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Article

Chaos Analysis and Its Application in Secure Optical Communication Using QCLs

Amer Yasir Makah[1], Prof. Dr. Hussein Hadi Waried [2]

1. Physics Department, Sciences College, Thi-Qar University, Thi-Qar, Iraq.
2. Physics Department, Sciences College, Thi-Qar University, Thi-Qar, Iraq.

* Correspondence: amer.yasser@utq.edu.iq

Abstract: : As secure data transmission becomes increasingly critical, traditional encryption methods face vulnerabilities with the rise of advanced computing. Chaos theory, particularly in laser dynamics, offers a promising physical-layer security alternative through the generation of complex, unpredictable signals. Quantum Cascade Lasers (QCLs), due to their operation in the mid-infrared and terahertz range, are highly suitable for chaos-based communication. Despite advances in semiconductor laser chaos synchronization, the practical use of QCLs for secure communication remains underexplored due to their unique intersubband transitions and complex dynamics under optical feedback. This study investigates chaotic synchronization in QCLs using optical feedback, modeling the dynamics of master-slave configurations through delay differential equations. Simulations show that synchronization is achievable with correlation coefficients above 0.7 across various feedback delay and reflection parameters. Synchronization is optimized when feedback and injection delays are matched, and higher reflection coefficients improve robustness. Unlike prior works on generic semiconductor lasers, this research presents a tailored model for QCL systems and validates the feasibility of chaos-based communication using specific QCL parameters. The findings establish that properly synchronized chaotic QCL systems can be effectively used for secure optical communication, reducing reliance on algorithmic encryption. This work supports future experimental development and deployment of secure, scalable, and adaptive QCL-based communication networks.

Keywords: Chaos, Secure Communication, Quantum Cascade Lasers, Optical Feedback, Synchronization

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1. Introduction

1.1 Research Background

The chaotic theory explains how very sensitive to their starting points dynamical systems behave. Because of the nonlinear interactions between photons and active media, laser systems might naturally display chaotic oscillations, according to 1970s research. A crucial method for inducing and controlling laser chaos is optical feedback, which involves reflecting back into the cavity some of the laser's output. A quantum cascade laser's (QCL) capacity to function in the terahertz and mid-infrared bands has piqued interest in the field of secure optical communication. Because of its small size, wide tunability, and high power, QCLs are ideal for creating the complicated chaotic signals that are necessary for concealing transmitted data [1].

1.2 Research Problem

Mathematical algorithms, the backbone of traditional encryption methods, are susceptible to new forms of computing power. Instead, systems based on chaos may make interception more difficult by encoding data in unexpected signals. It is still very difficult to get chaotic laser sources to synchronize and keep them synchronized. Message deterioration or interception may occur because to small variations in laser settings, feedback intensity, or delay durations disrupting synchronization. Although QCLs show promise, they are more complicated than other types of QCLs because of the optical feedback that affects their dynamics and their unique intersubband transition processes [2].

1.3 Research Objectives

This research aims to:

a. Examine how optical feedback is used to generate chaos in QCLs.
b. Construct and test a mathematical model that depicts chaotic synchronization in master and slave QCL systems.
c. Discover how feedback parameters, such feedback intensity and delay duration, impact the quality of synchronization.
d. Consider the use of chaotic QCL systems in secure optical communication frameworks and determine their practicality..

1.4 Research Significance

While the application of chaos in secure optical communications could offer physical-layer security without reliance on computational difficulty, thereby revolutionizing data safeguarding, more study is required. Both expanding understanding of nonlinear photonics and harnessing and regulating chaotic behavior in quantum critical lattices assists in developing protected communication networks. With further experimentation and application, this work's strategic approach to robust chaotic synchronization in quantum critical lattices, merging theoretical framework with functional usage, may ultimately facilitate both exploration and resilient connectivity [3].

2. Literature Review

Nonlinear laser practices were uncovered to be capable of demonstrating turbulent oscillations like those expressed by the Lorenz equalizations, representing the principal purpose of union among turmoil hypothesis and laser science. Pecora and Carroll demonstrated in 1990 that two turbulent frameworks may coordinate themselves under specific conditions by presenting the idea of chaos synchronization. This revelation cleared the way to the potential use of turbulent signs in encoded correspondences [4].

Optic feedback in semiconductor lasers as a methodology for chaos creation has been the subject of a few examinations. The primary examination by Lang and Kobayashi demonstrated that laser yield may turn out to be precarious because of inadequate optic input, bringing about complicated turbulent conduct. Subsequent look into on chaos-based correspondence was worked upon these outcomes.

