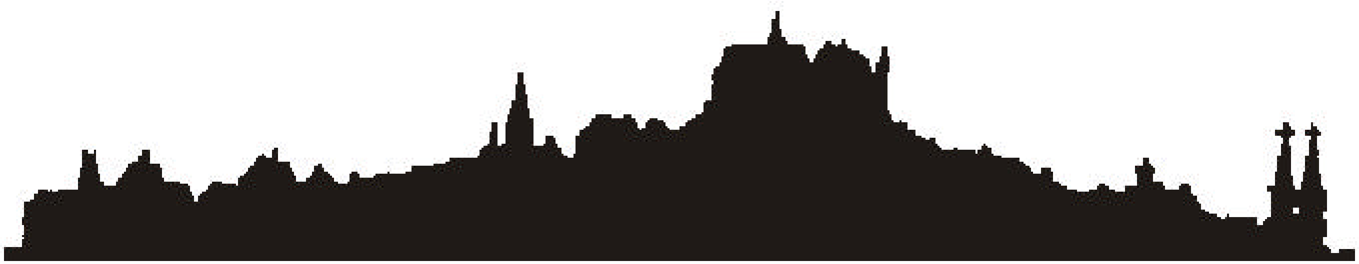
Optical Properties of Semiconductor Photonic-Crystal Structures

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

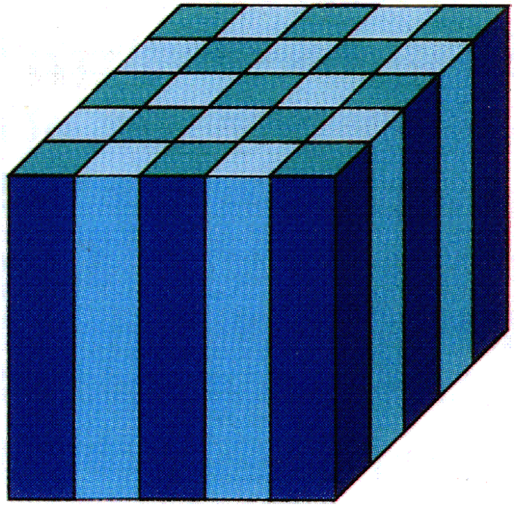
Department of Physics and Material Sciences Center,
Philipps-University Marburg, Germany



Photonic crystals and semiconductors

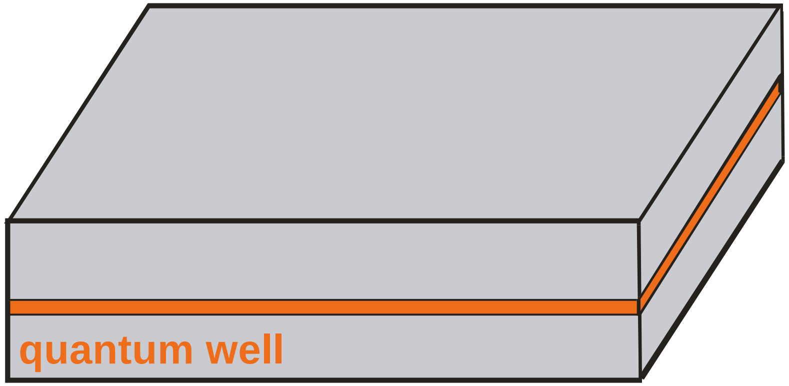
Photonic crystals

- 1D, 2D, 3D
- photonic bandstructure
- light propagation, nonlinearities, …
- interaction with atomic 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

☛ **Brief description of theoretical approach**

☛ **Influence of modified transverse fields**

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

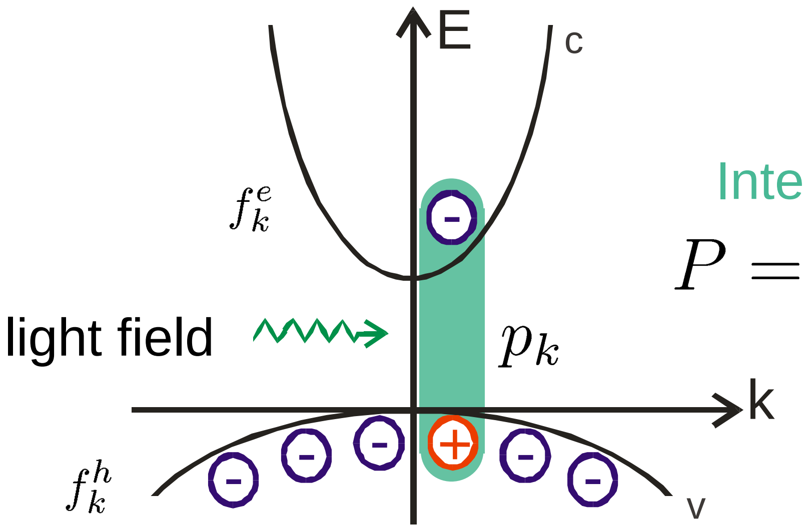
☛ **Influence of modified longitudinal fields**

- dielectric shifts result in spatially inhomogeneous band gap, exciton binding energy, and carrier occupations
- wave packet dynamics

☛ **Self-consistent solutions of Maxwell-Bloch equations**

- enhanced light-matter interaction due to light concentration
- strongly increased absorption and gain

Photoexcited semiconductors

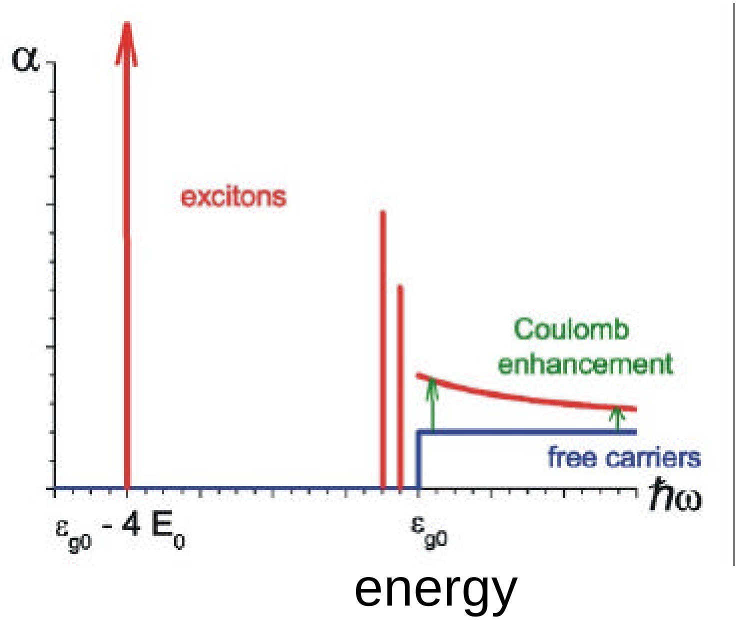


Interband polarization

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

Electron-hole attraction

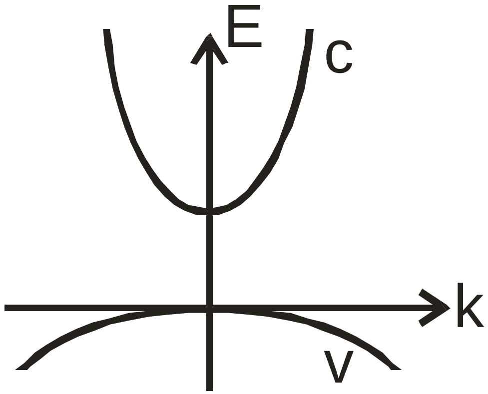
⇒ hydrogenic series of exciton resonances below band gap



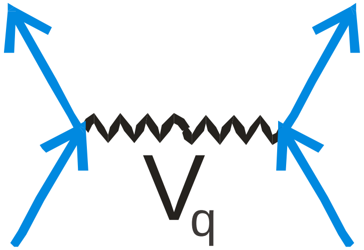
Theoretical description of semiconductor optics

minimal Hamiltonian

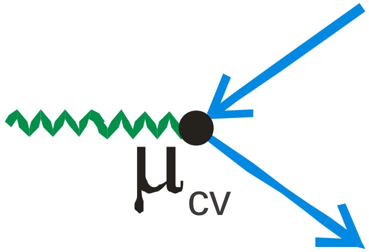
$$\hat{H} = \hat{H}_{bandstructure} + \hat{H}_{Coulomb} + \hat{H}_{light-matter}$$



single-particle states



many-particle
interaction



interband excitation

Coulomb interaction introduces many-body problem
⇒ Consistent approximations required: Hartree-Fock,
second Born, dynamics-controlled truncation, cluster expansion,
...

