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RESEARCH PAPER

# Effect of Time Delay on the Incoherent Output of a QDSEL (Quantum Dot nanoparticles) Using a Closed-Loop System with Optical Feedback

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## ABSTRACT

The effect of time delay on the incoherent output dynamics of a Quantum Dot Semiconductor Laser (QDSEL) operating in a closed-loop optical feedback system is theoretically investigated. Quantum dots (QDs) possess unique nanoscale properties, including three-dimensional carrier confinement, discrete energy levels, enhanced modulation response, and reduced threshold current, making them attractive candidates for high-speed photonic and optical communication applications. In the present study, the temporal evolution of the laser field is analyzed under different feedback delay conditions and injected current values. The delay time ($\tau$) is varied from 100 to 500 ps while maintaining a fixed linewidth enhancement factor of $\alpha = 3$. The influence of optical feedback on the dynamical behavior, synchronization characteristics, and stability of the QDSEL output is examined. Numerical results reveal that the injected current plays a dominant role in determining the system dynamics, whereas the delay time acts as a secondary control parameter that modifies the transition boundaries between stable, periodic, and chaotic operating regimes. Furthermore, the interaction between injected current and feedback delay induces complex nonlinear oscillations and synchronization phenomena. These findings demonstrate that nanoscale quantum-dot-based lasers exhibit rich dynamical behavior under delayed optical feedback, providing valuable insights for the design of secure chaotic optical communication systems, photonic networks, and advanced nanophotonic devices.

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## INTRODUCTION

The subject of secure optical communications is rapidly developing due to the reliance on chaotic synchronization systems, which have emerged as an important control mechanism for regulating the complicated dynamics of nonlinear systems [1]. In this context, semiconductor laser beams stand out due to their extreme sensitivity to external stimuli, particularly when subjected to optical feedback [2, 3].

Quantum Dot semiconductor lasers (QDSELs) are sophisticated photonic Nano platforms built on nanostructured semiconductors (with zero dimension ranging from 2 to 10 nm) that induce quantum confinement phenomena, resulting in the formation of discrete energy levels mimicking

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single atoms [4]. These devices outperform standard lasers in dynamic applications due to their unique qualities such as low α-factor, low threshold current, and good thermal stability [5]. The QD SL is found to be more sensitive to the changes in time delay compared with other SLs and a complicated routs are seen in the behavior of QD SL [6]. The use of quantum dot (QD) nanostructures in the active region of SLs is increased in this decade. They are an excellent candidate 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 [7]. The system transit to chaos under short delay times, which important in secure optical communications. A complete synchronization was obtained at long delay time which is also important in the of coding and decoding for communication security applications [8]. These dynamics may be used efficiently in encrypted communication applications, where chaotic signals act as secure information carriers that are difficult to intercept or decipher [9-11].

Recent research has revealed that QDSELs are one of the most effective platforms for producing synchronized chaos via optical feedback systems[12], in which a transmitter laser drives a receiver laser, resulting in temporal delays and complicated nonlinear interactions [13-14]. Theoretical models have confirmed that these devices' unique characteristics make them ideal candidates for achieving effective chaotic synchronization [15]. Optical feedback-based chaotic synchronization systems are typically classified into three main configurations: closed-loop systems (CLS), open-loop systems (OLS) [16], and mutual coupling systems, each with distinct feedback dynamics and behaviors [17].

However, the systematic evaluation of the performance of these three configurations in QDSELs is still insufficient, particularly in terms of synchronization stability under changing time delay circumstances and signal quality in practical communication channels. Furthermore, the effects of the device's structural factors on the effectiveness of chaotic synchronization in each configuration have not been completely investigated. This study aims to analyze and evaluate the performance of chaotic synchronization systems in quantum dot semiconductor lasers (QDSELs) under different optical feedback conditions, focusing on the comparison of basic configurations (CLS, OLS, and mutual coupling), and determining the optimal configuration for secure communications based on stability and security criteria.

The pursuit of robust physical-layer security in optical communications has brought semiconductor lasers with external disturbance to the forefront as high-speed entropy generators. Quantum Dot Semiconductor Lasers (QDSELs) have quickly differentiated themselves from quantum well and bulk equivalents due to their inherent dynamical benefits. The cornerstone of this advantage is their extraordinary resistance to coherence breakdown under optical feedback, a feature thoroughly described in the seminal work of Huyet et al. (2005). QDSELs' stability is attributed to their three-dimensional carrier confinement, which results in a low linewidth enhancement factor (α-factor), decreased phase-amplitude coupling, and reduced relaxation oscillations [18]. Based on this stable chaotic base, research has grown along three main, application-oriented directions.

Critical Analysis and Identification of the Research Gap.

