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Gain optimization of the optical waveguide based on the quantum box core/shell structure

H. Rasooli S.[*]
S. K. Seyyedi S.
S. Zabihi A.

Department of Electrical Engineering, College of Technical & Engineering, Tabriz Branch, Islamic Azad University, Tabriz, Iran.

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ABSTRACT

In order to implement an integrated optical quantum circuit, designing waveguides based on the quantum box is of prime importance. To do this we have investigated optical waveguide both with and without optical pumping. The rate of absorption and emission using an array of AlGaAs/GaAs quantum box core/shell structure in the optical waveguide with various pumping intensities has computed. By considering an external pumping with maximum emission, the gain of the optical waveguide based on the AlGaAs/GaAs quantum box core/shell structure, for two different sizes 3×3×3 nm and 6×6×6 nm has been optimized. We have shown that in the absence of any external excitation with different pumping power, the amount of absorption energy in the array of quantum box is greater than the amount of emission energy, and resulting in the positive gain. Finally, we noticed that by increasing the dimension of the quantum box, the optimum gain is achieved for the smaller wavelength.

Keywords: *Quantum dot waveguide; Absorption; Emission; Gain; Next nano.*

INTRODUCTION

Technological advances in the electronics, optoelectronics industry, communication, and others has made the applications of nano-size electronic components necessary inorder to be able to implement optical quantum dot integrated circuits. This in turn has necessitated the studying of optical quantum dot waveguides [1].In our previous work [2,3], we have shown that the size and the type of the quantum box directly effects maximum gain of the spectrum. In this paper we have chosen Core/Shell structure of $Al_xGa_{1-x}As/GaAs$ with two different dimensions of 3×3×3 nm and 6×6×6 nm respectively. In both cases the difference between quantum well energy levels are computed. We then have considered the absorption behavior and the emission properties of the quantum box with respect to the input signal with and without applying external optical excitation. Finally, the so obtained results are extended to the array of quantum box.

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[*] Corresponding author:
Hasan Rasooli Saghai
Department of Electrical Engineering, College of Technical & Engineering,Tabriz Branch, Islamic Azad University, Tabriz, Iran.
Tel +989143156503
Fax +984113328560
Email h_rasooli@iaut.ac.ir

COMPUTATIONAL METHODES

Computation and simulation method

- **Solving absorption, emission, and gain equations in the quantum box and optical waveguide**

The quantum box energy block diagram is shown in Figure 1. The structure is chosen to be $Al_xGa_{1-x}As$/GaAs with core lengths Lx, Ly, Lz, and shell lengths Wx, Wy, and Wz. Inorder to compute the difference between quantum well energy levels we have set the Mole fraction number at 0.47. Thus by considering:

$$Eg = \begin{cases} 1.424 + 1.247x \ \ eV & , \quad x < 0.45 \\ 1.9 + 0.125x + 0.143x^2 & , \quad x > 0.45 \end{cases} \qquad (1)$$

$$\Delta_0 = 0.34 - 0.04x \quad ev \qquad (2)$$

$$n_r = 3.3 - 0.53x \ \ 0.09x^2 \qquad (3)$$

Where Eg, Δ_0, and n_r are being the energy gap, spin-orbital splitting energy, and intrinsic carrier concentration respectively [4], the difference between energy levels (ΔEc) in the quantum well is simulated from the Eq.4 using the so called the "next nano" software which is based on the Schrodinger and Possion equation as follows:

$$\left[-\left(\frac{\hbar^2}{2m_{c1,2}}\right)\frac{\partial^2}{\partial z^2} + V_{cz}(z)\right]\emptyset_{czl}(z) = E_{czl}(z)\emptyset_{czl}(z) \qquad (4)$$

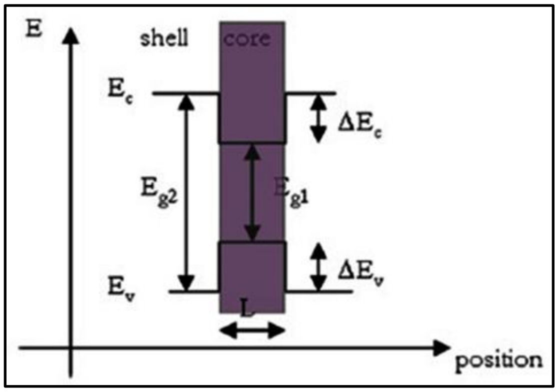

Fig.1. Potential well energy diagram representation of Core/Shell quantum box structure.

