Session 4

Photonic Crystal Slabs

Controlling and Confining Light On the Nanoscale

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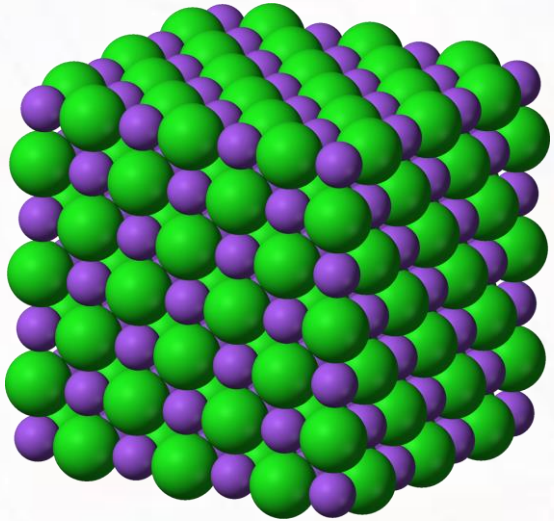
March 1, 2024 • 1PM CST

Crystals

- Periodic arrangement of atoms
- Bloch theorem: the energy eigenmodes can be written as

$$\psi(\mathbf{r}) = e^{i\mathbf{k}\cdot\mathbf{r}} u(\mathbf{r}),$$

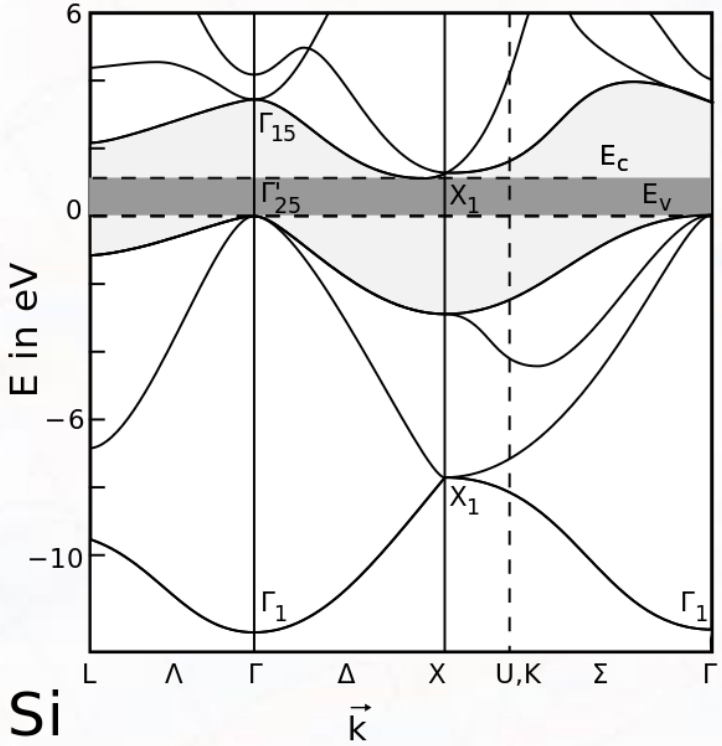
where **k** is called the Bloch vector and *u(**r**)* has the same periodicity as the lattice.



https://en.wikipedia.org/wiki/Crystal#/media/File:Sodium-chloride-3D-ionic.png

Crystals

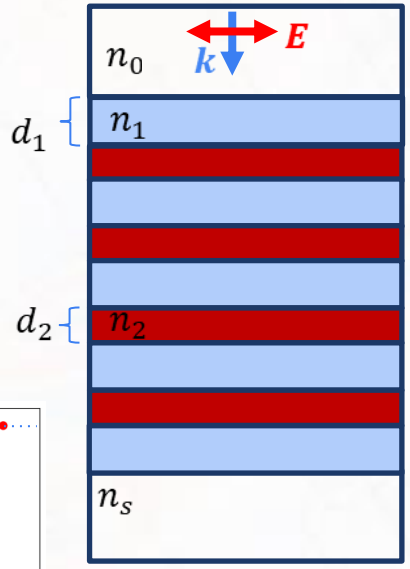
The states can be analyzed through the band structure, a plot of *E(**k**)*, which itself is periodic as a function of **k**.



