Journal of College of Education for pure sciences(JCEPS)
Web Site: http://eps.utq.edu.iq/ Email: com@eps.utq.edu.iq
Volume 7, Number 4, December 2017

Dynamics of quantum dot laser with direct current modulation

Zahraa Khaleel Sharbak and Shakir D. Sarsooh Al-Saeedi

shakiralsaeedi455@gmail.com

Physics Department, College of Science, Thi-Qar University.

Abstract:

In this work, the quantum dot (QD) lasers dynamics were studied, with modulated injection current. A model of its rate equations were solved numerically using Runge-Kutta method. The effect of the modulation current amplitude, frequency and the bias dc current were included. The study shows that the QD lasers dynamics includes different behaviors such as stable, periodic, multi- periodic and self- pulsing, then the system ending to the chaotic state.

Key words: QD laser, Direct modulation, Chaos**.**

Journal of College of Education for pure sciences(JCEPS)
Web Site: http://eps.utq.edu.iq/ Email: com@eps.utq.edu.iq
Volume 7, Number 4, December 2017

حركيات ليزر النقطةالكمية عند تضمين التيار المباشر

الخلاصة:

في هذا البحث تم حل نموذج معادلات المعدل عددياً باستخدام طريقة رانج- كوتا ودراسة النظام تحت تضمين تيار الحقن المباشر. بينت الدراسة ظهور سلوكيات مختلفة لليزر النقطة الكمية تحت التضمين المباشر للتيار مثل الحالة المستقرة، الدورية ، متعددة الدوريات ، شبه الدورية و التنبيض- الذاتي ، ثم ينتهي النظام الى حالة الفوضى.

الكلمات المفتاحية: ليزرالنقطةالكمية ، التضمينالمباشر ، الفوضى.

1- Introduction:

Quantum dot (QD) laser is a component of the development of technology for semiconductor lasers. These lasers have several factors that differ from that of quantum well (QW) lasers such as low threshold injection current, thermal stability, chirp, and feedback dynamics [1, 2]. Wide applications make the QD lasers preferred than other lasers such as low cost transmitter modules by releasing the need for temperature control, isolators, and external modulators. But the feasibility of high-speed transmission rates strongly depends on the damping rate of the relaxation oscillations ROs which inevitably appear in gain-switched operations [3]. Since 1997, the response of QD lasers have been systematically investigated through RO measurements [2-6] showing stronger damping than conventional QW lasers. These measurements used the expressions for the RO frequency and damping rate of QW lasers [7-8] and recent efforts have been directed to formulate more appropriate rate equations for QD lasers. The rate equations model produces the different behaviors in the output of laser that suitable with the essential QD dynamical properties [9-10]. The two-variable QD rate equations indeed correspond to the limit of very large capture rates but a different limit is possible if the dots are nearly saturated by the carriers.

In this work the rate equations of the QD laser were solved numerically to observe the time evolution of the QD laser output by adding a modulation term to the injection current with different values for its bias, modulation amplitude and the modulation frequency.

2-Theoretical model:

In this paper, the effect of the direct current modulation on the quantum dot laser dynamics was studied by changing the amplitude (m), the modulation frequency (f_m) and the direct part of the injection current(b). [11].The formula of the rate equations for QD laser model in this study is given by [12]:

$$\frac{d\tilde{N}}{dt} = \frac{\eta i\tilde{I}}{qV} - \tilde{N}\left(\frac{1}{\tau_{sp}} + \frac{1}{\tau_{nr}}\right) - v_g g\tilde{N}_p \quad (1)$$

$$\frac{d\tilde{N}_p}{dt} = \left[\Gamma v_g g - \frac{1}{\tau_p}\right]\tilde{N}_p + \Gamma B_{sp}\frac{\tilde{N}}{\tau_{sp}} \quad (2)$$

Where η_i is the fraction of terminal current that generates carriers in the active region, q is the electron's charge and I is the injection current,τ_p is the photon life-time, β_{sp} is the spontaneous emission factor, Γ is the confinement factor, υ_g isthegroup velocity, $\tilde{N}$ is the Carrier density in the well, V is the volume of active region, g is the gain, τ_{sp} is the time of the spontaneous emission, τ_{nr} is the nonradiative emission time and $\widetilde{N}_p$ is the photon density . The injection current in eq.1, is replaced by the following relation [13, 14]:

$$I = I_{dc} + I_{ac} \sin\left(2\pi f_m t\right) \quad (3)$$

Where I_{dc} is the dc bias current

I_{ac} is the modulation current and

$$I_{dc} = b \times I_{th} \quad ,$$

$$I_{ac} = m \times I_{th}$$

$\widetilde{I}$ is the total injection current, b the dc bias strength, m is the modulation depth, $f_m = \frac{w_m}{2\pi}$ is the modulation frequency. The modulation current for sinusoidal wave as noted in eq.(3) depends onthe wave amplitude (m) and its frequency (Ḇ . ;I_{th} is the threshold injection current value and its value in this study is 4.3 mA.

3- Results and discussions

The system in this study which consists of two equations that describe the time change of carriers and photons in quantum dot laser, that are not able to produce a nonlinear dynamics, so the purpose of access to the chaos must enter a new degree of freedom of the system, represented by introduction the direct modulation of injection current term, where it has been studying the system under the direct modulation of the current with changing the parameters (modulation parameters) *m*, *b* and Ḇwith a choice of the given system parameters in Table. 1.

Table (1): Numerical parameters used in the simulation [12].

Symbol	Meaning of symbol	Value
η_i	Fraction of terminal current	0.8
q	Electron charge	$1.6x10^{-19}$ C
υ_g	Group velocity	$1x10^{8}$ m / s
τ_p	Photon life-time	$2.77x10^{-12}$ s

β_{sp}	Spontaneous emission factor	$1x10^{-4}$
Γ	Confinement factor	0.38
V	Volume of the active region	$4.8x10^{-18}$ m^3
τ_{sp}	Time of the spontaneous emission	$0.5x10^{-9}$ s
τ_{nr}	Nonradiative emission time	$1x10^{-3}$ s

We obtained the following results:

3-1: When choosing value for b=0.5 for different value of m with the change of the modulation frequency values,f_m, note the following result were obtained :-

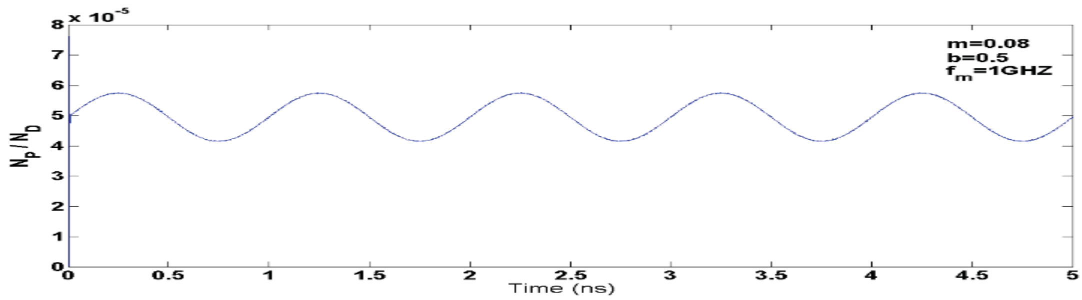
1-For a certain value of the modulation frequency f_m=1GHZ and different values of m the results were periodic as in the figure ((1)-a-b-c).

2-When the value of f_m=5GHz, notes transmission of the system dynamics from the periodic state to the self-pulsing state as in figure ((2)-a-b-c).

3-Repeated the former behavior when increasing the modulation frequency to f_m=10GHZ and f_m =15GHZ, as shown in figures ((3)-a-b-c) and ((4)-a-b-c).

4-When the value of $f_{m=}$25GHZ, The behavior begins periodically at small value of m=0.01, then becomes quasi-periodic and it ends with a chaotic situation as in figure (5).

