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The dynamical characteristics of InAs/ InGaAs Quantum dot semiconductor laser under optical feedback

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Abstract :

We study the effects of optical feedback on the dynamics of *InAs/InGaAs* quantum dot semiconductor laser via the use of five equations model that describe the dynamics of such lasers and the addition of a new term that takes into account the effects of feedback and six equation concerning the phase of the electric field .The effect of a number of control parameters viz optical feedback strength, phase shift and round-trip time of light in the external cavity is being tested. Rich and varieties of dynamics appeared to occur ranging from periodic to chaotic ones.

Key Words: *Optical feedback, QD lasers*,Chaos

1.Introduction:

A semiconductor laser SCL receiving optical feedback from a conventional mirror is the most basic example of a laser subject to delayed feedback [1]. This system is technologically relevant because in applications, such as optical data storage and optical communication[2],reflections are often unavoidable. Furthermore, it is known that feedback of less than 1% can already totally destabilize the operation of a SCL. The laser then typically switches at irregular intervals [3] ; one also speaks of low frequency fluctuations .This is why SCLs with conventional optical feedback have received a lot of attention ,both experimentally and in terms of mathematical modeling [4]. The semiconductor laser with external optical feedback has attracted much attention during the last two decades due in part to its application to optical communications. SCLs are highly nonlinear ,and in the presence of optical feedback from an external mirror they exhibit a rich variety of dynamics regimes ,as we show in discussing the results ,when control parameters are carefully chosen. Even for small reflections in the percentage range were found to affect the laser stability dramatically .Although external optical feedback can be considered as a source of instability in many situations ,it also produces several beneficial effects that can improve laser performance .

Quantum dot laser QDL, on the other hand, has attracted much attention in recent years due to their superior properties, such as ultra-low and temperature –stable threshold current density ,high –speed operation, and low frequency chirping[5]. These properties together with low linewidth enhancement factor and broad spectrum make QD materials(*InAs/InGaAs*) extremely attractive for applications such as light emitters or amplifier, compact disc players and laser printers, and play critical roles in optical communication systems. In all these applications, part of the output power of the QDL can be fedback to the laser cavity where it can affect, as it was mentioned earlier, all the dynamics of the QDLs. To the best of our knowledge there is shortage in literature concerning the subject of feedback effects on the dynamics of InAs/InGaAs quantum dot laser both experimentally and theoretically. In this work we present the results of numerical experiments carried out to investigate the effects of feedback on the QDL dynamics.

2.Rate equations model:

The quantum dots (QDs) embedded into two dimensional quantum well (QW) acting as a carrier reservoir .A band structure of the device is shown in Fig(1)[6].

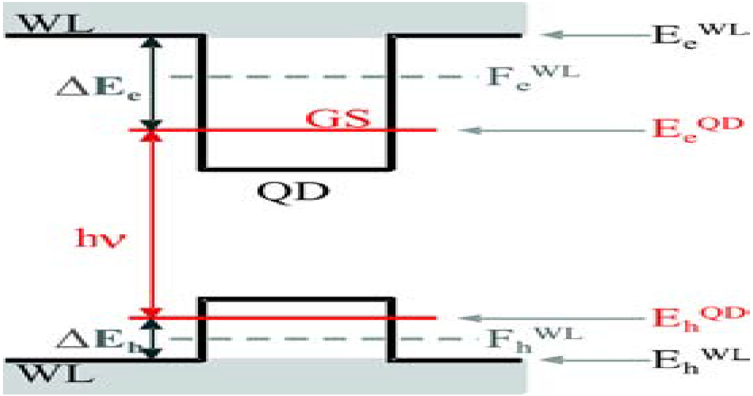


Figure 1: Energy diagram of the QD and WL system[6].

The crucial parameters in the quantum dot are the confinement energies ΔE_c and ΔE_h which represent the differences between the QD ground state and the band edge of the surrounding QW for electrons and holes ,respectively. The QD laser model is based on the works of Ludge [7,8] regarding the turn-on dynamics of the QD semiconductor laser already been studies extensively by the present authors [9,10].

The coupled nonlinear rate equations contain the electron and hole densities in QDs , n_e and n_h respectively. It contains too the electron and hole densities in QW ,i.e. w_e and w_h respectively.

QD laser under optical feedback considered 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, reflecting back the light into the gain region (see figure 2 [11]).

The gain section of length *L* shown in Fig(2) of the QD laser is modeled microscopically based on rate equations system [6]. It allows for separate treatment of electron and hole dynamics in the QD as well as the surrounding wetting layer (WL). The present system of equations reads:

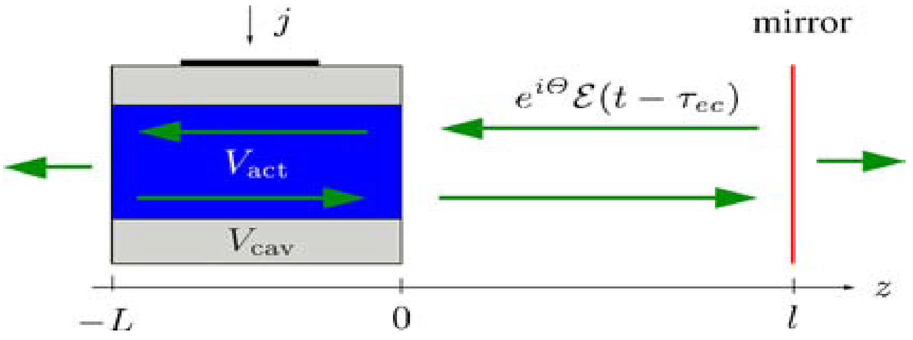


Figure 2: Schematic setup of the considered QD laser device with optical feedback from a short external cavity[11].

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

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

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

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

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

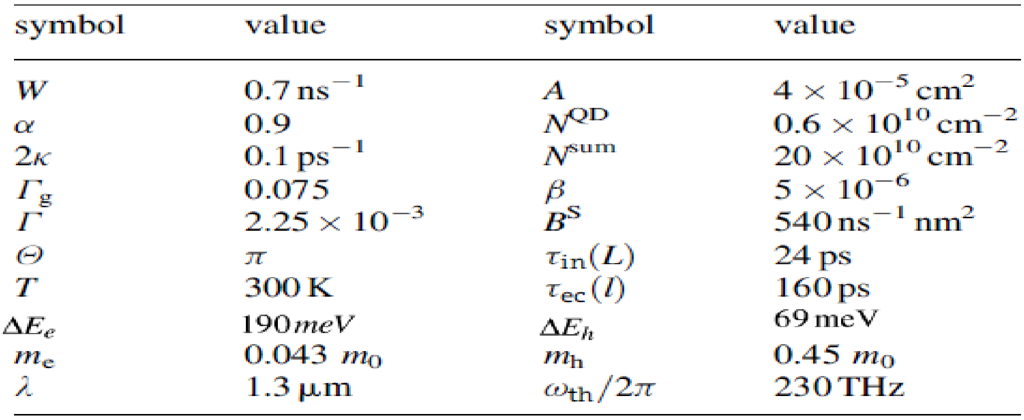
$$\dot{\phi} = \frac{\alpha}{2}\left\{\Gamma W A(n_e + n_h - N^{QD}) - 2k\right\} - \frac{K}{\tau_{in}}\sqrt{\frac{n_{ph,\tau_{ec}}}{n_{ph}}}\sin(\phi - \phi_{\tau ec} + \Theta) \tag{6}$$

