

Theory and Simulation of Ultrafast Carrier Dynamics and Nonlinear Pulse Propagation in Quantum Dot Semiconductor Amplifiers

Simulations on the coupling between light-field
and carrier-dynamics in Quantum Dot Amplifiers
based on a **Maxwell-Bloch** description

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OUTLINE

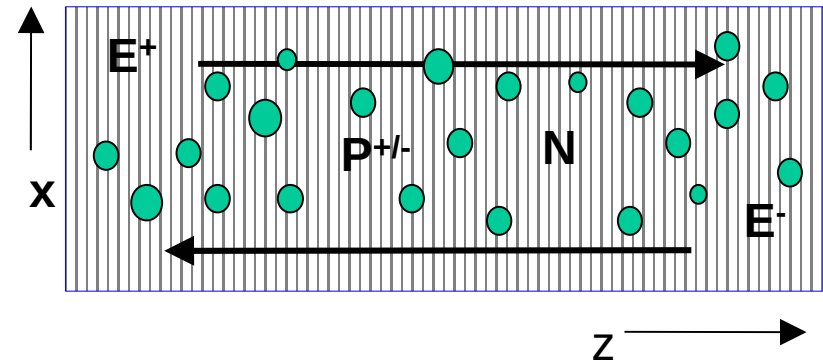
- **Theoretical Description: QD-Maxwell-Bloch equations**
- **Dots-in-a-well Quantum Dot structure investigated**
- **Amplification of Ultrashort Pulses**
 - visualization of laser-internal pulse propagation
 - visualization of microscopic carrier dynamics
 - dynamics of gain and refractive index
- **Conclusion and Outlook**

Theoretical Description: Quantum Dot Maxwell-Bloch Equations

wave propagation and diffraction:

$$\left(\frac{\partial}{\partial t} \pm \frac{c}{n_{eff}} \frac{\partial}{\partial z} \right) E^{\pm} = \frac{i}{2\omega_{op}} \left(\frac{c}{n_{eff}} \right)^2 \Delta E^{\pm} + \frac{i\omega_{op}}{2} \left(\frac{c}{n_{eff}} \right)^2 \mu_0 \Gamma(x) P_{nl}^{\pm}$$

$$P_{nl}^{\pm} = \frac{1}{V} \sum_{i,j} p^{\pm}(j, i)$$



polarization dynamics and dephasing:

$$\frac{\partial}{\partial t} p^{\pm}(j, i) = -[i\tilde{\omega}_{j,i} + \gamma_p] p^{\pm}(j, i) + \frac{i}{2\hbar} \mu_{i,j}^* \mu_{i,j} [1 - n_e(i) - n_h(j)] E^{\pm}$$

frequency
offset

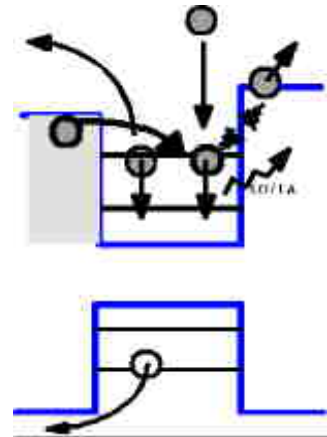
gain term

Theoretical Description: Quantum Dot Maxwell-Bloch Equations

Level population dynamics electrons:

$$\frac{\partial}{\partial t} n_e(i) = \frac{i}{2\hbar} \sum_j \{ p^{+\star}(j,i) E^+ - p^+(j,i) E^{+\star} + p^{-\star}(j,i) E^- - p^-(j,i) E^{-\star} - \Gamma_{sp} n_h(j) n_e(i) \}$$

$$- \frac{\partial}{\partial t} n_e(i)|_{QD}^{c-ph} - \frac{\partial}{\partial t} n_e(i)|_{QD-WL}^{c-c}$$



Level population dynamics holes:

$$\frac{\partial}{\partial t} n_h(i) = \frac{i}{2\hbar} \sum_j \{ p^{+\star}(j,i) E^+ - p^+(j,i) E^{+\star} + p^{-\star}(j,i) E^- - p^-(j,i) E^{-\star} - \Gamma_{sp} n_h(j) n_e(i) \}$$

