Theoretical study of Semiconductor Laser dynamics

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Abstract

In the present work, we study the dynamics of semiconductor laser as the time behavior of the carriers and photons densities , the output power and finding the threshold injected current at steady state. Output intensity of the semiconductor laser under the effect of injection current modulation was studied too.

Keywords: Semiconductor laser, Rate equations, Steady state.

1- Introduction

Semiconductor lasers (SCL) have become the most important class of lasers, they are used in applications such as cable TV signal transmission, telephone and image transmission, computer interconnects, network, compact disc (CD) player, bar-code readers ,laser printers and many military applications[1,2].By the end of the year 1962 four different scientific groups separately announced the production of the first semiconductor laser based on doped GaAs [3-5] and in $Ga(As_{1-x}P_x)$ [6].

The performance of semiconductor laser was improved a lot after the proposition (in 1963) of the concept of heterostructure, which consists in the junction of two semiconductor materials having different energy gaps, causing a discontinuity in the resulting energy band and, thus providing carrier confinement in the growth direction [7]. The structure of semiconductor lasers is based on the p-n junction of the semiconductor materials and the laser oscillation is realized by the emission of light due to carrier recombination between the conduction and valance bands [8].The population inversion in general laser system is simply replaced the carrier density produced by electron-hole recombination, the photon number(which is equivalent to the absolute square of the field amplitude) and the carrier density are frequently used as the variables of the rate equations for semiconductor lasers[8].The reason for using the semiconductors for the device applications is that electrical properties can be modified significantly by the incorporation of small amount of impurities or other kind of defects [1].

2-Theory

Semiconductor lasers are lasers based on semiconductor gain media, where optical gain is usually achieved by stimulated emission at an interband transition under conditions of a high carrier density in the conduction band. The physical origin of gain in a semiconductor (for the usual case of an interband transition) is illustrated in Figure (1) [9].

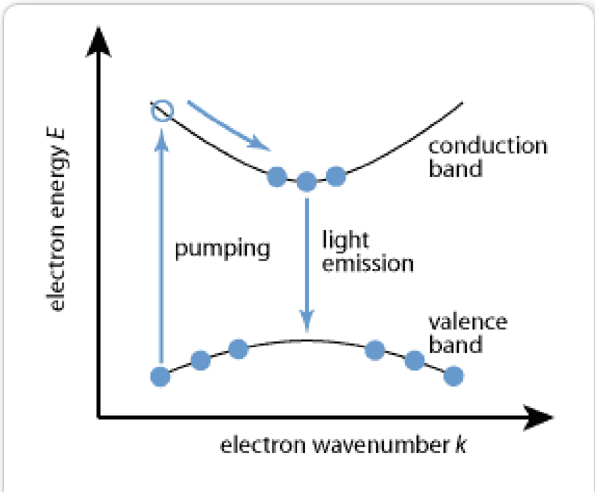


Figure (1): Physical origin of gain in a semiconductor[9].

Without pumping, most of the electrons are in the valence band. A pump current with enough energy can excite electrons into a higher state in the conduction band, from where they quickly relaxes to states near the bottom of the conduction band. At the same time, holes generated in the valence band move to the top of the valence band. Electrons in the conduction band can then recombine with these holes, emitting photons with an energy near the band gap energy. This process can also be stimulated by incoming photons with suitable energy[9]. Figure(2) shows spontaneous emission describes the process where an electron in an excited state falls back to the ground state. The energy of the photon emitted by this process is given by the energy difference between the excited state E_2 and the ground state E_1 [10].

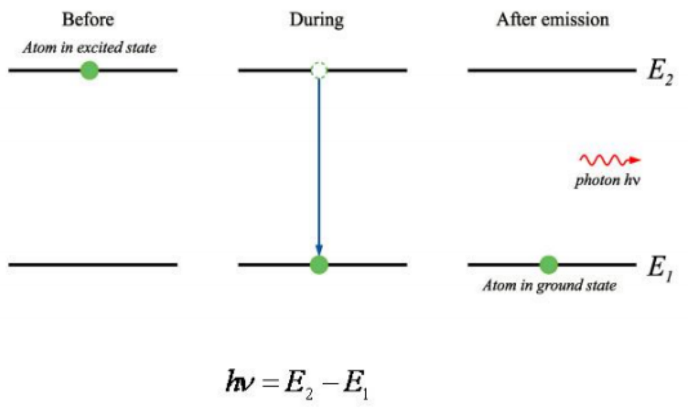


Figure (2): Schematic illustration of spontaneous emission of a photon by an optical transition of an electron [10].

