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Dynamics of Quantum Dot Laser with Direct Current Injection Density Modulation

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Abstract:
In this work, the dynamics of quantum dot laser are studied. Turn on dynamics with increasing the injection current density leads to increase the laser output and carriers in quantum dot level. The system under the effect of direct current modulation appears various dynamics with variation of control parameters of modulation (m, b, f_m). The scenario will be finished in the steady state to periodic, chaotic and spiking behavior with increasing the modulation frequency and return to steady state. Carriers are increasing in wetting layer with increasing the temperature.

Key words: *Quantum dot laser, Injection current modulation, Dynamics.*

1-Introduction:

Semiconductor quantum dot laser (QDL) is a recent class of laser sources which is an alternative to the conventional bulk and quantum well lasers [1]. In the development of laser sources an important step concerns the modeling of the devices to be realized, and this requires the use of good methods able to incorporate various physical phenomena present in real devices [2]. The implementation of a quantum dot laser simulator and apply it to simulate the switching-on behavior and other characteristics of a real quantum dot laser source.

The description here presented intends to be a help for teaching or even basic-research in that particular field of optoelectronics [3-5]. The understanding of quantum-dot semiconductor lasers is a great current interest. Because these materials have discrete energy. Transitions, one could expect symmetric emission lines and therefore a low a factor. This has motivated many studies, with expected benefits including elimination of chirp in high-speed applications, broad-area devices operating without filamentation, and lasers that are insensitive to optical feedback. Bulk and quantum-well semiconductor lasers exhibit high sensitivity to back reflections, with optical isolators being required in many applications [3-6]. Many forms of dynamic behavior are possible under these conditions. Analysis of rate equation models for external-cavity lasers has shown that a factor, the laser relaxation oscillations, and the external-cavity round-trip time are important parameters for the appearance of these instabilities [8-9].

2-Theroetical model:

A simple description of laser operation can be achieved using rate equations for carriers (electrons and holes) and photons [208,209], which describe the interaction of electrons and photons by stimulated and spontaneous emission mechanisms as well as the pump process. Besides the low threshold of a laser also its ultimate modulation speed is a very important parameter for data communication applications. According to the expected higher gain g and differential gain ∂g/∂N [5,6] the modulation bandwidth of a dot laser should overcome the modulation bandwidth of a QW. There are dynamical effects that occur with increasing injection current density. The shift of the device temperature inside an electrically pumped optical amplifier (with identical active region) is affected by changing the injection current density [6,7] .

Rate equations

The rate equations that describe the model of QD laser [7]:

$$\dot{S} = -\frac{S}{\tau_s} + g_0 v(2\rho - 1)S$$

$$\dot{\rho} = -\frac{\rho}{\tau_d} - g_0 v(2\rho - 1)S + F(N, \rho)$$

$$\dot{N} = J - \frac{N}{\tau_n} - 2N_d F(N, \rho)$$

Where S is the photon density, below threshold the dot population ρ, and thus the gain, saturates as the injection current is increased

$$\rho_{th} = \frac{1}{2} + (2\tau_s g_0 \nu)^{-1}$$

$g_0 = \sigma_{res} v_g$ Where σ_{res} is the cross section of interaction of carriers in the dots with photons;

$\boldsymbol{v_g}$ is the group velocity

ρ is the occupation probability in a dot

τ_s is the photon lifetime

τ_n and τ_d are the carrier lifetime in the well and the dot

N_d is the two-dimensional density of dots

J is the pump

Function $F(N$, r) describes the rate of exchange of carriers between the well and the dots

The system of QDL under direct current modulation is resulted by the relation:

$J_{dc} + J_{ac} \sin(2\pi f t)$ where *ac* current is $J_{ac} = m J_{th}$ and *dc* current $J_{dc} = b J_{th}$; d is dc part, m is modulation depth and f_m is the modulation frequency

3-Results and discussion:

The dynamics of QDL are studied and analysis for turn on case and the system with the effect of direct current modulation operator:

Table (1): Parameters used in the simulation

Symbol	Value
C	10^{-20} m^4/s
R_{esc}	0
B	0
N_d	$2*10^{15}$ m^{-2}
ϑ	$2.4*10^{22}$ m^{-3}
$\tau_n = \tau_d$	1 ns
τ_s	3 ps

a- Turn-on dynamics: In this part of results, we introduce the free running laser output and carriers, variation with increasing the injection current density. From the following results, we see that the output increases with increasing the injection current density as shown in figures (1,2 and 3). The threshold injection current density($j_{th} = 4.3 \times 10^5 A/m^2$

