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InAs/InGaAs quantum dot semiconductor laser under the compound effect of optical feedback and direct current modulation

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Abstract:

Several dynamics of directly modulated *InAs/InGaAs* quantum dot semiconductor laser in the presence of optical feedback have been studied extensively. The effect of feedback strength,linewidth enhancement factor, dc bias strength of the injection current, the modulation strength and modulation frequency are studied. Various types of dynamics ranging from periodic to chaotic ones are seen to occur. Coherence collapse (output drop out) occurs as a result of choosing certain combinations of the control parameters appeared in the theoretical model.

Key words: Quantum dot semiconductor laser,Optical feedback, Injection current modulation,Coherence collapse,Chaos.

Introduction:

Nonlinear dynamics of semiconductor lasers (SCLs) have been widely studied due to the important roles of SCLs play in conventional and chaotic optical communication systems [1]. They with optical feedback are a category of nonlinear systems that exhibit a variety of chaotic dynamics. They are attractive systems from the viewpoint of investigating chaos dynamics in optics [2]. Optical feedback gives rise to periodic and chaotic oscillations in the laser output power and sometimes leads to internal mode hopping or coherence collapse [3,4]. SCLs can be affected directly by their injection current modulation [5]. The modulation is usually performed in GHz frequency domain. It is well known that SCLs show highly complex phenomena such as sub-harmonic generation,chaos and multistability under strong modulation at this frequency range [6]. When a SCLs are under the effect of both input current modulation and optical feedback,rich and variety of dynamics can be enhanced [7-12].

The rapid progress in epitaxial growth techniques have led to the design of complex SCL devices with nanostructured active regions and, therefore interesting dynamical properties can be obtained. Future high-speed data communication applications demand devices that are insensitive to temperature variations and optical effects, and provide features such as high modulation bandwidth and low chirp[13]. Currently, self–organized semiconductor quantum dot laser SCQDL are promising candidates for telecommunication applications[14-17]. In optical fiber network or as a writer or reader in computers, QD laser as a source may be perturbed by unavoidable optical feedback from fiber pigtails or fiber connector unless expensive optical isolators are used. For communication QDLs might be modulated via modulating its input current. So, the study of feedback and injection current modulation is of great importance. There are limited resources concerning the study of the effect of feedback on the dynamics of the QDLs [18-22] while,almost, no attempt to study the effect of modulating the injection current on the dynamics of QDLs [13]. To our best knowledge we believe that no work available in literature concerning the study of the effect of input injection current modulation together with feedback on the dynamics of QDLs. In this article we present the result of such study theoretically.

Theoretical model

The model used in this work to study the dynamics of InAs/InGaAs quantum dot laser under the effect of feedback is based on the work of Ludge etal [21 ,22].The details of energy diagram and feedback process are shown in figures (1 and 2). QD laser under optical feedback is considered to consist of a gain section of length L that contains the layers of self organized QDs as the active medium, and a feedback section given by a mirror at a distance *l* with respect to the end facet of the QD laser, reflection back the light into the gain region. The gain section of the QD laser is modeled by a microscopically based rate equations system [21]. It allows for separate treatment of electron and hole dynamics in the QD as well as the surrounding wetting layer (WL). The theoretical model consists of five rate equations describing the turn on dynamic of photon density n_{ph}, electron n_e and hole n_h densities in the quantum dots and electron w_e and hole w_h carrier densities in the wetting layer. The introduction of an optical feedback and modulation of injection current requires the addition of two terms taking into account the feedback and phase of the electrical field added to the equation of photon density and to a sixth equation written to describe the phase variation of electric field with time. The modulation of injection current required a new definition of the injection current density that appeared in the equation of electron and hole densities , w_e and w_h , in the wetting layer. The energy scheme of the QD laser is shown in figure (1).The present system of equations reads:

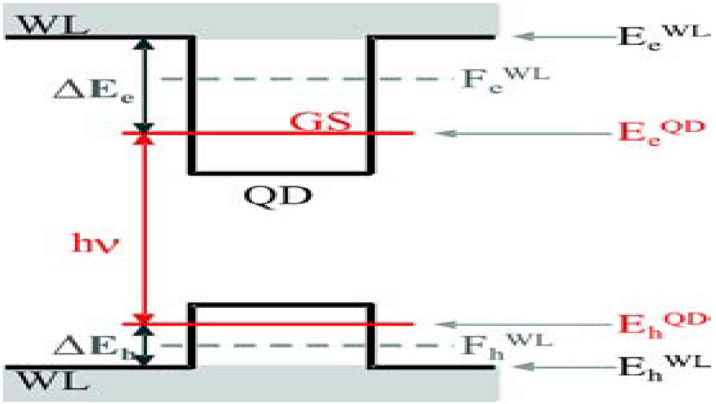


Figure 1: Energy diagram of the QD and WL system[21].

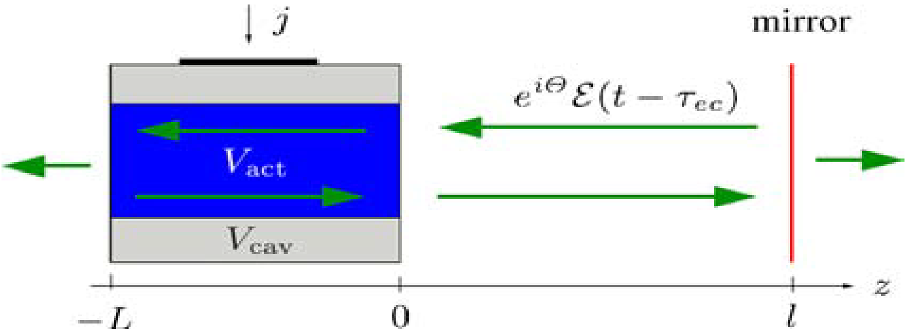


Figure 2: Schematic setup of the considered QD laser device with optical feedback from a short external cavity[22].

