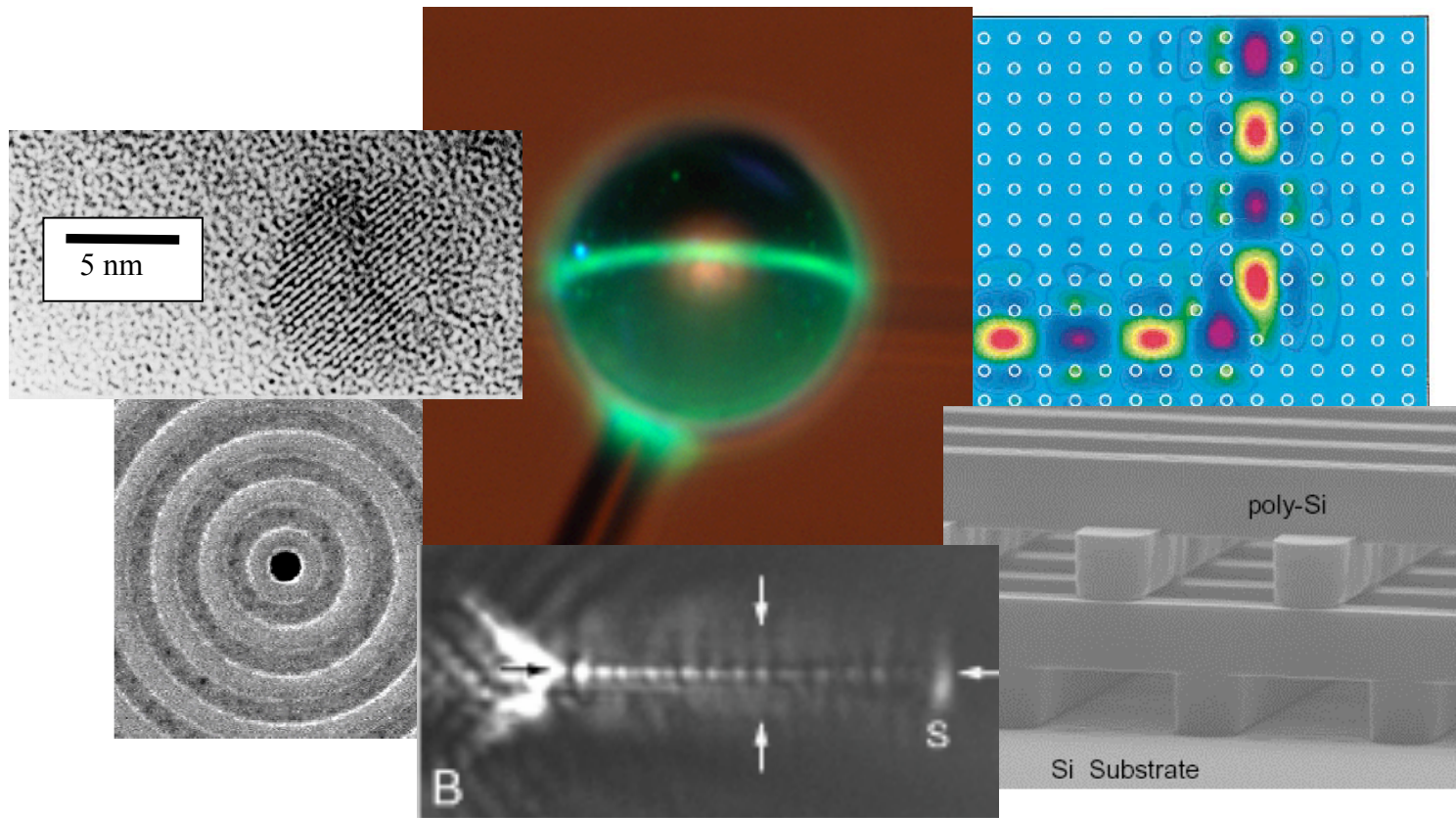


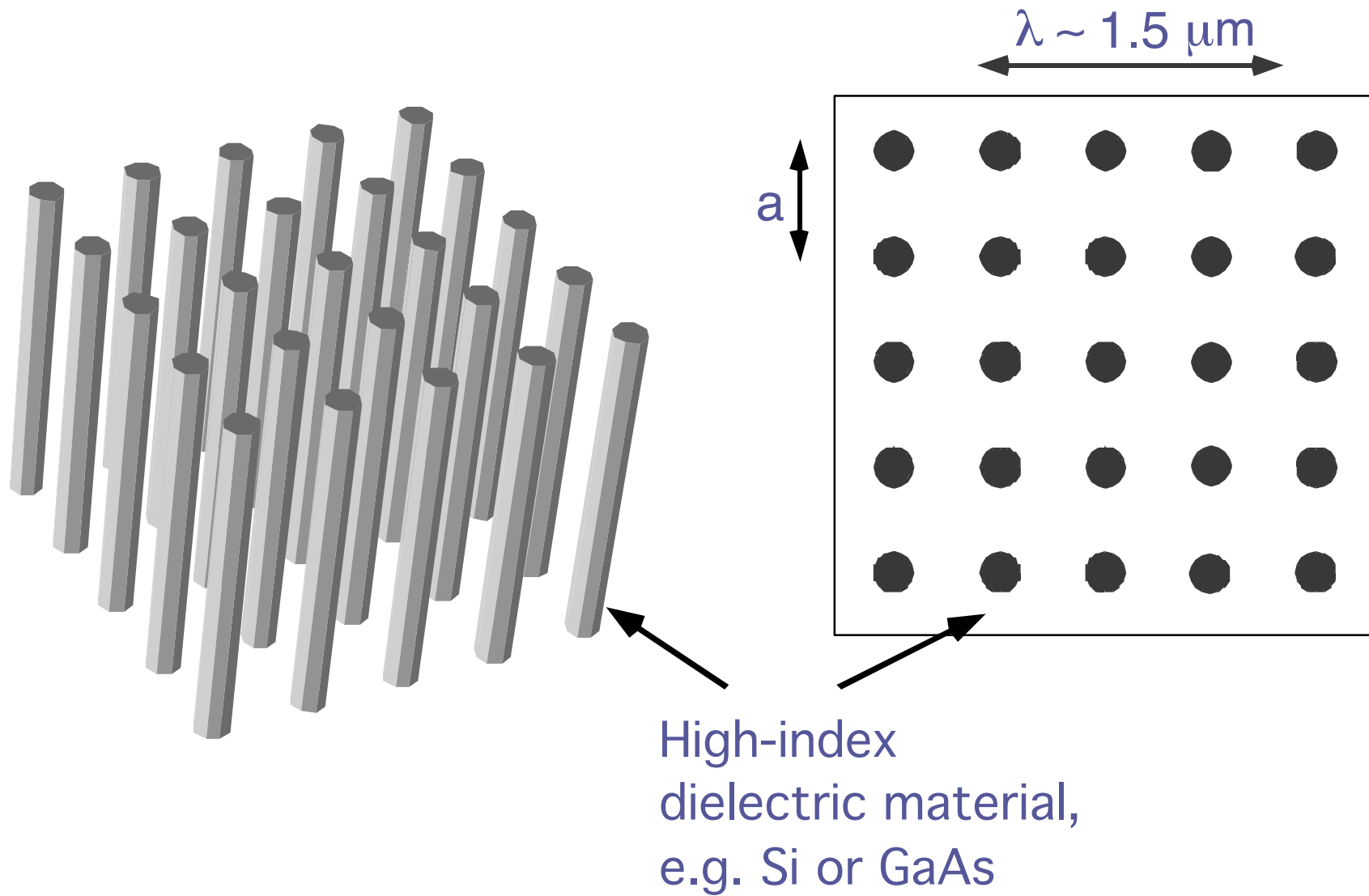
Lecture 6: Basic Properties of Electromagnetic Effects in Periodic Media



Lecture 6: Two-dimensional system

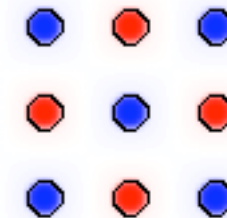
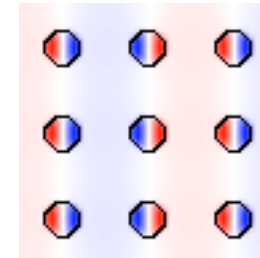
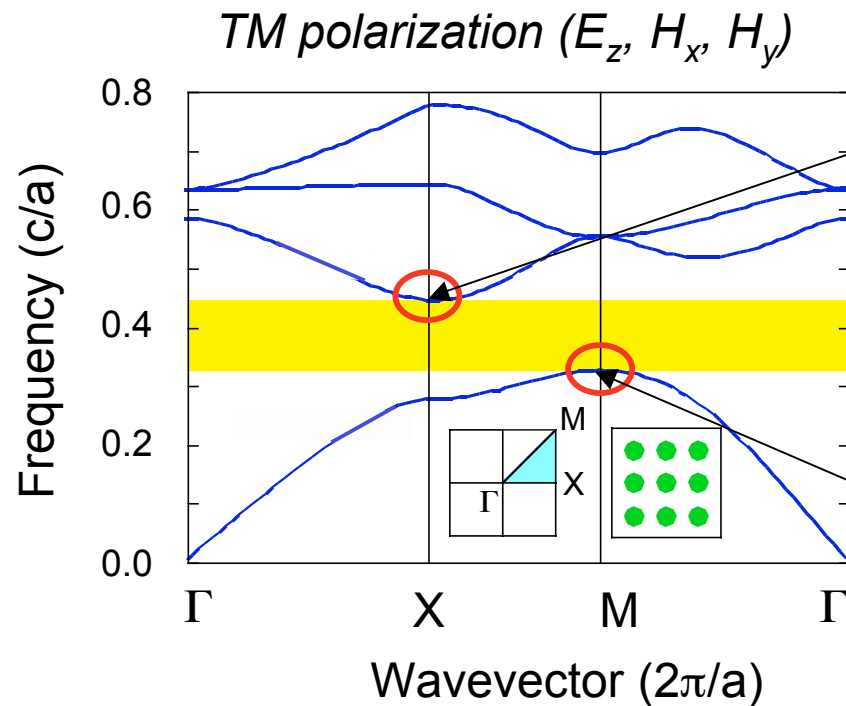
- *Overview of two-dimensional band structure.*
- *Surface and defect states.*
- *Optical components based upon defect states.*
- *Superprism and related effects in bulk crystals.*

