Linewidth Enhancement Factor Impact on Optical Feedback Mutual Coupled Quantum Dot Lasers

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Abstract

In this article, we numerically study and analyse the roles of linewidth enhancement factor (α) in the dynamic operation of the mutual regime of the transmitter and receiver quantum dot laser lasers supported by optical feedback. A set model of adequate rate equations describing the overall dynamics in a quantum dot system subjected to optical feedback were solved numerically. The results reveal a clear chaotic regime between the receiver and the transmitter lasers at $\alpha = 3$, which is incredibly advantageous for secure optical communications and encoding decoding data transmission. Moreover, at the other value of linewidth enhancement factors, namely 2, 2.5, 3.5 and 4, the optical regime works in high synchronisation with either periodic or steady state forms.

Key Words: Chaos, Optical Feedback, Quantum Dot Laser, Nonlinear Dynamic, Synchronisation.

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Introduction

Chaos regimes can be generated in semiconductor laser systems by way of three different techniques, optoelectronic feedback (Ghalib *et al*, 2015; Ghalib *et al*, 2012; Ali *et al*, 2019), optical injection (Qiao *et al*, 2019; Ghalib *et al*, 2013; Zhang *et al*, 2018) and optical feedback (Yan, 2009; Masoller, 2001; Rontani *et al* 2007). Literally, a semiconductor laser with optical feedback is most commonly employed as a chaotic source in optical communications due to its specific characteristics, such as simple configuration, small scale, manageable control and rich chaotic dynamics. Optical feedback (OFB) is the process in which a small fraction of the laser's output light is reinjected back into the optical device to modify its behaviour. This is typically undertaken in semiconductor lasers by way of an external cavity. Despite the fact that OFB can cause excessive instability in the performance of the laser, this can be beneficial with regard to improving mode stabilisation (Wenke, 1987), linewidth narrowing (Harrison & Mooradian, 1989), mode locking (Gray, 1995) and reducing frequency chirp (Agrawal & Henry, 1988). Moreover, the numerous possible applications of the chaotic regime are the product of secure optical communications as well as encoding-decoding network systems (Sanchez-Diaz et al, 1999; Zhao & Yin, 2013; Liu *et al*, 2020; Hoang *et al*, 2016). Chaos and its control in optical feedback semiconductor lasers has been extensively studied. For example, the effect of bias current on chaos regime was studied comprehensively in (Jiang *et al*, 2011; Younis *et al*, 2016; Al Bayati *et al*, 2020). Likewise, the roles of time delay roles of the external cavity on the chaotic regime were introduced in (Rontani *et al*, 2009; Wu *et al*, 2010; Guo *et al*, 2012).

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Additionally, the influence of optical feedback strength was reported in (Al Bayati *et al*, 2018; Abd Ali *et al*, 2019; Fan *et al*, 2014). Consequently, we believe that the linewidth enhancement factor, α, of the semiconductor laser could play a role in the dynamics of the chaos and its control in optical-feedback semiconductor lasers. Therefore, in this case, we have designed and analysed the mutual coupling of quantum dot lasers subject to optical feedback and study the chaos and synchronic statues in this regime to test the potential of this regime in secure optical communications. A package of MATLAB software code was produced to numerically resolve the specific dynamic rate equations of the quantum dot laser via the Runge-Kutta method. We study the dynamical response of the mutual coupling regime under different values of supposed linewidth enhancement factors as a control parameter in the study.

Rate Equation in Quantum Dot Laser and Modelling Details

To study the role of the line width enhancement factor on the dynamic operation of the semiconductor laser subjected to optical feedback, we designed a mutual coupling regime comprising two identical quantum dot semiconductor lasers, namely transmitter and receiver lasers. Both lasers are subject to the same geometric optical feedback and coupled to each other mutually as outlined in Figure 1.