$$\dot{n}_e = -\frac{1}{\tau_e} n_e + S_e^{in} N^{QD} - \Gamma R_{ind}(n_e, n_h, n_{ph}) - R_{sp}(n_e, n_h) \tag{1}$$

$$\dot{n}_h = -\frac{1}{\tau_h} n_h + S_h^{in} N^{QD} - \Gamma R_{ind}(n_e, n_h, n_{ph}) - R_{sp}(n_e, n_h) \tag{2}$$

$$\dot{w}_e = \frac{j(t)}{e_o} + \frac{n_e}{\tau_e}\frac{N^{sum}}{N^{QD}} - S_e^{in} N^{sum} - \tilde{R}_{sp}(w_e, w_h) \tag{3}$$

$$\dot{w}_h = \frac{j(t)}{e_o} + \frac{n_h}{\tau_h}\frac{N^{sum}}{N^{QD}} - S_h^{in} N^{sum} - \tilde{R}_{sp}(w_e, w_h) \tag{4}$$

$$\dot{n}_{ph} = -2k\,n_{ph} + \Gamma R_{ind}(n_e, n_h, n_{ph}) + \beta R_{sp}(n_e, n_h) + 2\frac{K}{\tau_{in}}\sqrt{n_{ph,\tau_{ec}}\, n_{ph}}\cos(\phi - \phi_{\tau_{ec}} + \Theta) \tag{5}$$

$$\dot{\phi} = \frac{\alpha}{2}\left\{ \Gamma W A \left(n_e + n_h - N^{QD} \right) - 2\kappa \right\} - \frac{K}{\tau_{in}} \sqrt{\frac{n_{ph,\tau_{ec}}}{n_{ph}}} \sin\left(\phi - \phi_{\tau_{ec}} + \Theta \right) \qquad (6)$$

The induced electron and hole processes of absorption and emission are modulated by a linear gain $R_{ind}(n_e, n_h, n_{ph}) = WA(n_e + n_h - N^{QD}) n_{ph}$. The spontaneous emission in the QDs is approximated by $R_{sp}(n_e, n_h) = (W / N^{QD})\, n_e\, n_h$ .The spontaneous recombination rate in the WL is given by $\tilde{R}_{sp}(w_e, w_h) = B^S\, w_e\, w_h$ where B^S is the band–band recombination coefficient in the WL. $\Gamma = \Gamma_g N^{QD} / N^{sum}$ is the optical confinement factor. Γ_g is the geometric confinement factor. N^{sum} is twice the density of the total QD and N^{QD} denotes twice the QD density of the lasing subgroup (the factor 2 account for the spin degeneracy). W is the Einstein coefficient and A is the wetting layer normalized area. β is the spontaneous emission coefficient, $j(t)$ is the injection current density, e_o is the electronic charge. 2κ is the optical intensity loss, α is the linewidth enhancement factor and K is the strength of the optical feedback. Carrier–carrier scattering rates (nonlinear scattering rates) S_e^{in} and S_h^{in} for electron and hole capture from the WL into the QD levels and scattering times are $\tau_e = (S_e^{in} + S_e^{out})^{-1}$ and $\tau_h = (S_h^{in} + S_h^{out})^{-1}$, S_e^{out} and S_h^{out} are the scattering rates out of the QD levels towards the WL . The time given by the single –pass time of gain region $\tau_{in} = L / c_m$ where c_m is the speed of light inside the gain region .The phase shift of light during one round-trip in the external cavity ($\tau_{ec} = 2l / c$) is given by $\Theta = \omega_{th}\, \tau_{ec}$ with ω_{th} denoting the frequency of the solitary laser at the lasing .The number of photon which is labeled by the subscript τ_{ec} ,i.e. $n_{ph,\tau_{ec}}$ and the optical phase ϕ_{ec} are taken at a delayed time $(t - \tau_{ec})$. ϕ is the electric field phase. The injection current density in the pumping term $[\frac{j(t)}{e_o}]$ in equations (3) and (4) has been replaced by a source of injection current density written as follows:

$$j(t) = j_b + j_m \sin(2\pi f_m t) + K\, n_{ph,\tau_{ec}} \;.......................... (7)$$

Where j_b is the *dc* part of the injection current and j_m is the amplitude of the *ac* part of the injection current .

Where

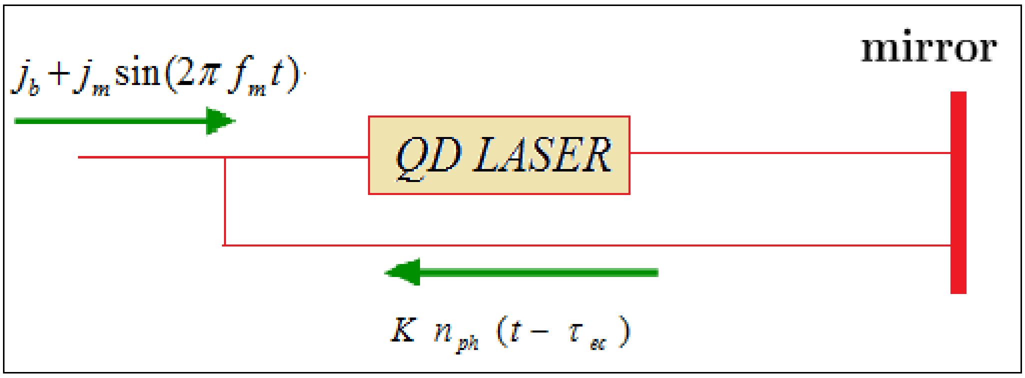
$j_b = b \times j_{th}$, b is the bias strength,

$j_m = m \times j_{th}$, m is the modulation depth

$f_m = \frac{\omega_m}{2\pi}$ is the modulation frequency.

j_{th}: is threshold current density

($j_{th} = 90.5\, Acm^{-2}$ [23]).



