Space-dependent optical and electronic properties of semiconductor photonic-crystal structures

B. Pasenow, M. Reichelt, T. Stroucken,
T. Meier, P. Thomas, and S.W. Koch

Department of Physics and Material Sciences Center,
Philipps-University Marburg, Germany

Overview

- The Transverse part of the electromagnetic field is modified due to photonic environment (→ photonic bandgap, etc.)
- In the immediate vicinity of a photonic crystal the longitudinal part of the electromagnetic field leads to significant space-dependent modifications of the Coulomb-interaction
- Combining semiconductors and photonic crystals these modifications can be used to

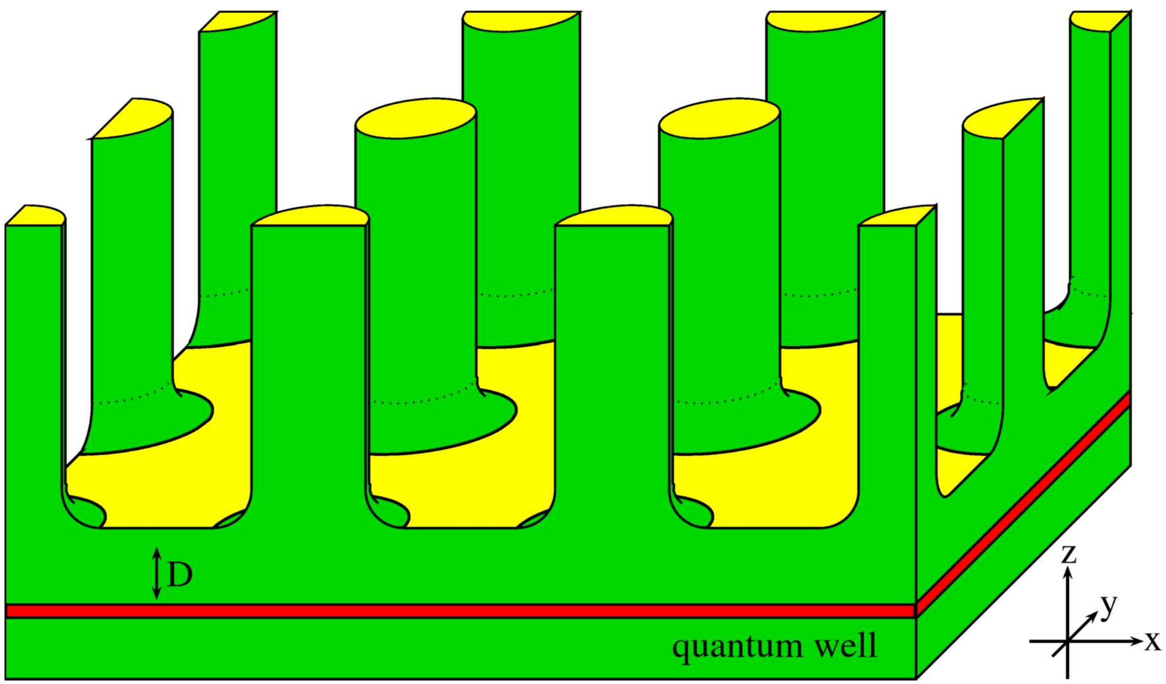
    # get additional bound excitonic states

    # localize electrons and holes at special points

    # modify the laser threshold (gain for lower densities)

Model system

- Microscopic theory for the semiconductor dynamics
- The transversal effects of the photonic crystal are neglected.
- Investigation of the longitudinal effects (Coulomb potential)
- For schematic studies the quantum well can be replaced by a quantum wire (1d inhomogeneous system).

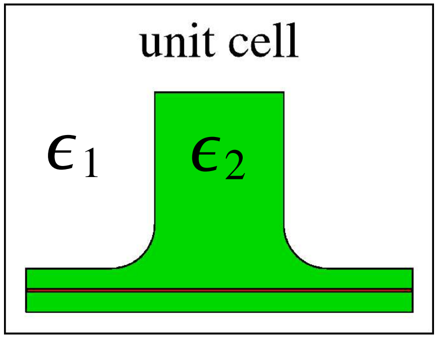


Coulomb modifications (1)

- Poisson's equation in inhomogeneous media:

$$-\nabla\cdot\left[\epsilon(r)\cdot\nabla V(\vec{r},\vec{s})\right]=4\pi\delta(\vec{r}-\vec{s})$$

with $$V(\vec{r},\vec{s})=V^{\text{bulk}}(\vec{r}-\vec{s})+\delta V(\vec{r},\vec{s})$$

