International Journal of Applied and Natural Sciences (IJANS);
ISSN(P): 2319-4014; ISSN(E): 2319-4022;
Vol. 5, Issue 1, Dec - Jan 2016; 31-38

International Academy of Science, Engineering and Technology
Connecting Researchers; Nurturing Innovations

ATTRACTOR BEHAVIOR OF CARRIERS POPULATION AND PHOTON-ASSISTED POLARIZATION IN SEMICONDUCTOR QDL

RA'ED M. HASSAN

Department of Physics, College of Education for Pure Science, University of Basrah, Basrah, Iraq

ABSTRACT

The pump rate is one of control parameters in the quantum dot laser (QDL). In the present work, we study the effect of this parameter on the dynamical characteristics and carrier's population of a CW InGaAs/GaAs semiconductor QDL output. The operation lasing with CW wavelength of 1.3μm at room-temperature is including the photon-assisted polarization contribution. We studied the variable attractor's dependence of the delay time, rise time, oscillation region time and photon number on the pump rate.

KEYWORDS: Quantum Dot laser, QD Carrier Populations, Photon-Assisted Polarization, Attractor Behavior

INTRODUCTION

The QDs and the wetting layer (WL) constitute a coupled system with common electronic states. Where free carrier dispersion with effective masses for electrons and holes is assumed, the geometry of this kind of QDs allows for a description within the effective mass approximations [1, 3]. One can consider the first two confined shells of such a system, which are denoted by s and p according to their in-plane symmetry. The s-shell is only spin degenerate, while the p-shell has additional angular- momentum two-fold degeneracy [4]. Although the term sub band is somewhat misleading for the QD case, as these possess only a discrete spectrum due to the additional in-plane confinement. The spectrum of the potential well introduces a splitting into sub bands with a spacing that depends on the strength of the axial confinement [5]. The localized states exist only below the quasi-continuum states of the WL so the discrete states are located energetically below a quasi –continuum of delocalized states, corresponding to the two-dimensional motion of carries in a WL [6, 7]. The localized states and the WL states are solutions of the single-particle problem for one common confinement potential. A characteristic feature of a QD laser is the phase transition from a thermal into a coherent light state as a function of pump rate [8]. The pump rates have to be large and the photon storage time is long in order to achieve threshold [9]. Our aim here, how to gain a deeper understanding of important role of pump rate in the laser dynamics characteristics using a site of master equations of semiconductor QD lasers.

The same argument electrons and holds for the pump rate at which two-level systems are excited. The total number of excited systems is given again by the time integral over the pump rate [10, 11]. The excitation takes place at a constant rate in the CW case, and the total number of two-level excitations scales again with the integration time of the measurement [1, 12]. So the CW result can be shifted relative to the pulsed curves along the diagonal when comparing input/output traces on a logarithmic scale [13].

THE THEORETICAL MODEL

One can use the QD laser master equations model (MEM) including photon-assisted polarization to study the control parameters effects. This model based on four levels system that are available in two pump levels for electron / hole per p-shell and two emission levels for electron / hole per s-shell [14-16]. The QD laser dynamics in this model are based on the following; the laser micro cavity of QD can be considered as a four level system where holes have two levels (s- and p-shell) in valence band and electrons have two levels (s- and p-shell) in conduction band. QD laser procedure includes the direct pumping between p-shell holes to p-shell electrons, then through equilibrium transition between holes state, i.e. holes rise from p-shell to the s-shell in valence band and electrons relaxes from p-shell to s-shell in conduction band. The laser operation occur through the recombination process between descending captured electrons from s-shell and capture of rising holes from s-shell, then the light is emitted. Each of the six variables in the model under investigation has its own dynamics.

