Modulation Dynamics For QD Laser On Photonic Crystal

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Abstract:

A quantum dot laser that can be turned on at low pump powers, it is directly modulated at high speeds and that can produce sufficiently high output powers. This is very interesting for applications ranging from optical telecommunications and optical interconnects.

Quantum dot laser on photonic crystal nanocavities at a low threshold power comparing to those of single photonic crystal cavity lasers.

The system of rate equations is solved by matlab program with ode45 method (4^{th} Runge-Kutta at initial values of the variables of the system).

Different dynamics ranging from one period to chaos are produced in the photons density of quantum dot laser under the effect of injection current modulation using a theoretical model. From the theoretical results, the weak and strong modulation of the injection current led to periodic, self-pulsing and chaotic states.

Keywords: Quantum dot laser, Photonic crystals, Injection current modulation.

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حركيات التضمين لليزر النقطة الكمية في البلورة الفوتونية

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الخلاصة:

ليزر النقطة الكمية يشتغل عند قدرات الضخ الواطئة ، تضمن مباشرة عند السرع العالية ويمكن أن ينتج قدرة خرج عالية بصورة كافية . هذا يكون مفيد جدا للتطبيقات والتي تتحدد في تطبيقات الاتصالات البصرية واتصالات الانترنت .

ليزرات النقطة الكمية في البلورة الفوتونية ذات التجاويف النانوية عند قدرة عتبة واطئة مقارنة مع ليزرات البلورة الفوتونية ذات التجاويف المفردة.

تم حل نظام معادلات المعدل باستخدام ماتلاب بطريقة رانج - كوتا (عند شروط ابتدائية لمتغيرات النظام).

تنتج حركيات مختلفة ظهرت من دورة واحدة إلى الفوضوية في كثافة الفوتونات تحت تأثير تضمين الحقن باستخدام النموذج الرياضي.

من النتائج النظرية، التضمين الشديد والضعيف لتيار الحقن يؤدي إلى الدورية ، التنبيض الذاتي وحالات فوضوية .

1-Introduction:

The concept of photonic crystal (PC) was proposed by Yablonovitch andJohn in 1987 [1]. Yablonovitch reported that a three-dimensional periodic structure has an electromagnetic bandgap, and the spontaneous emission of atoms in the periodic microstructure can be rigorously forbidden when the electronic band edge overlaps the electromagnetic bandgap [2]. It is worth to note that the strong localization of photons could occur in a frequency range in certain disordered super-lattice microstructures with sufficiently high dielectric contrast [1-3]. Owing to their unique ability to control the propagation states of photons, photonic crystals have great potential applications in the fields of optical computing, integrated photonic circuits, and ultrahigh-speed information processing [3].

Quantum dot semiconductor lasers are central components of optical systems. Quantum dot laser (QDL) is a semiconductor laser which contains few million nano-sized crystals called quantum dots (QDs) in the active section.Semiconductor nano-cavity systems with a self-assembled single quantum dot (QD) have been investigated because of their unique physics based on cavity quantum electrodynamics and their potentials in future applications such as quantum information processing [1-6].

Modulation is concept frequented in the field of communications and transition information. It is intended to load specific amplitude wave and a specific frequency on another wave of different amplitude and frequency different from the loaded wave [7-9]. Chaos communications several approaches have been adopted to perform digital communications using synchronized chaotic lasers.

Due to their direct compatibility with existing optical fiber communications technology, semiconductor lasers have gained widespread attention for use in optical chaos communications [9-12]. One has attempted to incorporate QDs in the active region of electrically pumped PC optical micro-cavities [6].

2-Theoretical Model:

The dynamics of QDL describes the variation of variables forasystem, i.e., the time behavior of carriers and photon. The interesting phenomenon in lasing is the observed lasing wavelength switching thatcontrolled by injection current or temperature. 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[7-9]. A numerical model is used to study carrier dynamics in thelowest energy level of an

InAs/InGaAs/GaAs quantum dot system. In this model, the dynamics of carriers and photons. Here ,it has been present a coupled set of rate equations to calculate the lasing properties of quantum dot lasers. Our model describing the carrier dynamics in QD lasers is based on the work [7]. It shows the physical structure of the carrier transition process in the active region of quantum dot laser on photonic crystal [12]. Let us consider that n_G is the carrier number in the quantum dot.

The injected carriers diffuse through the quantum well (QW), and then relax into the dot. Above lasing threshold current, carriers in the ground state emit photons into the lasing mode primarily due to the stimulated emission process. To study the dynamics quantum dot laser, for simplicity in this model. The rate equations for the

Carrier–photonsystems are [7]:

$$\frac{dp}{dt} = g(n_G)p + \frac{F_m n_G}{\tau_r} - \frac{p}{\tau_p} \quad \text{.....(1)}$$

$$\frac{dn_G}{dt} = \frac{n_E}{\tau_{E,f}} - n_G\left(\frac{F_m + F_{PC}}{\tau_r} + \frac{1}{\tau_{PC,nr}}\right) - g(n_G)p \quad \text{.....(2)}$$

$$\frac{dn_E}{dt} = \eta\frac{L_{in}}{\hbar\omega_p} - n_E\left(\frac{1}{\tau_{E,r}} + \frac{1}{\tau_{E,nr}} + \frac{1}{\tau_{E,f}}\right) \quad \text{.....(3)}$$

In the above equations, the cavity photon number is driven by the QW through stimulated emission (gain term $g(n_G)$ and spontaneous emission SE (at the resonant mode's Purcell-enhanced rate F_m/τ_r). $1/\tau_p$ is the cavity photons loses rate.

The carrier number $n_G$in the center equation is pumped by carrier relaxation from the pump level population $n_E$at rate $1/\tau_{E,f}$.

Besides pumping the cavity, $n_G$decays through NR channels at rate $1/\tau_{PC,nr}$ and PC leaky modes at rate F_{PC}/τ_r, where $F_{PC}\approx 0.2$ expresses SE rate quenching inside the PC bandgap compared to the SE rate $1/\tau_r$ in the bulk QW (following simulations in [5]). In the bottom equation, the $n_E$level is pumped through above-band optical excitation with power L_{in}at frequency ω_p (the first term) and decays through carrier relaxation ton$_G$, NR recombination, and SE (second term). In the following text, we will use these rate equations to model the lasing action of single and coupled PC lasers, at both room and low temperature and containing QWs or QDs as gain material. One use a logarithmic gain model for QWs and a linear gain model for QDs.

One of the advantages of the semiconductor lasers over the other lasers is the possibility of direct current modulation. The short optical pulses required for optical communications can be generated by the modulation of input current [13].

The sinusoidal modulation of a semiconductor laser is commonly used for many applications and that can be done by injecting a current signal in the form [1].

Dynamics of QDL with direct current modulation lasers haveenormous applications for photonics technology.

