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Performances and Effects for Quantum Dot Laser (QDL) Investigation under Optical Feedback

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Abstract: In this study, we investigate the influence of external optical feedback on laser output and carrier density. It is observed that the impact of optical feedback intensifies as the length of the external cavity is reduced. The system of rate equations is solved using Matlab software (dde23), incorporating initial conditions for photon intensity, carrier density, and phase. A reduction in the external cavity length leads to the emergence of multimode (chaotic behavior) output in the laser, as evidenced by the fast Fourier Transform. Analyzing these fluctuations through the Fast Fourier Transform reveals a spectrum of behavioral patterns. Various methodologies, including time series analysis, fast Fourier transform, and phase space with attractors, are employed to assess the dynamics of laser output. The dynamics are evaluated using time series data of output intensities or power, as well as three-dimensional phase space representations.

Keywords: Quantum dot laser, External optical feedback, Chaotic dynamics.

1. Introduction

The study of optical feedback effect for quantum dot laser (QDL) for the research by explaining its context and motivations. It starts with a look at the main features and challenges of fiber-optic communication networks. Next, it provides a brief history of quantum dot lasers (QD), pointing out their potential in optical communications. The section then introduces QD lasers and discusses significant advancements in the field. The focus of the thesis is on using the unique properties of QDs, especially in QD lasers with external control, to create new integrated photonics solutions [1-3].

These solutions aim to develop all-optical wavelength converters, isolator-free transmitters, and low phase noise oscillators. The field has made significant advances, particularly with hetero-structure and quantum well laser designs. In the 1970s, the introduction of bulk hetero-structure semiconductor lasers improved the control of carriers in the active area [4,7].

The double hetero structure has been key in moving semiconductor lasers from labs to real-world. Quantum confinement happens when the size of the - is close to the de Broglie wavelength of carriers, which is usually around 10 nanometers, and many applications for quantum dot devices [8-12]. External optical feedback is a well-known method to adjust laser dynamics. In some laser systems, feedback strength may cause complex applications. The study the dynamics of quantum dot (QD) lasers under external optical feedback. This effect alters the density of states and divides the energy bands of bulk semiconductors into separate energy levels [12-16].

2. Theoretical analysis of external optical feedback:

Conventional Optical Feedback is utilized in a laser diode by reflecting a segment of the emitted light back into the laser cavity. As depicted in Figure 1, this optical feedback is accomplished by placing a mirror in the path of the beam [9-11]. The distance from the laser to the mirror, referred to as, is associated with the external round-trip time in the external cavity, which is defined as follows [13-15]:

$$\tau_{ext} = \frac{2\, n_{ext}\, L_{ext}}{c}$$

The refractive index of the external cavity is represented by $next$, and c signifies the speed of light. In practical scenarios, the reflectivity of the re-injecting facet, denoted as R, is generally greater than zero. Consequently, the reflected light may experience multiple round-trips within the external cavity. This configuration can present considerable difficulties, especially in the case of short external cavities, as it effectively extends the beam's travel path.

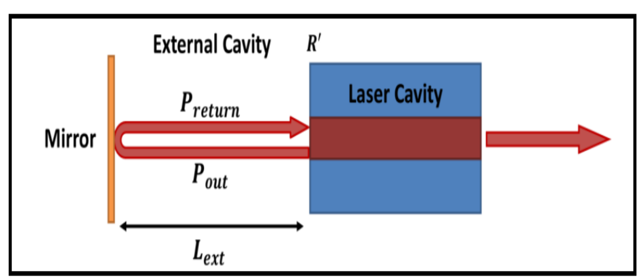

Fig. 1: Diagram illustrating a semiconductor laser experiencing conventional optical feedback (COF).

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The strength of feedback can be defined by the ratio of the output power ($Pout$) emitted from the laser facet that receives optical feedback to the power that is reflected back ($Preturn$),

$$r_{ext} = \frac{P_{return}}{P_{out}}$$

The forthcoming discussion will demonstrate the significant impact of feedback intensity, mirror reflectivity, and the distance to the reflection point on the behavior of the laser. By considering $\tilde{A}(t)=A(t)\exp(i\Phi(t))$, where $A(t)$ and $\Phi(t)$ represent the amplitude and phase of the field respectively [6], it becomes evident how these factors interact. When external feedback is introduced, there is a reduction in carrier density, which in turn decreases the lasing threshold. Other research, R. Lang and K. Kobayashi [2] formulated the equation for the threshold current with optical feedback, taking into account multiple round trips within the external cavity [16-20]. The rate equations for the system of QDL under optical feedback are given by the following equations:

$$\frac{dA(t)}{dt} = \frac{1}{2}\Gamma G_N \left[(N(t) - N_{tr}) - \frac{1}{\tau_p}\right] A(t) + kA(t - t_{ext})\cos\theta(t) \quad (1)$$