The fourth and third terms in equations (5) and (6)respectively takes into account the optical feedback been applied to the InAs/InGaAs QDSL. n_{ph} is the density of photons, the induced 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 electrons and holes capture into the QD levels, S_e^{out} and S_h^{out} for carrier escape from the QD levels for electrons and holes and scattering times $\tau_e = (S_e^{in} + S_e^{out})^{-1}$ and $\tau_h = (S_h^{in} + S_h^{out})^{-1}$. τ_{in} is 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 the 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 labeled by the subscript τ_{ec} , i.e. $n_{ph,\tau_{ec}}$ and the optical phase ϕ_{ec} are taken at the delayed time $(t - \tau_{ec})$. ϕ is the electric field phase. α plays a fundamental role in causing the enhancement of the laser linewidth and also having decisive importance for many dynamical process such as modulation response ,frequency chirp, and ,in particular, optical feedback effects. The relaxation oscillation of the SCLs under quite moderate values of the feedback can be sustained and destabilized an effect that can lead to number of instabilities[12].

3-Results and discussion:

The set of equations (1-6) describes the overall dynamics of an QDL under the effect of feedback. Many distinct control parameters that can play the roles of these control parameters viz feedback strength ,K, round-trip time in the external cavity ,τ_{ec}, linewidth enhancement factor , α , and phase shift during one round trip in the external cavity, Θ.The set of equations (1-6) were solved using the fourth order Runge-Kutta numerical method and the Matlab system making use of certain initial conditions. Table 1 shows the parameters values used in the calculations and obtaining the results [6].

Table 1 :Parameters values used in the simulations[6]



symbol	value	symbol	value
W	$0.7\ \mathrm{ns}^{-1}$	A	$4 \times 10^{-5}\ \mathrm{cm}^2$
α	0.9	N^{QD}	$0.6 \times 10^{10}\ \mathrm{cm}^{-2}$
2κ	$0.1\ \mathrm{ps}^{-1}$	N^{sum}	$20 \times 10^{10}\ \mathrm{cm}^{-2}$
Γ_g	0.075	β	5×10^{-6}
Γ	2.25×10^{-3}	B^S	$540\ \mathrm{ns}^{-1}\ \mathrm{nm}^2$
Θ	π	$\tau_{in}(L)$	$24\ \mathrm{ps}$
T	$300\ \mathrm{K}$	$\tau_{ec}(l)$	$160\ \mathrm{ps}$
ΔE_e	$190\, meV$	ΔE_h	$69\ \mathrm{meV}$
m_e	$0.043\ m_0$	m_h	$0.45\ m_0$
λ	$1.3\ \mu\mathrm{m}$	$\omega_{th}/2\pi$	$230\ \mathrm{THz}$

Figure (3) shows the effect of τ_{ec} (140,160,180) ps on the temporal behavior of the photon density ,n_{ph}, for three chosen values of linewidth enhancement factor, α, (0.1,0.9,2,2.5) [12] for the values of other parameters that appeared in the set of equations (1-6) . It can be seen that when α increases the QDL shows dynamics complicated as short as τ_{ec} is , since the increase in α values leads to the increase of refractive index , i.e. the increase in the nonlinearities[12], see Fig (3).When α is small, injection strength K has reverse effect ,i.e. as it increases, the system behave in stable fashion as can be seen in Fig (4), i.e. photon density and electron density are stable .When α approaches 3, the QDL approaches stability in the K range (0.12-0.3) as can be seen in Fig(5) and Fig(6); the carrier density as well as the photons behave in a stable way as K increases. Fig(7) indicates the last conclusion. Fig(8) shows this special type of behavior of carrier and photon densities .Once more as K in the range ≤ 0.3 the system behaves in a complex way. Figure(9) shows that for high values of τ_{ec} the system behave in complex fashion as K varies from 0.3 to 0.9 . As τ_{ec} varies between (100-200) ps or (140-180) ps as the case shown in Figure (10), the system shows some kind of complexity .Figure (11) insures the previous conclusion where the QDL behaves in a complex fashion when K values are low, i.e. 0.2 and 0.228 at special time τ_{ec} . As α increases from 0.9 to 2 at K=0.12 , i.e. small, the photon density passes from stable state to another one through complex state as can be seen in figure (12) .This conclusion is cemented by Figure(13) as the phase angle Θ increases from 0 to 1.5 π . As α ,K and Θ increases chaotic state appeared in the behavior of carrier and photon densities as can be seen in Figure (14).The three dimension Figures of n_{ph}, n_e and time and n_{ph}, n_e and n_h give clear dependence of photon density on these quantities and direct comparison between n_{ph} or n_e or n_h and time for any chosen values of the parameters K, α, τ_{ec} and Θ.