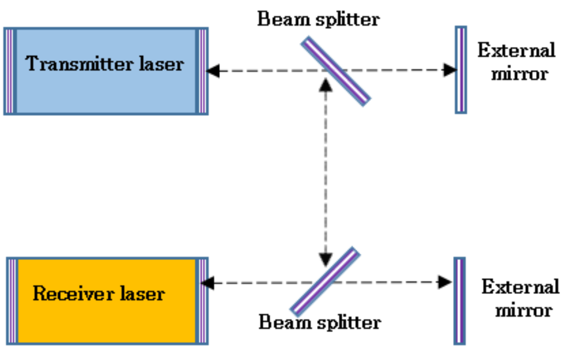


Figure 1. Mutual coupling regime (transmitter laser and receiver lasers)

We employed a set of equations that described the dynamic operation of the transmitter and the receiver whereby the quantum dot lasers are subject to optical feedback described by the Lang–Kobayashi equations (Lang& Kobayashi, 1980), which can be given as:

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

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

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

The indices $_T$ and $_R$ which appear in equation 1-3 indicate the transmitter laser and receiver laser, respectively, E is the electric field, t is the delay time, γ is feedback level factor, $\left|E_{(T,R)}\right|^2$ represents the photon density, ρ is the probability of filling in the dot, N is the carrier density in the well, t_s is the lifetime of the photon, t_w is the lifetime of the carrier in the well, t_s is the lifetime of the carrier in the dot, g_o is gain factor, v is group speed and β is the spontaneous emission factor. We choose the 1.33 μm In As quantum dot laser in our simulation due to the significance of this wavelength in optical communication (Wang *et al*, 2011; You *et al*, 2013). Conversely, the quantum dot laser offers crucial advantages such as low threshold current density (Krysa *et al*, 2016), high quantum efficiency (Karomi *et al*, 2021) broad optical gain (Karomi *et al*, 2015), temperature insensitive operation (Schekin & Deppe, (2002), high modulation bandwidth (Todaro *et al*, 2007) and low chirp (Saito *et al*, 2000). We solved the ordinary differential equations 1-3 numerically using the specific Runge-Kutta method of integration order 23, known as the delayed differential equations (dde23) in the MATLAB software suite. The program was run for five cases of linewidth enhancement factor, namely α = 2, 2.5, 3 3.5 and 4. The delay time for the external optical feedback of both devices is maintained at 294.5 ps, while the driven current is fixed at 1.5 times the threshold current density (J_{th}). The other factors used in the simulation, which were carefully selected, are listed in Table 1.

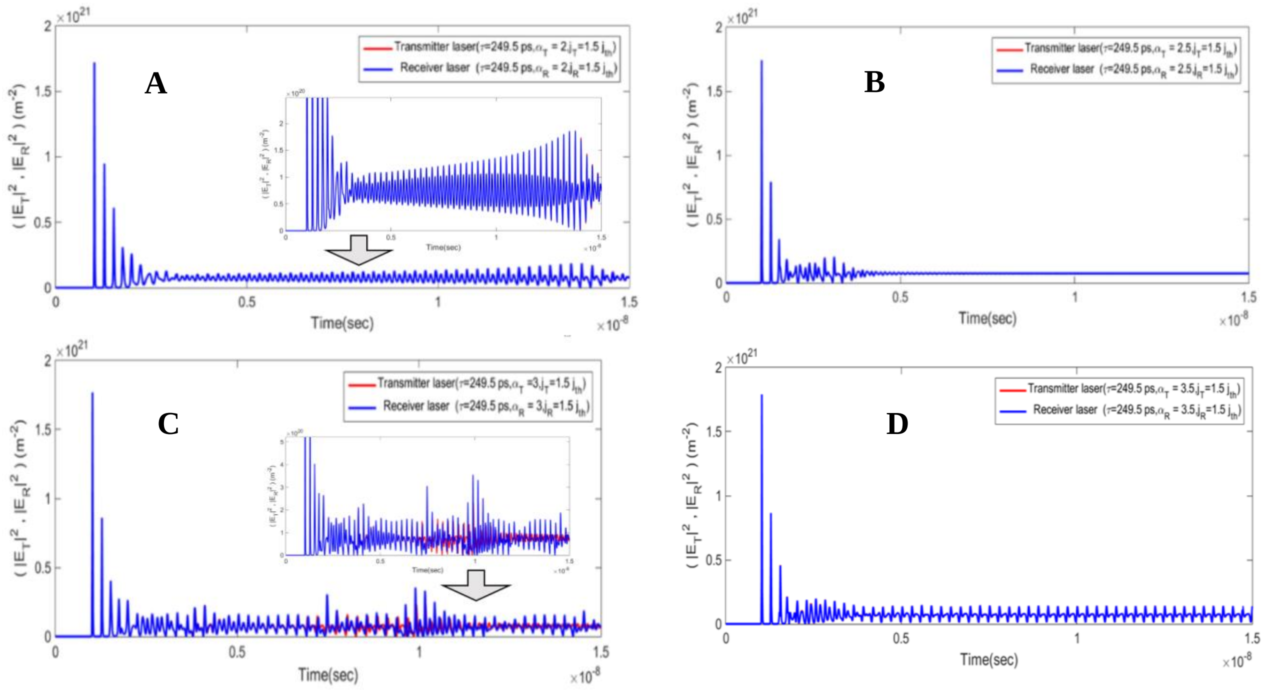
Table 1. Allocated parameters used for modelling