Two-dimensional photonic crystal



Band structure of a two-dimensional crystal

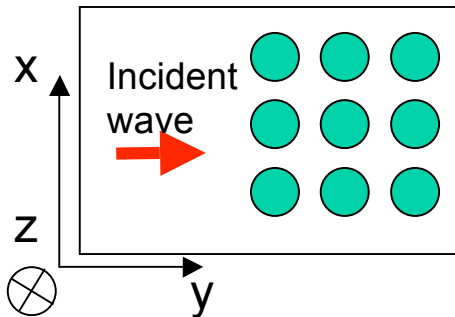
Electric field parallel to the cylinder



Axis of the cylinder along the z-direction

Gap region: where light can not propagate.
Band region: where light can propagate.

TE/TM polarization in two-dimensional system



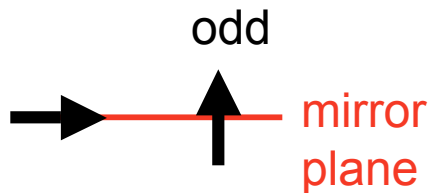
For waves that are propagating in the xy plane in a system that is uniform along the z -direction, the solutions of the system can be exactly separated in two polarizations:

TE polarization: only (H_z, E_x, E_y) are non-zero.

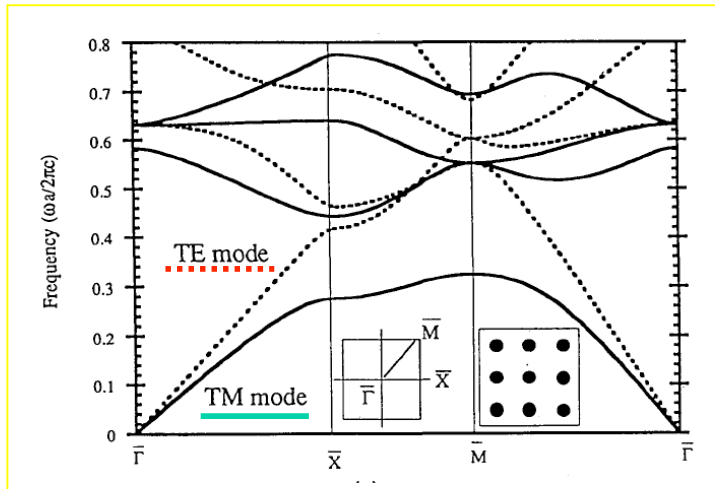
TM polarization: only (E_z, H_x, H_y) are non-zero.

Proof:

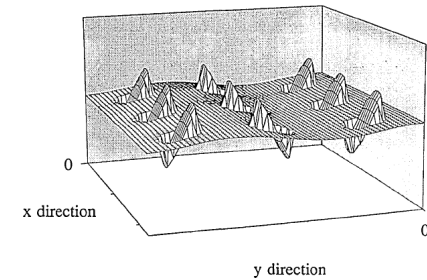
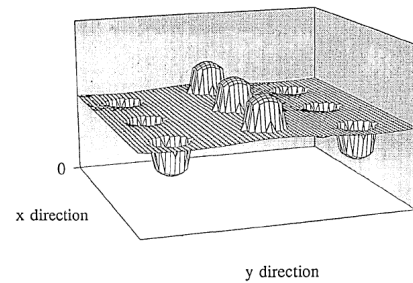
Let's focus on the E-field, $z=0$ is a mirror plane of the system. Thus the solution is only even or odd with respect to this mirror plane. On the plane $z=0$, if the field is even, then $E_z = 0$, and the only non-zero component for E are E_x and E_y . If the field is odd, then E_x and $E_y = 0$, and the only non-zero component for E is E_z . The fields however, are uniform along the z -direction, which proves the statement that we make about E.



Isolated structures favours TM gap

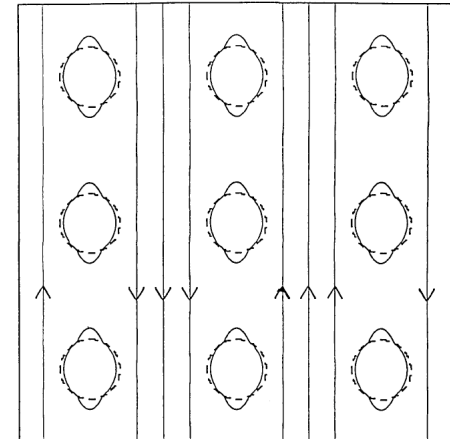
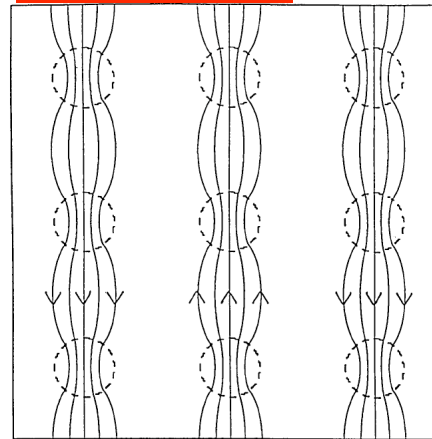


TM modes (E_z)

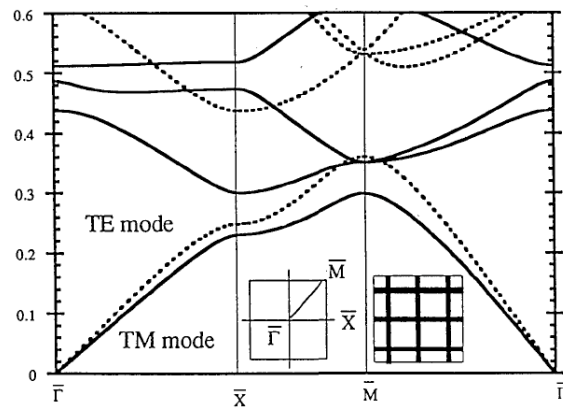


- Large TM band gap and small TE band gap for structures with isolated dots.
- Notice the displacement field is confined in the high dielectric region in the TM case. And the displacement field has to extend into the air region in the TE case.

TE modes (E_x, E_y)

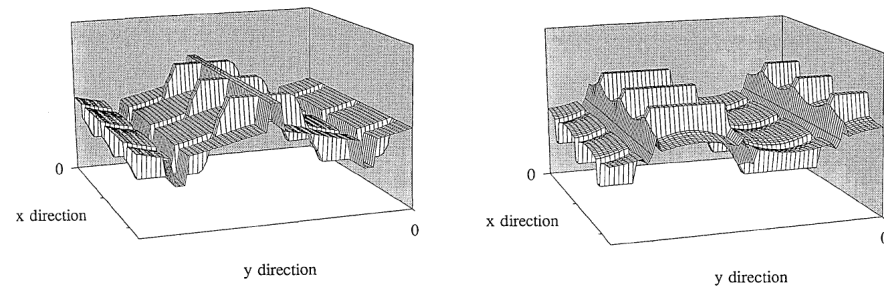


Connected structure favour TE gap

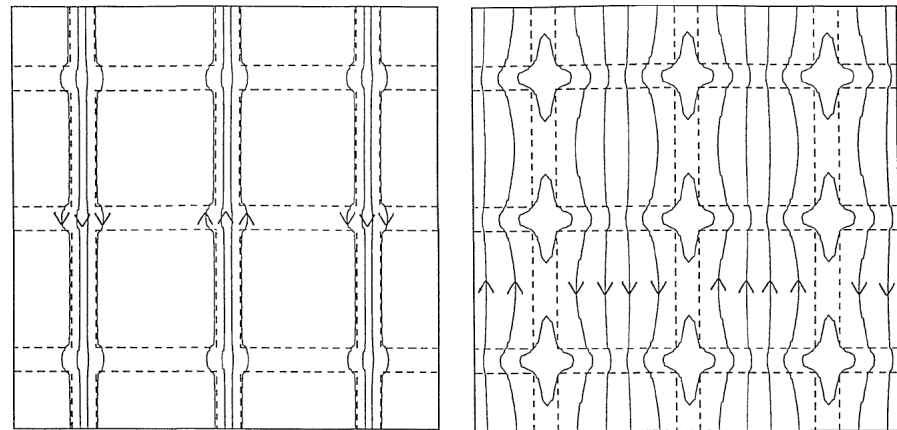


- Large TE band gap and small TM band gap for structures with connected dielectric networks.

