Journal Of Education For Pure Science- University Of Thi-Qar
Vol.9, No.1 (March 2019)
Website: jceps.utq.edu.iq *Email: jceps@eps.utq.edu.iq*

DOI: http://doi.org/10.32792/utq.jceps.09.01.10

Dynamics Of Photonic Crystal Quantum Dot Lasers

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Abstract:

Photonic crystal nano-cavity laser has many photonic applications including optical communications and networks. Rate equations of quantum dot laser on photonic crystal describes the behaviors of variables of the system. The theoretical model has been solved by matlab program (with Runge kutta 4th ode 45 method). The results are included variations of photon density and population of carriers on the active region. From the results, the output photon density and the carrier density are increased with increasing the input power and the photon life time. Increasing the volume of photonic crystal driving to increase the output power.

1-Introduction:

The photonic crystal PhC nanocavity laser is considered as one of thebest candidates for ultralow threshold lasers due to their small mode volume of the order of cubic wavelength and high quality factor [1]. In the past decade, some groups have been strived to achieve laser operation in PhC nano cavities with quantum well QW or quantum dot QD , nano cavity lasers with QWs and with QDs were reported with optical pulsed excitation. More lasers with QWs , continuous-wave cw laser operation at low temperature and room temperature has been reported in PhC nano cavities with QDs. The light-in versus light-out plots of these lasers show soft turn-on behavior around the laser thresholds, while conventional lasers show pronounced kinks. Most research on photonic crystal lasers has so far focused on near-infrared wavelength emission using InAs or InGaAs active material due to the applications in optical data communication [1-3]. Visible photonic crystal lasers operating in the spectral vicinity of (wave length =670nm) could enable a broad range of important applications, including high density optical recording and compact spectroscopic sources as ultra small sensors for biological and chemical detection[4-5].

2-Theoretical analysis of a nano cavity (QD) laser:

Photonic crystal lasers, with small mode volumes (V) and high Quality (Q) factors, have enhanced photon emission below threshold via Purcell effect, and can operate with high modulation speeds. Moreover, threshold -less lasing has been predicted in photonic crystal cavities, with necessary but not sufficient condition that the spontaneous emission factor (β) amounts to unity[2-5]. Most photonic crystal lasers so far have been demonstrated based on two-dimensional (2D) photonic crystal slabs. Recently nanobeam structures attracted extensive interests because of their capability to achieve ultra-high Q/V factors in much smaller footprint. We emphasize a small mode volume of these resonators, close to the diffraction limit [(λ/2n)3], that is crucial for realization of large Purcell factor in solid-state emitters with a considerable homogeneous broadening (e.g. bulk semiconductors, we report the experimental demonstration of photonic crystal nanobeam lasers operating at room temperature. A QD laser has the potential to achieve very high differential gain, and the gain spectral width, to be reduced to less than that of planar quantum wells [6-9]. In contrast, because the planar quantum well has a continuous density of states, the room temperature, probability is small for its electrons and holes to occupy only those states that couple to the lasing mode.

The rate equation for the carrier-photon system in this model are [6] :

$$\frac{\mathrm{d}p}{\mathrm{d}t} = g(n_G)p + \frac{F_{\mathrm{m}} n_G}{\tau_r} - \frac{p}{\tau_p} \qquad \text{..............(1)}$$

$$\frac{\mathrm{d}n_G}{\mathrm{d}t} = \frac{n_E}{\tau_{E,f}} - n_G\left(\frac{F_{\mathrm{m}} + F_{PC}}{\tau_r} + \frac{1}{\tau_{PC,\mathrm{nr}}}\right) - g(n_G)p \qquad \text{...............(2)}$$

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

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 to n_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.

The rate equations model described in equations (1) and (3) are solved numerically using Rang- Kutta method and Matlab program

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 [7]. 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].

The laser oscillation in semiconductor micro cavity systems that contain only a single QD is currently of considerable interest. Thus far, micro cavity lasers with single QD gain have been fabricated using micro disk [8] and micro pillar [9] structures. These micro cavity systems contained tens or hundreds of QDs per cavity. Therefore, interference arises not only from the target QD but also from other QDs, hindering access to the delicate physics of a single QD cavity system. This deviation in behavior from an isolated quantum system can be minimized by employing a small cavity in a wafer with an extremely low areal density of QDs. Due to the small mode volume and high cavity quality factor (Q), the use of a photonic crystal (PhC) nanocavity [10] is one of the most promising approaches for investigating physics of single QD-cavity systems. We have fabricated nanocavity systems with highly isolated single QDs (~0.4 QD/cavity), using a small PhC nano cavity and an ultra-low density QD sample.