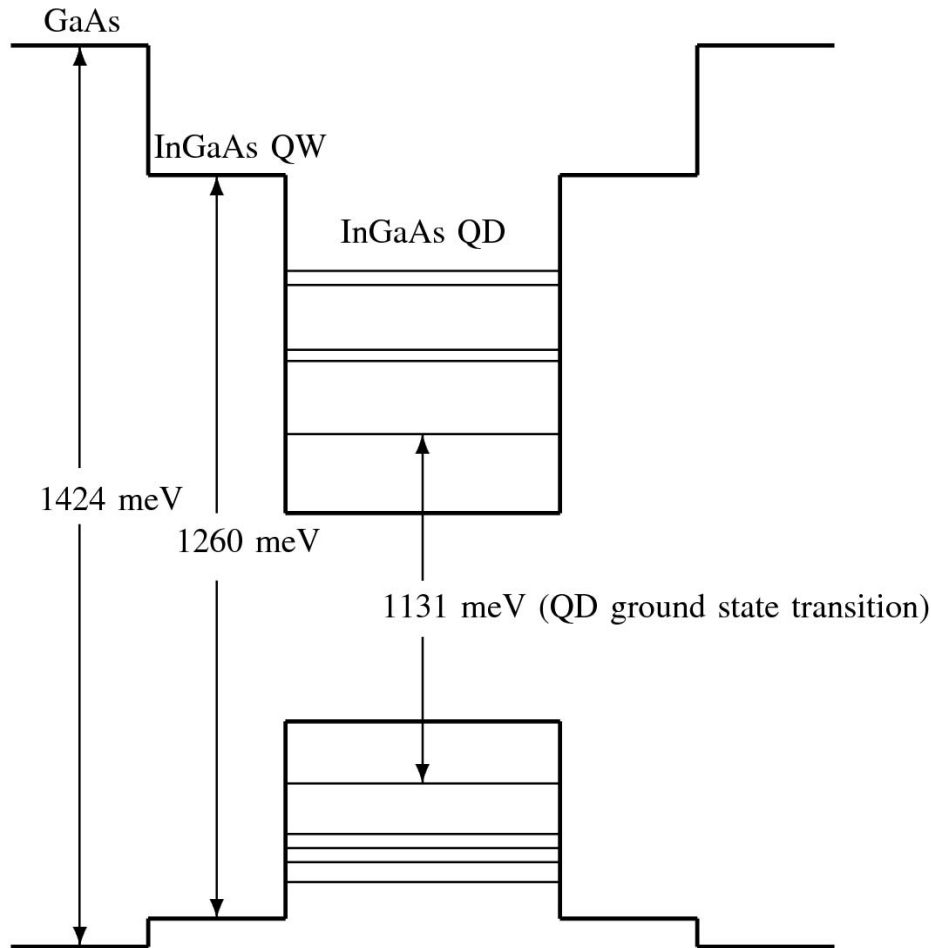
$$- \frac{\partial}{\partial t} n_h(i)|_{QD}^{c-ph} - \frac{\partial}{\partial t} n_h(i)|_{QD-WL}^{c-c}$$

