ECE 695
Numerical Simulations
Lecture 6: Photonic Bandstructures

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Outline

- Bandstructure symmetries
- 2D Photonic bandstructures
- Photonic waveguide bandstructures
- Photonic slab bandstructures
- 3D Photonic lattice types + bandstructures

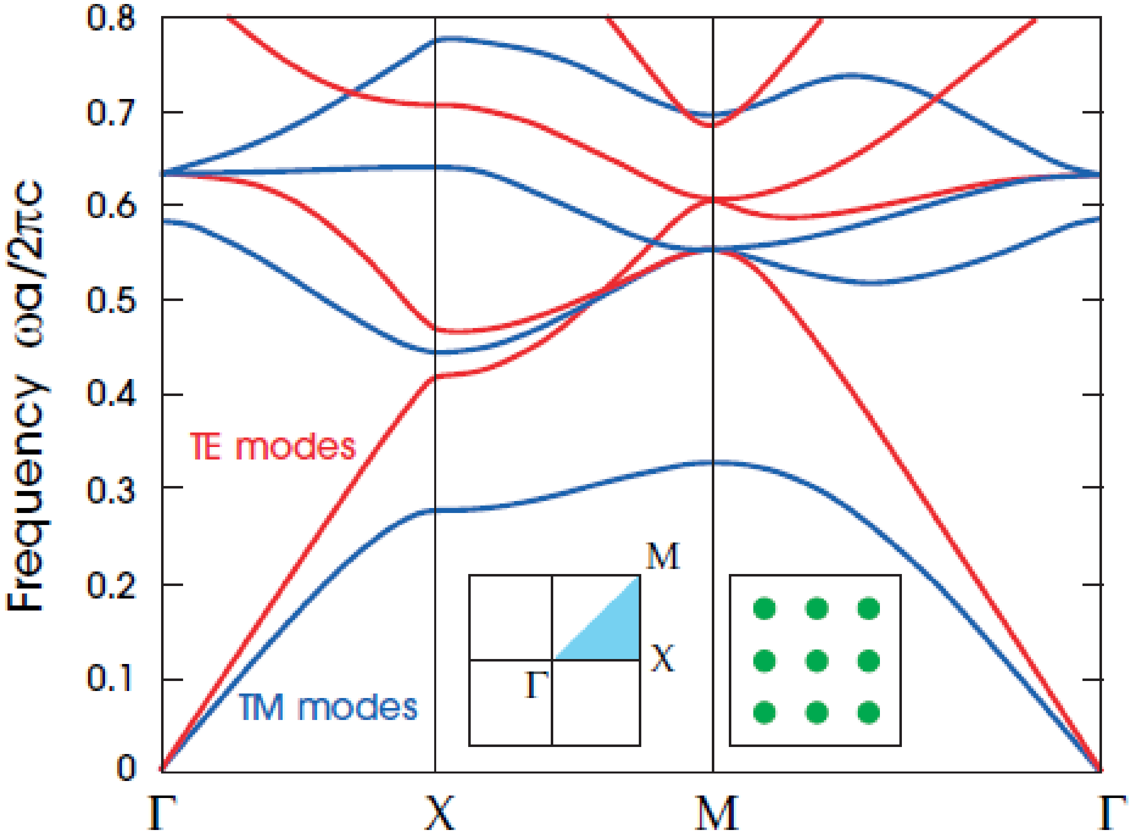
Bandstructure Symmetries

- Can be formally defined as operators that commute with eigenproblem operator
- Periodicity gives rise to *k* vectors and Brillouin zone
- Time-reversal invariance:
  - True for all Hermitian operators
  - Implies $\omega_n(k) = \omega_n(-k)$

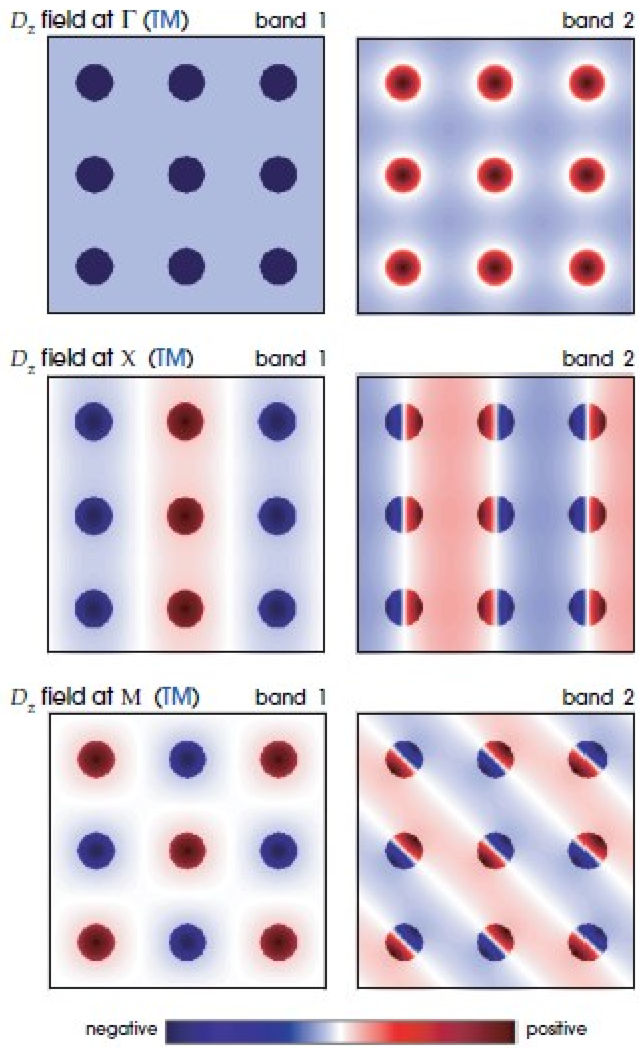
Bandstructure Symmetries

- Mirror-plane symmetries
  - Mirror reflection defined s.t. $\hat{M}H = \pm H$
  - In 2D, z-reflection gives rise to TE and TM polarizations
- Rotational symmetries
  - Defined s.t. $\omega_n(k) = \omega_n(\mathcal{R}k)$
  - $\mathcal{R}$ depends on crystallographic point group
  - In 2D, 3-fold, 4-fold, and 6-fold symmetries
  - Other symmetries give rise to quasicrystals