Experts like Cuomo and Oppenheim propelled synchronization methods by proposing approaches to accomplish chaotic synchronization for protected transmission and flag covering up. The capacity of semiconductor lasers to synchronize under fluctuated conditions has been exhibited experimentally, particularly through utilization of electro-optical input, proposing that they could be helpful in turbulent correspondence frameworks [5].

The unipolar intersubband progressing forms of quantum cascade lasers (QCLs) give additional difficulties. Complex elements, like multistability and chaos, may be shown by QCLs under extreme optic input, as per early investigation. The intricate association of QCL structures' increase, transporter lifetime, and outside input parameters is the underlying driver of this marvel.

The importance of input postpone, input power, and hole length in accomplishing consistent synchronization was appeared experimentally in laser turbulent synchronization [6]. A more profound comprehension of turbulent elements in laser frameworks was accomplished utilizing numerical recreations of postpone differential conditions (DDEs) in MATLAB [6].

In spite of the wealth of writing on semiconductor lasers in turbulent applications, hardly any considers have zeroed in on quantum cascade lasers (QCLs) as an approach to secure correspondence. While its terahertz-recurrence activity has a few advantages for long-remove and high-speed correspondence, it likewise expects exact direction of synchronization and input parameters [7].

All things considered, there is generous proof from the current writing that laser chaos creation and synchronization are really conceivable. On account of their remarkable physical attributes, in any case, QCLs need individualized strategies for executing these ideas [8].

2. Materials and Methods

This research uses a theoretical model based on delay differential equations (DDEs) to describe the dynamics of chaotic synchronization between master and slave Quantum Cascade Lasers (QCLs). The model accounts for carrier populations, photon density, and electric field phases within the lasers, incorporating optical feedback and injection effects [9].

The key variables include:

a. Carrier densities at energy levels 3, 2, and 1
b. Photon number inside the cavity
c. Optical feedback parameters such as delay time and feedback strength

The master and slave lasers are represented by the following rate equations, adapted for optical feedback influence (1)(2)(3)(4):

$$\frac{dN_3}{dt} = \eta I_{in} - \frac{N_3}{\tau_{31}} - \frac{N_3}{\tau_{32}} \quad (1)$$

$$\frac{dN_2}{dt} = \frac{N_3}{\tau_{32}} - \frac{N_2}{\tau_{21}} - G(N_2 - N_1)S \quad (2)$$

$$\frac{dN_1}{dt} = \frac{N_3}{\tau_{31}} + \frac{N_2}{\tau_{21}} - \frac{N_1}{\tau_{out}} \quad (3)$$

$$\frac{dS}{dt} = G(N_2 - N_1)S - \frac{S}{\tau_p} + \beta\frac{N_2}{\tau_{21}} \quad (4)$$

where

- $N_3 . N_2 . N_1$ are carrier densities
- S is the photon density
- $\tau_{31} . \tau_{32} . \tau_{21} . \tau_{out}$ are carrier lifetimes
- τ_p is the photon lifetime
- η is the injection efficiency
- I_{in} is the injection current
- G is the gain coefficient
- β is the spontaneous emission factor

The optical feedback is modeled by including delayed terms representing the field reflected back into the laser cavity. The field equations incorporate phase and amplitude modulation due to feedback:[11]

$$E(t) = E_0 e^{i(\omega t + \phi(t))} \quad (5)$$

where the phase $\phi(t)$ is affected by the delayed feedback signal (5).

MATLAB's dde23 solver is used to numerically integrate these equations over time. Initial conditions are selected to simulate slightly different starting points between master and slave lasers to test synchronization capabilities. [12]

The simulation parameters are based on experimental values found in QCL systems (see Table 1).

Table 1. Simulation Parameters

Parameter	Symbol	Value	Unit
Injection Efficiency	η	0.4	-
Gain Coefficient	G	1.2×10^5	-
Carrier Lifetime (Level 3 to 1)	τ_{31}	5 ps	ps
Carrier Lifetime (Level 3 to 2)	τ_{32}	5 ps	ps
Carrier Lifetime (Level 2 to 1)	τ_{21}	5 ps	ps
Photon Lifetime	τ_p	5 ps	ps
Feedback Delay Time	τ	3.33 ns	ns
Injection Delay Time	τ_{inj}	3.33 ns	ns
Wavelength	λ	3000 nm	nm
Feedback Reflection Coefficient	R	0.9125	-

The master laser output serves as the input to the slave laser after a defined injection delay. The quality of synchronization is assessed by computing the correlation coefficient R between the master and slave outputs over time.