Gain

Spontaneous emission

Carrier-phonon scat. Carrier-carrier scattering

Material Parameters of Investigated Quantum Dot Structure

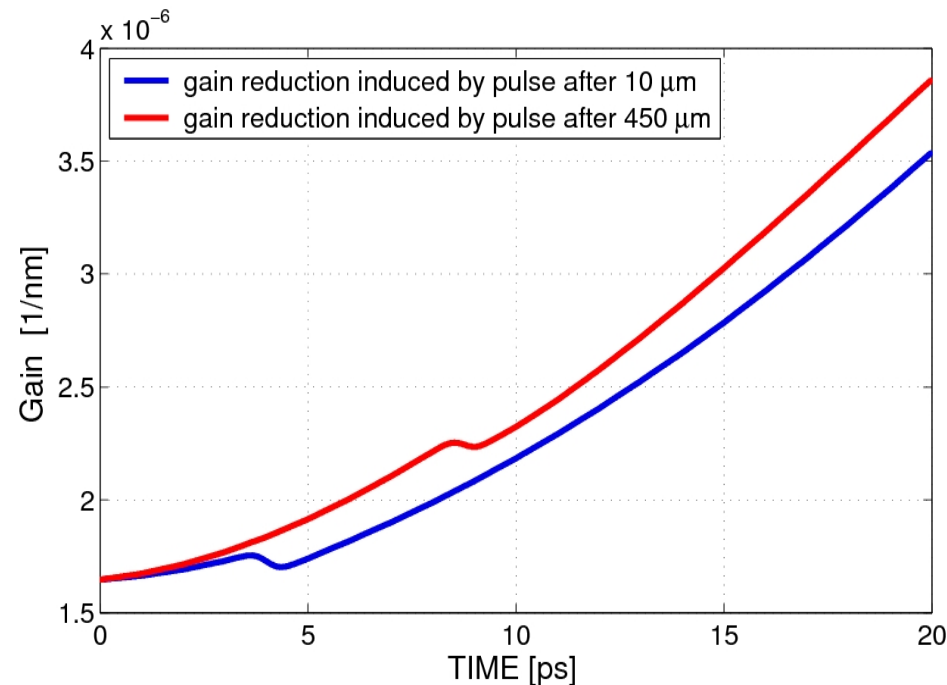
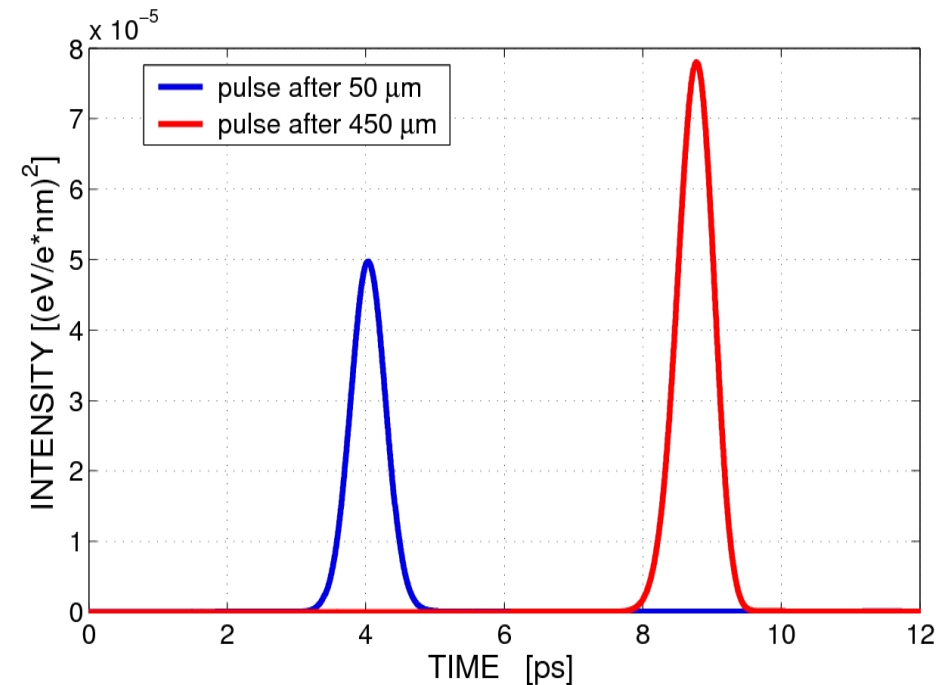


In_{0.65}Ga_{0.35}As QDs overgrown with a layer of **In_{0.2}Ga_{0.8}As** of ~5nm width.



