Perpendicular photonic devices for scintillation detectors

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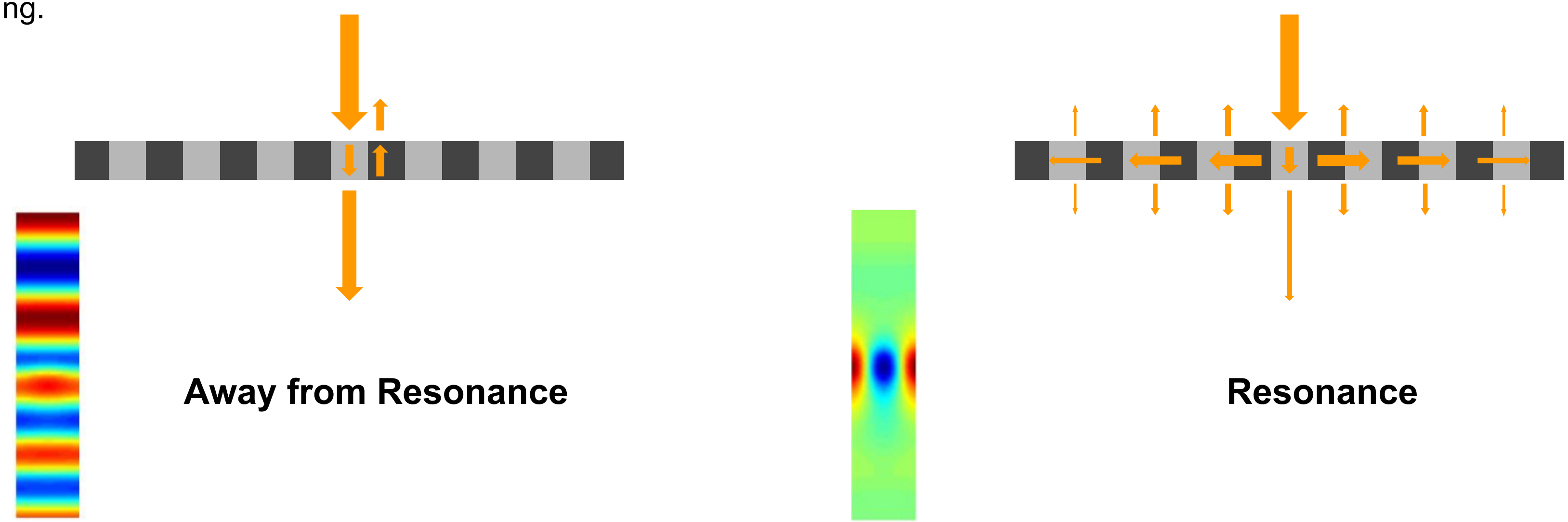
Multiwave Metacrystal®

Photonic Crystal Slab & Physics of Guided-Mode Resonance (GMR)

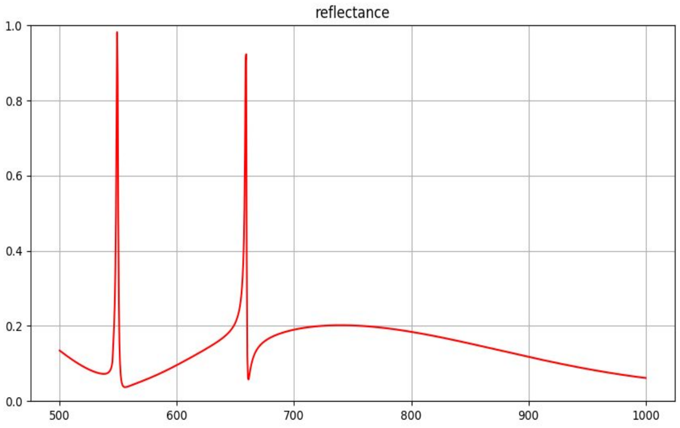
The phenomenon of so-called guided-mode resonance occurs inside a dielectric slab with nanostructure, so that its optical property (permittivity or permeability) varies periodically with the position on the plan. This kind of device is usually called Photonic Crystal Slab (PhC slab). It combines the property of planar waveguide (high effective index) and that of diffraction grating.



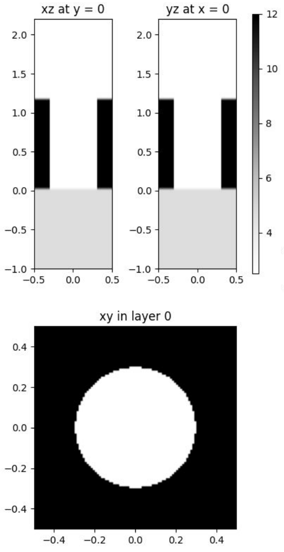
When a wave at resonant frequency for a specific planar wave vector arrives on the slab, part of its energy will be coupled into a quasi-guided mode of the PhC slab. Then this pack of energy will propagate transversely along the slab surface, and meanwhile leaks slowly out into PhC slab's upper and lower cladding.