Symbol	Description	Value	Units
t_s	Photon lifetime	3.4	*ps*
t_w	Carrier lifetime in well	1	*ns*
t_d	Carrier lifetime in dot	1	*ns*
β	Spontaneous recombination factor	$3\ x10^{-5}$	---
Γ	Confinement factor	0.3	---
g_o	Effective gain factor	$0.414\ x10^{-16}$	---
γ_o	Photon decay rate	$5\ x10^{11}$	s^{-1}
N_{tr}	Number of transparency carriers	$1.8\ x10^{18}$	cm^{-3}
N_e	Quantum dot density	$2\ x10^{14}$	cm^{-3}
v_g	Group velocity	$7.14\ x10^{7}$	ms^{-1}
C	Velocity of light	$3\ x10^{8}$	ms^{-1}
Q	Electron charge	$1.6\ x10^{-19}$	C

Results and Discussion

1. Photon Density Dynamic of the Mutual Regime

Figure 2 represents the five cases of the temporal variation of the photon density dynamic of the optical feedback mutually coupled (transmitter and receiver) quantum dot laser, as calculated numerically from Equation 1 for different linewidth enhancement factors, α, of 2, 2.5, 3, 3.5 and 4. The delay time of the external optical feedback for each of the devices is taken to be 294.5 ps and the driven current is fixed at 1.5 times the threshold current density (I_{th}). Figure 2a shows the evolution of the photon density of the transmitter and receiver lasers at linewidth factor α = 2. It is evident that the transmitter and the receiver lasers are operating synchronically and that the waveform of the laser output is stable and cyclical. The photon density reaches 16 x 10^{20} m^{-2}, then decreases and stabilises at a value of 1.1 x 10^{20} m^{-2}. In the case of α = 2.5 (Figure 2b), the transmitter and the receiver lasers still operate in a synchronic manner. Moreover, after a specific time the mutual regime exhibited almost CW-like operation. Figure 2c at α = 3 reveals that the photon density is unstable and the synchronisation between the transmitter and the receiver lasers breaks down; hence, the mutual regime in this case is working in a chaotic form. This could be the most important operating case of the mutual system due to the chaotic generation that offers the potential for application in secure optical networks for encoding data. Figure 2d shows the case of α = 3.5. It is noticeable that the transmitter and the receiver lasers are in synchronous form and that the mutual system is working in pulse periodic mode. Finally, the fifth case of operation, that of α = 3.5, is depicted in Figure 2e. It demonstrates high synchronisation between the transmitter and receiver lasers and after a period of photon density, the system shows a high stability and the mutual regime exhibits high CW-like operation. Table 2 summarises the important features of the mutual regime found in Figure 2 and its potential applications for different values of linewidth enhancement factor (2, 2.5, 3, 3.5 and 4) at a delay time of 294.5 ps and where the driven current is 1.5 I_{th}. 39