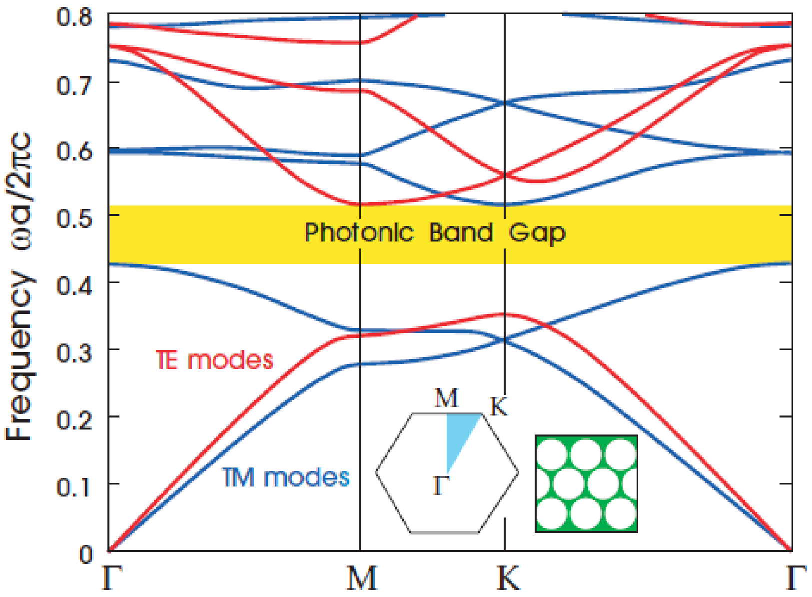
Photonic Bandstructures: 2D

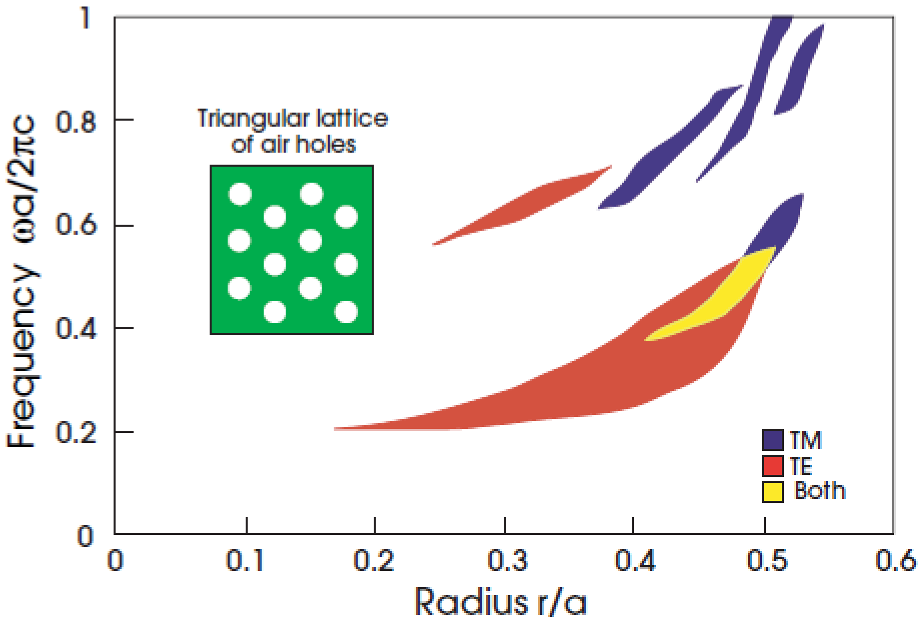


Photonic Bandstructures: 2D



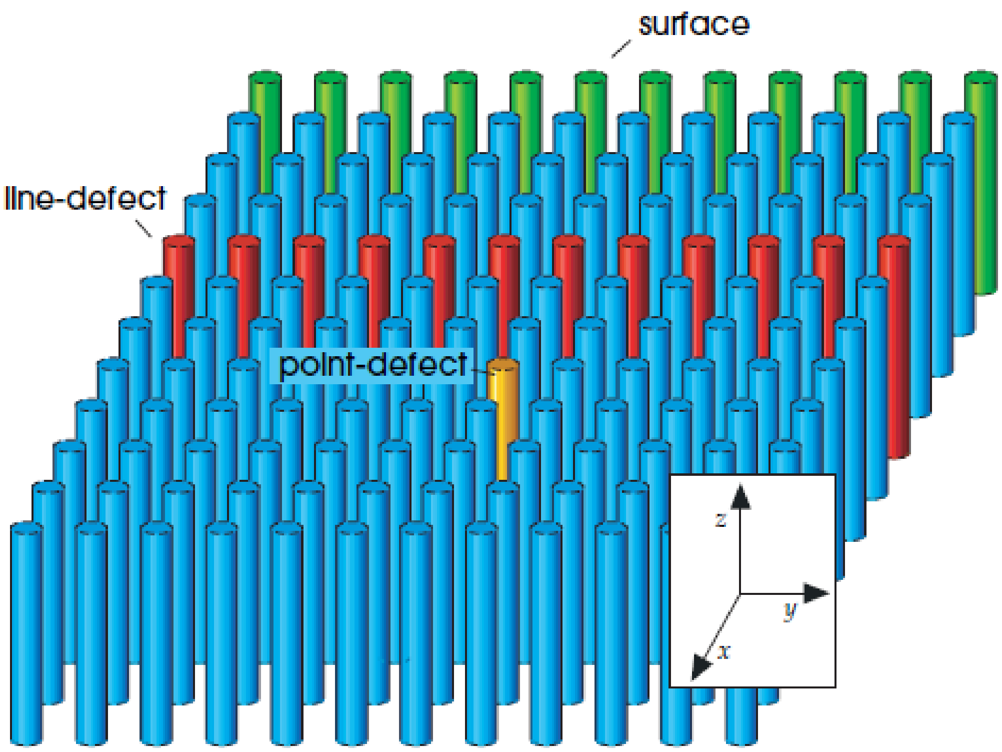
2D Photonic Crystals





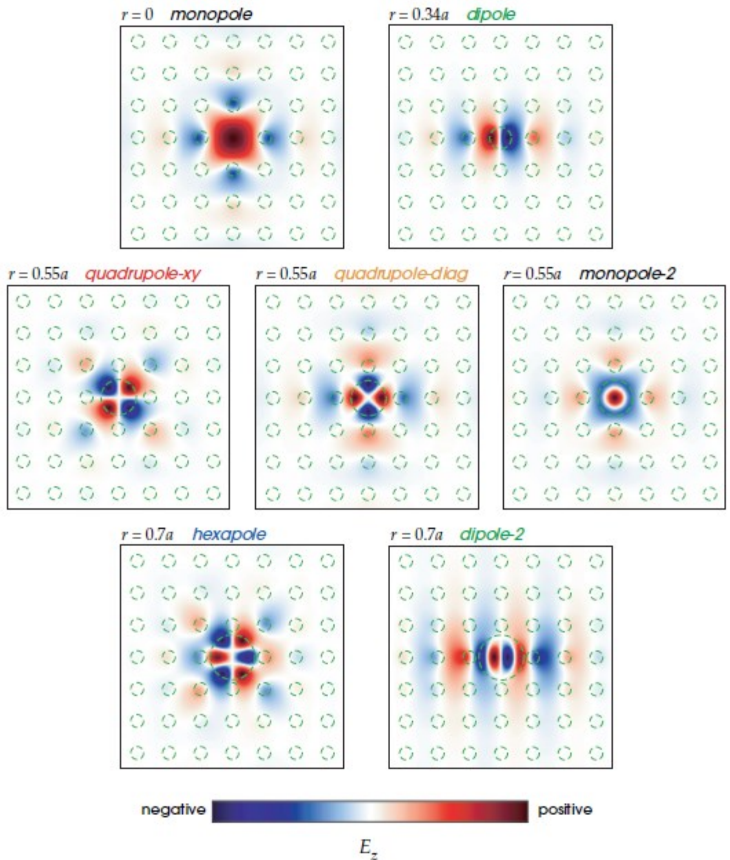
- 2D triangular lattice can give rise to band gap for all polarizations for certain radii

2D Photonic Crystals



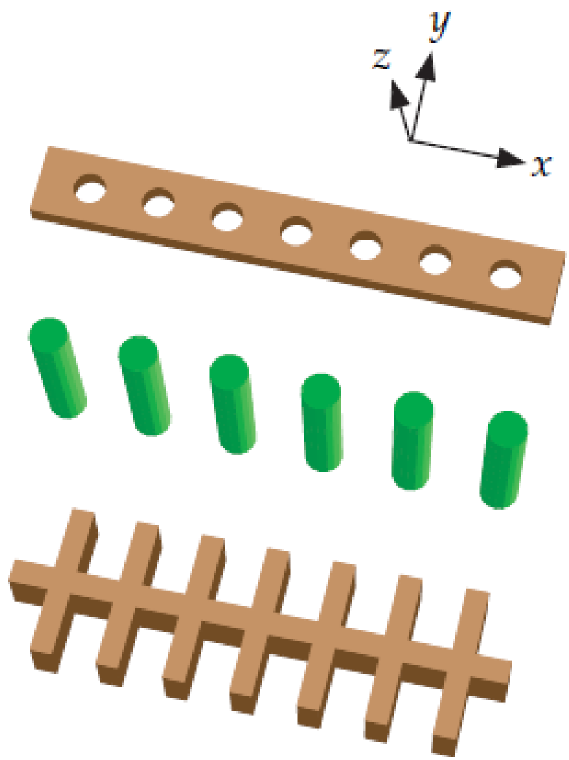
- Introducing defects can give rise to states in the bandgap

2D Photonic Crystals



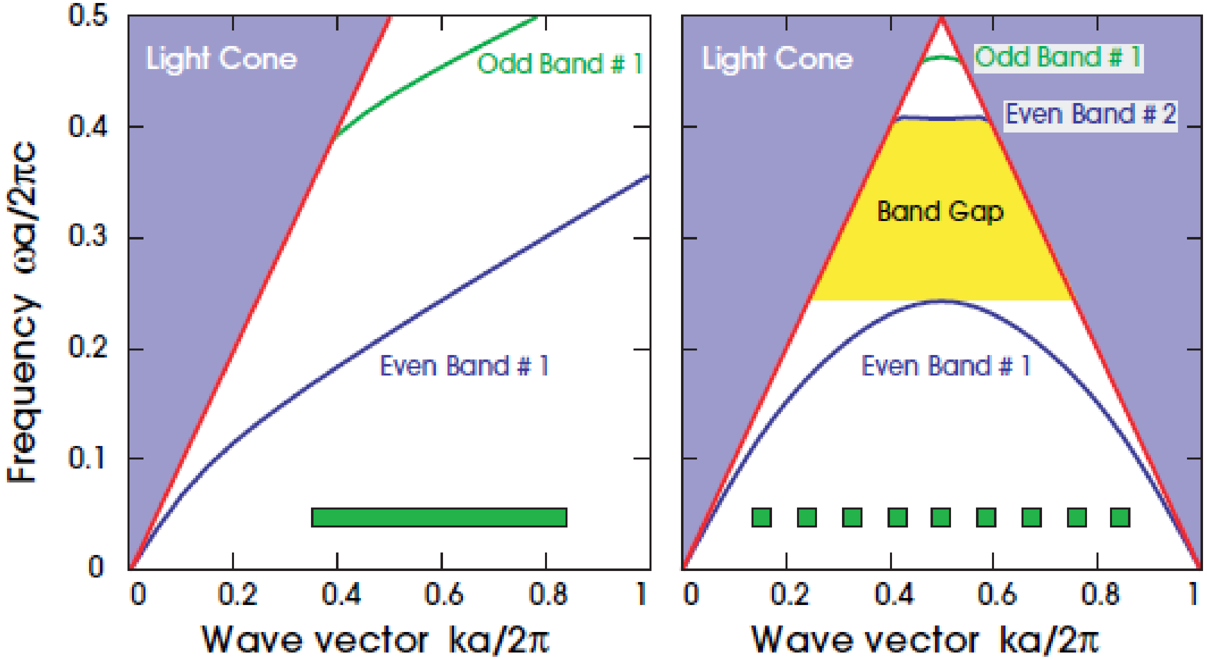
- Various localized modes observed front a point defect in a square lattice of rods

Periodic Dielectric Waveguides



- To confine light to a small volume, can combine a 1D photonic crystal with index guiding in other 2 dimensions

