Semiconductor photonic-crystal structures: Optical spectra and carrier dynamics

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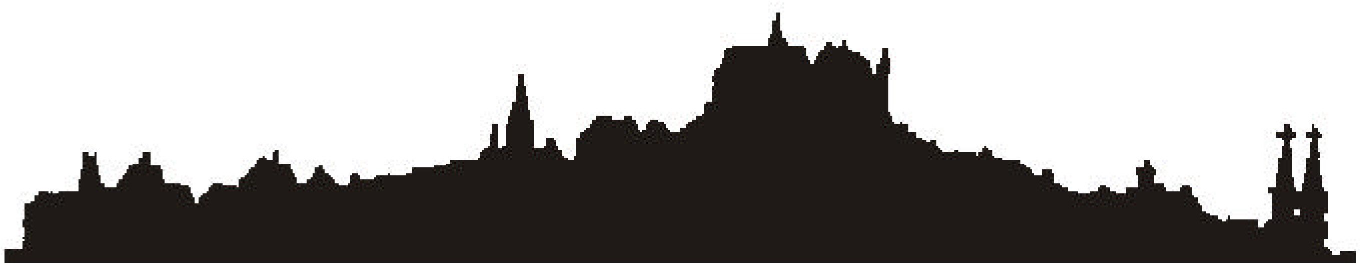
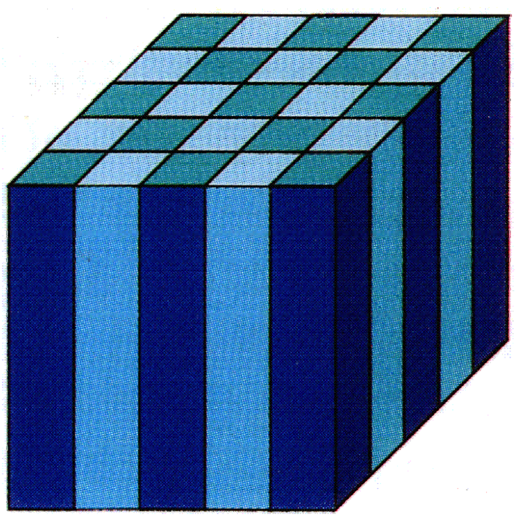


Photonic crystals and semiconductors

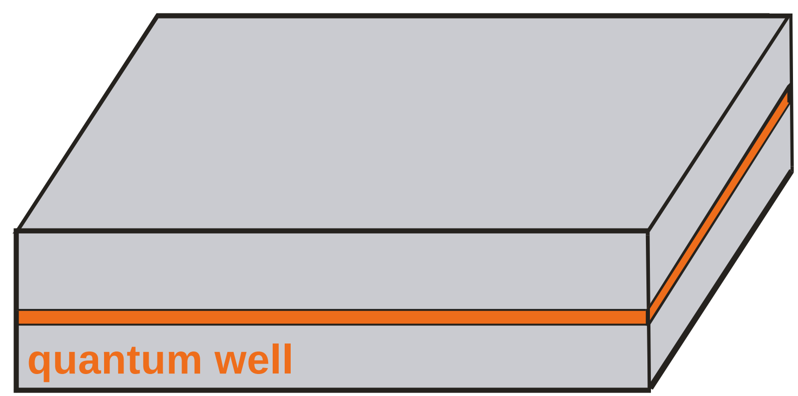
Photonic crystals

- 1D, 2D, 3D
- photonic bandstructure
- light propagation, nonlinearities, …
- interaction with atomic optical resonances = level systems



Semiconductors and heterostructures

- bulk and quantum wells, wires, dots
- electronic bandstructure and confinement
- Coulomb interaction important for optical properties (excitons, etc.)
- level systems not adequate, instead many-body theory required



Outline

Theoretical description of semiconductor optics

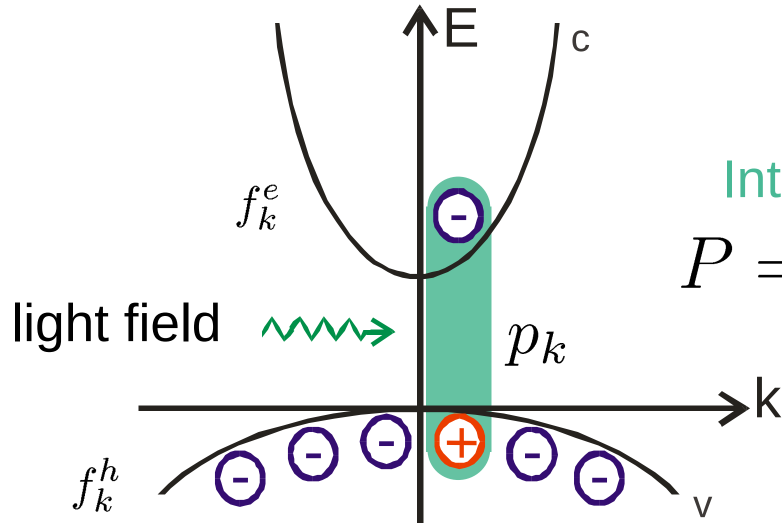
Influence of modified transverse fields

- consequences of inhibited spontaneous emission
- changes of exciton statistics and photoluminescence

Influence of modified longitudinal fields

- spatially inhomogeneous band gap, exciton binding energy, and carrier occupations
- wave packet dynamics
- lasing of spatially inhomogeneous structure