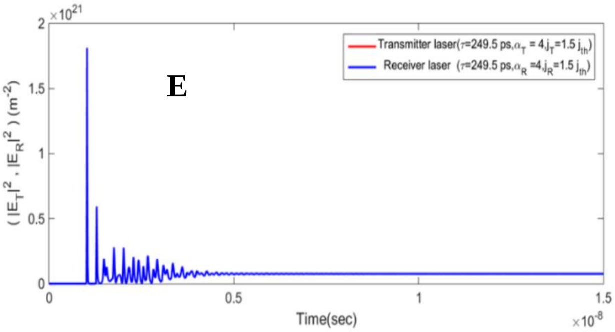


Figure 2. Photon density time series in transmitter and receiver lasers at (a) α = 2, (b) α = 2.5, (c) α = 3, (d) α = 3.5 and (e) α = 4

Table 2. Important features of the mutual regime and its potential applications

Linewidth enhancement factor (α)	Dynamic state of the mutual coupling regime	Potential applications
2	Synchronism, periodic	Biomedical and communications
2.5	Synchronism, steady state	Biomedical and communications
3	Desynchronisation, chaotic nonlinear	Data encryption and secure communications
3.5	Synchronism, periodic	Biomedical and communications
4	Synchronism, steady state	Biomedical and communications

2. Photon Density Evolution in the Mutual Regime

Figure 3 represents the five cases of the photon density relationships for the mutually coupled (transmitter and receiver) quantum dot lasers as calculated numerically from equation 2 at different values of linewidth enhancement factor (α = 2, 2.5, 3, 3.5 and 4). The delay time of the external optical feedback of both devices is taken as 294.5 ps and the driven current is fixed at 1.5 I_{th}. In Figures 2a, 2b, 2d and 2e, the photon densities of both the transmitter and receiver lasers are almost identical. In Figure 2c, where α = 3, at the low region of the photon density, the system shows nonlinearity, which indicates highly chaotic operation.