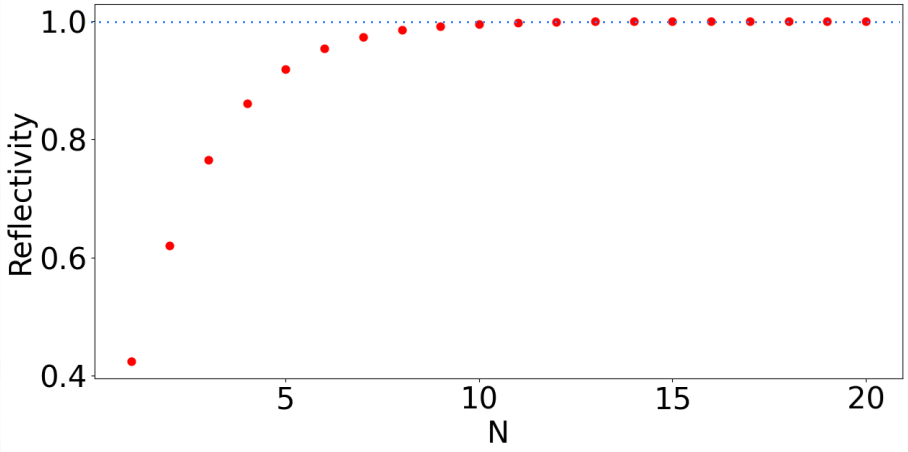
https://en.wikipedia.org/wiki/File:Band_structure_Si_schematic.svg

Reminder: Distributed Bragg reflector (DBR)

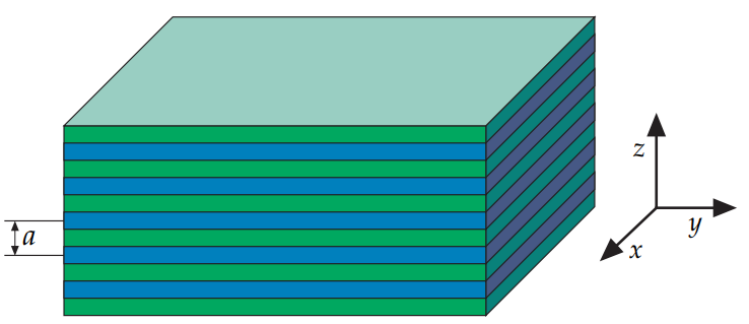
- N-pairs of thin films with refractive index n_1 and n_2
- The thicknesses are $d_1 = \frac{\lambda}{4n_1}$ and $d_2 = \frac{\lambda}{4n_2}$



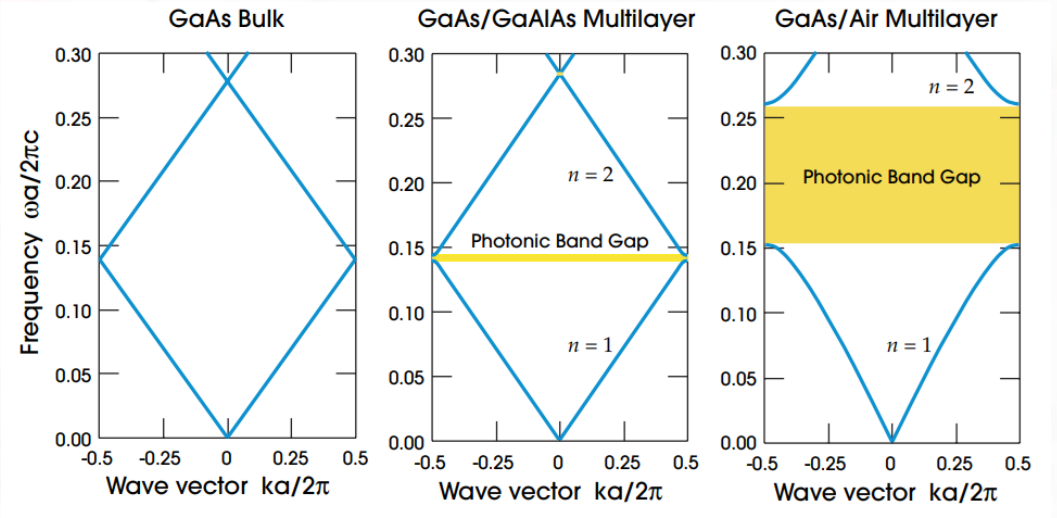
$$r = \frac{n_s n_0 n_1^{2N} - n_2^{2N+2}}{n_s n_0 n_1^{2N} + n_2^{2N+2}}$$