Photoexcited semiconductors

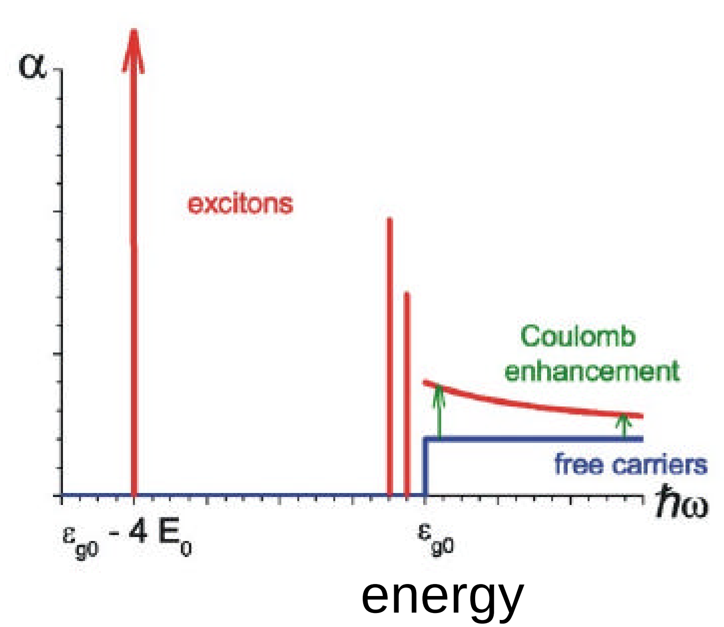


Interband polarization

$$P = \sum_k \mu_{cv}^* p_k + \text{c.c.}$$

Electron-hole attraction

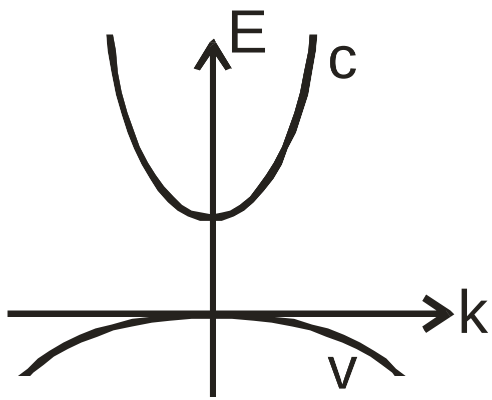
$\Rightarrow$ hydrogenic series of exciton resonances below band gap



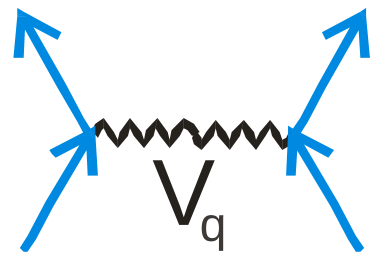
Theoretical description of semiconductor optics

minimal Hamiltonian

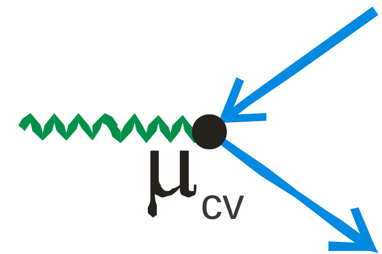
$$\hat{H} = \hat{H}_{bandstructure} + \hat{H}_{Coulomb} + \hat{H}_{light-matter}$$



single-particle states



many-particle interaction



interband excitation

Coulomb interaction introduces many-body problem

$\Rightarrow$ Consistent approximations required: Hartree-Fock,
second Born,
cluster expansion, ...

Equations of motion and light-matter interaction

- semiclassical equations of motion for material excitations (density matrix): semiconductor Bloch equations

$$i\hbar\frac{\partial}{\partial t}p_k = \hbar\omega_k p_k + \underbrace{\left[f_k^e + f_k^h - 1\right]}_{\text{phase space filling}}\left(\mu_{\text{cv}}\cdot E + \underbrace{\sum_{k'\neq k} V_{|k-k'|}p_{k'}}_{\text{Coulomb renormalization}}\right) + \underbrace{i\hbar\frac{\partial}{\partial t}p_k\Big|_{\text{corr}}}_{\text{scattering and correlations}}$$

and similar equations for carrier occupations f_k^e and f_k^h

- Maxwell equation

$$\nabla^2 E - \left(\frac{n}{c}\right)^2\frac{\partial^2 E}{\partial t^2} = \mu_0\frac{\partial^2 P}{\partial t^2}$$

- material response described by $P = \sum_k \mu_{cv}^* p_k + \text{c.c.}$

$$p_k = \langle a_{v,k}^\dagger a_{c,k}\rangle$$

Theoretical description of semiconductor optics

- classical light field:

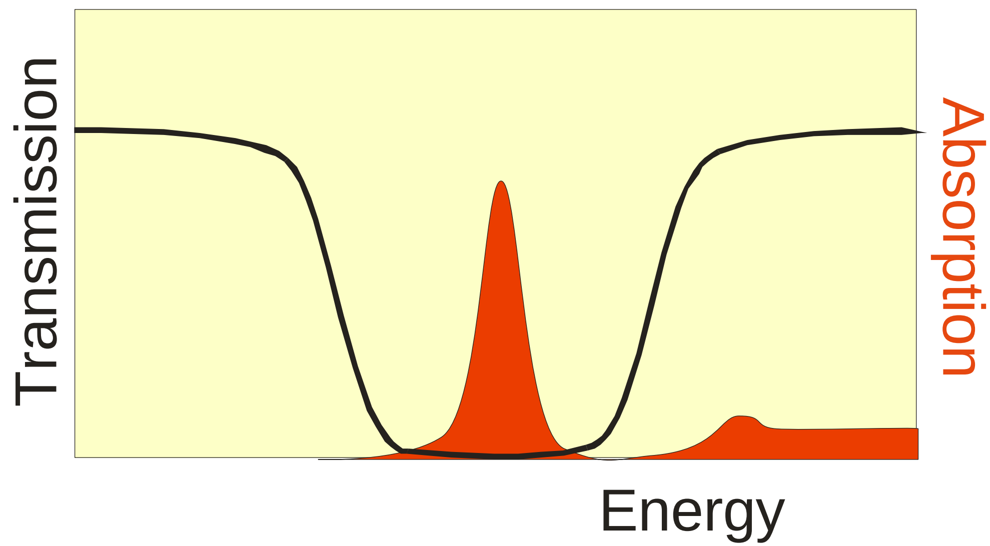
  semiconductor Bloch equations + Maxwell's equations

- quantized light field
  (required for consistent description of luminescence):

  semiconductor luminescence equations
  = coupled dynamics of material and light-field modes
  including photon-assisted density matrices

$\Rightarrow$ **Consistent solution of coupled dynamics of light and material system**

Influence of transverse fields on semiconductor optics



Exciton resonance lies in a photonic band gap

Model study of exciton formation after injection of thermal electrons and holes in the bands:

Quantum wire in a photonic crystal.