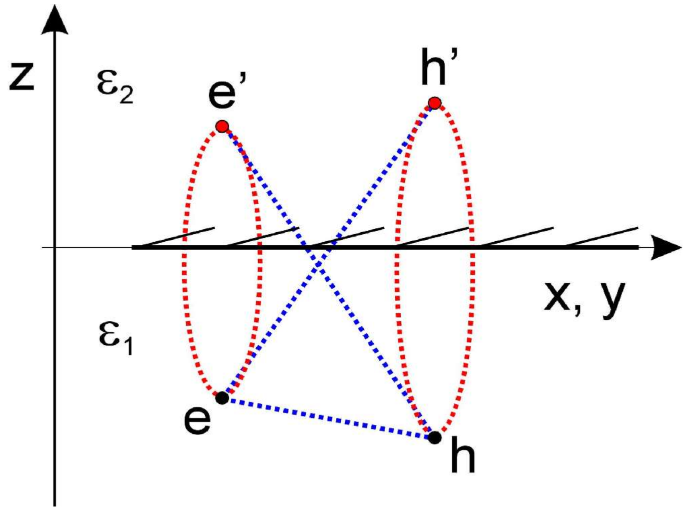


- Inhomogeneity leads to significant space-dependent Coulomb modifications due to surface polarizations in the photonic crystal.

- For a planar interface the effect can be explained by the image charge concept:

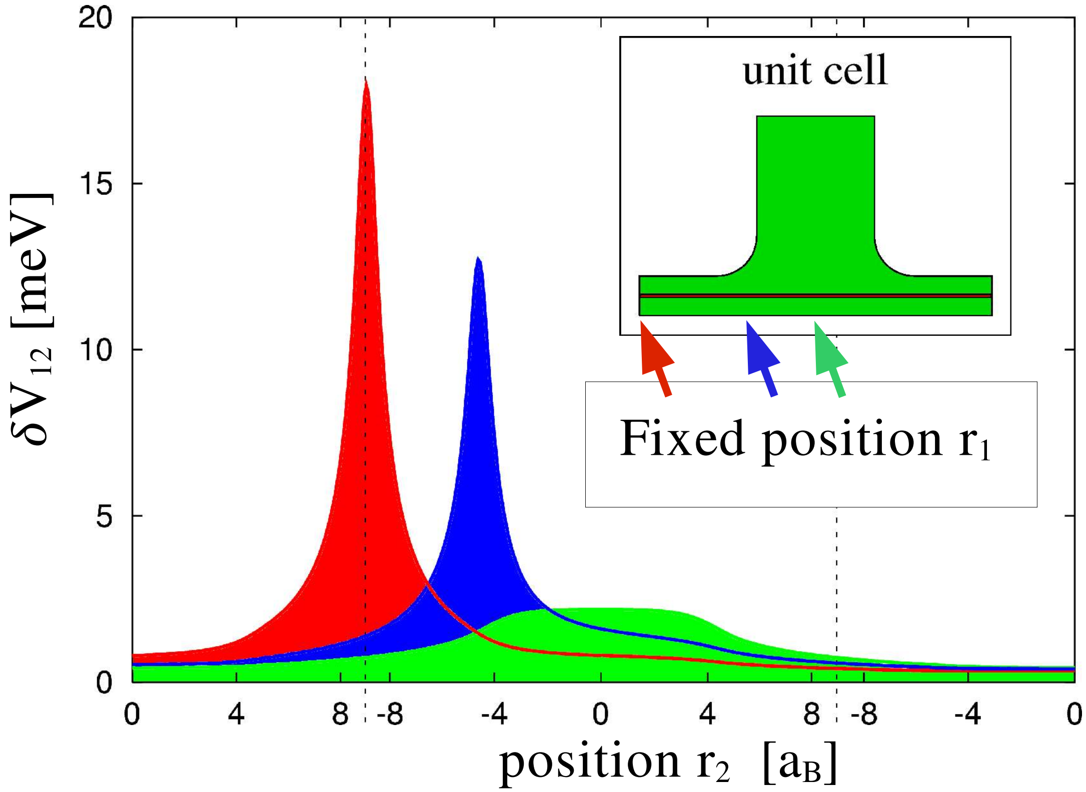
  # Mutual Coulomb interaction

  # Self interaction with respective self-image charge



Coulomb modifications (2)

- The Hamiltonian for the equations of motion of the polarization, electron and hole densities contains a kinetic part, the interaction with the E-field and the Coulomb interaction.
- The Coulomb part differs from homogeneous case in the space-dependent Coulomb modifications and the self interaction part.