3- Dynamics of quantum dot laser with direct current modulation.

One of the advantages of the semiconductor lasers over the other lasers is the possibility of direct current modulation. The short optical pulses required for optical communications can be generated by the modulation of input current [10]. The sinusoidal modulation of a semiconductor laser is commonly used for many applications and that can be done by injecting a current signal in the form [7-13].

Quantum dot laser under the direct injection current modulation can be appeared different behaviors such that periodic, multi- periodic, quasi- periodic, self- pulsing, then the system ending to the chaotic stats, this behavior is very important because it is usually employed insecurity optical communications, by including its

output into a wide ranges of frequencies [15-17].The photon will have an energy determined by $\eta\omega_p$, and one can therefore realise that:

$$\frac{I}{q}=\frac{L_{in}}{\eta\omega_p} \qquad (4)$$

where ,

L_{in} is the input power,

In this part, 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).The injection current in equation (5), is replaced by the following relation [15].

$$I = I_{DC} + I_{AC}\sin(2\pi f_m t) \qquad (5)$$

where,

is the modulation current and I_{DC} is the DC bias current I_{AC}

$I_{DC} = b \times I_{th}$, and $I_{AC} = m \times I_{th}$,

I :is the total injection current, b is the dc bias strength, m is the modulationdepth, $f_m=\frac{w_m}{2\pi}$is the modulation frequency.

The modulation current for sinusoidal wave is noted in eq.(5) dependent on the amplitude of the wave (m) and its frequency (f_m).

I_{th} is the threshold current.

Table(1): Simulation parameters

Symbol	Physical Meaning	The value
τ_p	The photon life time of the cavity	1 ps
τ_r	The radiative recombination life time	600 ps
$\tau_{pc,nr}$	The non-radiative recombination life time	100 ps
V_g	The group velocity of light in the active medium	1x 10^{10}cm/s
β	The fraction of spontaneous emission	1x10^{-4}
g_o	The gain coefficient	6.2 ×10^4cm^2
N_{tr}	The transparency carrier density	7.9 ×10^{15}cm^{-3}
η	The fraction of incident pump power	1.3×10^{-5}
$L_{in,th}$	Input pump power	48 μW
F_m	Purcell-enhanced parameter	1
Γ	Confinement factor	0.028

Table (2) :Injection parameters

Symbol	Meaning of symbol	Value						
b	The DC bias Strength	1			2		3	
m	Modulation depth	0.1		0.5	0.8	0.9	1.2	
f_m (GHz)	Modulation frequency	1	3	5	10	15	35	45

4-Results and discussion:

The simulation of this work is done on the InAs which is match with GaAs, the set of parameters are listed tables (1 and 2) under the effect of direct modulation factors b, m and $f_m$are the bias current, the modulation depth, respectively .The theoretical results can be summarized as following:

1-At b=1 , m=0.1 and modulation frequency in the rang, f_m = (1 GHz -35 GHz), the system starts with a periodic behavior p_1 and then oscillates with increasing frequency with a small amplitude as shown in fig.(1-a-b-c-d).

2- Increasing the value of m to the value m=0.3 and b=1 when the same range of modulation frequency is observed, the transmission from the self – pulsing fig. (2-a-) to quasi-periodic state fig. (2-b), then the regime goes into chaotic state fig. (2-c-d).

3- By increasing the value of m to the value m=0.5 with the same value of b, b=1, and the same range of modulation frequency,one observe that the system moves by increasing the frequency to chaotic state as infig. (3-c-d).

4-At a value of m=0.8, b=1, and for the modulation frequency ranges from (1GHz - 45 GHz), the same preceding behavior and the transition of the system from the state of self-pulsing to the chaotic state as in the fig. (4-a-b), fig. (5-a-b) and fig. (6-a-b) respectively.

5- By changing the values of b=2, m=0.9, with the same range of the modulation frequency (1Hz - 45GHz), it is observed that the system begins with self-pulsing state, as shown in fig. (7-a-b), so the system ends up in chaos as in fig.(8-a)

6- For the same value of b, b=2 ,m=1.2, for the same range of modulation frequency ($_k$=1GHz - 45GHz) , it is noted that the system begins with the self-pulsing state as in fig.(9-a-b), and finally the system ends up with chaotic state as in fig.(10-a-b)

7- When changing the value of b to b=3, and the value of m=0.1, and the modulation frequency in the range ($_k$=1GHz – 45 GHz), it is noted that the behavior of the system is periodic and ends in a stable state as in fig.(7-a-b). When the value of m=0.3, the system starts with the periodic state and ends with the steady state as in fig.(12-a-b).

8-when the value of b is b=3, and m=0.5, for the same modulation frequency range (1GHz -45 GHz), it is observed that the system transited from periodicity to the steady state with slight fluctuation as in fig. (13-a-b). When the value of m becomes m=0.9 the system stars with periodic state and ends with a semi-stable output with noise, seefig. (14-a-b).

9- And for the same values of b and f_m mentioned in above paragraph,but the value of m ,(m=1.2) , the system shows a periodic oscillation which moves from one period p_1 to multi-periodic p_2, then ends with a stable output with low oscillation intensity see the fig.(15-a-b-c).

The above results are agreement with the researches [15,17]