Equations of motion and light-matter interaction

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

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

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 $P = \sum_k \mu_{cv}^* \underset{\langle a^\dagger_{v,k}a_{c,k}\rangle}{\underset{\shortparallel}{p_k}} + \mathrm{c.c.}$

Theoretical description of semiconductor optics

- classical light field:

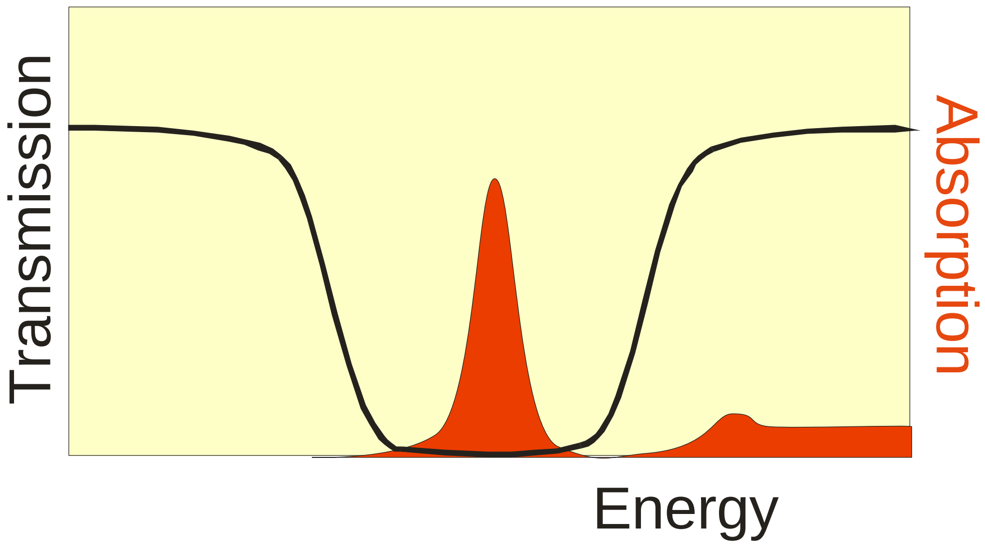
  semiconductor Bloch equations + Maxwell's equations

- 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

⇒ 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.

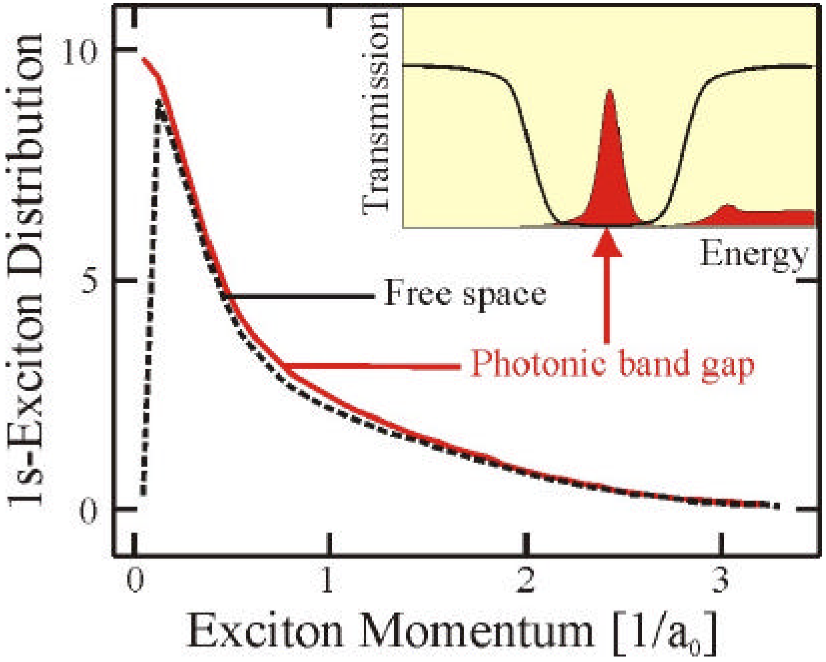
Lowest exciton level lies inside photonic band gap (modeled by reduced recombination).

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)

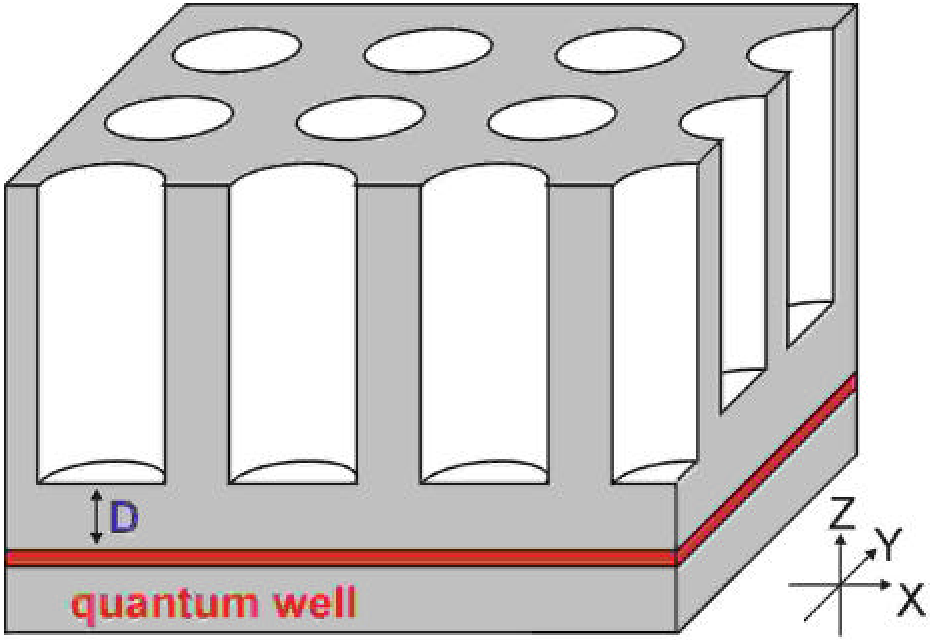


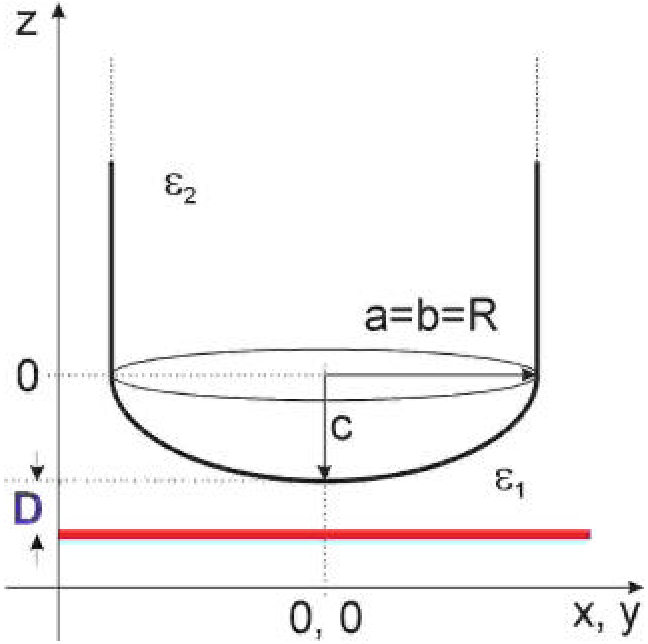
- strong depletion of $q = 0$ excitons in free space
- overall shape NOT Bose-Einstein distribution
- resulting influence on photoluminescence