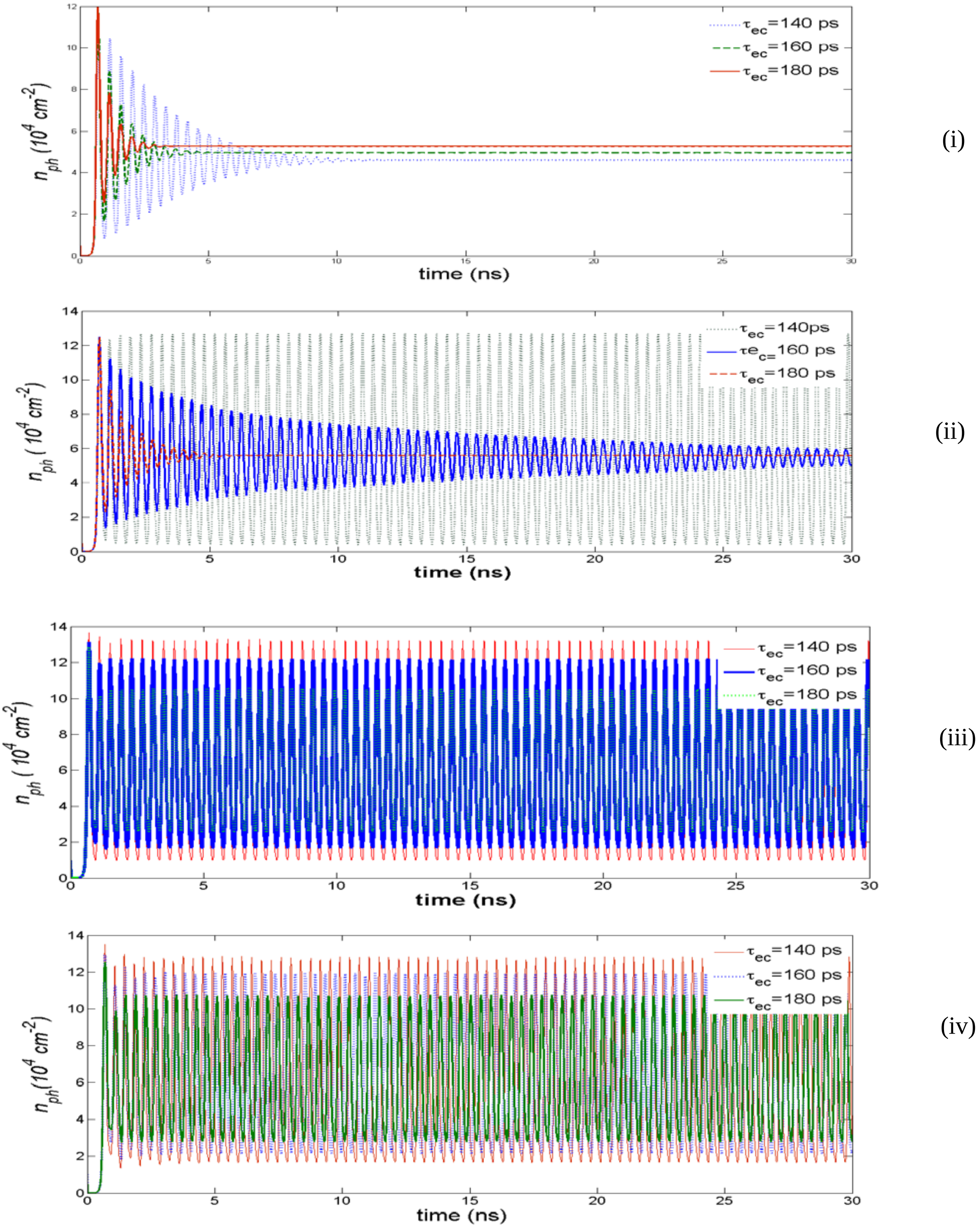
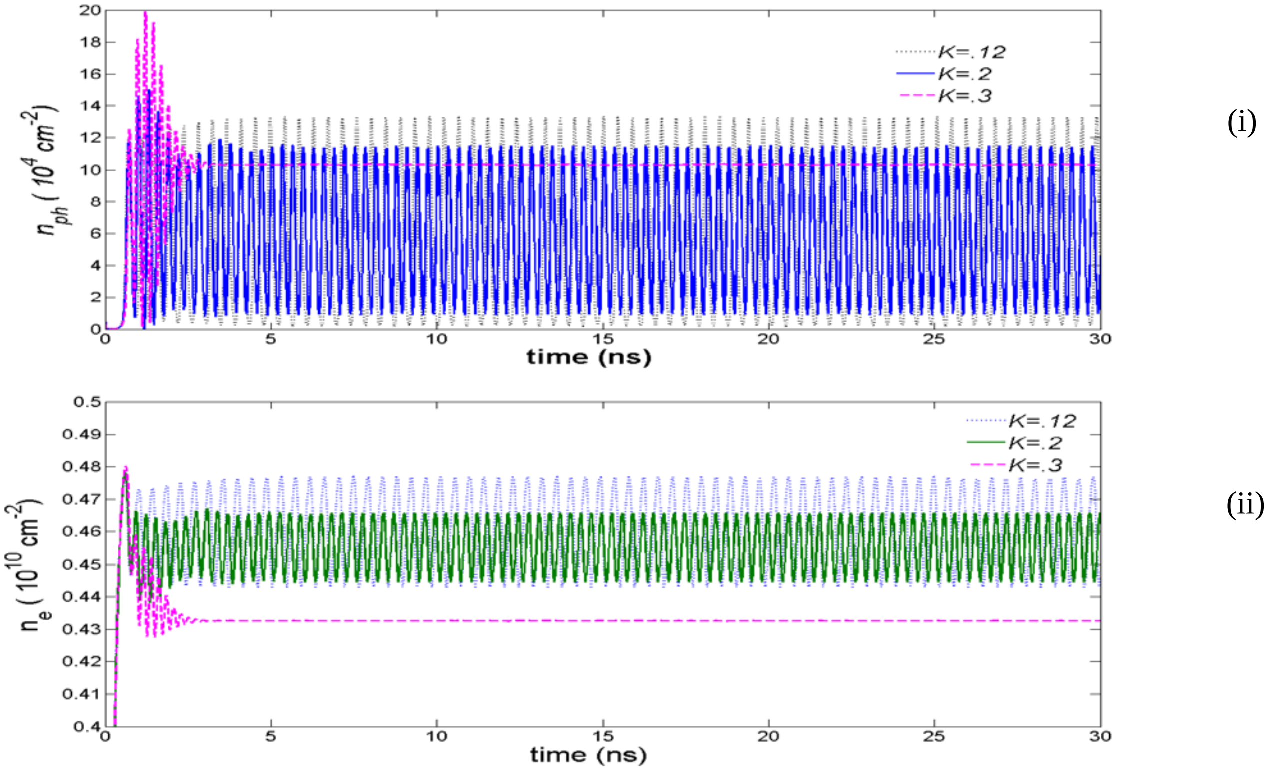
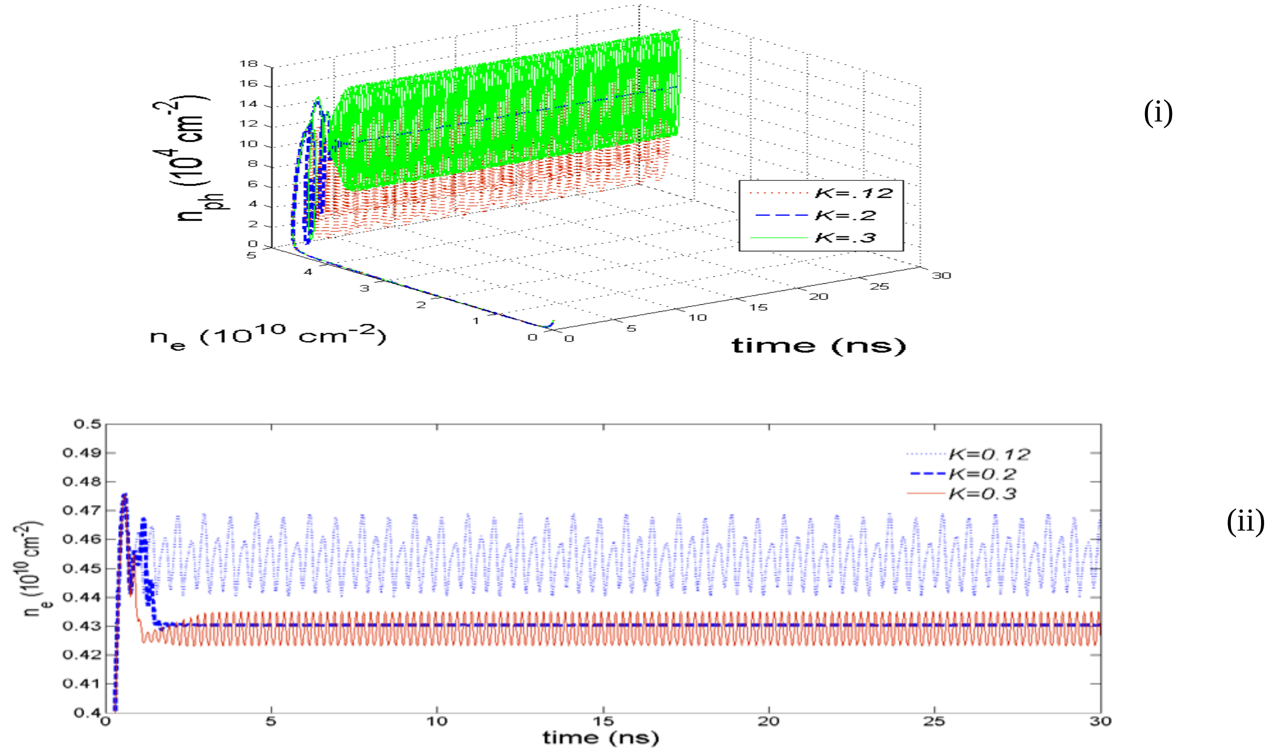