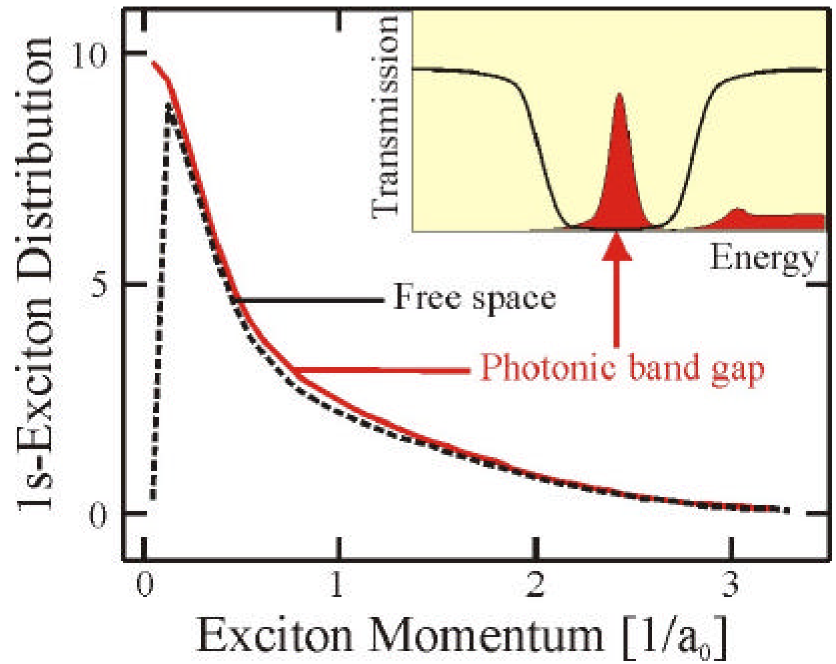
Lowest exciton level lies inside photonic band gap (modeled by reduced recombination).

Solution of semiconductor luminescence equations.

Exciton distribution in quantum wire

• T = 10 K, strong vs. weak recombination

(free space) (1/100 due to photonic band-gap)



• strong depletion of q = 0 excitons in free space
• overall shape NOT Bose-Einstein distribution
• resulting influence on photoluminescence

Phys. Rev. Lett. **87**, 176401 (2001)

Influence of longitudinal fields on semiconductor optics

generalized Coulomb gauge

$$\nabla \cdot [\varepsilon(\vec{r})\vec{A}(\vec{r},t)] = 0$$

generalized Poisson equation

$$-\nabla \cdot [\epsilon(\mathbf{r})\nabla\phi(\mathbf{r},t)] = 4\pi\rho(\mathbf{r},t)$$

generalized Coulomb potential V_C

$$-\nabla \cdot [\epsilon(\mathbf{r})\nabla V_C(\mathbf{r},\mathbf{r}')] = 4\pi\delta(\mathbf{r}-\mathbf{r}')$$

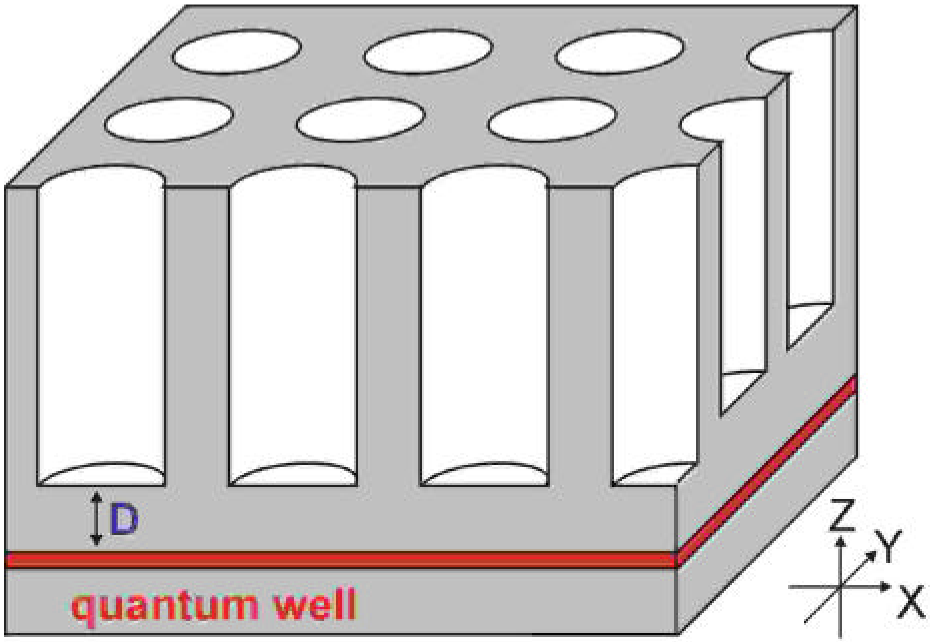
solution for piecewise constant $\mathcal{E}(\mathbf{r})$

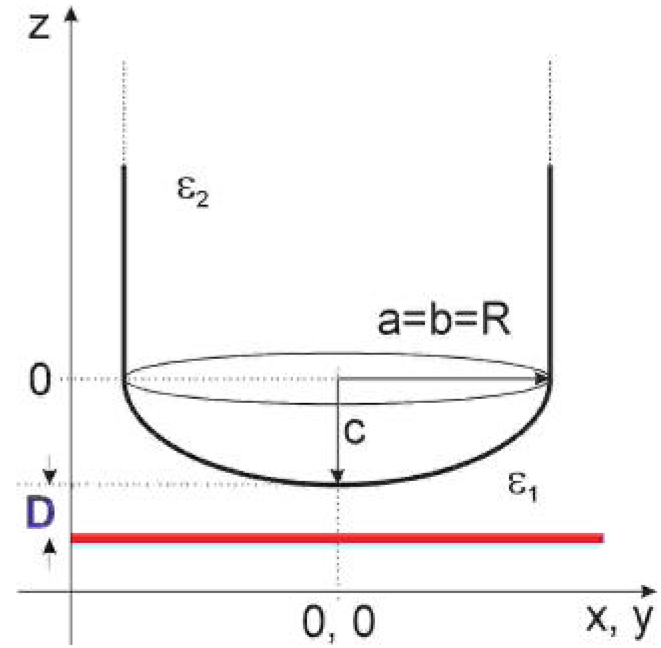
$$\begin{aligned} V_C(\mathbf{r},\mathbf{r}') &= \frac{1}{\epsilon(\mathbf{r}')}\frac{1}{|\mathbf{r}-\mathbf{r}'|} - \frac{1}{4\pi}\sum_{ij}\left(\frac{1}{\epsilon_i}-\frac{1}{\epsilon_j}\right)\int_{\partial D_{ij}} da''\frac{1}{|\mathbf{r}''-\mathbf{r}|}\mathbf{n}_i'' \cdot \mathbf{D}_l(\mathbf{r}'',\mathbf{r}') \\ &= V_0(\mathbf{r},\mathbf{r}') + \delta V(\mathbf{r},\mathbf{r}') \end{aligned}$$