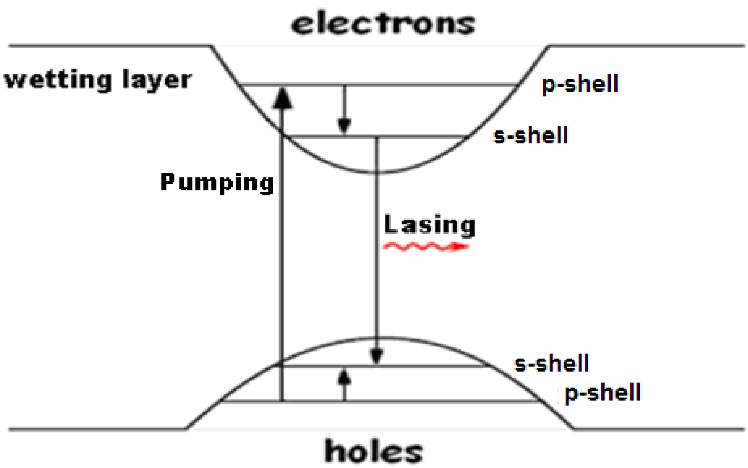


Figure 1: QD Laser Model with Carrier Generation in the p-Shells and the Laser Transition between the s-Shells of Electrons (Top) and Holes (Bottom)

The total Hamiltonian for the system has the following contributions [17]:

$$H_{Total} = H_{Carrier} + H_{Field} + H_{Coulomb} + H_{Interaction} \tag{1}$$

Where $H_{Carrier}$ is the free carrier Hamiltonian, which contains information about the single-particle spectrum and describes a system of non-interacting charge carriers. $\mathcal{H}_{Field}$ Is the total energy of the free electromagnetic field Hamiltonian? $H_{Coulomb}$ Is accounted for the Coulomb interaction between the carriers Hamiltonian. $H_{Interaction}$ is the light-matter interaction Hamiltonian in dipole approximation. The transition of an electron from the valence into the conduction bands (or vice versa) by absorption (emission) of a photon is associated with resonant elementary process.

The photon-assisted polarization from this model is formed of the higher-order correlations and ignoring spontaneous emission for the above - threshold solution. For this purpose, we can use the stationary limit of MEM are given as [15, 16]:

$$\dot{f}_{photon}(t) = -\frac{2k}{\hbar} f_{photon}(t) + \frac{2\tilde{N}}{\beta\hbar}\tilde{O}A_s(t) \tag{2}$$

$$\dot{f}_s^{\,e}(t) = -2\frac{\sigma\tilde{O}}{\hbar}A_s(t) - \gamma_s(1-\beta)f_s^{\,e}(t)f_s^{\,h}(t) + \gamma_\perp^e(1-f_s^{\,e}(t))f_p^{\,e}(t) \tag{3}$$

$$\dot{f}_s^{\,h}(t) = -2\frac{\sigma\tilde{O}}{\hbar}A_s(t) - \gamma_s(1-\beta)f_s^{\,e}(t)f_s^{\,h}(t) + \gamma_\perp^h(1-f_s^{\,h}(t))f_p^{\,h}(t) \tag{4}$$

$$\dot{f}_p^{\,e}(t) = P(t)(1-f_p^{\,e}(t)-f_p^{\,h}(t)) - \gamma_p f_s^{\,e}(t)f_s^{\,h}(t) - \gamma_\perp^e(1-f_s^{\,e}(t))f_p^{\,e}(t) \tag{5}$$

$$\dot{f}_p^{\,h}(t) = P(t)(1-f_p^{\,e}(t)-f_p^{\,h}(t)) - \gamma_p f_s^{\,e}(t)f_s^{\,h}(t) - \gamma_\perp^h(1-f_s^{\,h}(t))f_p^{\,h}(t) \tag{6}$$

$$\dot{A}_s(t) = -\frac{(k+\eta)}{\hbar}A_s(t) + \frac{1}{\hbar}f_s^{\,e}(t)f_s^{\,h}(t) - \frac{1}{\hbar}(1-f_s^{\,e}(t)-f_s^{\,h}(t))f_{photon}(t) \tag{7}$$