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

Influence of longitudinal fields on semiconductor optics

model system





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

- ellipsoidal shape of cylinder bottom

Influence of longitudinal fields on semiconductor optics

longitudinal part: 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 $\mathcal{E}(\mathbf{r})$

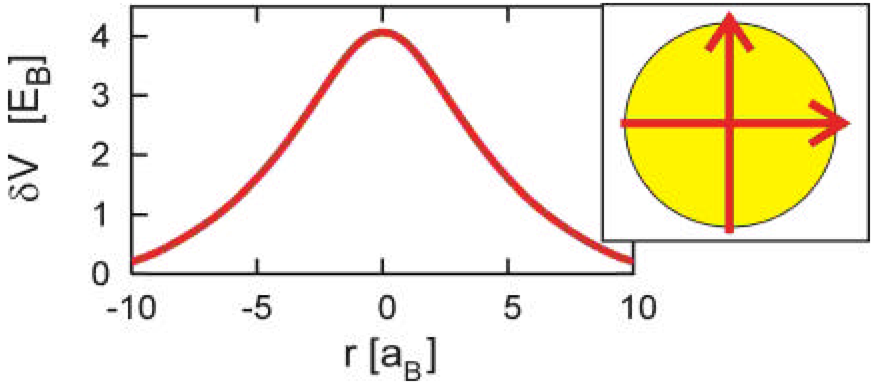
$$\begin{aligned} V_C(\mathbf{r},\mathbf{r}') &= \frac{1}{\epsilon(\mathbf{r}')}\frac{1}{|\mathbf{r}-\mathbf{r}'|} - \frac{1}{4\pi}\sum_{ij}\left(\frac{1}{\epsilon_i}-\frac{1}{\epsilon_j}\right)\int_{\partial D_{ij}} da''\frac{1}{|\mathbf{r}''-\mathbf{r}|}\mathbf{n}_i''\cdot\mathbf{D}_l(\mathbf{r}'',\mathbf{r}')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

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

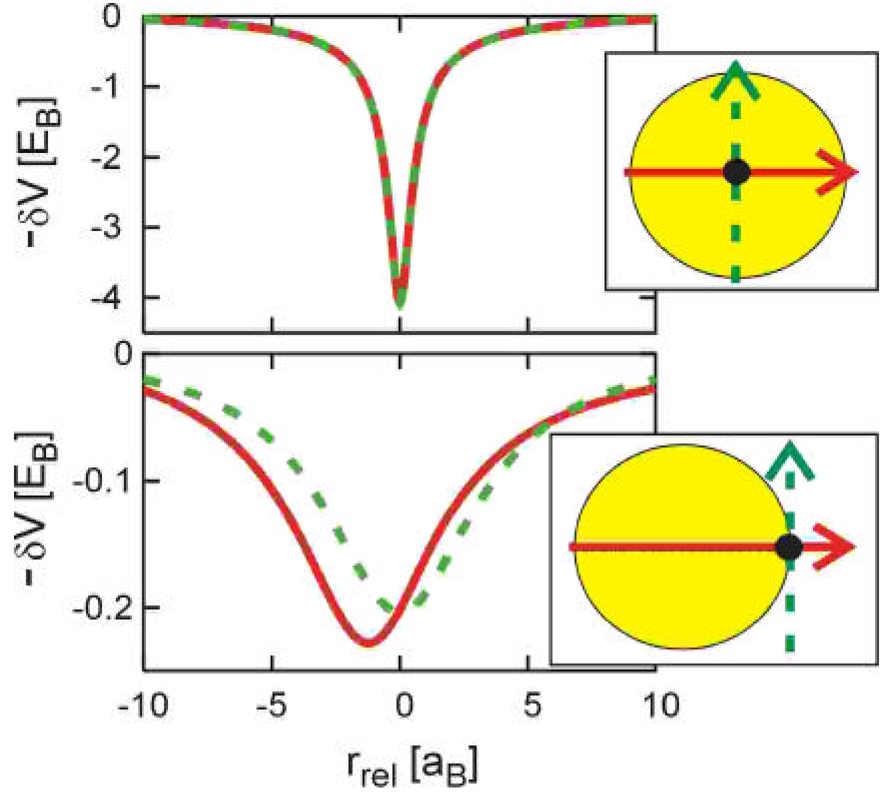
J. Opt. Soc. Am. B **19**, 2292 (2002)

Corrections due to generalized Coulomb potential

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

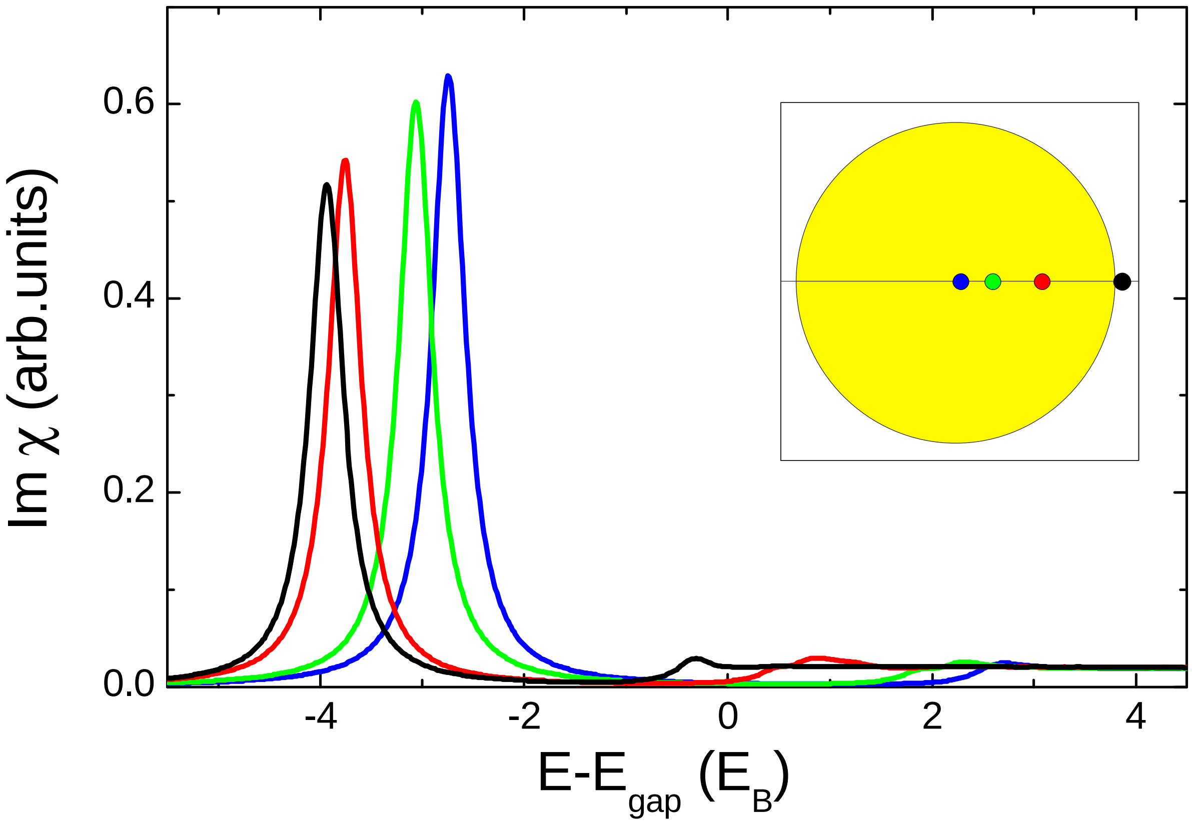


- position-dependent electron-hole attraction: strongest underneath center of the air cylinders