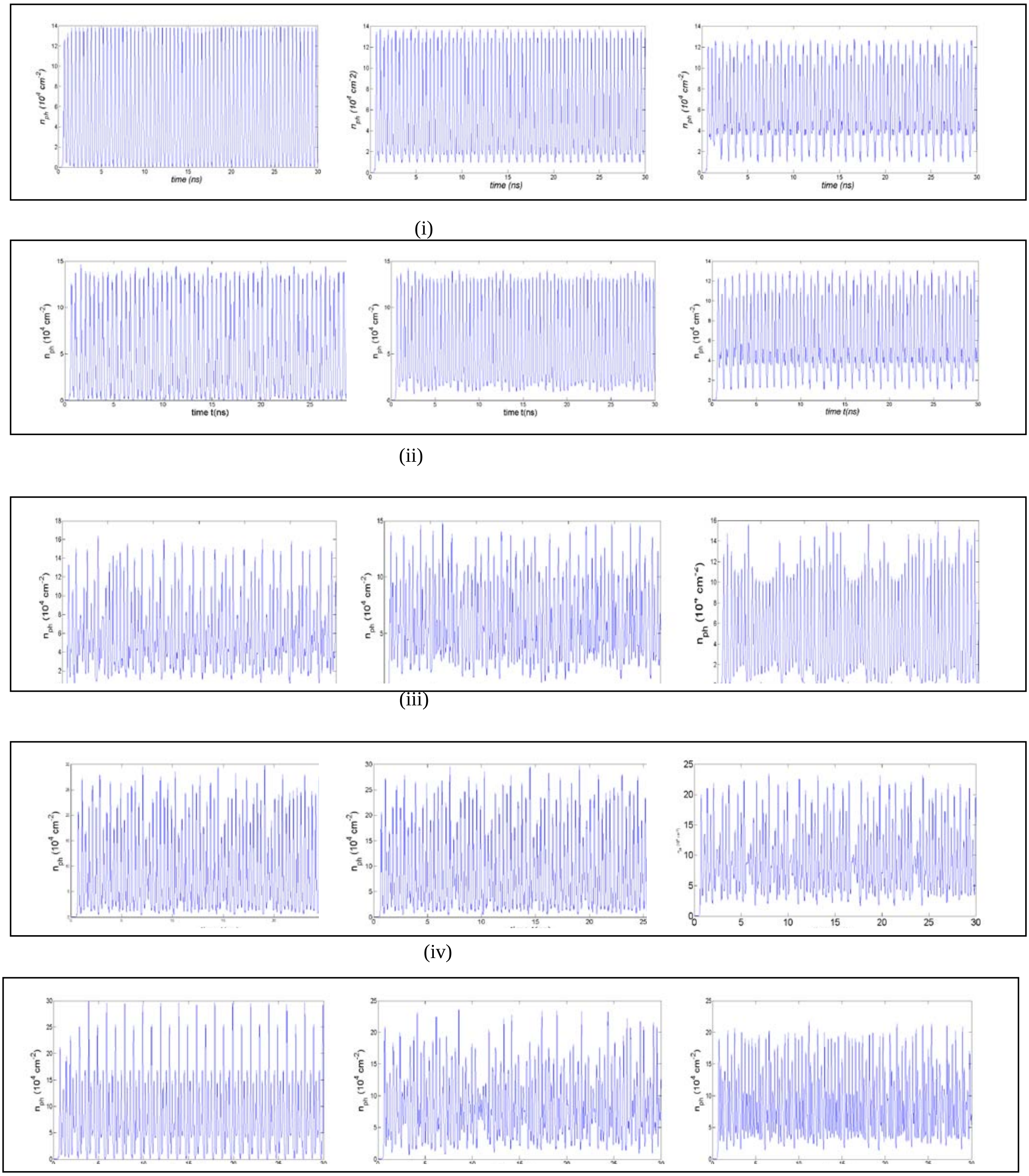
Fig(3):Schematic diagram of the delayed optical feedback and injection current modulation.

Results and discussion

The dynamics of QDSCLs under the effect of both feedback and direct injection current modulation are studied by solving the set of equations (1-6) together with equation (7) that takes into account both the feedback and modulation of the injection current using the fourth-order Runge-Kutta numerical method and Mat Lab for certain chosen initial conditions. To carry- out the simulation we make use of the parameters values given in Table (1)[21] . The injection parameters ,i.e. the dc bias current, j_b, the dc bias strength, *b*, the modulation current, j_m, modulation depth ,m, and modulation frequency, f_m , have been chosen according to Table (2). Fig (4) shows the direct comparison of the QDL photon density for the feedback case alone and feedback together with injection current modulation case, respectively. Clear effects can be noticed whether the feedback

Table(1):Meaning and values of the parameters in equations (1-7) for the *InAs/InGaAs* QDSCL[21].

Symbol	Meaning of symbol	Value
W	The Einstein coefficient	$0.7\,ns^{-1}$
T	Temperature	300 K
2κ	The total cavity loss	$0.1\,ps^{-1}$
Γ_g	The geometric confinement factor	0.075
Γ	Optical confinement factor	2.25×10^{-3}
A	WL normalization area	$4 \times 10^{-5}\,cm^2$
N^{QD}	Twice the QD density of the lasing subgroup	$0.6 \times 10^{10} cm^{-2}$
N^{sum}	Twice the total QD density	$20 \times 10^{10} cm^{-2}$
N^{WL}	Carriers density in WL	$2 \times 10^{13} cm^{-2}$
B^S	The band–band recombination coefficient in the WL	$540\,ns^{-1}\,nm^2$
β	The spontaneous emission coefficient	5×10^{-6}
λ	The emission wavelength of lasing mode	$1.3\,\mu m$



(i)

(ii)

(iii)

(iv)

(v)

Fig(4). Comparison of the temporal behavior of photons for selected K=0.12 for (i) feedback without modulation and with modulation for (ii) (b=2.5,m=1, f_m =5); (iii): (b=2.5,m=5, f_m =5) and (iv): (b=1.3,m=1, f_m =5) for (v):(b=1.3,m=5, f_m =5) where α=0.9,2,3.2 changed from the left to right respectively, for each row.