Modes of Photonic Crystal Slab

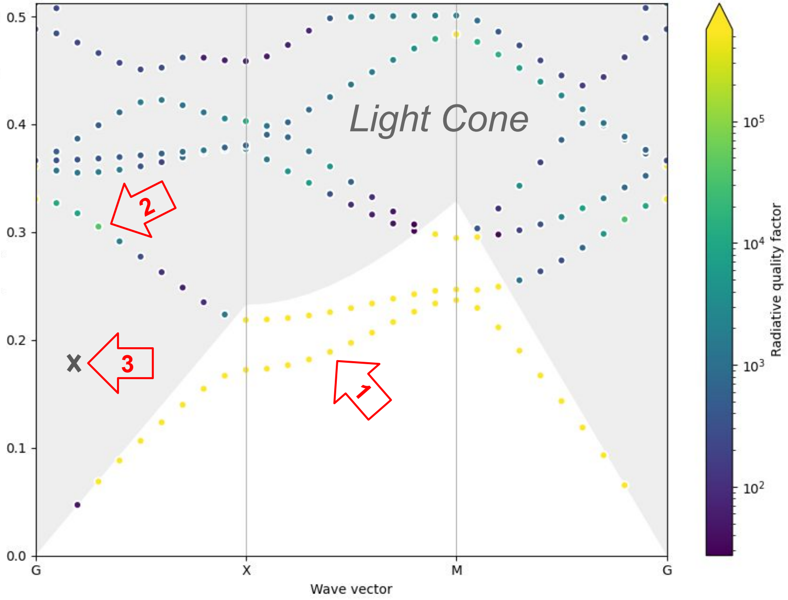
The sharp peak Reflectance/Transmittance spectra (as shown in figure below) gives a direct way to identify the resonant frequency of a PhC slab. The sudden change in reflectance happens due to the slab's coupled-in and slow leak mechanisme.



But, to fully understand the behavior of a Photonic Crystal slab, a complete band structure is the most recommended tool.



permittivity



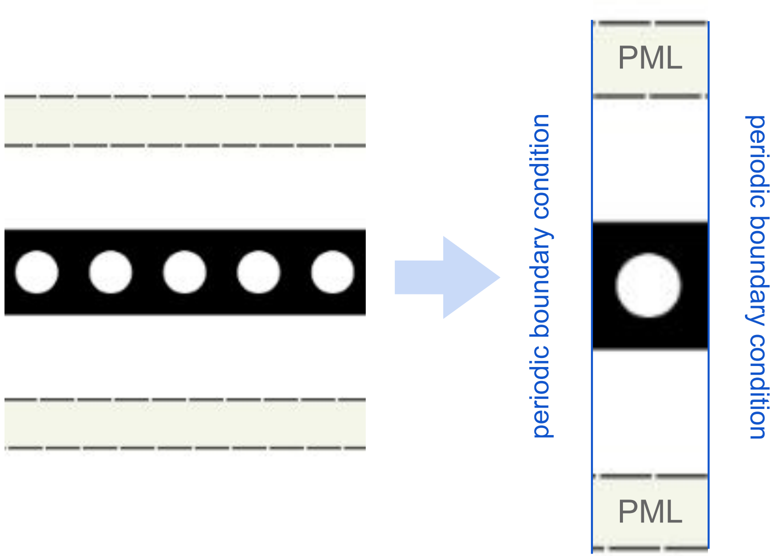
In the band structure diagram, a point with specific planar wavevector and frequency represents a mode. Depending on its location, the modes can be classified into 3 types:

1. **Guided mode** : positioned under light cone and on a band curve
2. **Leaky mode** : positioned in light cone and on a band curve
3. **Extended mode** : positioned in light cone but not on band curve.

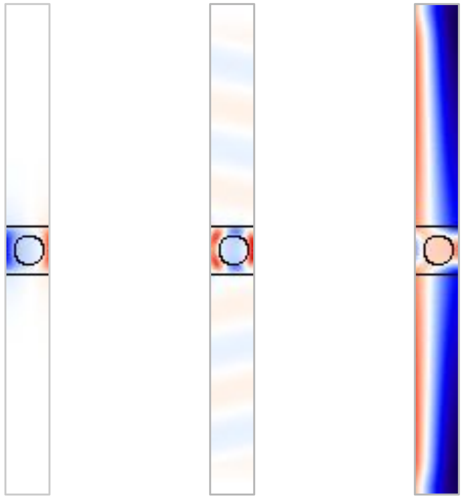
<u>In fact, the GMR correspond to the leaky modes of a PhC slab.</u>

Behavior of Photonic Crystal Slab modes

FDTD is used to simulate the behavior of previously presented 3 kinds of modes for a given one-dimensional Photonic Crystal Slab. The structure is plotted in left figure. Through imposing periodic boundary condition, the computational domain is reduced to one unit cell of the periodic structure, as plotted in the right figure.



Z-component of E field in a period



Guided mode : propagating along slab, evanescent in claddings.
Leaky mode : propagating along slab with radiation loss per oscillation.
Extended mode : propagating in claddings and through slab, not localized inside the slab at all.

Numerical tools for GMR analysis

How to locate GMR frequency for given incident angle?