Along with the development of semiconductor lasers, a set of coupled rate equations, which involves injection current ,injected carrier density and photon density in the active region, has been found very useful in understanding the behavior of semiconductor lasers[9].

2-1 Rate equations description

The rate equations method, includes a set of at least two coupled equations; one for the carrier density (*N*)and the other for the photon density(S). They are given in equations (1-2) shown below [11].

$$\frac{dN}{dt} = \frac{I}{qV_{act}} - g_o(N - N_o)(1 - \varepsilon S)S - \frac{N}{\tau_n} + \frac{N_e}{\tau_n} \tag{1}$$

$$\frac{dS}{dt} = \Gamma g_o(N - N_o)(1 - \varepsilon S)S + \frac{\Gamma \beta N}{\tau_n} - \frac{S}{\tau_p} \tag{2}$$

$$\frac{S}{P_f} = \frac{\Gamma \tau_P \lambda_o}{V_{act} \eta hc} \tag{3}$$

Where, N is the carrier density, S is the photon density , P_f is the laser output power, I is the injection current, V_{act} is the active region volume, g_o is the gain coefficient, N_0 is the optical transparency density, ε is gain compression factor,

τ_n is the carrier lifetime, N_e is the equilibrium carrier density, Γ is the optical confinement factor, β is the spontaneous emission coupling factor, τ_p is the photon lifetime, η is the differential quantum efficiency per facet, λ_o is the emission wavelength, q is the electron charge, h is Planck's constant, and c is the speed of light in vacuum. The photon density S is defined as $\Gamma S_{tot}/V_{act}$, where S_{tot} is the total number of photons in the active volume and Γ account for the fact that only photons in the active region are affected by gain or loss[12].

2-2-Direct current modulation:

The direct current modulation is considered as one of methods to enhance the nonlinearities in the laser output . The injection current can be written as a combination of two quantities, a dc part and a variable ac part

which are given as follows

$$I(t) = I_b + I_m \sin(2\pi f_m t) \qquad (4)$$

I_b is the constant part contribution of the injection current, I_m is the modulation depth or the peak of the ac part of the variable injection current, f_m is modulation frequency and t is time .

$I_b = b I_{th}$ and $I_m = m I_{th}$, where b and m are positive real numbers and I_{th} is the threshold injection current .

3- Results and discussion:

To find out the threshold injection current of the semiconductor laser the set of equations (1-2) were solved using the fourth Runge-Kutta method and the Matlab system the photon density (S) with varying injection current from zero to 50mA and finding the threshold injection current at steady state with the help of the Table(1). The intersection of straight line curve with current axis determines the injection current at threshold for the parameters given in Table(1) ,which is equals to11.8 mA as shown in fig.(3). In fig.(4) we note that :(i) rise time of the photon density shortens when the injection current increases,(ii) dc signal of the photon density increases with the increasing of injection current,(iii) and the photon density signal arrival time decreases under the same effect of current . In fig.(5) ,the behavior of carrier density shows fast rise time with small peak at gain constant values (at constant injection current) .The rise time at carrier density (N) decreases as the injection current increases . From fig.(6) we find that the reduction of the switching-on time of the laser output with the injected current current . The power output P_f was calculated using equation(3), as shown in fig.(7).

Table (1) : Parameters used in simulation [11].

Symbol	Value
V_{act}	$9\times10^{-11}\ cm^3$
g_o	$3\times10^{-6}\ cm^3/s$
ε	$3.4\times10^{-17}\ cm^3$
τ_n	*Ns*
N_e	$5.41\times10^{10}\ cm^{-3}$
Γ	0.44
β	4×10^{-4}
τ_p	1 *ps*
η	0.1
λ_o	1.502×10^{-4} cm
h	6.625×10^{-34} J .sec
c	3×10^{8} m/s

The injection current given in equation (1) replaced with that defined in equation (4), then the system of equations (1-2) was solved using the fourth order Runge-Kutta method and the Matlab system to obtain the photon density (S) for the parameters values given in Table (2).