$$\frac{d\phi(t)}{dt} = \frac{1}{2}\alpha_H \Gamma G_N \left[(N(t - N_{tr}) - \frac{1}{\tau_p}\right] - k\frac{A(t - \tau_{ext})}{A(t)}\sin\theta(t) \quad (2)$$

$$\theta(t) = w_\circ \tau_{ext} + \phi(t) - \phi(t - \tau_{ext}) \quad (3)$$

$$\frac{dN(t)}{dt} = \frac{n_i I}{q\,V} - \frac{N(t)}{\tau_c} - G_N(N(t) - N_{tr})A^2(t) \quad (4)$$

where Γ is confinement factor, G_N is gain, τ_p is photon lifetime, k is feedback strength, α_H is linewidth enhancement factor, η_i is internal efficiency , I is injection current, q is electron charge, υ_g the group velocity, v is volume of active medium and τ_c is electron lifetime. $f_{ext} = \frac{c}{2L_{ext}}$ is the frequency of the external cavity. where k is the feedback coefficient given by [10]:

$$\kappa = \frac{1}{\tau_{in}} 2C_l\sqrt{r_{ext}} \quad \text{where} \quad C_l = \frac{1-R_2}{2\sqrt{R_2}}$$

3. Results

The rate equations of system for QDL under external optical feedback are solved by matlab program with (dde23 method). Table.1 acted the parameters of the system with effect of factors of external optical feedback on QDL. Decreasing the external cavity length (L_{ext}) leads to time series behavior for (photons output) as shown in figure (2), Fast Fourier Transform with establishes the scenario with decreasing the L_{ext} that leads to more modes at chaotic behaviors, as shown in figure (3) and phase space with decreasing L_{ext} that leads to many modes are oscillated is shown in figure(4).

Table 1: Parameters of the system of QDL under optical feedback

Symbol	Physical meaning	Value
Γ	confinement factor	1×10^{-4}
G_N	Gain coefficient	$4cm^{-1}$
τ_p	photon lifetime	10.6×10^{-12} sec
r_{ext}	feedback strength	0.016
α_H	Line-width enhancement factor	2
η_i	injection efficiency	1.2×10^{-12} sec
τ_c	electron lifetime	1.2
V	volume of active medium	$30\times10^{-18}\,cm^{-3}$
I_{th}	Threshold current	96.5 mA

The behavior of Quantum Dot Semiconductor Lasers with a short External Cavity subjected to Optical Feedback is analyzed. This study emphasizes the effects of the short external cavity length on the performance of QDL. The governing rate equations for the dynamics of QDL are solved using numerical techniques. Simulation findings reveal that photon density exhibits a strong sensitivity to changes in the short external cavity length. This research illustrates that the dynamics of QDL are notably affected by the short external cavity length, particularly in the realm of optical feedback within chaotic communication lasers.

The rate equations for Quantum Dot Lasers (QDL) subjected to external optical feedback are solved through a MATLAB program utilizing the dde23 method. The parameters of the system are detailed in Table.1, which emphasizes the effect of external optical feedback on QDL performance. A decrease in the external cavity length L_{ext} produces a time series response in the photon output, as demonstrated in Figures (2a –(stable behavior), 2b- (periodic behavior), 2c- (self-pulsating) and 2d - (nonlinear or chaotic behavior)).

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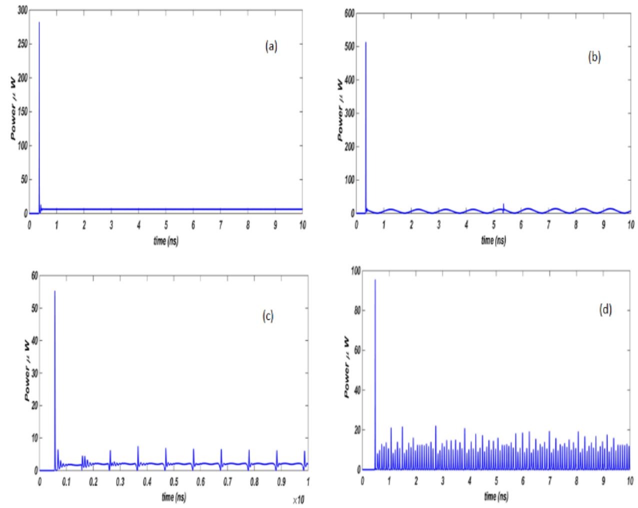

Fig. 2: Time behavior for QDL under eternal optical feedback when external cavity length: a. $L_{ext} = 25\,cm$, b. $L_{ext} = 17\,cm$, c. $L_{ext} = 10\,cm$ and d. $L_{ext} = 3\,cm$.