5-When the value of modulation frequency is f_m=35GHZ, the behavior of the system begins periodic state and then move to qusi-periodic state and then ends with a chaotic state as in figure (6).



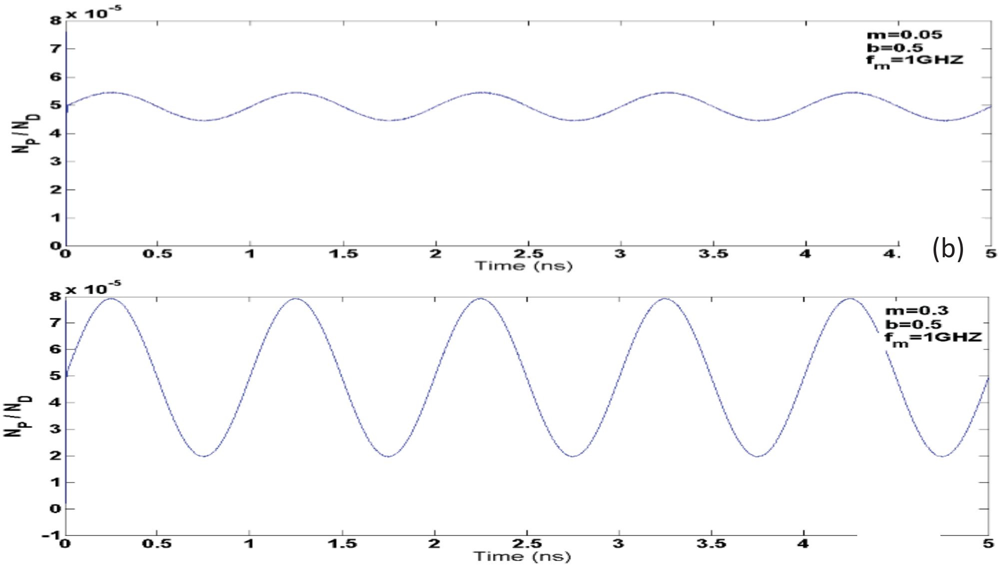


Fig.(1): Time behavior of photon density $\widetilde{N}_P$ for parameters m, b and f_m(GHz) respectively: (a) 0.08, 0.5, 1 ; (b) 0.05, 0.5 ,1 ; (c) 0.3 , 0.5, 1.

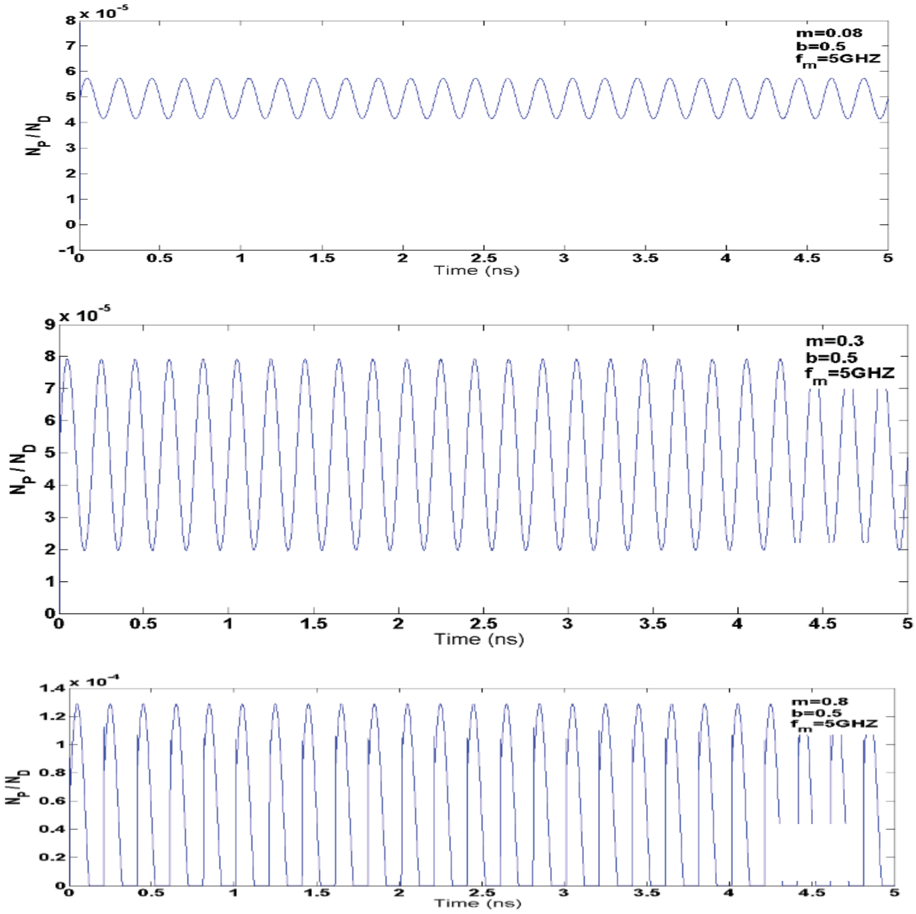


Fig.(2): Time behavior of photon density $\widetilde{N}_P$ for parameters m, b and f_m(GHz) respectively: (a) 0.08 ,0.5 , 5 ; (b) 0.3 , 0.5 , 5 ; (c) 0.8 , 0.5 , 5