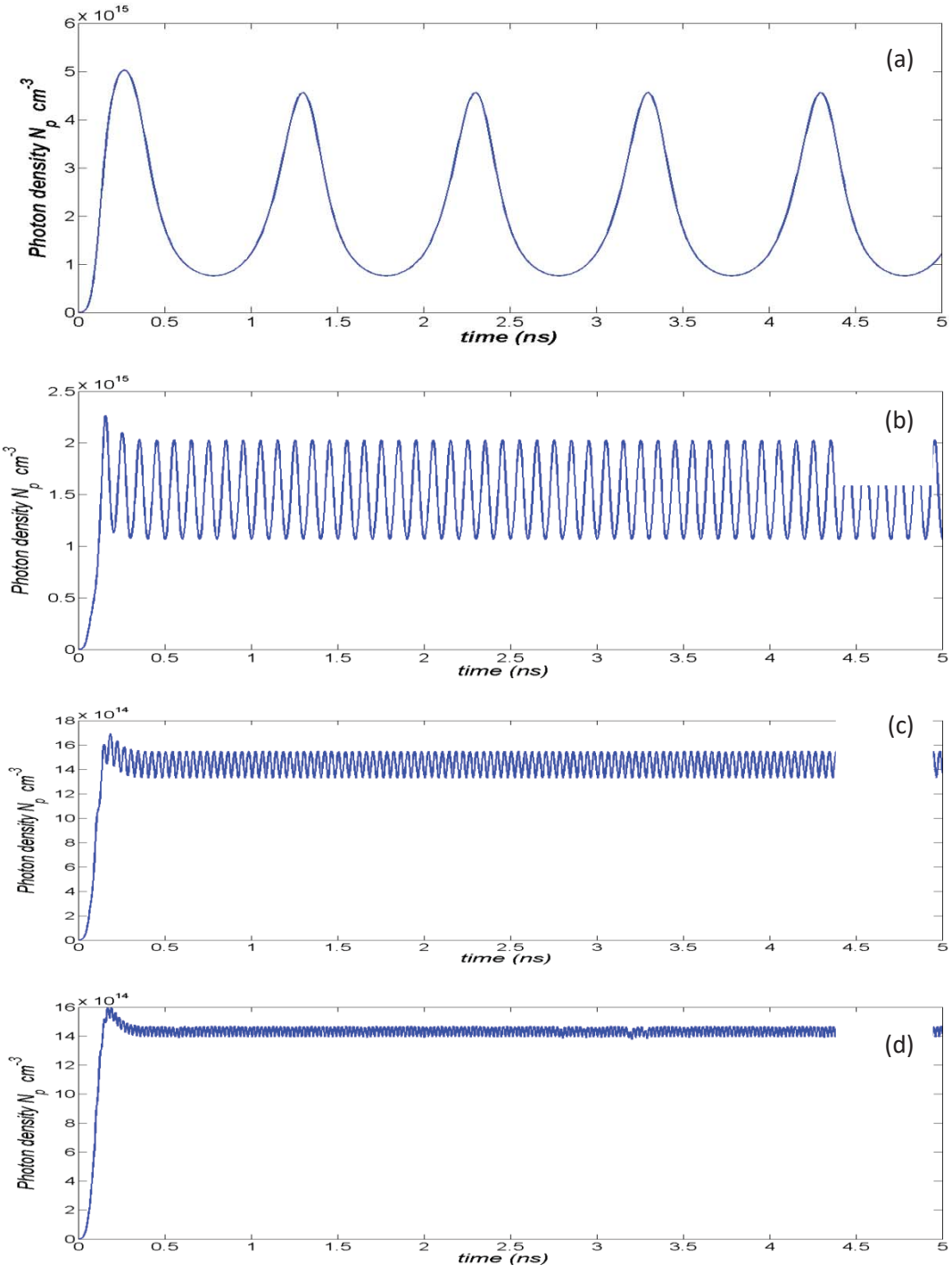


Fig.(1): Simulation of time series for photon density N_P for parameters b, m and (GHz) respectively: (a) 1 , 0.1 , 1; (b) 1 , 0.1 , 10 ; (c) 1 , 0.1 , 25 ; (d) 1 , 0.1 , f 35.

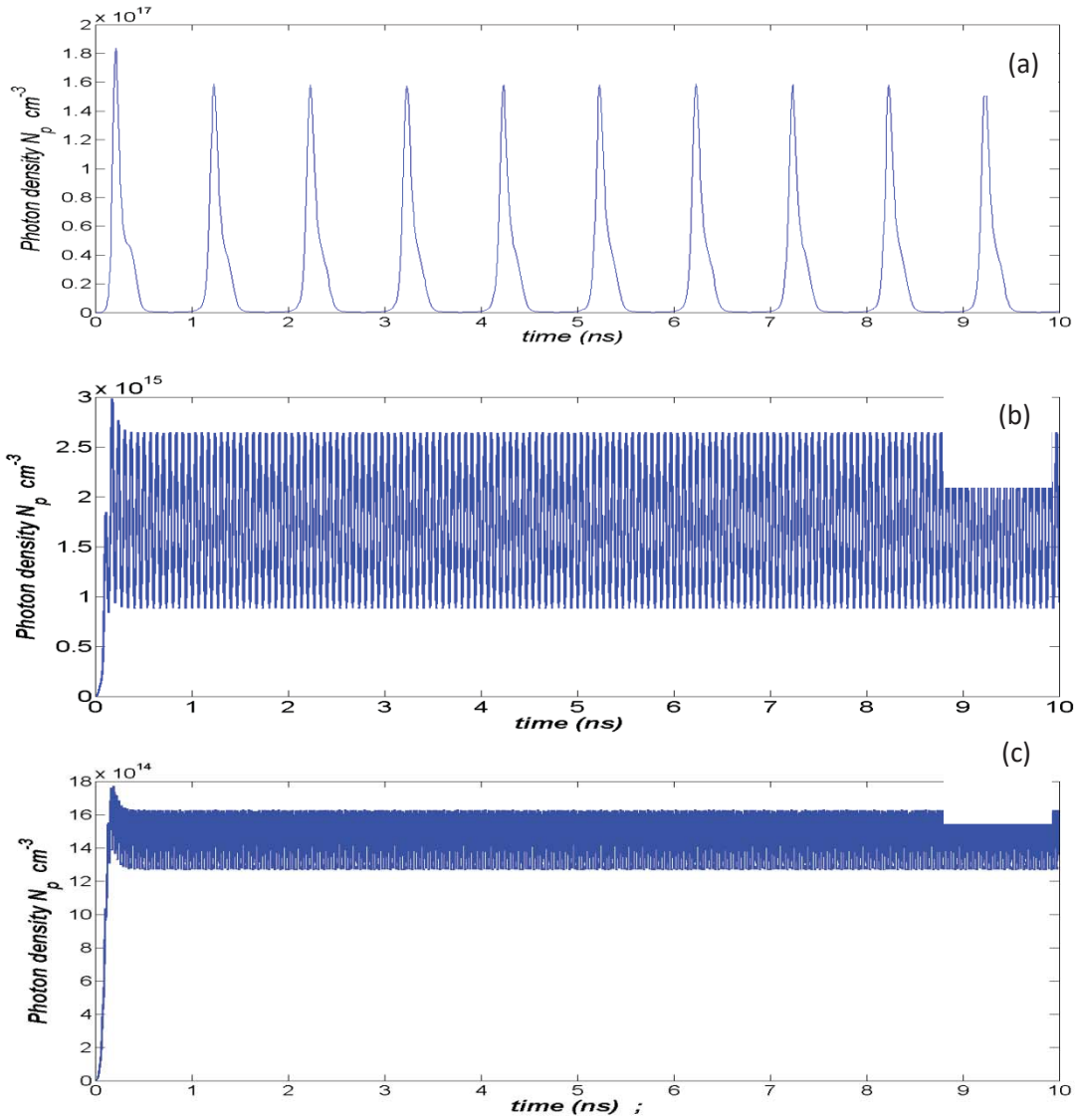


Fig.(2): Simulation of time series for photon density N_P for parameters b, m and (GHz) respectively: (a) 1 , 0.3 , 1 ; (b) 1 , 0.3 , 15 ; (c) 1 , 0.3 , 15 ; (d) 1 , 0.3 , 35.