3- Steady state derivation of model :

At steady state of model, the equations (1-3) can be equal to zero to estimate the initial values and determine the threshold input power as shown the following:

$$\frac{dp}{dt} = \frac{dn_G}{dt} = \frac{dn_E}{dt} = 0$$

$$\frac{dp}{dt} = \mathrm{g}(n_G)\mathrm{p} + \frac{F_m\, n_G}{\tau_r} - \frac{p}{\tau_p}$$

$$0 = \mathrm{g}\; p_0 + \frac{F_m\, n_{G_0}}{\tau_r} - \frac{p_0}{\tau_p}$$

$$0 = \mathrm{g}\; p_0 - \frac{p_0}{\tau_p} + \frac{F_m\, n_{G_0}}{\tau_r}$$

$$p_0 = - \frac{\frac{F_m\, n_G}{\tau_r}}{g - \frac{1}{\tau_p}} \;\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

$$\frac{dn_G}{dt} = \frac{n_E}{\tau_{E,f}} - n_G\left(\frac{F_m+F_{pc}}{\tau_r} + \frac{1}{\tau_{pc,nr}}\right) - \mathrm{g}(n_G)\mathrm{p}$$

$$0 = \frac{n_{E_0}}{\tau_{E,f}} - n_{G_0}\left(\frac{F_m+F_{pc}}{\tau_r} + \frac{1}{\tau_{pc,nr}}\right) - \mathrm{g}\; P_0$$

$$-\frac{n_{E_0}}{\tau_{E,f}} = -n_{G_0}\left(\frac{F_m+F_{pc}}{\tau_r} + \frac{1}{\tau_{pc,nr}}\right) - \mathrm{g}\; P_0$$

$$n_{G_0} = - \frac{\mathrm{g}\; P_0 + n_{E_0}}{\left(\frac{F_m+F_{pc}}{\tau_r} + \frac{1}{\tau_{pc,nr}}\right)} \;\ldots\ldots\ldots\ldots(5)$$

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

$$0 = \eta \frac{L_{in}}{\hbar\omega_p} - n_{E0}\left(\frac{1}{\tau_{E,r}} + \frac{1}{\tau_{E,nr}} + \frac{1}{\tau_{E,f}}\right)$$

$$-n_{E_0}\left(\frac{1}{\tau_{E,r}} + \frac{1}{\tau_{E,nr}} + \frac{1}{\tau_{E,f}}\right) = -\eta \frac{L_{in}}{\hbar\omega_p}$$

$$n_{E_0} = \frac{\frac{\eta L_{in}}{\hbar\omega_p}}{\left(\frac{1}{\tau_{E,r}} + \frac{1}{\tau_{E,nr}} + \frac{1}{\tau_{E,f}}\right)} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

By substituting equations(5) and (6) in equation (4), one can found the information for the system model.

4-Result and discussion:

In this work, the model of system is solved by matlab language with initial condition. The parameters are used in this work mentioned in Table (1) .

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	$1\text{x}10^{-4}$
g_o	The gain coefficient	$6.2 \times 10^4 \text{cm}^2$
N_{tr}	The transparency carrier density	$7.9 \times 10^{15} \text{cm}^{-3}$
η	The fraction of incident pump power	1.3×10^{-5}
$L_{in,th}$	Input pump power	$48\,\mu W$
F_m	Purcell-enhanced parameter	1
Γ	Confinement factor	0.028

The theoretical model shows the following turn on dynamics.

1- The threshold of input power is estimated at steady-state and its value is 48 μw, see in fig. (1).

2- Increasing the input power, L_{in} leads to increase the output density of photons and carrier densities , n_E and n_G which reducing the switch on time as shown in fig.(2-a,b,c).

3- When the photons lifetime, τ_p , increases , the output photons density raises and also the carrier density n_G, but the carrier density n_E decreases. That is noticed in fig.(3-a,b,c).