The simulation results for the material-type structure, well potential configuration, and wave function of Eq.4 using quantum box Core/Shell structure is shown Figure 2a, 2b, and 2c, respectively.

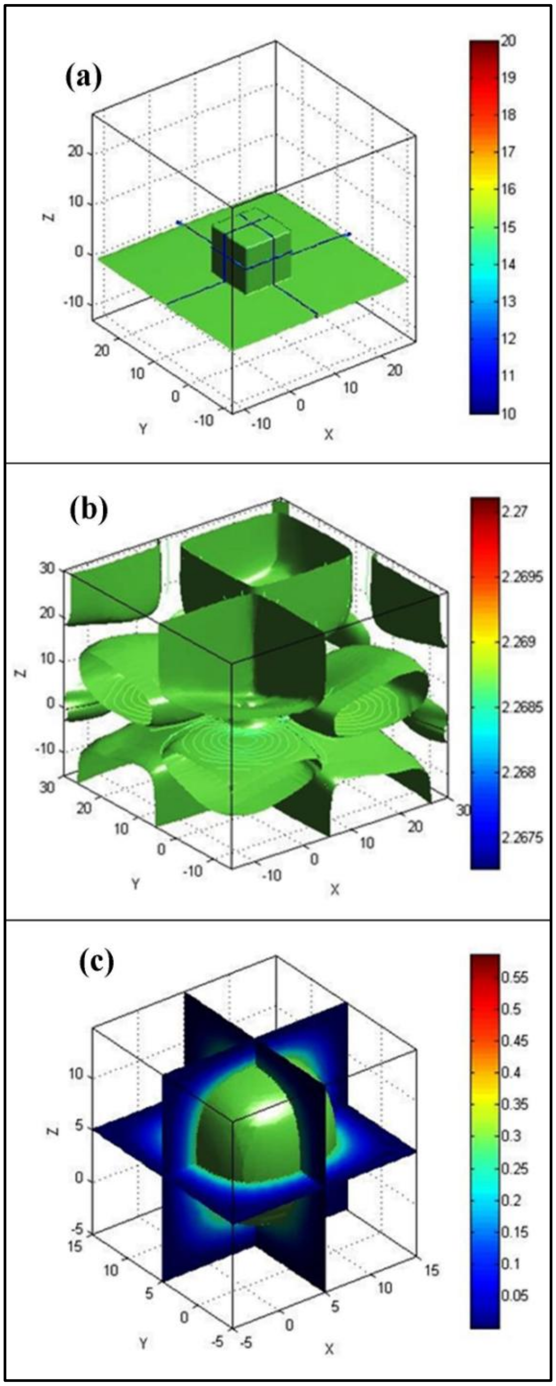

Fig. 2. Simulations of (a) the material-type structure, (b) well potential configuration, and (c) wave function for 3D of quantum box by using nextnano software.

To compute the absorption and emission functions we first by using equations (5) and (6) compute the number of electrons and holes respectively in the quantum box structure of Figure 3 with no external excitation as follows:

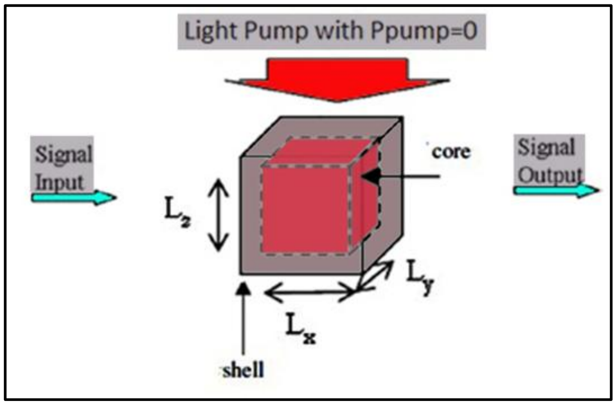

Fig. 3. Schematic of quantum box waveguide with no external pumping.

$$n=\sum_{lnm}\frac{2}{\left[1+exp\left(\frac{E_{cnml}-E_{fc}}{kT}\right)\right]L_xL_yL_z}=\sum_{lnm}\frac{2f_c(E_{cnml})}{L_xL_yL_z}$$

(5)

$$p=\sum_{lnm}\frac{2}{\left[1+exp\left(\frac{E_{fv}-E_{vnml}}{kT}\right)\right]L_xL_yL_z}=\sum_{lnm}\frac{2(1-f_v(E_{vnml}))}{L_xL_yL_z}$$

(6)

R_{ch} and g_{ch} are the dipole moment and level density, respectively. The net gain also using the equations (4-8) is computed as:

$$G(\omega)=e(\omega)-\alpha(\omega)$$

$$G(\omega)=\frac{\omega}{n_r}\sqrt{\frac{\mu_0}{\varepsilon_0}}\sum_{lmn}\int_{E_g}^{\infty}\langle R_{ch}^2\rangle\frac{g_{ch}[f_c(E_2)-f_v(E_1)]\hbar/\tau_{in}}{(E_{ch}-\hbar\omega)^2+(\hbar/\tau_{in})^2}dEch$$

(9)

Where the results of absorption, emission, and gain as a function of the wavelength is plotted in Figure 4 and Figure 5 for 3×3×3 nm and 6×6×6 nm $Al_{0.47}Ga_{0.53}As/GaAs$ Quantum box without pumping, respectively