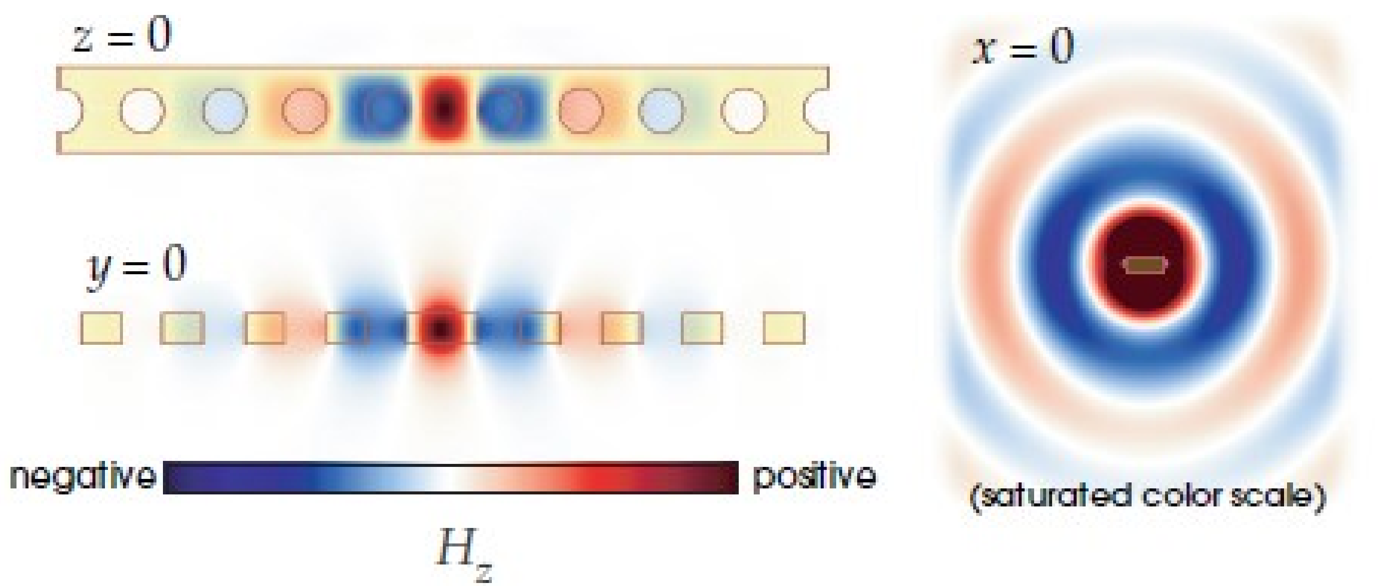
Periodic Dielectric Waveguides



Uniform index waveguide Periodic graded waveguide

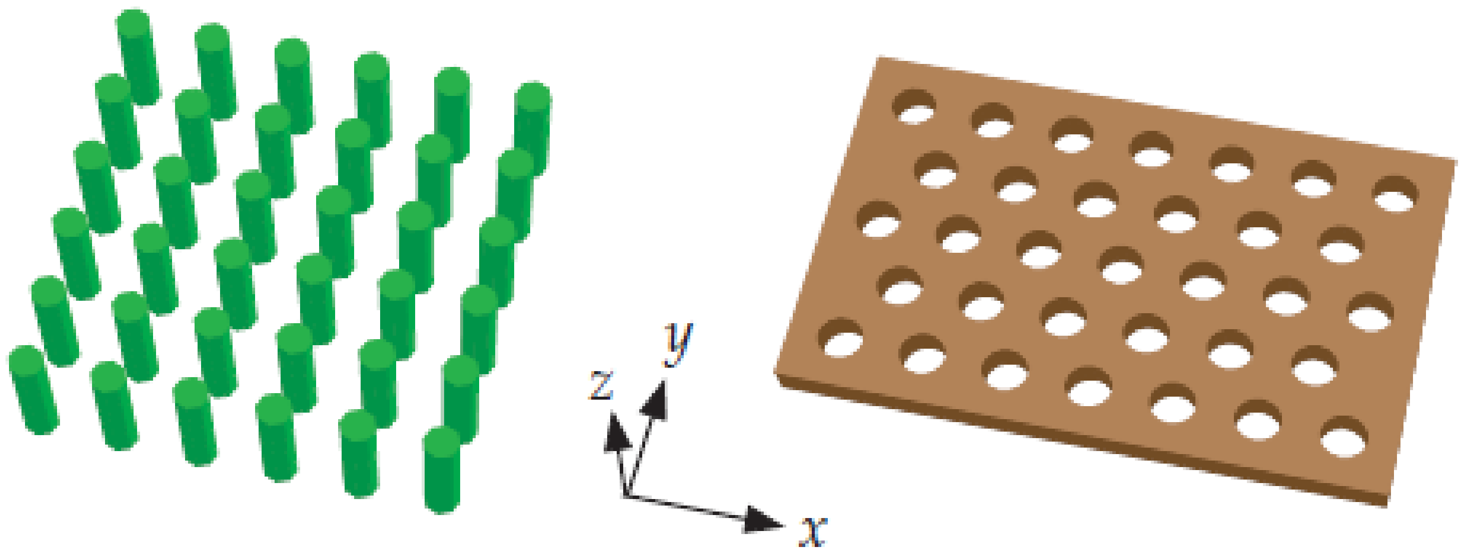
- Bandstructures for index-guided waveguides
- Introducing periodicity restricts Brillouin zone

Periodic Dielectric Waveguides



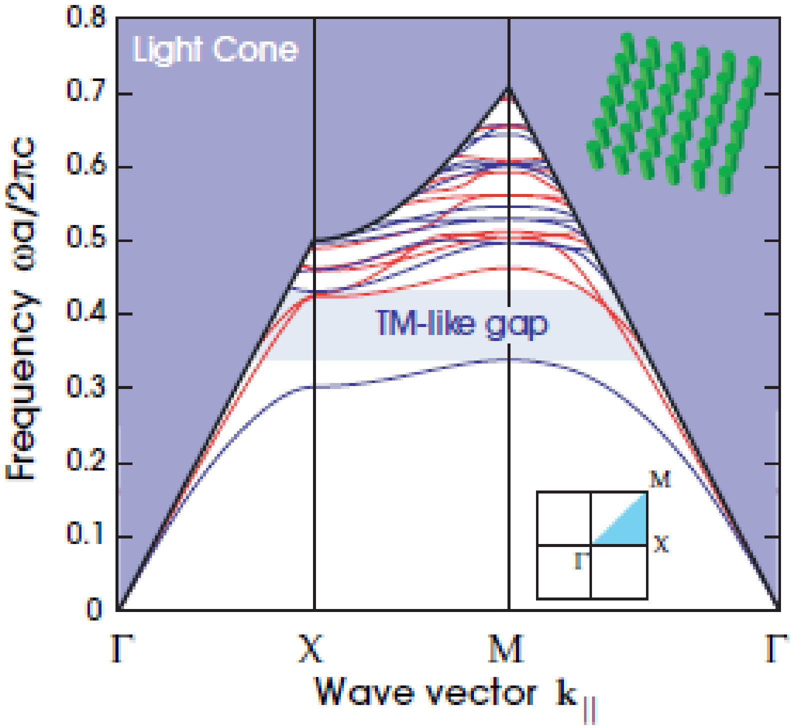
- Introducing a pointlike defect creates 3D confinement at one or more bandgap frequencies

Photonic Crystal Slabs

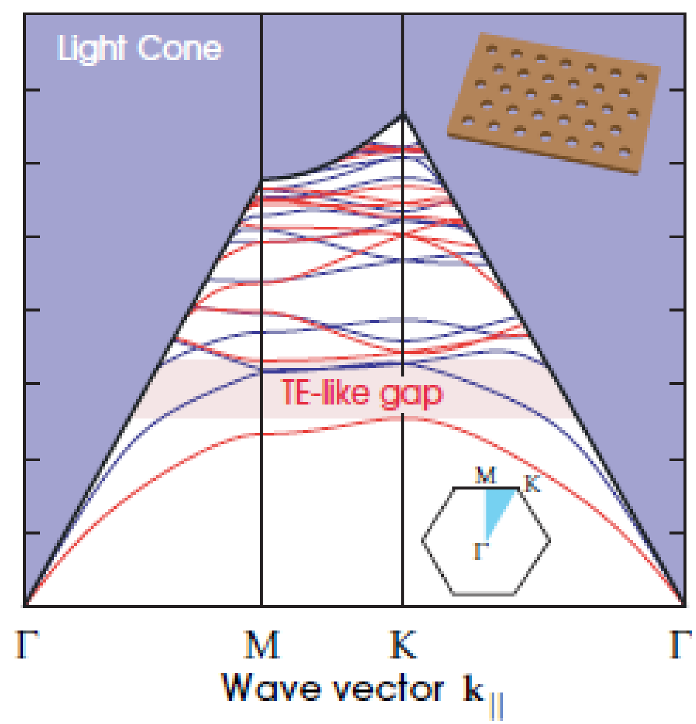


- To confine light in 3D, use bandgap in plane and index confinement out of plane