⇒ near a periodically structured dielectric
the Coulomb potential varies periodically in space

J. Opt. Soc. Am. B **19**, 2292 (2002)

Model system



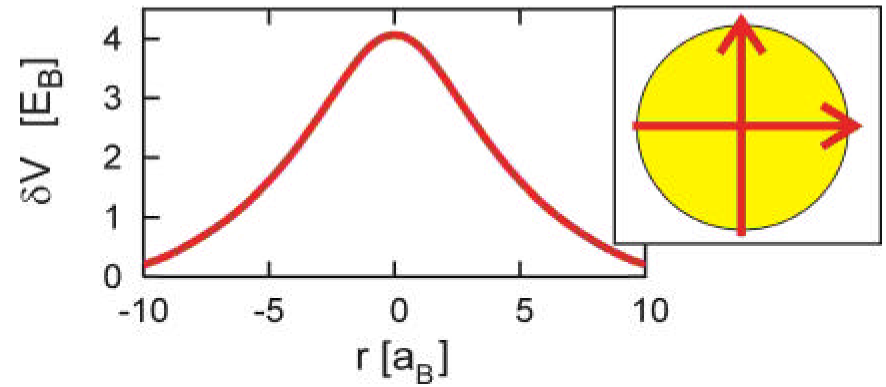


- 2D photonic crystal (air cylinders surrounded by dielectric medium)
- cap layer
- semiconductor quantum well