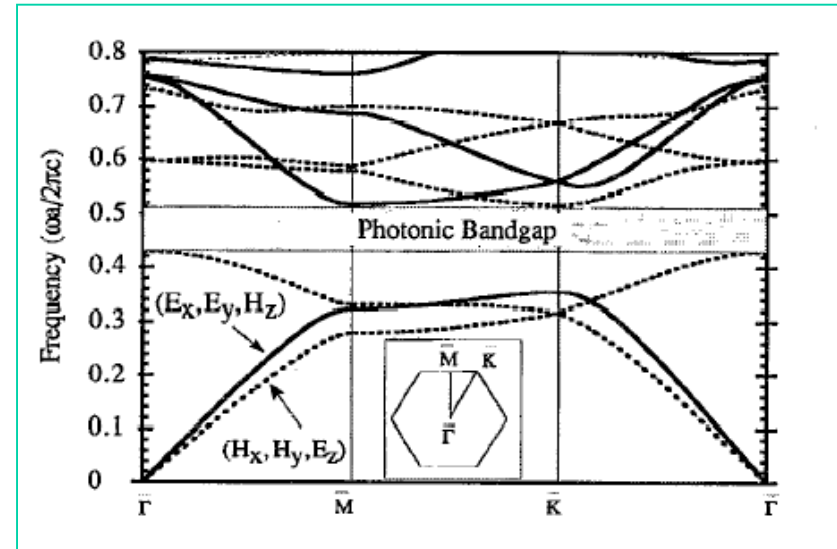
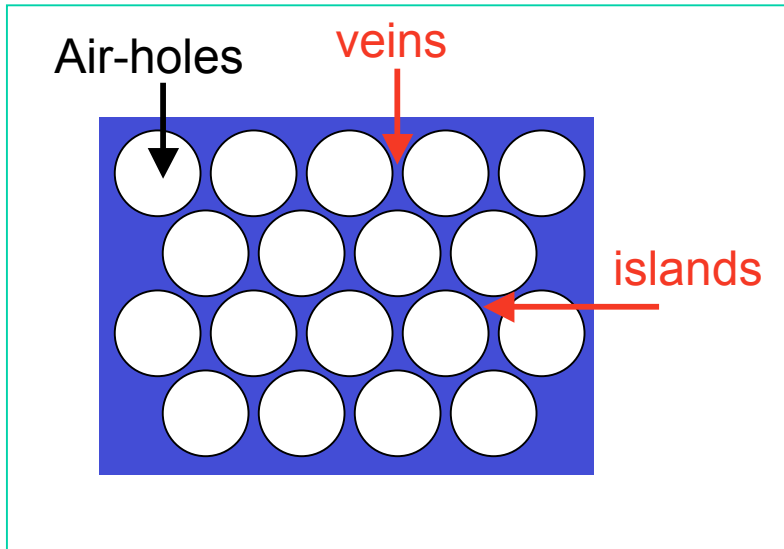
TM modes (E_z)



TE modes (E_x, E_y)

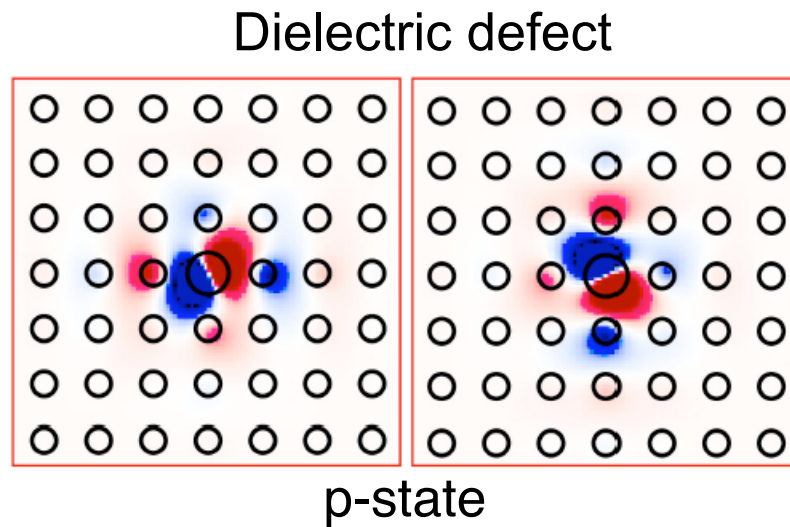
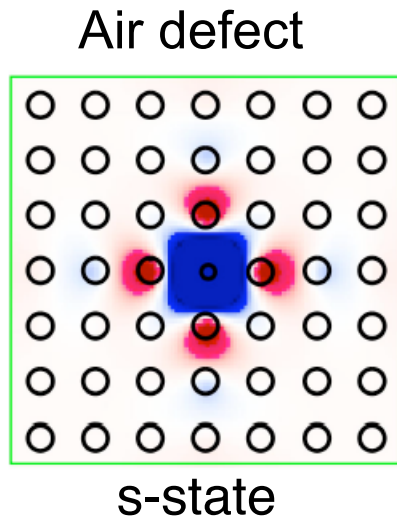
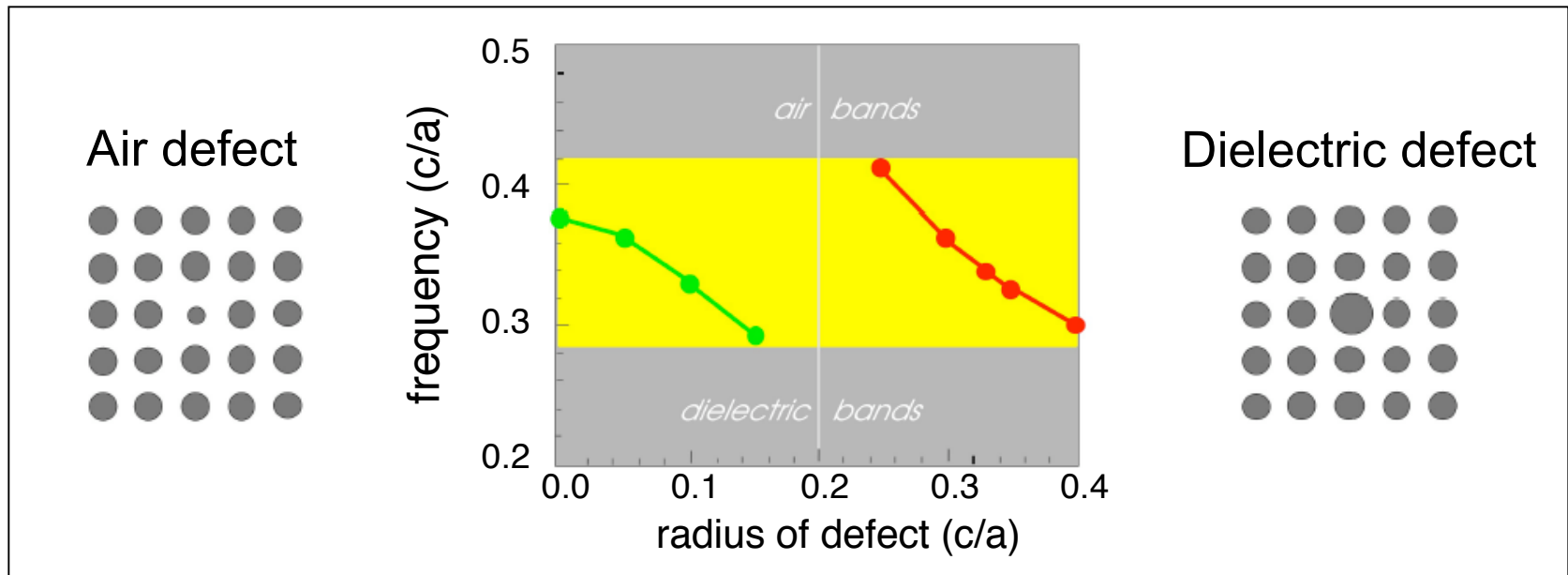