DBR as a photonic crystal

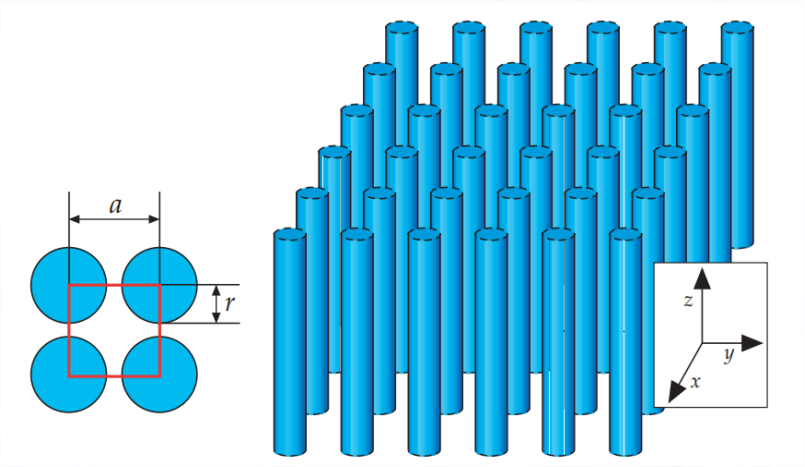


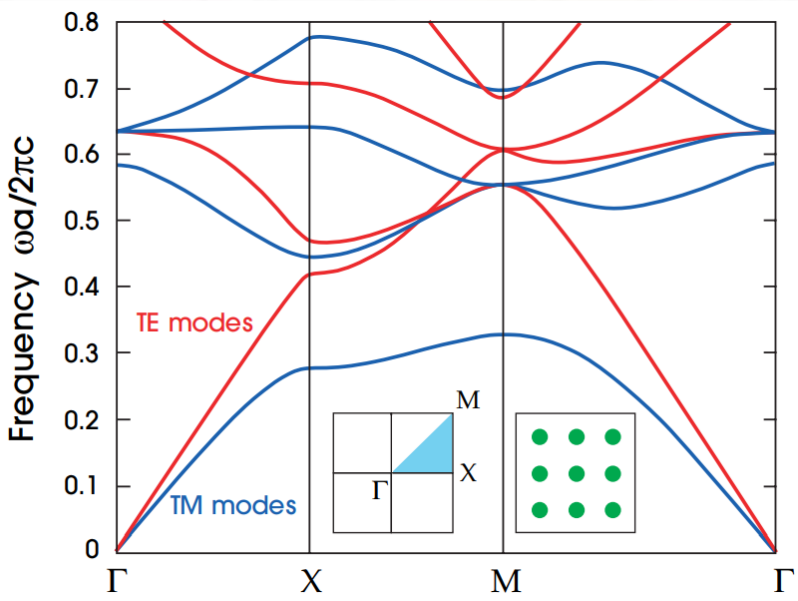
$$\mathbf{H}_{n,k_z,\mathbf{k}_\parallel}(\mathbf{r}) = e^{i\mathbf{k}_\parallel\cdot\boldsymbol{\rho}} e^{ik_z z}\mathbf{u}_{n,k_z,\mathbf{k}_\parallel}(z)$$