While these trajectories show significant improvement, a further examination exposes

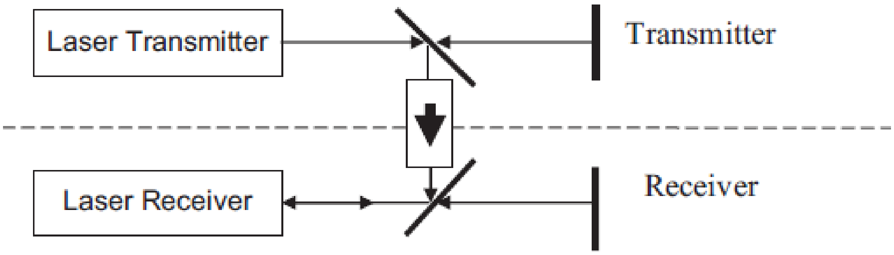


Fig. 1. Schematic of the closed-loop optical feedback system in quantum dot semiconductor lasers [22].

a common limitation: the current research technique is mostly compartmentalized. Under unique and non-standardized experimental conditions, investigative efforts [19-21] have yielded profound, but isolated, insights into specific setups or performance measures. This has resulted in a fragmented knowledge, with no direct, quantifiable comparisons across the main chaos-generation architectures—Conventional Optical Feedback (COF), Optical Injection (OI), and Delayed Optoelectronic Feedback (DOEF)—in the existing literature.

This study is intended to address this critical question. We conduct a systematic, head-to-head comparison of a QDSEL's nonlinear dynamics under COF, OI, and DOEF. We used a unified experimental methodology and optimized the device's low-α regime to quantitatively connect essential control parameters with application-specific performance indicators. Our findings are combined into a cohesive design guideline, indicating the best operating regime for each configuration and offering an important technical blueprint for the creation of next-generation, high-security QDSEL-based communication transceivers.

## MATERIALS AND METHODS

Rather than sharing common variables, laser-based communication methods return a limited percentage of the output—typically the optical power or the complicated electric field—to the receiver laser. This design allows for chaotic synchronization, which is very sensitive to parameter mismatches between the transmitter and receiver lasers [22]. The system under research is a close-loop setup, also known as a unidirectional coupling system, in which the receiver laser is optically separated from the transmitter by an optical isolator. Both lasers have independent optical feedback loops [23], as shown in Fig. 1.

The rate equation for the chaotic synchronization phenomena was linked to generate a model formula for communication systems associated with temporal delays caused by optical feedback of semiconductor point lasers, which consists of three related formulas: (N) Carrier density ratio, (E) Photon density ratio, and (ρ) Filling probability ratio (Eqs. 1-3) [24-26].

$$\frac{dE_{(T,R)}}{dt} = E_{(T,R)}\left(-\frac{1}{2t_s} + \frac{g_0 v}{2}\left(2\rho_{(T,R)} - 1\right)\right) + \Phi_{PCM} + \frac{\gamma}{2}E_{(T,R)}\left(t - \tau_{(T,R)}\right) + R_{sp} \qquad (1)$$

$$\frac{d\rho_{(T,R)}}{dt} = -t_n\rho_{(T,R)} - g_0\left(2\rho_{(T,R)} - 1\right)\left|E_{(T,R)}\right|^2 + CN^2_{(T,R)}\left(1 - \rho_{(T,R)}\right) \qquad (2)$$

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

Where:$N_{(T,R)}$ carrier density of both transmitter and receiver lasers in (QDSEL), $E_{(T,R)}$:complex amplitudes of the electric fields of both transmitter and receiver lasers in (QDSEL), $\Phi_{PCM}$: phase congregate mirror ($\rho_{(T,R)}$):filling probability for both transmitter and receiver lasers in(QDSEL),$t_s$: photon lifetime for both transmitter and receiver lasers in(QDSEL),$t_n$, and $t_d$: are the carrier lifetime in the well and the carrier lifetime in the dot. ($J_{(T,R)}$):pump current for each of the transmitter and receiver lasers in (QDSEL): γ: visual feedback optical level representation, and τ:time delays for both transmitter and receiver lasers in (QDSEL), (C) is Auger carrier capture rate [27], the length of the closed-loop system's outer cavity (L) may be calculated using the time delay, the speed of light (c), and the equation $\tau=2L/c$ [28] .

## RESULTS AND DISCUSSION

The influence of critical parameters namely injection current density J, feedback delay time τ, and linewidth enhancement factor α is examined to determine the conditions under which the laser output transitions between different dynamic regimes. These regimes include stable emission, periodic oscillations, quasi-periodic behavior, multi-periodicity, and fully developed chaos.

In the simulation, the injection current is set to ($j=1.5,\ 2.5,\ 4.5\ j_{th}$) [6], with a linewidth enhancement factor of α=3, and feedback delay times ranging from (τ=100 to 500 ps). A time delay differential of (Δτ=10 ps) is introduced between the transmitter and receiver lasers to simulate realistic synchronization conditions.