where $f_{photon}(t)$ is photon number, $f_s^{\,e,h}(t)/f_p^{\,e,h}(t)$ is electron / hole populations of s-shell (p-shell), $A_s(t)$ is the photon-assisted polarization, $P(t)$ is the pump rate, k is the total cavity loss, σ is the dynamical delay factor (which one of the structure parameters that is a ratio of the doping barriers in quantum dots [15]), β is the spontaneous emission coupling factor, η is a phenomenological dephasing, $\gamma_{s,p}$ is s-shell (p-shell) spontaneous emission rate into non-lasing modes, and $\gamma_\perp^{e,h}$ is electron (hole) spontaneous emission rate into lasing modes. $\tilde{O}$ is absolute value square of the coupling between the mode and the carrier transition.

In the following we shall use the site of QD semiconductor laser MEM (2)-(7) to compute numerically and study the dynamical characteristics with contribution of pump rate effect in InGaAs /GaAs QD lasers. This system includes the time variation of $f_{photon}(t)$ in the QD laser cavity, photon-assisted polarization $A_s(t)$, and carrier's populations of electron / hole ($f_s^{\,e,h}(t)$ / $f_p^{\,e,h}(t)$ respectively). Those variables are functions to various parameters (i.e. control parameters). The pump rate is one of the important time dependent parameter.

The pump rate $P(t)$ is either a constant value in case of pulsed excitation of the time-dependent pump pulse, or in the case of CW excitation [18]

$$P(t) = \frac{\overline{P}e^{-\frac{1}{2}(\frac{t}{\Delta t})^2}}{\sqrt{2\pi}\Delta t} \tag{8}$$

Where Δt is a pulse width (pulse duration) and $\overline{P}$ is the pump pulse area, which is directly corresponds to the number of two-level systems excited by the pulse.

To control the dynamical interaction between carrier and the laser mode, parameter $P(t)$ in Eqs. (3) Play an important role to properties of QD laser. The tide denotes the photon number outside the cavity so that the total number of excited systems is given again by the time integral over $P(t)$, yielding $\overline{P}$ [15, 16]. The system is excited at a constant rate in a CW case, and after the switch-on dynamics that a stationary state is reached where the rate of emitted photons per time is constant. The signal at the detector is nevertheless integrated over a time window so that the collected photon number scales directly with the integration time [18-20].The excitation takes place at a constant rate, and the total number of two-level excitations scales again with the integration time window of the measurement.

THE RESULTS AND DISCUSSIOND

To begin, we present numerical solutions of the extended QD semiconductor laser based on MEM (2–7). One can solve this scheme by using the Mathematica software. The pump rate play very clear role to determine the characteristics of QD laser such as: the field, the delay time and oscillation region time of QD laser output. The delay time is inherent to occur between pumping process and building the enough population inversion, which leads to the gain and then the production of electromagnetic field. Figure 1 represents the variation of photon number as a function of this factor.