Excitons in photonic crystals

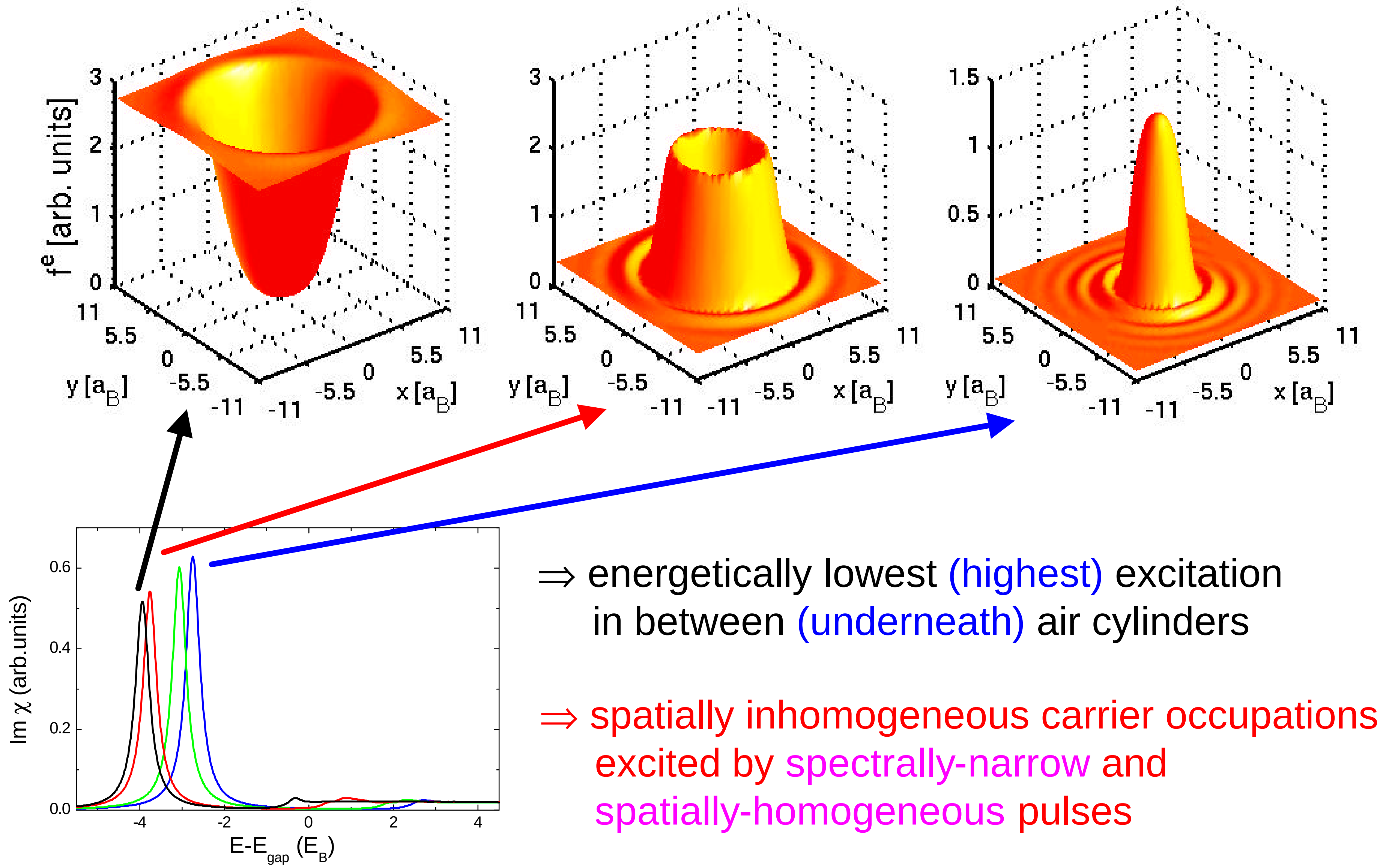
numerically calculated absorption spectra for fixed c.o.m. positions



⇒ spatial variation of band gap (~ 4E$_B$) and exciton binding energy (~ 2.5 E$_B$) with periodicity of photonic crystal

Appl. Phys. Lett. **82**, 355 (2003)

Spectrally selective excitation



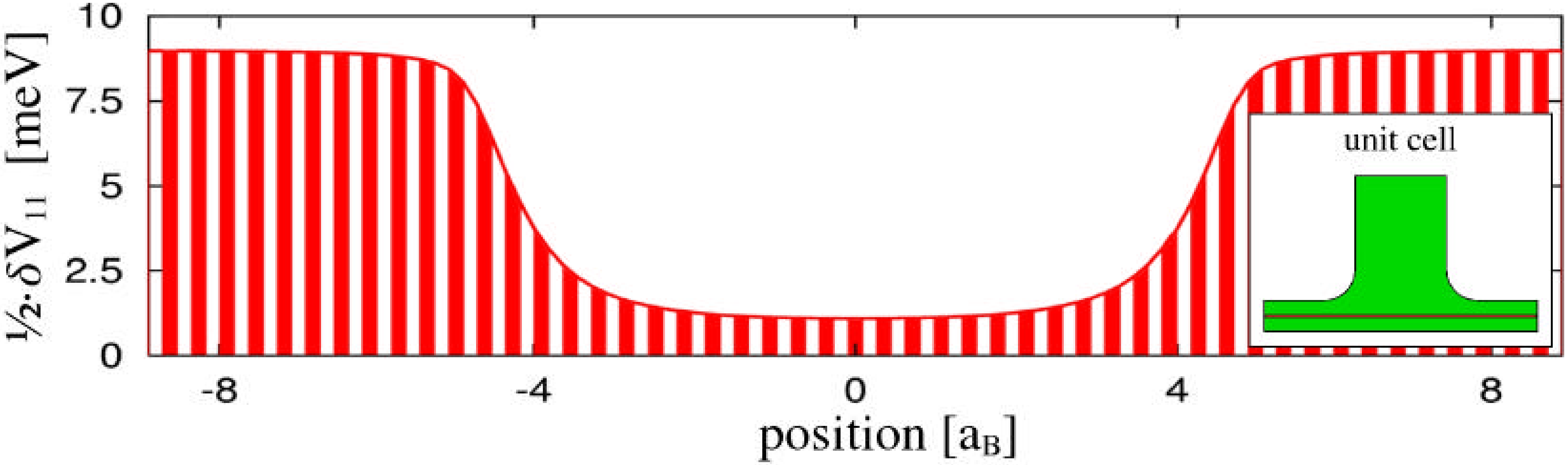
⇒ energetically lowest (highest) excitation
in between (underneath) air cylinders