Eigenvalue equation for P_{12}

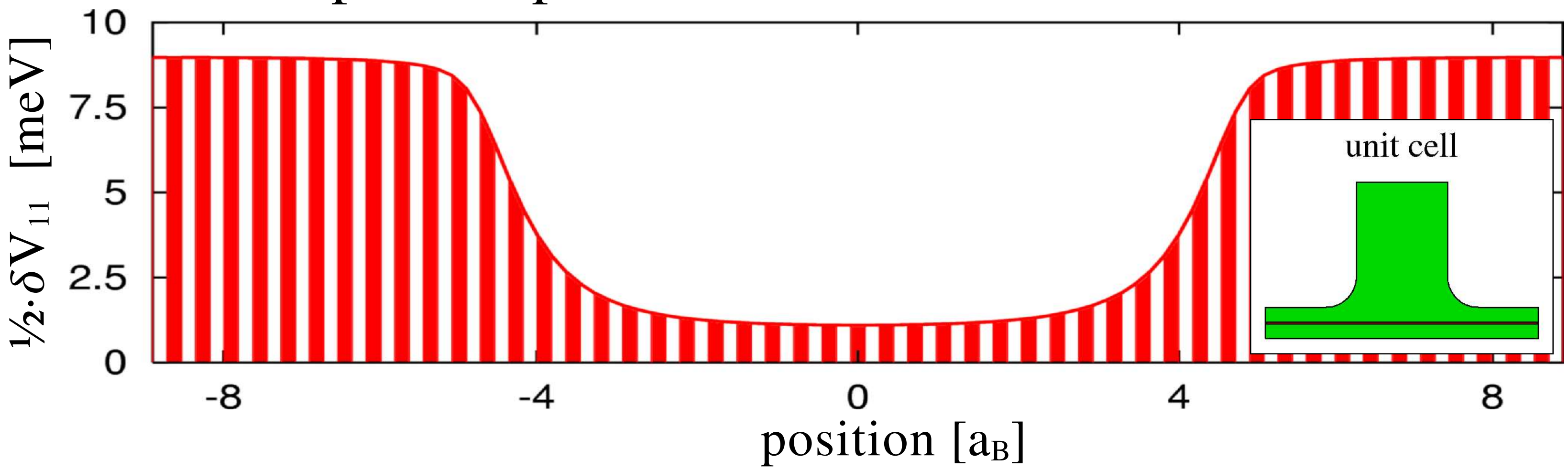
- Solving the linear polarization equation

$$E_\lambda P_{12}^\lambda = \left[E_G + E_{h,1}^{kin} + E_{e,2}^{kin} + \tfrac{1}{2} \cdot (\delta V_{11} + \delta V_{22}) - V_{12} \right] P_{12}^\lambda$$