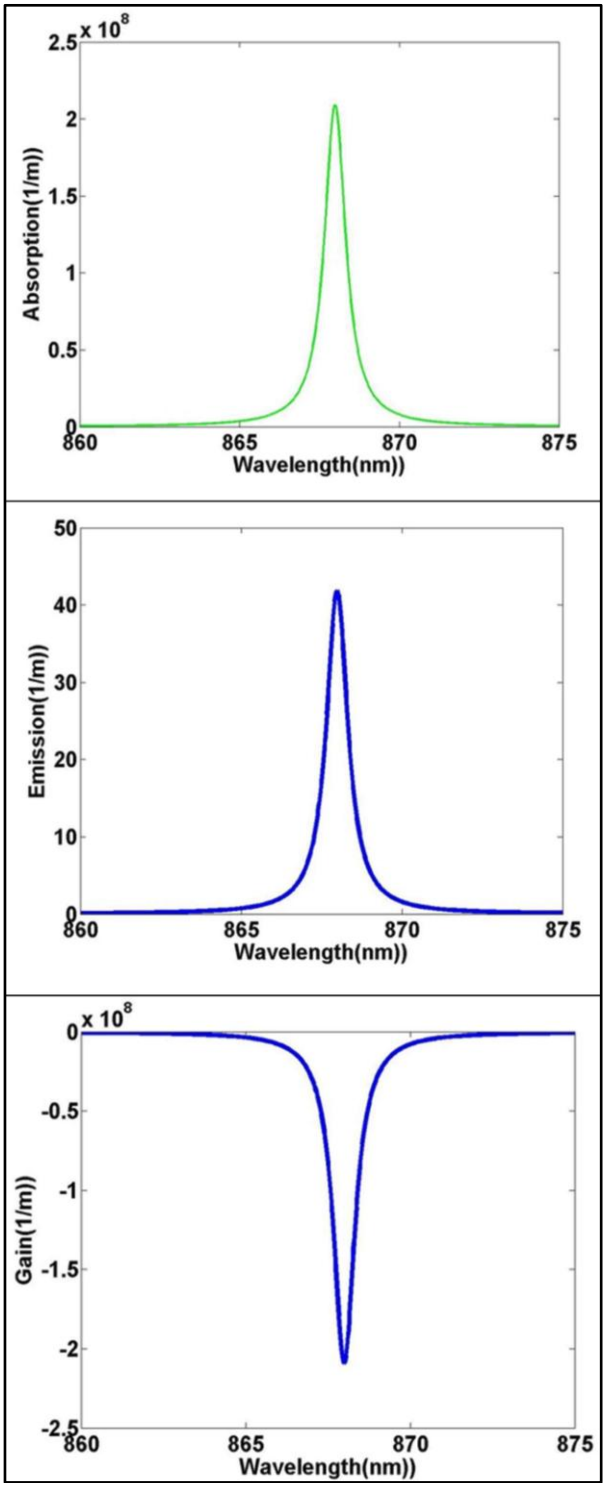

Fig. 4. Absorption, Emission, and Gain spectra for 3×3×3 nm $Al_{0.47}Ga_{0.53}As/GaAs$ Quantum box without pumping.

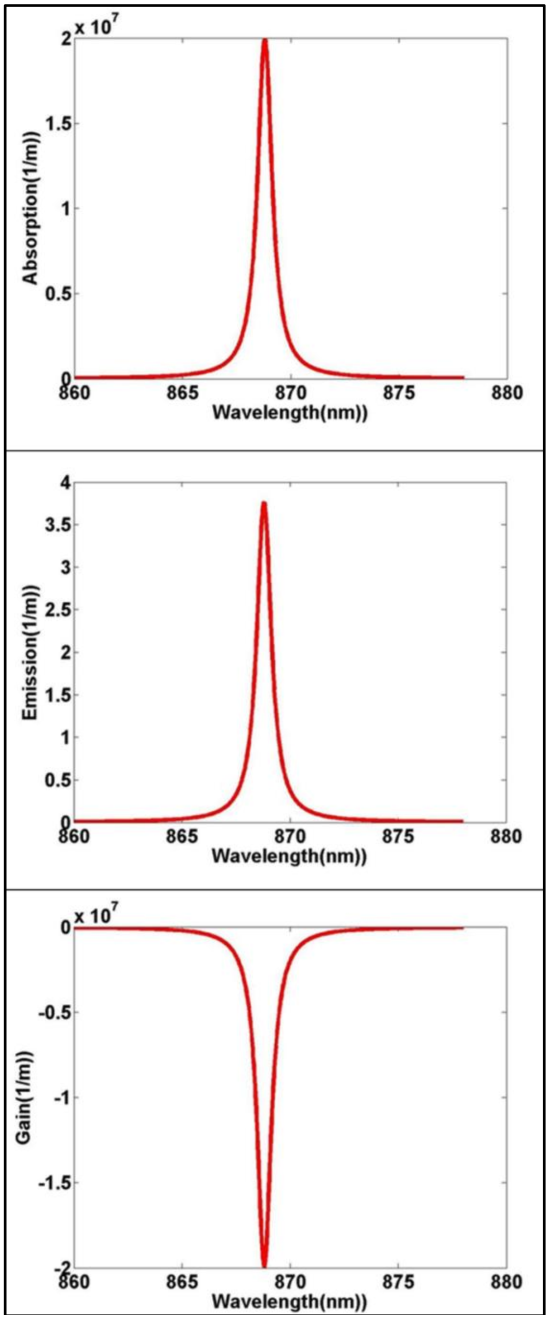

Fig. 5. Absorbtion, Emission and Gain spectra for 6×6×6 nm $Al_{0.47}Ga_{0.53}As$/GaAs Quantum box without pumping.