The nonlinear dynamics observed in quantum dot lasers under optical feedback present a significant potential for chaos. We illustrate a system of optical feedback that functions on high-frequency, specifically complex, chaotic dynamics, which are induced by external cavity modes. The process involves transforming a signal into its distinct spectral components, thereby yielding frequency information regarding the signal. Fast Fourier Transform (FFT) are employed for fault analysis, quality assurance, and the monitoring of machine or system conditions. The application of the Fast Fourier Transform reveals that this reduction L_{ext} corresponds to an increase in the number of modes displaying chaotic behavior, as illustrated in Figures (3a –(stable behavior), 3b- (periodic behavior), 3c- (self-pulsating) and 3d - (nonlinear or chaotic behavior)) where the Fast Fourier transform (spectrum modes frequencies), these variations yield a variety of behaviors..

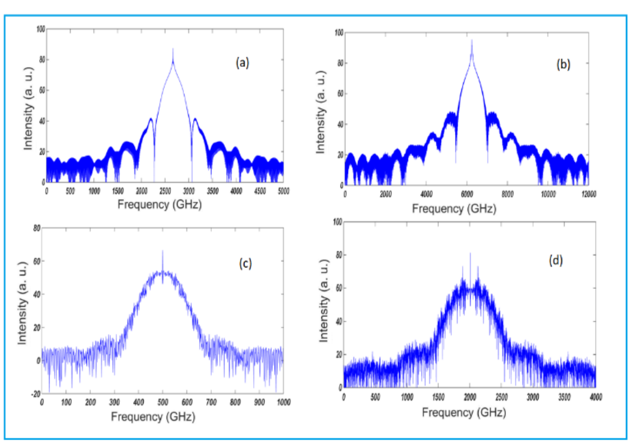

Fig. 3: Fast Fourier transform FFT under eternal optical feedback when external cavity length a. $L_{ext} = 25\,cm$, b. $L_{ext} = 17\,cm$, c. $L_{ext} = 10\,cm$ and d. $L_{ext} = 3\,cm$.

The behavior of quantum dot (QD) lasers is examined within the time domain. Utilizing the phase space method, a recognized analytical approach in applied mathematics, offers a more thorough understanding of the dynamics associated with semiconductor lasers. This phase space analysis serves as one of the techniques to evaluate the dynamics of QD lasers.

A semiconductor laser subject to optical feedback can be described by means of rate equations, which are mathematically constructed delay differential equations with an infinite dimensional phase space. This explains why this system has only been studied through numerical simulation up to this point from a theoretical standpoint. Using new numerical techniques for, namely the computation of unstable manifolds and the continuation of periodic orbits, we study bifurcations and paths to chaos in the system. The phase space analysis indicates that a shorter external cavity length leads to the emergence of multiple oscillating modes, as represented in figure (4). The dynamics are tested using time series of output intensities or power and phase space (three-dimensional figures) as shown in Figures (4a –(stable behavior), 4b- (periodic behavior),4- (self-pulsating) and 4d - (nonlinear or chaotic behavior)).

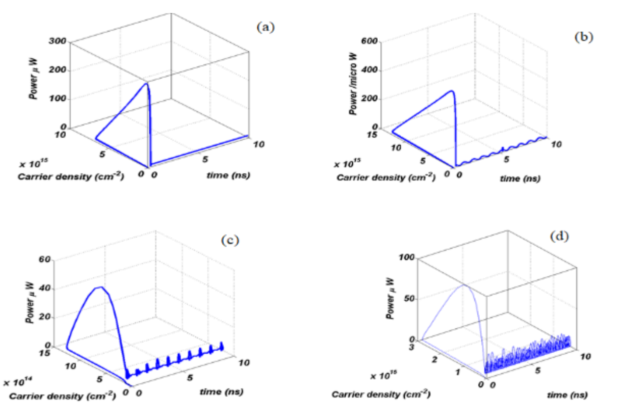

Fig. 4: Phase space (3D) under eternal optical feedback when external cavity length: a. $L_{ext} = 25\,cm$, b. $L_{ext} = 17\,cm$, c. $L_{ext} = 10\,cm$ and d. $L_{ext} = 3\,cm$.

4. Conclusions

The investigation of figures (2-4) shows that when the external cavity length is changed, chaotic behavior appears as the length decreases. This observation is consistent with a number of studies. The external frequency is affected by the length reduction, leading to the creation of nonlinear or chaotic frequency modes. The delay time (external feedback time) for the round-trip time between the laser cavity and external mirror is impacted by changes in the length of the external cavity; a shorter delay time results in the creation of modes that interact with modes inside the cavity. With the Fast Fourier transform (spectrum modes frequencies), these variations yield a variety of behaviors. The dynamics are tested using time series of output intensities or power and phase space (three-dimensional figures). The routes to reach the complex chaotic state agree in the three test cases in the results.

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