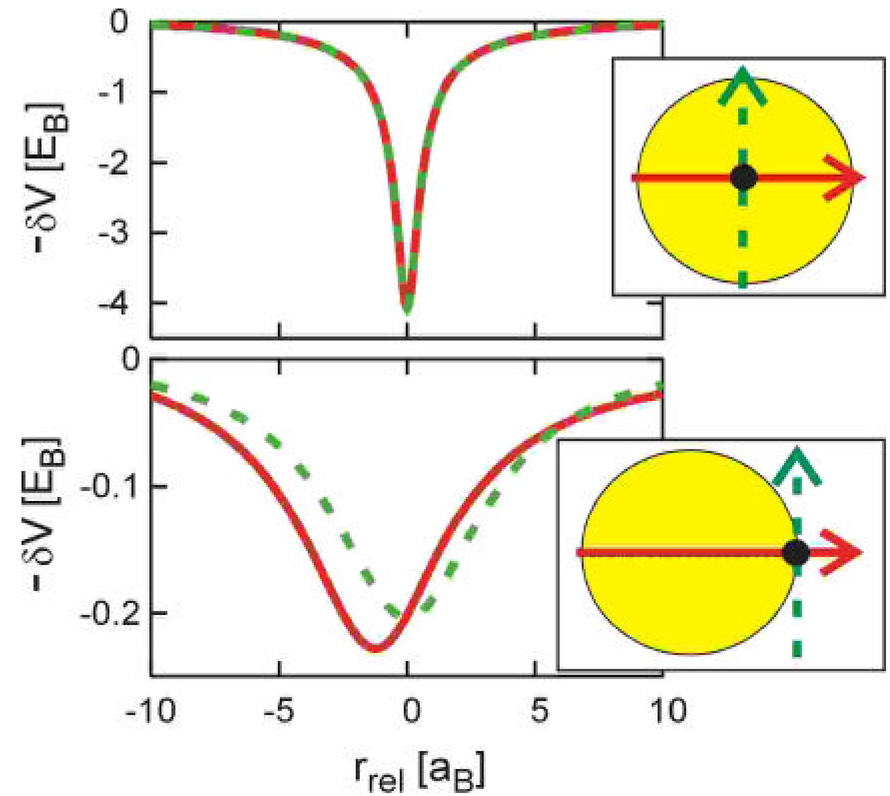
- ellipsoidal shape of cylinder bottom

Corrections due to generalized Coulomb potential

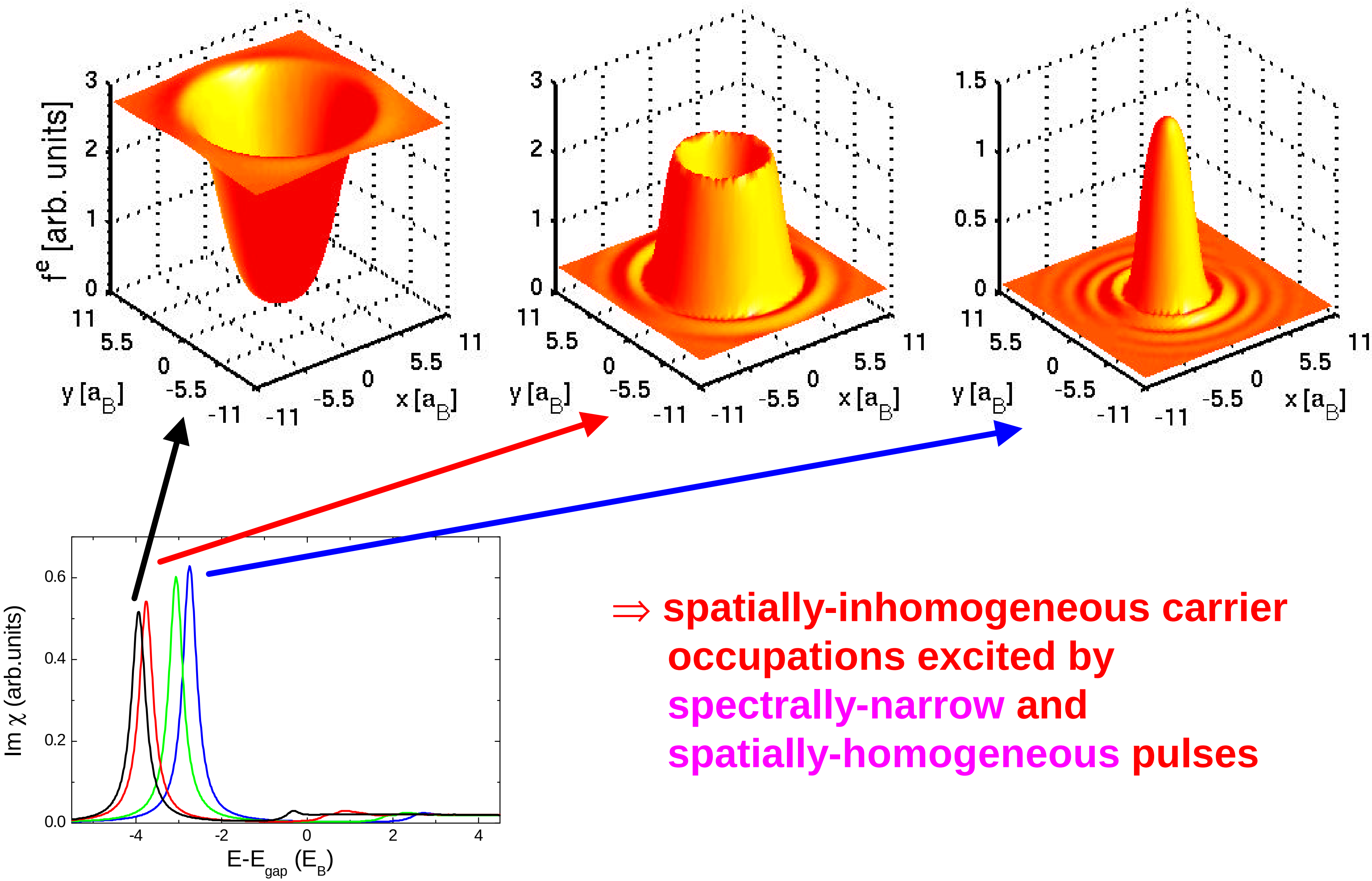
- position-dependent band gap: biggest increase underneath center of the air cylinders



- position-dependent electron-hole attraction: strongest underneath center of the air cylinders



Spectrally selective excitation

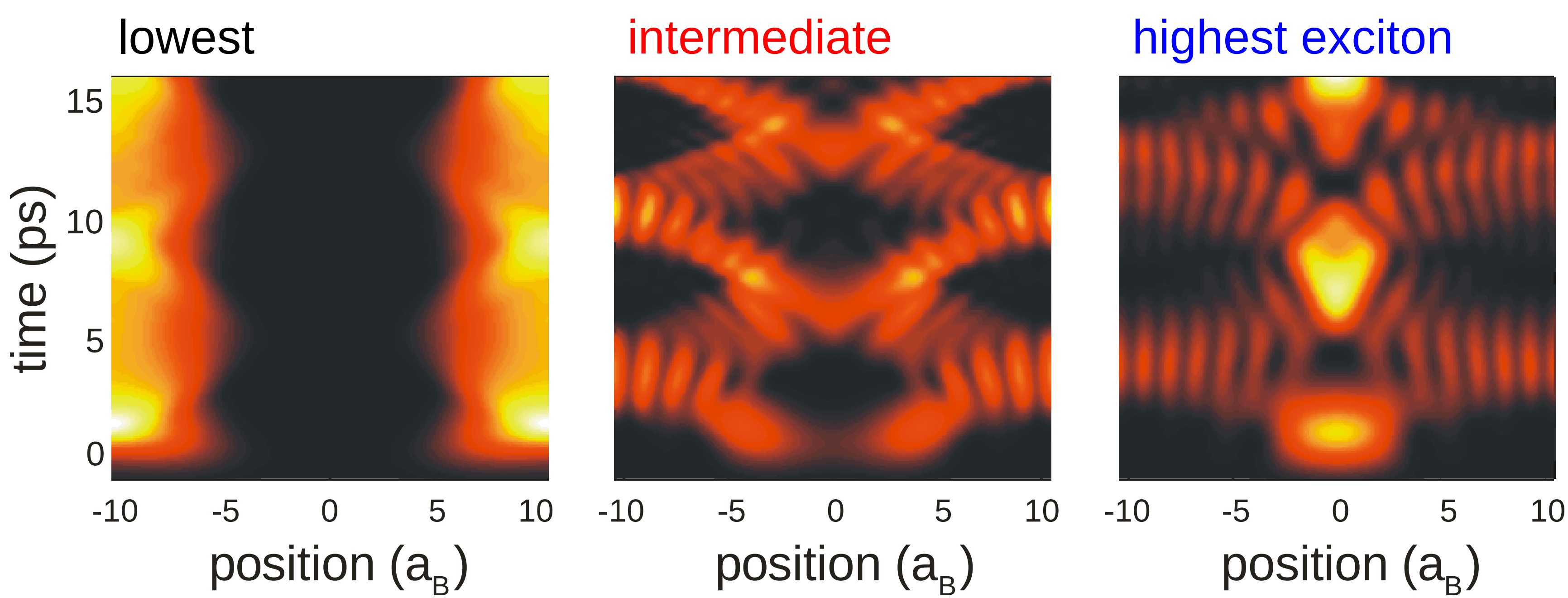


⇒ **spatially-inhomogeneous carrier occupations excited by spectrally-narrow and spatially-homogeneous pulses**

phys. stat. sol. (b) **238**, 439 (2003)