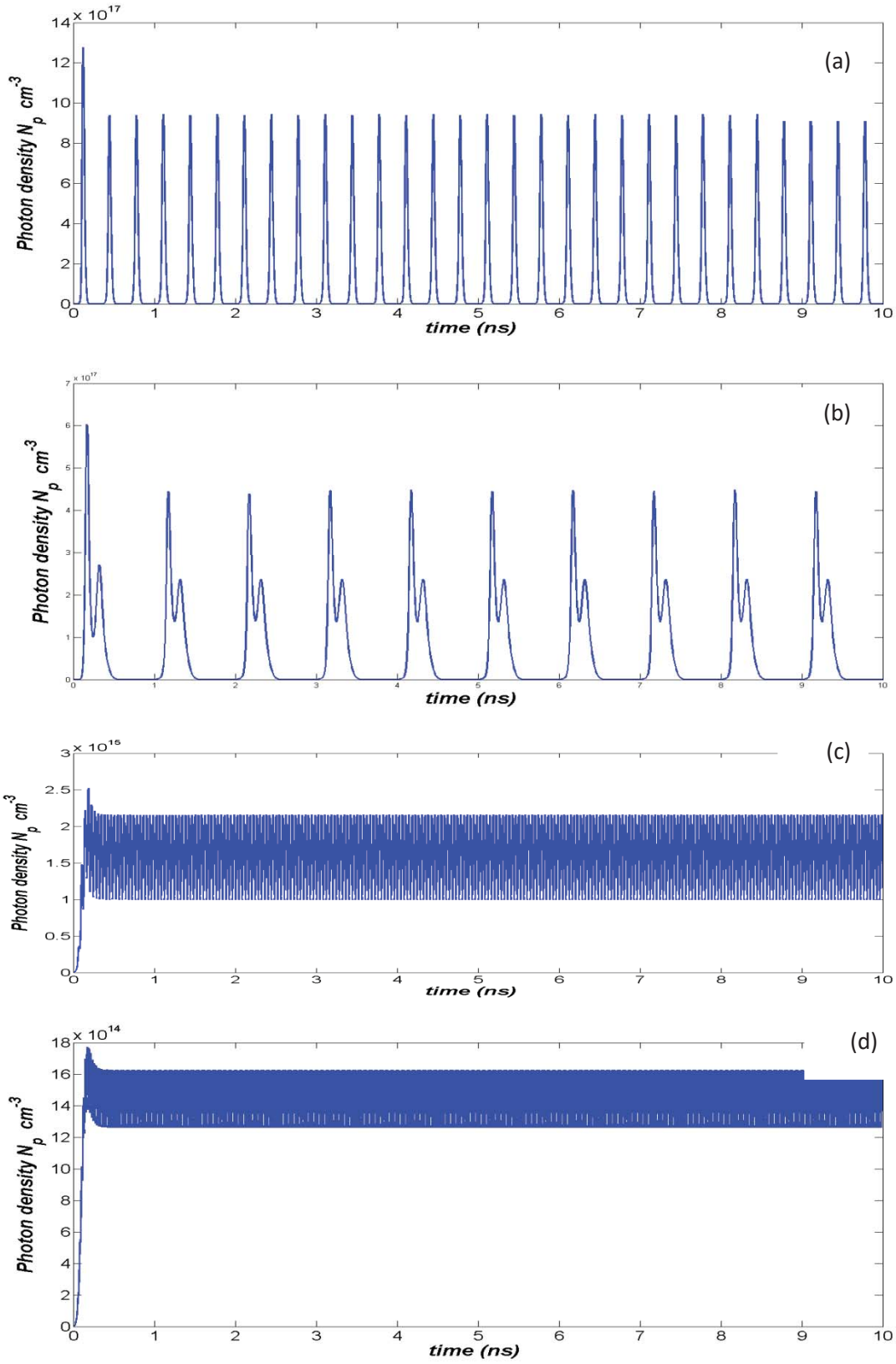


Fig.(3): Simulation of time series for photon density N_P for parameters b, m and f_m(GHz) respectively: (a) 1 ,0.5 , 3 ; (b) 1 , 0.5 , 1 ; (c) 1 , 0.5 , 25 ;(d)1 , 0.5 ,45.

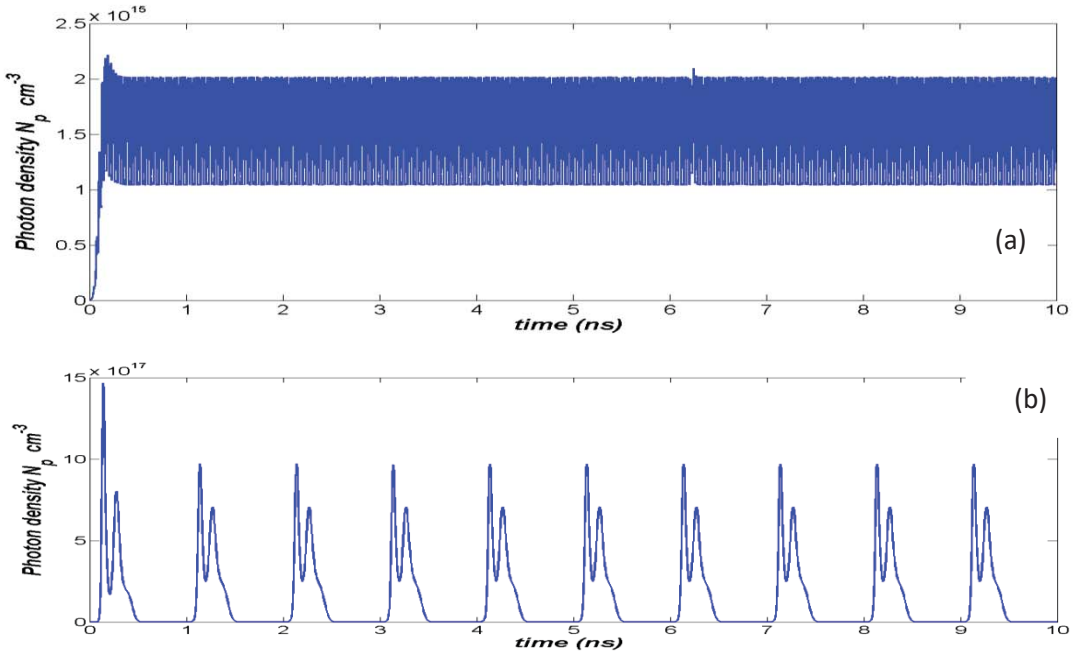


Fig.(4): Simulation of time series for photon density N_P for parameters b, m and f (GHz) respectively: (a) 1 ,0.8 , 3 ; (b) 1 , 0.8 , 35 .