We can now extend the above computations to the quantum box array as [2], [6]:

$$\begin{bmatrix} I_{out,+} \\ I_{out,-} \end{bmatrix} = M_{QD}.(M_{prop}.M_{QD})^{N-1}.\begin{bmatrix} I_{in,+} \\ I_{in,-} \end{bmatrix} \quad (10)$$

$$With \quad M_{QD} = \begin{bmatrix} 0 & 1 \\ -1 & 2e^{-G} \end{bmatrix} \quad and \quad M_{prop} = \begin{bmatrix} \eta & 0 \\ 0 & \eta^{-1} \end{bmatrix} \quad (11)$$

Where, M_{QD} is the matrix of the gain, and M_{prop} is the emission matrix that provides the loss component related to near-field energy transfer with the coupling efficiency [7]. As a result for this a N^{-} array of QDs, the total intensity M_{total}, is computed as:

$$M_{total} = M_{QD}.(M_{prop}.M_{QD})^{N-1} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \quad (12)$$

$$\begin{bmatrix} I_{out+} \\ I_{out-} \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \begin{bmatrix} I_{in+} \\ I_{in-} \end{bmatrix} \quad (13)$$

Note that the boundary condition in the last quantum box that is I_{out}, considered being zero. Then we are going to have:

$$\frac{I_{out,+}}{I_{in,+}} = \frac{I_{out}}{I_{in}} = m_{11} - \frac{m_{11}.m_{21}}{m_{22}} \quad (14)$$

As it can be seen from the Fig.6 considering a quantum box of no external excitation will result not only in no emission but also in negative net gain too.

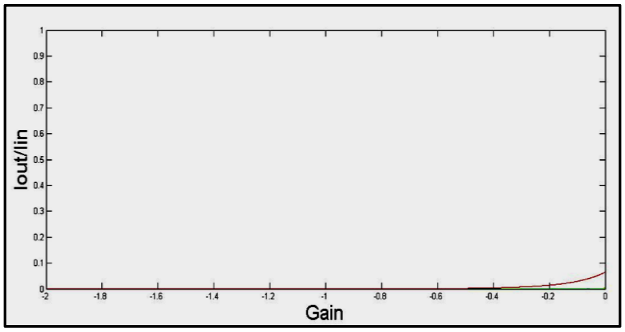

Fig. 6. $\frac{I_{out}}{I_{in}}$ **as a function of gain.**

RESULTS AND DISCUSSION

As it can be seen from Figure 6 this is also true for the quantum box waveguide [7-8]. In order to improve the net gain and signal emission along the waveguide, we need to use an external optical pumping according to what has been shown in Figure 7.

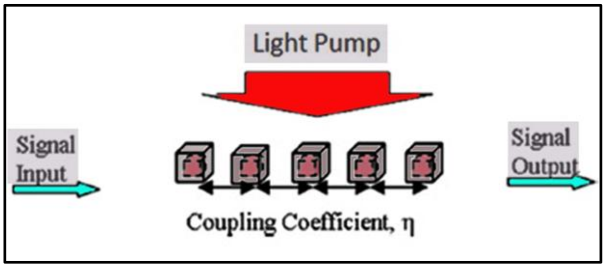

Fig. 7. Schematic of quantum box waveguide under pumping operation.

To do this, again we have considered an external excitation along with new n and p to get the equations (16) and (17):

$$n \cong p = \frac{P_{pump}}{L_x L_y \hbar\omega_p}\Delta t\alpha(\omega_p) \qquad (15)$$

$$N = \frac{P_{pump}}{\hbar\omega_p}\Delta t\alpha(\omega_p)L_z = \sum_{lnm}\frac{2}{\left[1+exp\left(\frac{E_{cnml}-E_{fc}}{kT}\right)\right]} \qquad (16)$$

$$P = \frac{P_{pump}}{\hbar\omega_p}\Delta t\alpha(\omega_p)L_z = \sum_{lnm}\frac{2}{\left[1+exp\left(\frac{E_{fv}-E_{hlmn}}{kT}\right)\right]} \qquad (17)$$

With Δt being the pumping interval that P_{pump} is the pumping power and ω_p is the pumping frequency. Considering the fact that the Quasi-Fermi energy levels E_{fc} , E_{fv} are functions of N and P, thus there will not be any change in the Eq.9 [2,9]. As a result using the above equations the output signals of absorption, emission, and gain in the quantum box with Core/Shell structure $Al_{0.47}Ga_{0.53}As/GaAs$ and dimensions of 3×3×3 nm and 6×6×6 nm after applying optical excitation are given in Figure 8 and Figure 9 for 3×3×3 nm and 6×6×6 nm $Al_{0.47}Ga_{0.53}As/GaAs$ Quantum box without pumping respectively.