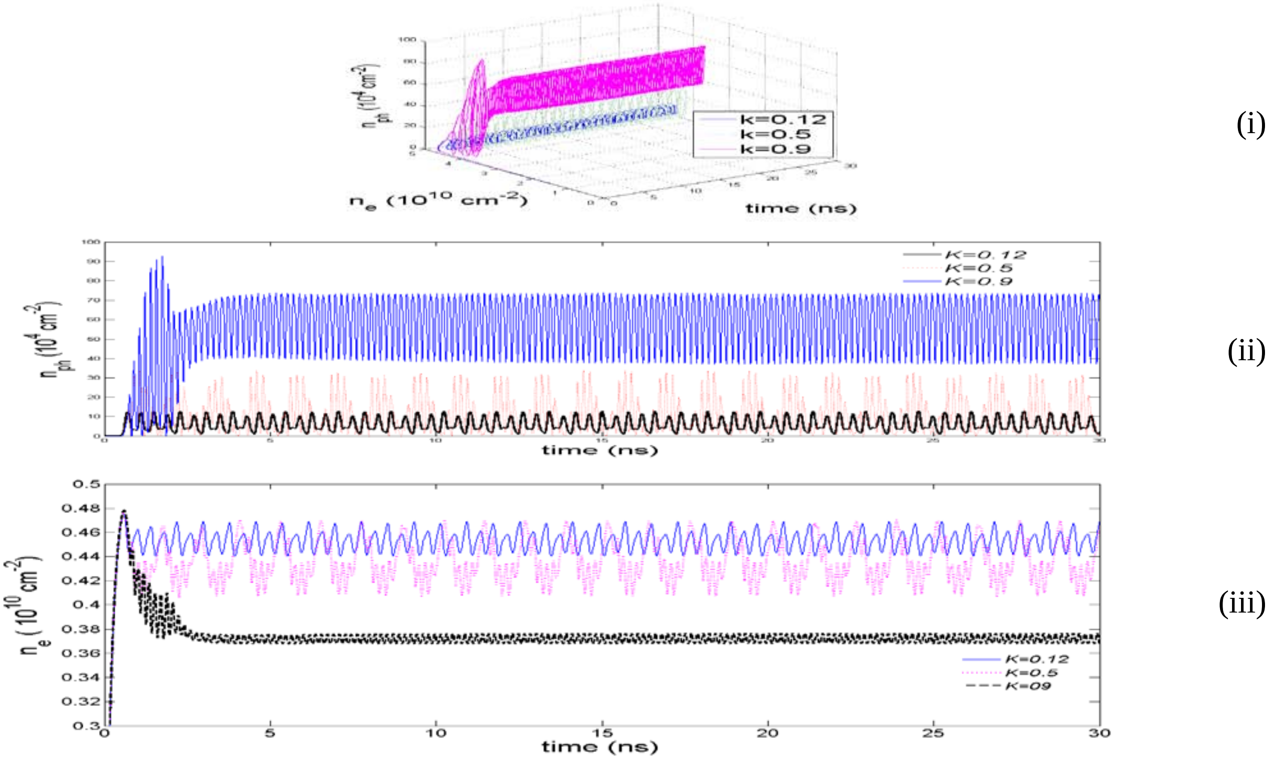
Figure (3). Time variation of photon density at three different values of time delay (τ_{ec}) for α and K values : (i) 0.1,0.12; (ii)0.9,0.12; (iii)2,0.12; (iv) 2.5, 0.12.