Photonic Crystals: Molding the Flow of Light

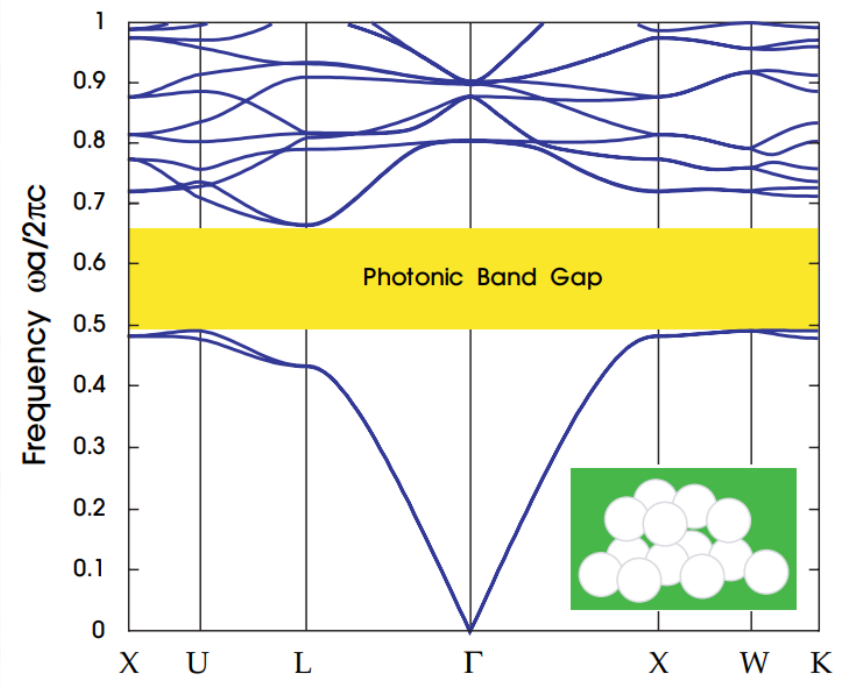
2D photonic crystals





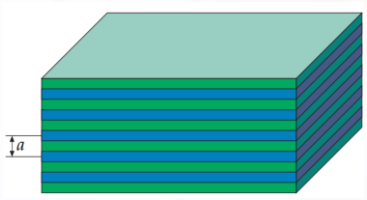
Photonic Crystals: Molding the Flow of Light

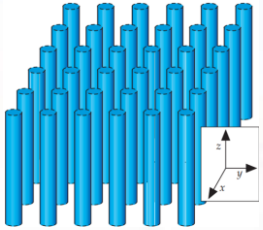
3D photonic crystals



Photonic Crystals: Molding the Flow of Light

1D, 2D, 3D photonic crystals





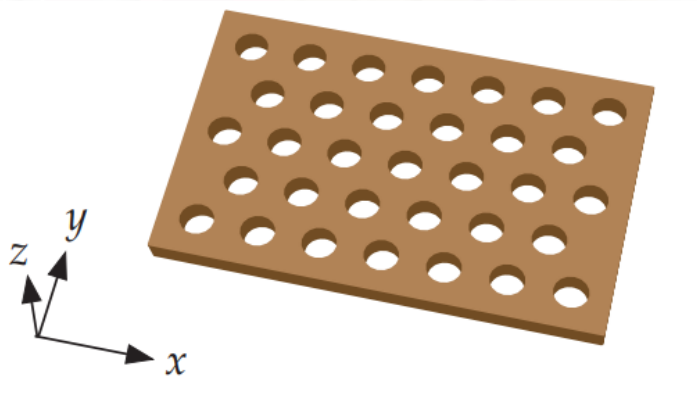
Band gap only along one or two directions.

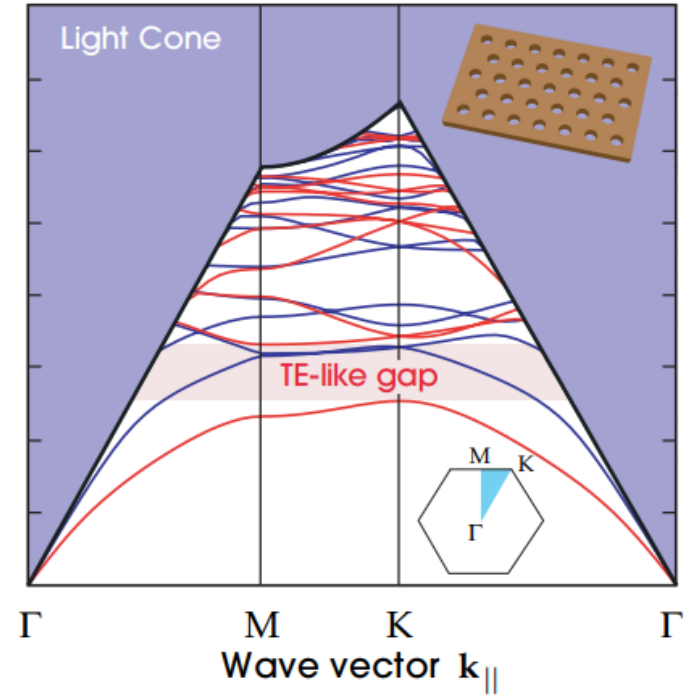
Need to be physically truncated somehow along the other dimension(s).