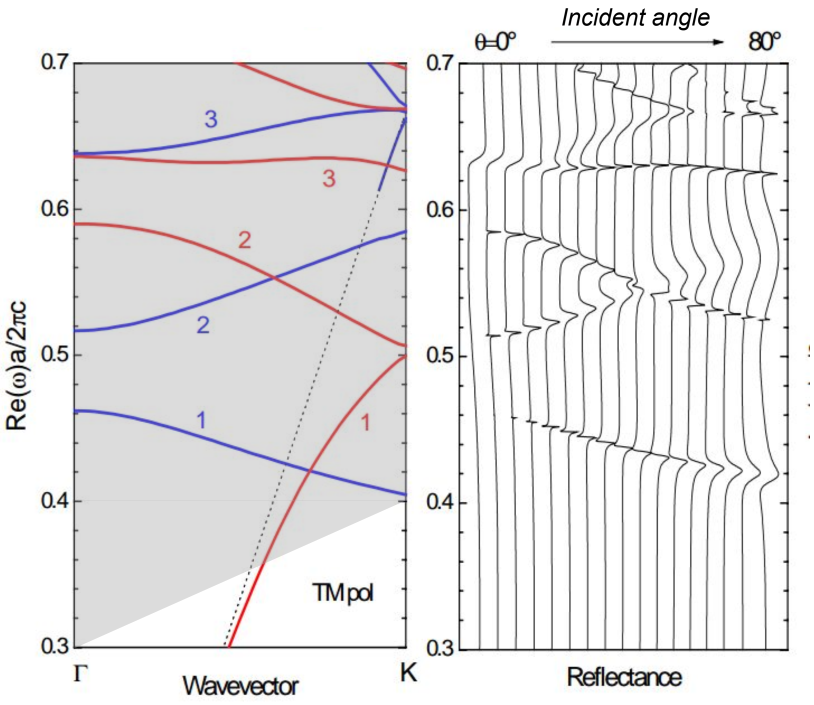
- Reflectance/Transmittance (R/T spectra)
- Dispersion curves (band structure)

Numerical tools:

- FDTD (R/T spectra, Band structure)
- Rigorous Coupled Wave Analysis (R/T spectra)
- Plane Wave Expansion Method (Band structure)
- Guided Mode Expansion Method (Band structure also for leaky modes)

Included in Multiwave's Computational Physic Toolkit

Exist in open source codes



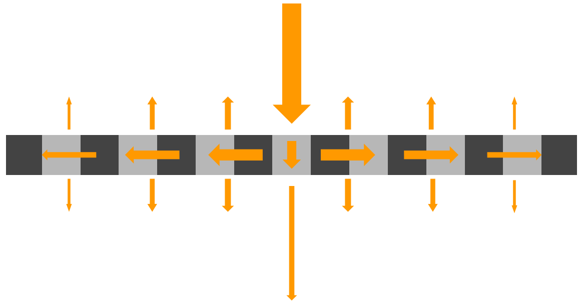
By computing the R/T spectra for different angles, we can almost reproduce the band structure inside light cone (upon light line)v

GMR enabled Meta-Scintillator

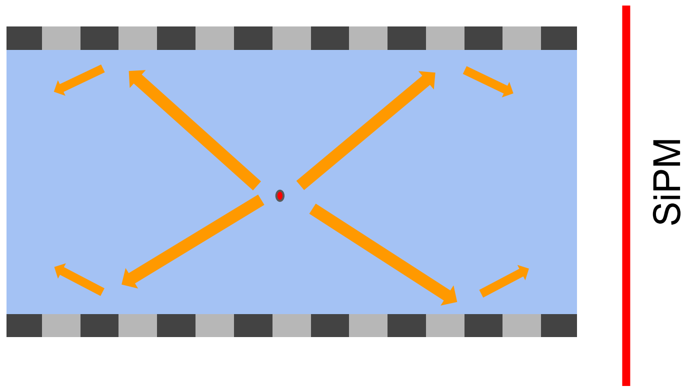
To augment the light extraction for multilayer meta-scintillator, the idea is to couple fast photons/waves raised inside plastic scintillator into a PhC slab placed at the interface of plastic and crystal(BGO/LYSO).

The improvement is expected to be brought from 2 factors:

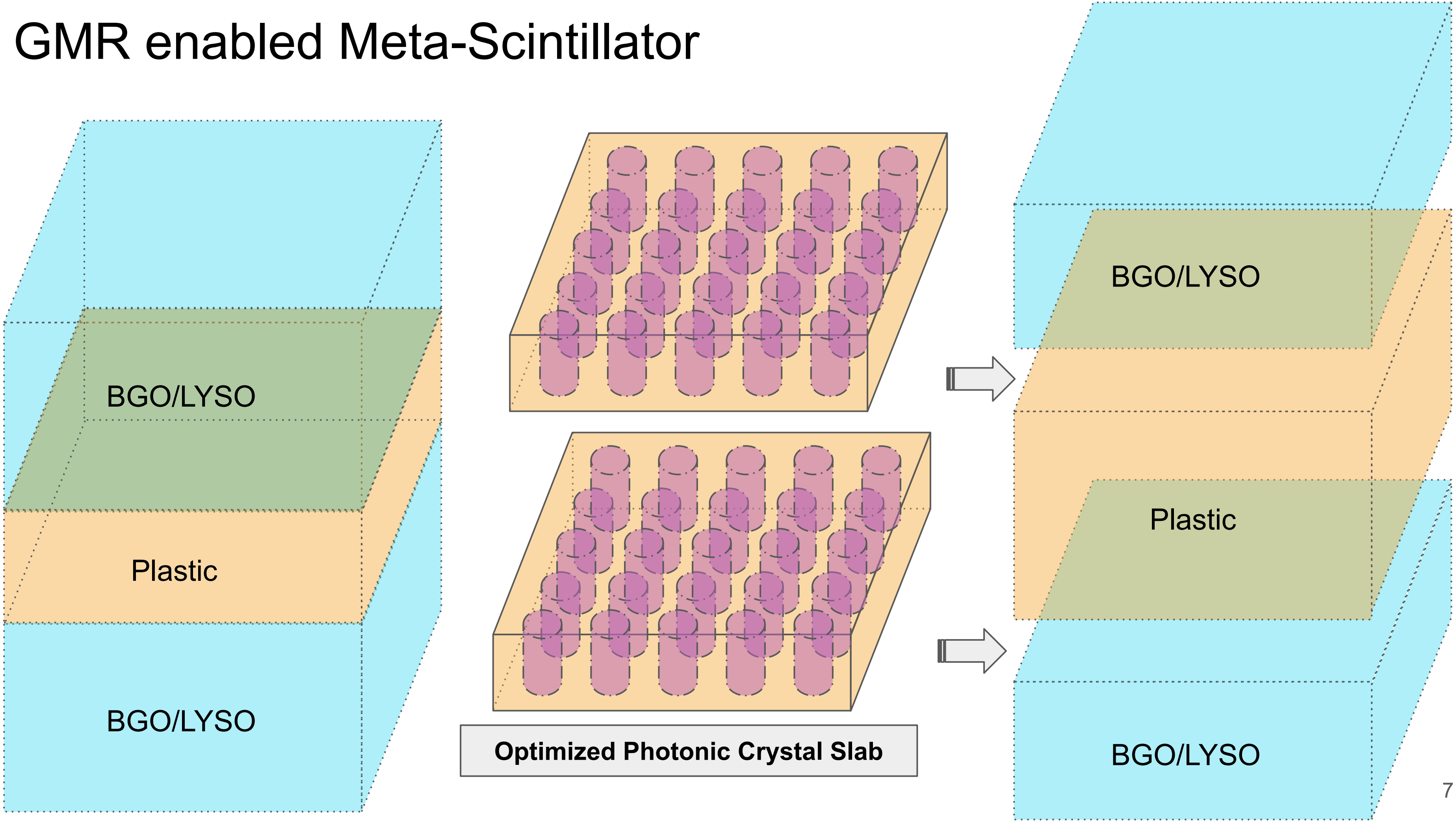
(1) Part of incident energy will convert into the PhC Slab's leaky mode and then propagate along the transverse plane.



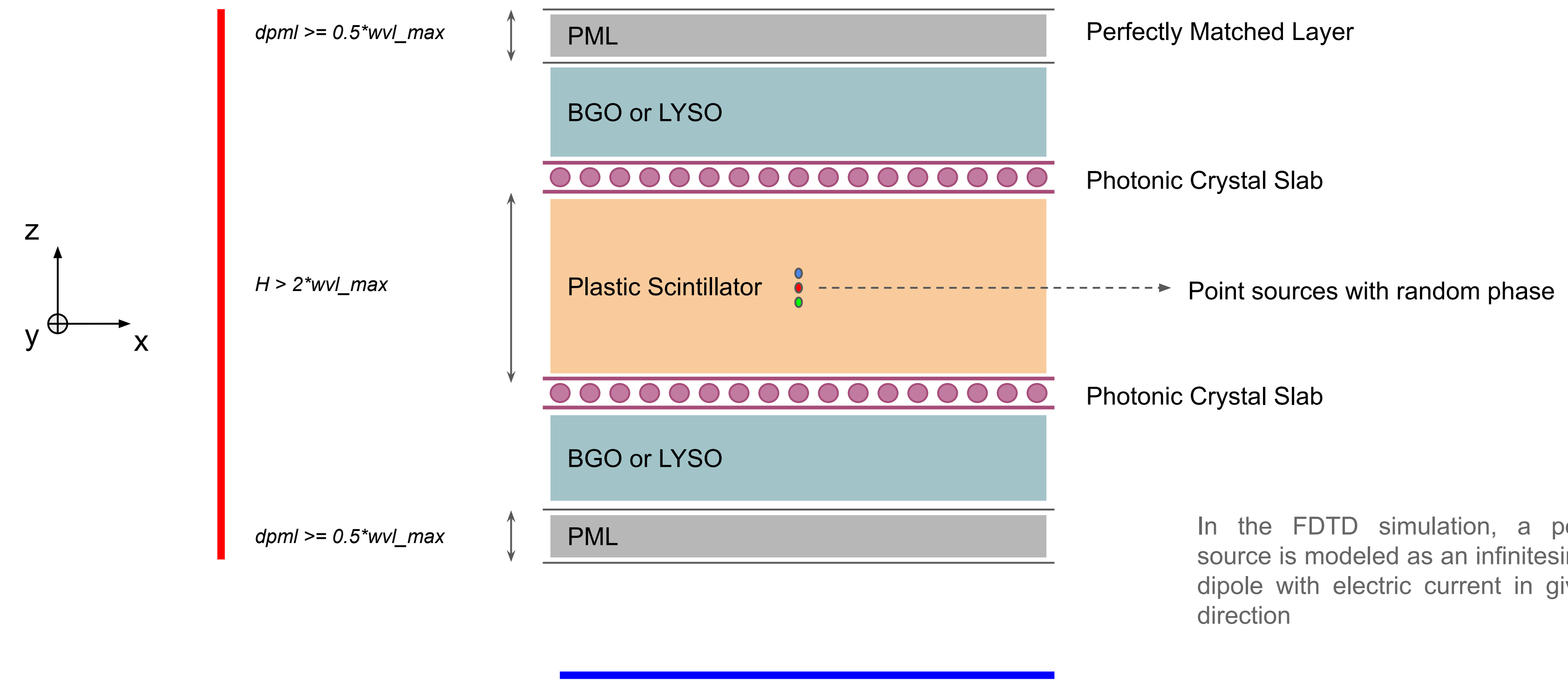
(2) The rest energy will be reflected back into plastic scintillator. For each plastic layer, both top and bottom sides are covered with reflective PhC slab, turn it into a kind of planar waveguide.