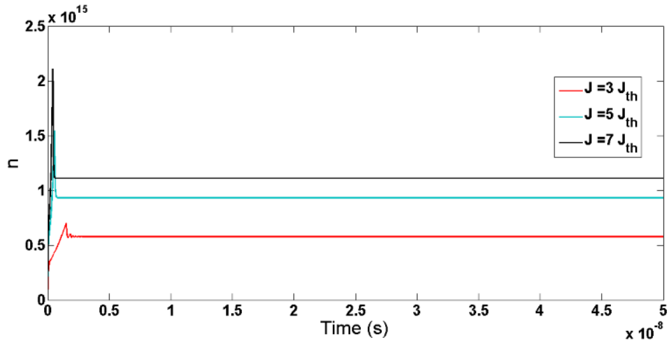

Figure (1): Time behavior of carrier density in wetting layer at different values of injection current density (J= 3J$_{th}$; J= 5J$_{th}$; J= 7J$_{th}$).

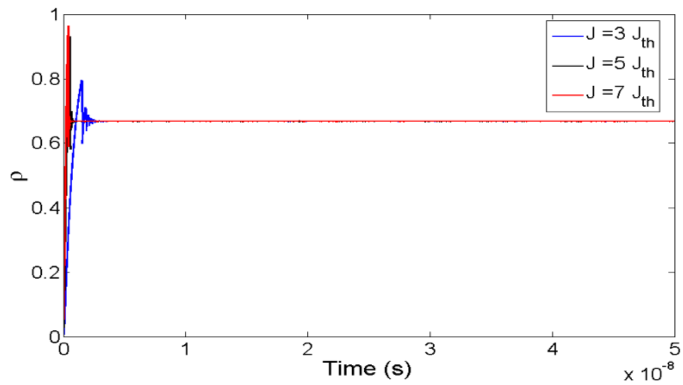

Figure (2): Time behavior of the occupation probability in a dot; at different values of injection current density (J= 3J$_{th}$; J= 5J$_{th}$; J= 7J$_{th}$).

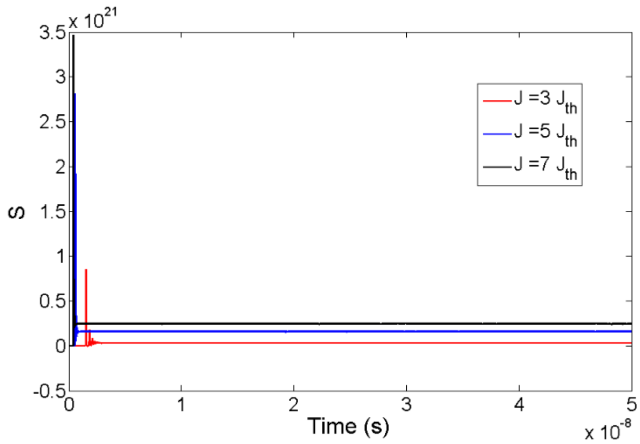

Figure (3): Time behavior of the photon density at different values of injection current density ($J= 3J_{th}$; $J= 5J_{th}$; $J= 7J_{th}$).

b-The system with injection current modulation appears many behaviors such as steady state, periodic and spiking (self-pulsing) with different values of control parameters, as follows:

1- Steady state time behavior of: (i) the photon density ; (ii) carrier density in wetting layer and (iii) the occupation probability in a dot under the direct current modulation with modulation parameters (b= 2 ; m=0.1 ; f_m =0.5GHz), as shown in figure (4).

2- Figure (5) represents to periodic time behavior of: (i) the photon density; (ii) carrier density in wetting layer and (iii) the occupation probability in a dot under the direct current modulation with modulation parameters (b=2, m=0.1 and increasing the modulation frequency f_m = 1GHz).

3- Figure (6) shows to periodic time behavior of: (i) the photon density; (ii) carrier density in wetting layer and (iii) the occupation probability in a dot under the direct current modulation with modulation parameters (b=2, m=0.1 and f_m = 5GHz).

4- Figure (7) refers to periodic time behavior of: (i) the photon density; (ii) carrier density in wetting layer and (iii) the occupation probability in a dot under the direct current modulation with modulation parameters (b=2, m=0.1 and f_m = 10GHz).

5- Figure (8) denotes to periodic time behavior of: (i) the photon density; (ii) carrier density in wetting layer and (iii) the occupation probability in a dot under the direct current modulation with modulation parameters (b=2, m=0.5 and f_m = 0.1GHz)

6- Periodic time behavior of: (i) the photon density; (ii) carrier density in wetting layer and (iii) the occupation probability in a dot under the direct current modulation with modulation parameters (b=2; m=0.5; f_m = 0.5GHz), is seen in figure (9).