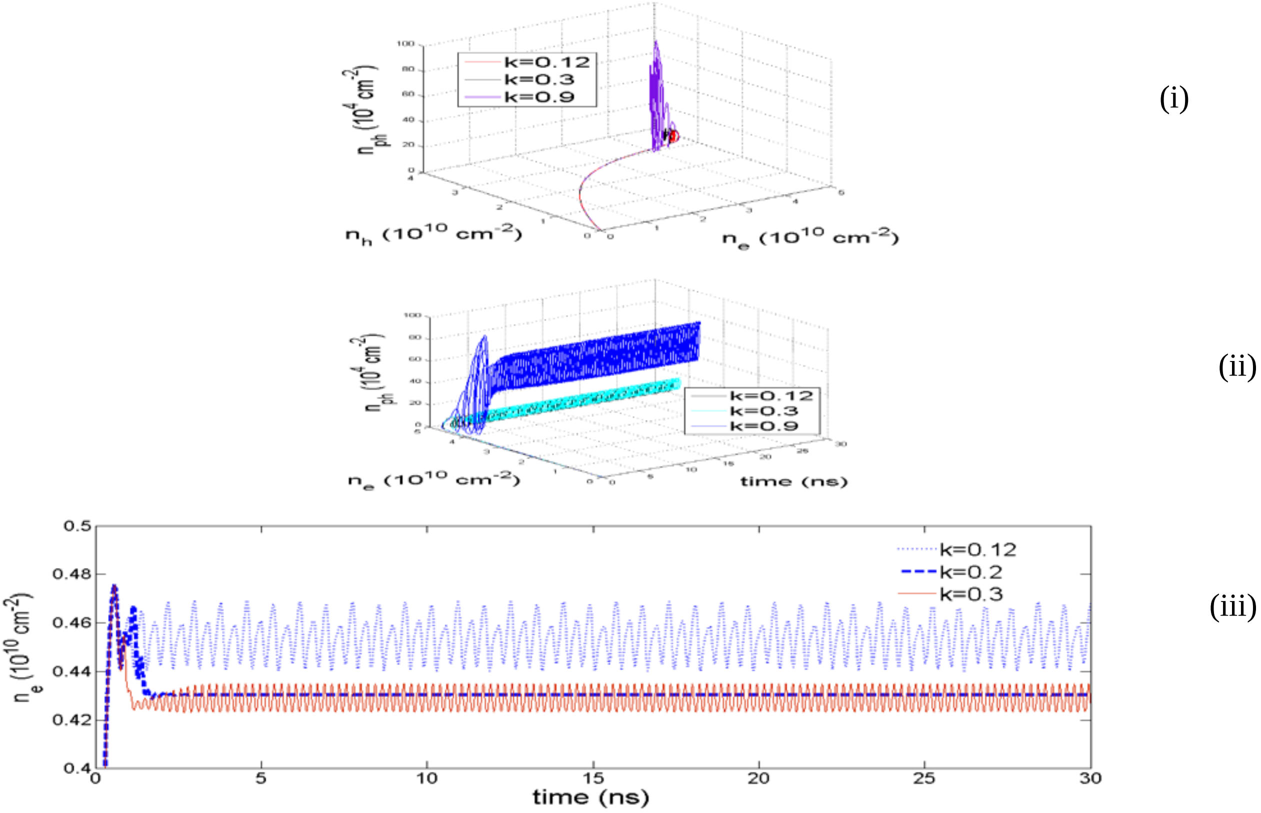
Figure(4). Time series of (i) photons density ; (ii) QD electrons density at three different values of K when α and τ_{ec} values are: 0.5, 160 *ps*



Figure(5).(i) Three dimensional plot of photon and QD electron densities vs. time;(ii) QD electron hole density at three different values of K when α and τ_{ec} are : 3,160 *ps*.



Figure(6).(i) Three dimensional plot of photon and QD electron hole densities vs. time; (ii) Time variation of Photon density and(iii)QD electron density at three different values of K when α and τ_{ec} values are : 3,160 *ps*.



Figure(7). (i) Three dimensional plot of photon density vs. QD electron and hole densities; (ii) Three dimensional plot of photon and QD electron densities vs. time and (iii)QD electron density at three different values of K when α and τ_{ec} values are: 3,160 *ps*.