one can compute

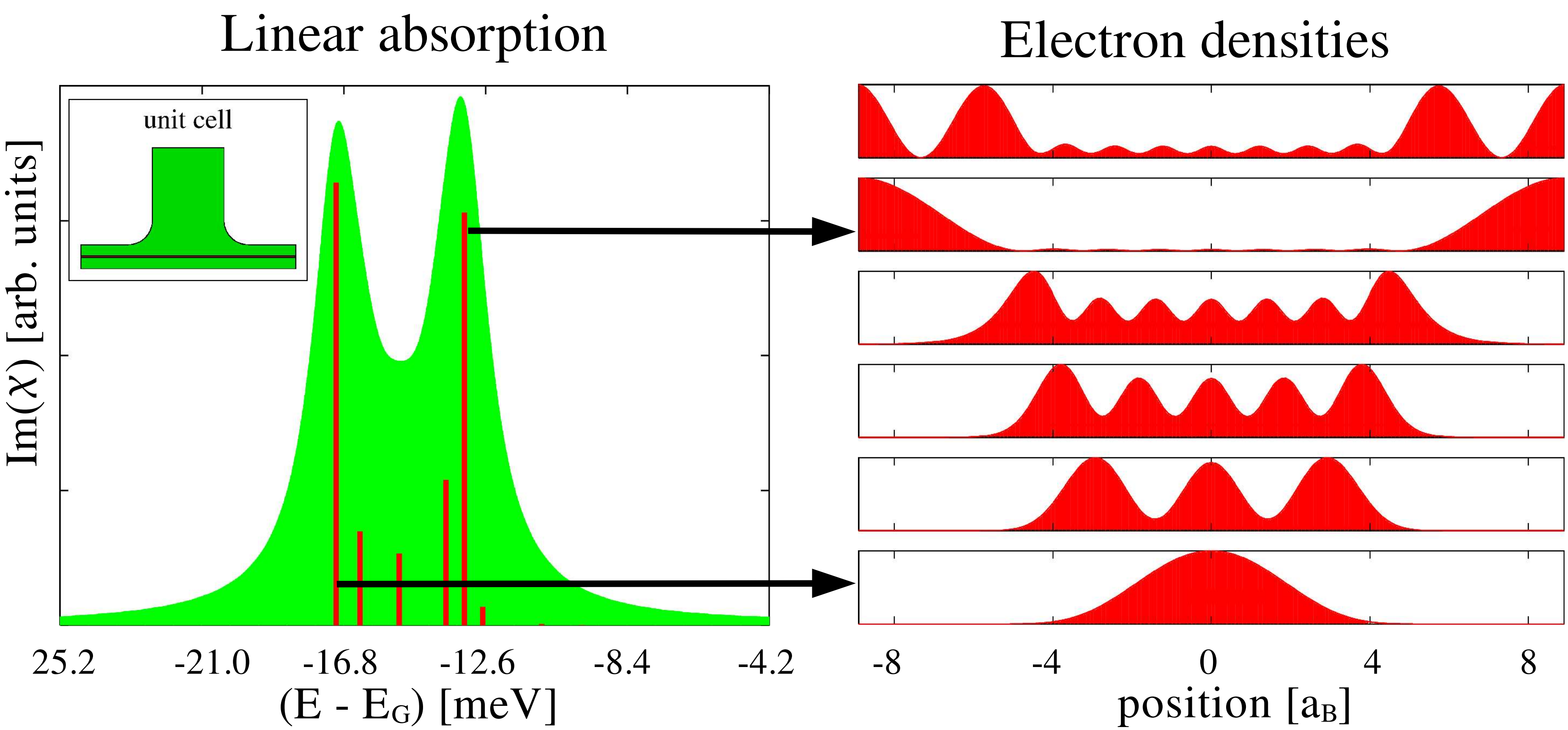
the eigenvalues, eigenfunctions and optical matrix elements.

- Periodic one particle potential:



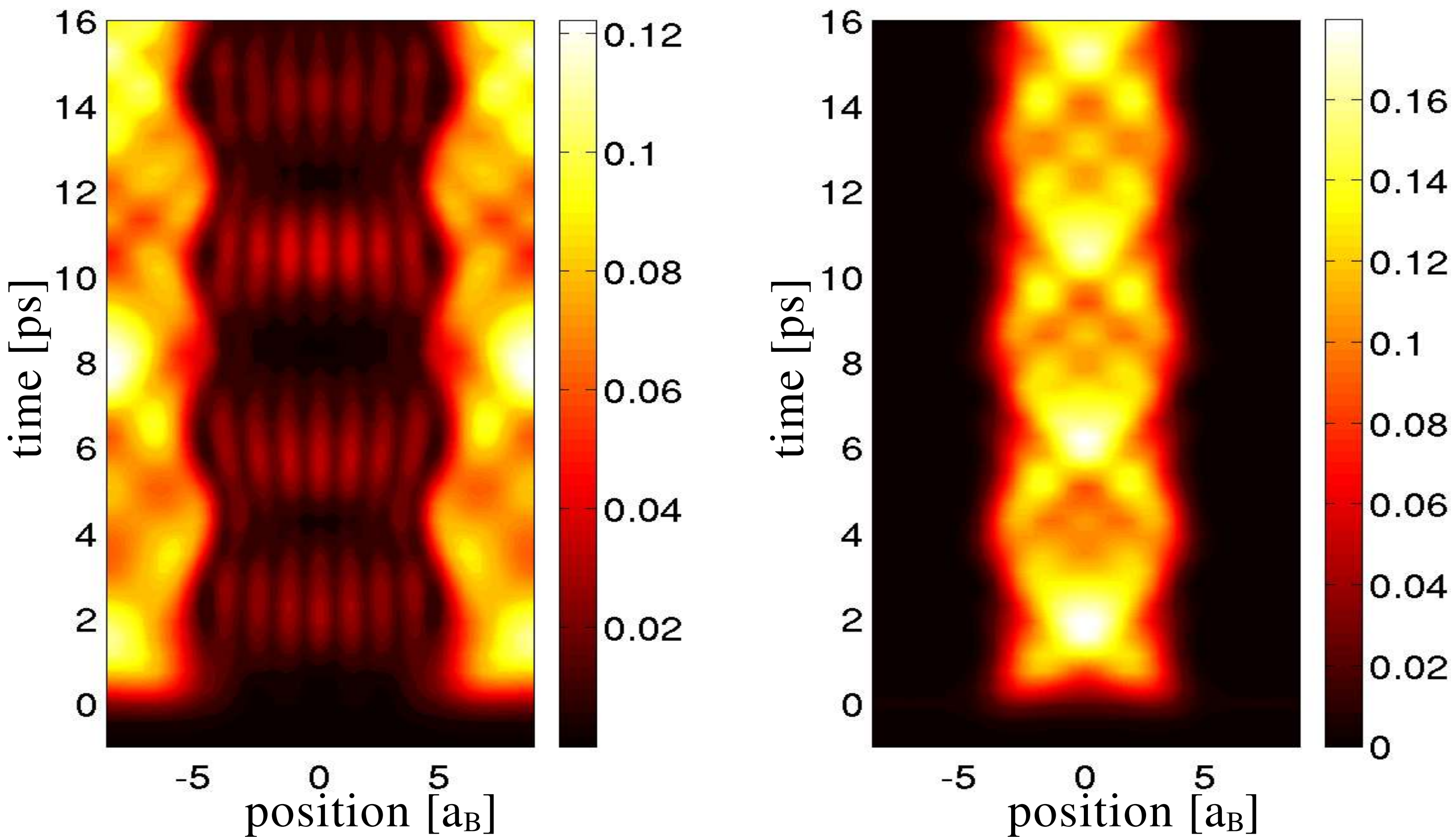
- Via χ^2-formalism (expansion in order of the E-field) particle densities can be calculated from the linear polarization.