7- Chaotic time behavior of: (i) the photon density; (ii) carrier density in wetting layer and (iii) the occupation probability in a dot under the direct current modulation with modulation parameters (b=2; m=0.5; f_m = 0.1GHz) is noticed in figure (10).

8- Periodic time behavior of: (i) the photon density; (ii) carrier density in wetting layer and (iii) the occupation probability in a dot under the direct current modulation with modulation parameters (b=2; m=0.5; f_m = 20GHz) is appeared in figure (11).

9- Spiking (self-pulsing) time behavior of the photon density under the direct current modulation with modulation parameters (b=2; m=0.9; f_m = 0.1GHz) is shown in figure (12).

10- Spiking (self-pulsing) time behavior of the photon density under the direct current modulation with modulation parameters (b=2; m=0.9; f_m = 0.5GHz) is appeared figure (13).

11- Time behavior of the photon under the direct current modulation with modulation parameters (b=2; m=0.9 and f_m = 1GHz) is shown in figure (14).

12- Time behavior of the photon density under the direct current modulation with modulation parameters (b=2; m=0.5; f_m = 25GHz) is appeared in figure (15).

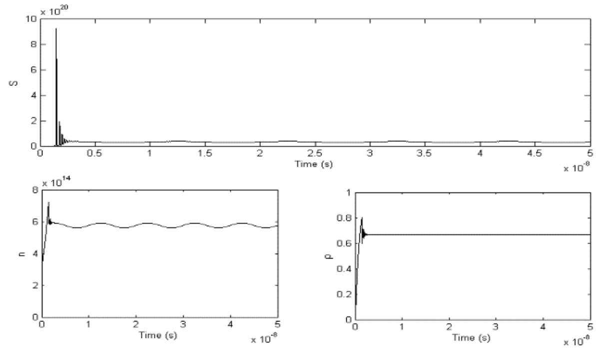

Figure (4): Time behavior of: (i) the photon density; (ii) carrier density in wetting layer and (iii) the occupation probability in a dot under the direct current modulation with modulation parameters (b= 2; m=0.1; f_m =0.5GHz).

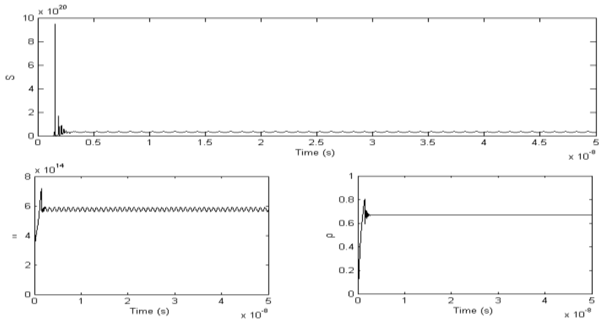

Figure (5): Time behavior of: (i) the photon density; (ii) carrier density in wetting layer and (iii) the occupation probability in a dot under the direct current modulation with modulation parameters (b=2; m=0.1; f_m = 1GHz).

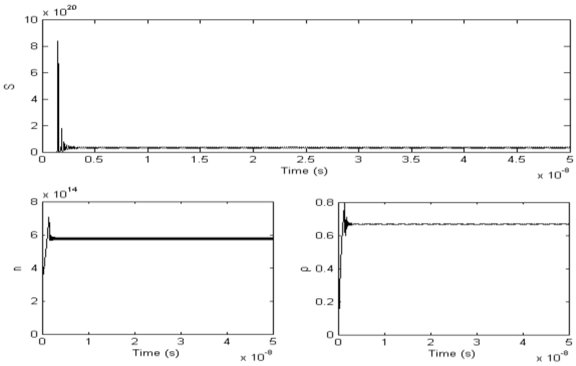

Figure (6): Time behavior of: (i) the photon density; (ii) carrier density in wetting layer and (iii) the occupation probability in a dot under the direct current modulation with modulation parameters (b=2; m=0.1; f_m = 5GHz)