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

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

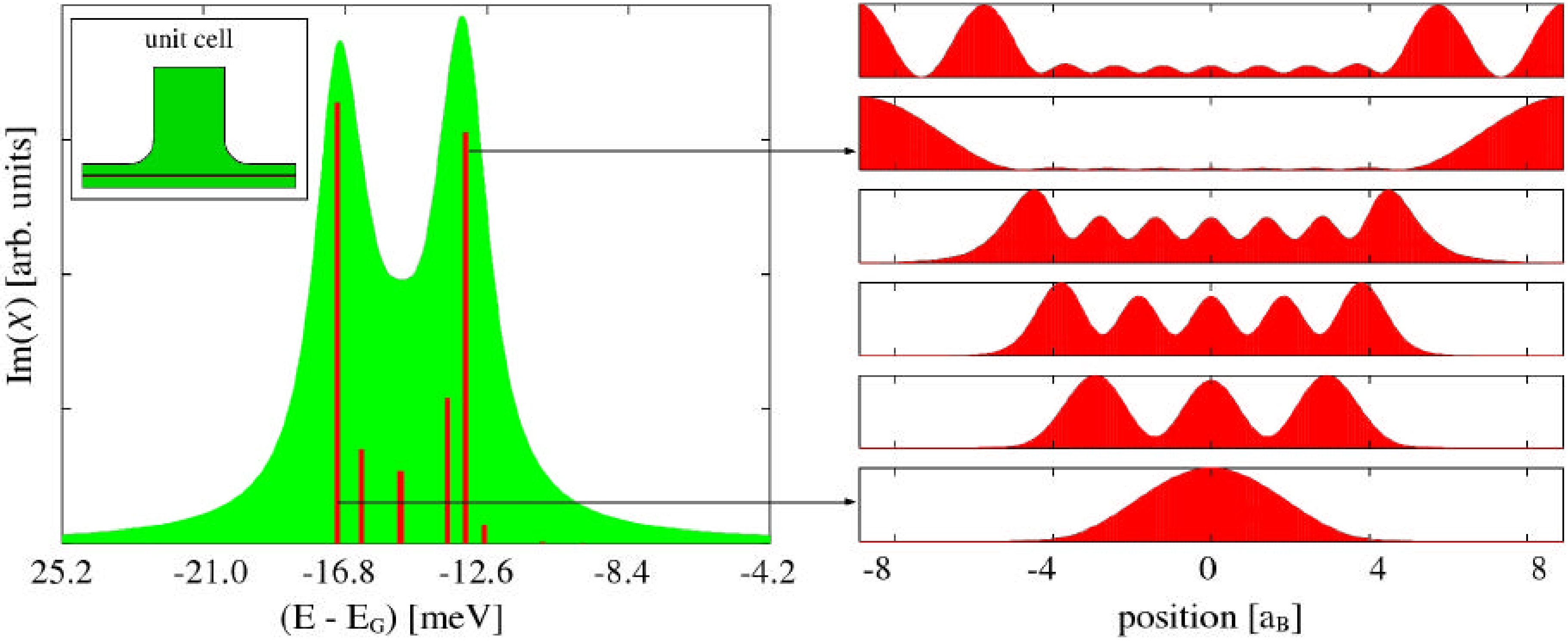
Excitons in photonic crystals II

Quantum wires underneath one-dimensional ridges of dielectric material



Excitons in photonic crystals II

Quantum wires underneath one-dimensional ridges of dielectric material

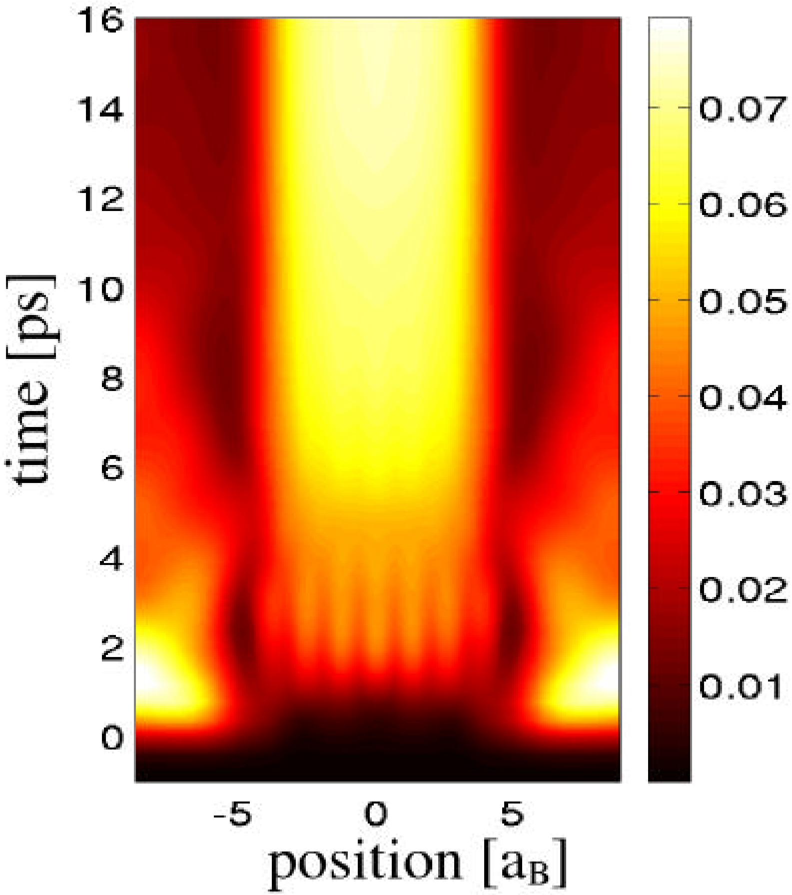


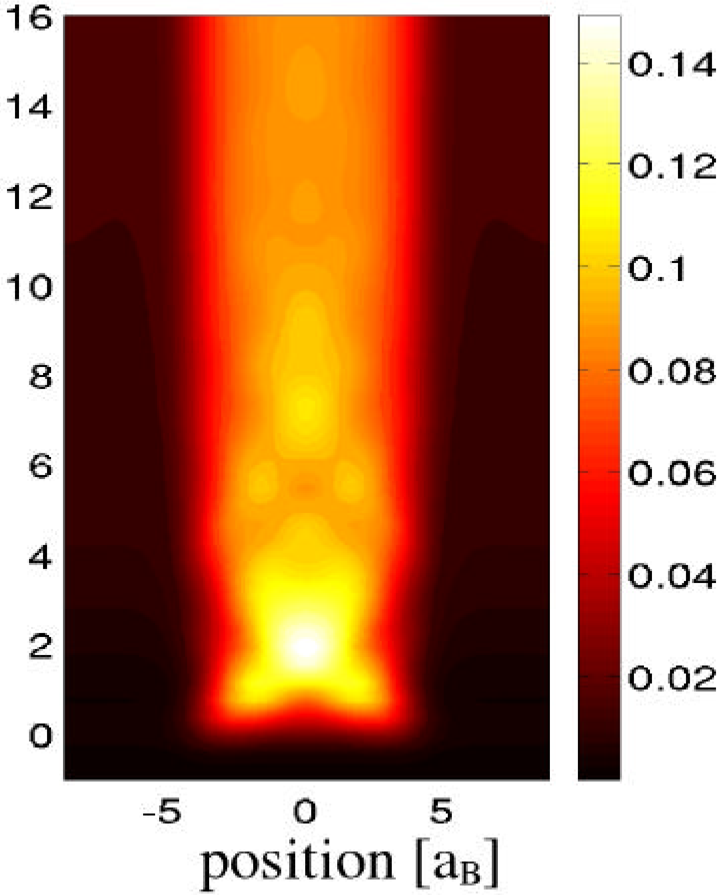
- ⇒ variety of inhomogeneous excitons
- ⇒ spectrally selective excitation leads to spatially inhomogeneous carrier distributions