GMR enabled Meta-Scintillator

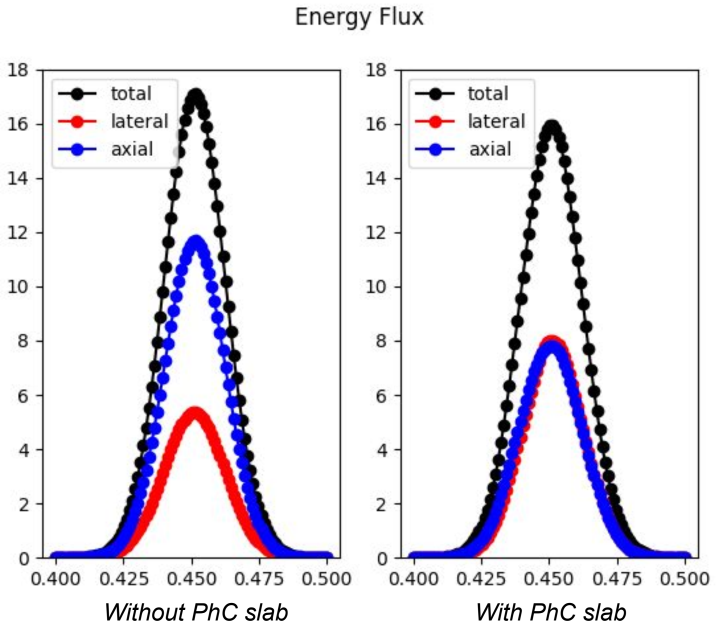


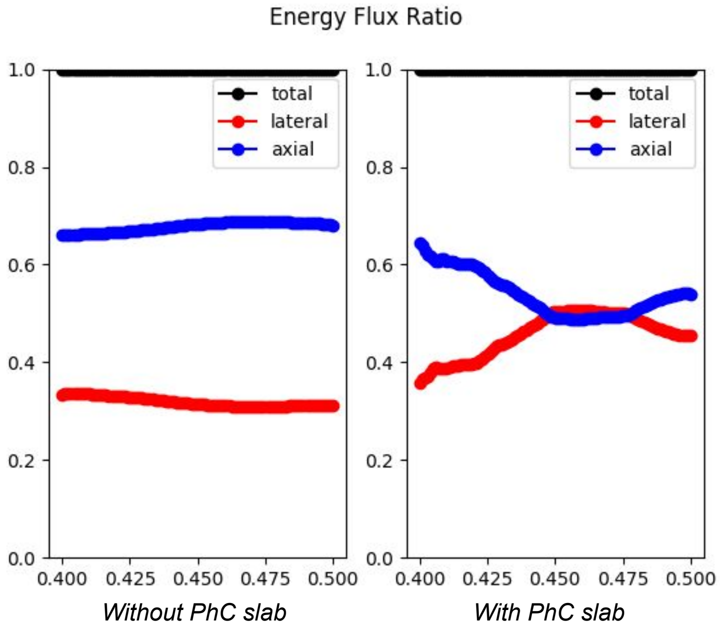
3D FDTD simulation: Configuration



In the FDTD simulation, a point source is modeled as an infinitesimal dipole with electric current in given direction