Table (2) Parameters values of direct modulation

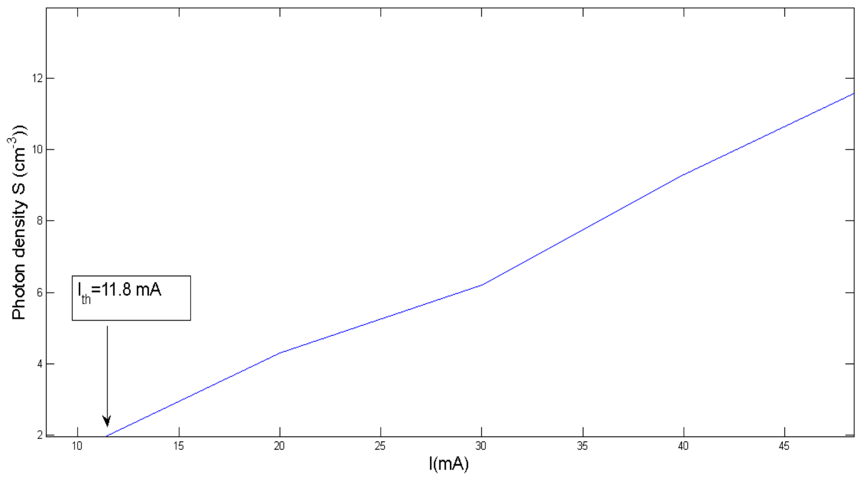
b	0.1		0.5	2	3	4	
m	0.1	0.5	0.7	0.8	1	1.2	1.5
f_m	0.1		0.5	2	5	10	

We find that

1. For : b=0.1 , m= 0.1 , changing the frequency in the range (0.1- 10) GHz , the system is started with periodic case at low frequency to a periodic case or chaotic one at high frequency; the same behavior is noticed for the values (b=0.1), (f_m =0.1- 10GHz) and m was changed from (0.1,0.2,0.3,0.6, 0.9, 1.2) as shown in figs.(8-10) .

2. At : b=0.1 and m= 0.1 , i.e. low value of modulation frequency and the values of modulation depth in characteristic values (m= 0.8,0.9,1.2, 1.5) we observed a characteristic behavior which is termed as self-pulsing (pulses separated by zero output regions of constant lenght) as shown in fig. (11). Noticed that the frequency of the self-pulsing does not equals the modulation frequency. It is affected by the combination (b,m). By increasing b to 0.5 m=0.9, 1.2, and =0.1 GHz , the same behavior (self-pulsing) appeared as shown in fig.(12). When increasing the value of b in the range (0.1-5) for m changes in the range (0.5- 0.7) and for different values of f_m =(2, 5, 10) GHz, we note that the general behavior is periodic and the power output decreases at these conditions these results are detailed in fig.(13).

When a semiconductor laser is modulated at a frequency above the intrinsic resonance frequency, the resonance peak shifts to lower frequency as the modulation current increased .When the frequency of the noise peak is moved to about half of the drive frequency ,the noise peak begins to be sharpened. That is the first harmonic is about to be generated .When the modulation current is increased further, the oscillation gradually becomes period one and so on. The combination (j_b, j_m, f_m) need not to be chosen to insure low or strong modulation as the obtained results pr oved that instabilities can be achieved for low biased current and *m* but high frequency of modulation. The obtained results agree well with those obtained in semiconductor lasers viz QW lasers [13], Vertical cavity surface emitting lasers - VCSELs[14].



Fig(3) : Laser photon density (S)versus the injected current.