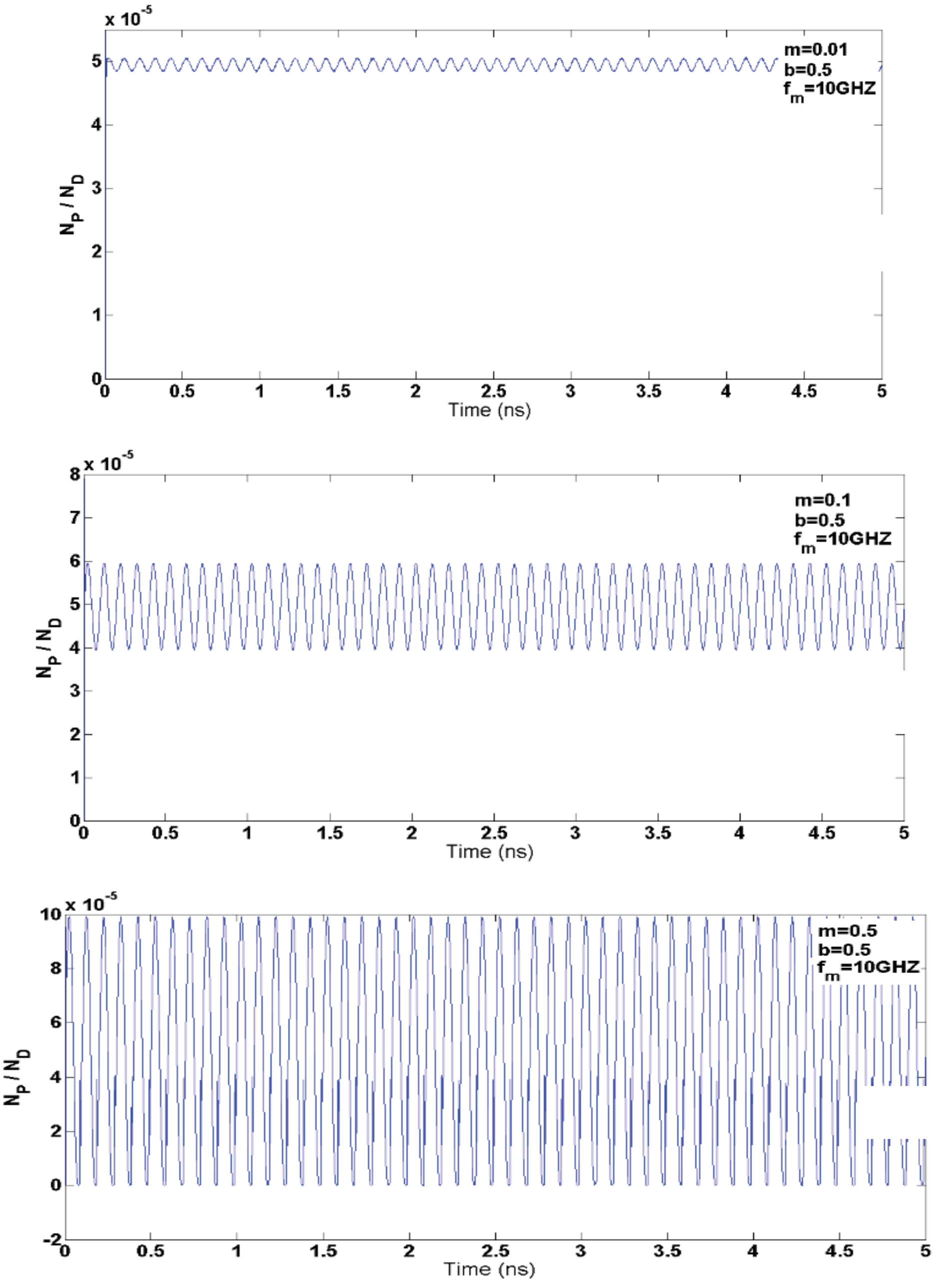
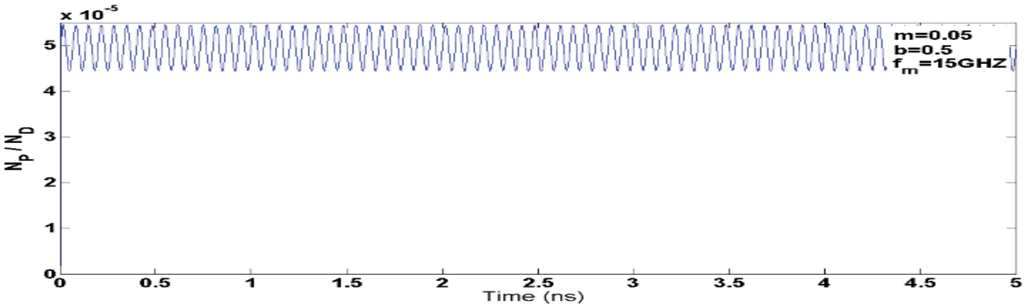


Fig.(3): Time behavior of photon density $\widetilde{N}_P$ for parameters m, b and f_m(GHz) respectively:(a) 0.01 , 0.5 , 10 ; (b) 0.1 , 0.5 , 10 ; (c) 0.5 ,0.5 , 10



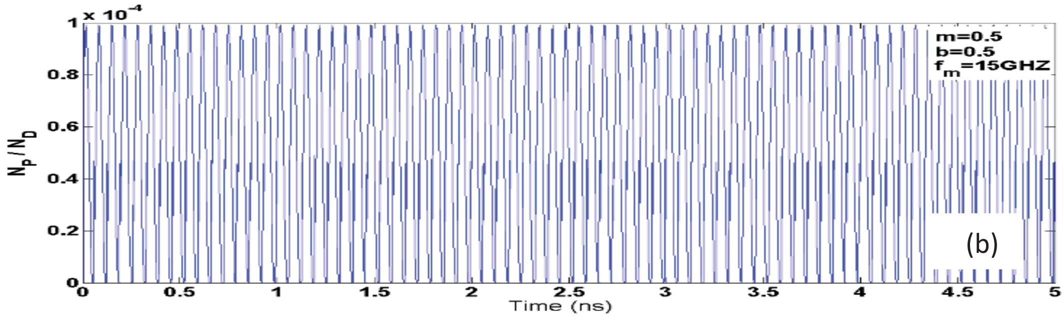


Fig.(4): Time behavior of photon density $\widetilde{N}_P$ for parameters m, b and f_m(GHz) respectively: (a) 0.05 , 0.5, 15 ; (b) 0.5 , 0.5 , 15

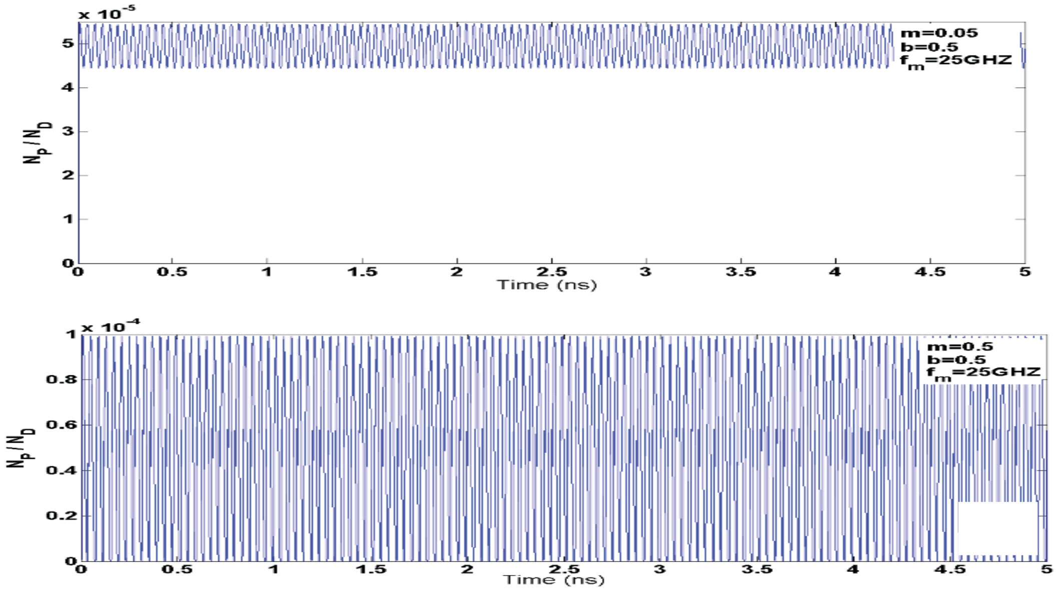
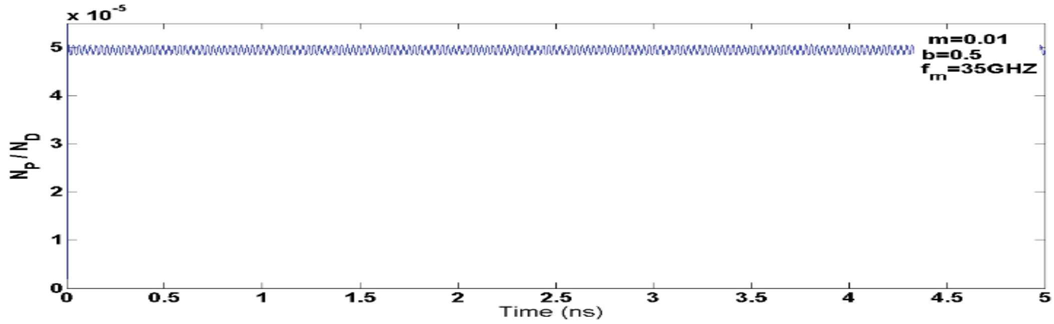


Fig.(5): Time behavior of photon density $\widetilde{N}_P$ for parameters m, b and f_m(GHz) respectively: (a) 0.05, 0.5 , 25 ; (b) 0.5 , 0.5 , 25



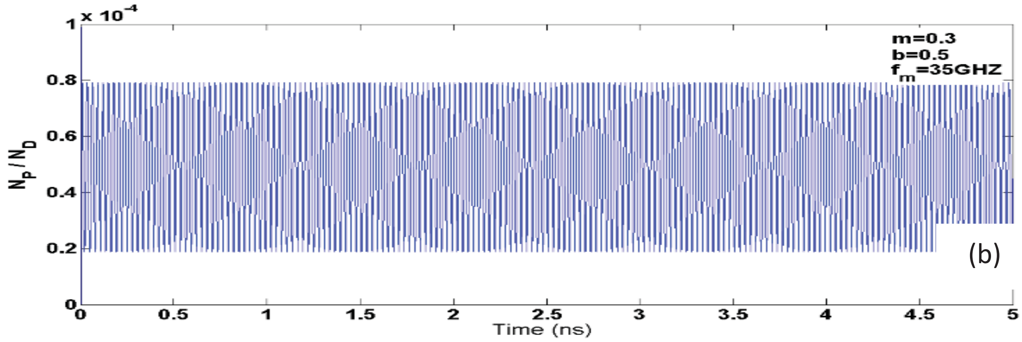


Fig.(6): Time behavior of photon density $\widetilde{N}_P$ for parameters m, b and f_m(GHz) respectively: (a) 0.01 , 0.5 , 35 ; (b) 0.3 , 0.5 , 35.