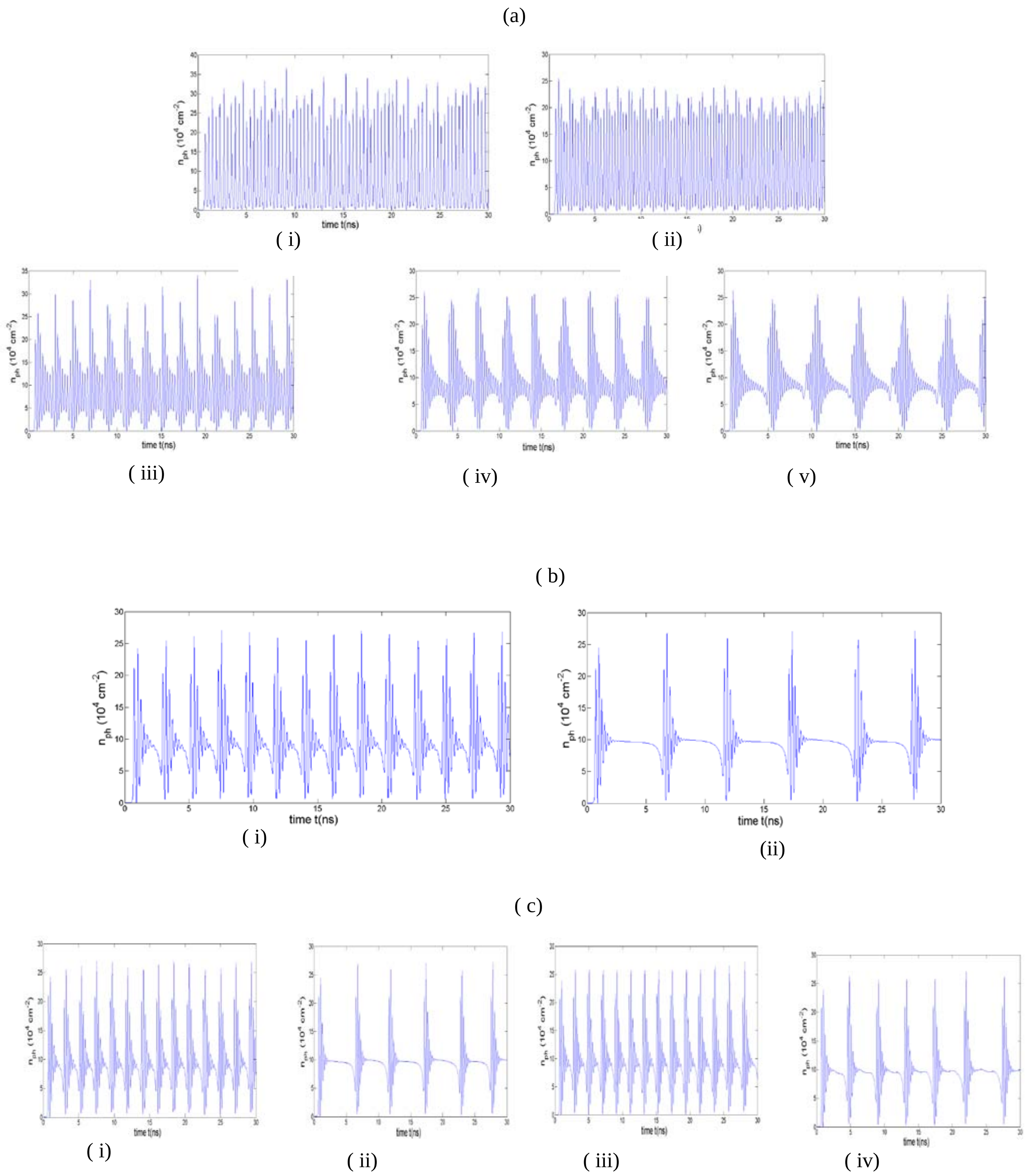
Table (2) Injection parameters

Symbol	Meaning of symbol	Value						
b	the dc bias strength	1.3			2.5			
m	modulation depth	0.1	0.5	1	1.3	1.5	2	5
f_m (GHz)	modulation frequency	0.1	0.5	1		5		10

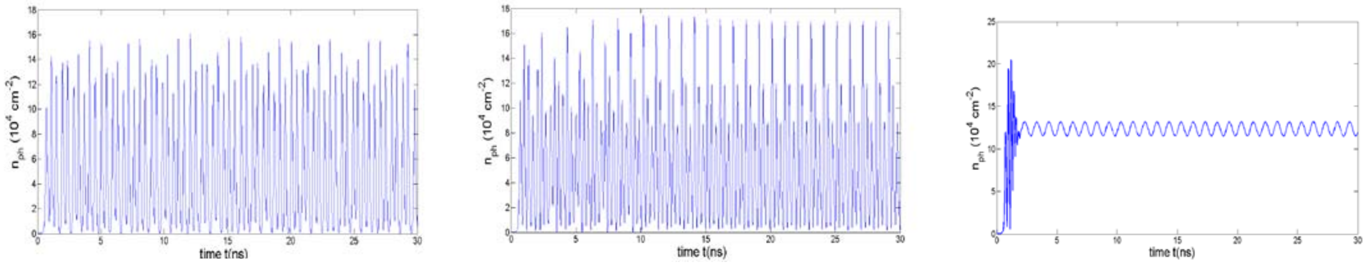
strength is low or high , for low bias strength or high for different modulation depth and frequency. The system output transfers from period one (P.1) to multiperiodic
or from multiperiodic to chaotic one as a result of the variation of injection current modulation.