Band gap in all directions, but really hard to make in practice.

Photonic crystal slabs





Bloch states in the xy-plane

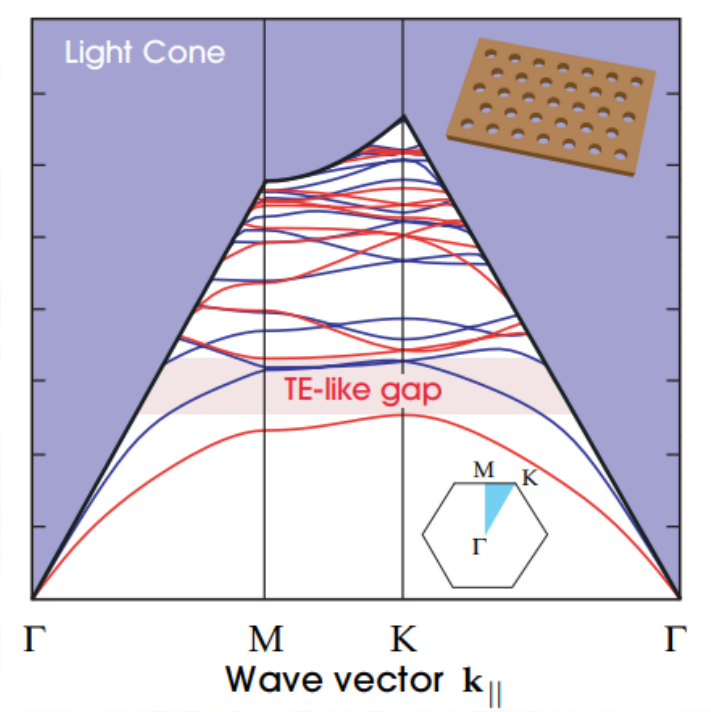
Total internal reflection confinement along z

Photonic Crystals: Molding the Flow of Light

Photonic crystal slabs

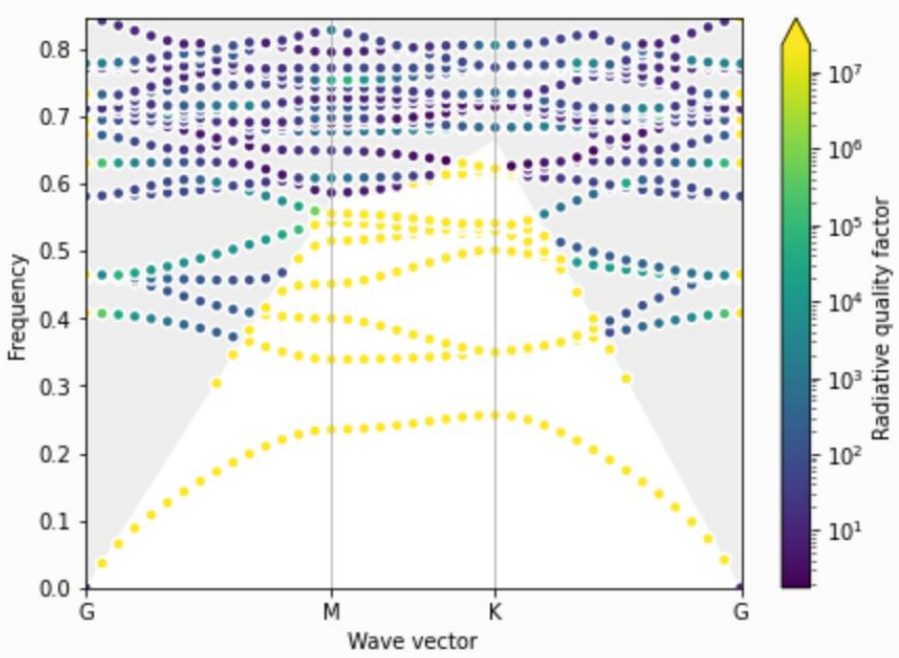
Partial band gap: there is a continuum of states inside the light cone.