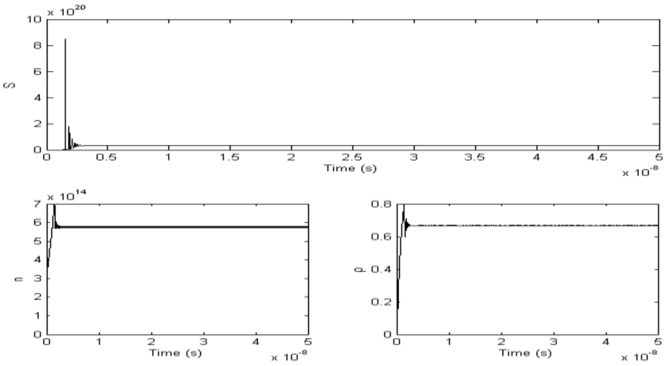

Figure (7): Time behavior of: (i) the photon density; (ii) carrier density in wetting layer and (iii) the occupation probability in a dot under the direct current modulation with modulation parameters (b=2; m=0.1; fm = 10GHz)

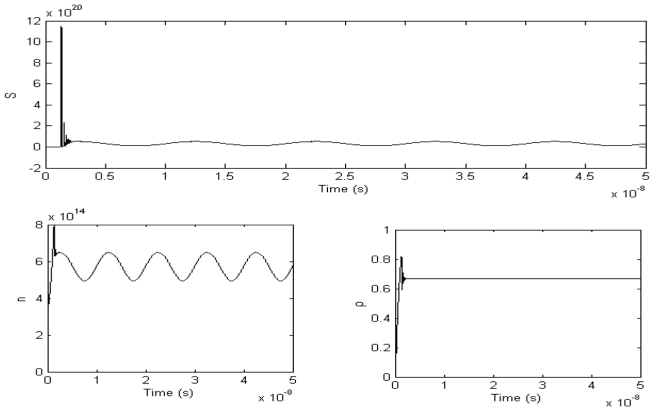

Figure (8): Time behavior of: (i) the photon density; (ii) carrier density in wetting layer and (iii) the occupation probability in a dot under the direct current modulation with modulation parameters (b=2; m=0.5; f_m = 0.1GHz)

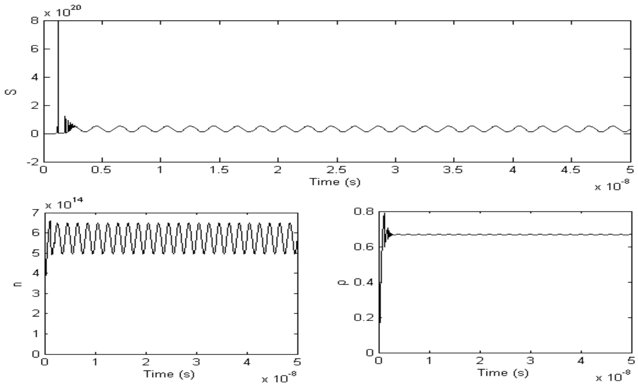

Figure (9): Time behavior of: (i) the photon density; (ii) carrier density in wetting layer and (iii) the occupation probability in a dot under the direct current modulation with modulation parameters (b=2; m=0.5; f_m = 0.5GHz)

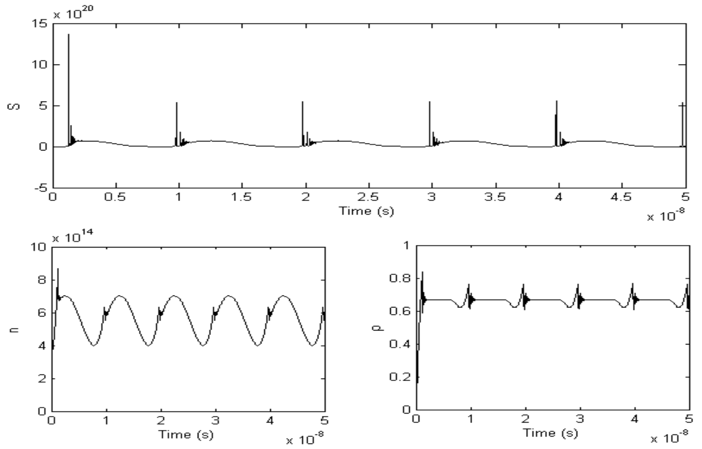

Figure (12): Time behavior of: (i) the photon density; (ii) carrier density in wetting layer and (iii) the occupation probability in a dot under the direct current modulation with modulation parameters

(b=2; m=0.9: f_m = 0.1GHz)