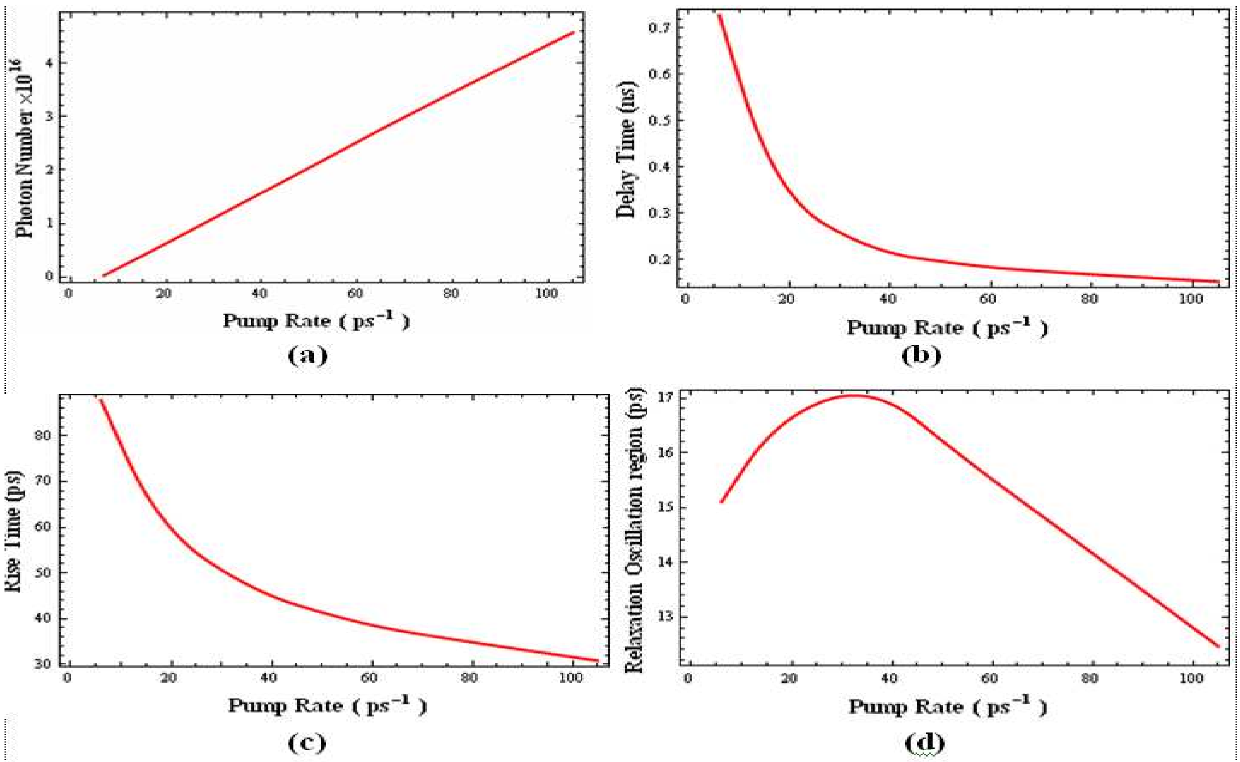
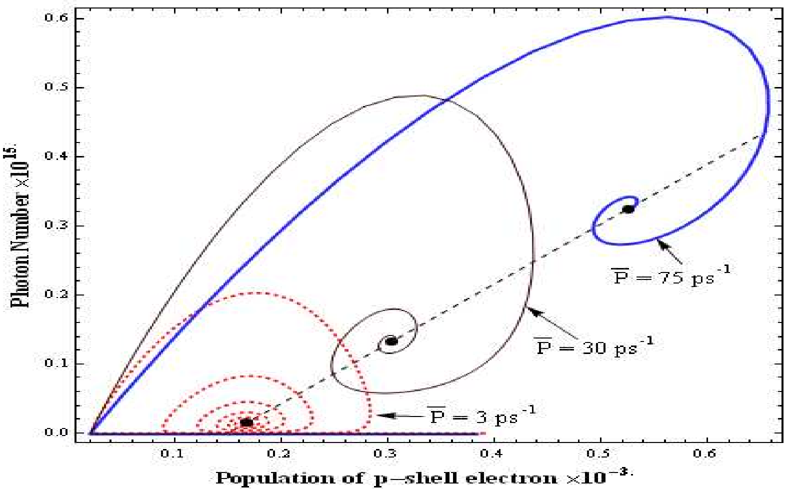