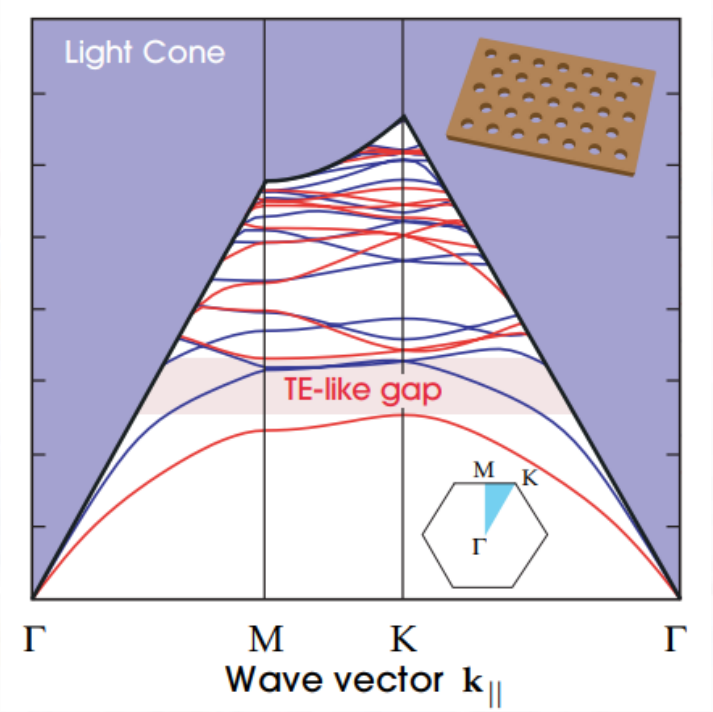
However: quasi-guided modes exist in the light cone, too!



Photonic Crystals: Molding the Flow of Light

Photonic crystal slabs





Simulating PhC slab modes in FDTD

- Randomly place point dipoles to excite arbitrarily looking modes
- Apply Bloch boundary conditions and iterate over various **k**
- Run the simulation and record time-domain fields after the source pulses have decayed
- Use “harmonic inversion” to compute the resonance frequencies and quality factors of all excited modes

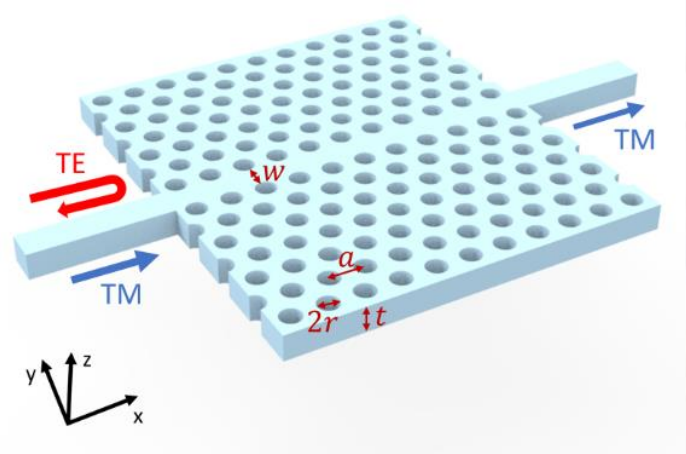
$$f(t) = \sum_k a_k e^{i\phi_k} e^{-2\pi i f_k t - \alpha_k t}$$