### *Dynamic analysis of the output of two identical lasers at (α(T,R) =3), (j(T,R) =1.5, 2.5, 4.5$j_{th}$), (τ =100 ps)*

The dynamic behavior of the emitted and received semiconductor laser beams was studied at different levels of injection current, with the line width enhancement factor fixed at (α=3) and the delay time at (τ=100ps) picoseconds. Both the transmitter and receiver exhibit a short transient period characterized by sharp increases in signal intensity, followed by a rapid convergence toward a stable state. The subsequent dynamics show weakly damped oscillations with an almost constant average signal intensity. Although the average signal intensity levels of the transmitter and receiver are similar, their temporal developments do not match exactly. This behavior indicates a stable non-chaotic system where no chaotic synchronization is observed. These results confirm that chaotic synchronization heavily depends on the level of injection current. While low current values produce stable non-chaotic dynamics and higher currents stimulate chaos, only sufficiently strong pumping allows for strong chaotic synchronization.

### *Dynamic analysis of the output of two lasers at ($\alpha(T,R)=3$), ($j(T,R)=1.5, 2.5, 4.5j_{th}$), ($\tau=150$ ps)*

The dynamic behavior of the transmitter receiver laser system was explored for different normalized injection current levels while maintaining the linewidth enhancement factor fixed at ($\alpha$=3) and at ($\tau$=150ps). For low injection current, ($j=1.5j_{th}$) Both the transmitter and receiver intensities display damped relaxation oscillations that quickly settle into a steady-state regime. The temporal progression is regular and periodic, indicating steady laser operating around the threshold. Although the transmitter and receiver signals are quite similar, this behavior is due to the system's intrinsic stability rather than chaotic synchronization. The injection current is raised to ($j=2.5j_{th}$) The system enters a transitional dynamical phase. The oscillation amplitudes rise, and the transient duration lengthens. The temporal signals exhibit somewhat irregular oscillations, but the dynamics remain constrained and predictable. This regime is classed as a pre-chaotic or quasi-periodic condition, meaning that nonlinear effects are intensified but inadequate to produce fully developed chaos. As a result, no chaotic synchronization is detected, despite the fact that the transmitter and receiver remain moderately similar. At a high injection current ($j$ = 4.5), the behavior changes significantly the laser intensities show broadband, aperiodic, and extremely irregular oscillations, which are distinct signs of chaotic dynamics. Most crucially, despite the chaotic character of each signal, the transmitter and receiver outputs exhibit a good temporal correlation. This implies the presence of chaotic synchronization, in which the receiver effectively reproduces the transmitter's chaotic dynamics via coupling. These findings show that chaotic synchronization occurs only when the system is deep in the chaotic regime, as in Fig. 2.

### *Dynamic analysis of the output of two identical lasers at ($\alpha(T,R)=3$), ($j(T,R) = 1.5, 2.5, 4.5j_{th}$), ($\tau=200$ ps)*

Increasing injection current ($j$) while maintaining constant values ($\alpha$=3, and $\tau$=200ps) results in: A distinct transition from quasi-periodic to chaotic dynamics. Improved synchronization quality between transmitter and receiver. Increased optical signal complexity and unpredictability. Among the three examples, ($j=4.5j_{th}$) provides the best balance of strong chaos and high similarity, whereas ($j=1.5j_{th}$) remains in a low-complexity regime, and ($j=2.5j_{th}$) acts as a transitional operating point. The given findings show that the injection current is an important control element that influences both chaos

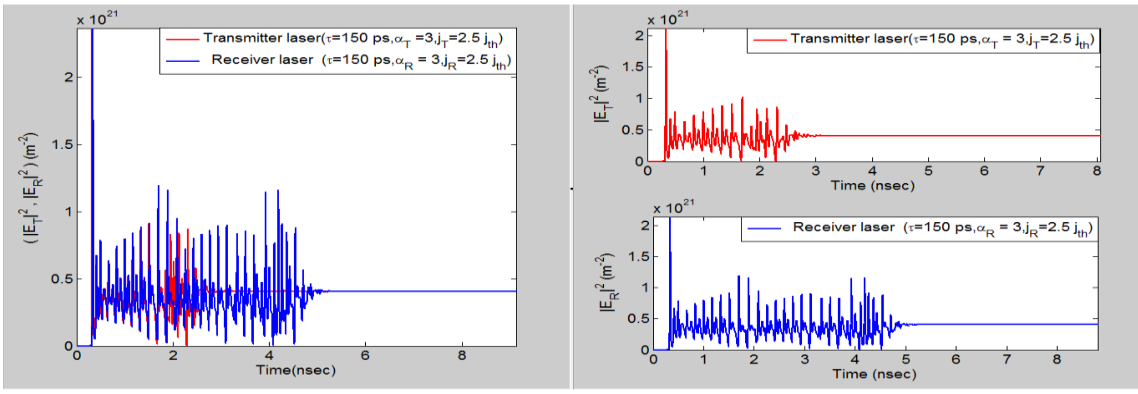


Fig. 2. Photon density for transmitter and receiver of QDSEL, at ($\alpha$=3), ($\tau$=150ps), and ($j=2.5j_{th}$).

formation and synchronization quality. These discoveries are directly applicable to the design of chaos-based photonic systems, notably in secure communications and random signal creation, as in Fig. 3.