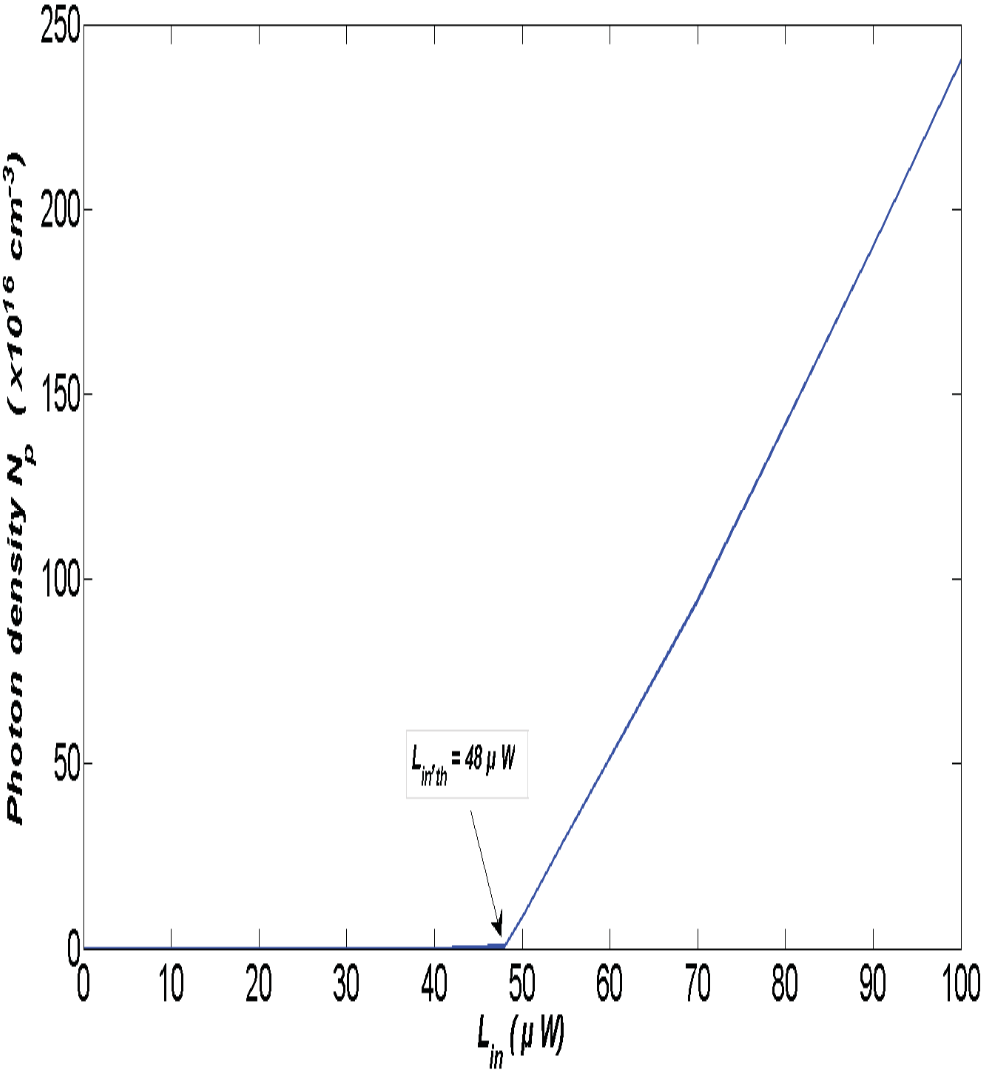

Fig.(1): Photon density vis. input power at steady state.

(Threshold input power estimation)

