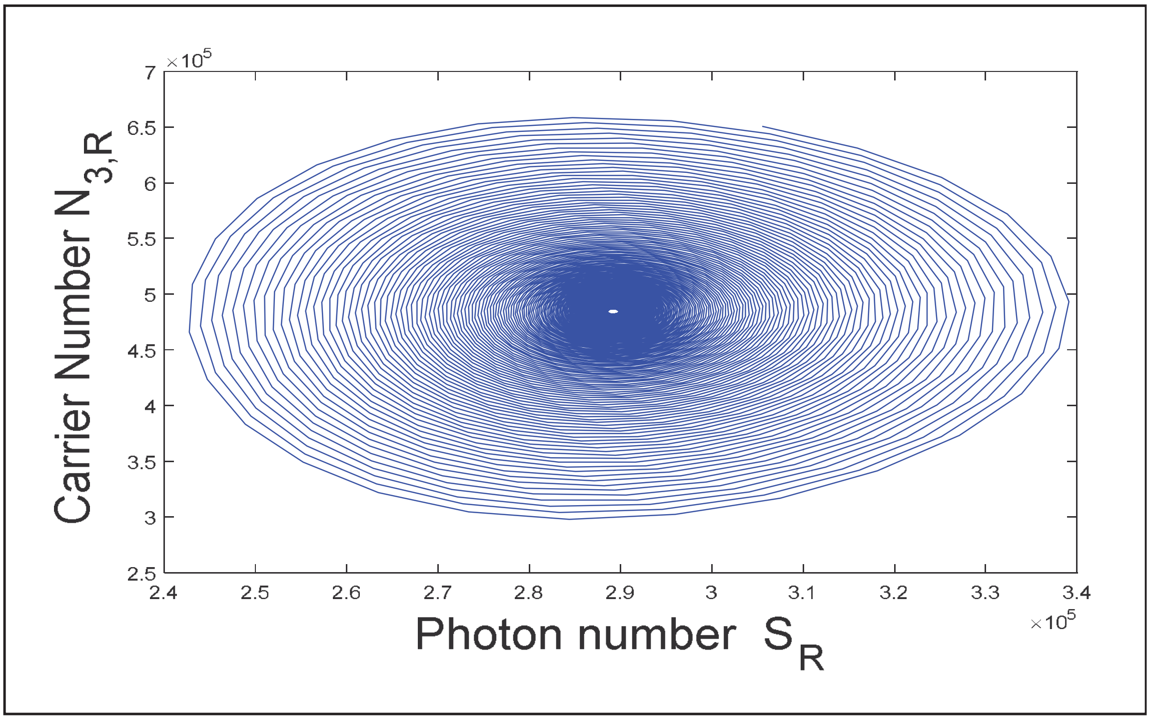


**Fig. 7.** The variation the number of carriers in the receiver laser as a function to variation the number of photons in the receiver laser when $\tau_T = 6\ ps$, $\tau_R = 7ps$, $\tau_C = 6\ ps$ and ρ=0.9964.

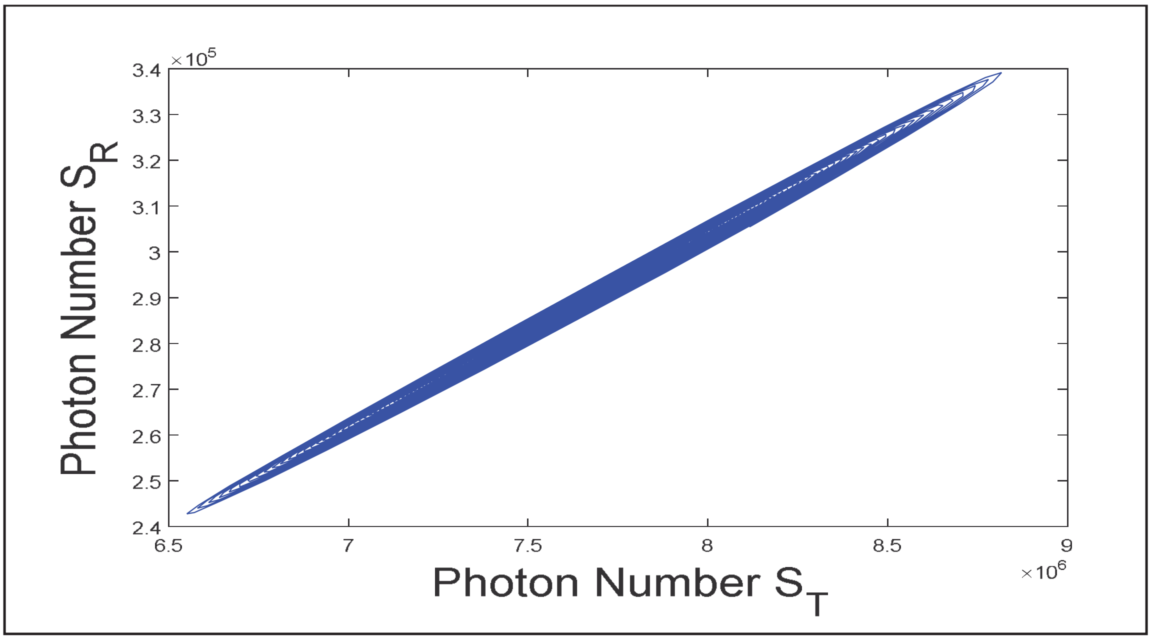


**Fig. 8.** variation the number of photons in the receiver laser as a function to variation the number of photons in the transmitted laser when $\tau_T = 6\,ps$, $\tau_R = 7\,ps$, $\tau_C = 6\,ps$ and ρ=0.9964.