3D FDTD simulation: Energy Flux Results

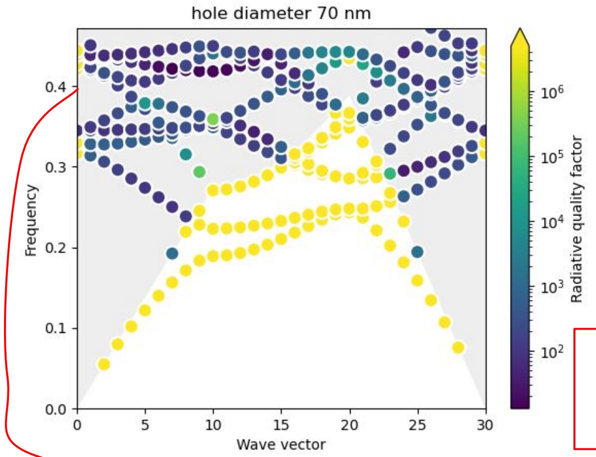




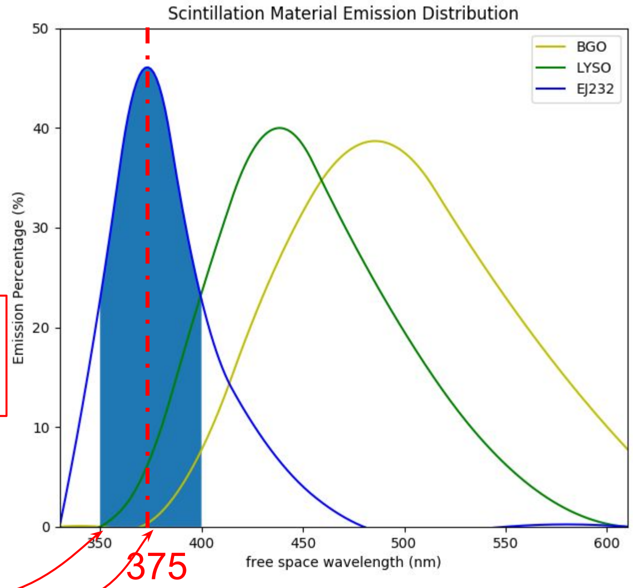
Source component = Parallel (Ex or Ey)
Resolution = 13
Number period = 20
Symmetry = None