Figure 2: Dynamical output characteristics of InGaAs /GaAs QDL at 1.3 µm wave-length as function of pump rate: (a) photon number, (b) delay time, (c) rise time, and (d) relaxation oscillation region. The parameters used [14]: $k = 20\ \mu eV$, $\sigma = 6.58\times10^{-16}$, $\eta = 10\ \mu eV$, $\tilde{O} = 324\ \mu eV^2$, $\gamma_s = 50\ ps$, $\gamma_p = 2\ fs$, $\gamma_\perp^e = 1.\ ps$, $\gamma_\perp^h = 5.ps$

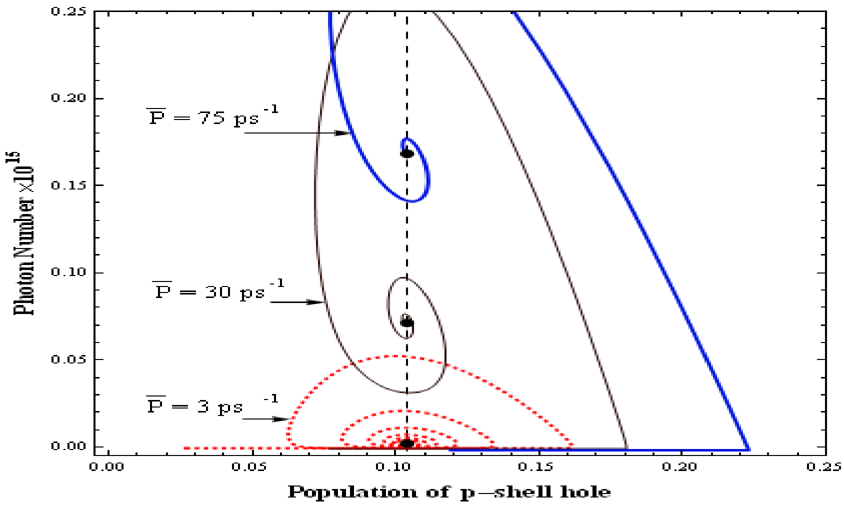
Above threshold, our theoretical results of the dynamical characteristics of CW InGaAs/GaAs QDL find the relation between the rate of pumping and the photon number is a linear as shown in Figure 1 (a). With the varying pump rate, the delay time decreases exponentially as can be seen in Figure 1 (b). In Figure 1 (c), the situation is similar to the rise time behavior. The instable increase of relaxation oscillation region increases with the increase of pump rate even up to the point of a coup when the pump rate value 33 ps^{-1} then decreases with farther increase as shown in Figure 1 (d).

During study of attraction between the population of pumping states and the photon number in Figure 2, we find that the effect of increasing the pumping reduces the number of fluctuations in the attractor with increase in the population of p-shell electron and photon number at steady state as shown in Figure 2 (a). As well as the least attractor, there is instable in the fluctuations of population of p-shell hole and the photon number increase at steady state with increase in pump rate. But that survival population of p-shell hole count in the amount of (0.104) as shown in Figure 2(b).

The theoretical results of attraction between the population of lasing stats and the photon number are shown in Figure 3. In Figure 3 (a), we found out states, the increase in pumping rate do reduce the fluctuation of population of s-shell electron attractor. Whenever, this parameter increases in photon number with survival situation the population of s-shell electron at the value (0.104). While the attractor declining to become a linear relationship of the population of s-shell hole with the increase in the pump rate of as shown in Figure 3 (b).