3-2: When increasing the value of b, b=1, for different values of m and f_m, the results are:-

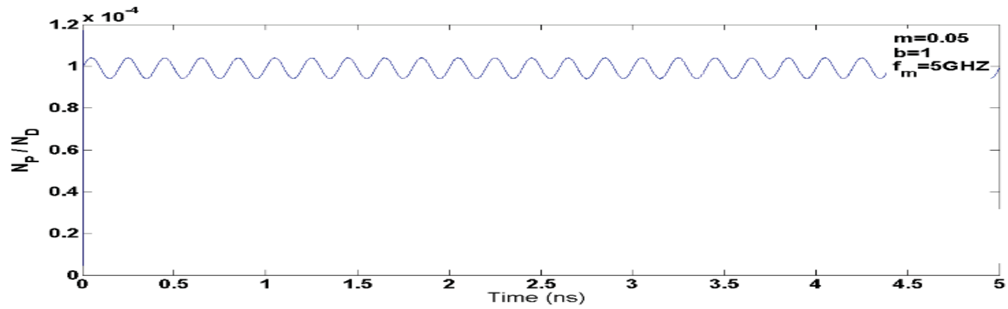
1-At f_m =1GHZ, we noted periodic appearance for different values of m with the increasing frequency to f_m=3GHZ, we observe the same behavior but with large amplitude. At f_m=5GHZ, it notes transmission the system from periodic case to self-pulsing state, as shown in figure (7).

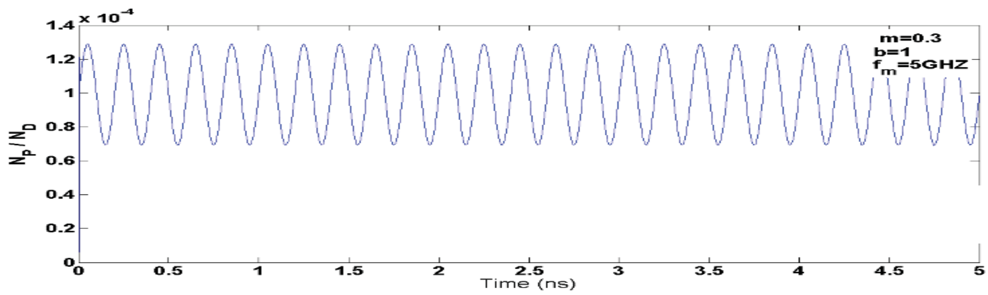
2- At f_m=10GHZ, the behavior is periodic then moves to quasi-periodic state.

3- When the value f_m=15GHZ, the system moves from periodic case to quasi-periodic state.

4-When increasing the value of modulation frequency f_m=25 and 35GHZ, the behavior of the system is periodic, and then becomes quasi-periodic as in figure (8).

5-At the frequency values from f_m=45 to 50GHZ and with increased the value of m and the value of b=1, it notes transmission the system of periodic status to the chaotic situation as in figure (9).





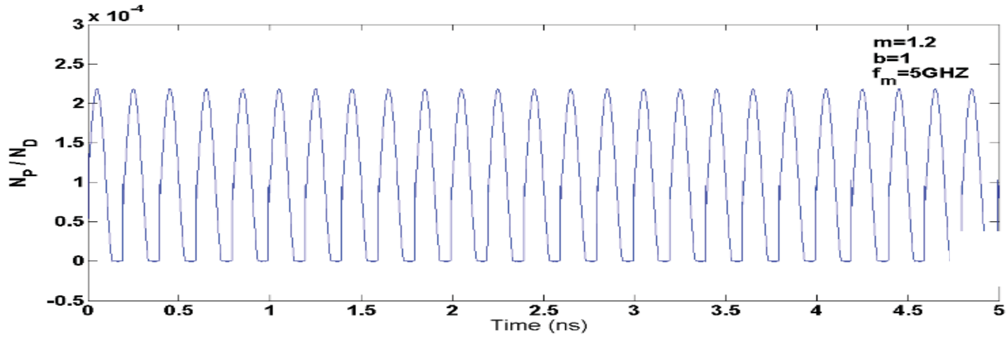
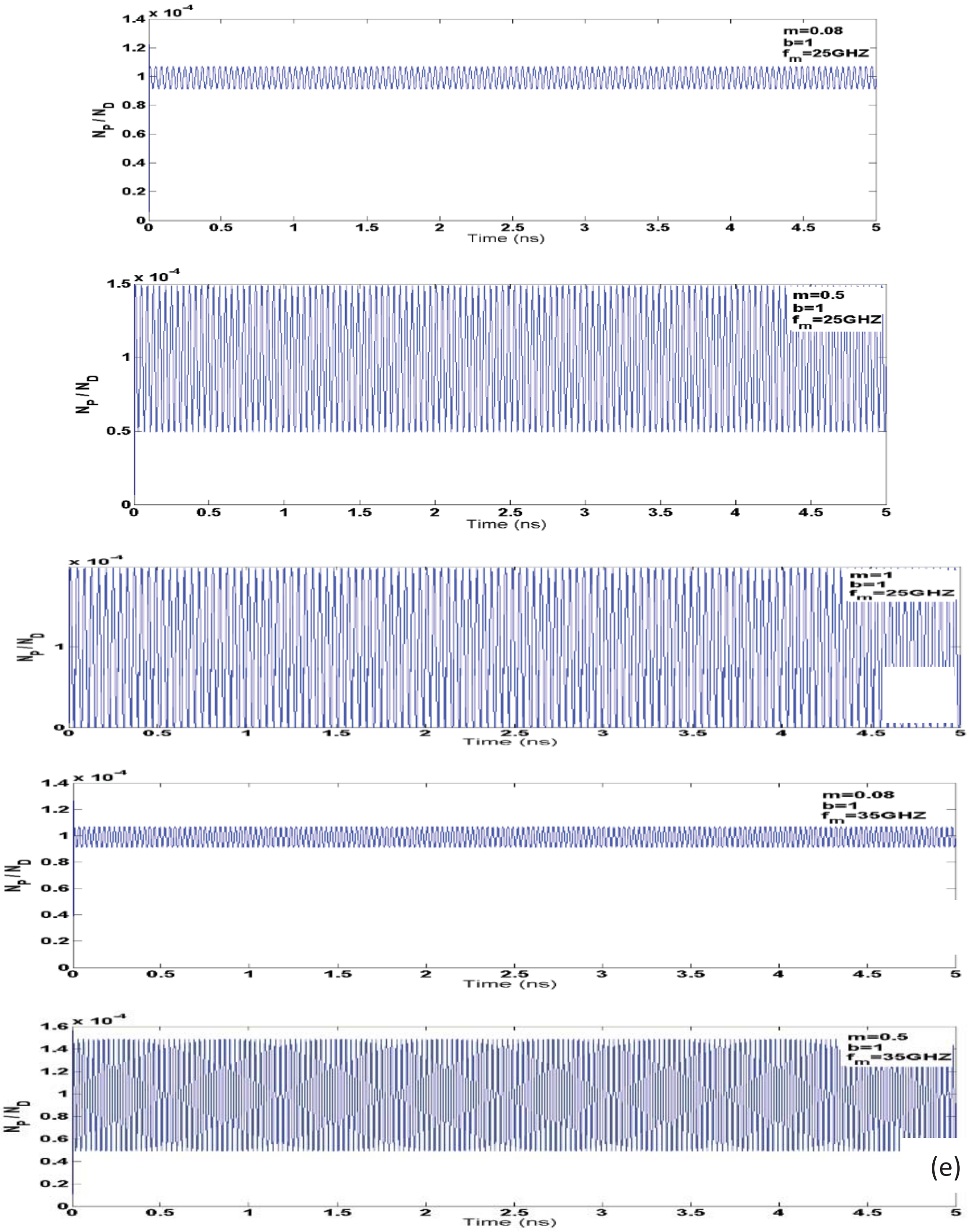