*Dynamic analysis of the output of two identical lasers at (α(T,R) =3), (j(T,R) =1.5, 2.5, 4.5$j_{th}$), (τ =250 ps)*

The temporal intensity dynamics of transmitter and receiver lasers were studied for various injection currents using a fixed linewidth enhancement factor (α=3) and time delay at (τ=250ps). At (j=1.5$j_{th}$) both lasers show damped relaxation oscillations and quickly converge to a stable continuous-wave (CW) regime, exhibiting linear and dynamic stability. Increasing the injection current (j = 2.5 $j_{th}$) results in prolonged, non-damped intensity oscillations, especially in the transmitter laser, indicating a nonlinear and chaotic domain caused by heightened amplitude-phase coupling. At greater injection current (j=4.5$j_{th}$), the system exhibits a brief pulsed response with abrupt intensity spikes, followed by rapid damping and return to a stable operating state due to gain saturation effects. The raising of the injection current causes the system to transition between stable as a continuous wave (CW), chaotic-like oscillations, and pulsed-stable operation. This highlights the injection current's non-monotonic function in influencing laser dynamics, as in Fig. 4.

*Dynamic analysis output of two identical lasers at (α(T,R) =3), (j(T,R) =1.5, 2.5, 4.5$j_{th}$), (τ =300 ps)*

At low injected current levels (j=1.5$j_{th}$), both the transmitter and receiver lasers show a transitory response characterized by damped oscillations associated with the turn-on process. These oscillations diminish quickly, bringing the system into a stable steady-state regime. After a brief transitory time, the transmitter and receiver's temporal intensity traces closely coincide, demonstrating good amplitude and waveform agreement. This tight temporal consistency shows that the two lasers are in perfect and stable synchronization. In this domain, no signs of chaotic activity are detected, and the intensity difference between the two signals is small, indicating a high degree of temporal similarity dominated by stable periodic dynamics. Increasing the injected current to (j=2.5$j_{th}$)causes greater oscillatory behavior and longer transient periods before reaching a steady state. The oscillation amplitudes rise significantly when compared to the lower current case. Despite the increased oscillations,

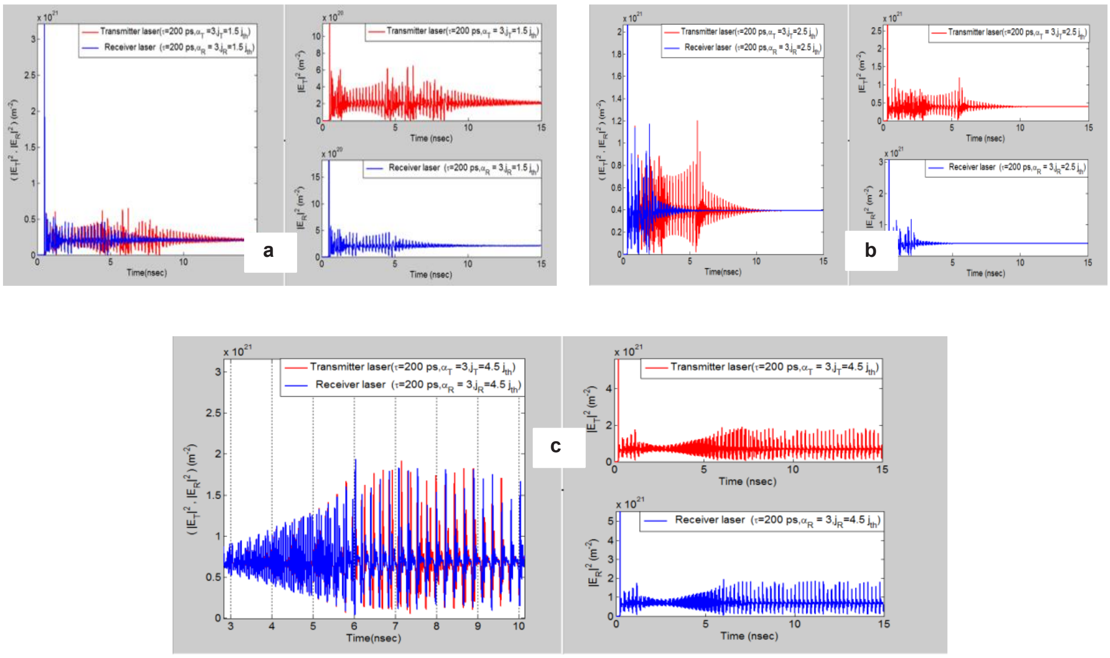


Fig. 3. (a,b,c) Photon density for transmitter and receiver of QDSEL, at (α=3), (τ=150ps), and (τ=200ps), and (j=1.5, 2.5,4.5$j_{th}$).