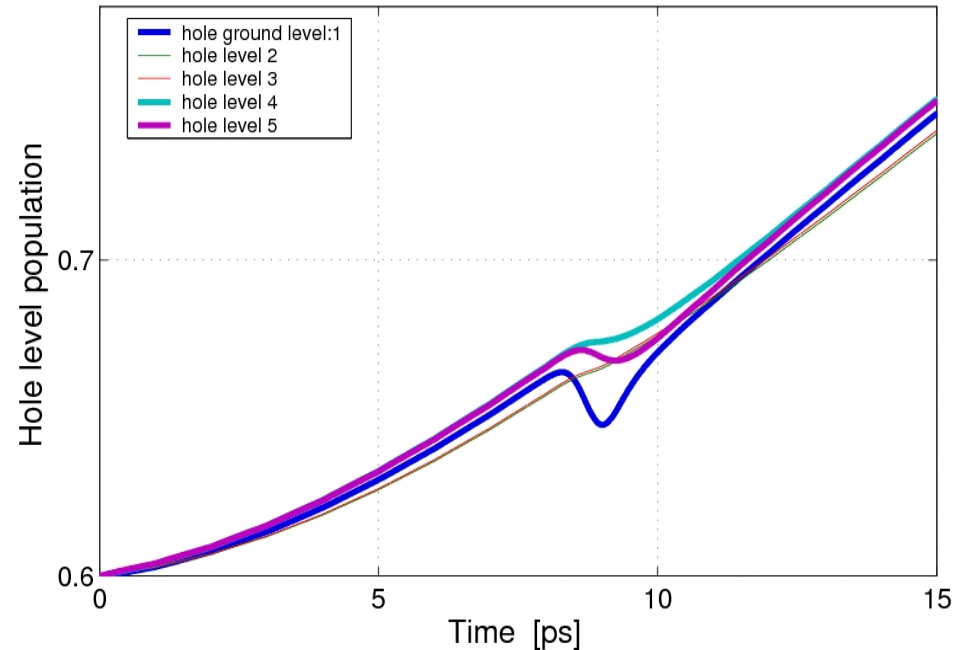
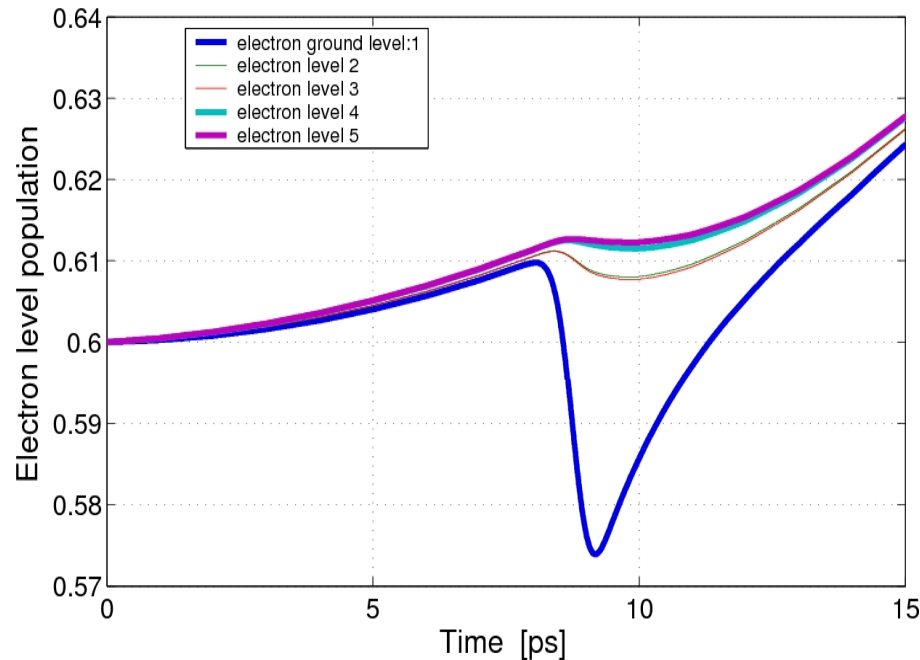
Material parameters provided by
Andrei Schliwa from TU Berlin