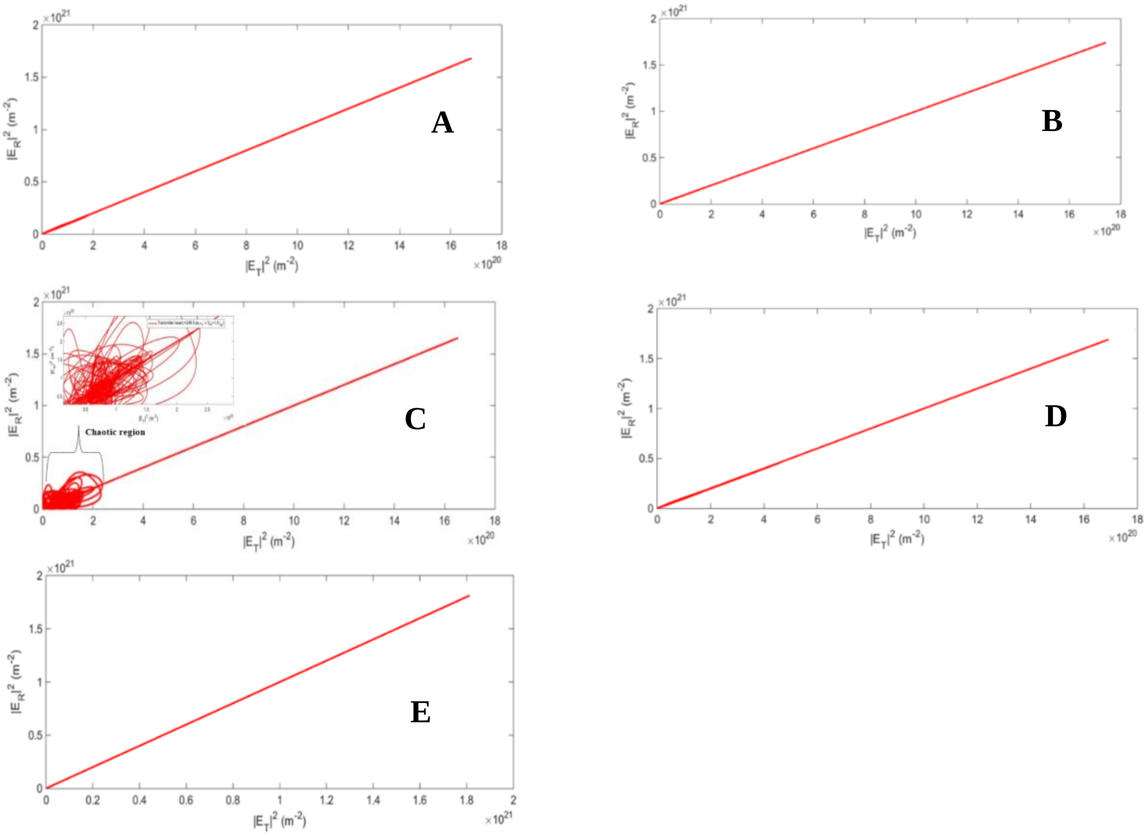


Figure 3. Photon density correlation plot between transmitter laser and receiver lasers at (a) α = 2, (b) α = 2.5, (c) α = 3, (d) α = 3.5 and (e) α = 4

3. Evolution of the Full Dynamic Behaviour in the Mutual Regime

Figure 4 represents the 3D plot of the evolution of the dynamic behaviour (the relationship between photon density, carrier density, and population inversion factor) of the mutually coupled (transmitter and receiver) quantum dot lasers calculated numerically from model equations 1-3 for various linewidth enhancement factors (α = 2, 2.5, 3, 3.5 and 4). The delay time of the external optical feedback of both devices is taken to be 294.5 ps and the driven current is fixed at 1.5 J_{th}. In Figures 4a and 4d, there is high symmetry in the dynamic behaviour in both the transmitter and receiver lasers. Meanwhile, Figures 4b and 4e complete the symmetric behaviour. In Figure 4c at α = 3, it is obvious that the symmetric behaviour of both the transmitter and receiver lasers is no longer established and the two behave asymmetrically. This is consistent with the results in Figures 2c and 3c (the case of α = 3), which is highly chaotic in the mutually coupled quantum dot lasers.