Triangular lattice of air holes

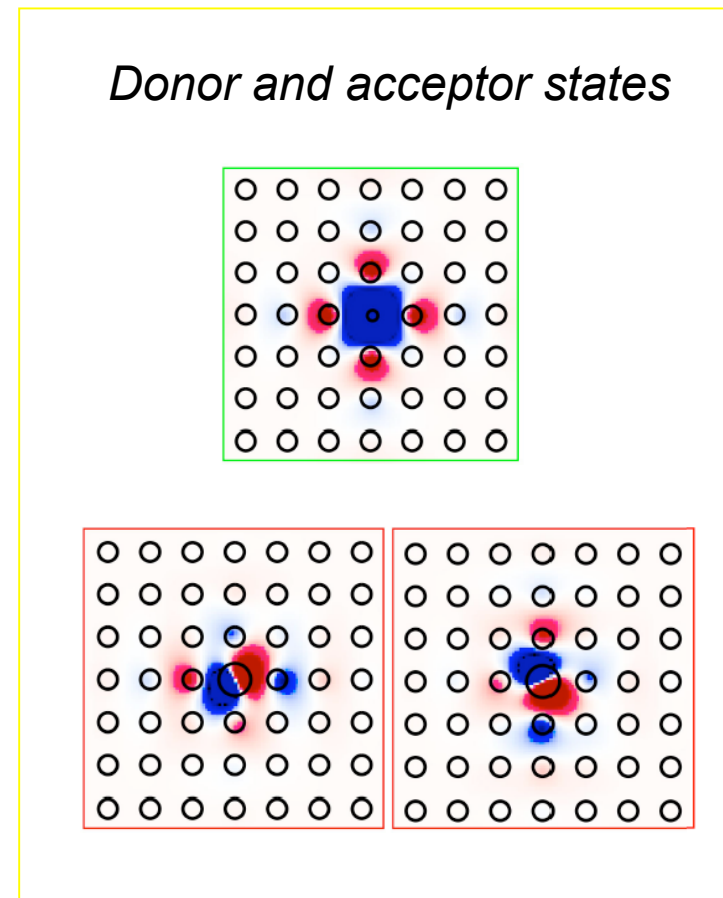
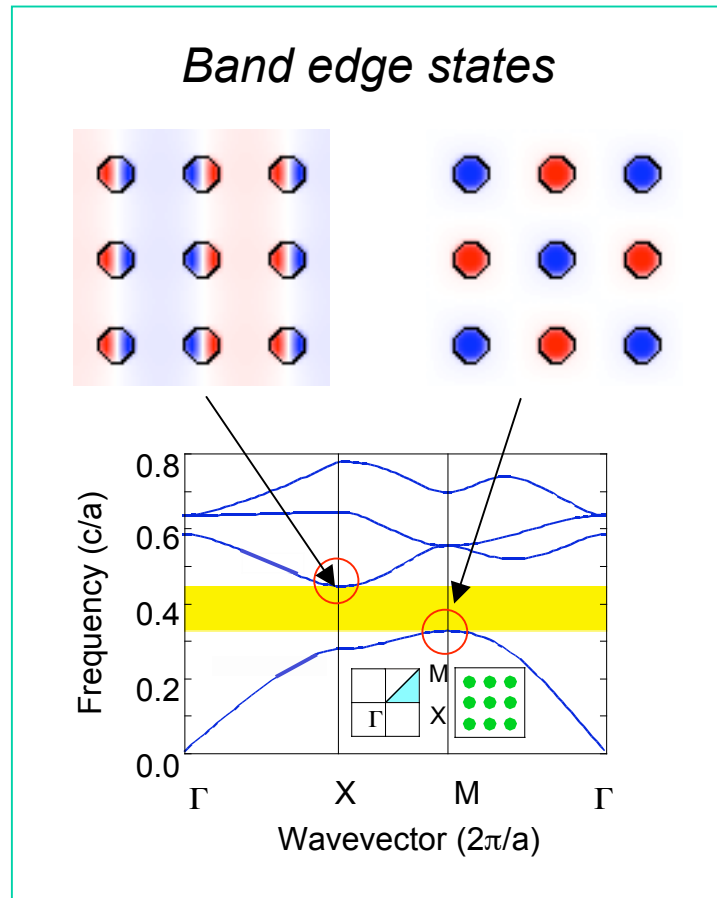


- *Isolated dielectric islands connected by thin dielectric veins. Large band gap for both polarizations.*
- *A near circular Brillouin zone for the triangular lattice also facilitates the enlargement of photonic band gap.*

Donor and Acceptor States



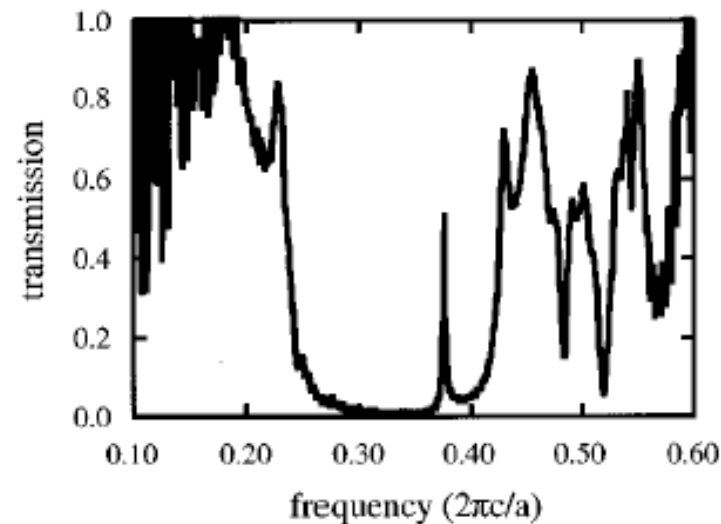
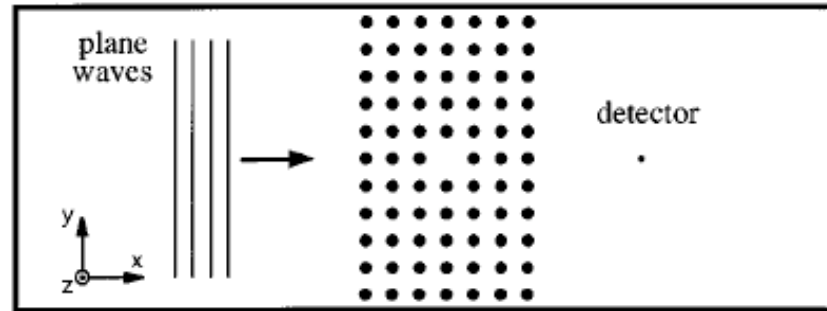
Connection of the defect states and band edge states



- Donor states are closely related to the states at the upper band edge.
- Acceptor states are closely related to the states at the lower band edge.

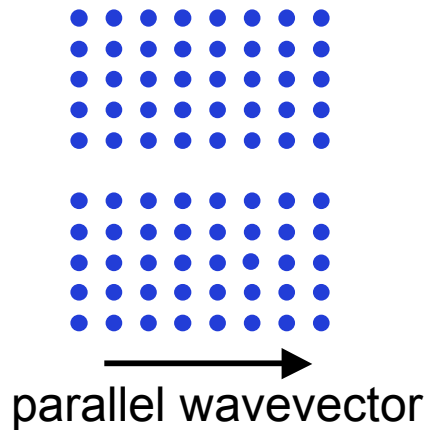
Resonant Tunneling into Defect States: Filters

- *No transmission in the band gap except at a defect state.*
- *Point defect state has well defined frequency.*
- *For the incident wave, only when the frequency coincides with the defect frequency will transmission occur.*

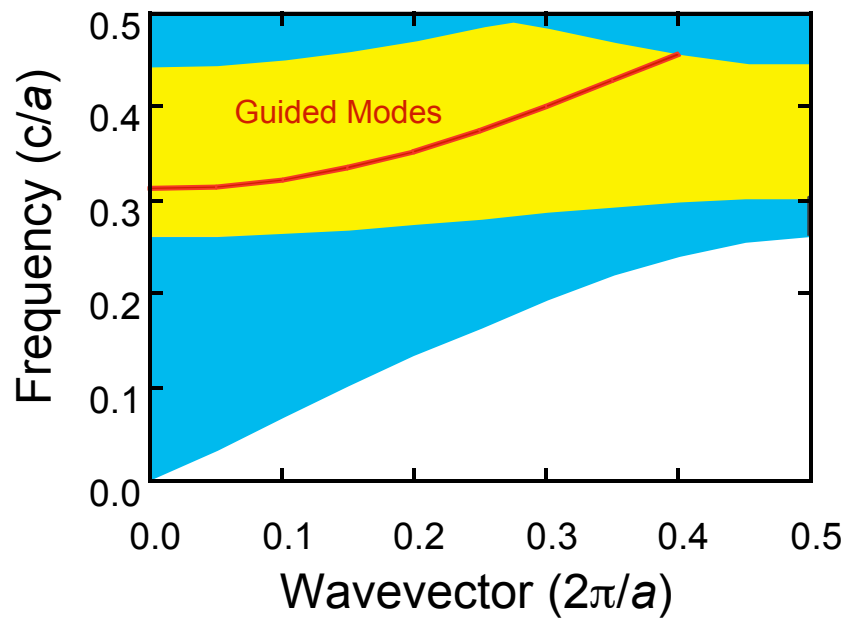
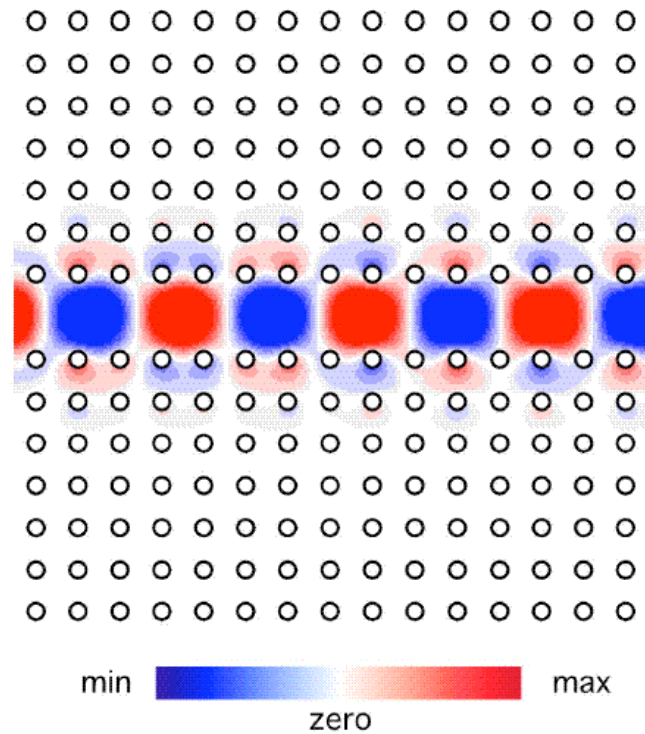