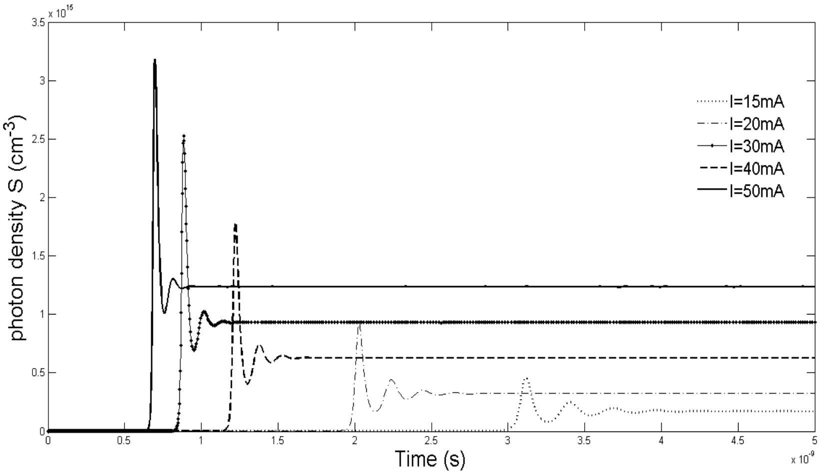


Fig.(4) : Time series of photon density (S) against the injected current for values(15, 20, 30, 40, 50) mA.

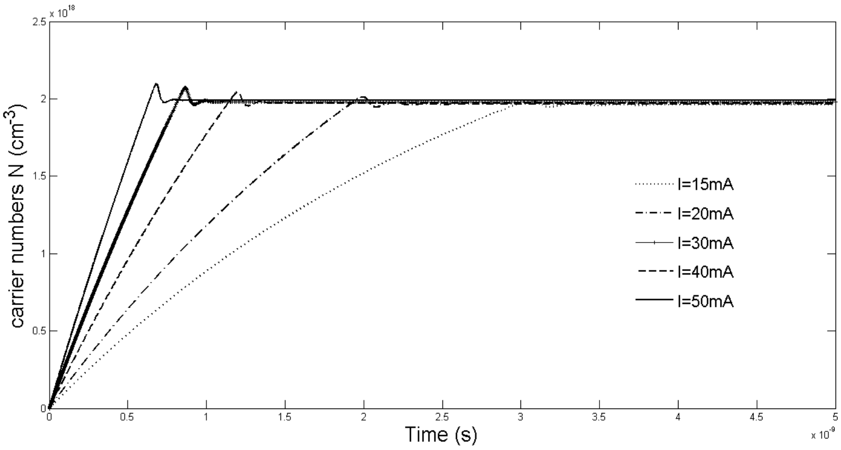


Fig.(5) : The time variation of carrier density(N) with changing the injection current for the values (15, 20, 30, 40, 50) mA.

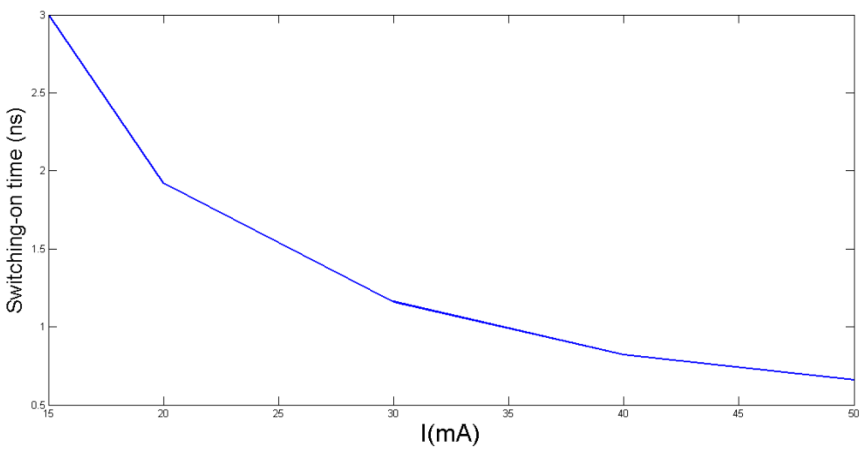


Fig.(6) : Switching-on time versus the injection current.