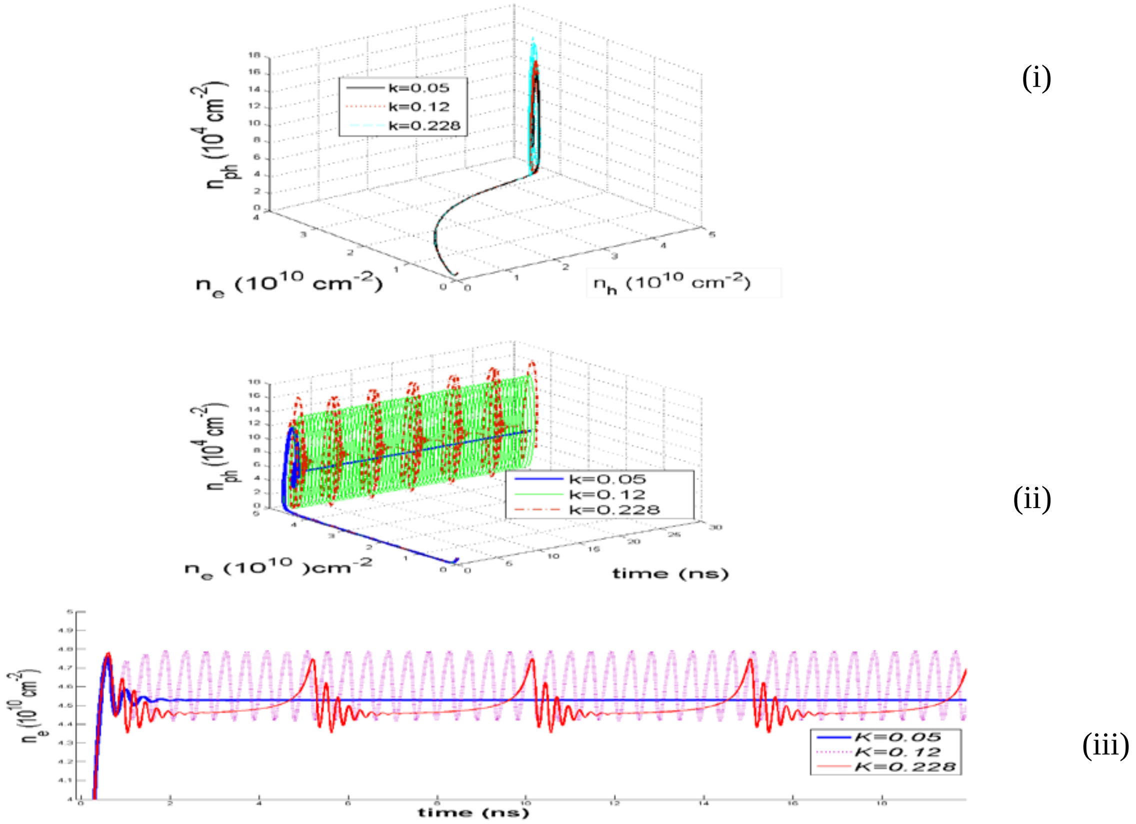
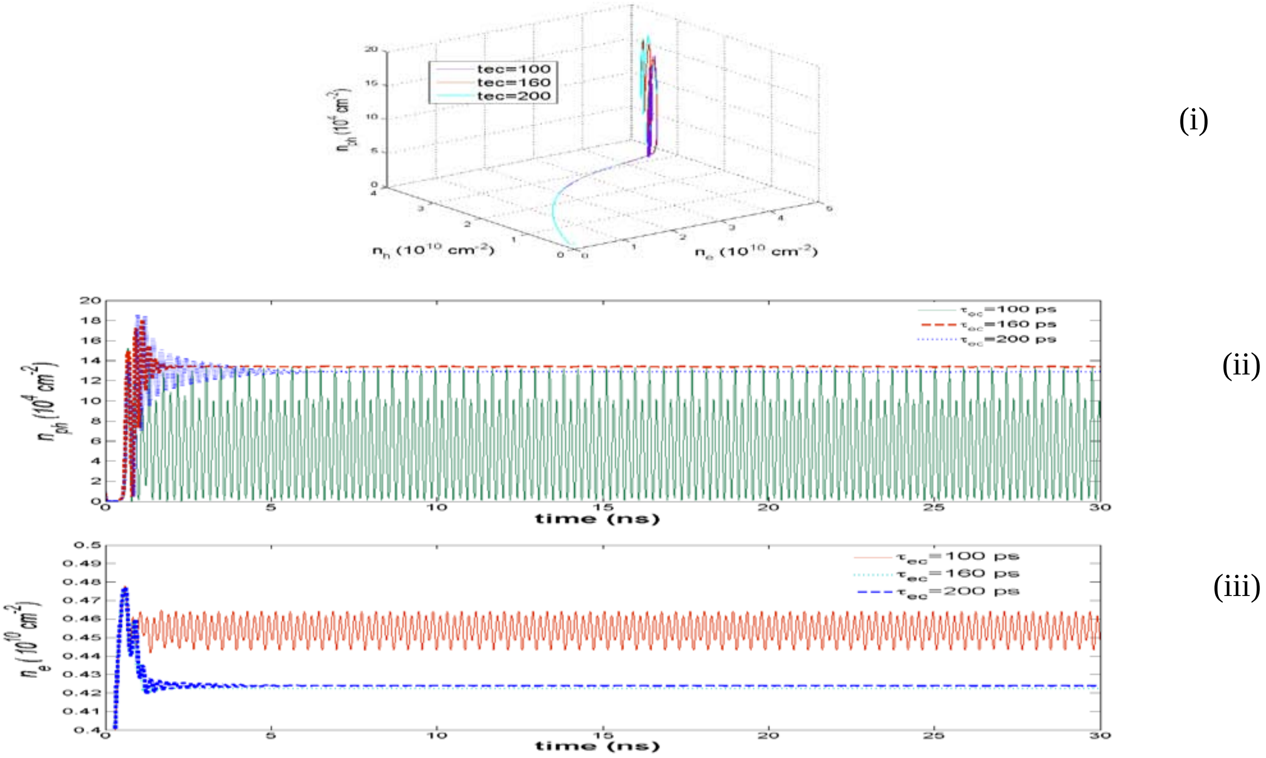
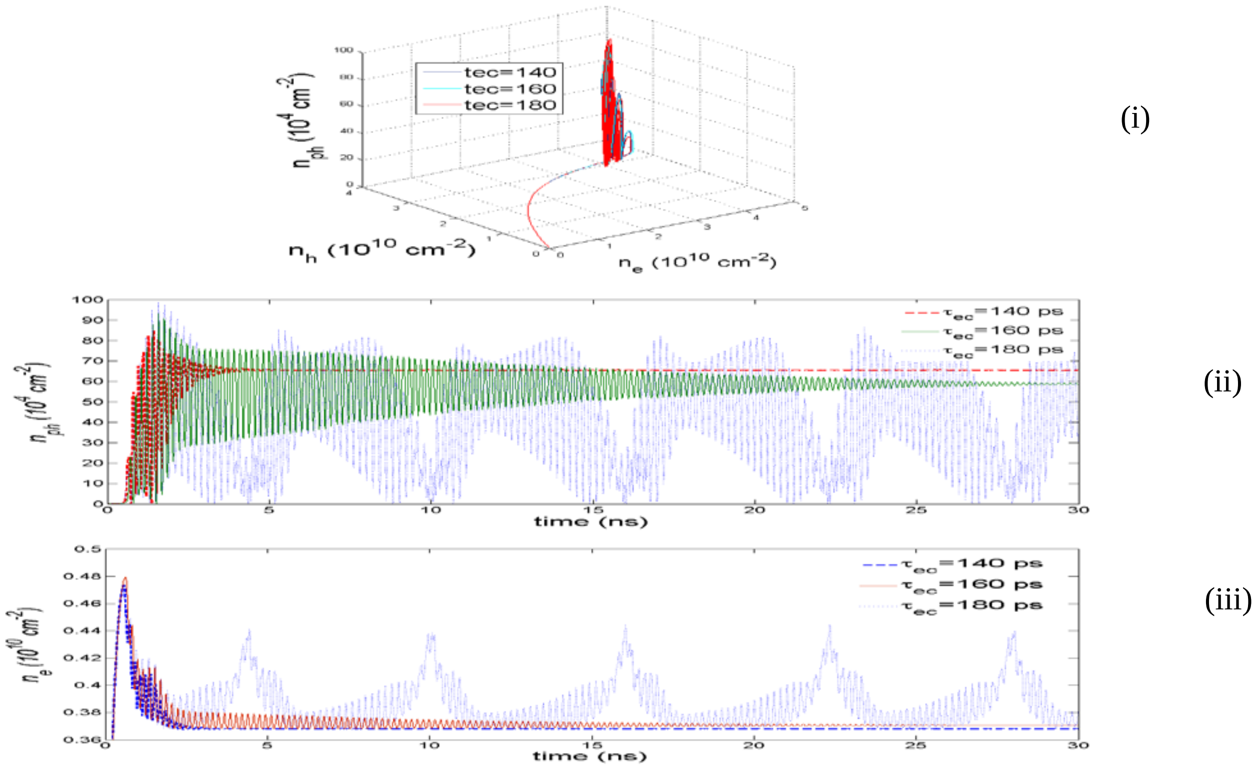


Figure (8). (i) Three dimensional plot of photon density vs. QD electron and hole densities; (ii) Three dimensional plot of photon and QD electron densities vs. time and (iii)QD electron density at three different values of *K* when $\alpha\ and\ \tau_{ec}$ values are: 0.9,160 *ps*.



Figure(9) (i) Three dimensional plot of photon density vs. QD electron and hole densities; (ii)Time series of photon density ; (iii) Time series of electrons density in QDL at three different values of τ_{ec} when $\alpha\ and\ K$ values are: 2, 0.3 .



Figure(10). (i) Three dimensional plot of photon density vs. QD electron and hole densities; (ii)Time series of photon density ; (iii) Time series of electrons density in QDL at three different values of τ_{ec} when α and K values are : 2, 0.9 .