Various types of chaotic output can be obtained for the group(K ,b, α ,m, f_m) even though the modulation depth and frequency are low, see fig(5a) .The self pulsing or breathing effect sustained autonomously as a result of increasing K values from 0.12 up to 0.229. Such effect developed to that shown in fig(5b) where the oscillatory behavior followed by a dc damped part which recovers to another oscillatory signal. The recovery time is a function of K .The signal frequency can increase for constant (b, α ,m, f_m) and increasing K. The increase of modulation frequency does not increase the signal frequency for K values as can be seen in fig(5c) where it can be seen that the oscillatory behavior frequency decreased as a result of increasing the K values although the modulation frequency increased five times (see fig5c ii and iv). Increasing K, m and f_m values changes the output state from chaos to self-pulsing then to P.1 case ,an indication of the reverse period doubling scenario, see fig(6a).

At α=3.2, m=2, f_m=0.1GHz and increasing K from 0.12 and 0.9 the output start chaotic then periodic of high frequency . Keeping the parameters as α=3.2,m=2 while increasing f_m switch to 1GHz and varying K through the same range once again the system passes from chaos to periodic one .The same behavior is reproduced when f_m=5GHz and 10GHz . Keeping the parameters values the same but increasing m to 1.3 the following is noticed: chaos at K=0.12 periodic at K =0.5 then chaos once more at K =0.9 . By varying K between 0.02 and 0.225 , α=0.1,b=1.3 and m=1.5 and varying f_m in the range (0.1-10) GHz the laser system shows varieties of dynamics most are periodic and other are chaotic and periodic chaos .The disappearance of the output and self-pulsing are noticed again as can be seen in fig(6b),for K=0.02-0.225 , α=0.1 ,m=1.5 and f_m=0.1GHz . When α=3.2, K=0.12-0.9,m=5 ,b=1.3and f_m=(0.1-10)GHz the dynamics are a mixture of period ,multiperiod and chaos .The frequency of the output increases with the increase of K as can be seen in fig(6c) . Reducing the depth of modulation (m) from 5 to 1.3 leads to the occurrence of various chaotic and various multiperiodic states from periodic one. For α=0.9,b=1.3, f_m=(0.5-10)GHz, m=2 and K=0.12-0.3 a coherence collapse or output dropout ,chaos and developed chaos occurs.

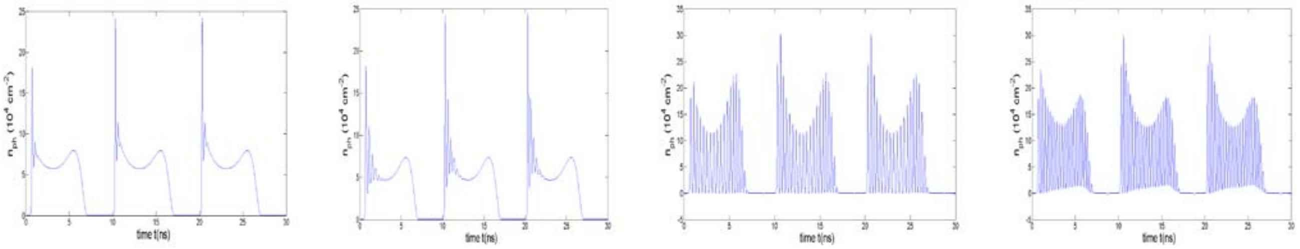


Fig(5): Time series of photon density (n_{ph}) for selected linewidth enhancement factor, α =0.5,bias strength, *b*=1.3 ,modulation depth ,*m*=0.1, modulation frequency (GHz), f_m =0.1, and strength of optical feedback ,*K,* (a): (i) 0.12 ; (ii) 0.18;(iii)0.12;(iv)0.225; (v) 229; (b): linewidth enhancement factor ,α =0.9,bias strength, *b*=1.3 ,modulation depth ,*m*=0.1, modulation frequency(GHz), f_m =0.1, and strength of optical feedback ,*K*,:(i) 0.225 ;(ii) 0.228;(c): linewidth enhancement factor α =0.9,bias strength, *b*=1.3 , modulation depth ,*m*=0.1, modulation frequency (GHz) , f_m , and strength optical feedback ,*K*, :(i)0.1, 0.225 ; (ii)0.1, 0.228;(iii) 0.5,0.225;(iv)0.5,0.228.



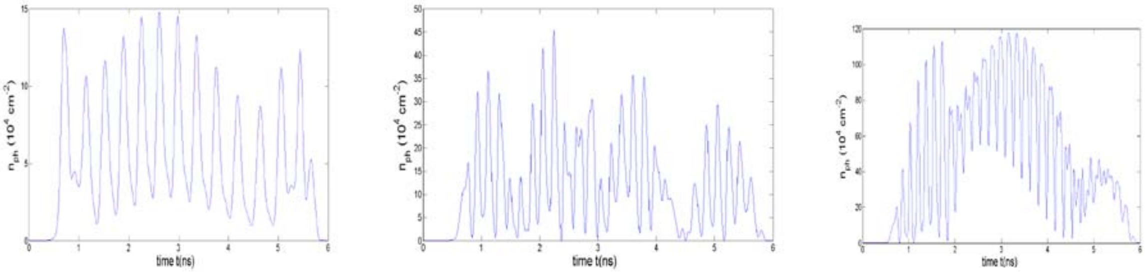
(i) i) (iii)