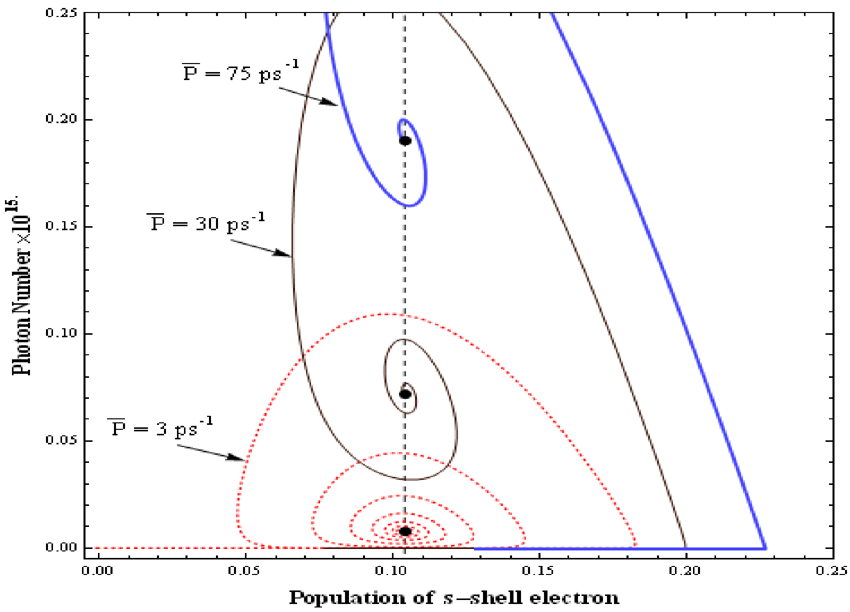
(a)



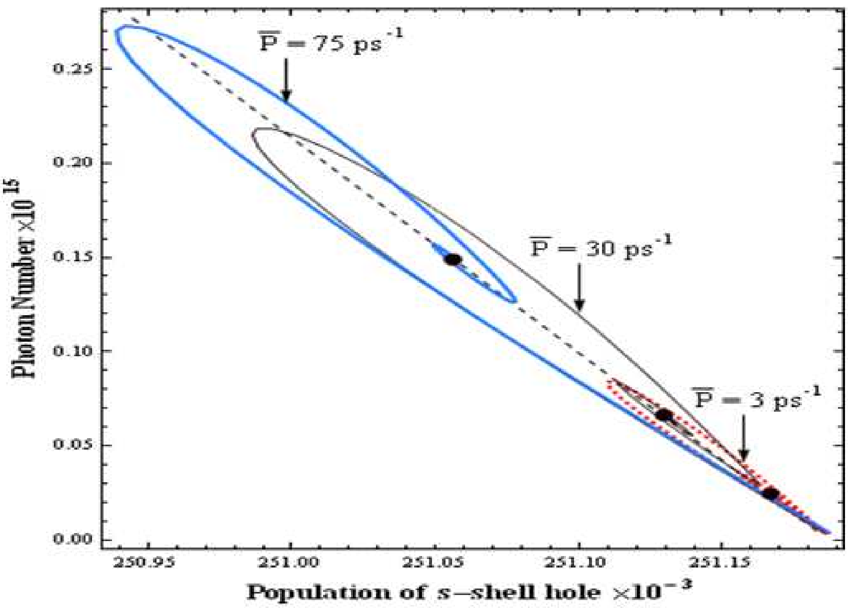
(b)

Figure 3: The Attractor between Population of Pump States $f_p^{e,h}$ and Photon Number of InGaAs/GaAs QDL at 1.3 µm Wave-Length: (a) Population of p-Shell Electron and (b) Population of p-Shell Hole for Different Values of Pump Pulse Area ($\overline{P}$): 3ps^{-1} (Dotted Curve), 30ps^{-1} (Thin Curve), and 75ps^{-1} (Thick Curve). The Black Point is the Fixed Point of the Attracter Curve in Steady State and the Dashed Line Illustrates the Pump Rate Effect on the Fixed Points

The theoretical results of attraction between the population of lasing stats and the photon number are shown in Figure 4. In Figure 4 (a), we found out states, the increase in pumping rate do reduce the fluctuation of population of s-shell electron attractor. Whenever, this parameter increases in photon number with survival situation the population of s-shell electron at the value (0.104). While the attractor declining to become a linear relationship of the population of s-shell hole with the increase in the pump rate of as shown in Figure 4 (b).



