

Saturated Gain of Doped Multilayer Quantum Dot Semiconductor Optical Amplifiers

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Abstract—The effect of the number of quantum dot (QD) layers on the saturated gain of doped QD semiconductor optical amplifiers (SOAs) has been studied using multi-population coupled rate equations. The developed model takes into account the effect of carrier coupling between adjacent layers. It has been found that increasing the number of QD layers (K) increases the unsaturated optical gain for $K < 8$ and approximately has no effect on the unsaturated gain for $K \geq 8$. Our analysis shows that the optimum p-type concentration that maximizes the unsaturated optical gain of the ground state is $N_A \approx 0.75 \times 10^{18} \text{ cm}^{-3}$. On the other hand, it has been found that the saturated optical gain for both the ground state and the excited state are strong function of both the doping concentration and K where we find that it is required to dope the dots with n-type concentration for very large K at high photon energy.

Keywords—doping, multilayer, quantum dot optical amplifier, saturated gain.

I. INTRODUCTION

RECENT advances in nanometer fabrication and material physics have created the opportunity to use quantum dots (QDs) and quantum dashes (QDshs) for next-generation devices. Quasi-zero dimensional quantum materials such as QDs and QDshs have been under intensive research due to their unique electrical and optical properties, which made them suitable for many advance applications including ultrafast pulse generation and amplification, optical sensing and networking and advance imaging [1]-[4]. The development of low threshold, high efficiency and low chirp QD lasers and semiconductor optical amplifiers (SOAs). Experiments have shown that the energy band of quantum dots consists of discrete electron and hole states in the conduction and valence bands. Due to the discrete nature of these states, QD-SOAs have experimentally demonstrated ultrafast gain response, high saturation power, low temperature sensitivity and ultra wide operating wavelength range [5]-[11].

Unfortunately the modal gain of single QD layer is limited to small value of about 6 cm^{-1} or lower for GaAs based devices [12]. Using single QD layer in the active region of SOAs requires low loss cavity and long SOA to achieve reasonable gain. Solving this problem can be done by using multiple QD layers to increase the net modal gain. The multiple QD layers strongly change the electronic/optical

properties of the active region due to strain variation, state intermixing and coupling between the QD layers. Multiple QD layers are expected to improve the performance of QD lasers and SOAs where it results in wide continuous electroluminescence spectrum, narrow lasing spectrum, higher single-mode output power, higher modal gain and improved carrier injection efficiency [13], [14]. Unfortunately, using multiple QD layers increases the strain in the active region and results in defect formation and increases the internal loss of the device [15] which may limit the performance of the SOA at high applied current and at large number of QD layers. Several methods such as strain compensation, selective evaporation and high growth temperature spacer layers have been used to improve the quality of multiple QD layers [16]. Also using large numbers of QD layers may reduce the optical gain at high doping concentrations.

Recent study of carrier coupling between adjacent vertically coupled QD layers in quantum-dot SOA [14] shows that the degradation in the unsaturated optical gain due to long coupling lifetimes is more severe in p-type doped QD-SOA compared with un-doped QD-SOA. To the best of our knowledge there is no work in the literature that studies the effect of the number of QD layers on the saturated gain of doped QD-SOAs. In this paper, detailed analysis of the effect of doping and the number of QD layers on the saturated optical gain of QD-SOA using multi-population coupled rate equations has been presented. This analysis is very important to obtain the proper number of QD layers and proper doping concentration for high gain applications.

II. SOA MODEL

The investigated QD-SOA heterostructure consists of multiple vertically coupled QD layers where K represents the number of QD layers. The typical energy band diagram of each quantum dot layer consists of multiple coupled energy states in the conduction and valence bands. Each layer has 3 non-degenerate energy levels in the conduction band and 8 non-degenerate energy levels in the valence band, and is accompanied by two-dimensional wetting layer (WL) states. The separations of the electron and hole energy states are 60meV and 10meV respectively. The vertically stacked QD layers are coupled via transport rates between the adjacent wetting layers and via tunneling rates between the adjacent quantum dot energy states [14]. Since electrons are faster and lighter than holes they determine the coupling rates. The transport rates and the tunneling rates are modeled as forward and backward rates. The transport rate depends on the capture rate of carriers from the continuum states to the confined

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states and on the diffusion rate of carriers through the barrier layer. For typical barrier thickness, the diffusion time is in femtoseconds and the transport rate will be mainly determined by the capture lifetime.