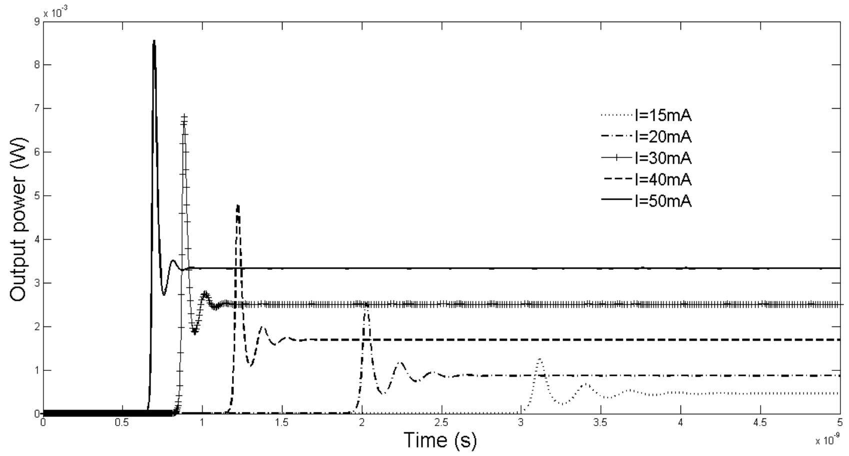


Fig.(7) : Output power time behavior at different values of the injected current.

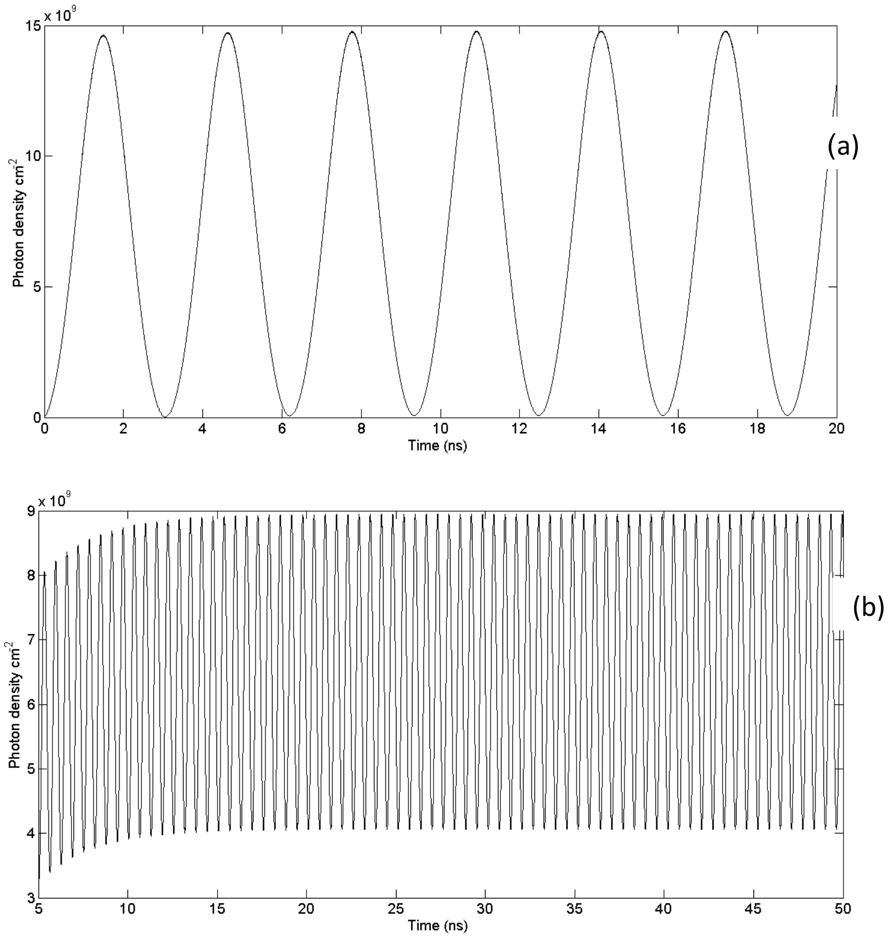
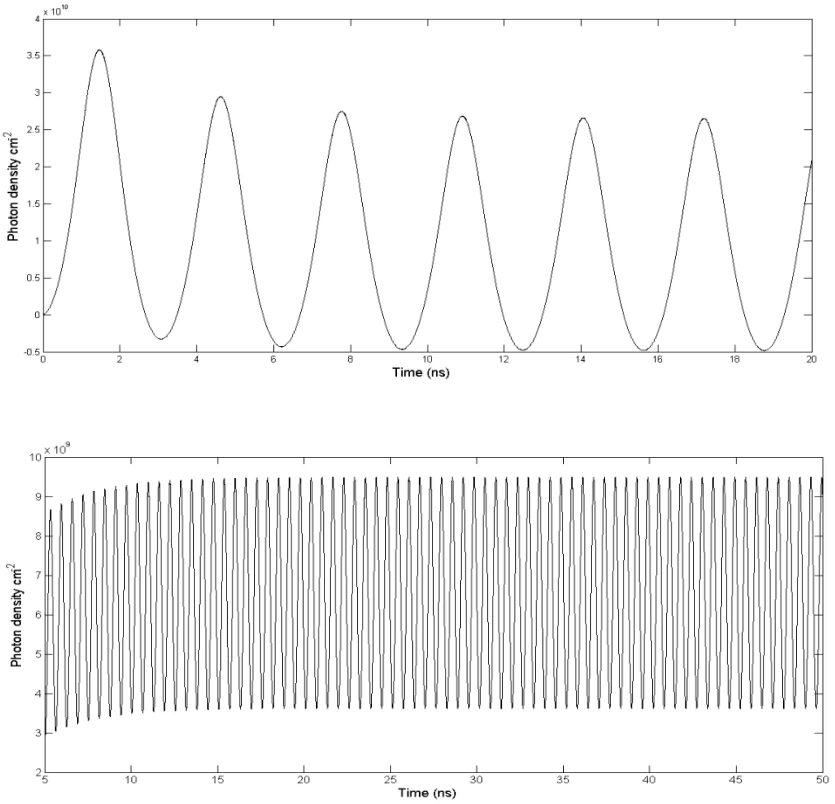