Coherent wave packet dynamics

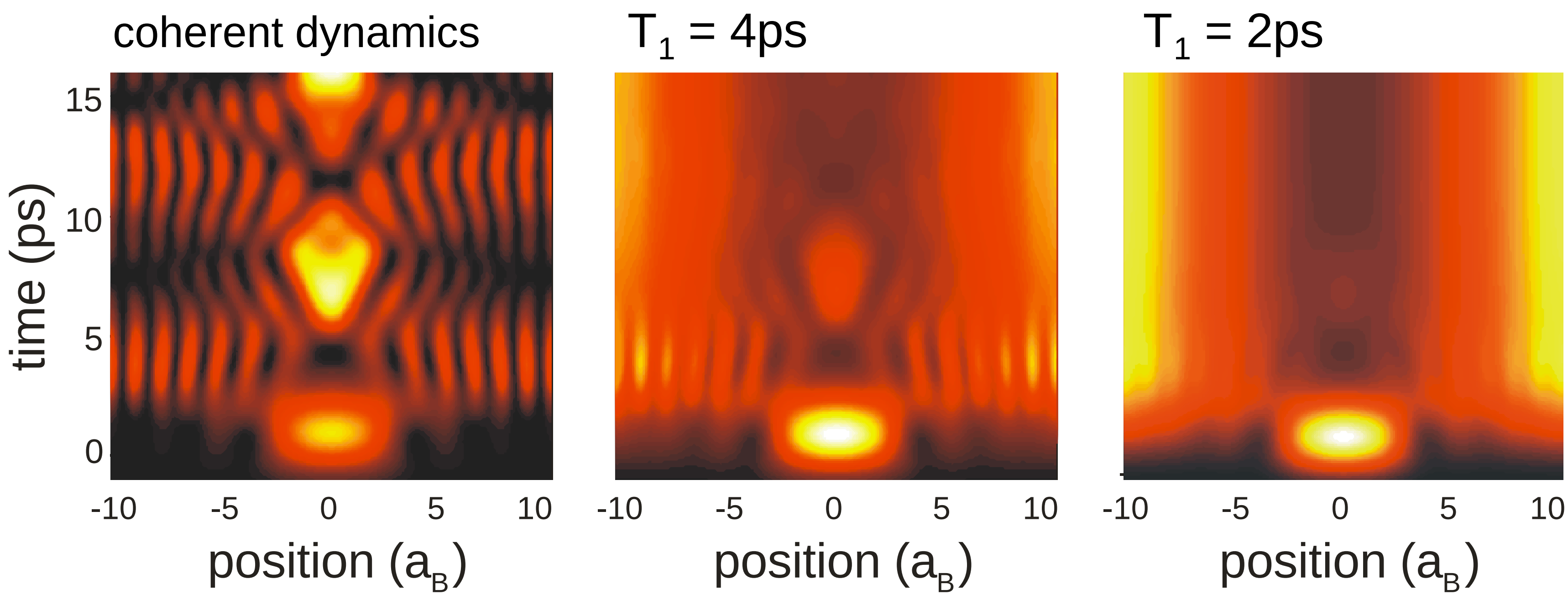
Spectrally selective excitation of quantum wire



⇒ spatially inhomogeneous carrier occupations evolve in time
due to wave packet dynamics

Incoherent processes: Dephasing and relaxation

Excitation at highest exciton.
Carrier relaxation modeled by thermalization time T_1. (T=50K)

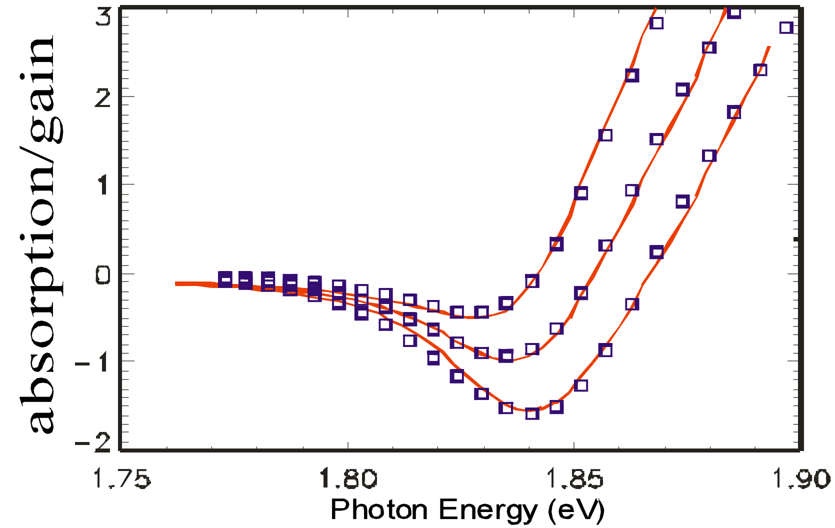


⇒ in quasi equilibrium carriers accumulate in between the air cylinders

Semiconductor lasers

⇒ gain spectra of semiconductor heterostructures, e.g., quantum wells, can be quantitatively described using many-body theory

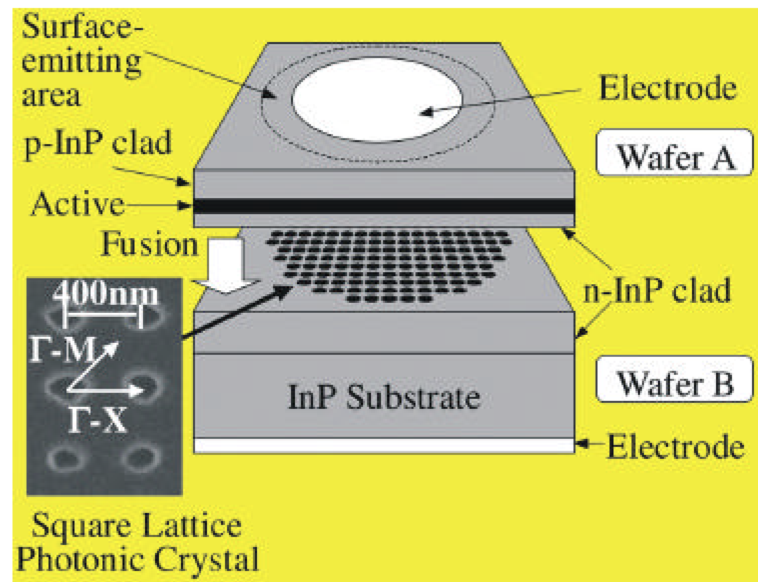
see, e.g., J. Optics B **3**, 29 (2001)