P. R. Villeneuve, S. Fan and J. D. Joannopoulos, Phys. Rev. B. 54, 7837 (1996).

Line defect states: projected band diagram

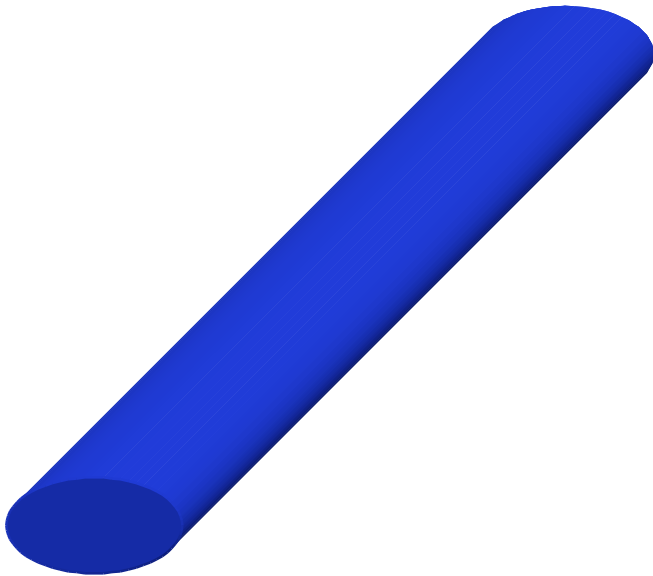


Electric field



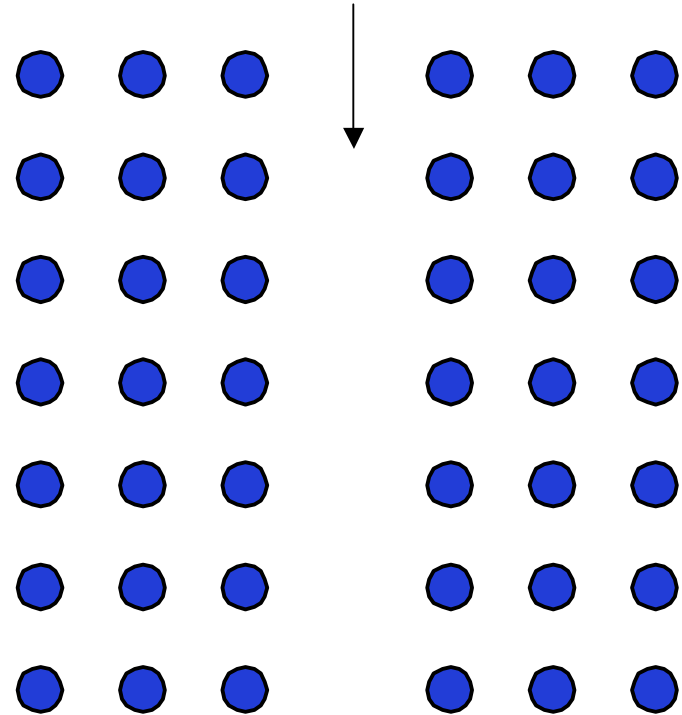
Photonic crystal vs. conventional waveguide

High-index region



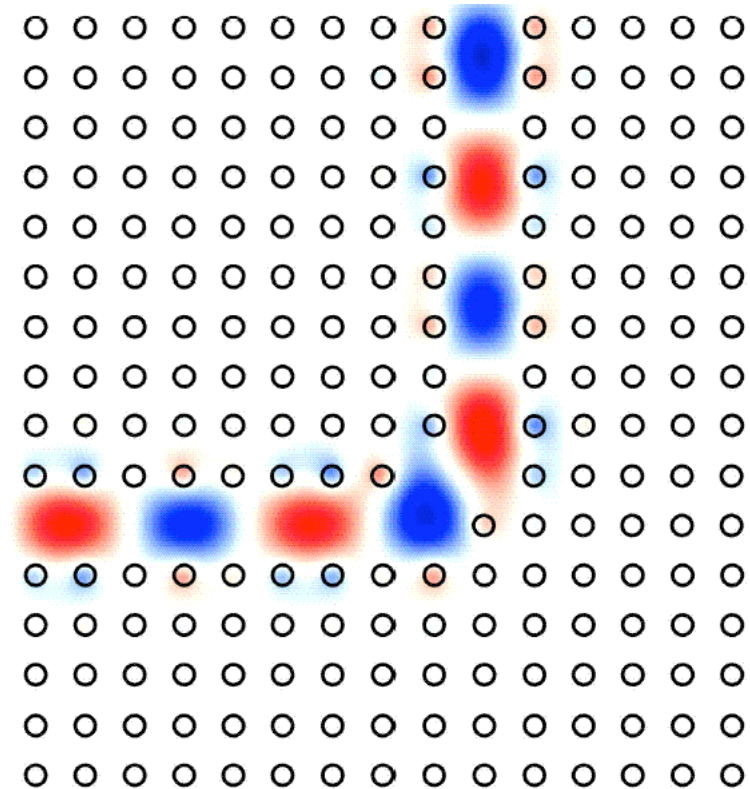
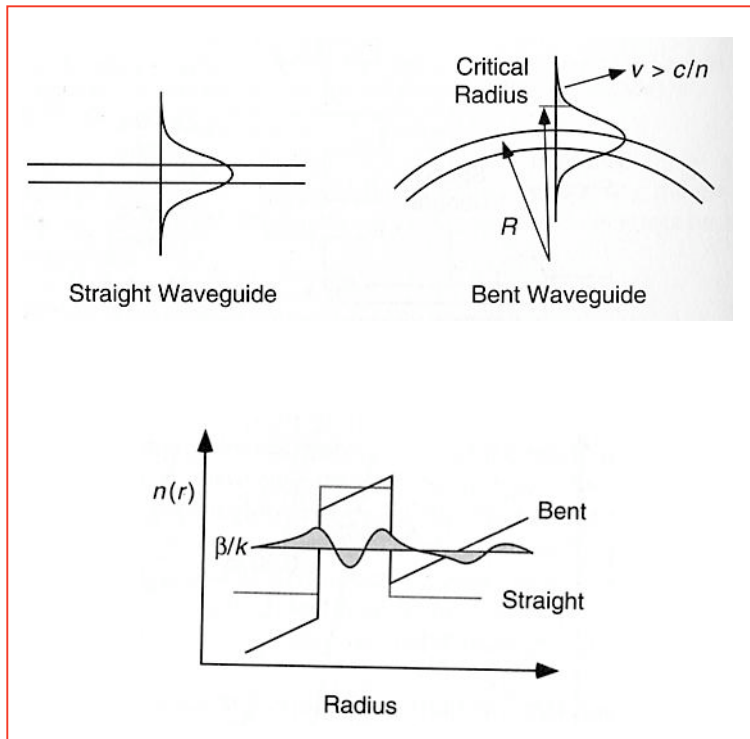
Conventional waveguide

Low index region



Photonic crystal waveguide

High transmission through sharp bends

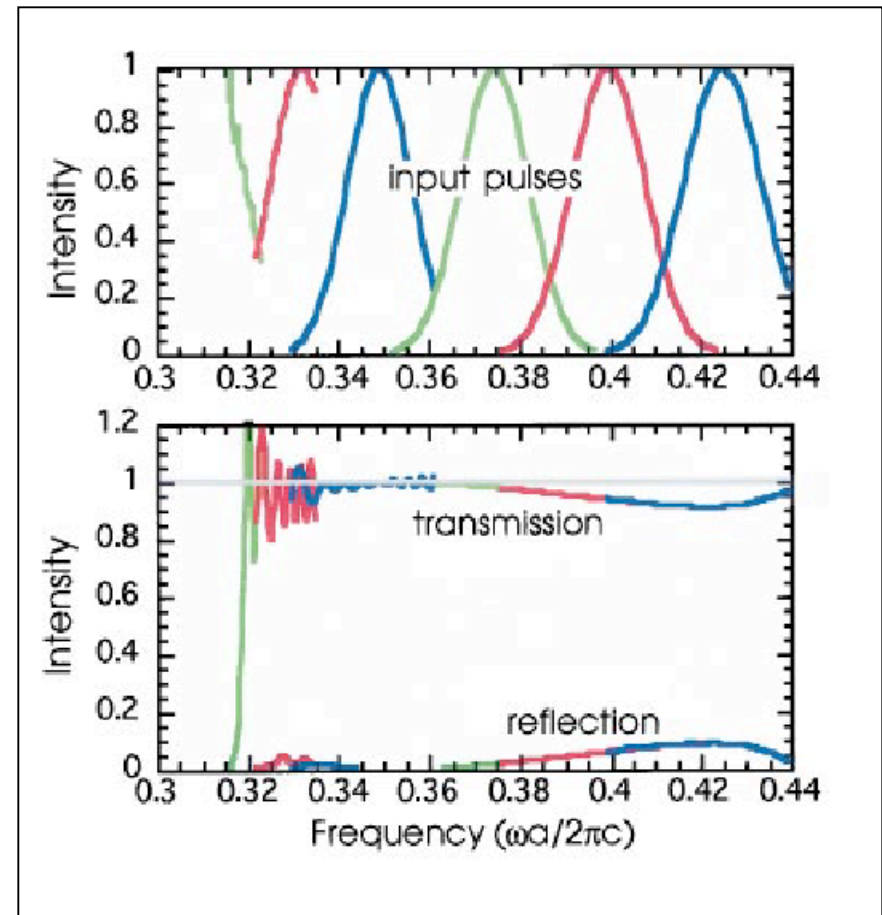
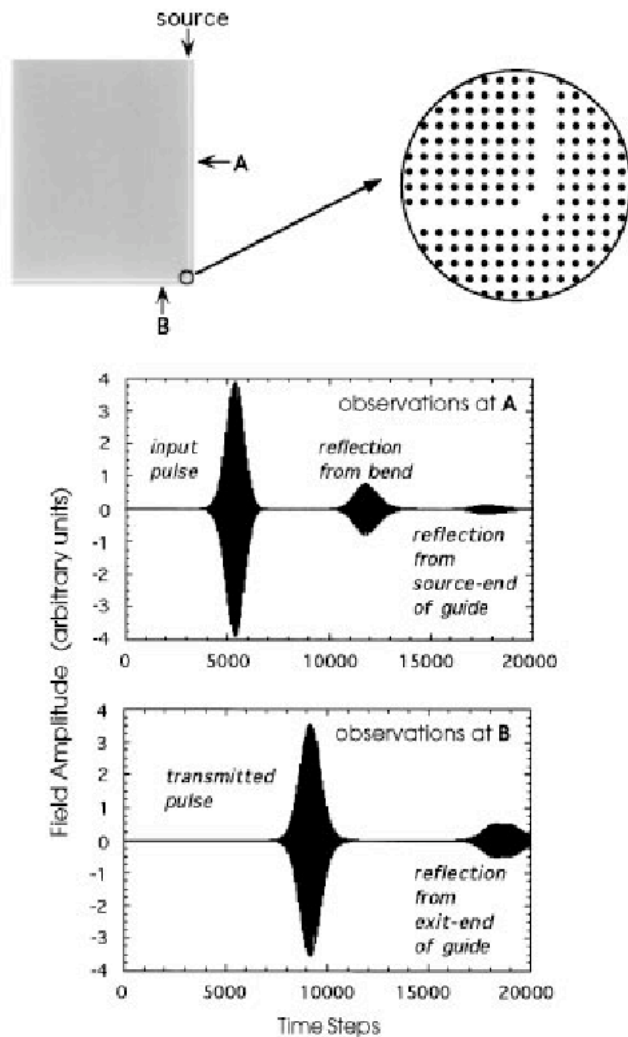