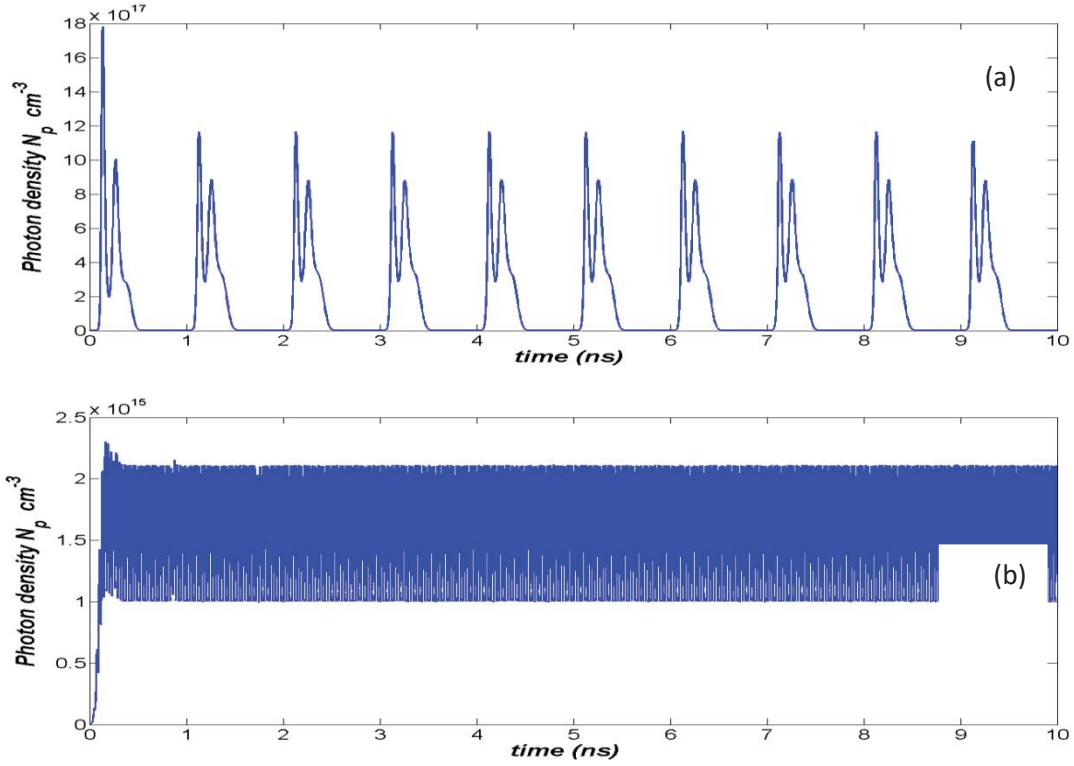


Fig.(5): Simulation of time series for photon density N_P for parameters b, m and (GHz) respectively: (a) 1 ,0.9 , 1 ; (b) 1 , 0.9 , 35 .

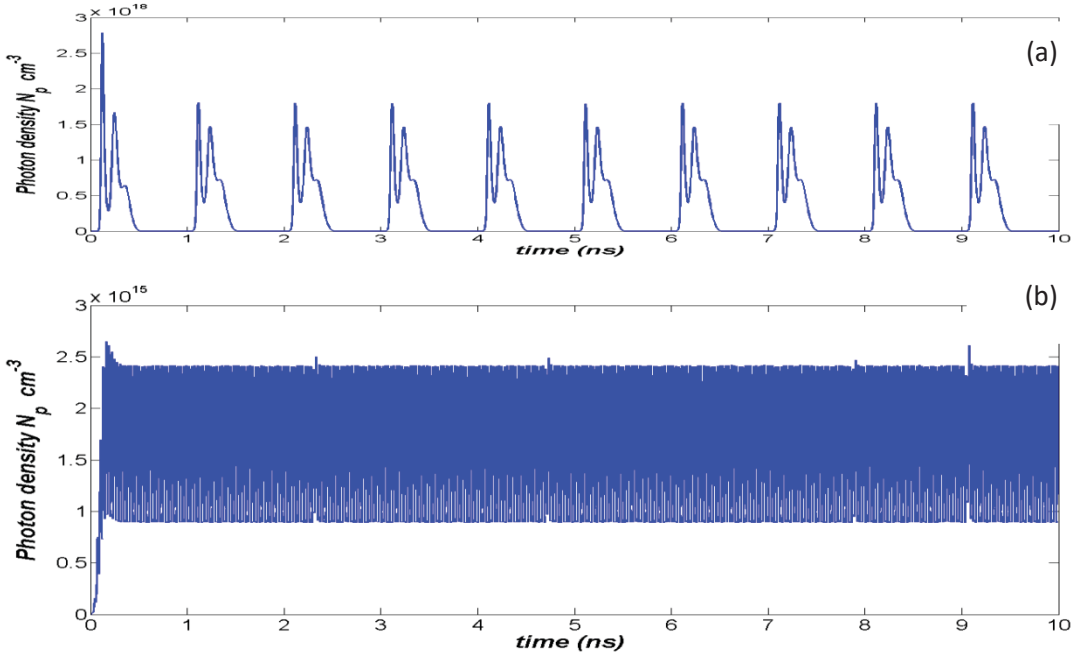


Fig.(6): Simulation of time series for photon density N_P for parameters b, m and f_m(GHz) respectively: (a) 1 , 1.2 , 1 ; (b) 1 , 1.2 , 35 .