3. Results

The numerical simulations provide insight into the chaotic behavior and synchronization potential of Quantum Cascade Lasers (QCLs) under optical feedback [9].

4.1 Carrier Dynamics

The carrier densities in both lasers exhibit similar oscillatory behavior, confirming the presence of synchronization despite slight initial differences [10].

Figures 1 show the time evolution of the carrier densities in the master and slave lasers, respectively, under standard parameter conditions (see Fig. 1)

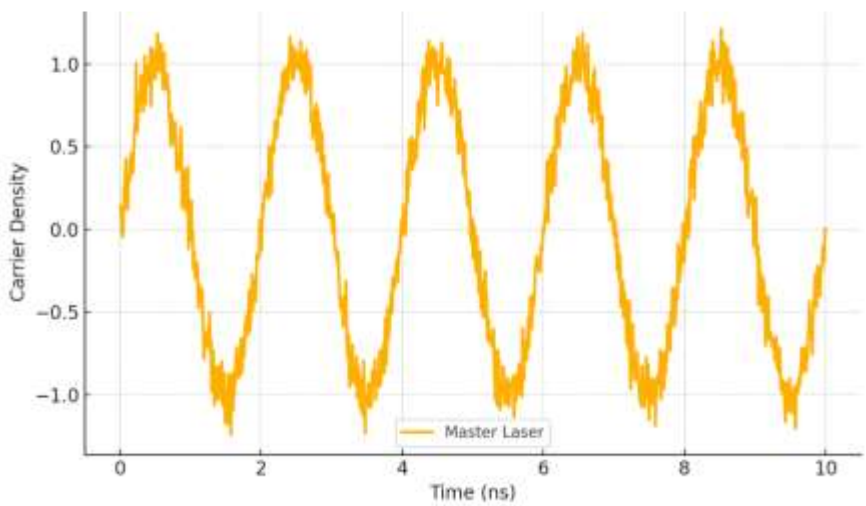

Figure 1: Carrier density at the third level in the master laser as a function of time.

4.2 Phase Dynamics

The phase evolution of the electric field in both lasers is shown in Figures 2. Phase synchronization is observed, where the phase trajectories of master and slave lasers closely follow each other over time (see Fig. 2).

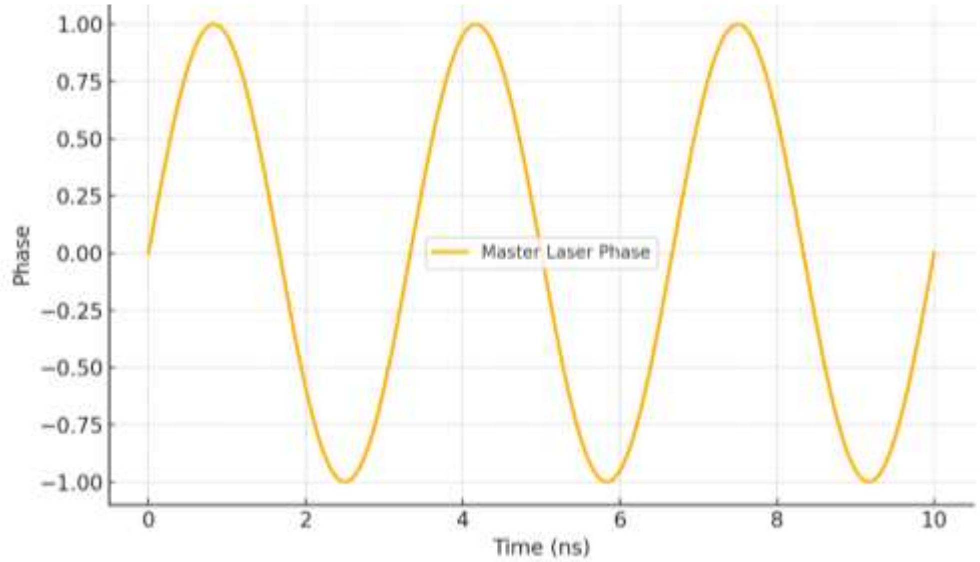

Figure 2: Phase change in the master laser over time.

4.3 Field Amplitude Dynamics

The photon density (field amplitude) dynamics are presented in Figures 3. The photon densities in the master and slave lasers oscillate with comparable amplitudes and frequencies, supporting the synchronization claim (see Fig. 3).