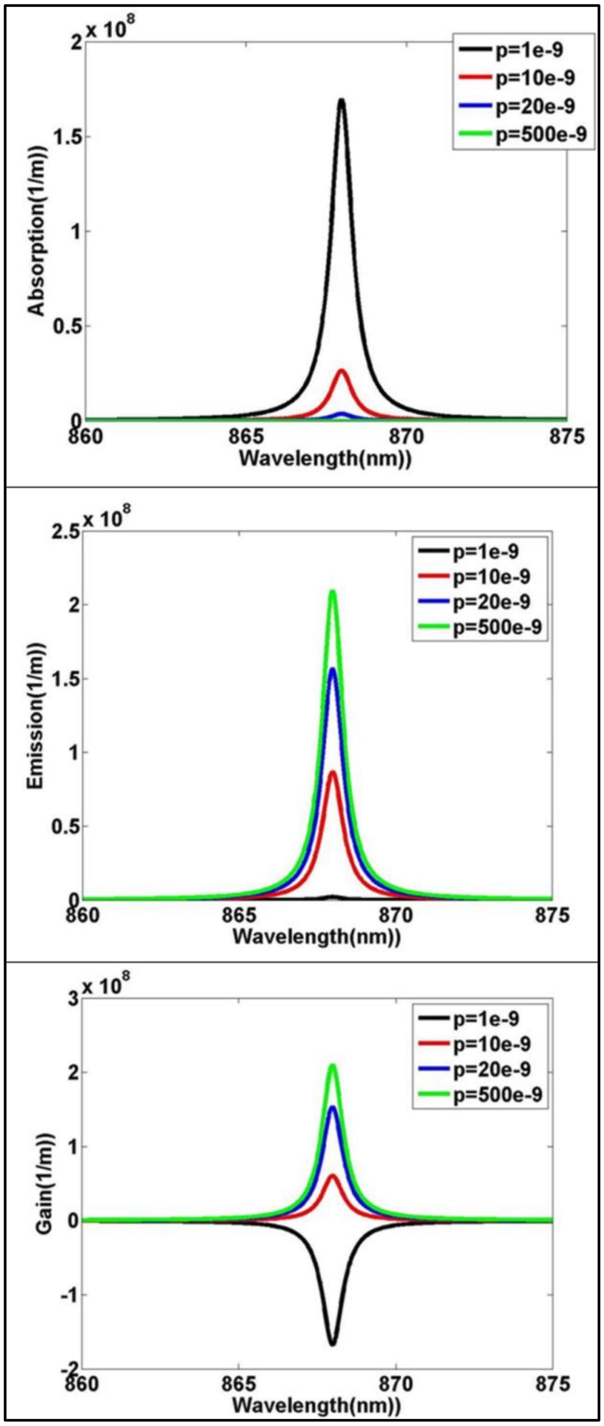

Fig. 8. Absorbtion, Emission and Gain spectra for 3×3×3 nm $Al_{0.47}Ga_{0.53}As/GaAs$ waveguide under pumping.