The multilayer rate equation, which include vertical coupling, for the electrons in the i -th state and the k -th layer is given by [14]:

$$\frac{\partial n_i^k}{\partial t} = \left(\frac{(1-n_i^k)n_{i+1}^k}{\tau_{i+1,i}^n} - \frac{n_i^k(1-n_{i+1}^k)}{\tau_{i,i+1}^n} \right) - \frac{n_i^k p_i^k}{\tau_{iR}} - \frac{v_g g_i (n_i^k + p_i^k - 1) S}{N_Q (1 + \epsilon S)} + \frac{n_i^{k-1} - 2n_i^k + n_i^{k+1}}{\tau_{it}^n} \quad (1)$$

where t is the time in a retarded time frame, i.e., $t = t' - z/v_g$ where t' is the time and z is the distance. n_i^k and p_i^k are, respectively, the occupation probability for the electrons and the holes of the i -th state and the k -th layer. v_g is the group velocity, N_Q is the dot volume density, S is the photon density and ϵ is the gain compression factor. $\tau_{i+1,i}^n$ is the electron relaxation time from the $i+1$ state to the i -th state and $\tau_{i,i+1}^n$ is the electron escape time from the i -th state to the $i+1$ state. g_i is the modal gain for the i -th state. τ_{iR} is the spontaneous radiative lifetime in i -th state. τ_{it}^n is the tunneling lifetime. For the first layer (i.e., $k=1$), the last term in (1) is equal to $\frac{-n_i^k + n_i^{k+1}}{\tau_{it}^n}$. Similarly for the last layer ($k=K$), the

last term in (1) is $\frac{n_i^{k-1} - n_i^k}{\tau_{it}^n}$.

The electrons rate equation in the wetting layer state of the k -th layer is

$$\frac{\partial n_w^k}{\partial t} = \frac{J^k}{\tau_{0R}} - \left(\frac{(1-n_{M_n}^k)n_w^k}{\tau_{w,M_n}^n} - \frac{n_{M_n}^k(1-n_w^k)}{\tau_{M_n,w}^n} \right) - \frac{n_w^k p_w^k}{\tau_{wR}} + \frac{n_w^{k-1} - 2n_w^k + n_w^{k+1}}{\tau_d^n} \quad (2)$$

n_w^k and p_w^k are the occupation probability for the electrons and the holes in the WL edge of the k -th layer, τ_d^n is the transport lifetime and τ_{w,M_n}^n is the electron relaxation time from the WL to the highest excited state and $\tau_{M_n,w}^n$ is the electron escape time from the highest excited state to WL. For the first layer (i.e., $k=1$), the last term in (2) is equal to $\frac{-n_w^k + n_w^{k+1}}{\tau_d^n}$. While for the last layer ($k=K$) the last term in

(2) is $\frac{n_w^{k-1} - n_w^k}{\tau_d^n}$. Here $J^1 = J_A$ where J_A is the normalized

applied current and $J^k|_{k \neq 1} = 0$. The transport lifetime may be

expressed as $\tau_d^n = \tau_C + \tau_{diff}$ where τ_C is the capture lifetime of carriers from the continuum states to the confined states and τ_{diff} is the diffusion lifetime that is given by

$\tau_{diff} = L_B^2 / (2D_n)$ where L_B is the barrier thickness and D_n the electron diffusion constant. The rate equations for the hole states are similar to (1) where n is replaced by p and p is replaced by n . At relatively high injection density, Auger-type carrier-carrier scattering is very important where electrons can relax to a lower state in the QD by losing their energy to another carrier in the higher continuum states. Since the hole states are dense and very close to each other electron-hole scattering will be large. Electron-hole scattering effects is taken into account by assuming that $\tau_{i+1,i}^n \propto 1 / (1 + c_{i+1,i}^n p_w^k)$

where $c_{i+1,i}^n$ is the Auger-assisted coefficient.

Charge neutrality, which relates the electron concentration with the hole concentration, is ensured by the following equation

$$N_A + N = P + N_D \quad (3)$$

where N and P are the electron and the hole concentration respectively, N_D is the donor concentration and N_A is the acceptor concentration. The electron and the hole concentrations are given respectively by

$$N = \sum_{k=1}^K \sum_{i=0}^{M_n} N_i n_i^k \quad (4)$$

$$P = \sum_{k=1}^K \sum_{i=0}^{M_p} N_i p_i^k \quad (5)$$

where N_i is the volume density of the i -th state, M_n is the number of the conduction band states and M_p is the number of the valence band states and K is the number of QD layers.