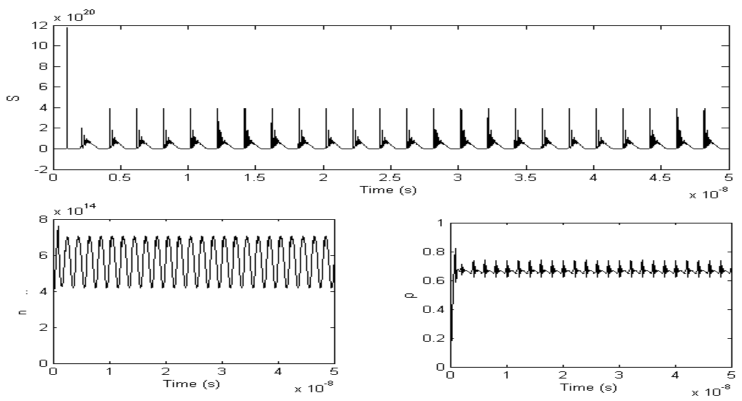

Figure (13): Time behavior of: (i) the photon density; (ii) carrier density in wetting layer and (iii) the occupation probability in a dot under the direct current modulation with modulation parameters

(b=2; m=0.9; f_m = 0.5GHz)

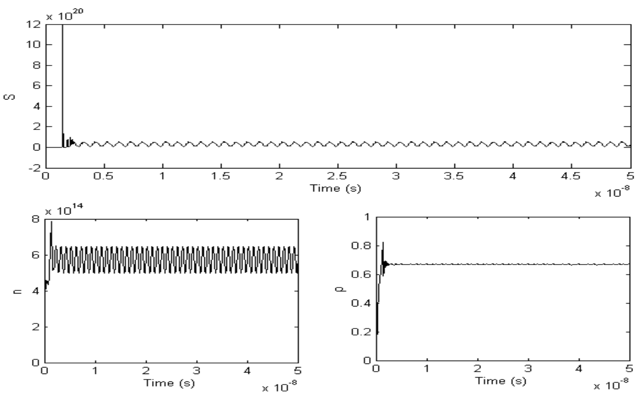

Figure (14): Time behavior of: (i) the photon density; (ii) carrier density in wetting layer and (iii) the occupation probability in a dot under the direct current modulation with modulation parameters

(b=2; m=0.9; f_m = 1GHz)

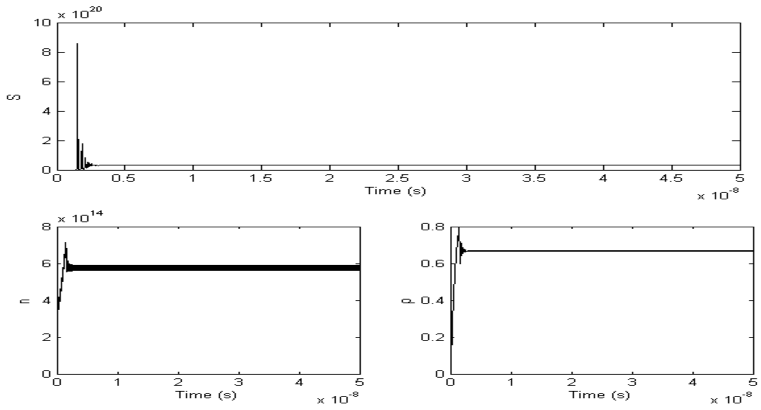

Figure (15): Time behavior of: (i) the photon density; (ii) carrier density in wetting layer and (iii) the occupation probability in a dot under the direct current modulation with modulation parameters (b=2; m=0.5; f_m = 25GHz)

The relation between the carrier density in wetting layer (n) and temperature (T) is given by the following relation: $\mathbf{T = 300K + 0.245.10^{12} nm^{8} (n)^{4}}$

Where the effect is appeared as in figure (16), the carrier density in wetting layer increasing with rising the temperature.

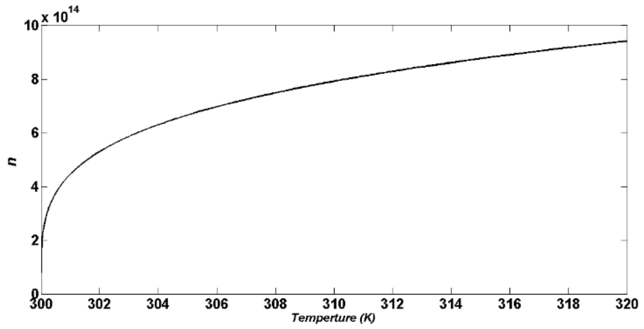

Figure (16): The variation of carrier in wetting layer with increasing the temperature.

4-Conclusions:

From the results, one has found that free-running dynamics is shown with increasing the injection current density remarks to rise the laser output and carriers in quantum dot level. The model under the effect of direct current modulation appear various dynamics with difference of control limits of modulation. The steady state to periodic, chaotic and spiking performance is obtained with increasing the modulation frequency and so arrival to steady state. The increasing of carriers in wetting layer is done with rising the temperature.

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