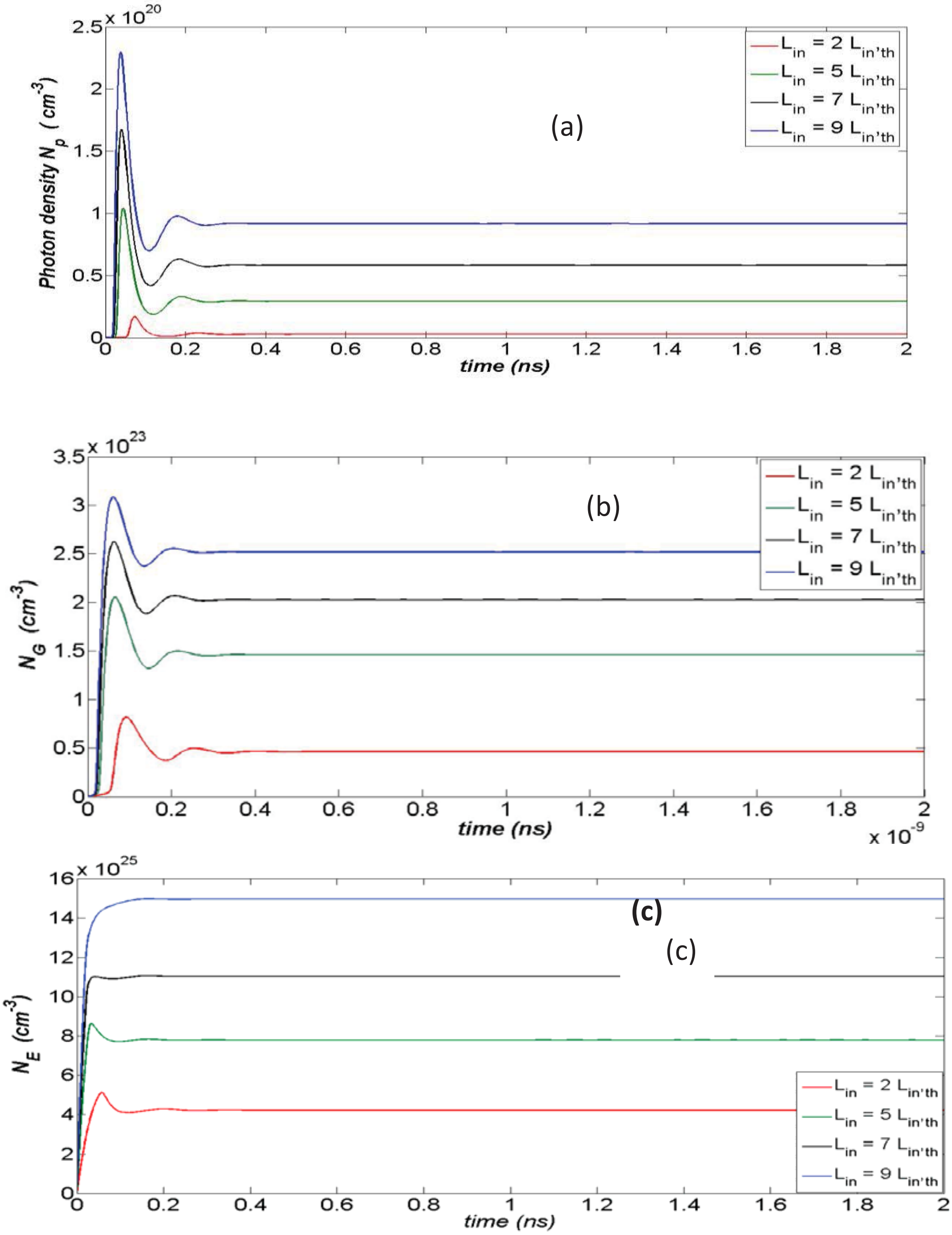

Fig.(2): The time behavior of (a) photon density , (b) n_G , (c) n_E .

($L_{in}= 2L_{in,th}$, $5L_{in,th}$, $7L_{in,th}$).