Dispersion Relation Optimization

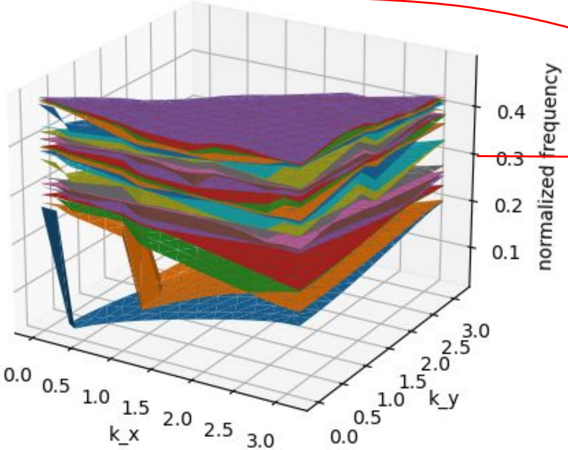
Band curves



ƛ = a / f_normalized
pitch size = 150 nm



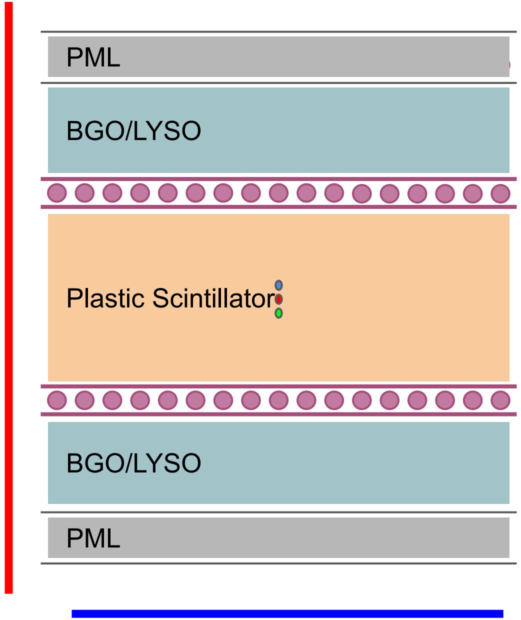
Isofrequency surfaces

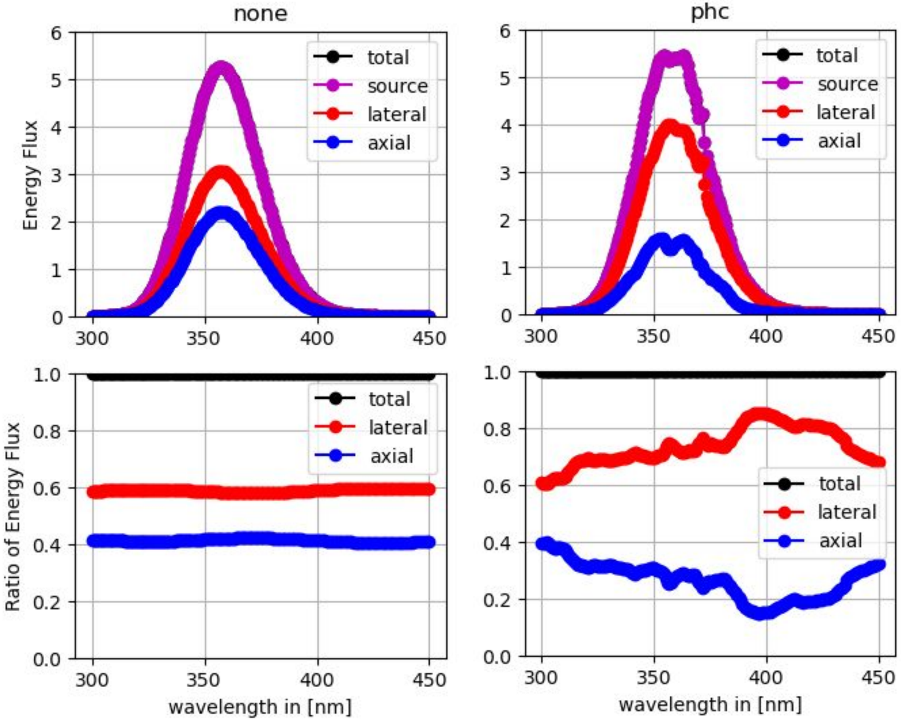


- Band structure computed with Guided Mode Expansion Method, double checked with RCWA.
- With fixed period pitch size, the physical wavelength of each mode can be solved.
- Optimization: Value function = [leaky mode density] * [EJ232 emission distribution].

Energy flux evaluation on optimized desing

Simulated Domain Size:
2.4 x 2.4 x 2.1 μm
With mesh of 2.7e7 elements.

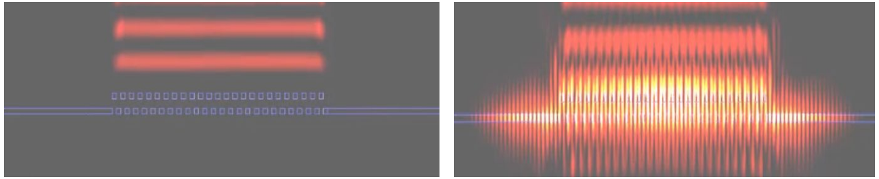




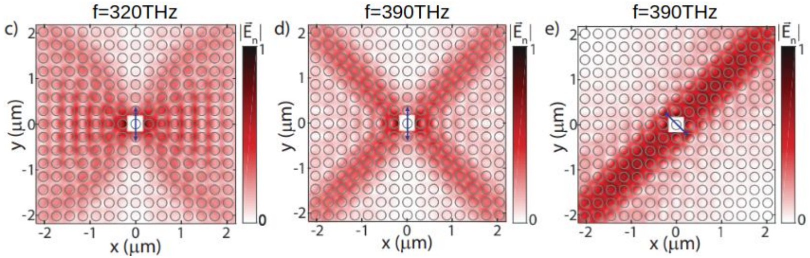
- Source component = Parallel (Ex or Ey)
- PhC slab helps to improve lateral energy flux ratio

Perspectives

- Study profoundly on the leaky mode: coupling efficiency, rigorous density of state, contribution to the lateral energy flux for further optimization.
- Integrate Wave simulation or its results into Ray-Tracing simulation.
- Consider new designs or structures
    - Grating coupler like structure: convert leaky mode into guided mode?
    -



    - Directional propagating or Self-collimation Guide Mode Resonance



Thanks and Questions?

Numerical analysis suite: metascint

Photonic Crystal Slab

Geometry
- Layers
- Unit Cell
- Features
- Reciprocal Space

Material
- Dispersive
- Import Database

Numerical Analysis

Guided Mode Expansion: Band structure

RCWA: Reflection/Transmission spectra

FDTD: Energy flux and others

Post-Processing

Visualization
- Field distribution
- Curves

Convergence

Optimization

Cost/Value functions

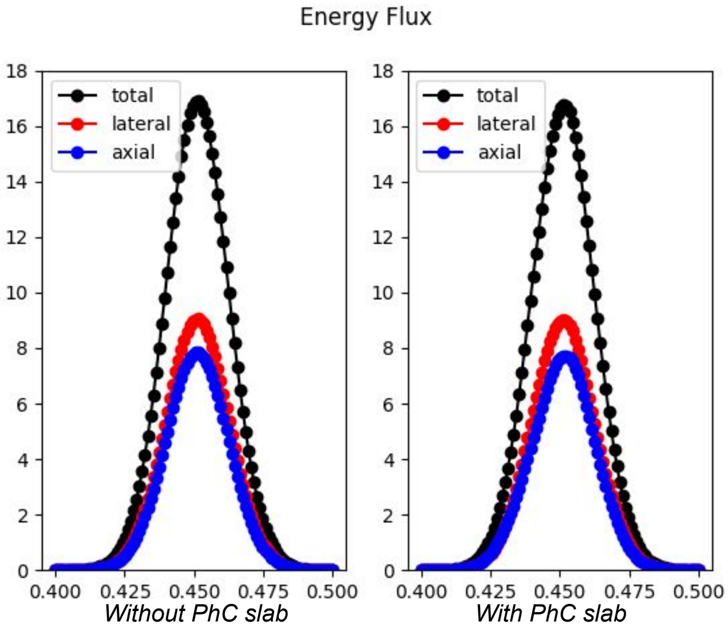
Optimize algorithms:
- Gradient based
- Genetic
- Others