Pasenow, et al., to be published

Coherent wave packet dynamics

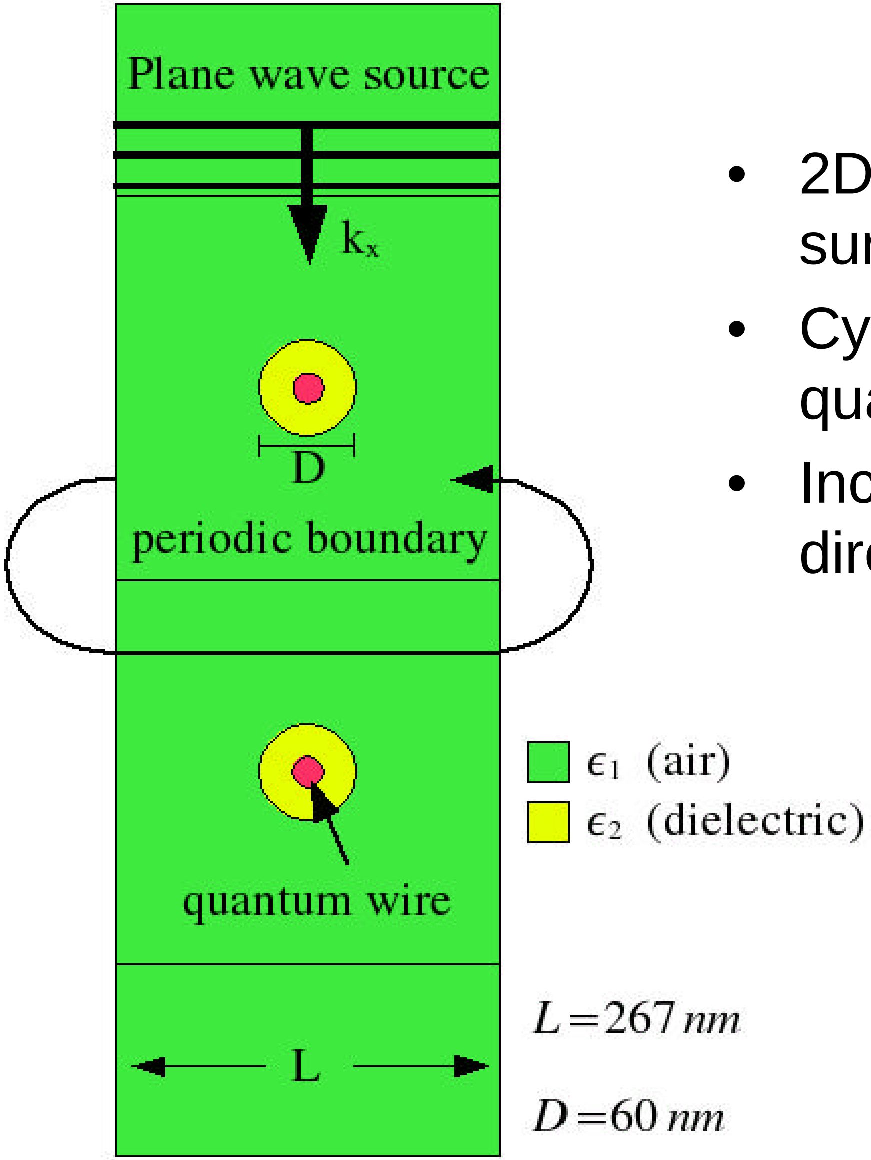
Spectrally selective excitation in quantum wire,
relaxation modeled by T_1 time (4ps)





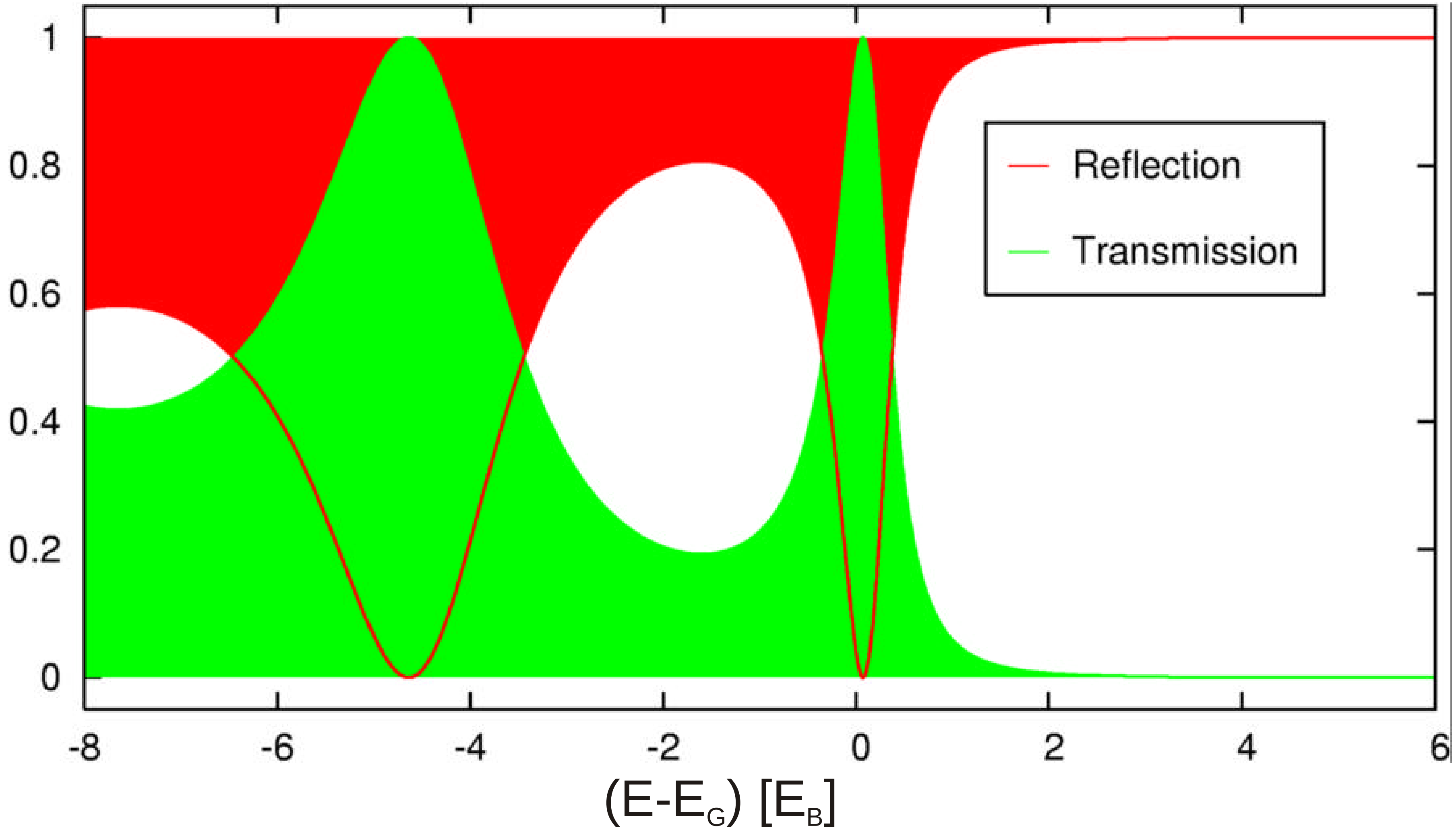
⇒ spatially inhomogeneous carrier occupations evolve in time
due to wave packet dynamics