Fig.(7): Time behavior of photon density $\widetilde{N}_P$ for parameters m, b and f_m(GHz) respectively: (a) 0.05 , 1, 5 ; (b) 0.3 , 1, 5 ; (c) 1.2 , 1, 5



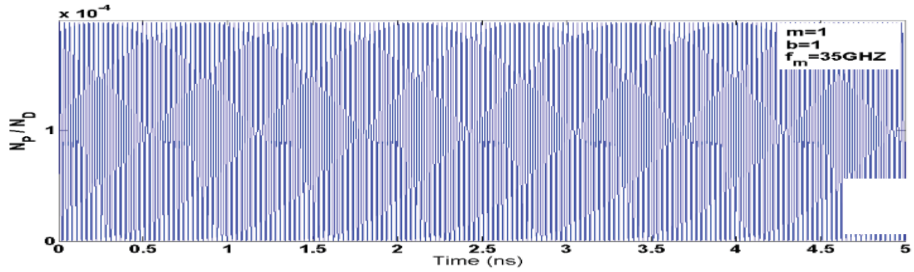


Fig.(8): Time behavior of photon density $\widetilde{N}_P$ for parameters m, b and f_m(GHz) respectively:(a) 0.08 , 1 , 25 ; (b) 0.5 , 1 , 25 ; (c) 1 ,1 , 25 ; (d) 0.08 , 1, 35 ; (e) 0.5 , 1 , 35 ; (f) 1 ,1 , 35

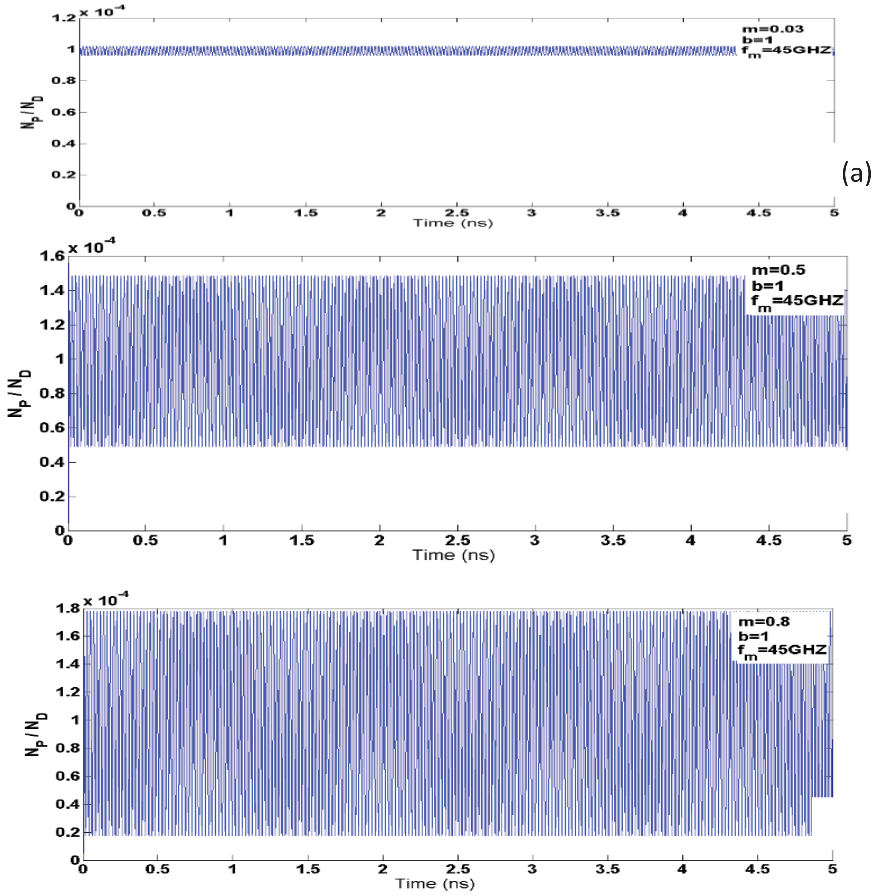


Fig.(9): Time behavior of photon density $\widetilde{N}_P$ for parameters m, b and f_m(GHz) respectively: (a) 0.03 , 1, 45 ; (b) 0.5 , 1, 45 ; (c) 0.8 , 1, 45

3-3: When the value of b=1.5, the behavior becomes as:

At b=1.5 and for different values of modulation frequency f_m and m, the results were as follows:

1-Atf_m=1GHZ and for different values of m, it was noted that the system behaving periodically, as the previous state that notice in small value of m andf_m.

2-When increasing the modulation frequency value from 3GHZ to 10GHZ, a transition from the periodic case to the self-pulsing case was observed as in figure (10).

3-At f_m=15GHZ, the system begins with periodic case moving into a state of self-pulsing.

4-When the value of modulation frequency is f_m=25GHZ, the behavior of the system is periodically, then becomes quasi-periodic and ends at the chaotic situation.

5-Increased the modulation frequency values to be f_m=35, 45 GHZ, the system starts a periodic behavior with low amplitude then the system behavior ends with chaotic behavior as in the figure (11).