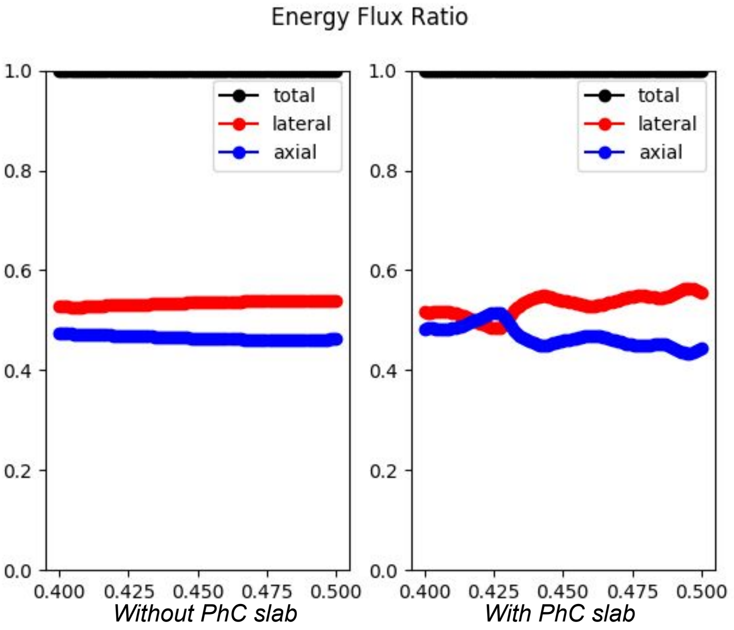
To be developed:

Integration & Communication for Wave simulation and Ray-Tracing simulation

Gate/Geant4 Application

3D FDTD simulation: Energy Flux Results



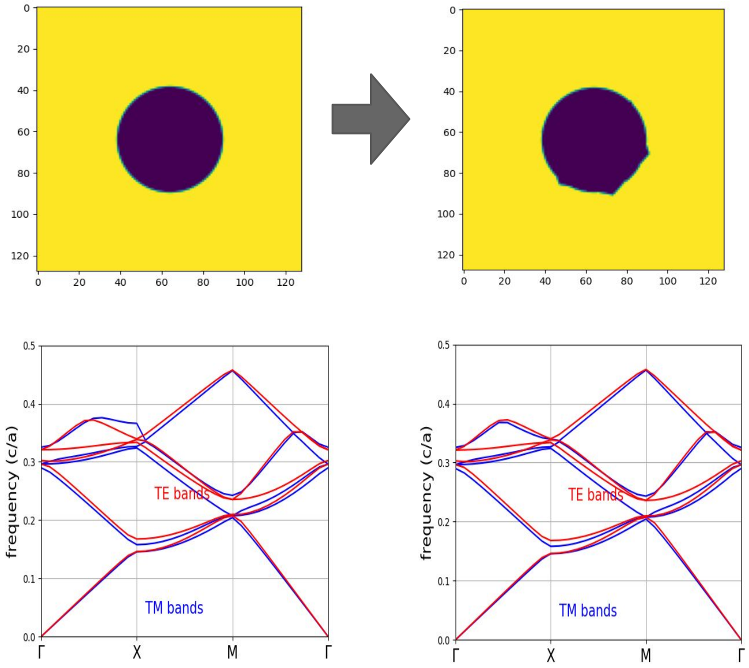


Source component = Perpendicular (Ez)
Resolution = 13
Number period = 20
Symmetry = None

Estimation on Influence of fabrication precision

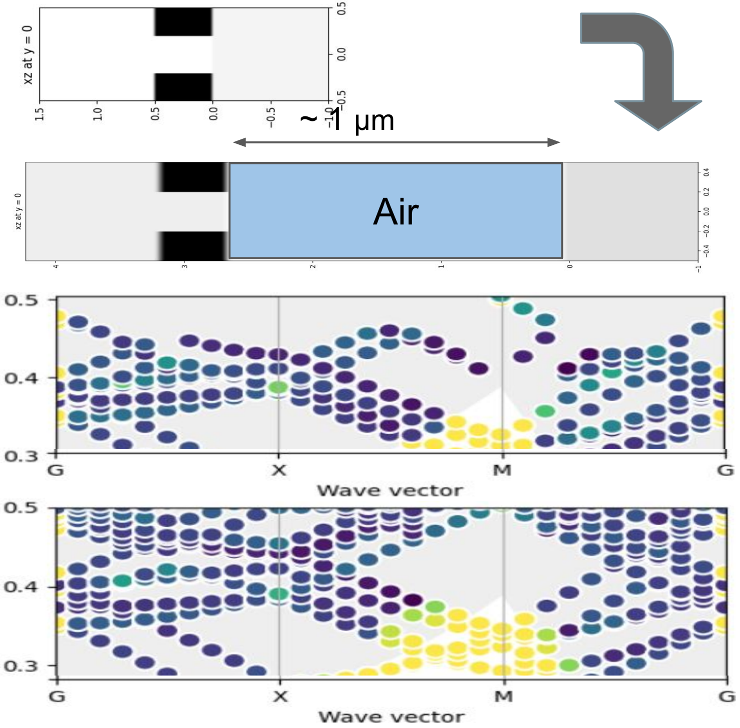
Fabrication errors

Inclusion: shape and position of holes



Almost no influence

Depositing of PhC slab on Crystal



Visible changement in frequency range of interest