Pulse Propagation in QD-SOAs



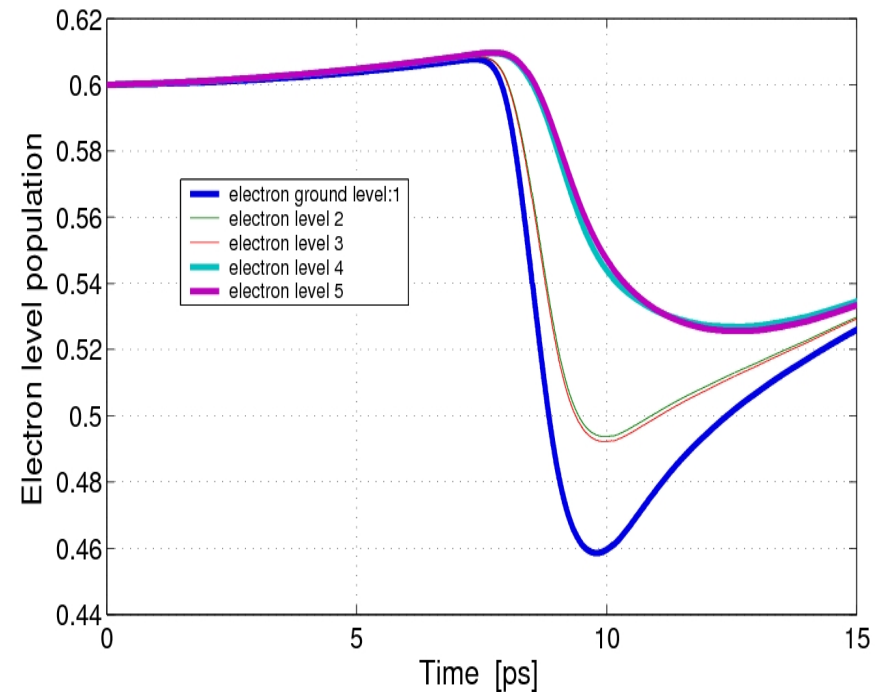
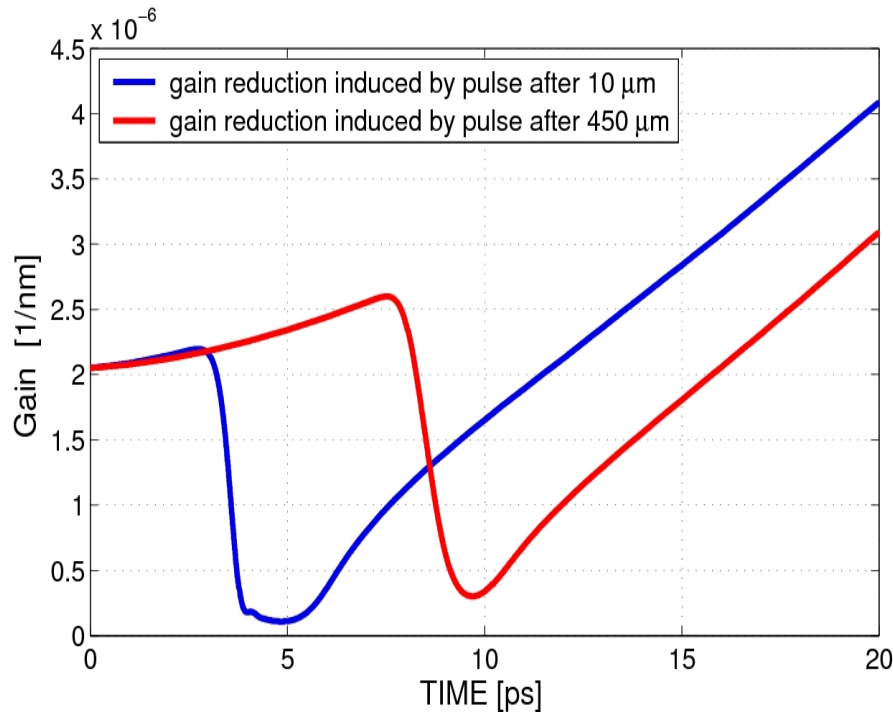
- **Amplification of a pulse during the propagation through the amplifier**
- **Duration of injected pulse: 0.5 ps**
- **Injected pulse intensity: 2 orders of magnitude below saturation power**
- **Local gain reduction caused by the incoming pulse**