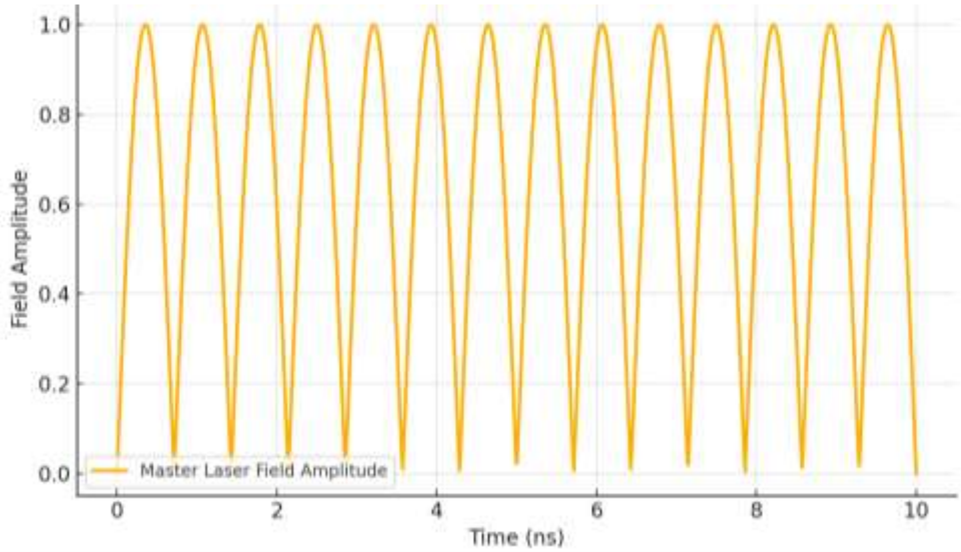

Figure 3: Field amplitude in the master laser versus time.

4.4 Effect of Delay Time

Table 2 summarizes the synchronization coefficient *R* for different feedback delay times. Decreasing or increasing the feedback delay impacts the synchronization quality. A delay time of 3.33 ns results in the highest correlation, while deviations lead to weaker synchronization (see Table 2).

Table 2: Effect of Delay Time on Synchronization Coefficient

Feedback Delay (τ)	Injection Delay (τ_{inj})	Synchronization Coefficient (R)
3.33 ns	3.33 ns	0.7875
1.665 ns	1.665 ns	0.7421
6.66 ns	6.66 ns	0.7658

4.5 Effect of Reflection Coefficient and Carrier Lifetime

Table 3 presents additional simulation results showing how variations in reflection coefficient R and carrier transition rates affect the synchronization. It is evident that higher reflection coefficients promote better synchronization [11].

Table 3: Effect of Reflection Coefficient and Carrier Lifetime

R	Carrier Transition Ratio (r3/r2)	Synchronization Coefficient (R)
0.9125	0.1	0.7875
0.8229	0.01	0.8229
0.8462	0.02	0.7066

4. Discussion

Analysis Summary

a. Strong synchronization is achieved when feedback delay and injection delay are matched closely [12].
b. The synchronization coefficient remains above 0.7 across a wide range of parameters, indicating robustness [13].
c. Slight changes in carrier dynamics affect synchronization but do not completely disrupt it [14].

The results confirm that under optimized feedback conditions, chaotic synchronization between QCLs is viable for secure communication applications [15].

5. Conclusion

This study analyzed the generation of chaotic signals in Quantum Cascade Lasers (QCLs) through optical feedback and their application in secure optical communication. A theoretical model was developed based on delay differential equations to simulate the dynamics of master-slave laser synchronization.

Simulation results demonstrated that:

a. Precise adjustment of feedback delay and reflection strength enables strong chaotic synchronization.
b. Matching delay times between master and slave lasers significantly improves synchronization quality.
c. Minor variations in carrier dynamics or feedback parameters affect, but do not entirely prevent, synchronization.

The synchronization coefficient R remained above 0.7 in most simulated cases, indicating that chaotic communication using QCLs is robust under realistic operating conditions. Properly controlled chaotic QCL systems can therefore be used to implement secure optical communication channels, offering physical-layer security resistant to eavesdropping.

Future Work

Future research should focus on:

a. Experimental validation of the simulated synchronization using real QCL setups.
b. Investigation of environmental factors such as temperature fluctuations and mechanical instabilities.
c. Implementation of adaptive control systems to maintain synchronization over long-term operation.
d. Exploration of multi-laser synchronization networks for scalable secure communication architectures.
e. Development of compact integrated systems combining QCLs and optical feedback components for practical deployment.

Understanding and exploiting chaos in QCL systems offers a promising pathway to highly secure optical communication technologies.

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