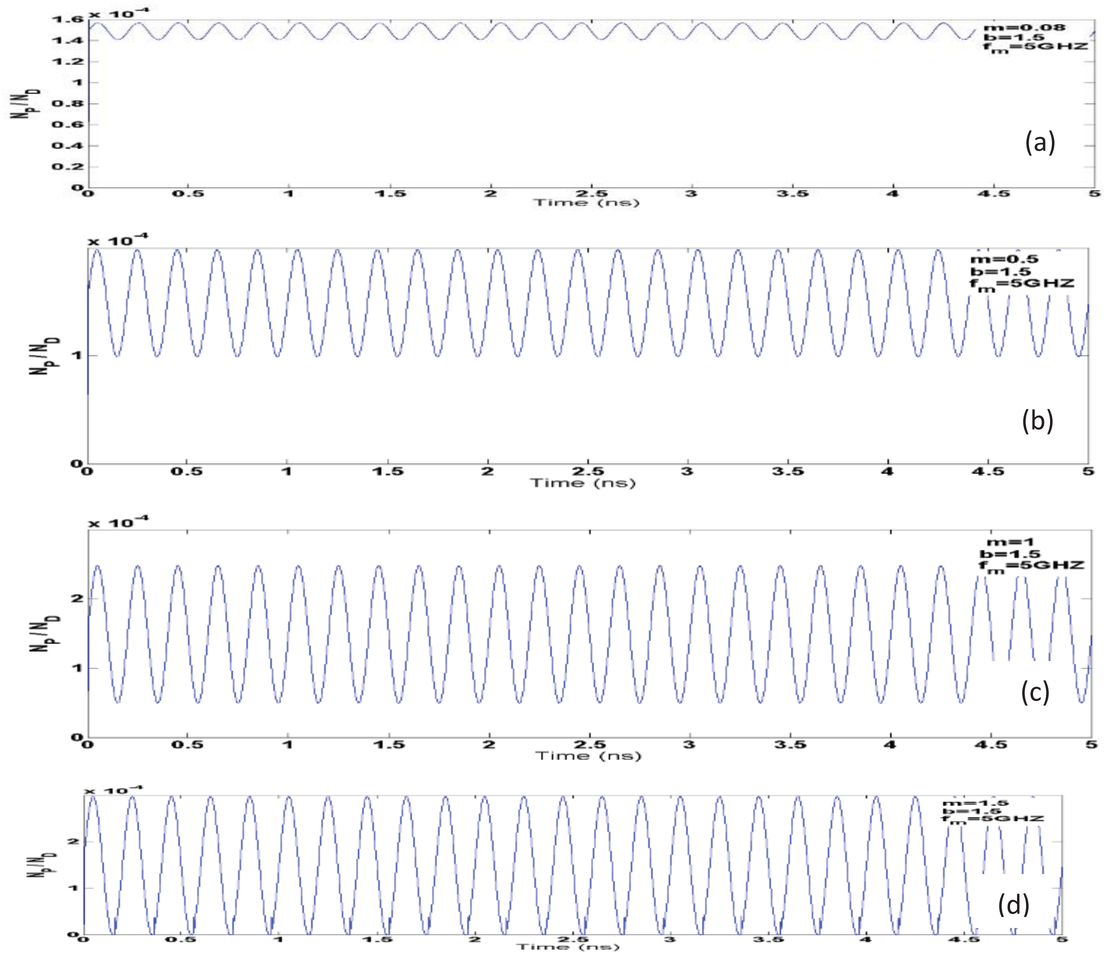
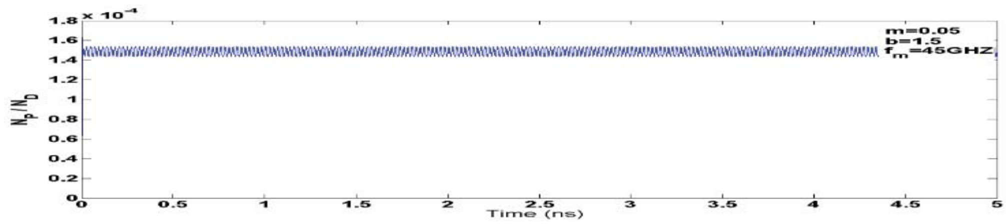


Fig.(10): Time behavior of photon density $\widetilde{N}_P$ for parameters m, b and f_m(GHz) respectively: (a) 0.08, 1.5, 5 ; (b) 0.5,1.5, 5 ; (c) 1, 1.5 ,5 ; (d) 1.5, 1.5 , 5



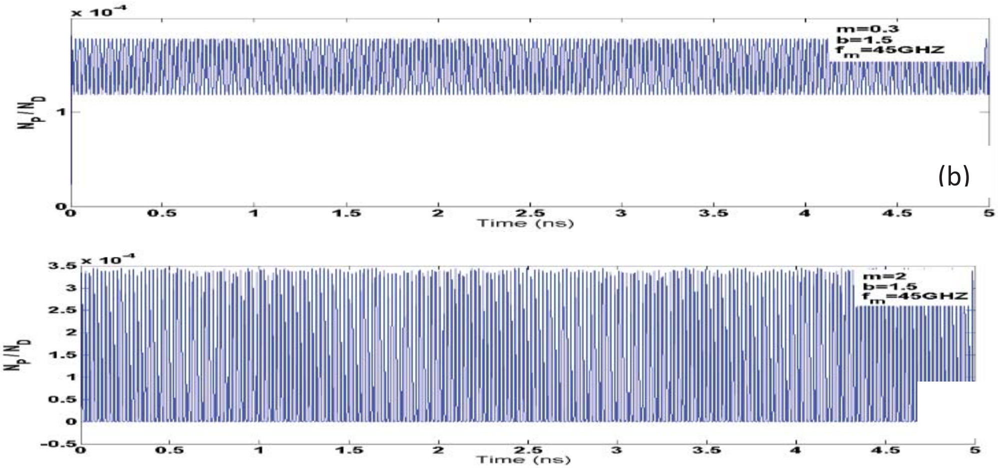


Fig.(11): Time behavior of photon density $\widetilde{N}_P$ for parameters m, b and f_m(GHz) respectively: (b) 0.05 , 1.5, 45; (d) 0.3, 1.5, 45; (c)2 ,1.5 , 45

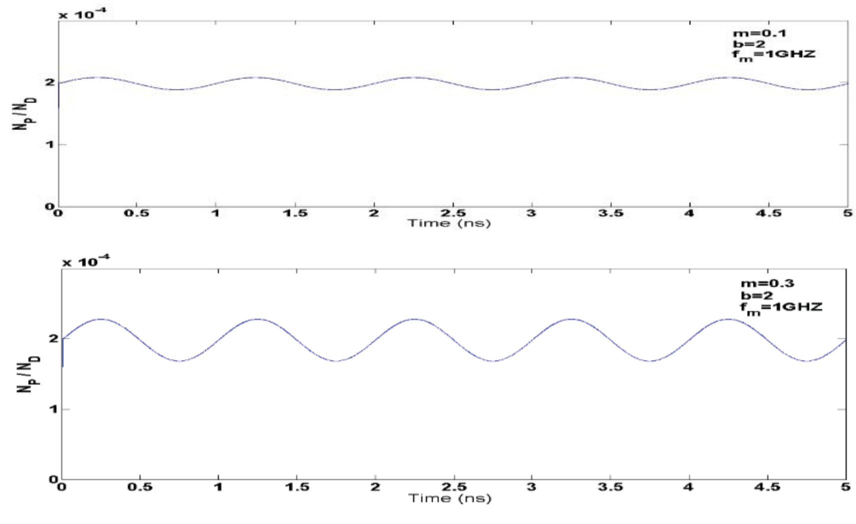
3-4: When the value of b=2.0 and for different values of modulation frequency, f_m and m, we noticed the following results:-

1-By choosing f_m=1GHZ, and with increasing the value of m, it was noted that the system shows periodic behavior where increasing the oscillation amplitude with increasing the value of m as in figure (12).

2-When increasing the modulation frequency from 3-15 GHZ, the system starts a periodic behavior ending to self-pulsing state as shown in figure (13).

3-At f_m=25GHZ, the behavior of the system is periodically and ends with a qusi-periodic state as observed in figure (14).

4-When the modulation frequency values are changed from 35GHZ to 50GHZ, the system shown periodically behavior with low amplitude oscillation and ends with the chaotic situation as in figure (15).