(a)



(b)

Figure 4: The Attractor between Population of Lasing States $f_s^{e,h}$ and Photon Number of InGaAs/GaAs QDL at 1.3 µm Wave-Length: (a) Population of s-Shell Electron and (b) (a) Population of s-Shell Hole for Different Values of Pump Pulse Area ($\overline{P}$): 3ps^{-1} (Dotted Curve), 30ps^{-1} (Thin Curve), and 75ps^{-1} (Thick Curve)

The study of the attraction between photon-assisted polarization and the photon number is shown in Figure 4. This is explaining a linear increase of photon-assisted polarization via the pump rate at the steady state. Due that linear increase is follows the variations of the electro-magnetic field (photon number) [16]. So, this former is a function of the later suggesting the correctness of the obtained results for the parameters used.

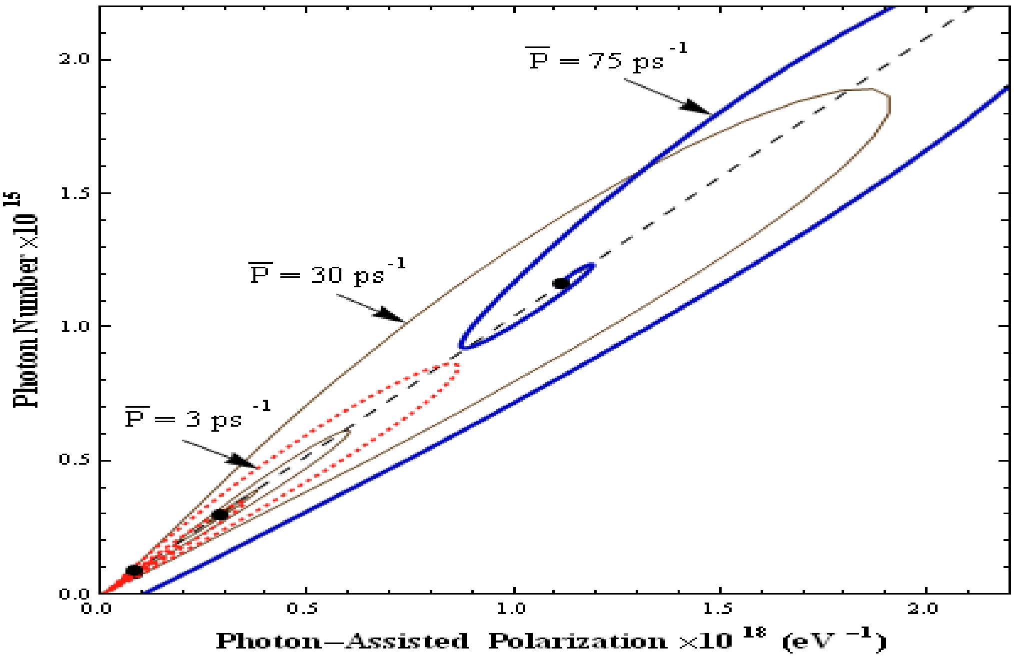


Figure 5: The Attractor between Photon-Assisted Polarization and Photon Number of InGaAs/GaAs QDL at 1.3 µm Wave-Length for Different Values of Pump Pulse Area ($\overline{P}$): 3ps^{-1} (Dotted Curve), 30ps^{-1} (Thin Curve), and 75ps^{-1} (Thick Curve)

CONCLUSIONS

The theoretical results given in this work provide a deeper understanding of the effect of increasing the pump rate on the attractor dynamics of pump, lasing populations and CW output lasing of QDL with wavelength of 1.3 µm at room-temperature. We find that the increase in this rate affect the system carrier's dynamics generally at steady state. The pump rate has effect on the attractor population of p-shell electron positively linear. On the contrary, it has effect on the attractor population of s-shell hole negatively linear. The other populations (p-shell hole and s-shell electron) settled at a fixed amount (which depended on the parameters used) with a linear increase in direct QDL output. So we can see an act of the QDL, there is stability of the lower level population attractor of lasing states ($f_s^h(t)$) and the upper level of pumping states ($f_p^e(t)$). At steady state, the pump rate increase will lead to an increase in the population attractor of upper-level population of lasing states (electrons). While, that is lead to decline in the population attractor of lower-level of pump state (holes). The impact of this factor is similar on each of the laser output and photon-assisted polarization.