Also, from Fig. 2 and Fig. 6 and on other hand Fig. 3 and Fig. 7, we can recognize two of two dynamic behaviors for photon number and carrier number in the two lasers. In the previous case the dynamic of photon number and carrier number indicates to the variation of carrier number and photon number between two fixed values while for the latter case the dynamic of photon number and carrier number takes damping behavior.

Fig. (9) shows the variation of the number of carrier in the transmitter laser as a function of the number of photon in the transmitter laser and Fig. (10) shows the variation of the number of carrier in the receiver laser as a function of the number of photon in the receiver laser. The variation of the number of photon in the receiver laser as a function of the variation the number of photons in the transmitted laser is shown in Fig (11) when $\tau_T = 6\,ps$, $\tau_R = 6\,ps$, $\tau_C = 7\,ps$ and ρ= 0.9598. As shown in figures, the results may be worse if the change in time delay is large enough. Therefore, the optimum selection of the times delays in receiver circuit, transmitter circuit and transmission time leads to full synchronization.

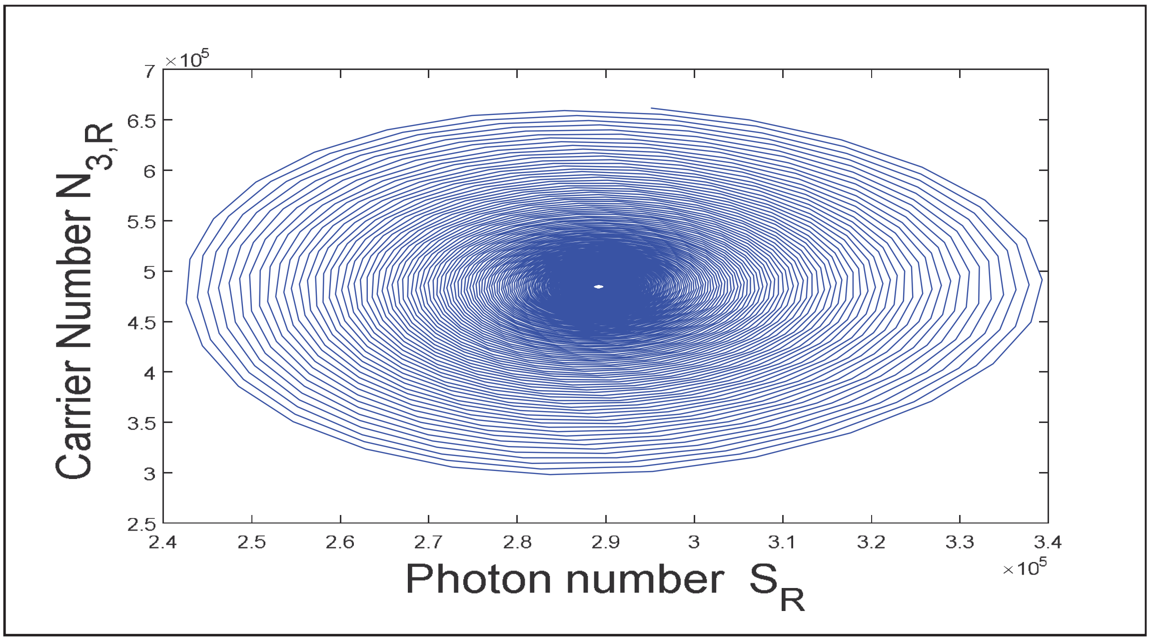


**Fig. 9.** The variation of the number of carriers in the receiver laser as a function of the variation of the number of photons in the receiver laser when $\tau_T = 6\,ps$, $\tau_R = 6\,ps$, $\tau_C = 7\,ps$ and ρ= 0.9598.