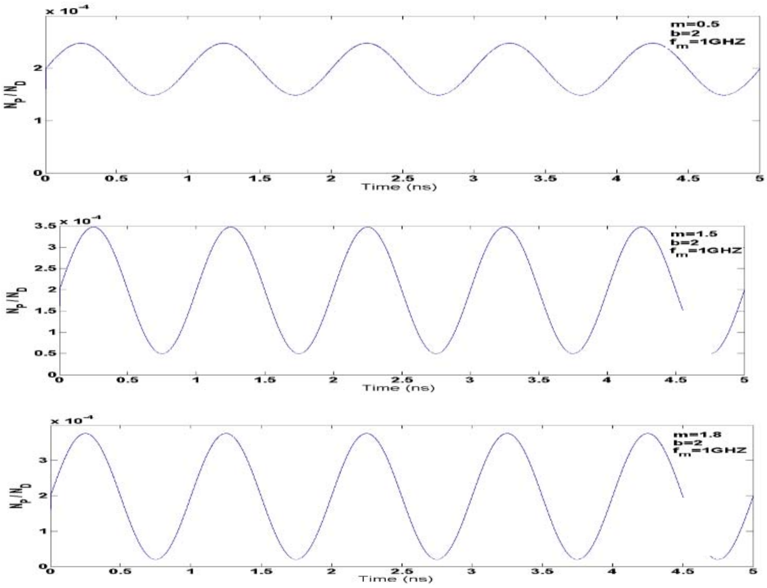


Fig.(12): Time behavior of photon density $\widetilde{N}_P$ for parameters m, b and f_m(GHz) respectively: (a) 0.1 , 2,1 ; (b) 0.3 , 2 , 1 ; (c) 0.5 , 2, 1 ; (d) 1.5 , 2 , 1 ; (e) 1.8 , 2 , 1

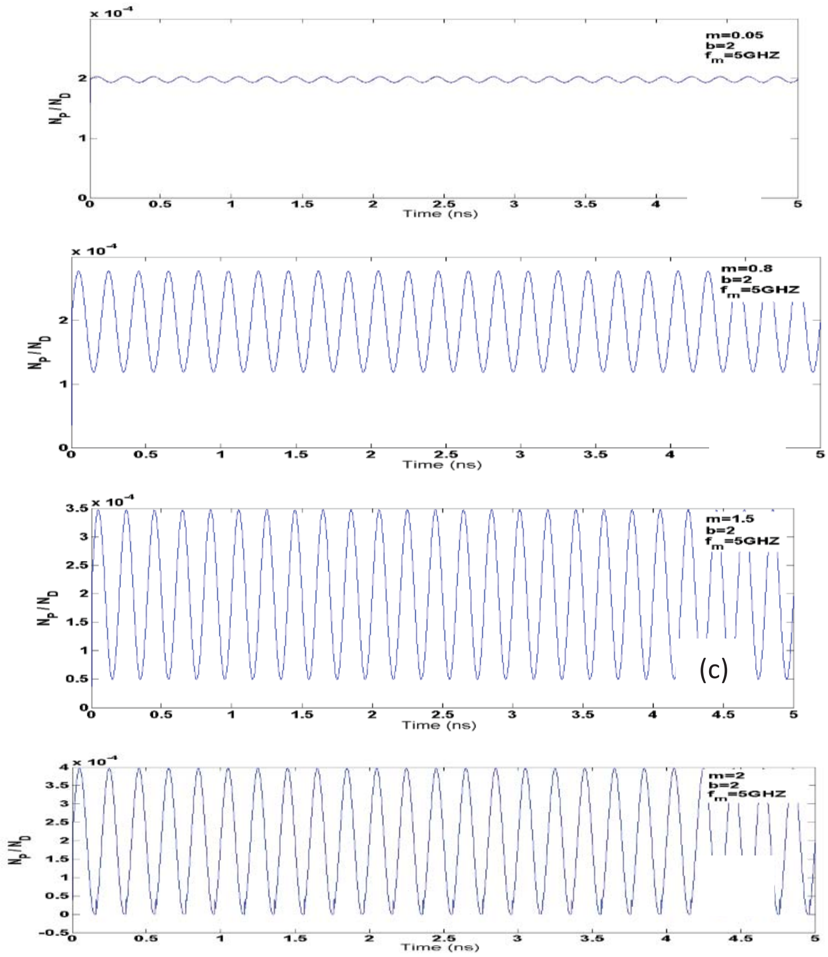


Fig.(13): Time behavior of photon density $\widetilde{N}_P$ for parameters m, b and f_m(GHz) respectively: (a) 0.05 , 2, 5 ; (b) 0.8 , 2, 5 ; (c) 1.5 , 2 , 5 ; (d) 2 , 2 , 5

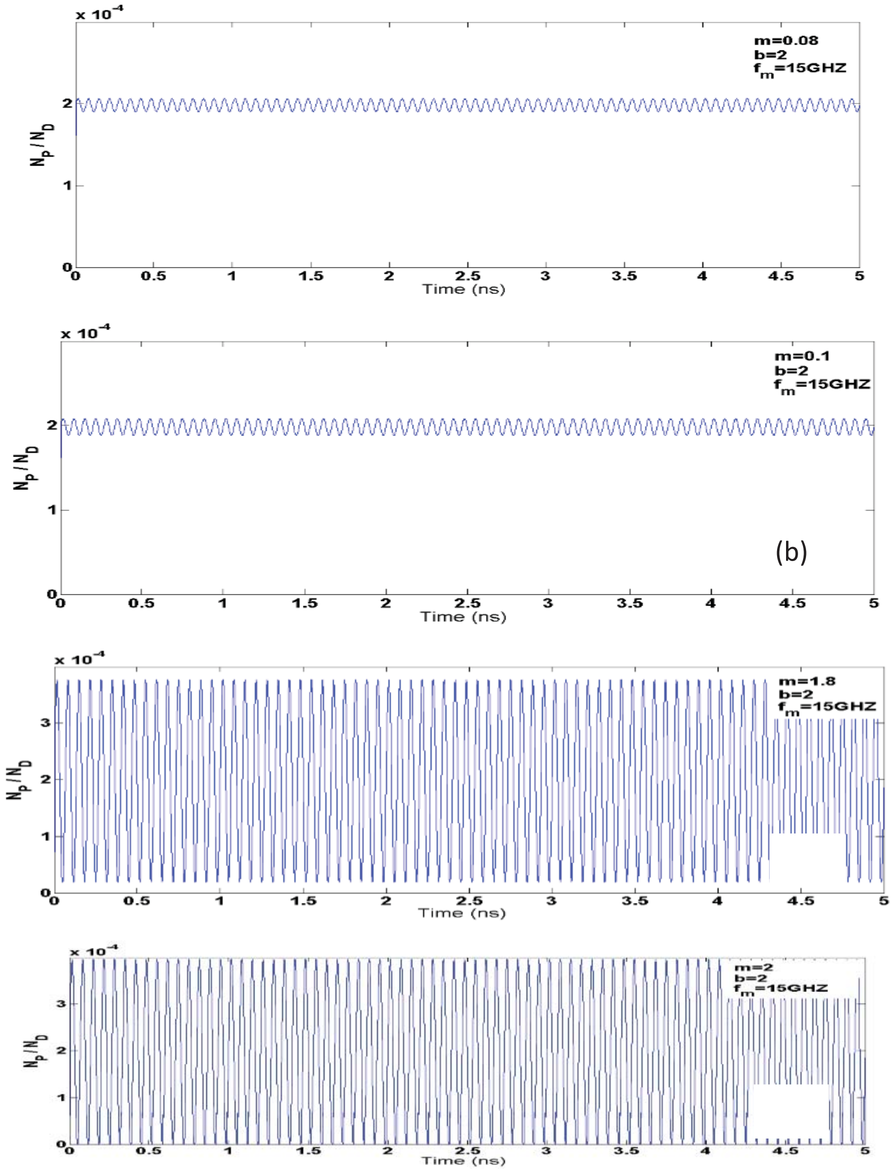
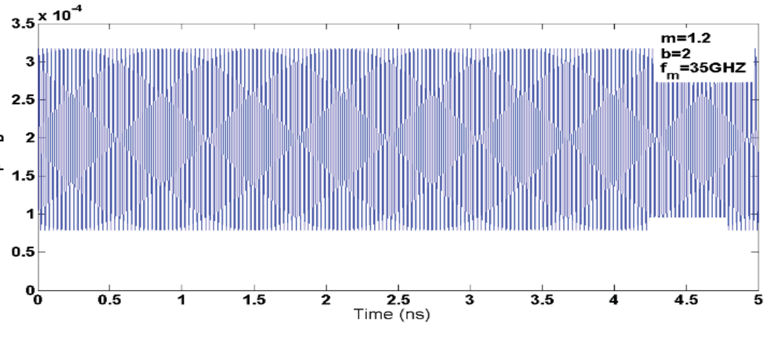