Photonic Crystal Slabs



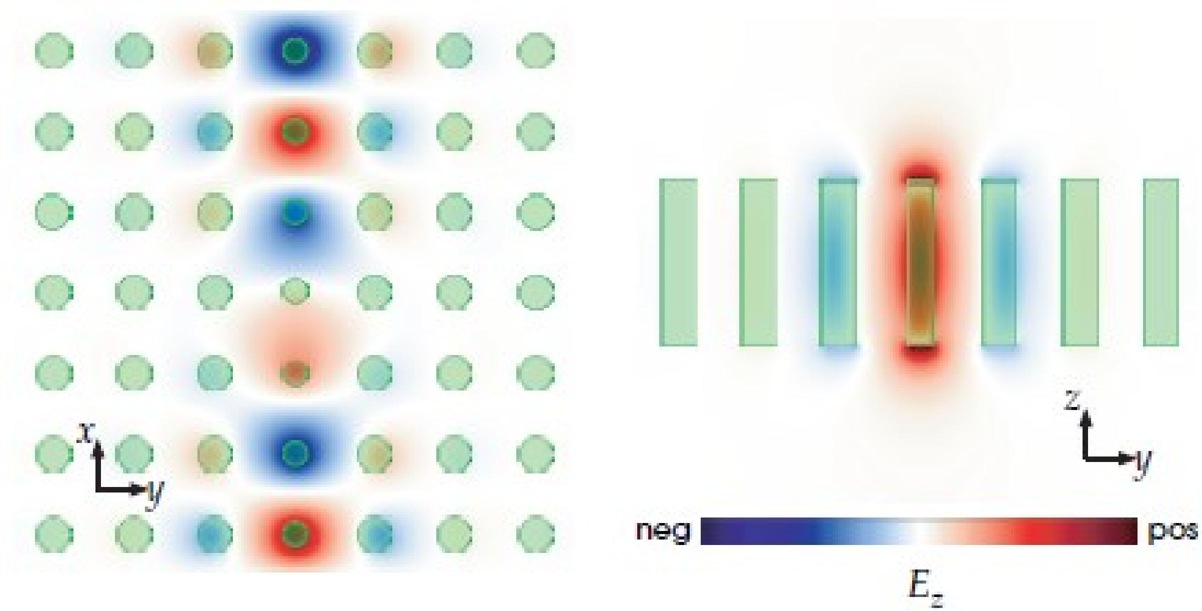
Square lattice of rods



Triangular lattice of holes

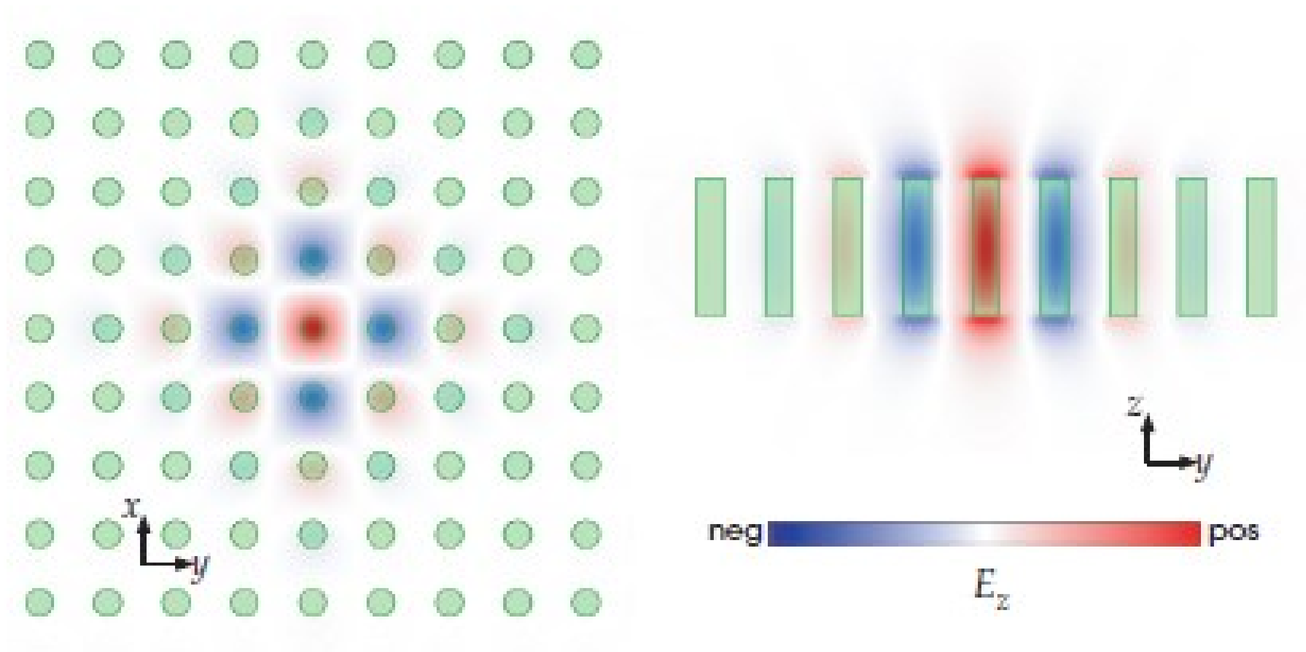
Photonic bandstructures for 2D slabs

Photonic Crystal Slabs



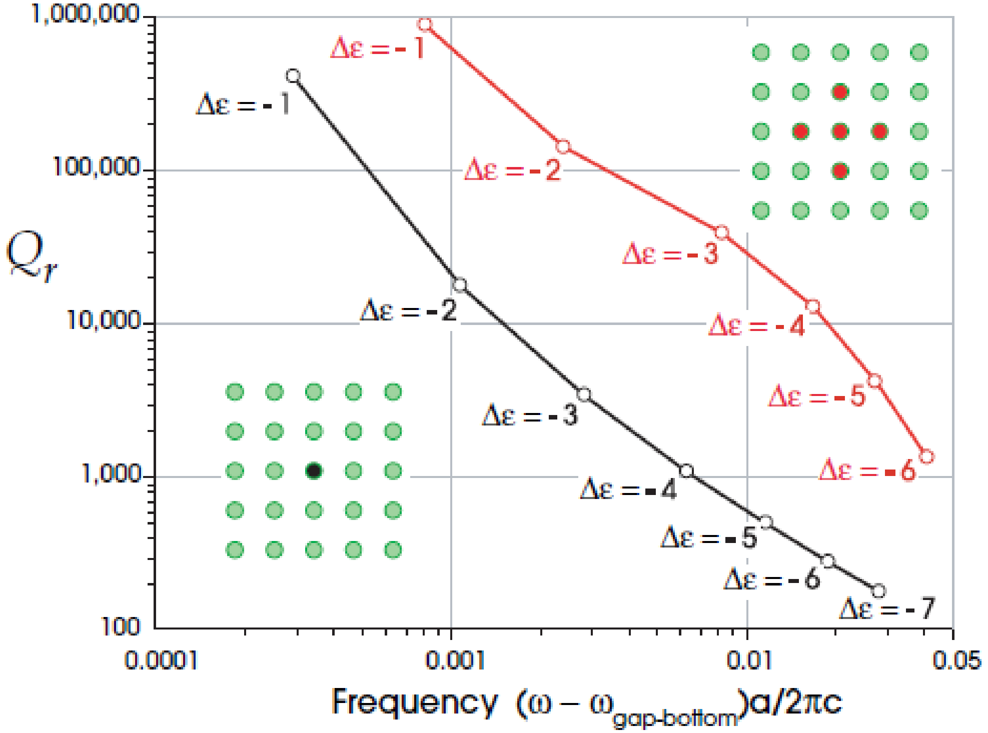
- Line defects create a low-loss waveguide; $\frac{dP}{dz} = \frac{\alpha}{v_g^2} + \frac{\beta}{v_g}$

Photonic Crystal Slabs



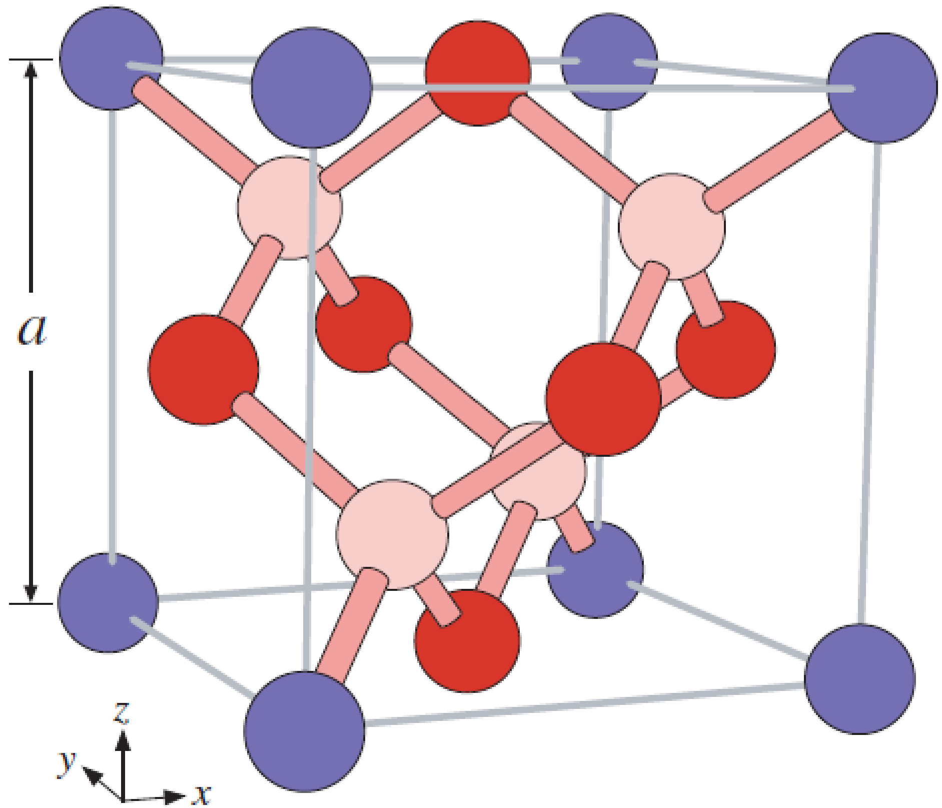
- Pointlike defects create a high quality-factor localized mode

Photonic Crystal Slabs



- Quality factor of pointlike defects varies strongly with frequency and index contrast