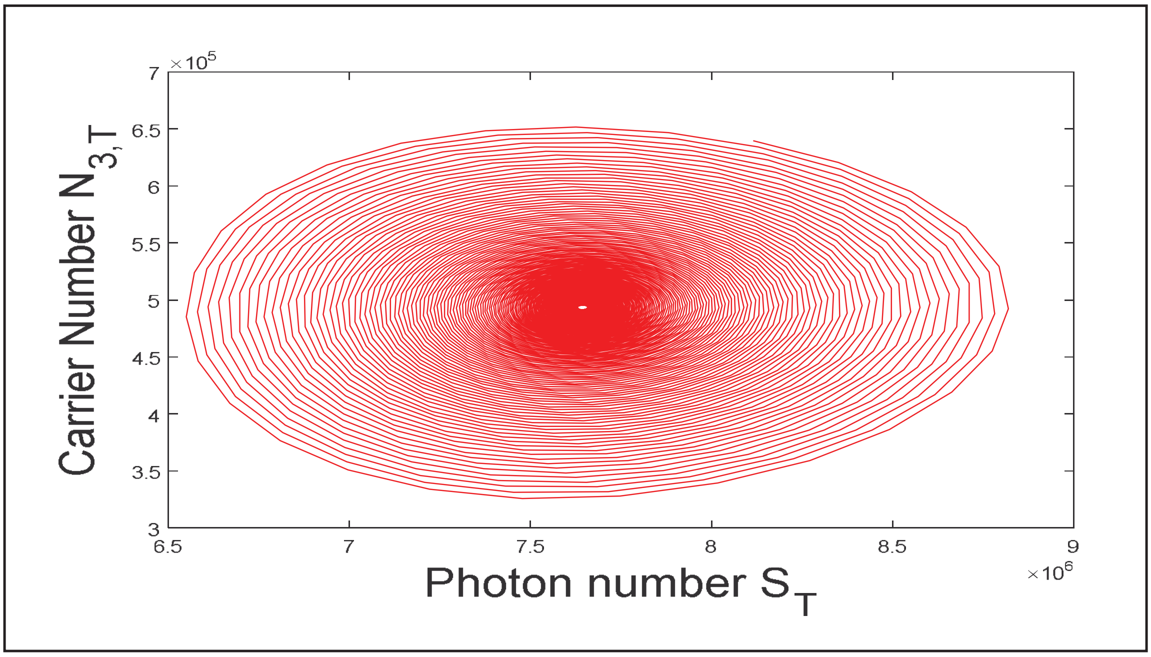


**Fig. 10.** The variation the number of carriers in the receiver laser as a function to variation the number of photons in the receiver laser when $\tau_T = 6\,ps$, $\tau_R = 6\,ps$, $\tau_C = 7\,ps$ and ρ= 0.9598.

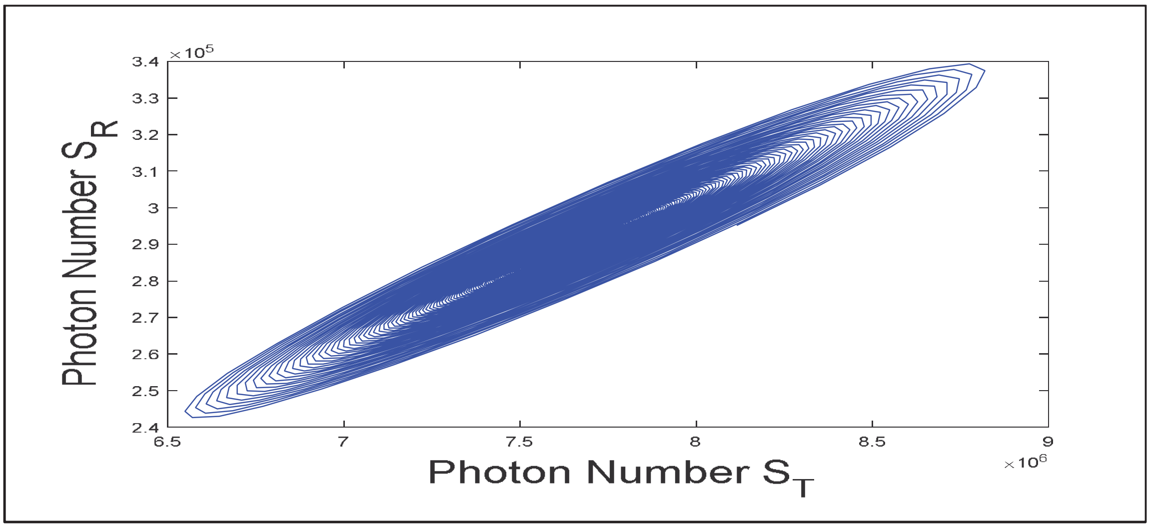


**Fig. 11.** variation the number of photons in the receiver laser as a function to variation the number of photons in the transmitted laser when $\tau_T = 6\ ps$, $\tau_R = 6\ ps$, $\tau_C = 7\ ps$ and ρ= 0.9598.

## III. CONCLUSIONS

In this study, synchronization of quantum cascade semiconductor lasers with optoelectronic negative feedback is presented. Synchronization in these lasers has been modeled by use of the rate equations model. It is found that the complete synchronization can be realized under suitable system parameters. Through numerically studying synchronization quality and the influence of parameter mismatches on synchronization, the delay time of the transmitter, the delay time of the receiver, and transmission time, have significant impact on the synchronization quality. Calculations indicate that correlation coefficient can be enhanced by similar delay times. The synchronization quality is sensitive to the mismatch in delay times has significant impact on the synchronization quality

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