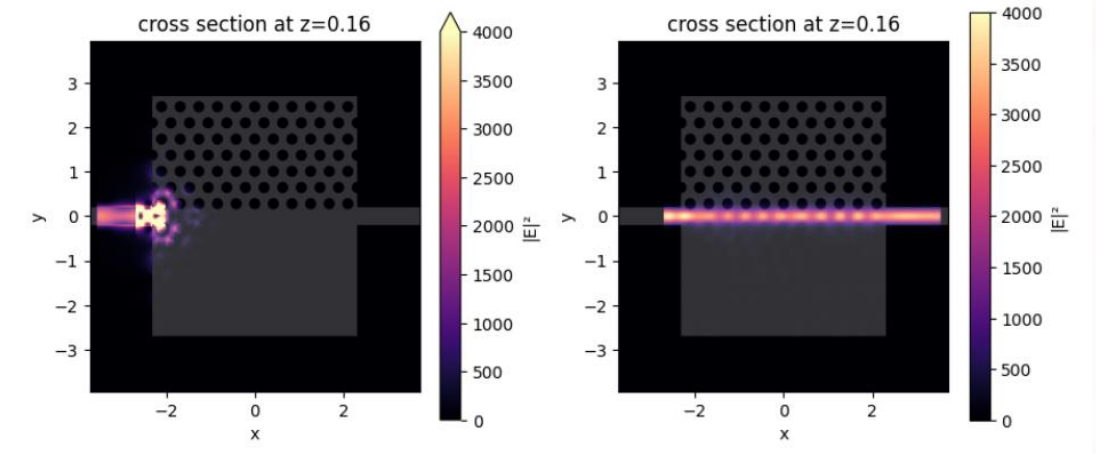
https://docs.flexcompute.com/projects/tidy3d/en/latest/api/_autosummary/tidy3d.plugins.resonance.ResonanceFinder.html

Hands-on activity

FDTD simulations to calculate the band structure of a PhC slab

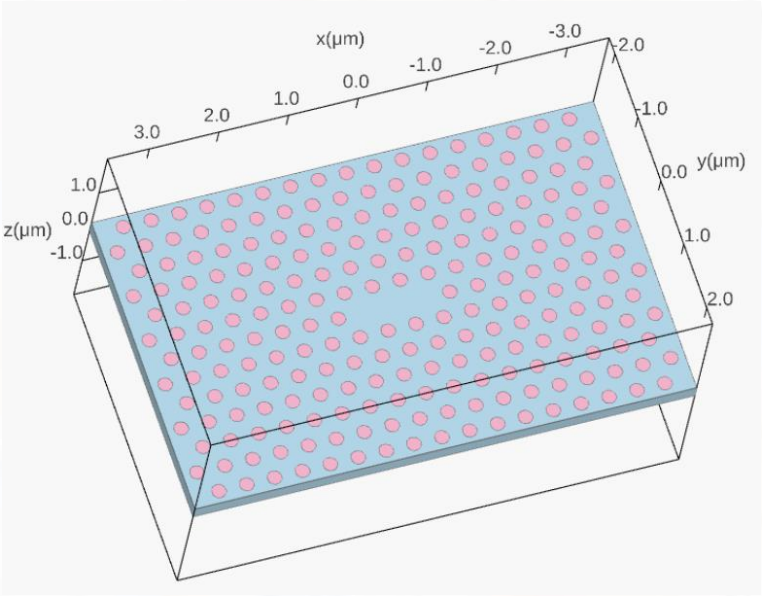
PhC slab waveguides

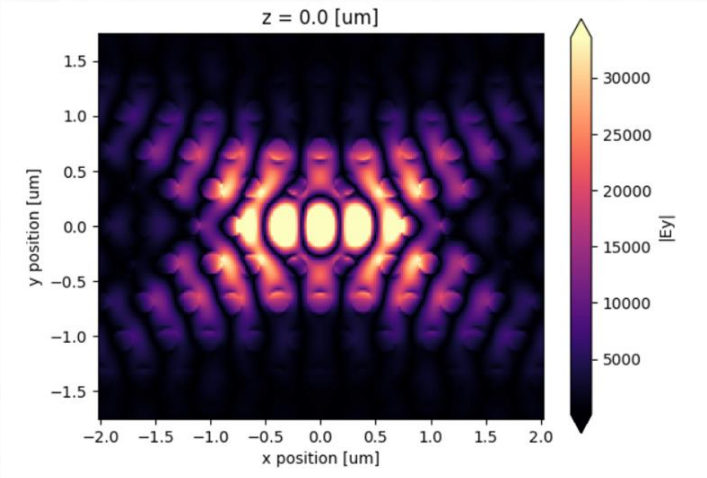




https://docs.flexcompute.com/projects/tidy3d/en/latest/notebooks/PhotonicCrystalWaveguidePolarizationFilter.html