the transmitter and receiver intensity signals are highly linked in time, suggesting satisfactory synchronization performance. However, minor amplitude and phase discrepancies develop, indicating a shift away from perfect synchrony. The system dynamics in this domain can be described as quasi-periodic, with no apparent transition to chaos. This result demonstrates that the lasers' coupling strength is still sufficient to maintain a strong dynamical similarity. At an injected current

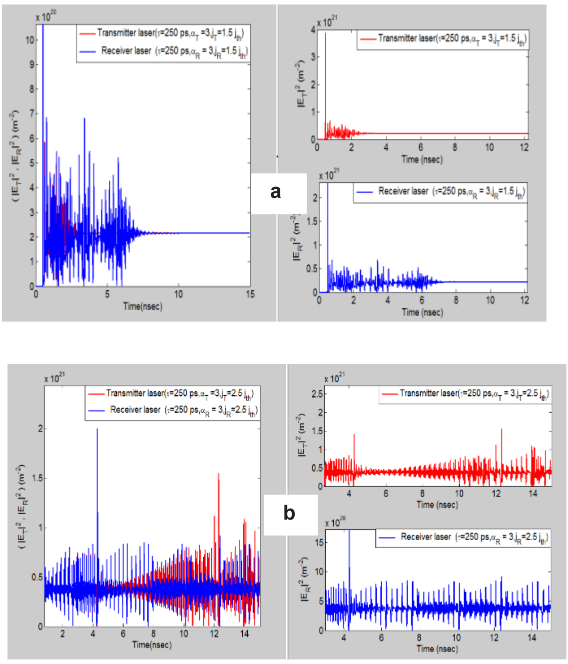
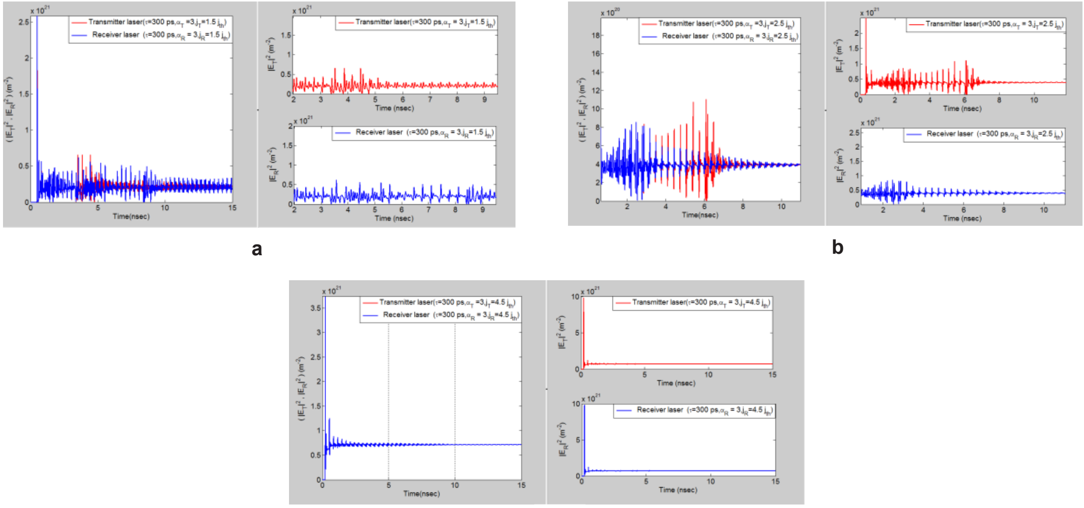


Fig. 4. (a,b) Photon density for transmitter and receiver of QDSEL, Photon density for transmitter and receiver of QDSEL, at (α=3), (τ=250ps), and ($j=2.5j_{th}$).



a

b

c

Fig. 5. (a,b,c) Photon density for transmitter and receiver of QDSEL, at (α=3), (τ=300ps), and ($j=1.5, 2.5, 4.5j_{th}$).

of ($j=4.5j_{th}$), the system reaches a chaotic state. Both the transmitter and receiver show irregular intensity variations with broadband properties and a high sensitivity to beginning circumstances, which are typical of chaotic dynamics, as in Fig. 5.