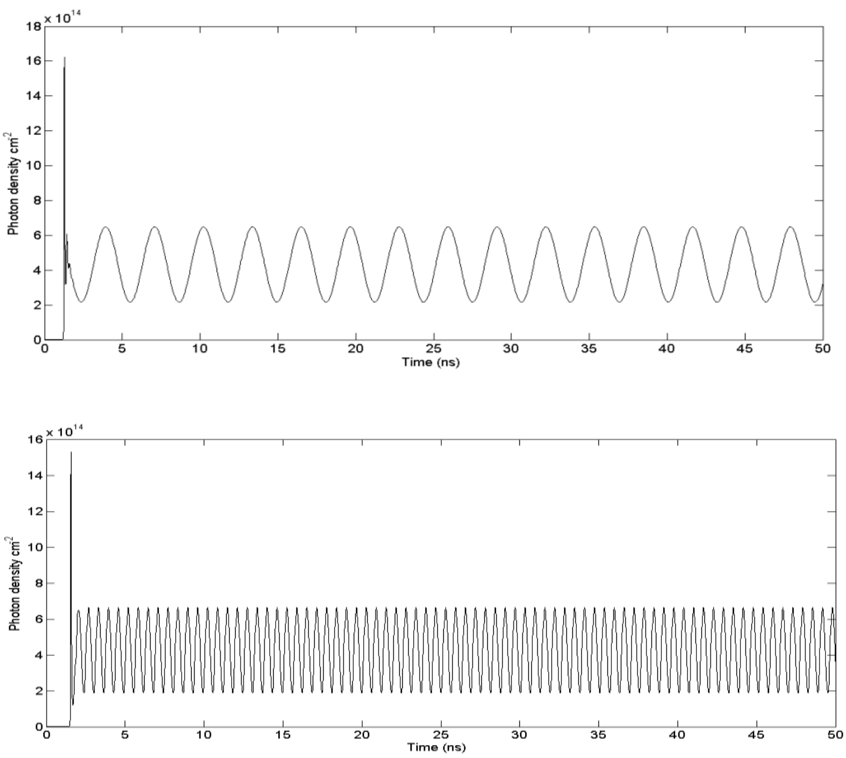
Fig.(8) : Output photon density time behavior for (a): (b=0.1 ;m=0.6; f_m =2 GHz); (b): (b=0.1 ;m=0.6; f_m =10 GHz)