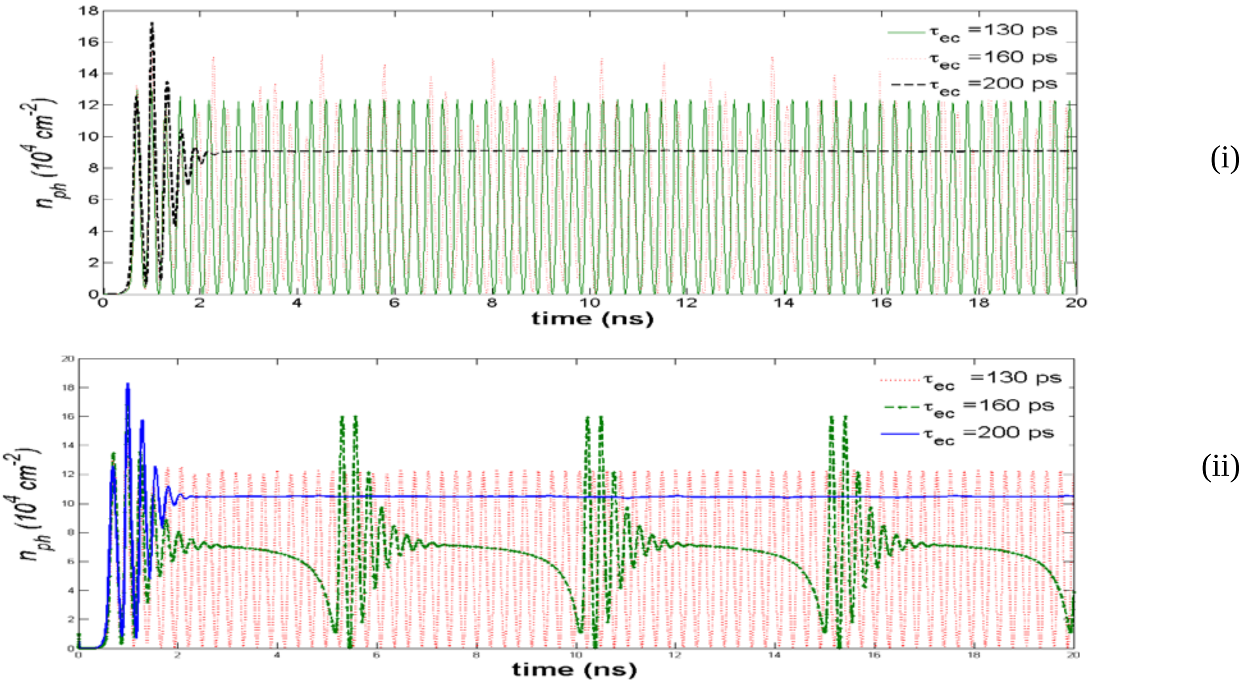


Figure (11). Time variation of Photon density at three different values of time delay (τ_{ec}) when α and K are : (i) 0.1,0.2; (ii)0.9,0.228.

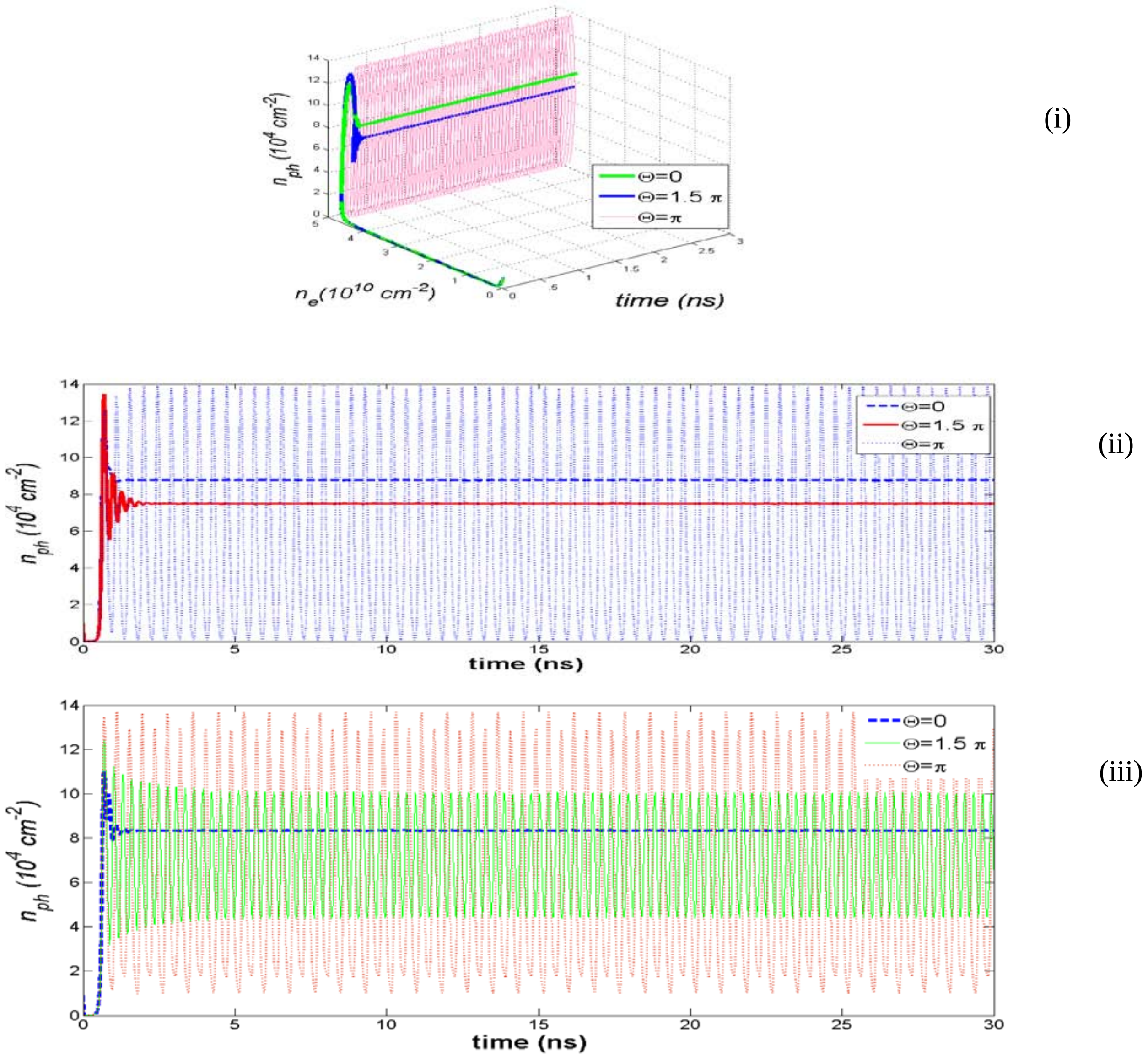


Figure (12).(i) Three dimensional plot of photon and QD electron hole densities vs. time when α and K are : 0.9,0.12;(ii) Time variation of Photon density at three different values of Θ when α and K are : 0.9,0.12 (iii) Time series of electrons density in QDL at three different values of Θ when α and K are : 2,0.12.