Carrier Level Population Dynamics



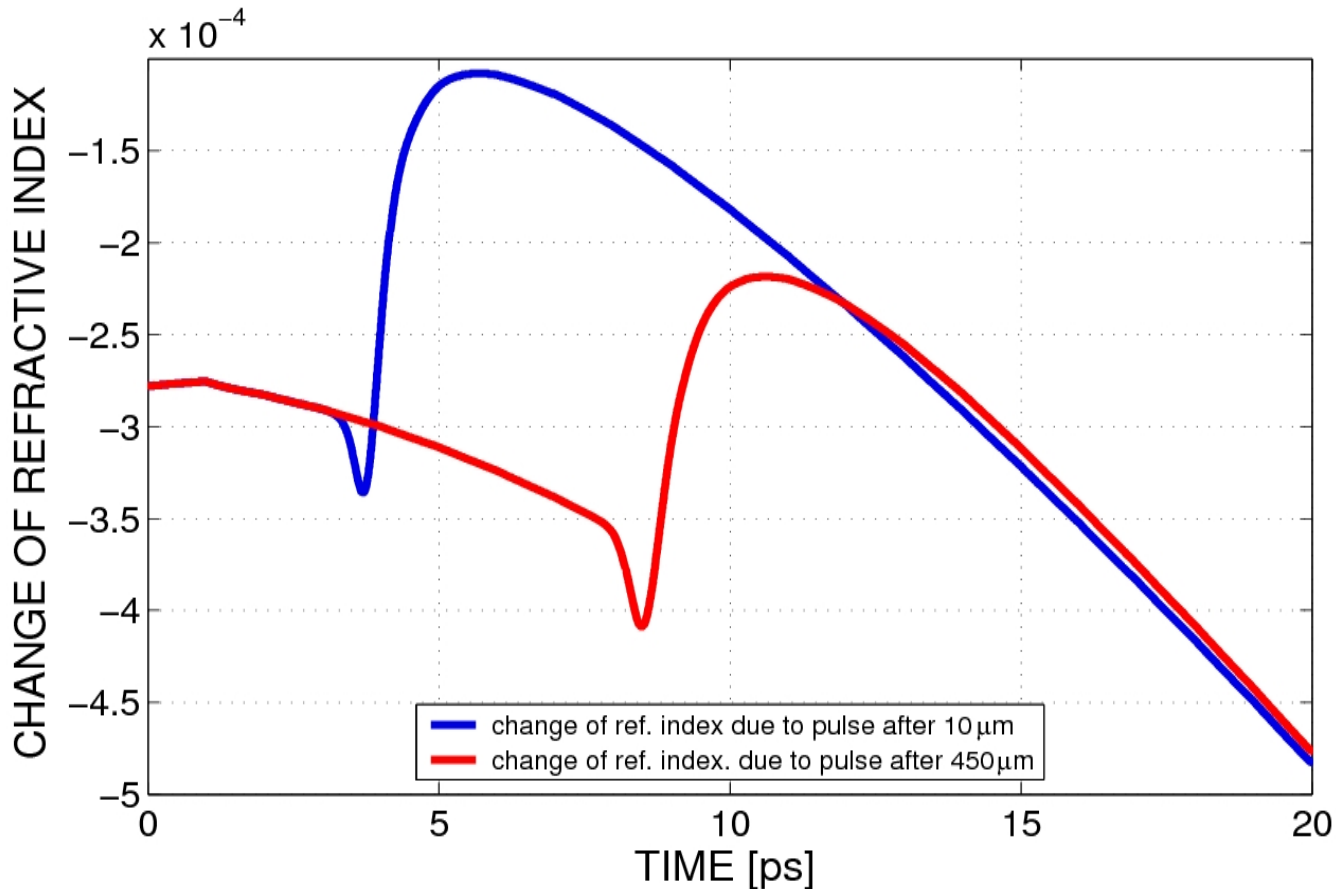
- Depletion of carriers in ground level due to incoming pulse
- Injected pulse duration 0.5ps, small signal regime
- Pulse energy offset with respect to ground level transition 20meV
- Fast repopulation of hole levels

Dynamics of Gain and Carrier Population



- Gain reduction due to incoming pulse
- Injected pulse duration 1ps, pulse intensity close to **saturation regime**
- Depletion of charge carriers in ground level below transparency

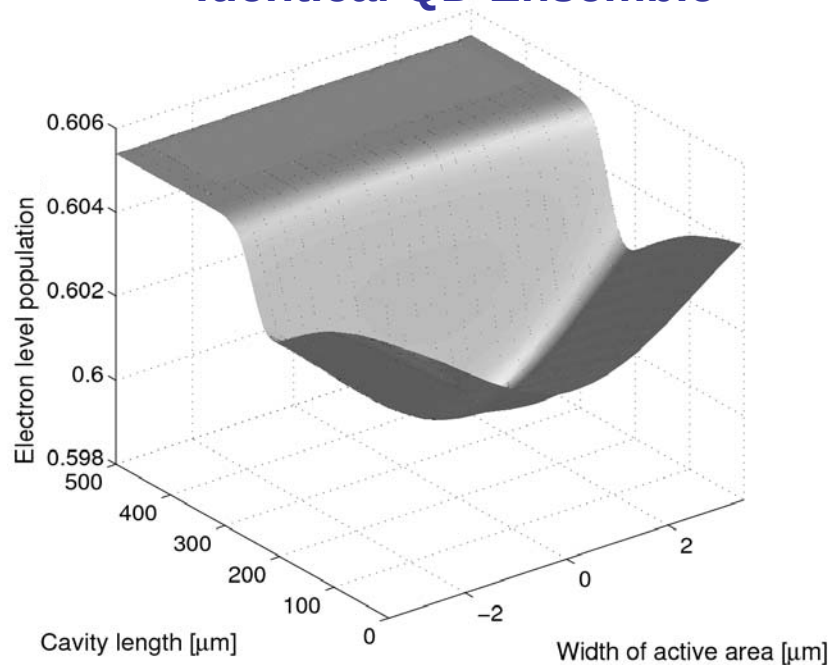
Dynamics of Carrier Induced Refractive Index