$$\alpha = \frac{1}{2} \left(\frac{\pi}{aV^3} \right)^{1/2} \left[\frac{\kappa a}{\gamma a K_1(\gamma a)} \right]^2 R^{-1/2} e^{-UR}$$

Polluck, Fundamentals of Optoelectronics, 1995

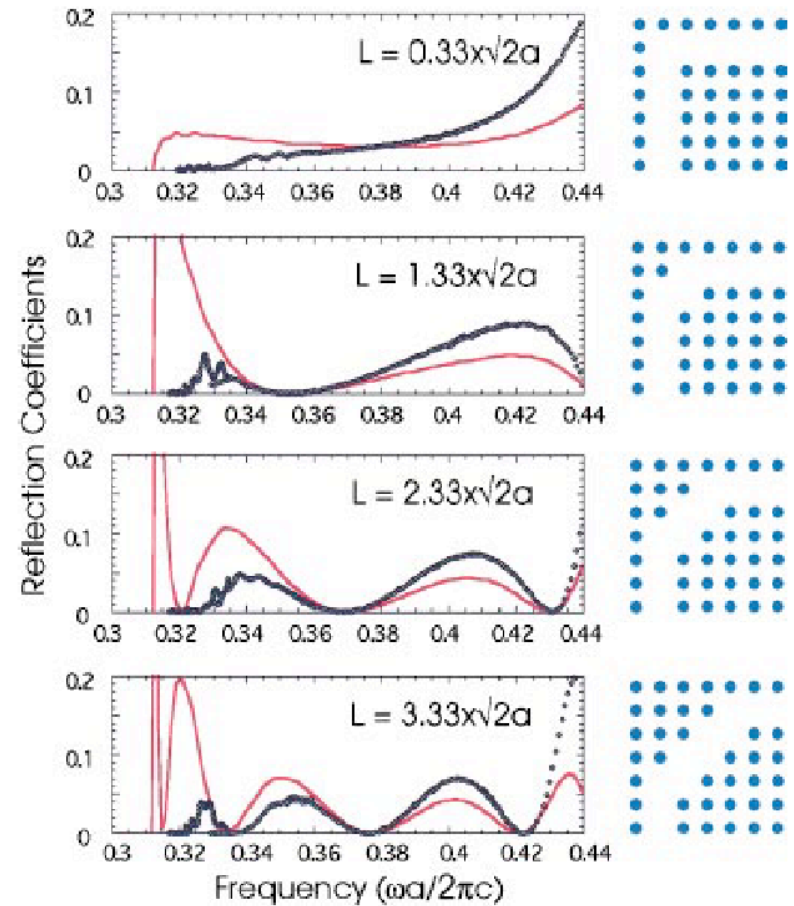
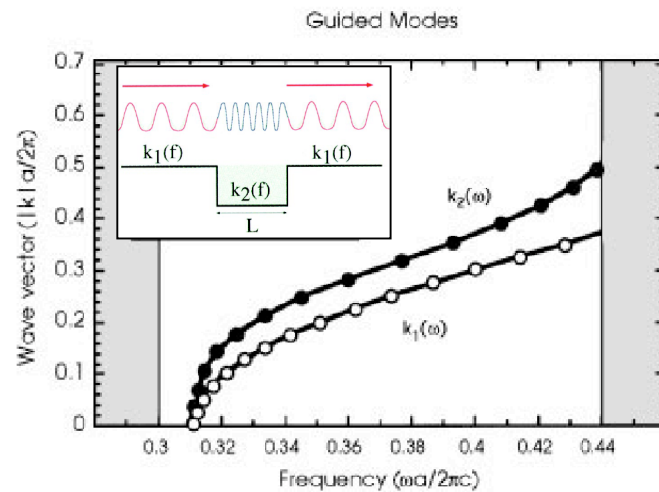
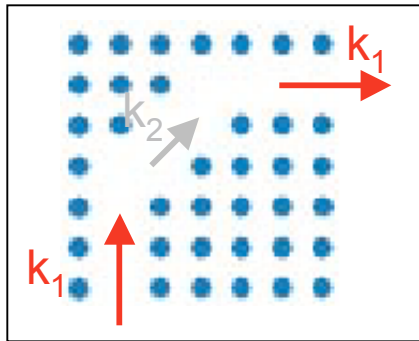
A. Mekis et al, PRL, 77, 3786 (1996)

Numerical simulation of waveguide bends



A. Mekis, J. C. Chen, I. Kurland, S. Fan, P. R. Villeneuve, and J. D. Joannopoulos, *Physical Review Letters* **77**, 3787 (1996).

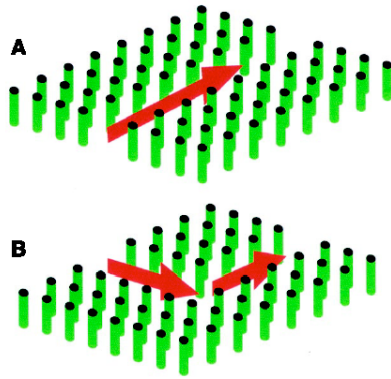
One-dimensional model for waveguide bends



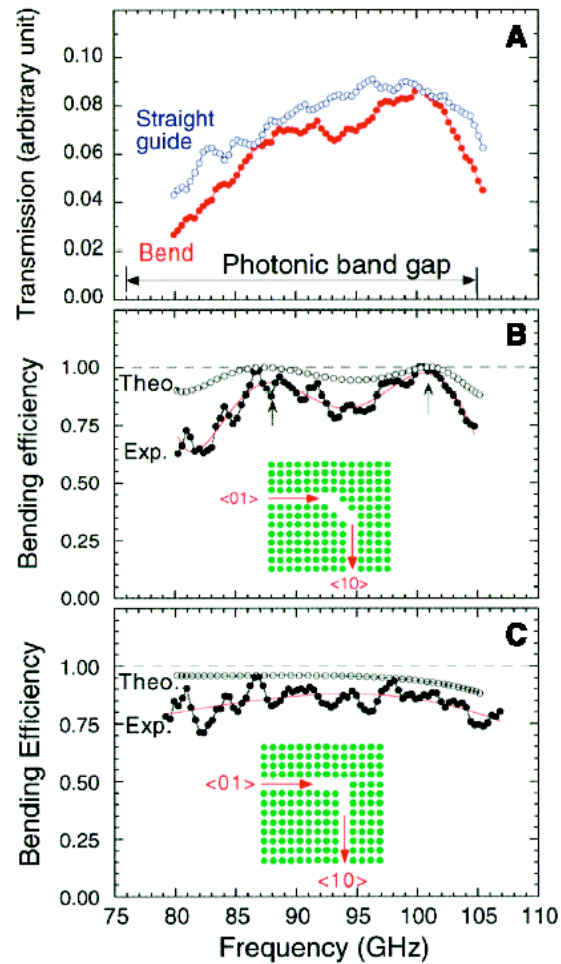
$$R(\omega) = \left[1 + \left(\frac{2k_1(\omega)k_2(\omega)}{[k_1^2(\omega) - k_2^2(\omega)] \sin[k_2(\omega)L]} \right)^2 \right]^{-1}$$

A. Mekis, J. C. Chen, I. Kurland, S. Fan, P. R. Villeneuve, and J. D. Joannopoulos, *Physical Review Letters* **77**, 3787 (1996).