*Dynamic analysis of the output of two identical lasers at (α(T,R) =3), (j(T,R) =1.5, 2.5, 4.5$j_{th}$), (τ =350 ps)*

Case($j=1.5j_{th}$) At low injected current, both the transmitter and receiver lasers display damped relaxation oscillations that coincide with the turn-on transient. After a brief transitory phase, the system swiftly settles into a steady-state mode. The two lasers' amplitude and phase overlap almost exactly, suggesting steady and full synchronization. No signs of chaos are detected, and the system dynamics are entirely periodic and stable. Case($j=2.5j_{th}$) Increase the injected current to 2.5. amplifies nonlinear effects in laser dynamics, resulting in oscillations with greater amplitudes and longer transient periods. Although the transmitter and receiver intensities remain strongly linked, tiny phase and amplitude discrepancies emerge. The system runs in a quasi-periodic domain, which maintains synchronization but is less perfect than the low-current scenario. Importantly, the dynamics have not yet demonstrated chaotic behavior. Case($j=4.5j_{th}$) (Chaotic regime)At large injection current levels, the system obviously enters a chaotic domain, characterized by erratic intensity fluctuations, lack of periodicity, and a high sensitivity to beginning circumstances. The transmitter and receiver lasers exhibit wideband

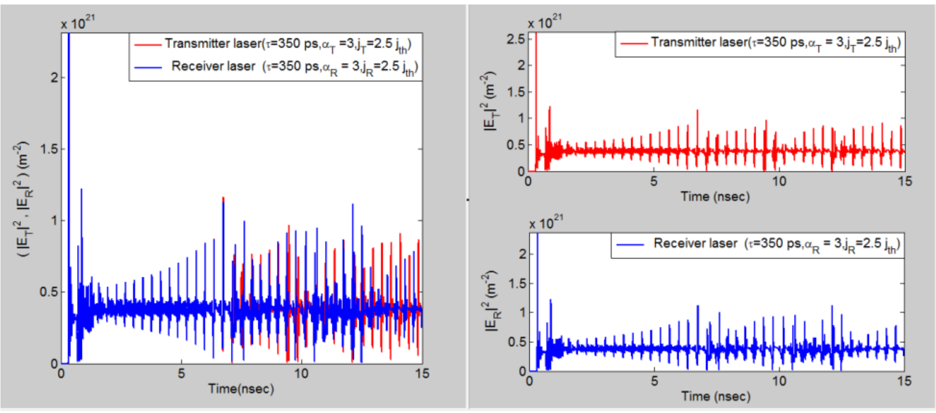


Fig. 6. Photon density for transmitter and receiver of QDSEL, at (α=3), (τ=350ps), and ($j=1.5, 2.5j_{th}$)

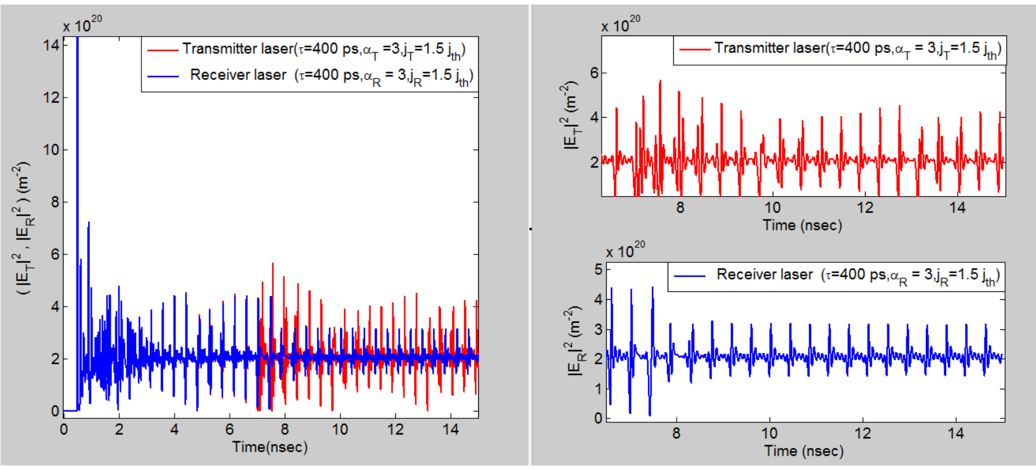


Fig. 7. Photon density for transmitter and receiver of QDSEL, at (α=3), (τ=400ps), and ($j=1.5, 2.5j_{th}$).

oscillations with considerable amplitude fluctuations. However, this synchronization is weaker than in the periodic and quasi-periodic regimes, as instantaneous discrepancies between the two signals increase due to the stronger nonlinear interactions, as in Fig. 6.