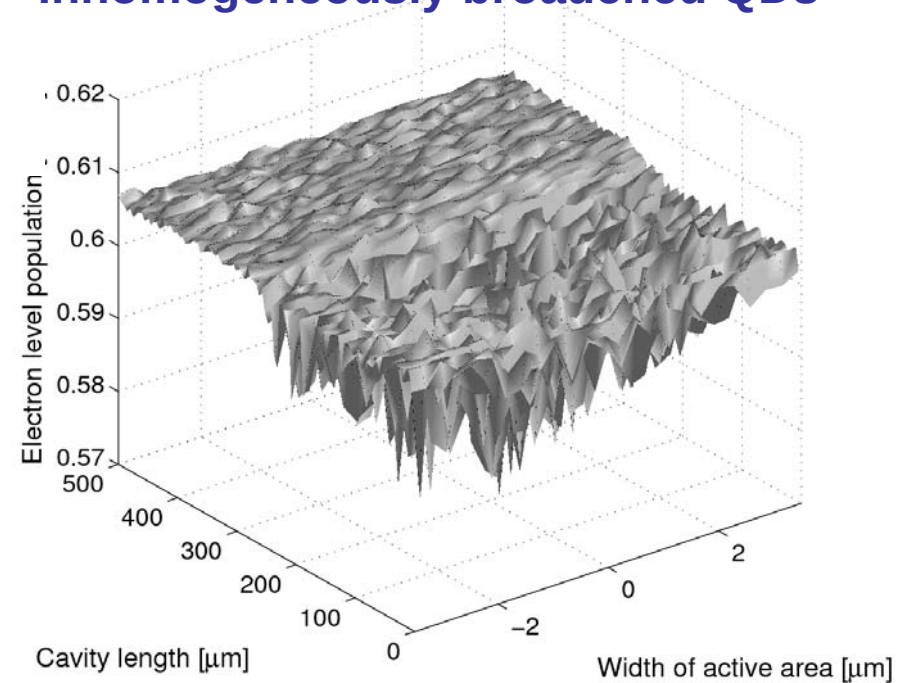
- Change of refractive index due to pulse induced change of carrier density
- Injected pulse duration 1ps, close to power saturation