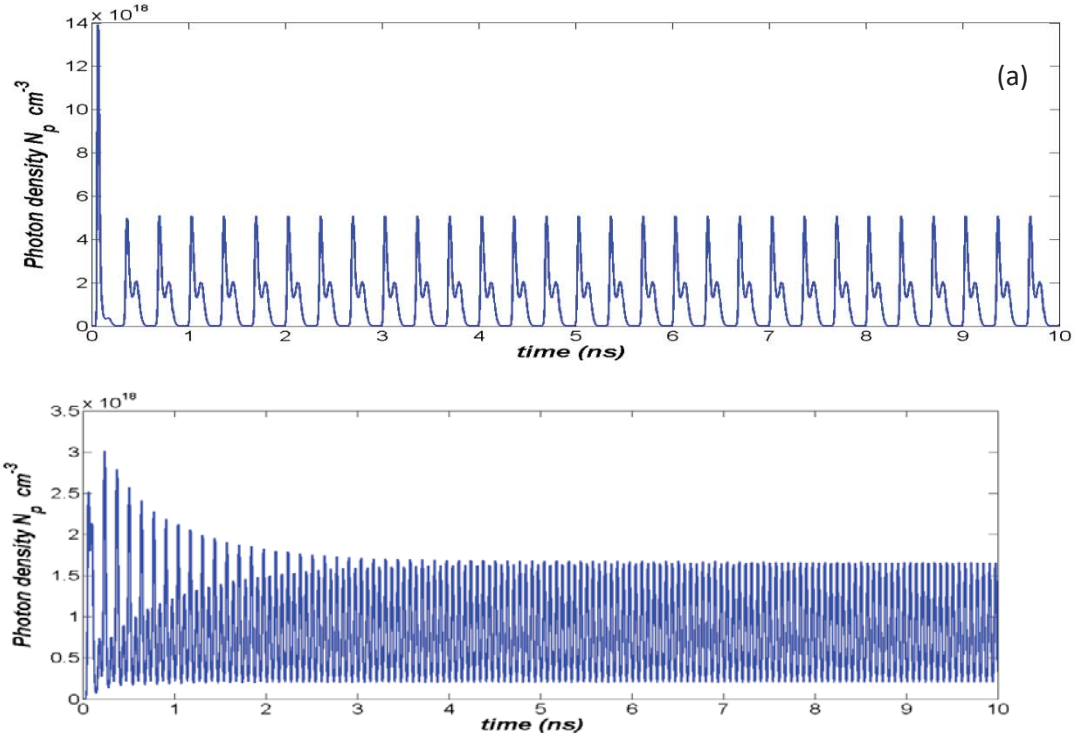


Fig.(7) : Simulation of time series for photon density N_P for parameters b, m and f_m(GHz) respectively: (a) 2 , 0.9 , 15 ; (b) 1 , 0.9 , 25 .

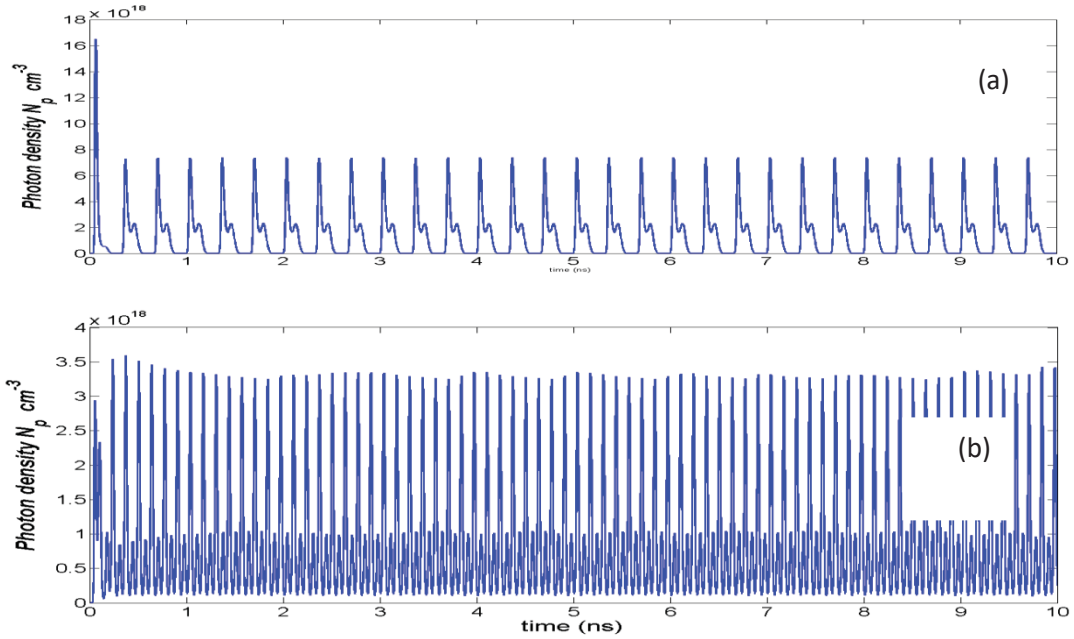


Fig. (8): Simulation of time series for photon density N_P for parameters b, m and (GHz) respectively: (a) 2,1.2,15; (b) 2,1.2,25.

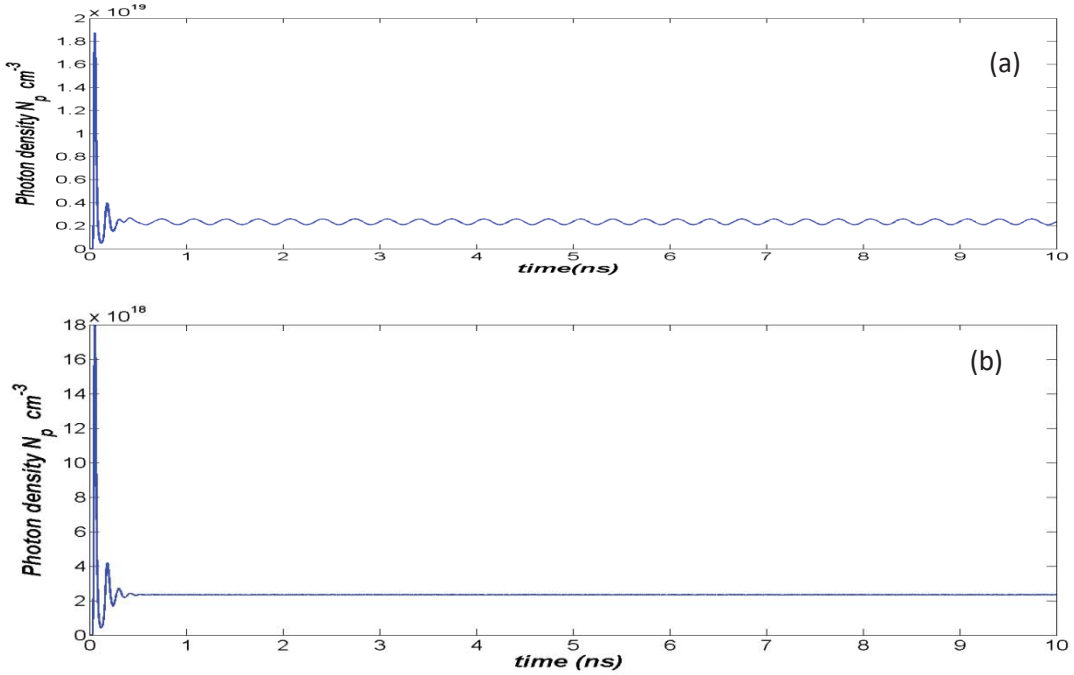


Fig.(9): Simulation of time series for photon density N_P for parameters b, m and (GHz) respectively: (a) 3,0.1 , 3 ; (b) 3 , 0.1 , 45 .