(b)



(i) (ii) (iii) (iv)

(c)



(i) (ii) (iii)

Fig(6): Time series of photon density (n_{ph}) for selected linewidth enhancement factor, α =0.9,bias strength, *b*=1.3 ,modulation depth ,*m*=2.5,and modulation frequency (GHz) , f_m = 1, and strength optical feedback ,*K*, (a) : (i) 0.12 ; (ii) 0.18;(iii) 0.3; (b): linewidth enhancement factor ,α =0.1,bias strength, *b*=1.3 ,modulation depth ,*m*=1.5,and modulation frequency (GHz) , f_m =0.1, and strength optical feedback ,K, (i) 0.02 ; (ii) 0.08; (iii)0.15; (iv)0.225;(c): linewidth enhancement factor, α =3.2,bias strength, *b*=1.3 ,modulation depth ,*m*=1.5,and modulation frequency (GHz) , f_m =0.1,

For α=2, ,m=1.3,2,5, b=2.5 and K=0.12-0.9 ,many chaotic states appear with power drop-out. Reducing m from 5 to 1.3 and for all the values of other parameters leads to the switching of chaos and multiperiodic states to periodic ones.

Fixing α at 0.9,b=2.5,m=2 and f_m=(0.1-10) GHz and K=0.12-0.3 all the dynamics either chaotic or P.1 as can be seen in fig(7a) .

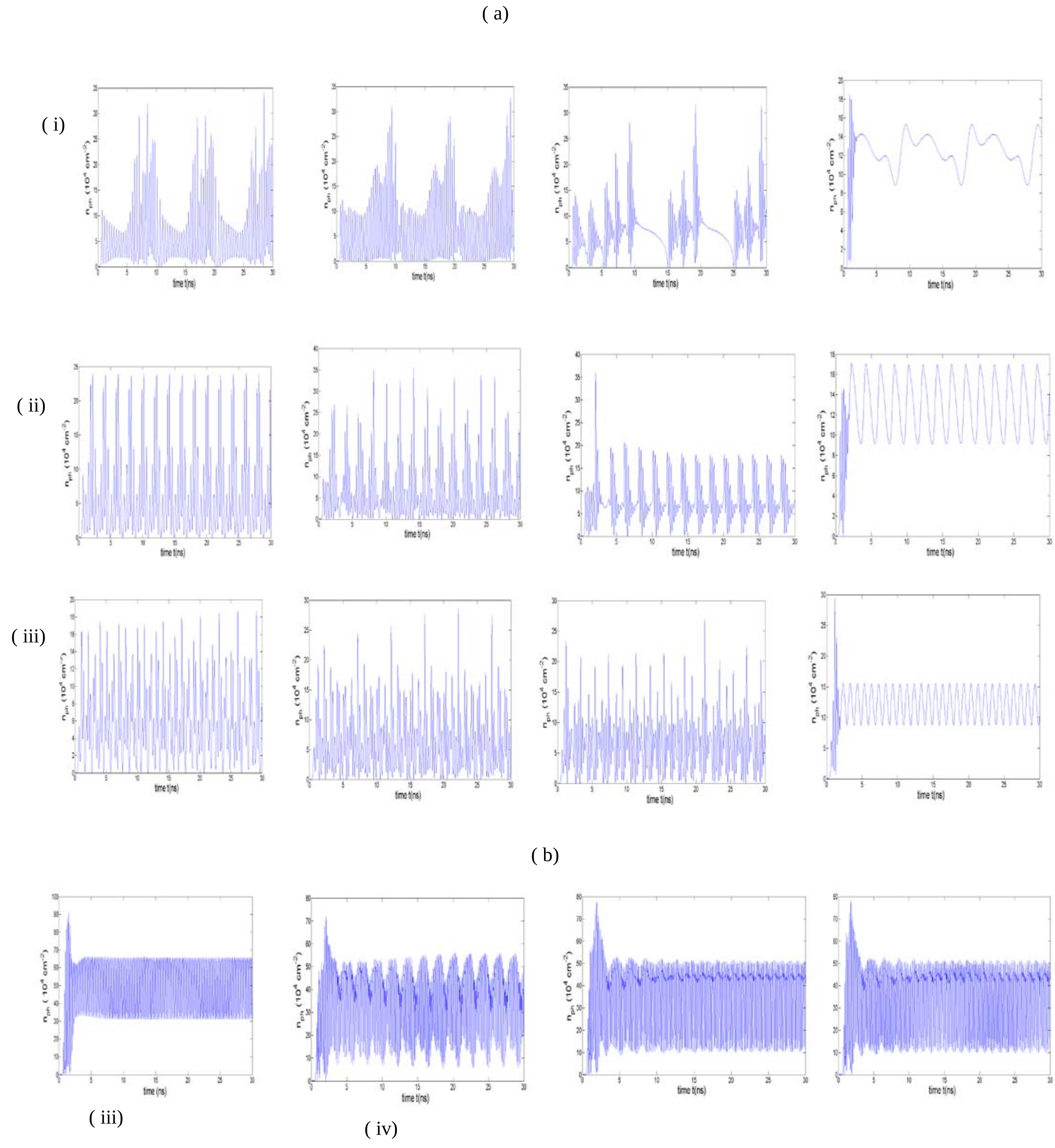
When α=3.2 and K=0.9,it drives the system towards multiperiodic from periodic or steady state and to chaotic from multiperiodic state as can be seen in fig(7b). At K=0.12 the system developed from P.2 to P.6 as can be seen in fig(8a) .