⇒ hybrid semiconductor photonic-crystals laser structures have been fabricated

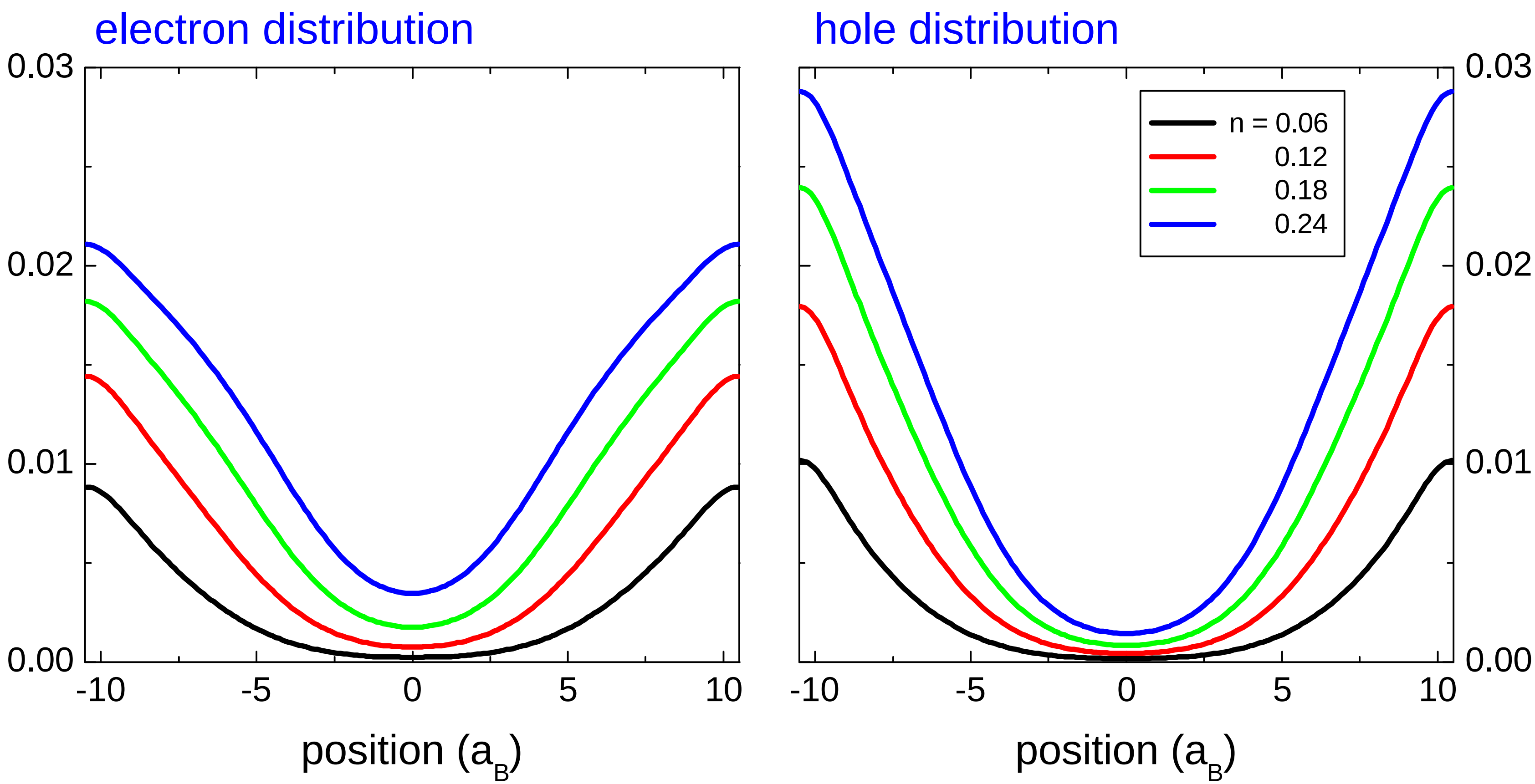
- photonic crystal next to quantum well
- injection pumped laser structure

Noda, et al., Science **293**, 1123 (2001)