3D Lattice Types

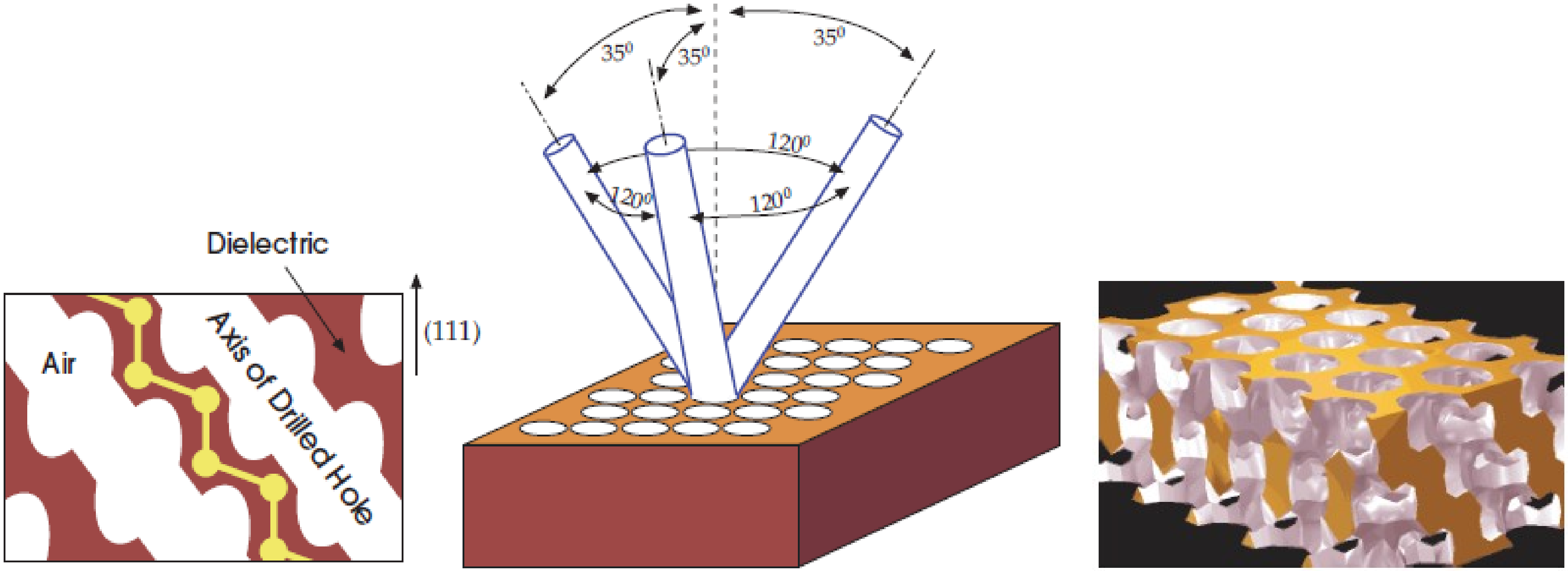


Blue = simple cubic lattice

Blue + Red = fcc lattice

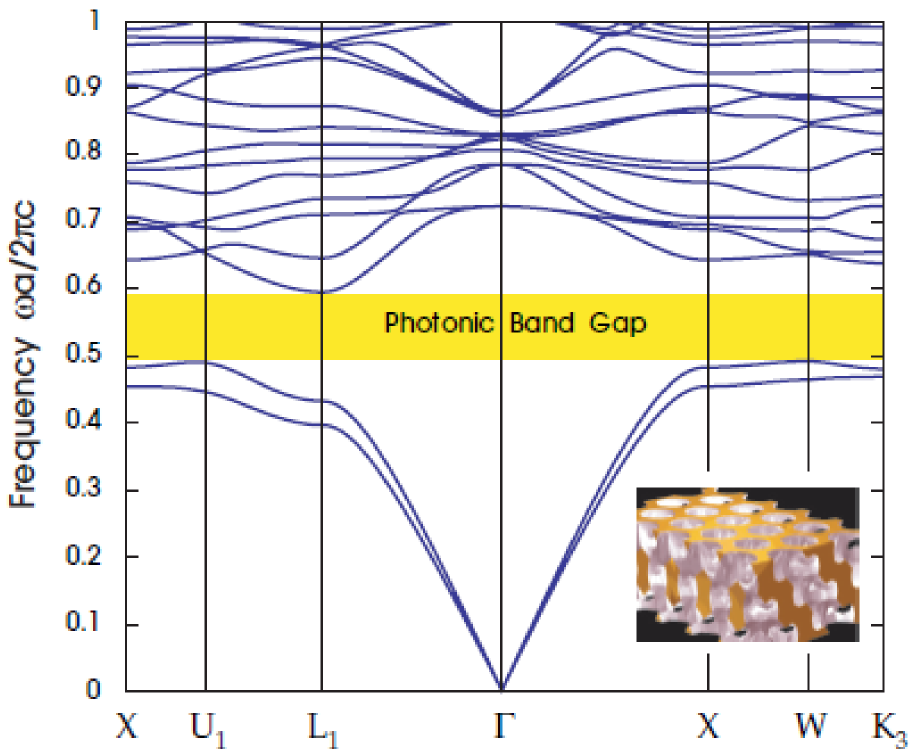
All = diamond lattice

Yablonovite



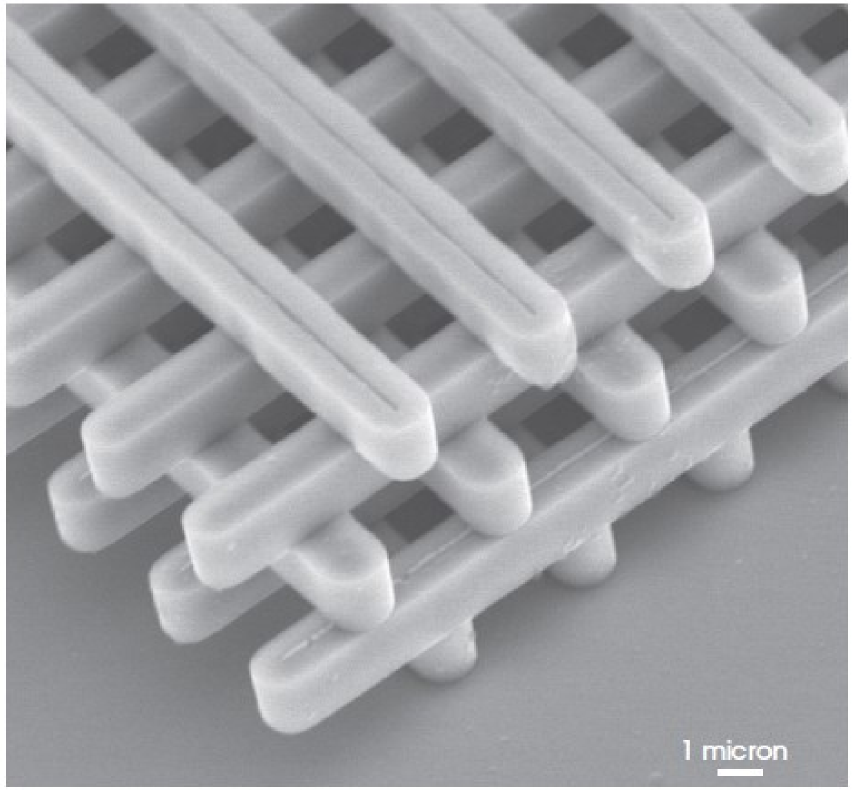
- First PhC, fabricated by Eli Yablonovitch group
- Built for microwaves via mechanical drilling

Yablonovite



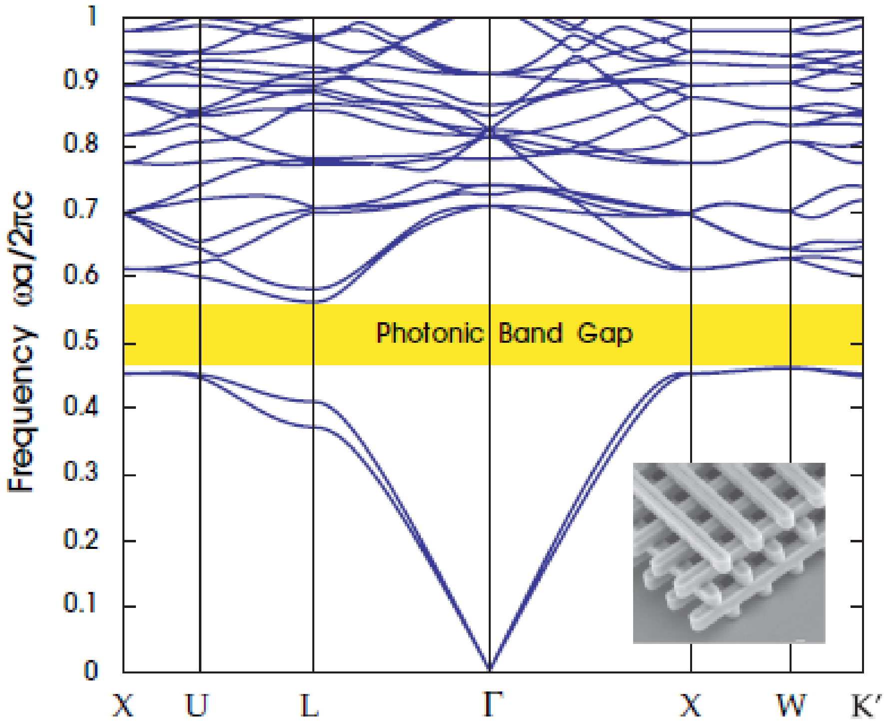
- Determined to have full 3D PBG after a pseudogap detected in first structure, as fabricated and tested by Gmitter