By comparison the signals in fig (7a) where the depth of modulation is different at α=3.2, K=0.9,m=5 ,b=1.3, f_m=10GHz with that of the absence of modulation (Fig7b (i)) it can be seen that the output becomes complex as m increases ,i.e. the increase of a mount of the ac part of injection current where it can be seen the disappearance of P.1 Fig 7b (i)) and a multiperiodic state appears (Fig7b (iii) and (iv)) that changes to chaos as shown in(Fig7b (ii)). By the comparison of the case of the absence of modulation

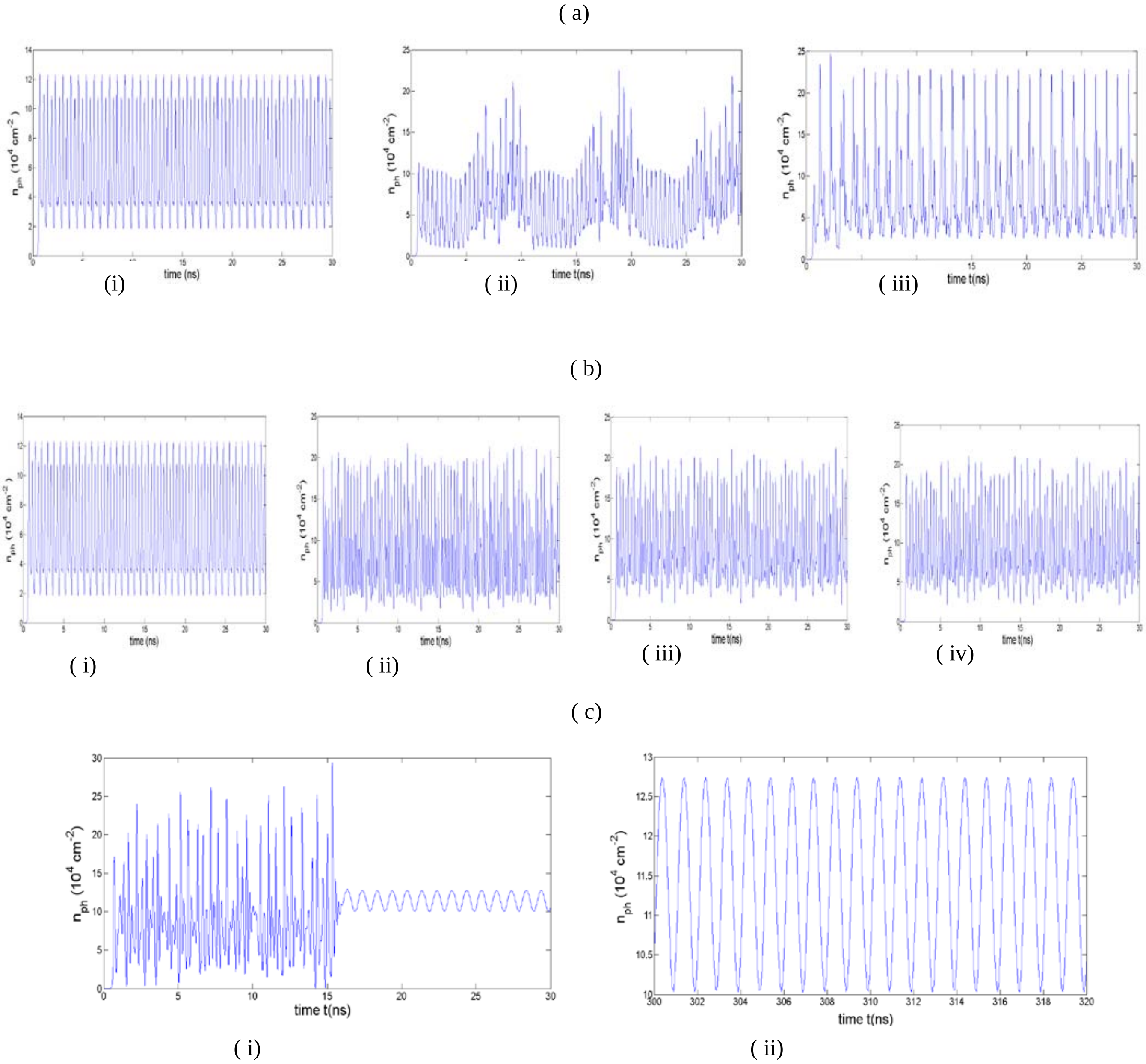
(Fig 8b(i)) with those of (Fig 8b(ii,iii,iv))) in the presence of modulation at f_m=5GHz, b=1.3,α=3.2 and K=0.12 create chaotic states from P.2,as shown in fig (21). When α and K are low while the frequency of modulation is doubled the system stays at the periodic state .The same behavior appeared up to f_m=10GHz . For higher (α =0.9) keeping f_m low the system enters different types of chaotic states as was shown in fig(5c). It is seen that whether at chaotic or periodic states increasing K (even for low m and f_m)the system produced a pulsating chaos of frequency lower than the previous chaotic state ,as was

shown in fig(5c).

Such effect continues to occur even for f_m=1GHz , 2GHz and 5GHz .Increasing α once more (=2) keeping m=0.5 and f_m=0.1 GHz ,the system is totally chaotic up to K=0.18 then it settles at P.1 of long period. It is interesting to mention that the system can show chaos and P.1 output for the same signal as can be seen in fig(8c) ,i.e. chaos followed by P.1 ,i.e. the system can recover after short period of time (≤ 15 *nsec*). At high f_m (5-10) GHz the system can switch to P.6 from chaos at low K then enters chaotic state once more as K=0.18 then switch to chaotic P.1 state ,i.e. chaotic output followed by the ordinary signal that appears when the laser work autonomously . The system can be driven from stable P.1 state of small amplitude (0.2) to either chaotic state by increasing f_m to 1GHz from 0.1 GHz or to another (P.1) state of large amplitude (14) by increasing the frequency to 5GHz from 1GHz, i.e. the system output is controlled by the frequency of modulation .The system can be driven from chaos to another one then to p.1 by changing m from 1.5 to 5 . By increasing K to 0.9 and varying m through the same mentioned range the system output is always at (P.1) .By increasing m only for various combinations of (K, α ,b, m, f_m),the system mostly stays in its state of lower m whether it was stable (,i.e. periodic) or unstable (chaotic).The previous conclusion is not always true .