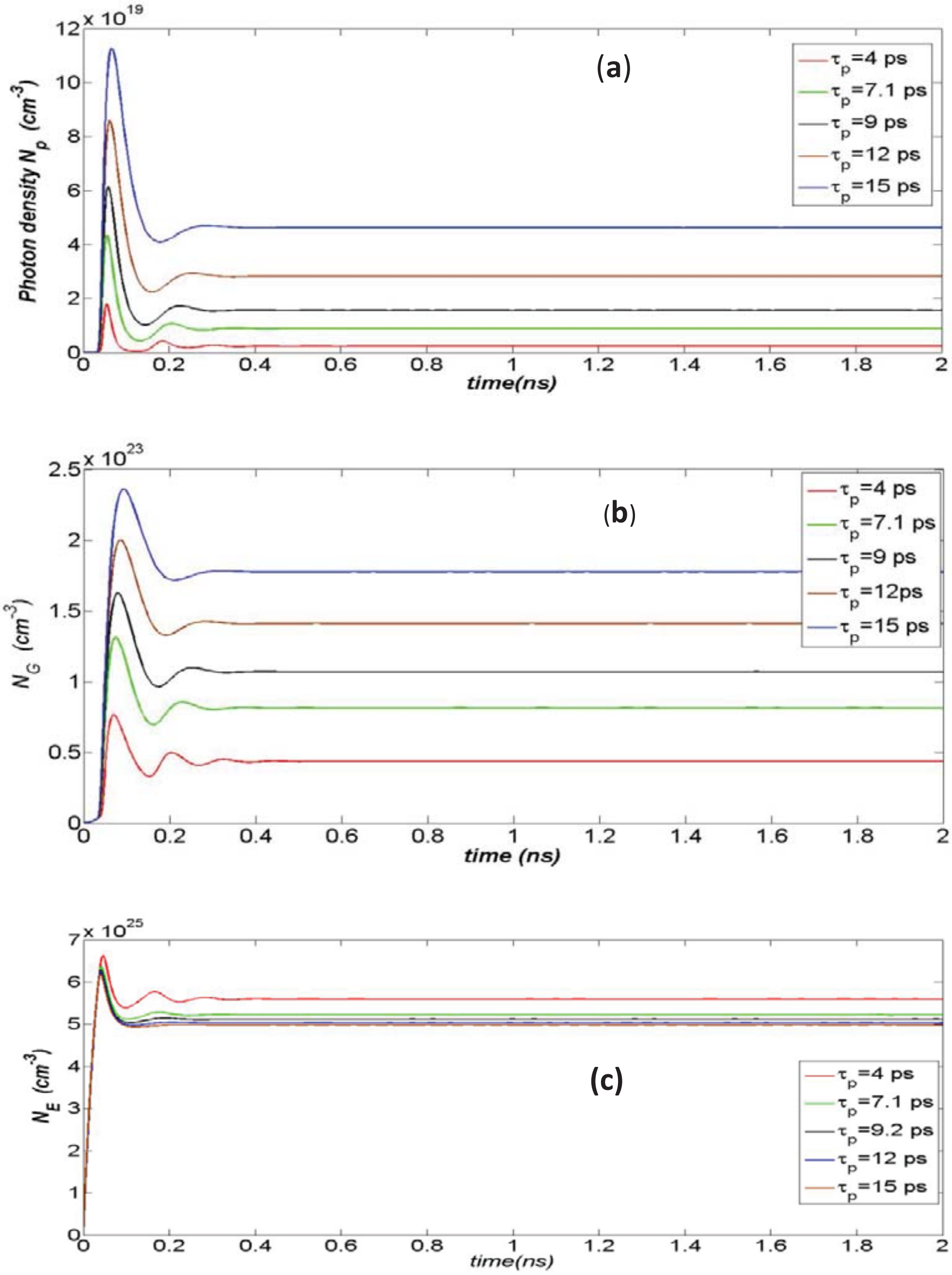

Fig.(3):The time behavior of : (a) Photon density N_P , (b) Lasing level carrier number n_G , (c) The carrier number of photons n_E at different time (τ_p = 4 ps, τ_p =7.1 ps, τ_p =9.2 ps, τ_p = 12 ps, τ_p=15 ps).

The output power can be described by [8] :

$$P_0 = \hbar \omega_p \eta_o v_g g_{th} V_P N_P \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

where ,

η_o is the output efficiency,

$\hbar$ is the Planck's constant divided by 2π,

ω_p is the output photons frequency,

V_p is the volume of carrier reservoir .

The increasing effect of carrier reservoir volume is led to increase the output power as shown in Fig.(4)