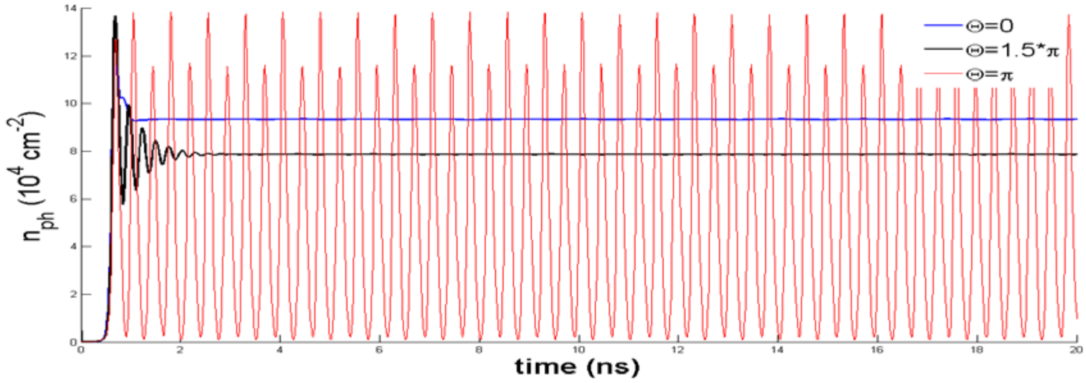


Figure (13). Time variation of Photon density at three different values of Θ when α and K are : 0.9,0.15

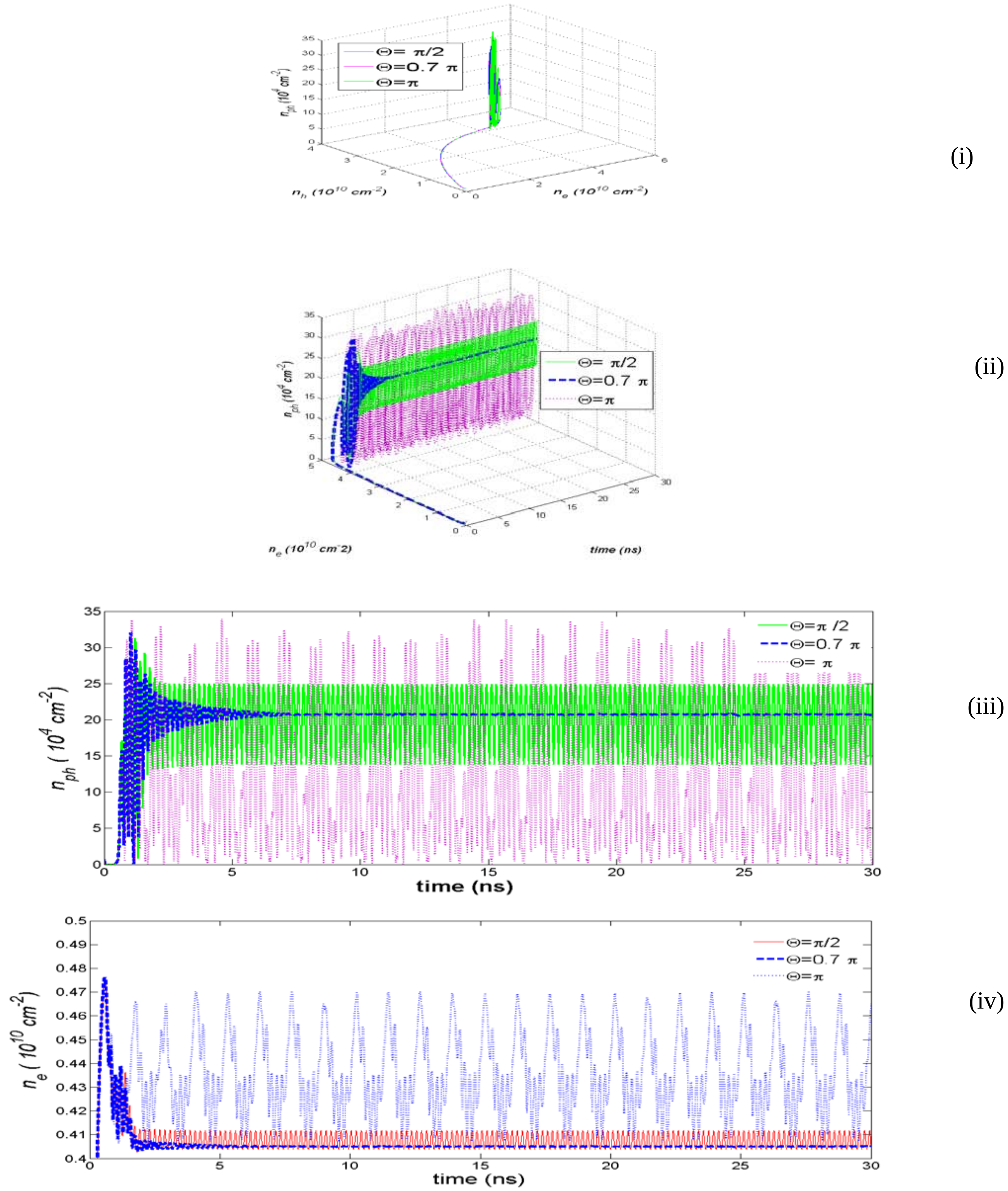


Figure (14).). (i) Three dimensional plot of photon density vs. QD electron and hole densities; (ii) Three dimensional plot of photon and QD electron densities vs. time ; (iii) Temporal variation of Photon density and (iv) Time series QD electron density at three different values of K when $\alpha\ and\ \tau_{ec}$ values are: 3,160 *ps*.

Conclusions:

The effects of optical feedback on the dynamics of *InAs/InGaAs* quantum dot semiconductor laser are tested against the feedback strength, round –trip time and light phase in the external cavity .It shown that varieties of outputs appears to occurs ranging from steady ,periodic to chaotic ones. Self –pulsing or breathing effects together with power dropout in the output occurs too. Results prove that QDSCLs are good candidates for studying nonlinear dynamics.

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خصائص ليزر شبه الموصل *InAs/InGaAs* نوع النقطة الكمية الحركية درست تحت تأثير التغذية الاسترجاعية البصرية

مشتاق عبيد عليوي و جاسب عبد الحسين مشاري
قسم الفيزياء /كلية التربية للعلوم الصرفة /جامعة البصرة
البصرة /العراق

مستخلص :

درسنا تأثيرات التغذية العكسية البصرية في حركيات ليزر شبه الموصل *InAs/InGaAs* نوع النقطة الكمية من خلال استعمال أنموذج يتكون من خمس معادلات تصف أساسا حركيات هذا النوع من الليزرات وبإضافة حد جديد يأخذ بنظر الاعتبار تأثيرات التغذية العكسية ثم إضافة معادلة سادسة تصف تغيرات طور المجال الكهربائي .تمت دراسة تأثير عوامل سيطرة وهي شدة التغذية العكسية البصرية وإزاحة طور الضوء وزمن رحلة الذهاب والإياب في التجويف الخارجي . تولدت حركيات عديدة وغنية امتدت من الدورية وحتى الفوضوية.