The photon rate equation including gain compression is given by

$$\frac{\partial S}{\partial z} = \frac{g_{QD} S}{1 + \epsilon S} - \alpha S \quad (6)$$

where α is the waveguide loss and g_{QD} is the modal gain of the device which is given by

$$g_{QD} = \sum_{k=1}^K \sum_{i=0}^M g_i (n_i^k + p_i^k - 1) \quad (7)$$

where M is the number of transitions. Gain dispersion effect is taken into account where

$$g_i = g_i^{\max} \frac{\hbar \omega_i^{\max}}{\hbar \omega} \text{Exp} \left(\frac{-(\hbar \omega - \hbar \omega_i^{\max})^2}{2\sigma_i^2} \right) \quad (8)$$

σ_i is the inhomogeneous line broadening, g_i^{\max} is the gain coefficient for the i -th transition, $\hbar \omega$ is the photon energy of the incident signal and $\hbar \omega_i^{\max}$ is the energy corresponding to the gain peak of the i -th transition.

The waveguide loss as a function of doping concentration and number of QD layers is given by

$$\alpha = \alpha_0 + K\alpha_s + \alpha_A P \quad (9)$$

where α_0 is the waveguide loss for un-doped active region and α_A is the loss parameters associated with p-type doping.

III. RESULTS AND DISCUSSIONS

In the following analysis we will present detailed analysis of the effect of doping and the number of QD layers on the saturated optical gain of semiconductor optical amplifier. Also we will show that doping the QDs will change the proper number of QD layers required for obtaining certain optical gain. The parameters of the investigated amplifier are [8], [11]: $c_{21}^n = 13$, $c_{10}^n = 53$, $N_Q = 2.5 \times 10^{17} \text{ cm}^{-3}$, $v_g = 8.45 \times 10^9 \text{ cm/s}$, $\alpha_0 = 2.5 \text{ cm}^{-1}$, $\alpha_s = 0.5 \text{ cm}^{-1}$, $\alpha_A = 10^{-18} \text{ cm}^2$, $\tau_{0R} = \tau_{1R} = \tau_{wR} = 0.2 \text{ ns}$, $\tau_{10} = 8 \text{ ps}$, $\tau_{21} = 2 \text{ ps}$. The length of the amplifier is $L = 3 \text{ mm}$. The gain coefficients for single QD layer are $g_0^{\text{max}} = 6 \text{ cm}^{-1}$ and $g_1^{\text{max}} = 12 \text{ cm}^{-1}$. The inhomogeneous line broadening is $\sigma_i = 34 \text{ meV}$ and ε is 10^{-17} cm^{-3} . Typical barrier thickness, which is chosen to enhance the coupling between the QD layers and to increase the modal gain, is $\sim 15 \text{ nm}$ where $\tau_d^n = 0.8 \text{ ps}$ and $\tau_{it}^n = 0.2 \text{ ps}$. For the following analysis, we presume that the input photon energy is equal to either the ground state (GS) transition energy or the first excited state (ES) transition energy. The input density for the following analysis is fixed at $0.1 \times S_R$ where S_R is the normalization density given by $S_R = N_Q \times (v_g g_0 \tau_{0R})^{-1}$. At this input density the SOA is fairly saturated.

The saturated optical gain of undoped QD-SOA is studied for different number of QD layers. The saturated optical gain as a function of applied current at the GS energy is shown in Fig. 1 for different number of QD layers. At low applied current, it is observed that few number of QD layers provide higher saturated optical gain due to lower transparency current originated from lower layer loss. On the other hand, at high applied current we find that large number of QD layers can provide higher saturated optical gain. It should be noted that the increase in the optical gain at high applied current is approximately small for $K > 6$ and negligible for $K \geq 8$.

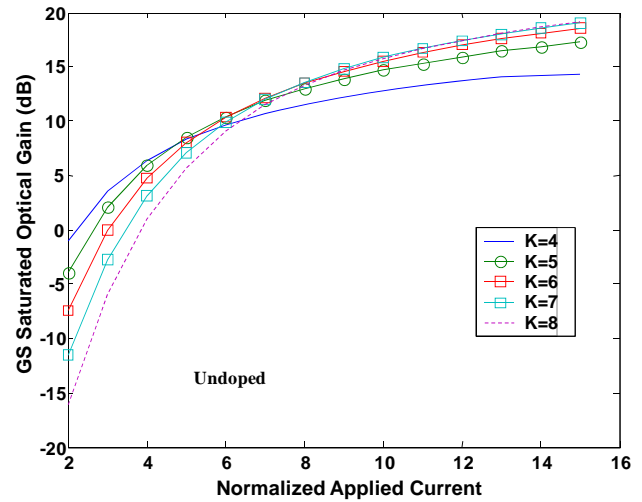


Fig. 1 Saturated optical gain of GS as a function of applied current for different number of undoped QD layers.