(a)

(b)

Fig.(9) : Output photon density time behavior for (a) :(b=0.1 ;m=1.2; f_m =2 GHz);(b=0.1 ;m=1.2; f_m =10 GHz)



(a)

(b)

Fig.(10) : Output photon density time behavior for (a): (b=2 ;m=0.6; f_m =2 GHz);(b=2 ;m=0.6; f_m =10 GHz)

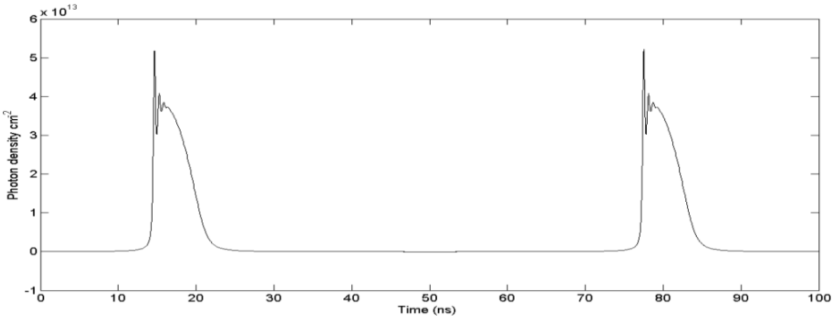


Fig.(11) : Output photon density time behavior at (b=0.1 ;m=0.8; f_m =0.1 GHz)

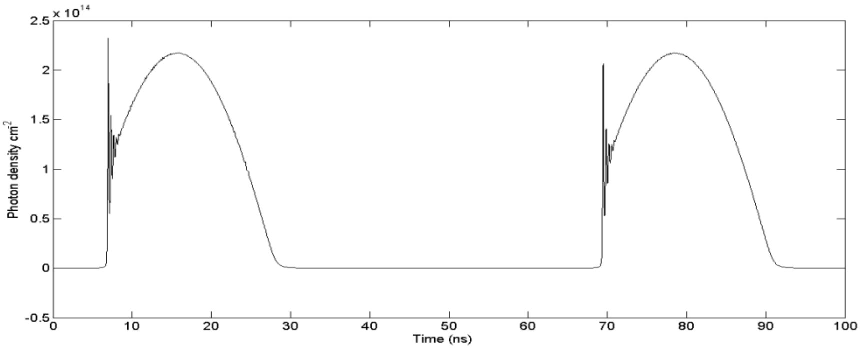


Fig.(12) : Output photon density time behavior at (b=0.5 ;m=0.9; f_m =0.1 GHz)