### *Dynamic analysis of the output of two identical lasers at (α(T,R) =3), (j(T,R) =1.5, 2.5, 4.5$j_{th}$), (τ =400 ps)*

At ($j$=1.5$j_{th}$) the temporal waveforms show damped oscillations associated with the turn-on transient, followed by a quick convergence into a quasi-steady state. In terms of temporal profile and amplitude development, the transmitter and receiver signals are nearly identical, with just minor deviations. This behavior demonstrates the presence of perfect and stable synchronization and implies a regular, periodic regime with no signs of chaos. At ($j$=2.5$j_{th}$) the oscillatory activity intensifies and lasts longer before stabilizing. Although the temporal signals are more complicated than the low-current scenario, the transmitter and receiver dynamics remain quite comparable. Minor phase shifts and amplitude mismatches begin to develop, indicating that synchronization is still functional but no longer optimal. In this regime, the system maintains a quasi-periodic state while remaining outside the truly chaotic region. At ($j$=4.5$j_{th}$) the system obviously enters a chaotic phase. The temporal responses are characterized by irregular oscillations, loss of periodicity, and a broad range of intensity levels, all of which are indicative of chaotic dynamics in nonlinear laser systems. Despite the chaotic character of the signals, the transmitter and receiver's overall temporal structure are noticeably comparable. This discovery suggests the occurrence of partial chaotic synchronization.

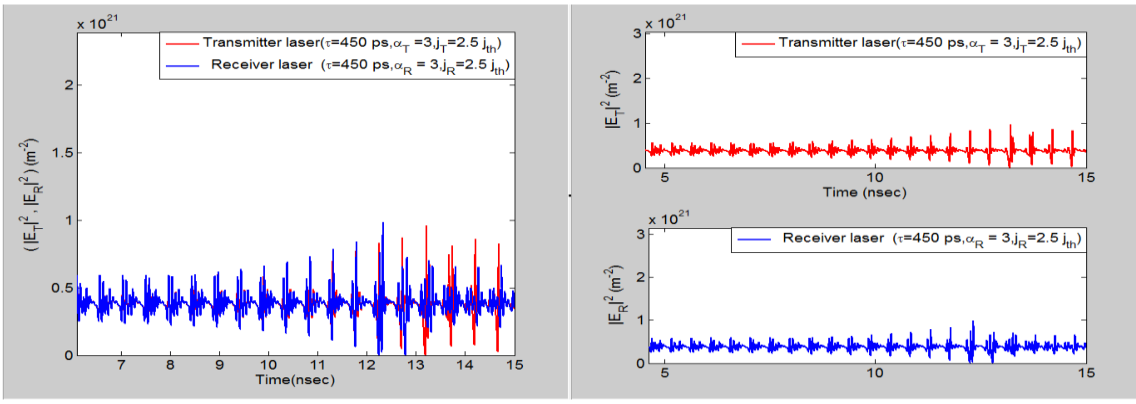


Fig. 8. Photon density for transmitter and receiver of QDSEL, at (α=3), (τ=450ps), and (2.5$j_{th}$).

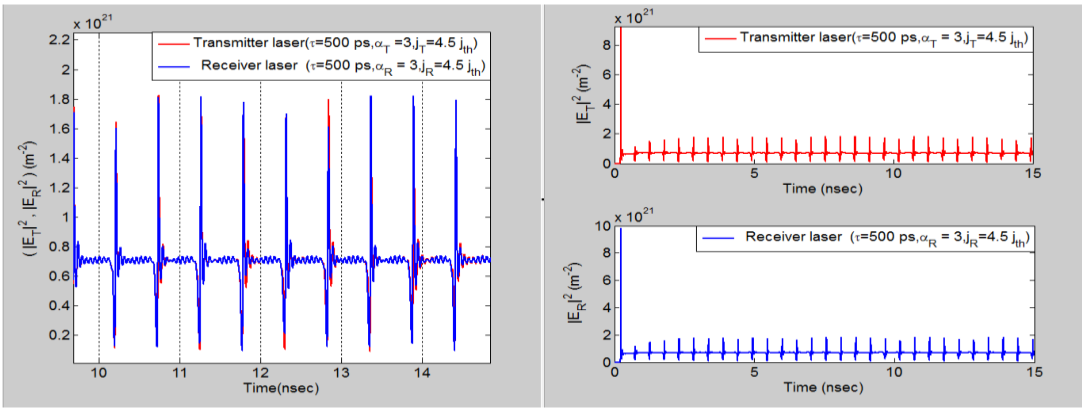


Fig. 9. Photon density for transmitter and receiver of QDSEL, at (α=3), (τ=500ps), and (j=4.5).

However, this synchronization is poorer than in lower-current regimes, with bigger instantaneous deviations caused by increased nonlinearity and sensitivity to beginning circumstances at high injection levels. Overall, these findings confirm that increasing the injected current causes a gradual transition from stable periodic operation to quasi-periodic behavior and, finally, chaos, while synchronization between the coupled lasers progresses from complete synchronization to partial chaotic synchronization. This characteristic is especially important for chaos-based secure optical communication systems, because regulated chaotic synchronization is a need for dependable encryption and decryption operations, as in Fig. 7.