Solution of Maxwell-Bloch equations



- 2D array of dielectric cylinders surrounded by air
- Cylinders filled with semiconductor quantum wire
- Incoming plane wave polarized in direction of wires (TM mode)

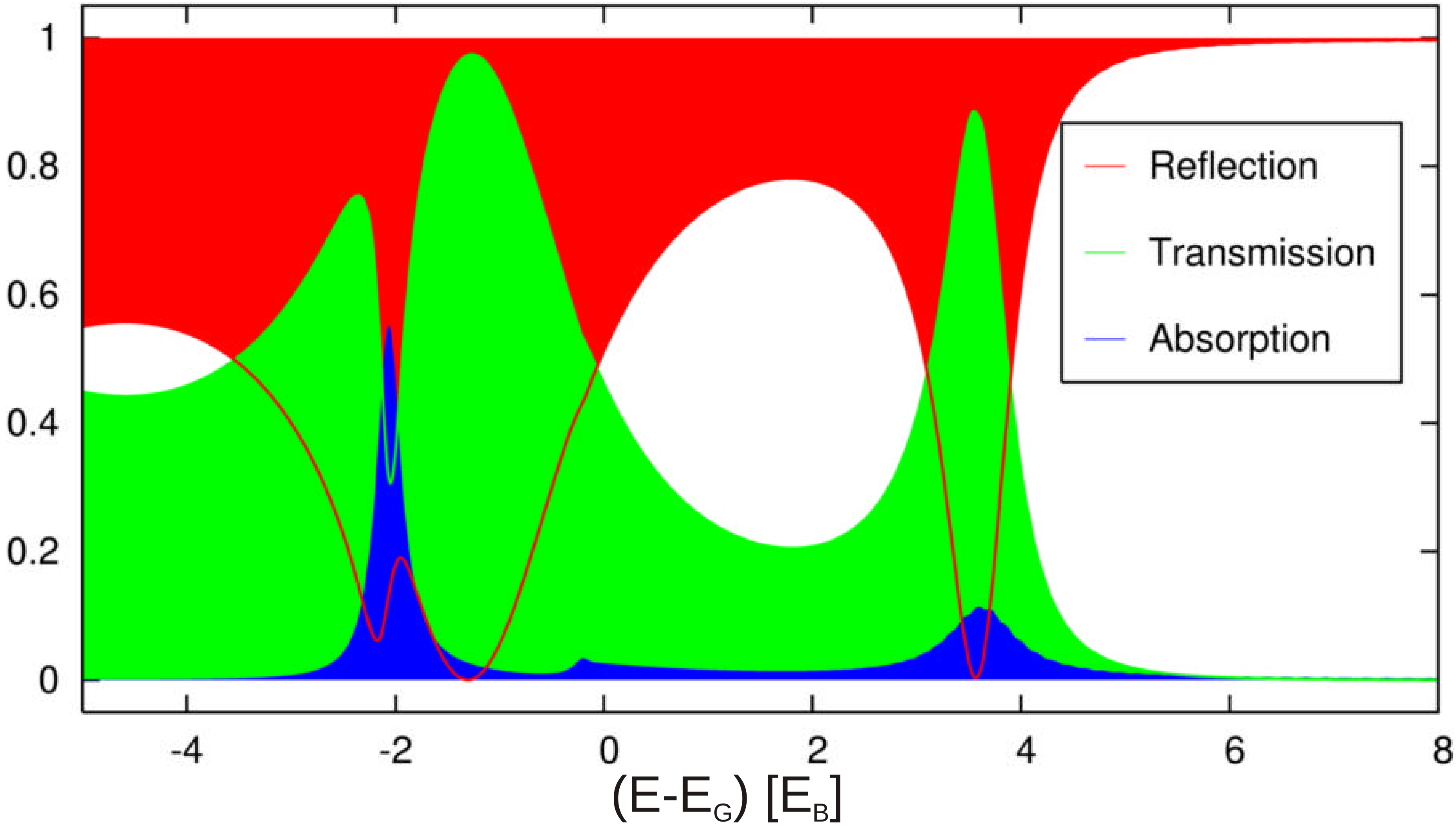
Optical spectra of photonic crystal



⇒ photonic bandstructure leads to frequency dependence

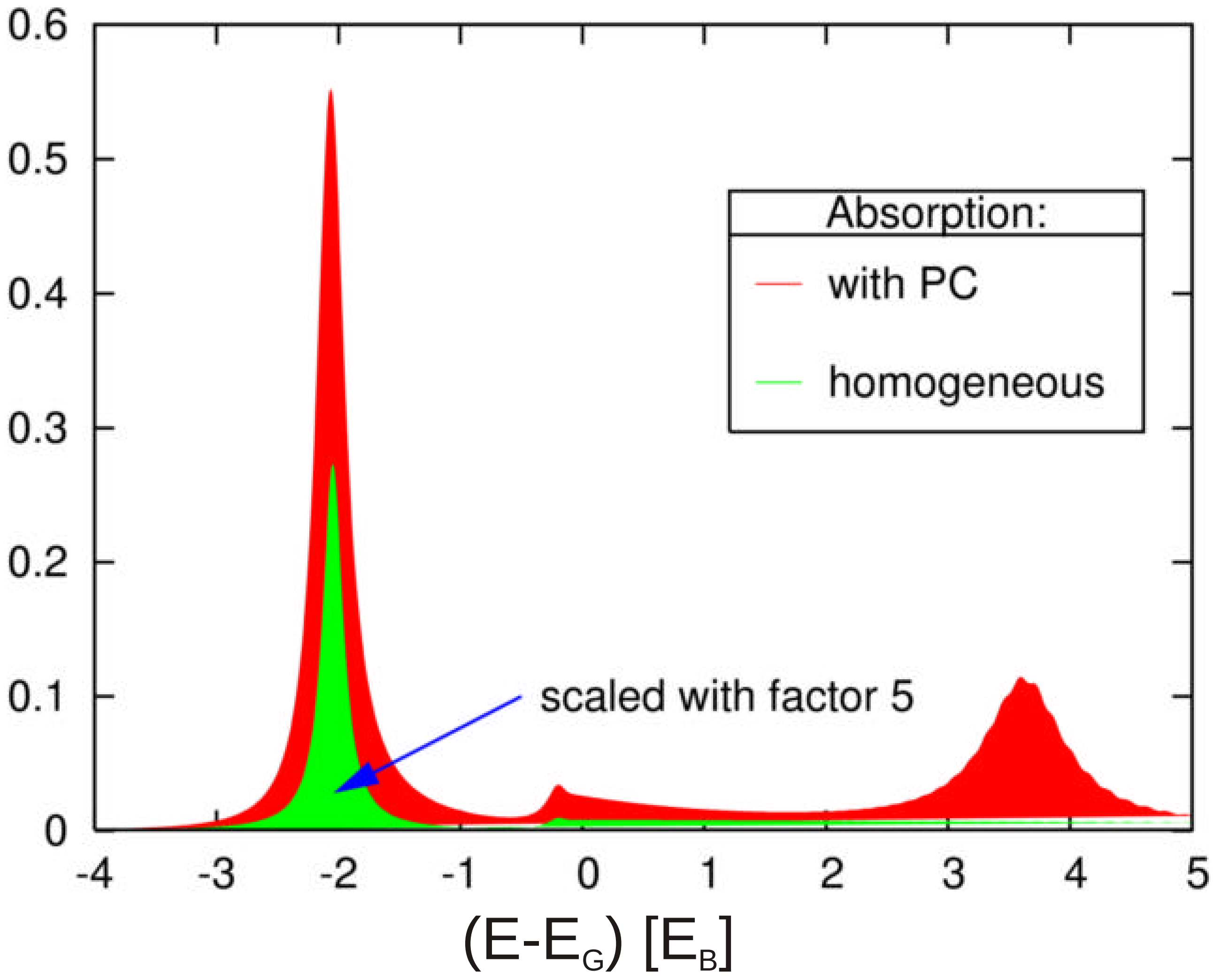
⇒ transmission vanishes in photonic band gap