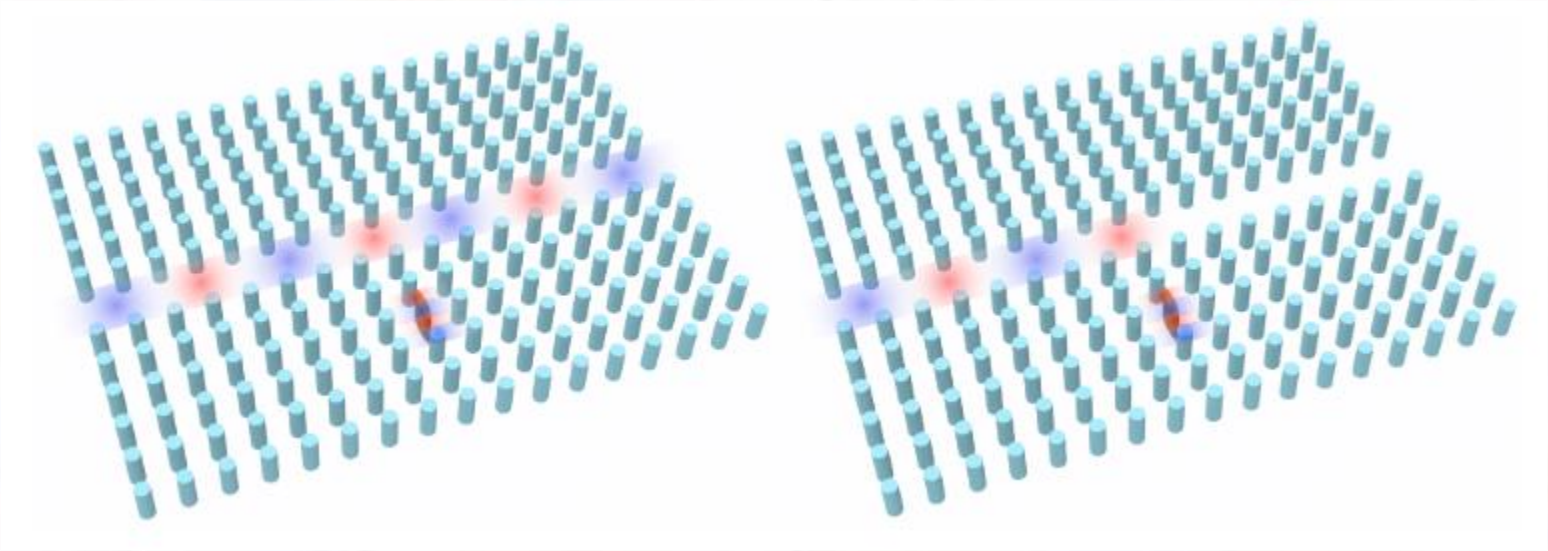
PhC slab cavities





https://docs.flexcompute.com/projects/tidy3d/en/latest/notebooks/OptimizedL3.html

PhC slab waveguide + cavity



https://docs.flexcompute.com/projects/tidy3d/en/latest/notebooks/BistablePCCavity.html

Other hot topics for PhC slabs

- Bound states in the continuum
- Topological photonics (pseudo-spin TIs, higher-order TIs)
- Metasurfaces
- Photonic crystal surface-emitting lasers (PCSELs)

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Multimode Photonics Design

Feb 16 Dr. Lucas Gabrielli • *Cornell*



Designing Filters + Reflectors

Feb 23 Dr. Tom Chen • *Stony Brook*



Photonic Crystal Slabs

Mar 1 Dr. Momchil Minkov • *EPFL, Stanford*



Inverse Design in Photonics

Mar 8 Dr. Tyler Hughes • *Stanford*

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