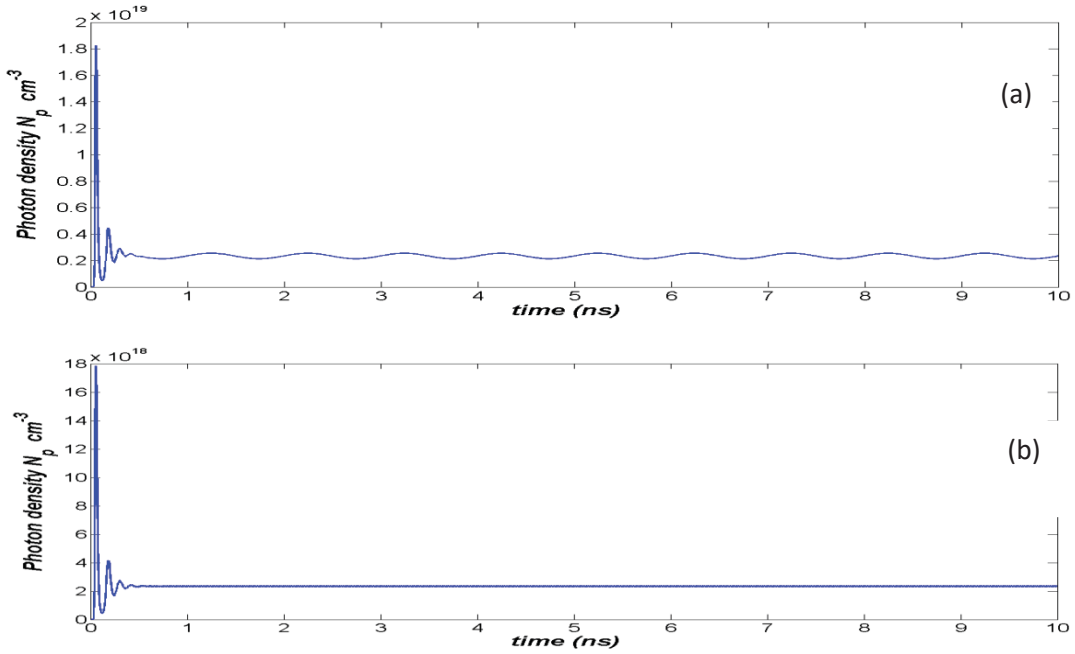


Fig.(10): Simulation of time series for photon density N_P for parameters b, m and f_m(GHz) respectively: (a) 3 ,0.3 , 1 ; (b) 3 , 0.3 , 45 .

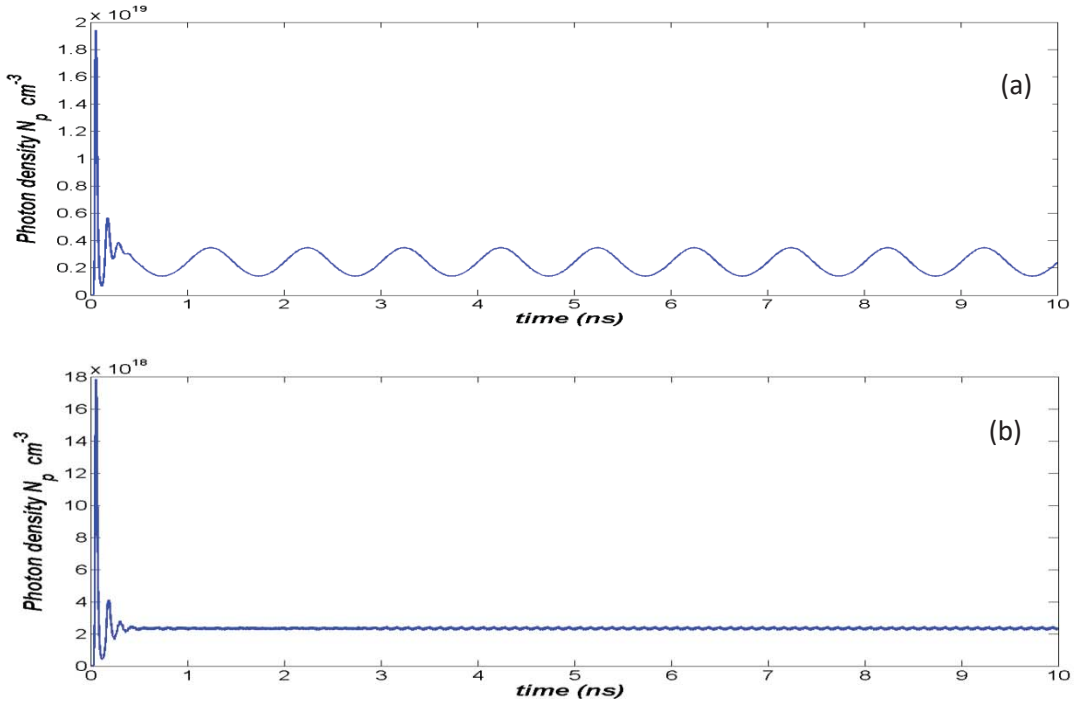


Fig.(11): Simulation of time series for photon density N_P for parameters b, m and f_m(GHz) respectively: (a) 3 ,0.3 , 1 ; (b) 3 , 0.3 , 45 .