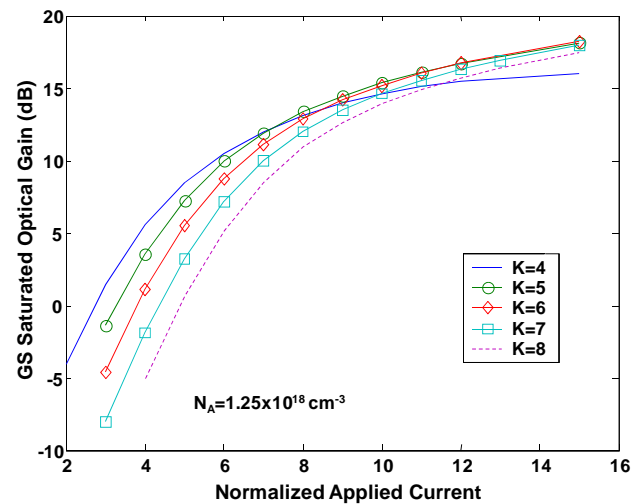


Fig. 2 Saturated optical gain of GS as a function of applied current for different number of P-type doped QD layers

The saturated optical gain of p-type QD-SOA ($N_A = 1.25 \times 10^{18} \text{ cm}^{-3}$) is also studied for different number of QD layers. The saturated optical gain as a function of applied current at the GS energy is shown in Fig. 2 for different number of QD layers. We find that at low applied current few number of QD layers provide higher saturated optical gain which is similar to the characteristics in Fig. 1. While at high applied current, we find that when the number of QD layers is more than $K \geq 7$, the saturated optical gain starts to reduce. This indicates that we may need to optimize both the layer number and the doping concentration to get high saturated optical gain.

Since most applications required large optical amplifications with relatively small applied current, let us focus on the optical gain at $J_A = 10$ and study the optical gain for different doping concentration and different number of QD layers. Since we find that there is a difference between the behavior of the saturated optical gain and unsaturated optical

gain of multiple layer QD-SOA, let us first study the effect of doping on the unsaturated optical gain. The unsaturated optical gain at the GS energy is calculated at $J_A=10$ for different number of QD layers and doping concentration as shown in Fig. 3. As obvious, increasing K increases the unsaturated optical gain where the increase in the unsaturated optical gain for $K \geq 8$ is relatively small. Also, we find that doping the dots with p-type concentration enhances the unsaturated optical gain where the highest unsaturated optical gain for $K=4$ and $K=8$ is obtained at $N_A=10^{18} \text{ cm}^{-3}$ and $N_A=0.5 \times 10^{18} \text{ cm}^{-3}$ respectively. The analysis is repeated for saturated optical gain for input density equal to $0.1 \times S_R$ as shown in Fig. 4. As obvious, for $K \leq 4$ the peak in the saturated optical gain is approximately located at $N_A=10^{18} \text{ cm}^{-3}$ which is the same as the unsaturated characteristics. However, for $K=8$, we find that the peak in the saturated optical gain is obtained when the QD-SOA is undoped. The saturated optical gain at the GS energy is calculated at $J_A=10$ as a function of K for different doping concentration as shown in Fig. 5. It is clear that for $K \leq 4$, the doping concentration that maximizes the saturated optical gain is $N_A=10^{18} \text{ cm}^{-3}$. While for five and six QD layers, the doping concentration that maximizes the saturated optical gain is $N_A=5 \times 10^{17} \text{ cm}^{-3}$. For seven QD layers, the doping concentration that maximizes the saturated gain is $N_A=2.5 \times 10^{17} \text{ cm}^{-3}$ and for $K=8$ undoped QD layers provides the highest saturated optical gain. Similar data is obtained for input density equal to $0.2 \times S_R$.