Linear absorption and electron densities



- With Lorentzian broadening of the optical matrix elements linear absorption spectra can be calculated.
- Double peaked excitonic resonance because of regions similar to half space and homogeneous volume material.

Density dynamics (electrons)



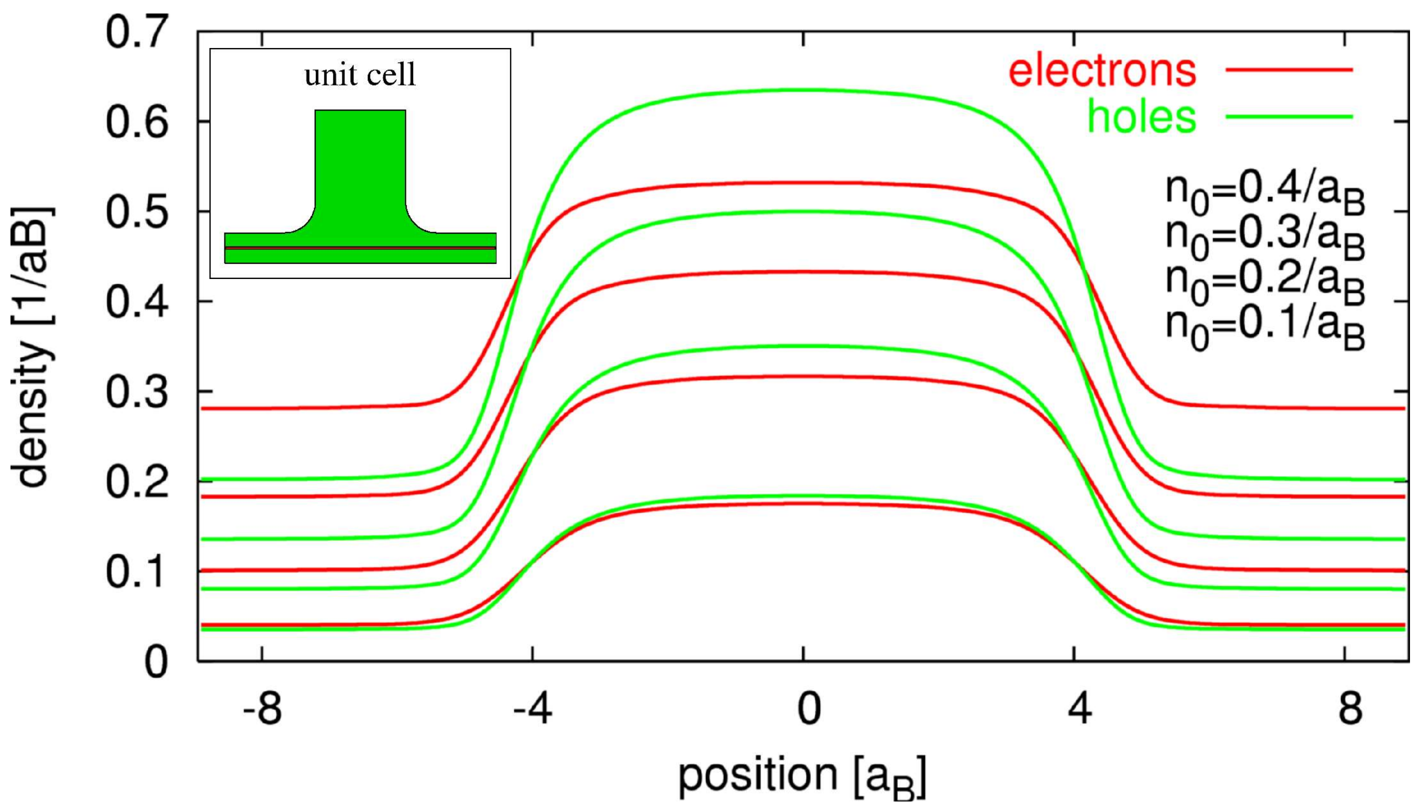
- The resonant excitation of special excitonic states creates the corresponding spatial density distributions.
- For later times: wave packet dynamics