Woodpile



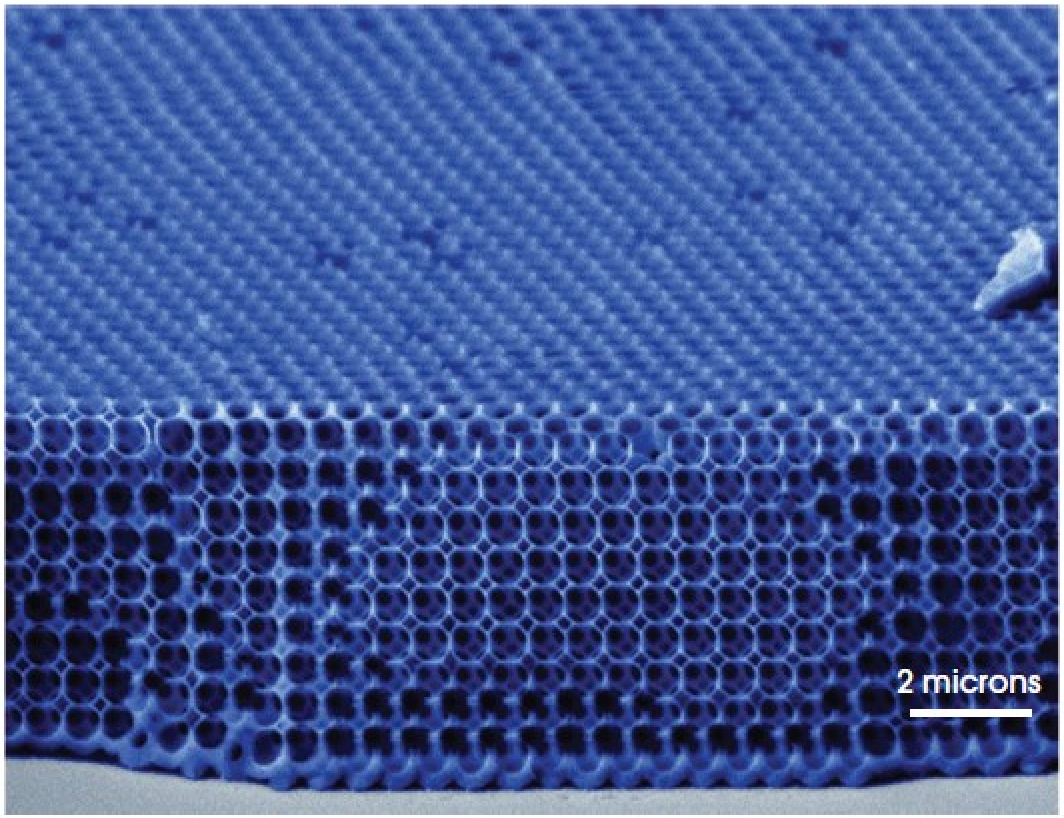
- Woodpile has alternating rod directions with half-period offsets, forming an fcc structure

Woodpile



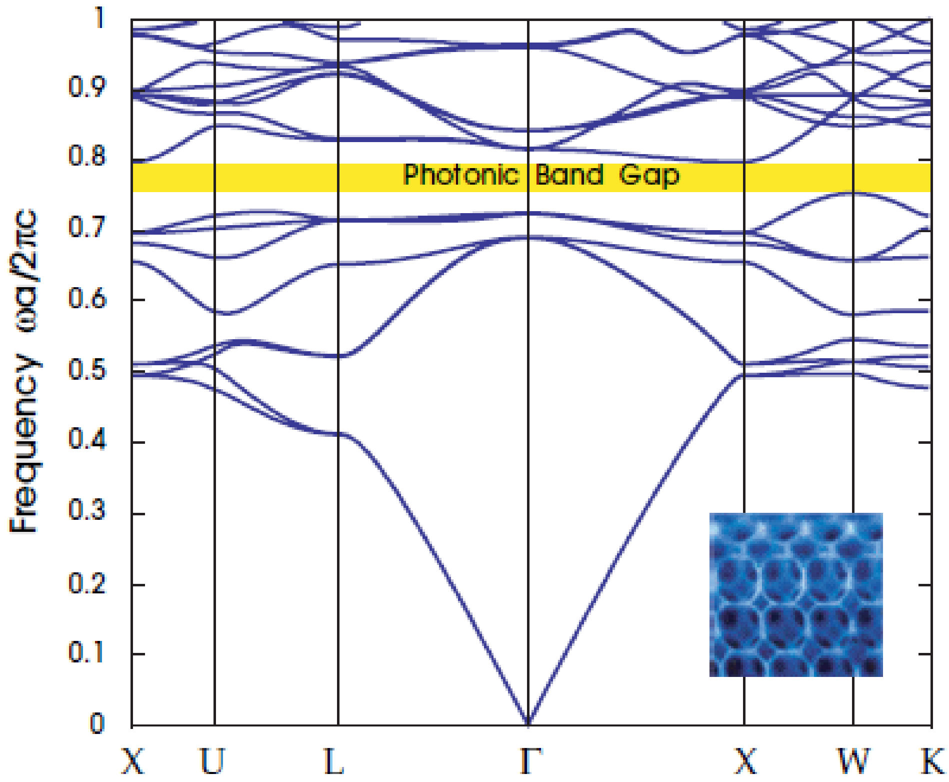
- Woodpile structures display a large bandgap with a relatively simple geometry

Inverse Opals



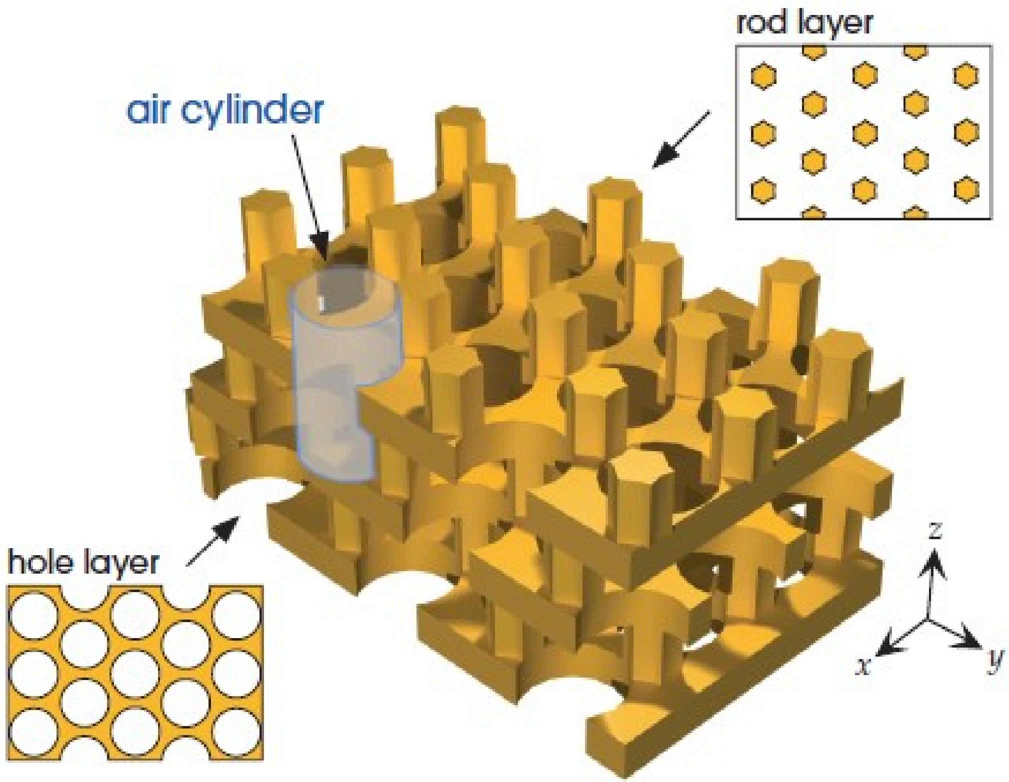
- Created via 3-step process:
  - Silica sphere assembly
  - LPCVD silicon infill
  - Silica etch (HF)

Inverse Opals



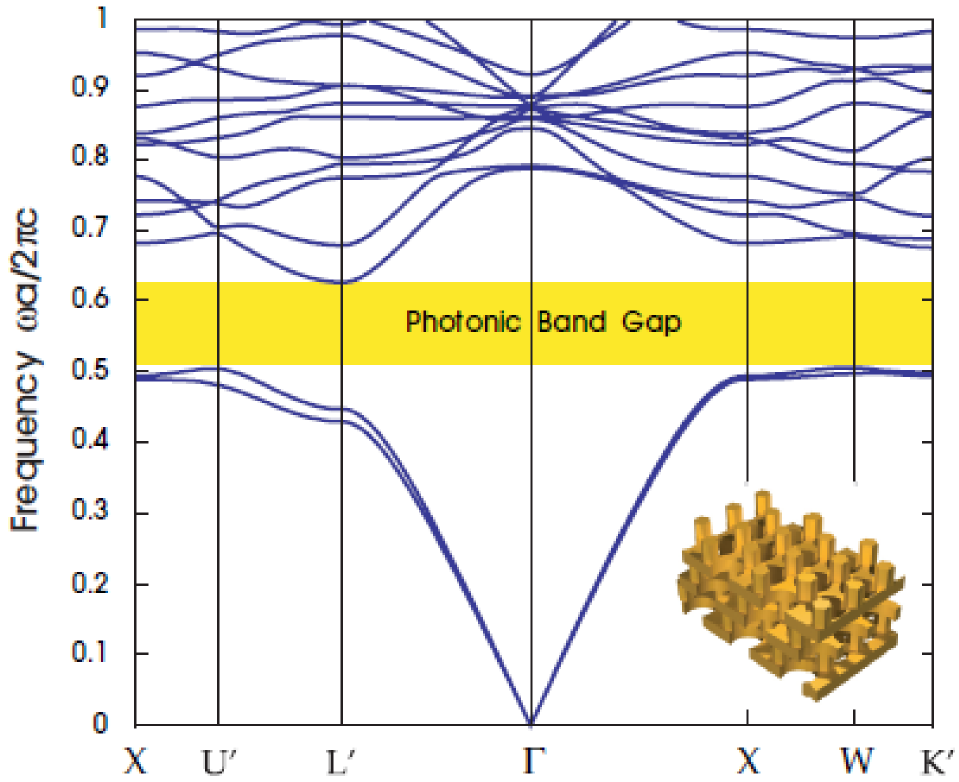
- Bandstructure shows significant full 3D bandgap