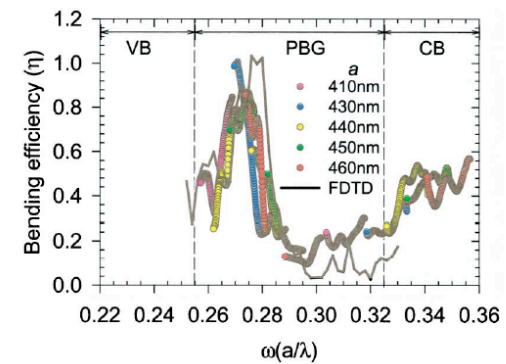
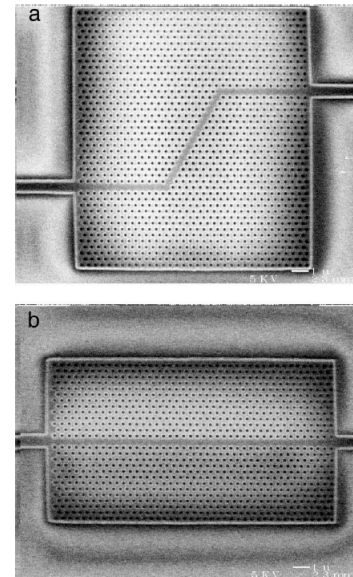
Experiments of waveguide bends



Alumina posts, lattice constant 1.27mm

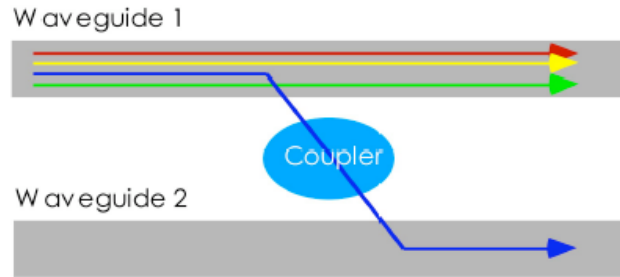


S. Lin et al, Science, 282, 274 (1999)

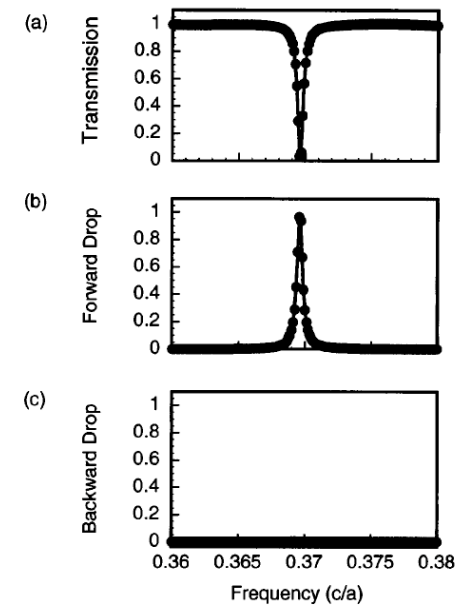
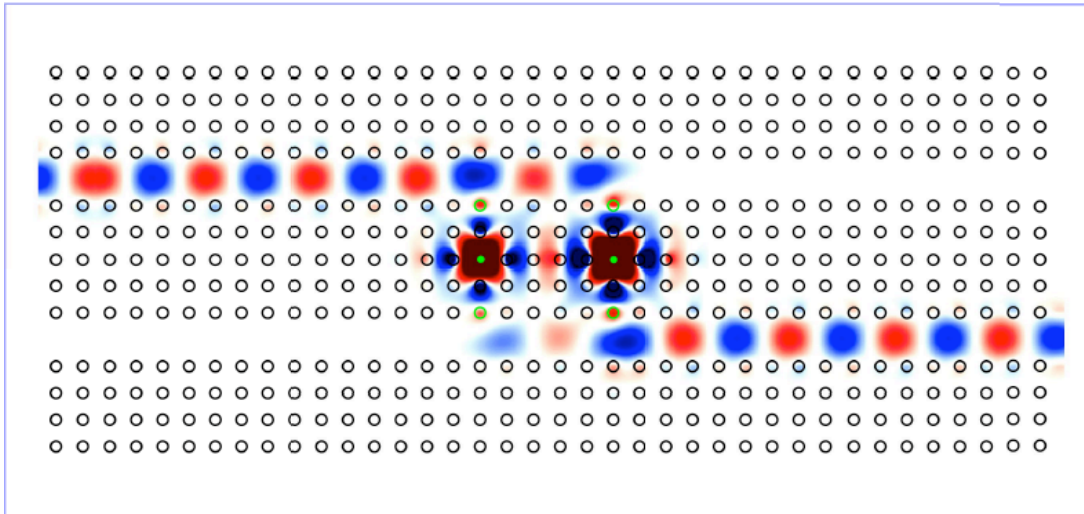


E. Chow et al, Optics Letters, 26, 286 (2001)

Micro add/drop filter in photonic crystals

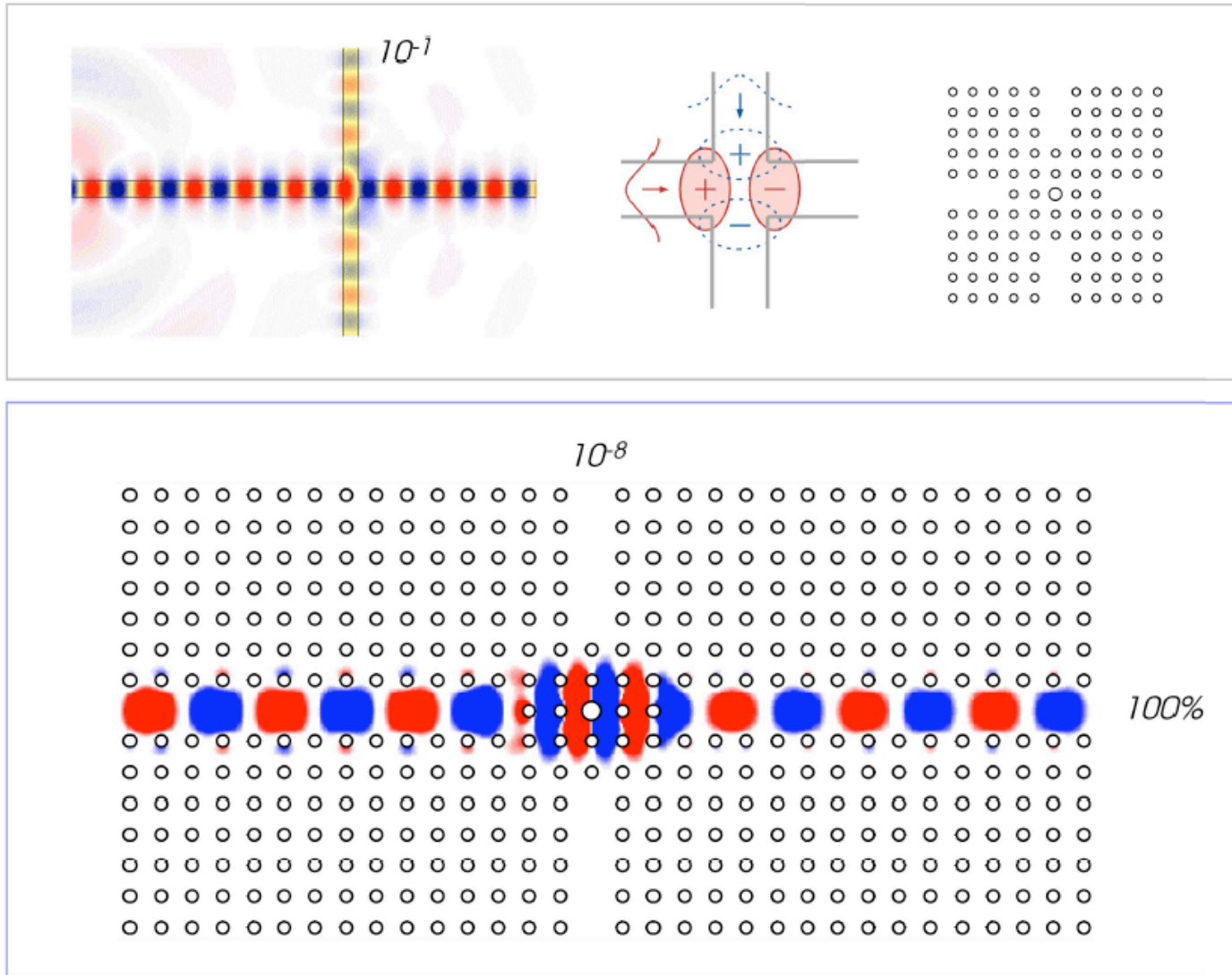


- *Two resonant modes with even and odd symmetry.*
- *The modes must be degenerate.*
- *The modes must have the same decay rate.*