Fig.(14): Time behavior of photon density $\widetilde{N}_P$ for parameters m, b and f_m(GHz) respectively: (a) 0.08, 2, 15 ; (b) 0.1 , 2 , 15 ; (c)1.8 , 2, 15 ; (d) 2,2, 15



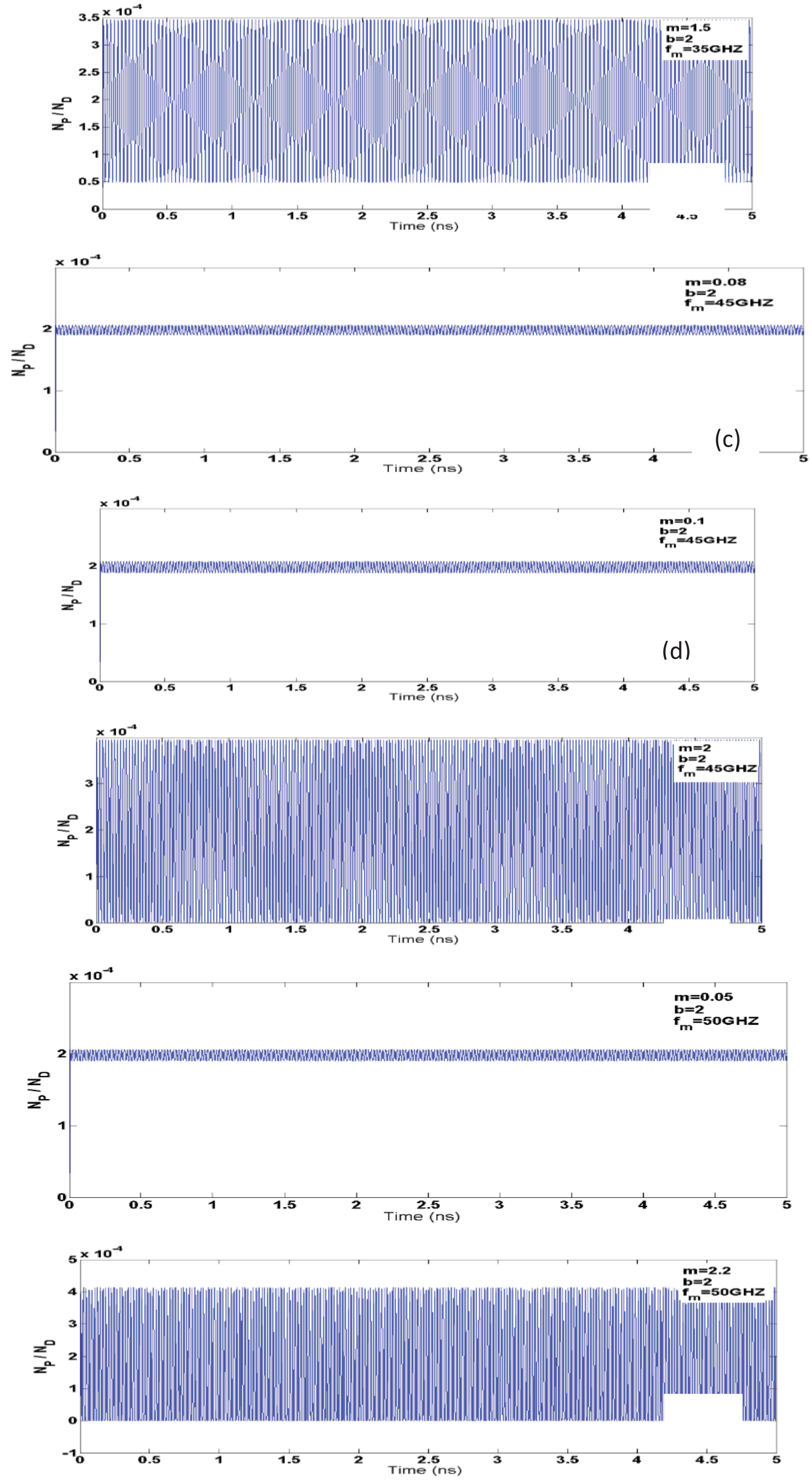


Fig.(15): Time behavior of photon density $\widetilde{N}_P$ for parameters m, b and f_m(GHz) respectively: (a)1.2, 2, 35 ; (b) 1.5 , 2,35 ; (c) 0.08 ,2,45; (d) 0.1,2,45 ; (e) 2 ,2 ,45 ; (f) 0.05,2,50 ; (g) 2.2 ,2,50

4- Conclusions:

We concluded that the possibility of chaotic behavior of high frequencies and different values of modulation depth, the increase the bias strength may lead to the enhancement of the linarites in the laser output on the consideration that the modulation is an addition to the free degree of the system and that the system does not show chaotic behavior, If it has at least three degrees of freedom. The system under study has two degrees of freedom so the modulation isconsidered additional freedom degree for the system which affects the possibility of starting the system by following a new behavior with wide application as in security communications. We have observed that the previous behavior of increasing the value of b repeated and be more clear for high ranges of frequencies, where we will not note the appearance of the condition of self-pulsing when increasing the value of b to high values.

5- References:

[1] D. Bimberg, M. Grundmann, and N. N. Ledentsov, Quantum Dot Heterostructures Wiley, New York, 1999.

[2] M. Kuntz, N. N. Ledentsov, D. Bimberg, A. R. Kovsh, V. M. Ustinov, A. E. Zhukov, and Y. M. Shernyakov, Appl. Phys. Lett. 81, 3846, 2002.

[3] N. B. Abraham, L. A. Lugiato, and L. M. Narducci "Instabilities in Active Optical Media," edited by, J. Opt. Soc. Am. A 21, 1985.

[4] M.-H. Mao, F. Heinrichsdorff, A. Krost, and D. Bimberg, Electron. Lett.33, 1641 1997.

[5] M.-H. Mao, T.-Y.Wu, D.-C.Wu, F.-Y.Chang, and H.-H. Lin, Opt. Quantum Electron. 36, 927, 2004.

[6] G. P. Agrawal and N. K. Dutta, Long-Wavelength Semiconductor Lasers Van Nostrand Reinhold, New York, 1986.

[7] K. Petermann, Laser Diode Modulation and Noise Kluwer Academic, Dordrecht, the Netherlands, 1988.

[8] E. Malic, K. J. Ahn, M. J. P. Bormann, P. Hovel, E. Scholl, A. Knorr, M. Kuntz, and D. Bimberg, Appl. Phys. Lett. 89, 101107, 2006.

[9] E. Malic, M. Bormann, P. Hövel, M. Kuntz, D. Bimberg, E. Schöll, and A. Knorr unpublished.

[10] M. Sugawara, K. Mukai, and H. Shoji, Appl. Phys. Lett. 71, 2791, 1997.

[11] M. Ishida, N. Hatori, T. Akiyama, K. Otsubo, Y. Nakata, H. Ebe, M. Sugawara, and Y. Arakawa, Appl. Phys. Lett. 85, 4145, 2004.

[12]JesperMørk, "Semiconductor Quantum Dot Lasers", Technical University of Denmark, 2013.

[13]B.M.Krishna, M. P. John and V. M. Nandakumaran, "Bidirectional communication using delay coupled chaotic directly modulated semiconductor lasers", Pramana-J.phys., 74, 177-188, 2010.

[14]M.O.Oleiwi, "Theoretical study on linear and nonlinear dynamics of InAs /InGaAs quantum dot laser", Ph.D. Thesis, Basrah University, 2014.