REFERENCES

1. Alex Zunger, MRS Bulletin 2 (1998) 35-42.

2. P. Harrison, Quantum Wells, Wires and Dots: Theoretical and Computational Physics of Semiconductor

Nanostructures, John Wiley & Sons Ltd, 2005.

3. W.W. Ruhle, S. Hallstein, J.D. Berger, M. Hilpert, H.C. Schneider, F. Jahnke, S.W. Koch, H.M. Gibbs, G. Khitrova, M. Oestreich, phys. stat. sol. (b) 206 (1998) 387-398.
4. H.Z. Song, Y. Tanaka, T. Yamamoto, N. Yokoyama, M. Sugawara, Y. Arakawad, Physics Letters A 375 (2011) 3517–3520.
5. N. Baer, C. Gies, J. Wiersig, and F. Jahnke, Euro. Phys. J. B 50 (2006) 411-418.
6. Herbert Vinck-Posada, Boris A. Rodriguez, Augusto Gonzalez, Physica E 27 (2005) 427–438.
7. M. Lorkea, F. Jahnke, W. W. Chow, Appl. Phys Lett. 90, (2007) 051112(1-3).
8. I. E. Protsenko, A. V. Uskov, O. A. Zaimidoroga, V. N. Samoilov, E. P. O’Reilly, Phys. Rev. A 71 (2005) 063812 (1-7).
9. Kunji Chen, Jian Huang, Zhongyuan Ma, Xiang Wang, Yao Yao, Jiumin Wang, Wei Li, Jun Xu, Xinfan Huang, Phys. Status Solidi C 6(3) (2009) 721–727.
10. S. Sauvage, P. Boucaud, F. Bras, G. Fishman, J.-M. Ortéga, J.-M. Gérard, G. Patriarche, A. Lemaître, phys. stat. sol. (b), 243(15) (2006) 3895-3899.
11. A. Krügel, A. Vagov, V. M. Axt, T. Kuhn,, Physical Review B, 76 (2007) 195302(1-11),
12. M Kaniber, A Neumann, A Laucht, M F Huck, M Bichler, M-C Amann, J. J. Finley, New Journal of Physics, 11 (2009) 013031.
13. P. Borri, W. Langbein, J. Mùrk , J. M. Hvam, F. Heinrichsdorff , M. H. Mao, D. Bimberg, Phys. Stat. Sol. (a), 178 (2000) 337-340.
14. C. Gies, J. Wiersig, M. Lorke, F. Jahnke, Physical Review A, 75 (2007) 013803 (1-11).
15. R. M. Hassan, C. A. Emshary, S. I. Easa, J. Basrah Researches (Science) 37(1) (2011) 8 – 26.
16. R. M. Hassan, C. A. Emshary, S. I. Easa, J.Babylon University, (to be published).
17. T. Feldtmann, L. Schneebeli, M. Kira, S. W. Koch, Phys. Rev. B 73 (2006). 155319 (1-13).
18. C. Gies, J. Wiersig, F. Jahnke, Phys. Rev. Lett., 101, (2008) 067401(1-4).
19. V.V. Zalipaev a, D.N. Maksimov b, C.M. Linton a, F.V. Kusmartsev, Physics Letters A 377 (2013) 216–221.
20. T. Feldtmann, L. Schneebeli, M. Kira, S. W. Koch, Phys. Rev. B, 73 (2006) 155319 (1-13).