*Dynamic analysis of the output of two identical lasers at (α(T,R) =3), (j(T,R) = 1.5, 2.5, 4.5$j_{th}$), (τ =450 ps)*

The graphs show damped initial oscillations associated with the startup phase, followed by a clear temporal stabilization at a quasi-constant value. After the transition phase, the signals of the transmitter and receiver converge significantly in terms of temporal shape and average values, with very minor differences. This behavior indicates stable and strong synchronization and control of a regular periodic system, with no signs of chaos appearing. When the current is increased to (j=2.5$j_{th}$). The oscillations become more complex, and the stabilization time increases compared to the first case, with relatively irregular vibrations appearing before reaching the steady state. Nevertheless, there is still a noticeable temporal similarity between the transmitter and receiver signals, albeit less ideal, with limited phase and temporal shape shifts observed. The behavior indicates that the system operates in a quasi-periodic range, with synchronization remaining but at a weaker degree than in the low current state. The results show a qualitative change in the dynamic behavior, where the clear periodicity disappears and irregular fluctuations and high sensitivity to temporal changes appear, which are characteristic features of the chaotic system. Nevertheless, the signals of the transmitter and receiver still retain a general similarity in temporal structure and average values, indicating the occurrence of partial chaotic synchronization. However, this synchronization is weaker compared to the previous two cases, with increased instantaneous differences due to nonlinearity amplification at high currents, as in Fig. 8.

*Dynamic analysis of the output of two identical lasers at (α(T,R) =3), (j(T,R) = 1.5, 2.5, 4.5$j_{th}$), (τ =500 ps)*

At an injected current (j=1.5$j_{th}$).the time-series plots reveal strong turn-on transients followed by fast damped oscillations. After a short period of time, the transmitter and receiver intensities reach a near-steady state. Over the entire observation frame, the temporal waveforms show very tight agreement in amplitude and temporal profile. This significant overlap implies the presence of perfect and stable synchronization, with solely regular and periodic dynamics and no trace of chaos. When the injected current is raised to (j=2.5$j_{th}$).the system reaction becomes more complicated. The oscillations last longer until stabilization, and their amplitude is substantially greater than in the low-current scenario. Despite the increased dynamical activity, the transmitter and receiver signals remain strongly linked in time, with only minor variations in phase and amplitude. This behavior relates to a quasi-periodic regime in which synchronization is maintained but is less optimal than the one point five threshold scenario. Importantly, the system has not yet reached entirely chaotic dynamics.

When the injected current is increased to (j=4.5$j_{th}$) the system obviously enters a chaotic state. The time traces show irregular, non-periodic oscillations with large fluctuations and a lack of temporal regularity, which are characteristic of chaotic laser dynamics. Although the instantaneous disparities between transmitter and receiver intensities become more dramatic, their overall temporal structure remains very comparable. This implies the presence of partial chaotic synchronization, in which both lasers develop chaotically while remaining dynamically coupled due to the coupling mechanism. However, the synchronization quality is worse than in lower-current regimes due to higher nonlinearity and susceptibility to beginning circumstances, as in Fig. 9.

## CONCLUSION

This study investigated chaotic synchronization in quantum dot semiconductor lasers (QDSELs) under optical feedback conditions by analyzing the effects of injection current density, feedback delay time, and linewidth enhancement factor on the dynamical behavior of coupled transmitter–

receiver systems. Numerical analysis was performed for injection currents of 1.5, 2.5, and 4.5 $jth$ with delay times ranging from 100 ps to 500 ps.

The results demonstrated that the injection current is the primary parameter controlling the transition between stable, quasi-periodic, and chaotic regimes. At low injection current ($j$=1.5 $jth$), the system exhibited stable periodic oscillations with strong synchronization between transmitter and receiver, but without chaotic behavior. At intermediate current ($j$=2.5 $jth$), nonlinear effects increased, leading to quasi-periodic oscillations and moderate synchronization quality. When the injection current reached $j$=4.5 $jth$, the system entered a fully chaotic regime characterized by irregular broadband oscillations and partial chaotic synchronization between the coupled lasers. The study also showed that increasing the feedback delay time enhanced the complexity of the laser dynamics and promoted the transition toward chaos. Delay times between 150 ps and 300 ps combined with high injection current produced the most effective synchronized chaotic behavior suitable for secure optical communication applications. Overall, the findings confirm that QDSELs are promising candidates for chaos-based secure communication systems due to their strong nonlinear response, high synchronization capability, and sensitivity to external feedback. Proper optimization of injection current and delay time enables reliable chaotic synchronization required for secure encryption and decryption processes in advanced photonic communication networks.

## CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript.

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