Quantum Dot Electron Population

Identical QD Ensemble

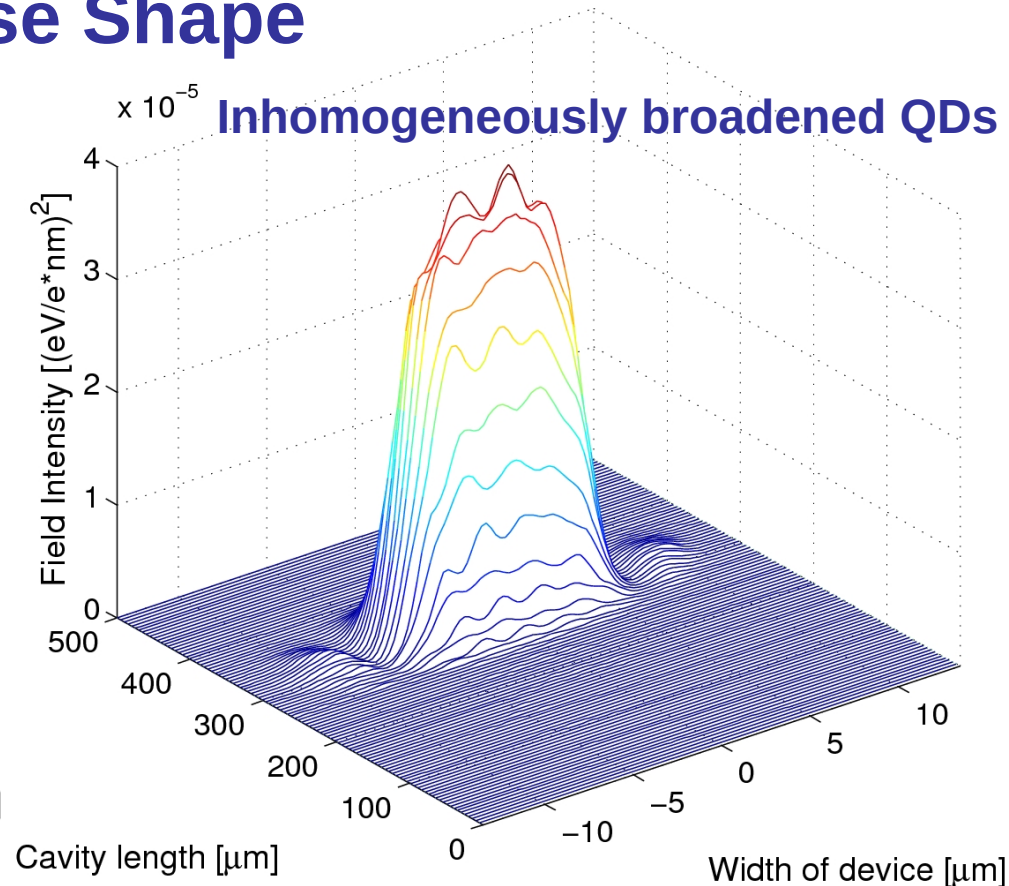
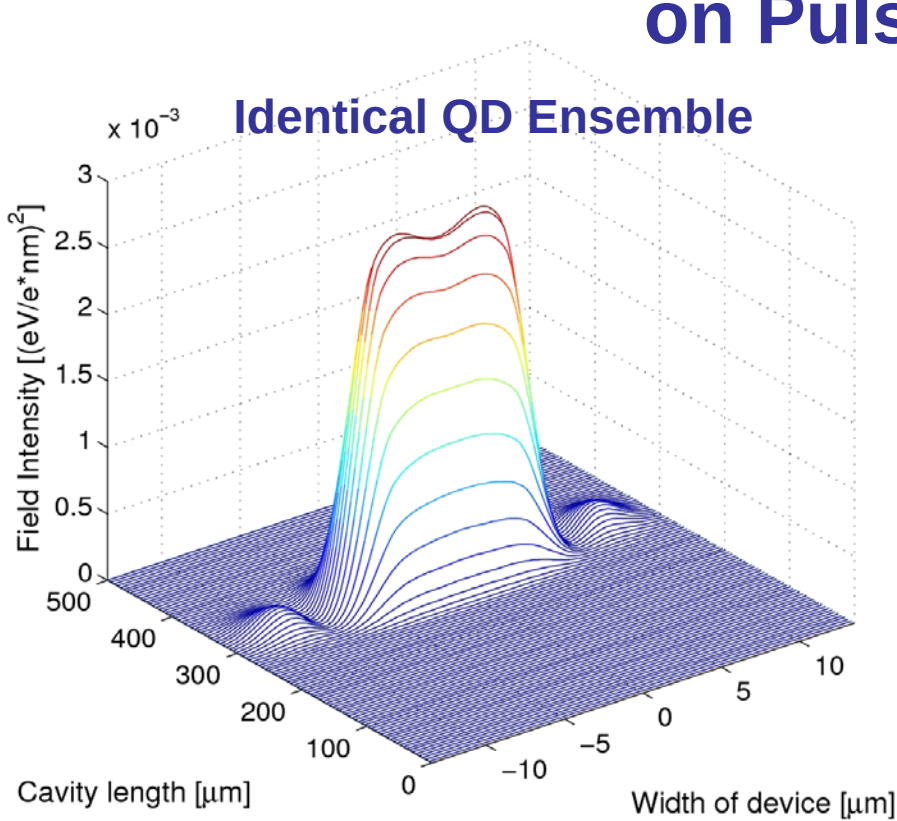


Inhomogeneously broadened QDs



- Inhomogeneous QD carrier density in active area of QD-SOA

Influence of Inhomogeneous Broadening on Pulse Shape



- **Deterioration of pulse shape due to inhomogeneous broadening**
- **Injected pulse duration 0.5ps, Pulse intensity close to power saturation**
- **Onset of transverse dynamics (cavity width $7\ \mu\text{m}$)**

Conclusion

Simulations on QD-SOAs based on **Maxwell-Bloch** equations showing:

- ❑ pulse propagation and amplification
- ❑ dynamics of gain and carrier induced refractive index
- ❑ dynamics of QD carrier population
- ❑ inclusion of inhomogeneous broadening using spatially dependent material properties
- ❑ pumping of QDs via scattering with quantum well carriers

Future investigations:

- ❑ Influence of various scattering processes
- ❑ Dependence on operating temperature and QD-SOA geometry