Quasi-equilibrium carrier occupations

carrier ocupations for quantum wire close to photonic crystal at T=20K

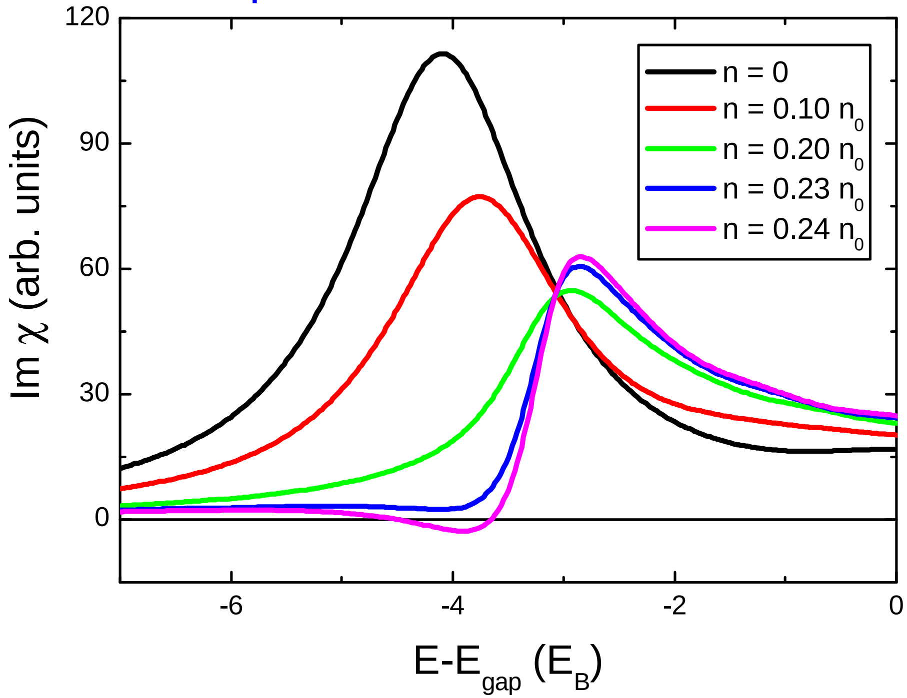


⇒ **electrons and holes avoid positions underneath air cylinders**

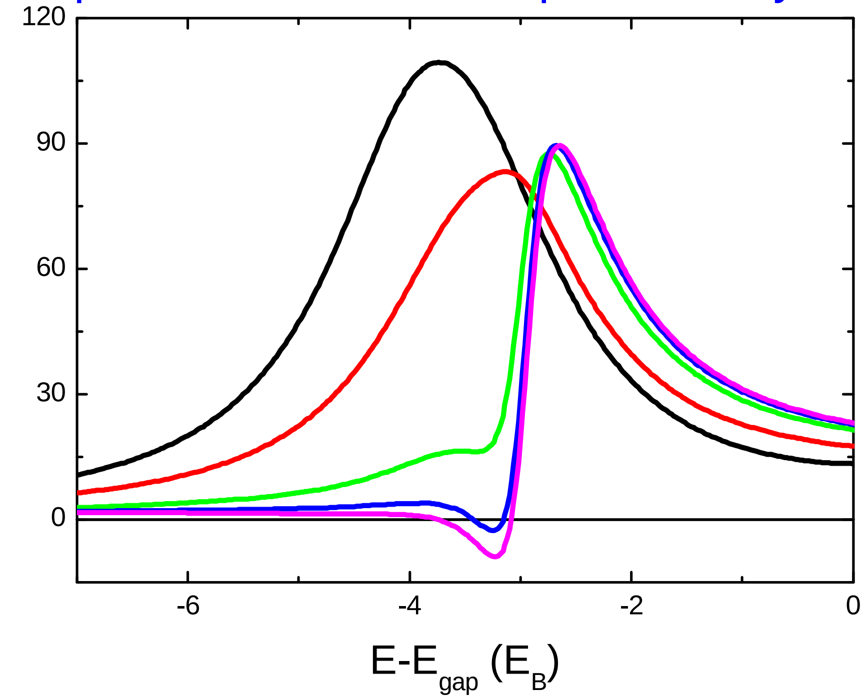
Influence of spatial inhomogeneity on absorption/gain spectra

quasi-equilibrium absorption for different carrier densities at T=20K

bare quantum wire



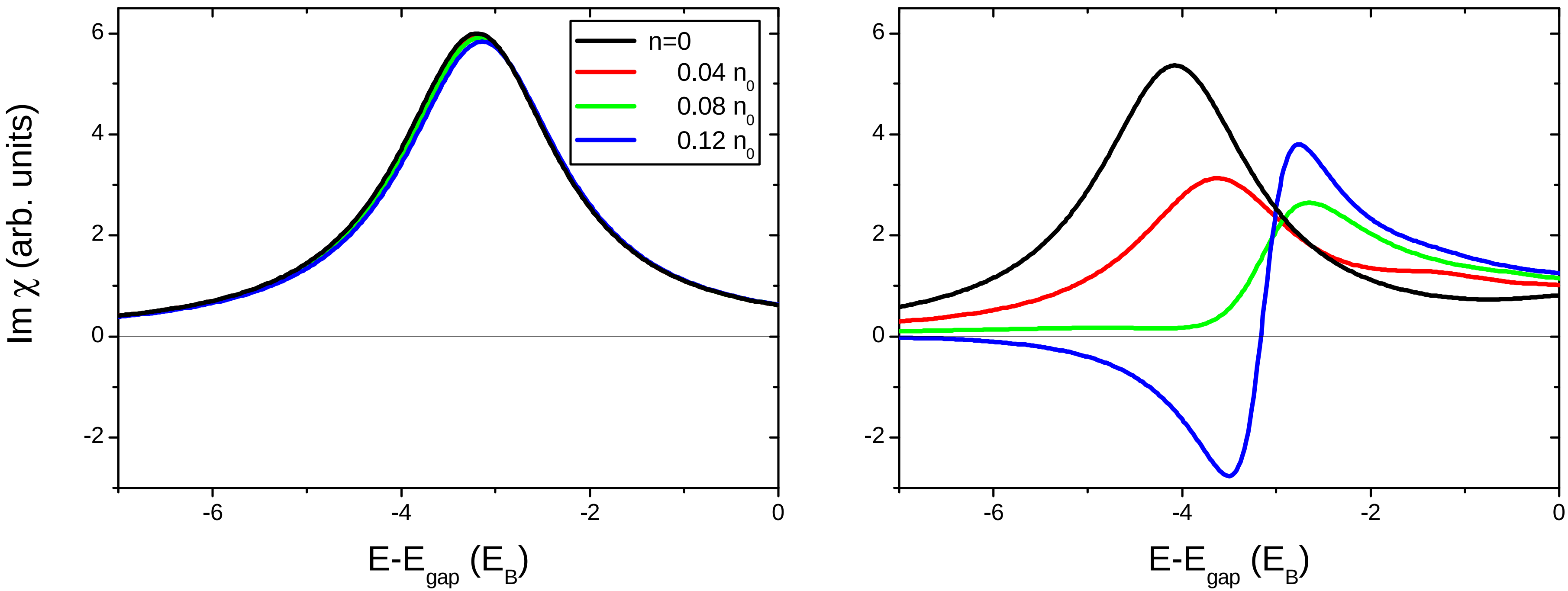
quantum wire close to photonic crystal



⇒ characteristic changes of lineshape
and gain at slightly lower total density
due to spatially-inhomogeneous carrier occupations

Spatially-resolved absorption/gain spectra

underneath air cylinder (low density) in between air cylinders (high density)



⇒ due to the space-dependent density
some regions are absorbing
whereas others show gain

Summary

Due to inhibited spontaneous emission a photonic band gap strongly influences material properties

- exciton formation and statistics, and photoluminescence

Coulomb interaction is altered near a photonic crystal

- spatially-varying band gap and exciton binding energy
- wave packet dynamics
- spatially-inhomogeneous quasi-equilibrium carrier occupations
- lasing of spatially-inhomogeneous structure

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cpu-time on parallel supercomputer