Rod-Hole 3D PhC



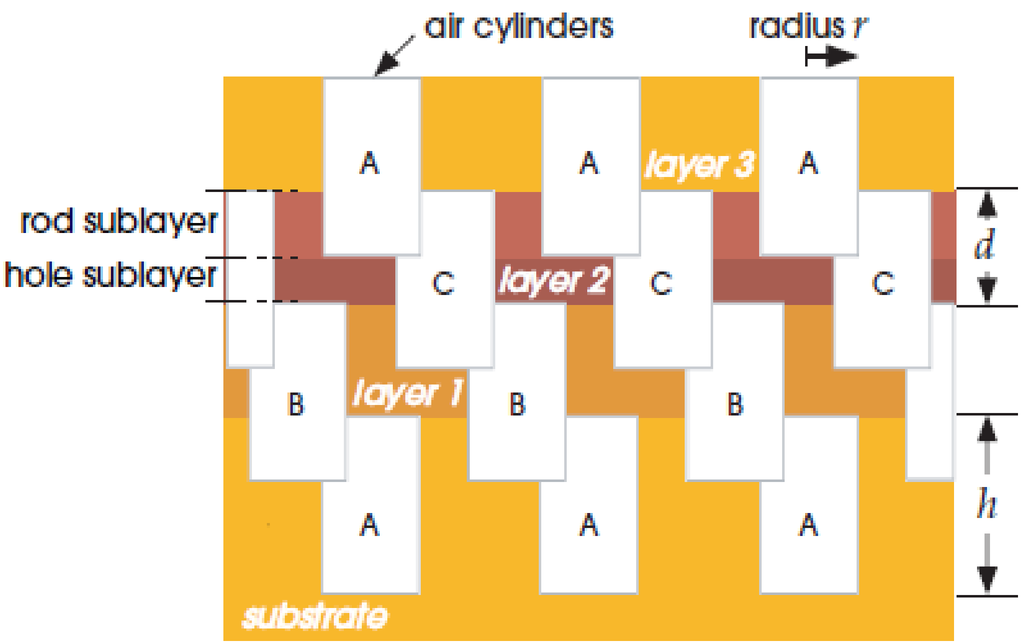
- Consist of alternating 2D PhC slab-like layers of rods and holes

Rod-Hole 3D PhC

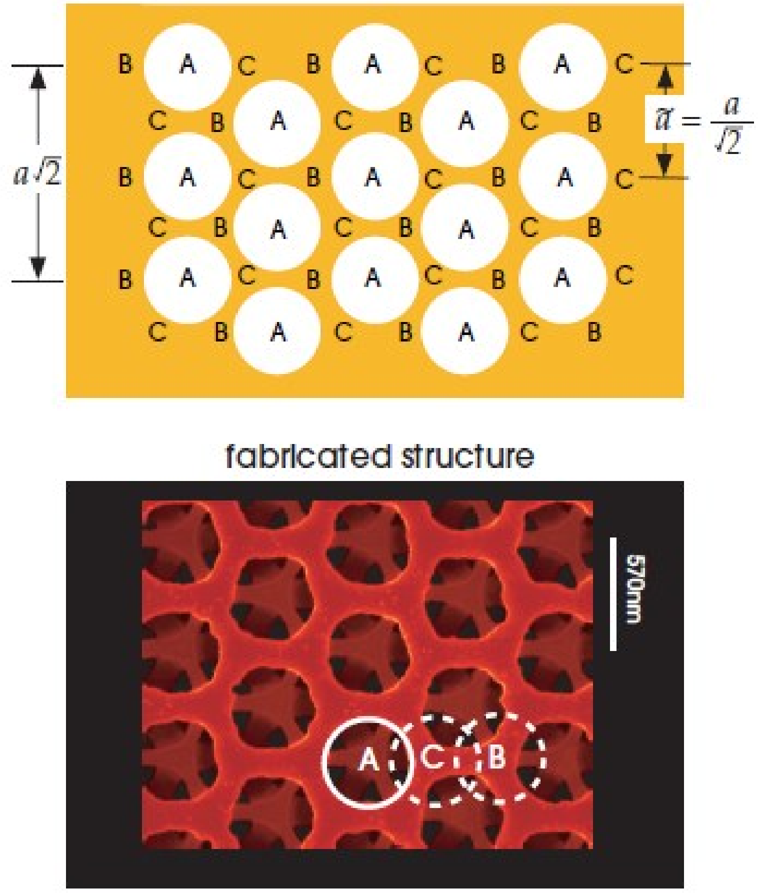


- 3D bandgap is fairly large
- Dramatically different from the individual 2D PhC slabs