Optical spectra



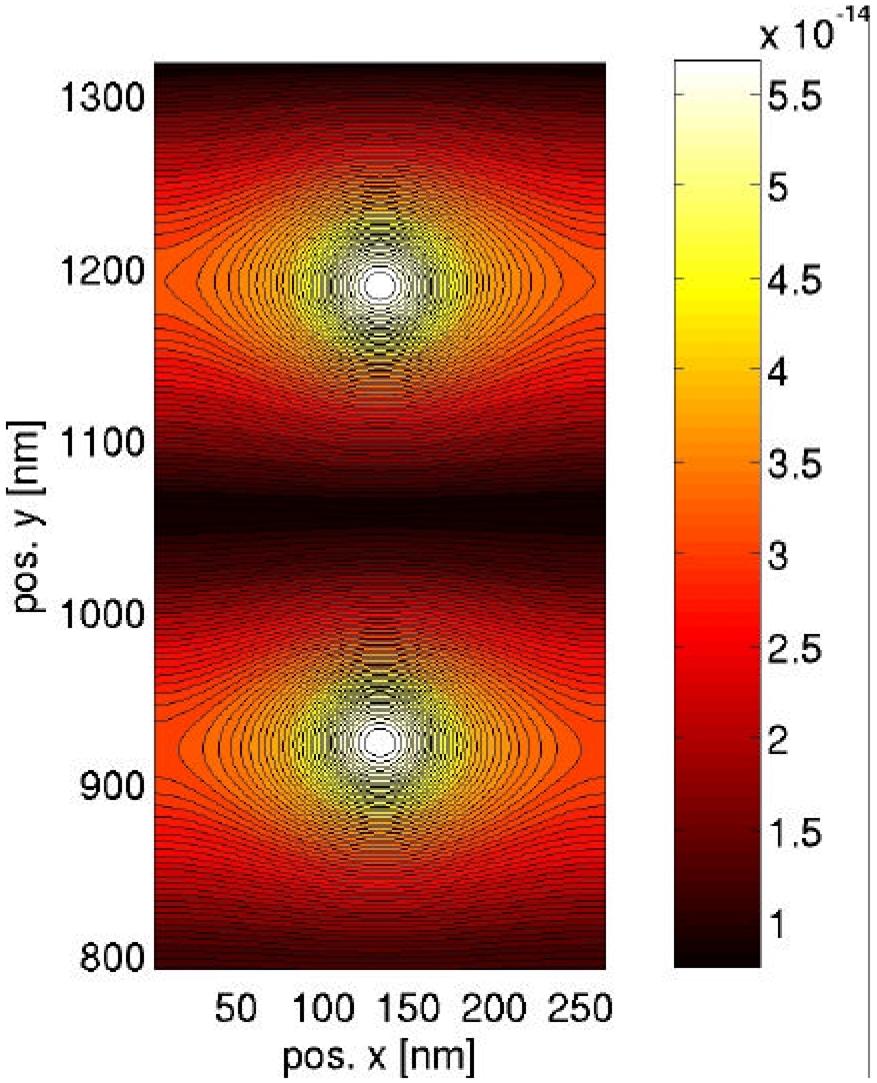
⇒ photonic bandstructure modifies absorption spectrum

Absorption spectra



⇒ **strongly enhanced absorption**

Field concentration



⇒ **field concentrates in dielectric cylinders**

Pasenow, et al., to be published

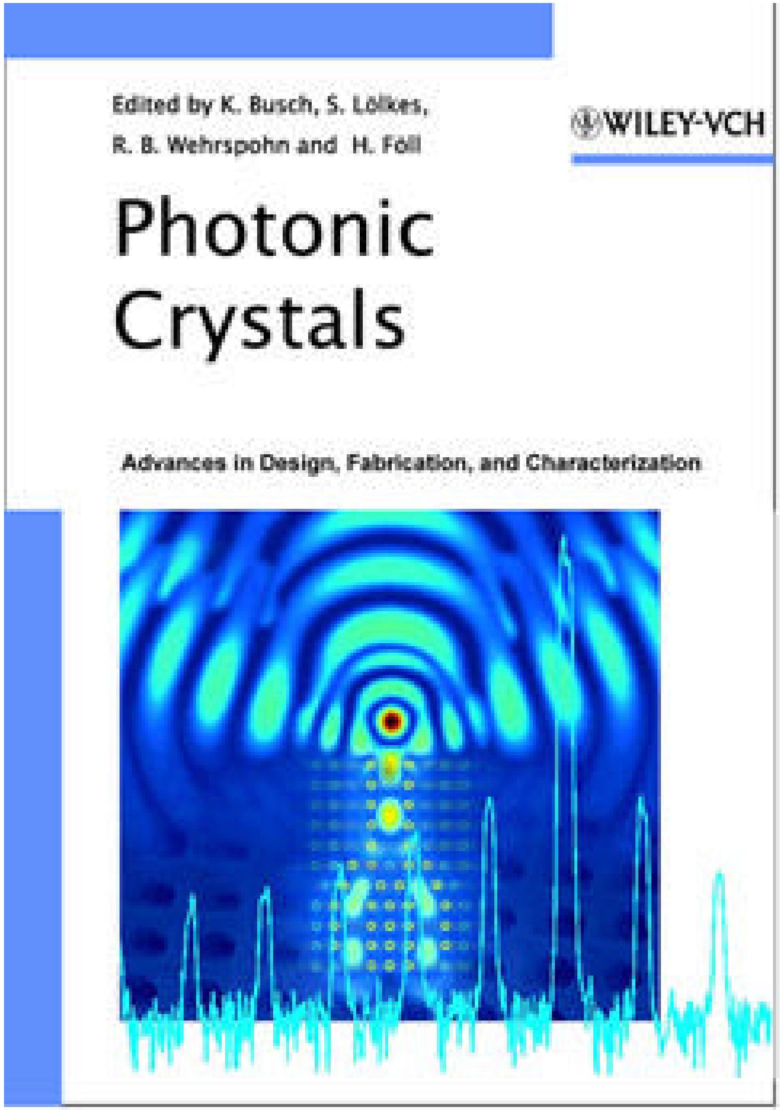
Summary

- **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

- **Light-matter interaction can be tailored**
  - enhanced absorption (and gain) due to light concentration

- **Outlook: full self-consistent treatment of transversal and longitudinal effects**
  - combining carrier and light concentration effects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Photonic
Crystals

Advances in Design, Fabrication, and Characterization

Interested in photonic crystals?

Activities of the groups funded by the DFG priority program *“Photonic Crystals”* are described in this book (published Spring 2004)

Acknowledgments

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DFG

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PhoCs

Forschungszentrum Jülich
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NIC

cpu-time on parallel supercomputer

Interdisciplinary Research Center *Optodynamics*,
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