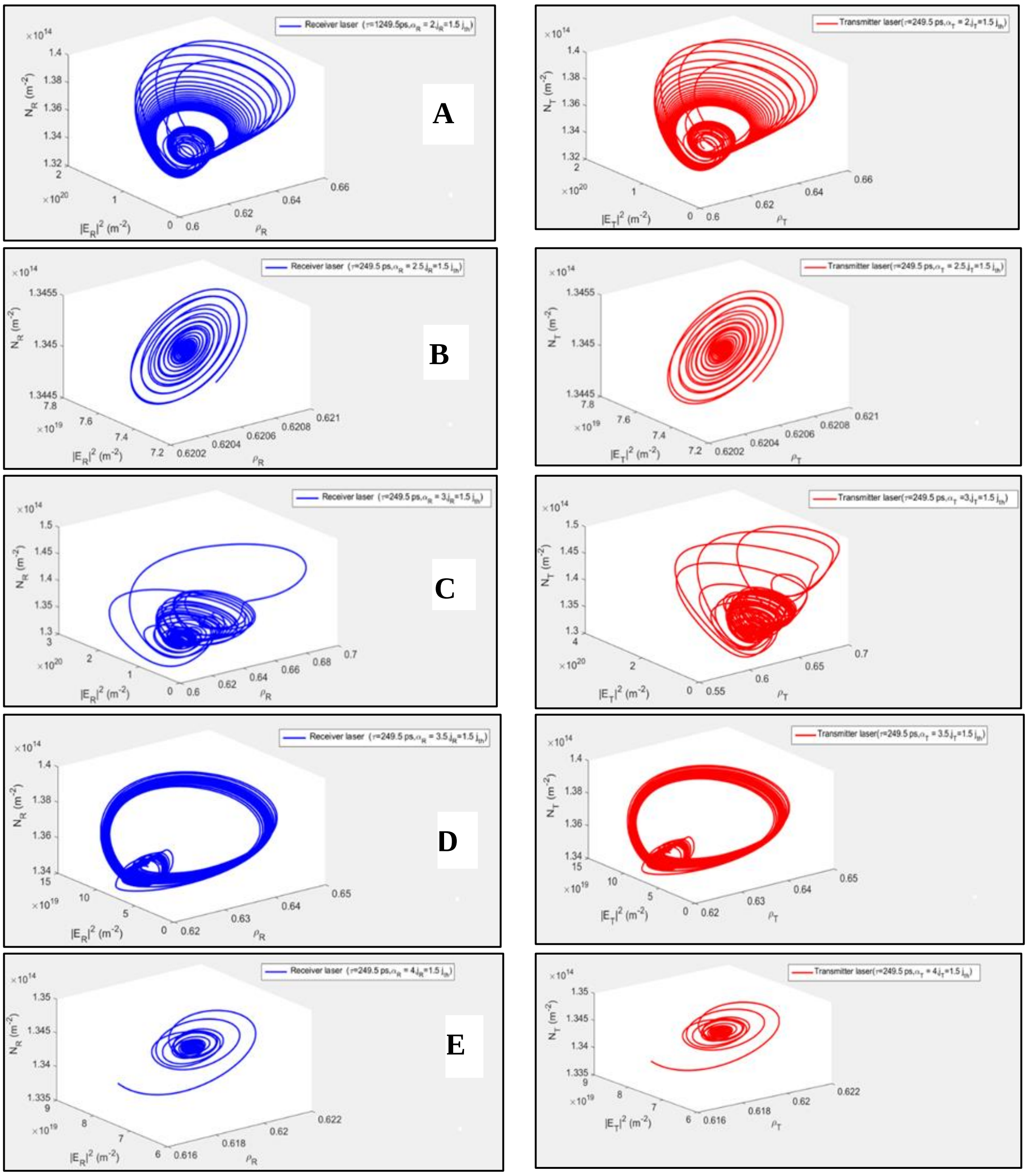


Figure 4. Evolution of the full dynamic behaviour in transmitter laser and receiver laser at (a) α = 2, (b) α = 2.5, (c) α = 3, (d) α = 3.5 and (e) α = 4

Conclusion

Using the explicit Runge-Kutta method in MATLAB, we numerically solved a set of modified rate equations for quantum dot semiconductor lasers for the mutual regime of a transmitter and receiver laser subjected to external optical feedback cavities. Five different linewidth enhancement factors (α = 2, 2.5, 3, 3.5 and 4) were simulated at a fixed delay time of 294.5 ps and pumped with a current of 1.5 J_{th}. The results revealed that a chaotic regime clearly existed between the receiver and the transmitter at α = 3, making it an appropriate candidate for encoding data transmission and secure optical communications. Likewise, for the other linewidth enhancement factors considered, the optical regime works in high synchronisation and could be employed in biomedical and communication applications. Furthermore, the designed mutual coupled regime showed diverse operational conditions, such as periodic, steady state and nonlinear chaos. Finally, our analyses reveals that linewidth enhancement factor plays a crucial role in the process of chaos and its control in quantum dot semiconductor lasers. We believe this work could add a valuable understanding to the nonlinear dynamics of semiconductor laser systems.

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