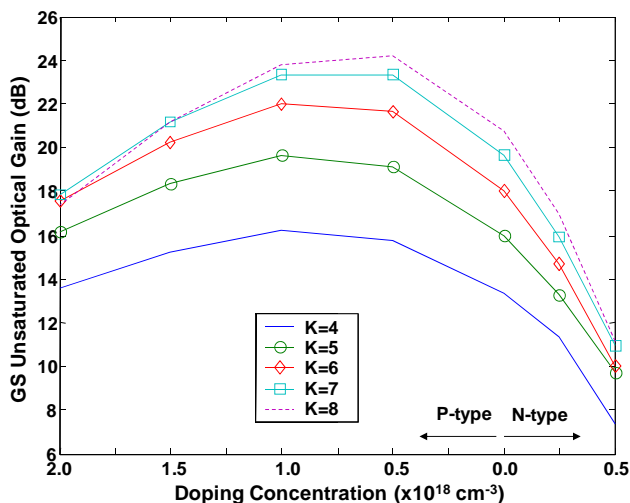


Fig. 3 Unsaturated optical gain of GS at $J_A=10$ as a function of doping concentration for different number of QD layers.

The analysis is repeated for different input photon energy where strong dependence on the photon energy is observed. The unsaturated optical gain at the ES energy is calculated at $J_A=10$ as a function of doping concentration for different K as shown in Fig. 6. As evident, when the input energy is equal

to the excited state transition energy, the doping concentration that maximizes the saturated optical gain is found to be stronger function of K. As apparent for $K=4$, the doping concentration that maximizes the unsaturated optical gain is $N_A=10^{18} \text{ cm}^{-3}$ while for $K=6, 7$ and 8 we find that undoped QD layers maximizes the unsaturated optical gain. The saturated optical gain at the ES energy is calculated at $J_A=10$ and at input density equal to $0.1 \times S_R$ as shown in Fig. 7. As evident when the number of QD layers is small ($K < 4$), we find that it is required to dope the dots with p-type concentration to enhance the saturated optical gain. While when the number of QD layers is large (for example $K=8$), we find that it is required to dope the dots with n-type concentration. We attribute this behavior to the fact that the transparency current for the excited state is larger than the ground state and the injection rate for $J_A=10$ is small especially when the number of QD layers is large.

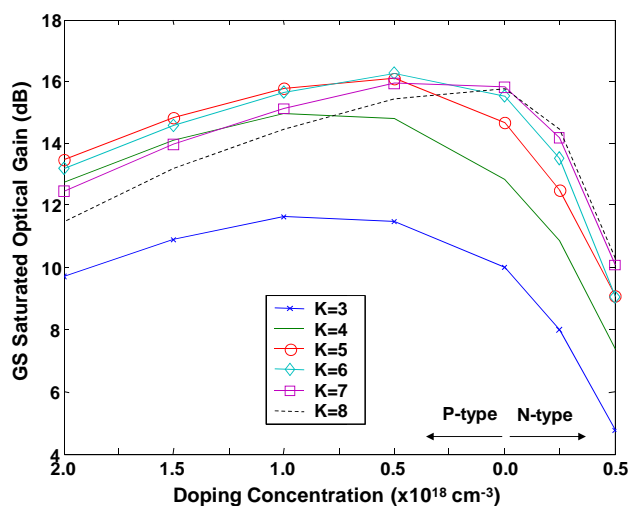


Fig. 4 Saturated optical gain of GS at $J_A=10$ as a function of doping concentration for different number of QD layers.

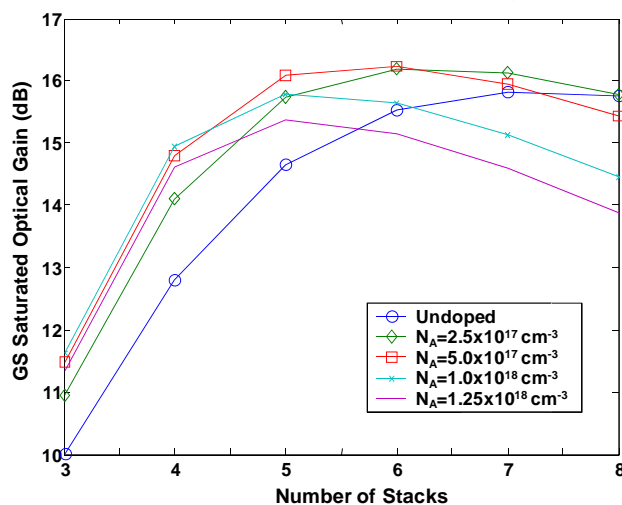


Fig. 5 Saturated optical gain of GS at $J_A=10$ as a function of number of QD layers for different doping concentration