Fermi-Dirac densities for electrons an holes

- One-particle Schrödinger equation in the periodic potential:

$$\left[E_{e,1}^{\mathrm{kin}} + ½ \cdot \delta V_{11} \right] \phi_{e,\lambda}(r_1) = E_{e,\lambda} \phi_{e,\lambda}(r_1)$$

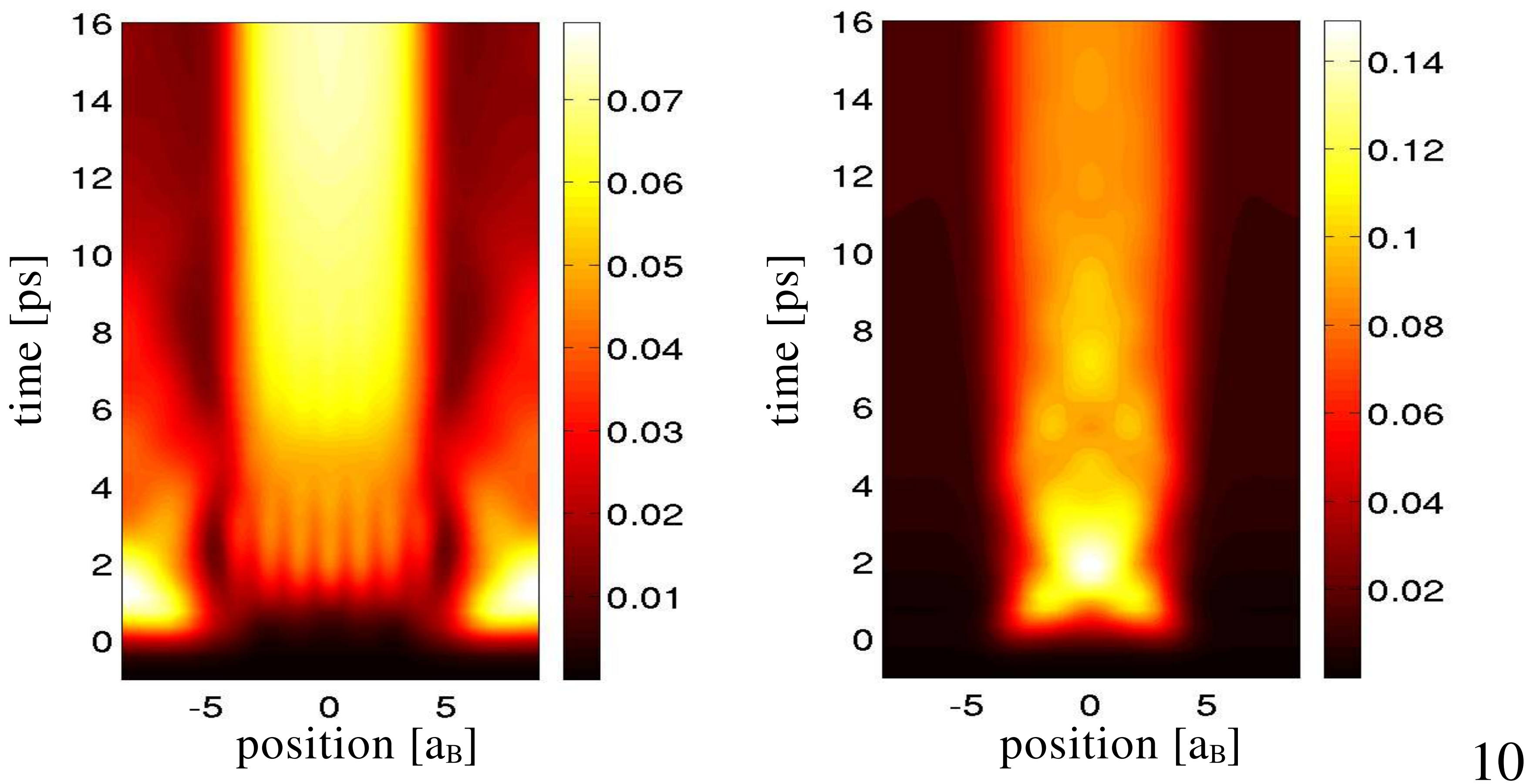
- Using a Fermi-Dirac distribution for the eigenenergies static real space (→ quasi-equilibrium) densities can be computed:



Linear Relaxation

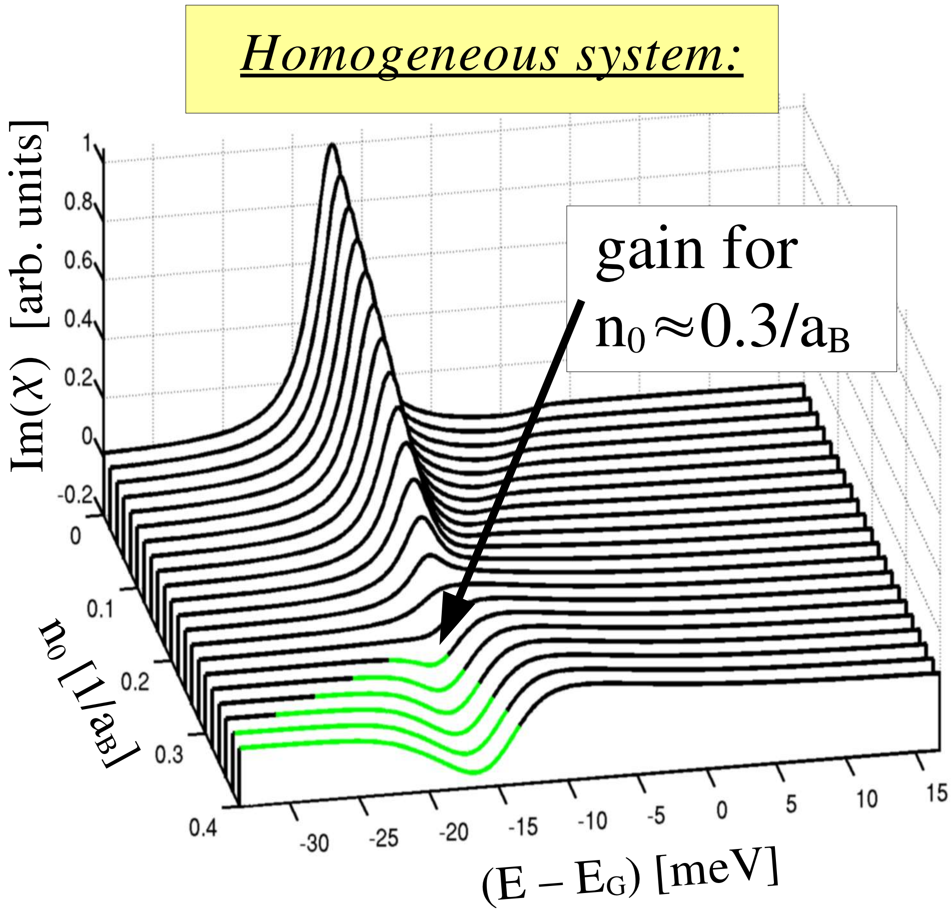
- Relaxation can be simulated through linear interpolation between the static Fermi-Dirac densities and the dynamic densities:

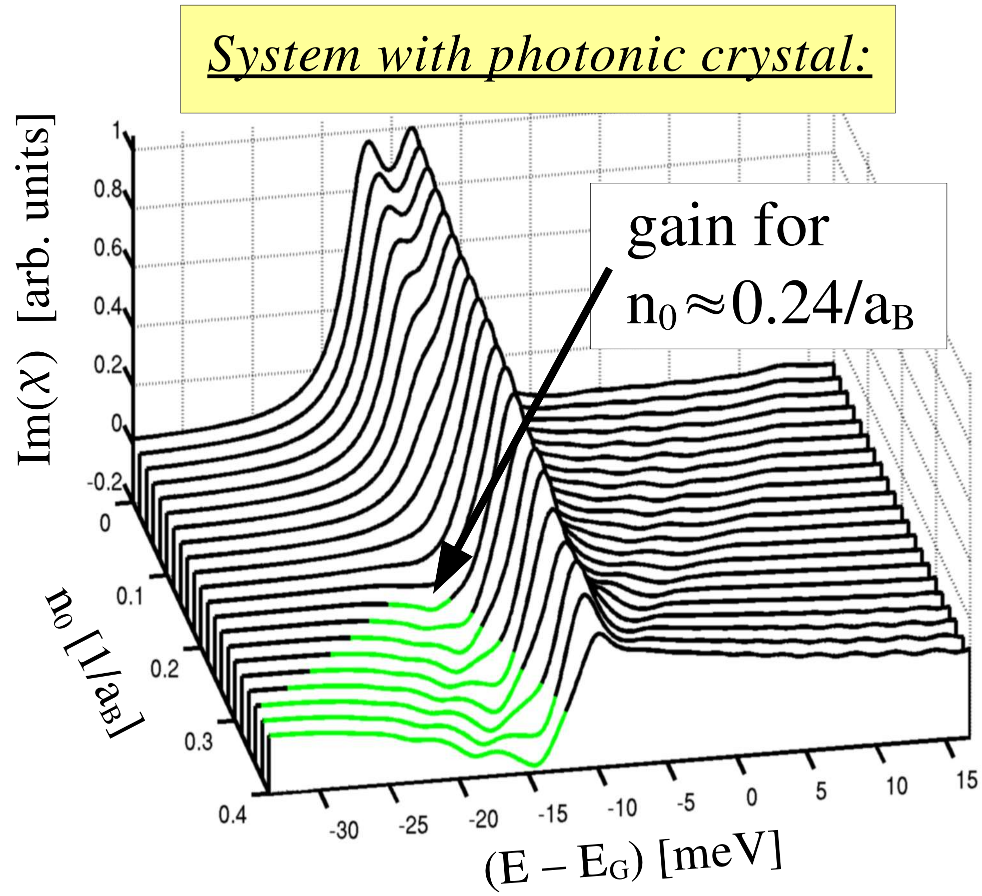
$$\frac{C_{12}(t)-C_{12}^{FD}}{T} \quad \text{and} \quad \frac{D_{12}(t)-D_{12}^{FD}}{T} \quad \text{with} \quad T \simeq 4\,ps$$



Quasi-equilibrium laser spectra

- Using static Fermi-Dirac densities laser spectra can be computed:





- The inhomogeneous arrangement of electrons and holes leads to laser gain for lower densities.

Summary

- The Coulomb interaction between charged particles in photonic crystals is space-dependent and follows the periodicity of the photonic environment.
- Surface polarization causes an image charge like self-interaction.
- This self-interaction potential leads to additional bound excitonic states and can be used to localize particles.
- The different excitonic wave functions can be excited by spectrally narrow laser pulses.
- The Coulomb modifications have influence on the laser threshold.

Publications

- T. Stroucken, R. Eichmann, L. Banyai, and S.W. Koch, **J. Opt. Soc. Am. B 19, 2292 (2002)**
- R. Eichmann, B. Pasenow, T. Meier, T. Stroucken, P. Thomas, and S.W. Koch, **Appl. Phys. Lett. 82, 355 (2003)**
- R. Eichmann, B. Pasenow, T. Meier, T. Stroucken, P. Thomas, and S.W. Koch, **phys. stat. sol.(b) 238, 439 (2003)**
- Semiconductor Optics in Photonic Crystal Structures, T. Meier and S.W. Koch, to appear in Photonic Crystals - Advances in Design, Fabrication and Characterization, Eds. K. Busch, S. Lölkes, R.B. Wehrspohn, and H. Föll, Wiley, 2004.