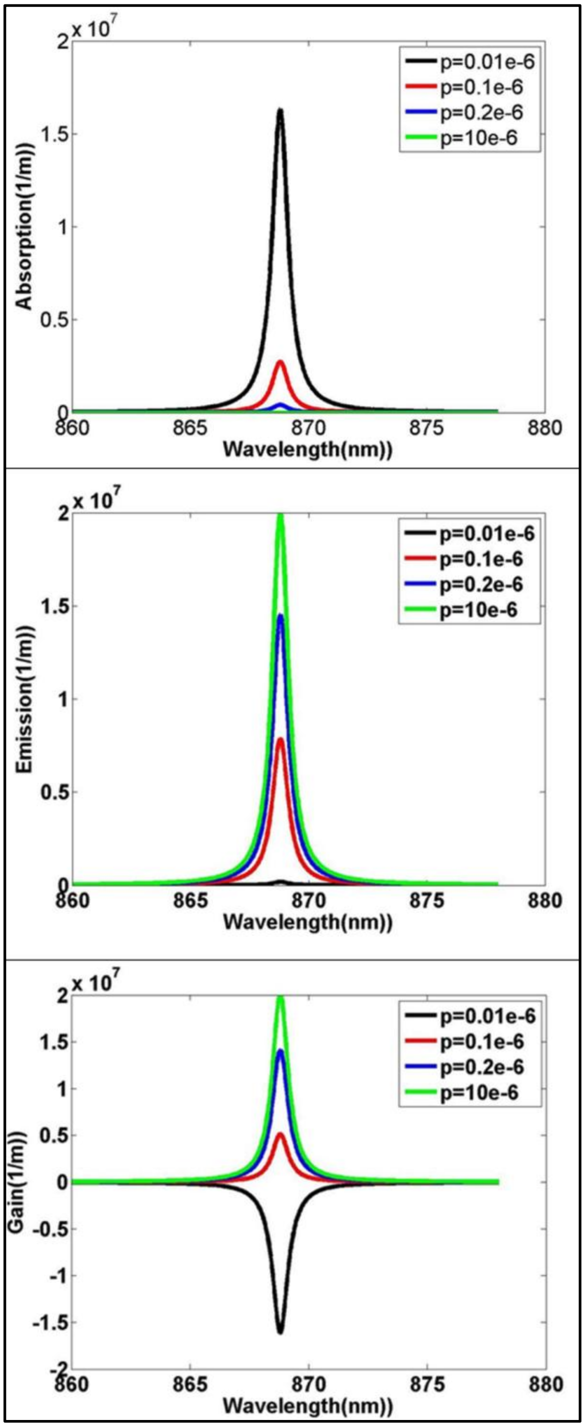

Fig. 9. Absorbtion, Emission, and Gain spectra for 6×6×6 nm $Al_{0.47}Ga_{0.53}As/GaAs$ waveguide under pumping.

By, repeating the equations (10-14), it can be shown that by applying an external excitation, the gain in the quantum box array will be as shown in Figure 10.

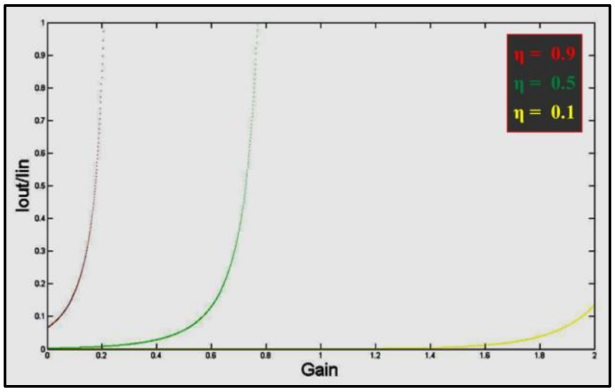

Fig. 10. Output versus input intensity as a function of gain through each QD given a range of coupling coefficients between adjacent QDs for a three QD waveguide under pumping operation.

CONCLUSIONS

In this paper the effects of the size and external pumping in the Quantum box array waveguide were considered. For the case of no external pumping, the absorption energy is greater than the emission energy, thus resulting in the negative gain. But, conversely in case of the external pumping, the absorption energy is less than the emission energy, thus resulting in the positive gain. Finally, we noticed that by increasing the dimension of the Quantum box, the optimum gain is achieved for the smaller wavelength.

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