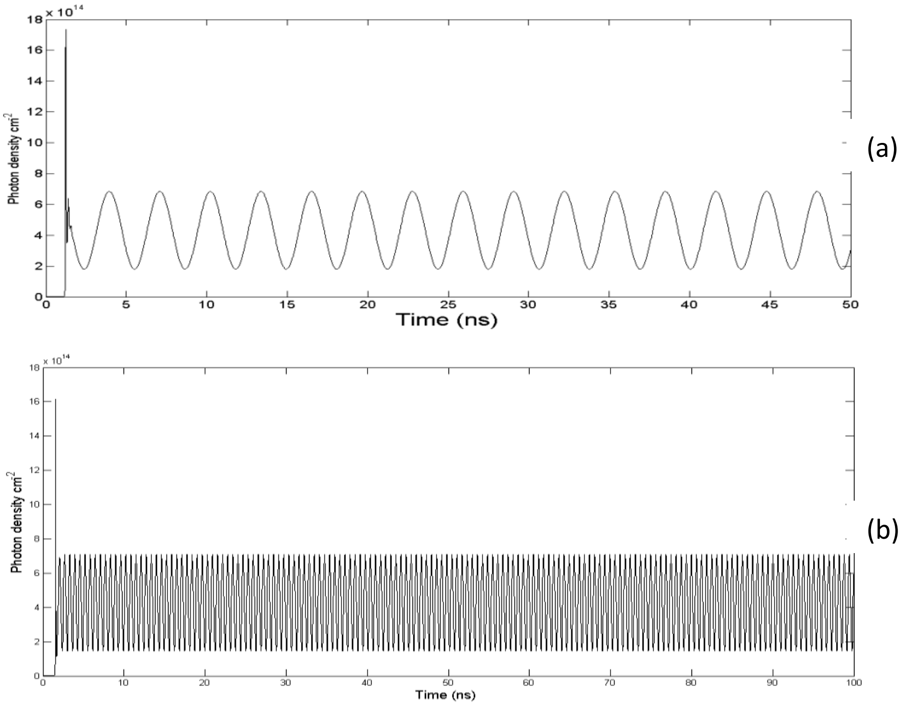
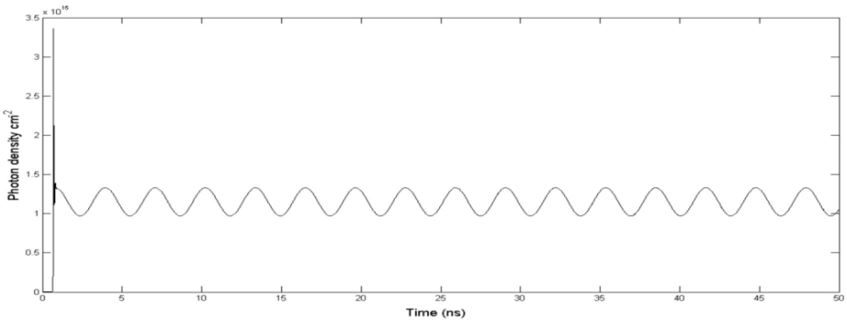
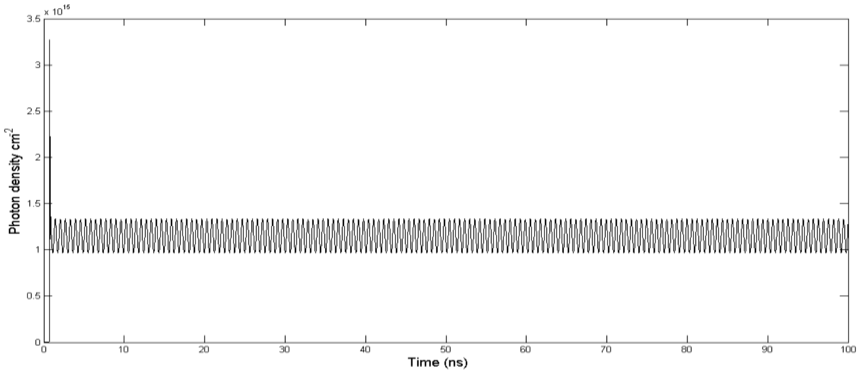


Fig.(13-d) : Output photon density time behavior for (a): (b=2 ;m=0.7; f_m =2 GHz); (b) : (b=2 ;m=0.7; f_m =10 GHz); (c): (b=4 ;m=0.5; f_m =2 GHz) and (d):(b=4 ;m=0.5; f_m =10 GHz)continue



(c)



(d)

Continued

4- Conclusions:

In the present work we achieved the study of dynamics of photon density (S) and carrier density (N) , and the threshold injected current is determined . These results refer to the increasing of photon density (S) and carrier density(N) with increasing the injected current I which leads to reduction of the switching-on time of semiconductor laser .The output photon density of the laser system under direct current modulation produced different dynamics, transition from periodic state to quasi periodic state at typical values of (b,m,f_m) as well as the self-pulsing behavior at low frequency values.

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دراسة نظرية لحركيات ليزر شبه الموصل

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الخلاصة

في هذا العمل قمنا بدراسة حركيات ليزر شبه الموصل عموما كالتصرف الزمني لكثافة الفوتونات وقدرة الخرج وإيجاد عتبة التيار عند الحالة المستقرة .شدة الخرج لليزر شبه الموصل تحت تأثير تضمين التيار المباشر درست أيضا.