Fig(7): Time series of photon density (n_{ph}) for selected linewidth enhancement factor ,*α*, bias strength, *b*,modulation depth ,*m*,and modulation frequency (GHz) , f_m , (α ,b,m, f_m): (a): (i) 0.9,2.5, 2 , 0.1; (ii) 0.9,2.5, 2 ,0.5;(iii) 0.9,2.5, 2 ,1; where *K*=0.12,0.18,0.225,0.3 (from the left to right for each row);(b): (i) without modulation (α=3.2,*K*=0.9) and with modulation (α ,b,m, f_m ,*K*): (ii)3.2,1.3,5,10,0.9;(iii) 3.2,1.3,2, 10 ,0.9; (iv) 3.2,1.3, 1.3,10,0.9.



(a)

(i) (ii) (iii)

(b)

(i) (ii) (iii) (iv)

(c)

(i) (ii)

Fig(8): Time series of photon density(n_{ph}) for selected linewidth enhancement factor, α, bias strength, *b*,modulation depth ,*m*,and modulation frequency (GHz) , f_m , and strength optical feedback ,*K*, (i) without modulation (α=3.2,*K*=0.12) and with modulation (α, b,m, f_m ,*K*):(ii)3.2,2.5,2,.1,0.12; (iii) 3.2,1.3,2, 1 ,0.12;(b) (i) without modulation (α=3.2,*K*=0.12) and with modulation (α ,b,m, f_m ,*K*) :(ii)3.2, 1.3,5,5,0.12;(iii) 3.2,1.3, 2, 5,0.12;(iv) 3.2,1.3, 1.3,5,0.12;(c) :(α ,b,m, f_m ,*K*): 2,1.3,0.5 ,1,0.18,for time (i)(0-30)ns; (ii)(300-320).

The introducing of feedback and injection current modulation creates two degrees of freedom available for the QDSCLs which increases the possibility for the system to reach chaos through the three known routes.

Optical feedback on its own ,improves the spectral properties of a single -longitudinal-mode SCLs, from external short cavity. In contrast, even for weak feedback from external long cavity can lead to the excitation of many external cavity modes formed by the laser and the external reflector. In fact in case of laser with external cavity formed by distant mirror, one can think of three compound cavities, one formed by the two mirrors of the laser, the second by rear laser mirror and external cavity mirror and third one formed by the far laser cavity mirror and external cavity mirrors. This situation complicates the competition between the modes available in these cavities .The frequency of the solitary laser mode is slightly modified by the feedback, which in addition introduces new modes, which are located in the frequency domain around the solitary laser frequency. For very low feedback levels many of the external cavity modes are stable ,and competition among the steady-state can occur. For large feedback, the mode competition is suppressed and the laser output is in a single external cavity modes. In the presence of injection current modulation the situation is improved towards instabilities and chaos especially when the modulation frequency ≥ relaxation oscillation frequency in the transient region. Moderate feedback induces a periodic modulation of the laser output which is driven to chaos when injection current modulation is present. Even larger feedback is only induced to chaotic state, with the broadband emission, termed coherence collapse[4,24]. The injection current modulation creates temporal and spatial gratings in the population inversion of the QDLs medium. These gratings modify the interaction between photon bouncing in the laser cavity in a way that leads to the occurrence of chaos. The output field reflected back to the laser cavity suffers phase variations after each round-trip which affects the total field inside the laser cavity. Such effect can improve the field in the laser cavity when the modulation of injection current is taken into account.

We believe that when the modulation frequency of the injection current is on the order of the relaxation oscillation in the transient region periodic to chaotic, output can be generated ,i.e. the modulation act to sustained the relaxation oscillation. Together with other effects of external cavity modes, phase variations of the feedback field makes it easy for the QDSCLs to show varieties of output.

Conclusion:

A delayed optical feedback and injection current modulation are employed theoretically to study the possibilities of obtaining chaotic output from *InAs/InGaAs* quantum dot semiconductor laser .Enormous dynamics are generated with help of feedback strength, the linewidth enhancement factor, the dc bias strength of the injection current, the modulation strength and modulation frequency of injection .Periodic output, multiperiodic output to chaotic seen to occur and the system mainly followed the bifurcation route to chaos. Different windows appear to occur such period 6 ,period 8 etc. Results obtained suggest that QDSCLs are prime candidates to study chaotic states, and enhance the possibility for such system to be used in the secured communications.

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ليزر شبه الموصل InAs/InGaAs نوع النقطة الكمية تحت التاثير المركب للتغذية العكسية البصرية وتضمين التيار المباشر

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الخلاصة :

درست حركيات عديدة لليزر شبه الموصل InAs/InGaAs نوع النقطة الكمية تحت تاثير التغذية العكسية البصرية بشكل واسع . بأختيار تاثير كل من شدة او مستوى التغذية العكسية ومعامل تعزيز عرض الخط ومقدار الانحياز المستمر لتيار الحقن ومقدار او عمق التضمين وتردد التضمين . نتجت من الدراسة حركيات مختلفة امتدت من الدورية وحتى الفوضى . باختيار مجموعة معينة من عوامل السيطرة واردة الذكر يمكن الحصول على ظاهرة انهيار التشاكة (او اختفاء الخرج) والواردة في الانموذج النظري.