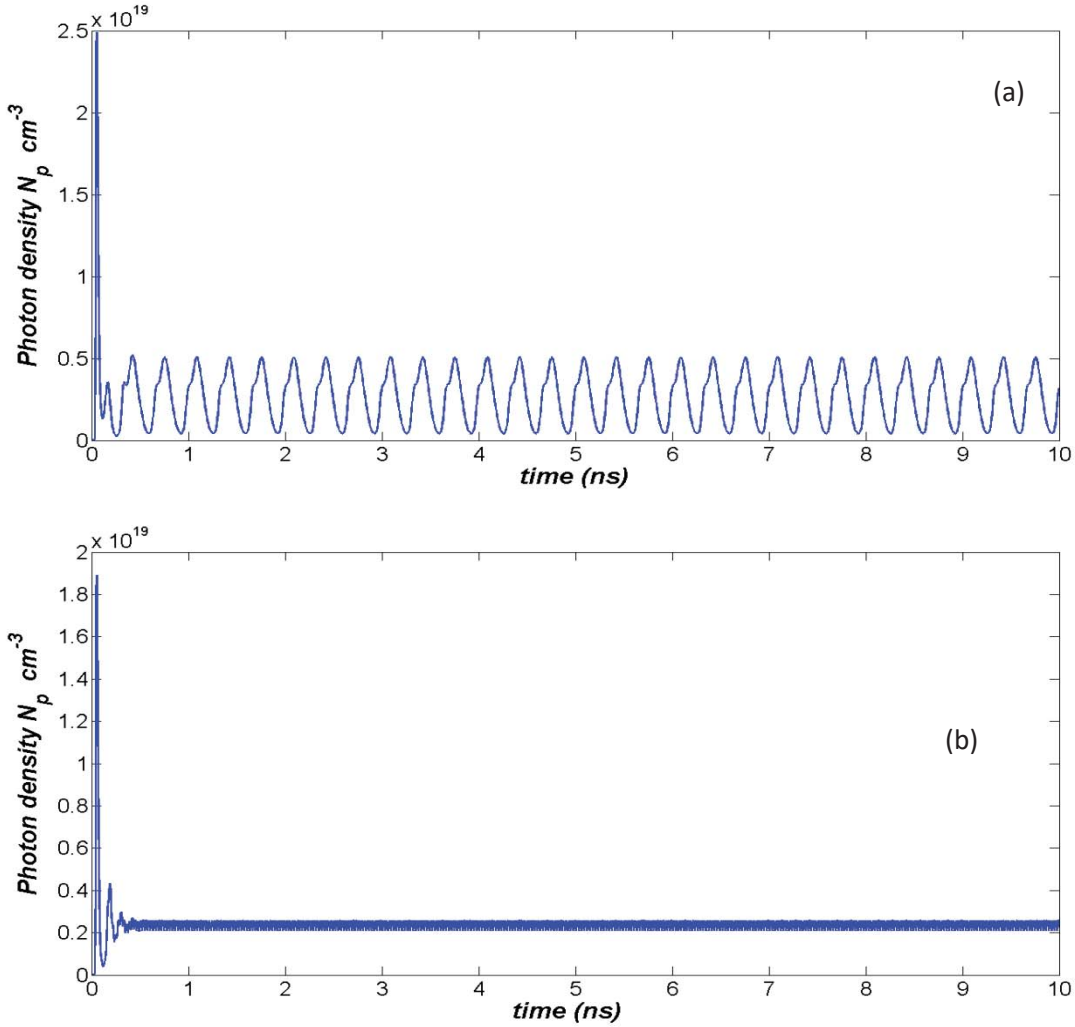
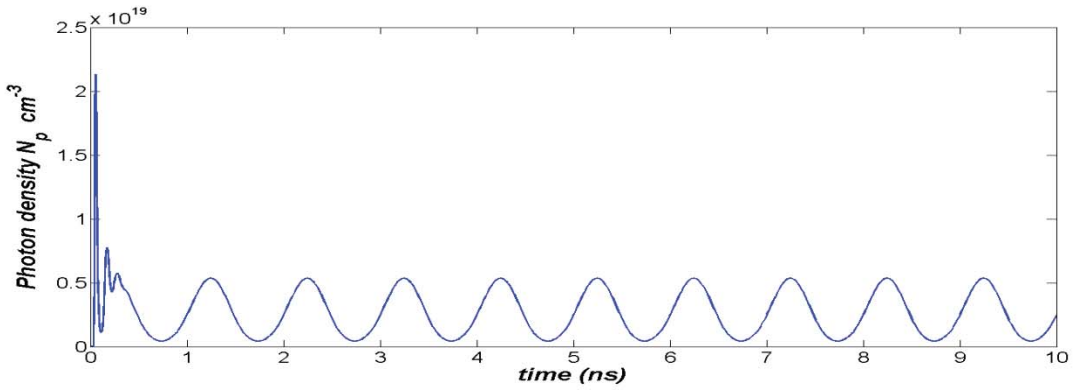


Fig.(12): Simulation of time series for photon density N_P for parameters b, m and (GHz) respectively: (a) 3 ,0.9 , 3



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(b) 3 , 0.9 , 35 .

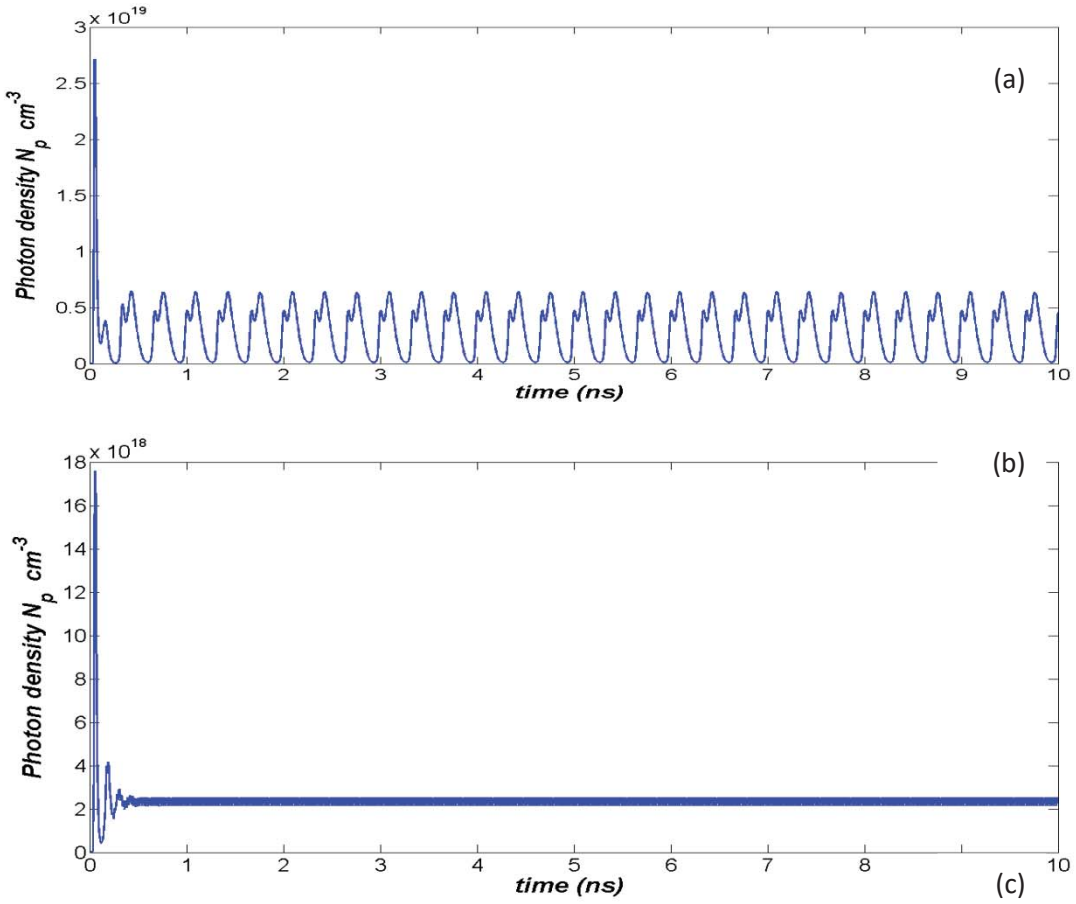

Fig.(13): Simulation of time series for photon density N_P for parameters b, m and f_m(GHz) respectively: (a) 3 ,1.2 , 1 ; (b) 3 , 1.2 , 3 ; (c) 3 , 1.2 , 45 .

5- Conclusions:

In this study, different dynamical behaviors are appeared such as steady state, periodic, multi-periodic, self-pulsing and chaotic behavior.

For various parameters of direct injection current modulation, the system transits from the steady state and periodic behavior on small values of modulation parameters to the multi-period state and self- pulsing and ending to chaotic state with higher values of the above parameters. The injection current modulation has much applications such as optical communications.

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