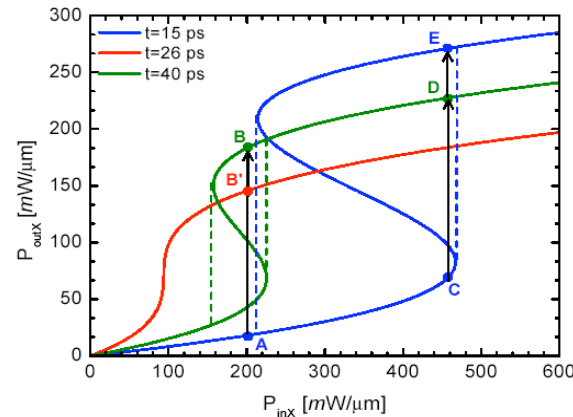
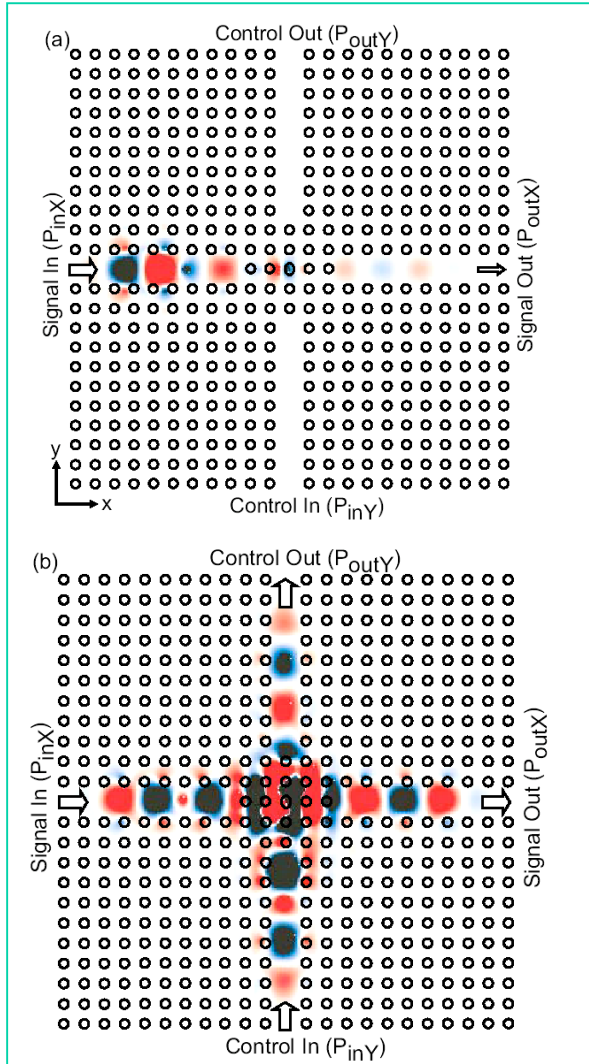
S. Fan, P. R. Villeneuve, J. D. Joannopoulos, and H. A. Haus, Physical Review Letters 80, 960 (1998).

Elimination of cross talk in waveguide crossings



S. G. Johnson, C. Manolatou, S. Fan, P. R. Villeneuve, J. D. Joannopoulos, and H. A. Haus, *Optics Letters* **23**, 1855 (1998).

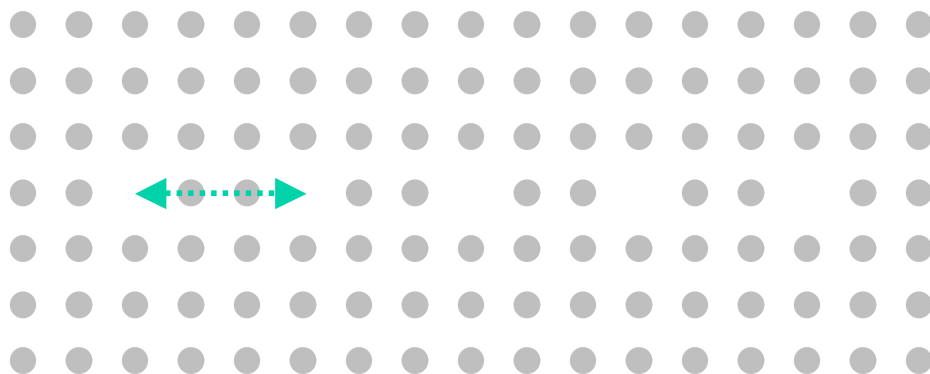
Micro-optical transistor in photonic crystals



- *Instantaneous Kerr nonlinearity at the cross-section of the waveguide.*
- *Fractional index shift required smaller than 10^{-4} .*
- *Low power (mW) and fast (ps) switching action with speed exceeding 10Gbit/s applications.*
- *Small footprint. A few micron square in area.*
- *No energy exchange between the control and the signal even in the nonlinear regime. Exact spatial and spectral separation for signal and control.*

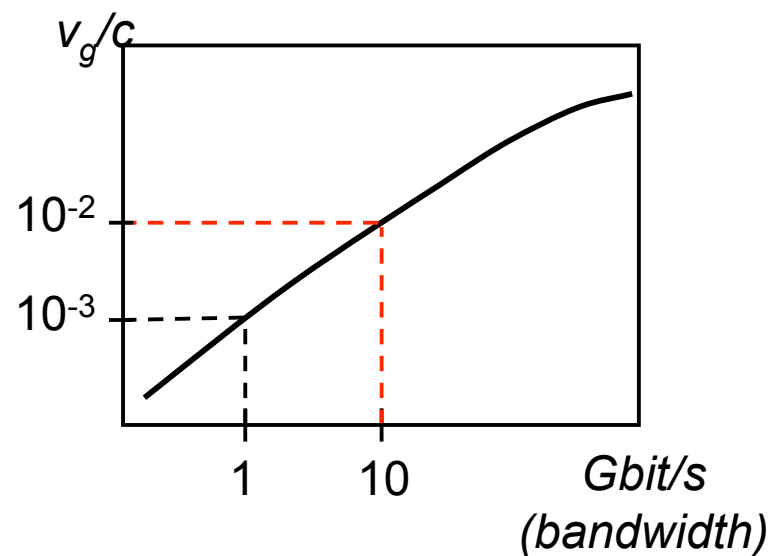
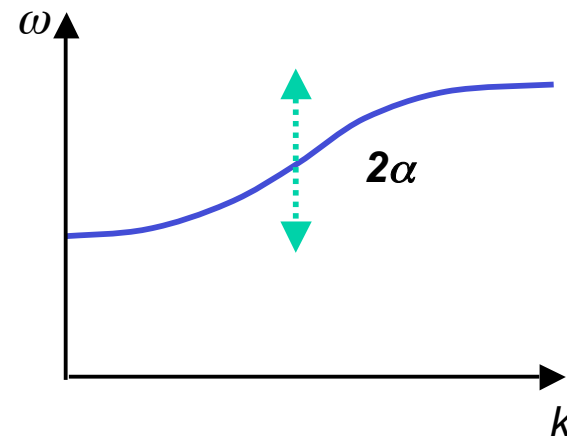
Slowing down light with static resonator

Coupled Resonator Optical Waveguide (CROW)
Stefanou et. al. (1998), Yariv et. al. (1999)

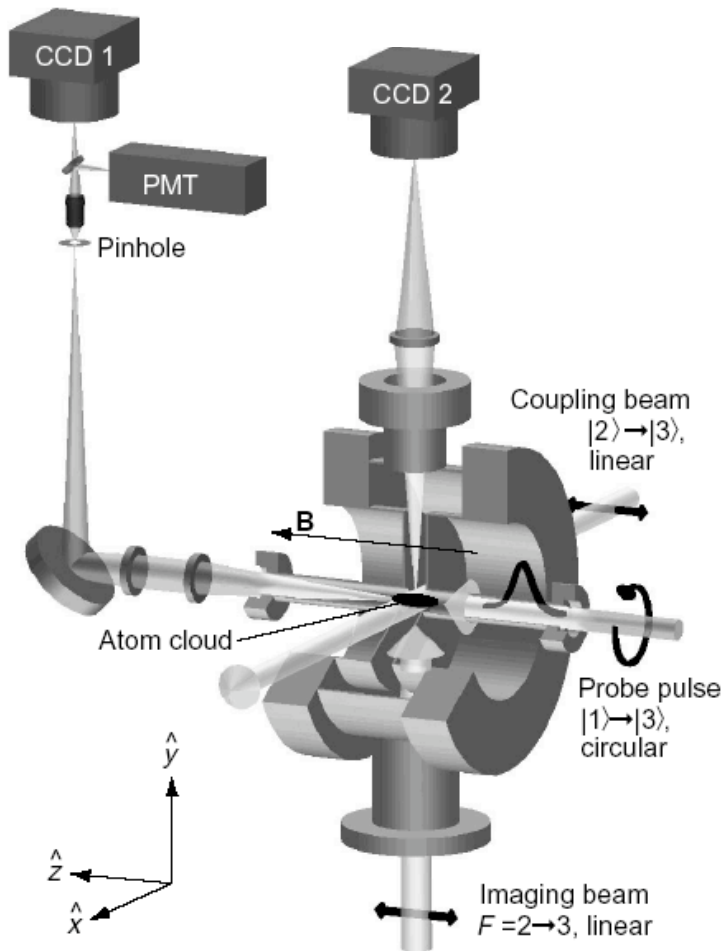


Photon tunnels between nearest neighbor cavity at a rate α

$$v_g = 2\alpha \cdot L$$



Towards All-optical Coherent Stopping And Storage Of Light



C. Liu et al, *Nature*, **409**, 490 (2001)
D. F. Philips et al, *PRL*, **86**, 783 (2001)

- **Using electronic states**

- Operation condition strongly constrained by atom properties
- Low temperature, ultra-high vacuum operations
- Very limited bandwidth, and wavelength flexibilities

- **Can one use optical resonators to stop light?**