IV. CONCLUSION

We have studied the effect of the number of QD layers on the saturated gain of doped quantum-dot semiconductor optical amplifiers using multi-population coupled rate equations. The analysis takes into account the effect of carrier coupling between adjacent layers and the effect of doping in the QD active region. We find that increasing the number of QD layers non-linearly increases the unsaturated optical gain where we find that very large number of QD layers does not markedly enhance the unsaturated optical gain. Our analysis shows that doping the dots with p-type concentration enhances the GS unsaturated optical gain where the peak of the unsaturated optical gain for $K < 8$ is obtained when $N_A \approx 0.75 \times 10^{18} \text{ cm}^{-3}$. For saturated SOA, we find that the doping concentration that maximizes the GS saturated optical gain is $N_A = 10^{18} \text{ cm}^{-3}$ for $K \leq 4$, $N_A = 5 \times 10^{17} \text{ cm}^{-3}$ for $5 \leq K \leq 6$, $N_A = 2.5 \times 10^{17} \text{ cm}^{-3}$ for $K=7$ and $N_A = 0 \text{ cm}^{-3}$ (i.e., undoped) for $K=8$. We find that when the input energy is equal to the excited state transition energy, the doping concentration that maximizes the saturated optical gain is strong function of K . Our analysis shows that the peak of the ES saturated optical gain is obtained when the dots are doped with $N_A \sim 5 \times 10^{17} \text{ cm}^{-3}$ p-type concentration for $K \leq 2$, $N_A \sim 2.5 \times 10^{17} \text{ cm}^{-3}$ p-type concentration for $K \leq 2$, $N_A \sim 0 \text{ cm}^{-3}$ (i.e., undoped) for $K=4$ and $N_D \sim 2.5 \times 10^{17} \text{ cm}^{-3}$ n-type concentration for $5 \leq K \leq 8$. Our analysis is very important to obtain the proper number of QD layers and proper doping concentration for high gain applications.

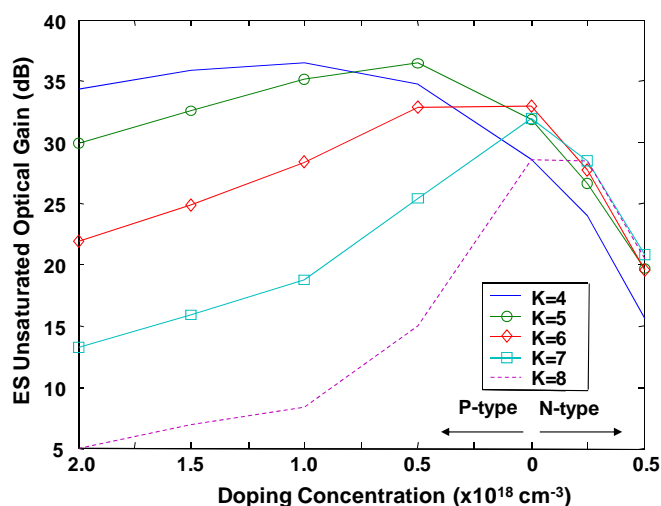


Fig. 6 Unsaturated optical gain of ES at $J_A = 10$ as a function of doping concentration for different number of QD layers

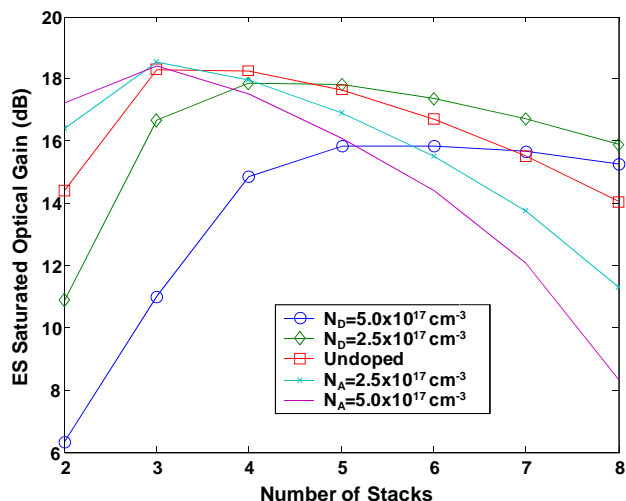


Fig. 7 Saturated optical gain of ES at $J_A = 10$ as a function of number of QD layers for different doping concentration

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