Rod-Hole 3D PhC

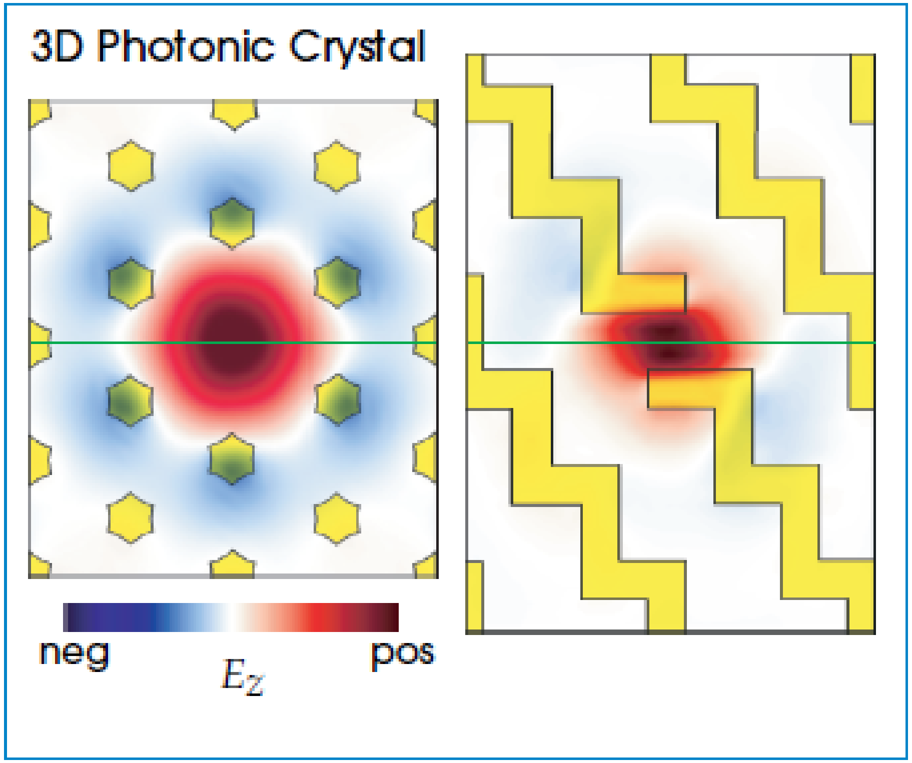


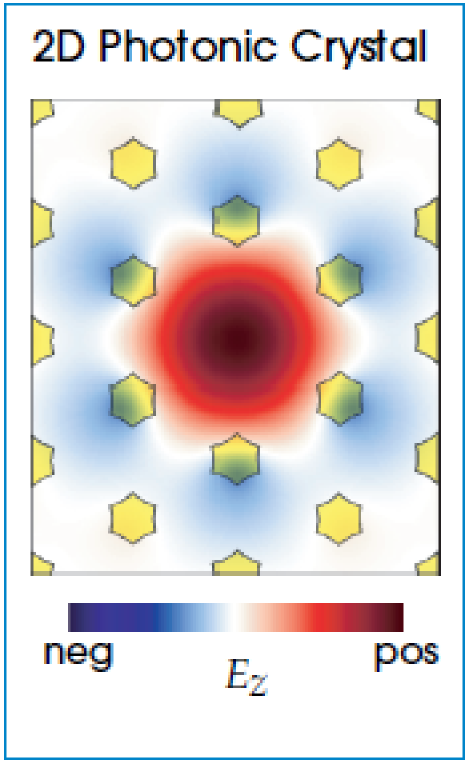
Cross-sectional view



Top view

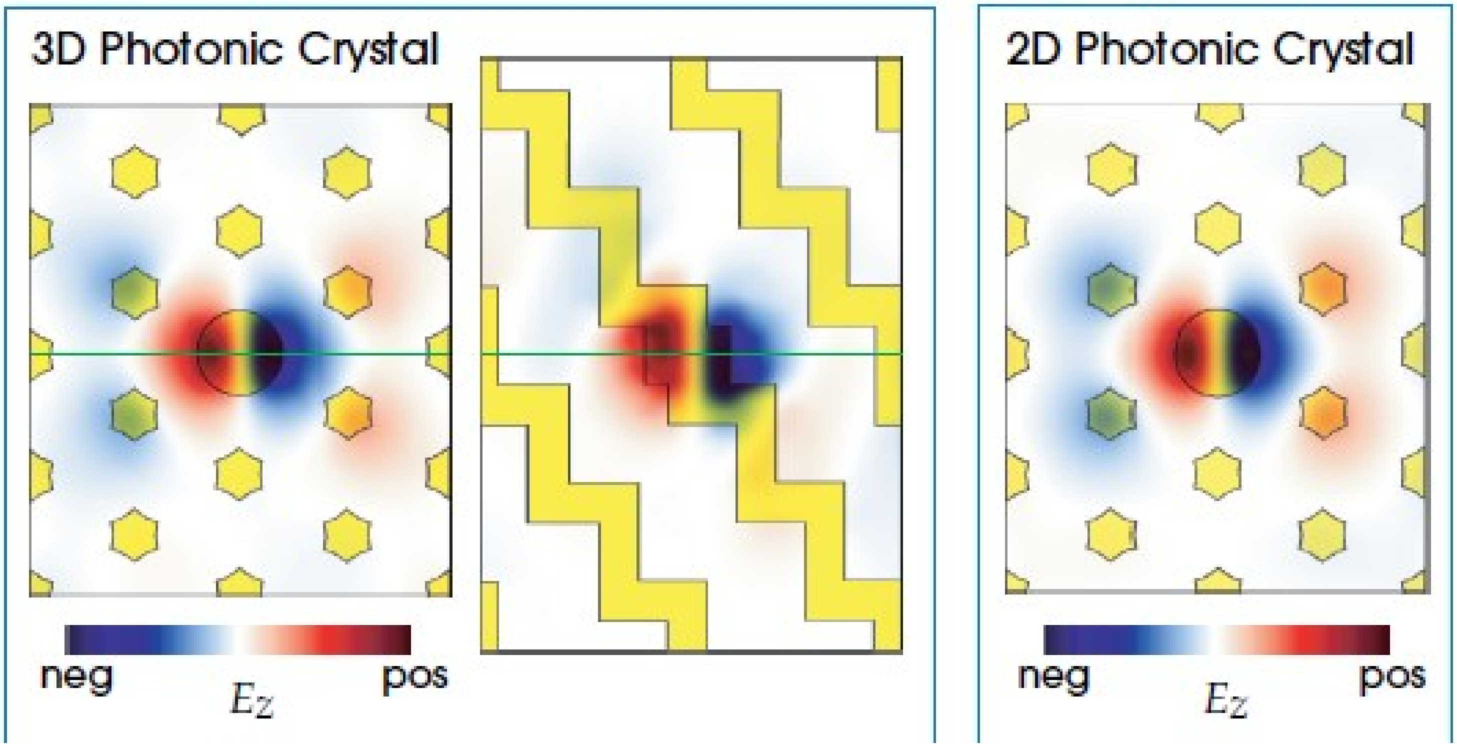
Role-Hole 3D PhC: Air Defect





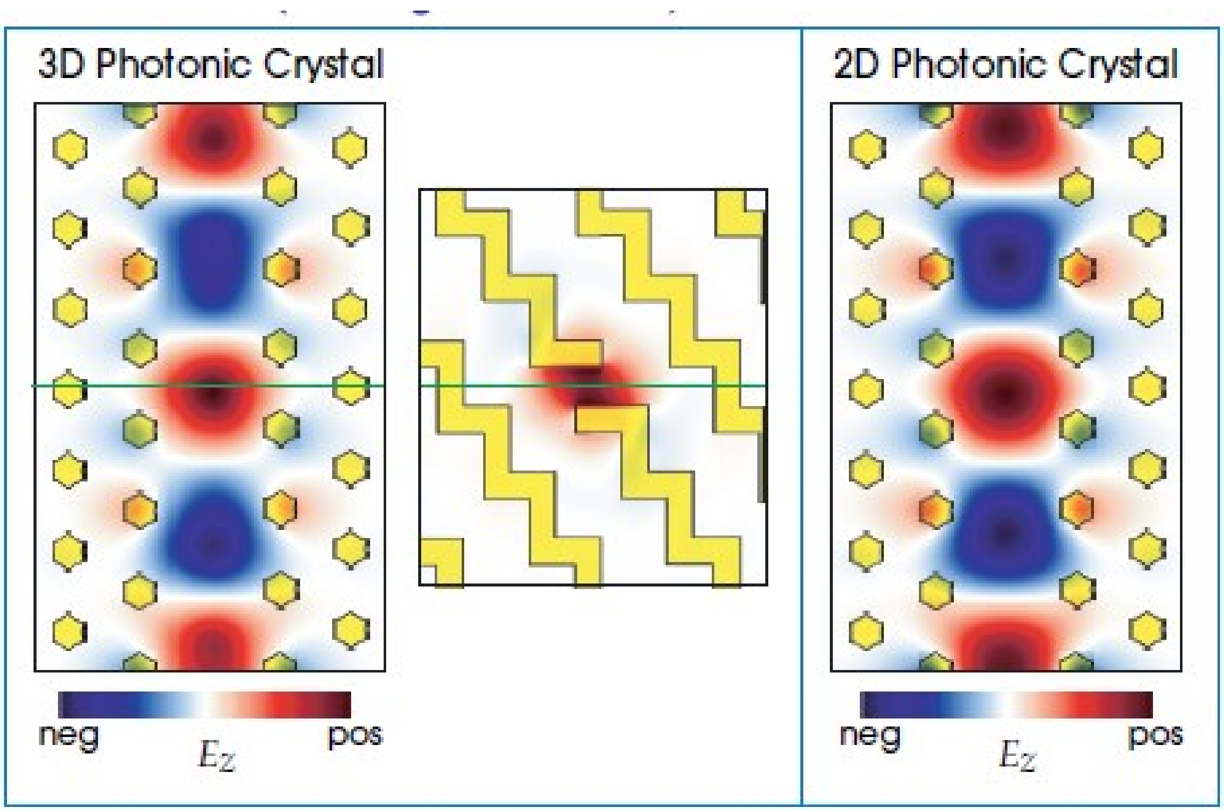
Removing a single rod creates 3D confinement in a very small volume

Rod-Hole 3D PhC: Dielectric Defect



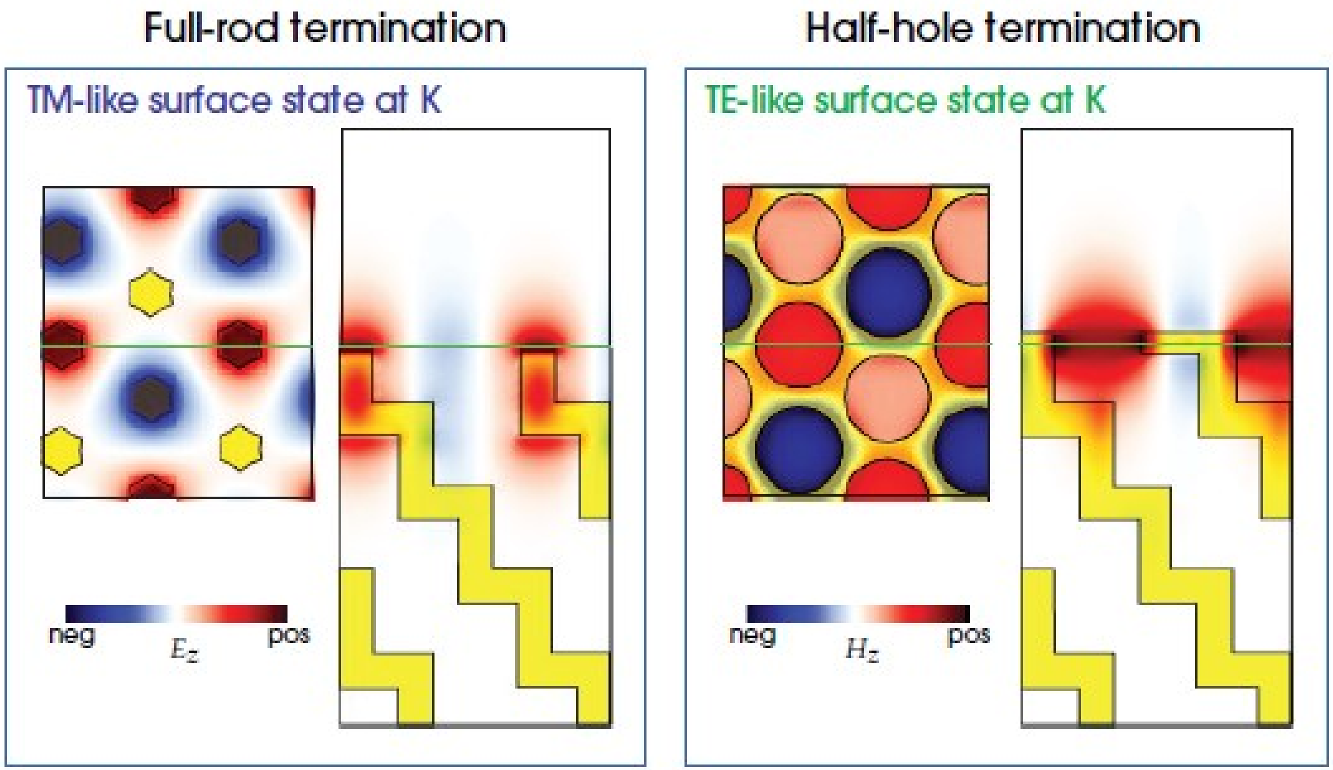
Similar 3D confinement also observed when increasing the radius of a single rod

Rod-Hole 3D PhC: Waveguide



Can create a waveguide much like in 2D PhCs by removing a whole row of rods

Rod-Hole 3D PhC: Surface States



Termination of 3D structure gives rise to surface states – cf. surface plasmons

Next Class

- Look at the tools behind 2D and 3D photonic bandstructures
- Reference: S.G. Johnson and J. D. Joannopoulos, "Block-iterative frequency-domain methods for Maxwell's equations in a planewave basis," *Optics Express* **8**, 173-190 (2001).