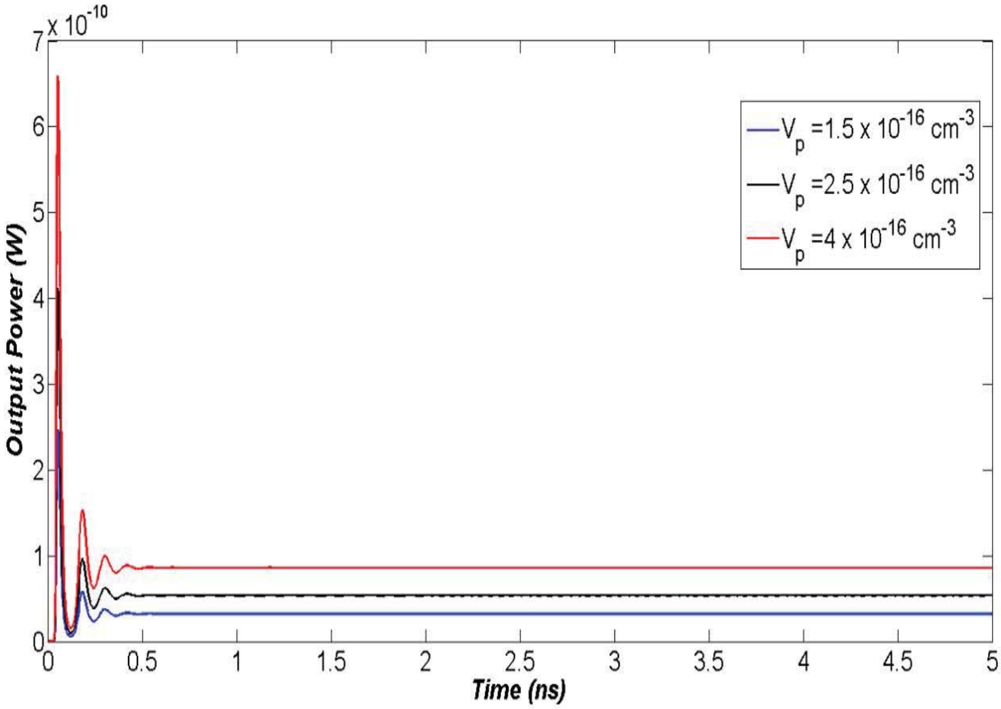

Fig. (4): Output power time behavior at different values photonic crystal volumes (V_P =1.5 x 10^{-16} cm^{-3}, V_P =2.5 x 10^{-16} cm^{-3} , V_P = 4 x 10^{-16})

5-Conclusions:

From the results, the variables of the system are increasing with increasing the input power and also the photon life time. The changing of the volume of photonic crystal for increase led to increase the output power. These effects have widely important.

6- References:

[1] E. Yablonovitch, "Photonic Crystals semiconductors of Light", Scientific American, Inc., (2001).

[2] Y. Gong, B. Ellis, G. Shambat, T. Sarmiento, J. S. Harris, and J. Vuckovi, "Nanobeam photonic crystal cavity quantum dot laser", Opt. Express, 18, 9, 8781-995,(2010).

[3] Y. Liang, T. Okino, K. Kitamura, C. Peng, K. Ishizaki, and S. Noda, "Mode stability in photonic-crystal surface-emitting lasers with large 1 D L", Applied Physics Letters 104, 2, 021102 (2014).

[4] A. Lupi, I. Chung, and K. Yvind, " Electrical Injection Schemes for Nano lasers", IEEE Pho. Tech. Lett., 26, 4, (2014).

[5] Song, B. S., et al. "Ultra-high-Q photonic double-heterostructure nanocavity". Nature materials 4, 207210 (2005).

[6] D. Englund , H. Altug, B. Ellis1, and J Vuˇckovi´ c1, "Ultrafast photonic crystal lasers", Laser & Photon. Rev., 1–7 (2008).

[7] E. Yablonovitch, "Photonic Crystals semiconductors of Light", Scientific American, Inc, (2001).

[8] Jonas Bach Olsen and Frederik Diethelm Jacobsen , "Extracting the β-factor of a photonic crystal laser", DTU Fontonik, (2016).

[9] Y. Gong, B. Ellis, G. Shambat, T. Sarmiento, J. S. Harris, and J. Vuckovi, "Nanobeam photonic crystal cavity quantum dot laser", Opt. Express, 18, 9, 8781-9, (2010).

[10] R. Buczynski, "Photonic crystal fibers", Acta Phys. Polonica, 2,106, 141-167,(2004).

[11] Farzaneh Kariminezhad, Esfandiar Rajaei, Alireza Fali, Reyhaneh Mirzaei, " Impact of gain compression factor on modulation characteristics of InGaAs/GaAs self-assembled quantum dot lasers", J Theor Appl Phys 10, 281–287, (2016).