Wavelength Agnostic Design of Next Generation 2D Photodetectors

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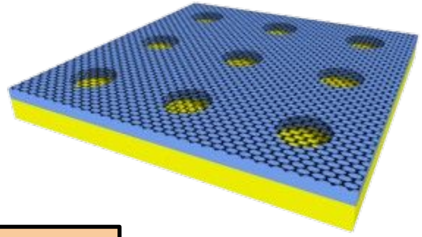
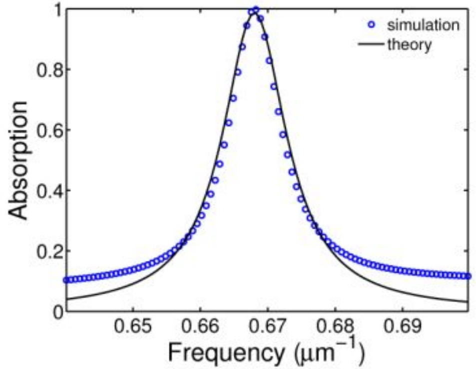
Motivation

Metasurfaces dramatically improve absorption in 2D materials through critical coupling and resonance[1]



Graphene - 0.34 nm!
Silicon Metasurface
Metal Reflector

Key Idea - Device optical response depends on metasurface structure



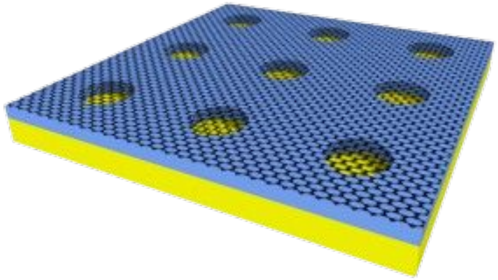
- Method to design structures - exhaustive search or manual trials through parameter space
- Parameters - hole radius, periodicity, thickness, etc.

[1] and Images: Piper, Jessica R., and Shanhui Fan. "Total absorption in a graphene monolayer in the optical regime by critical coupling with a photonic crystal guided resonance." *Acs Photonics* 1.4 (2014): 347-353.

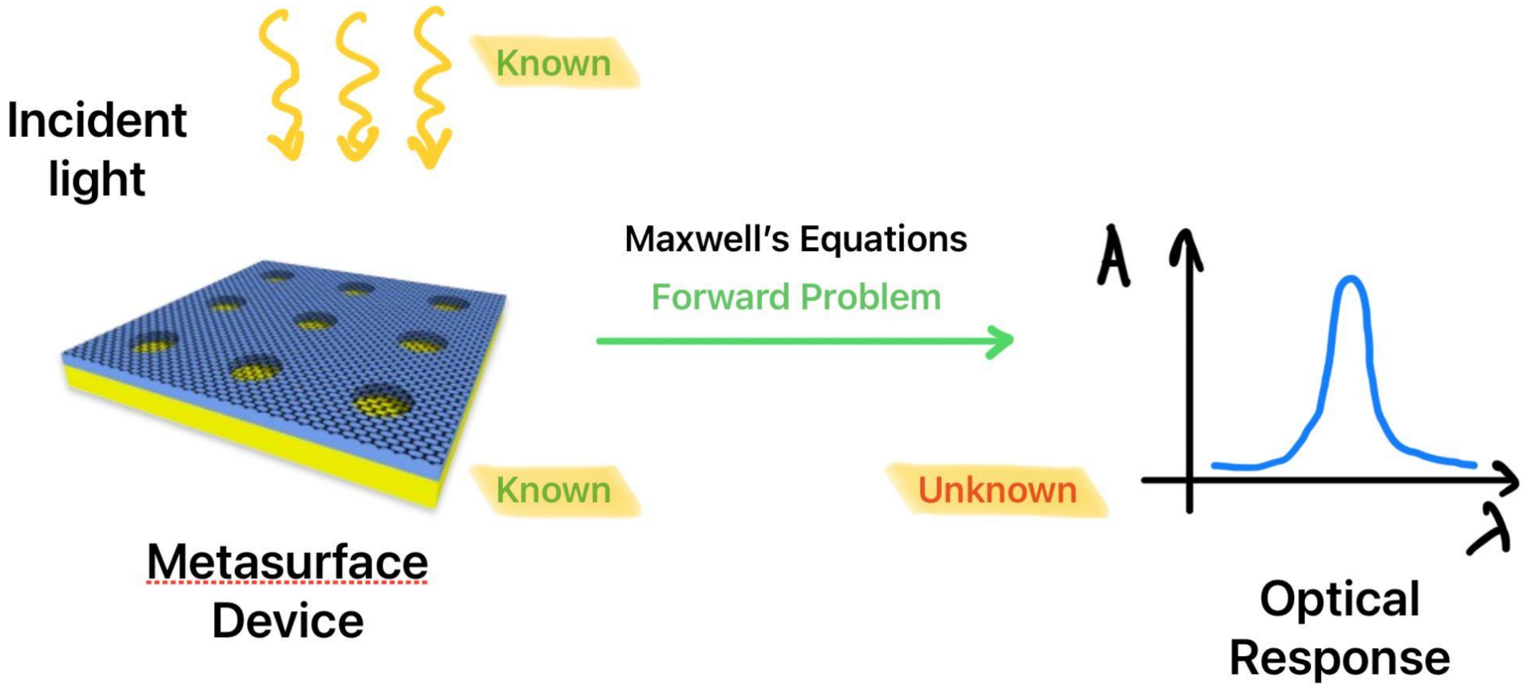
Intuition

Challenge: Several emerging 2D materials and metasurface choices - How much will you search?

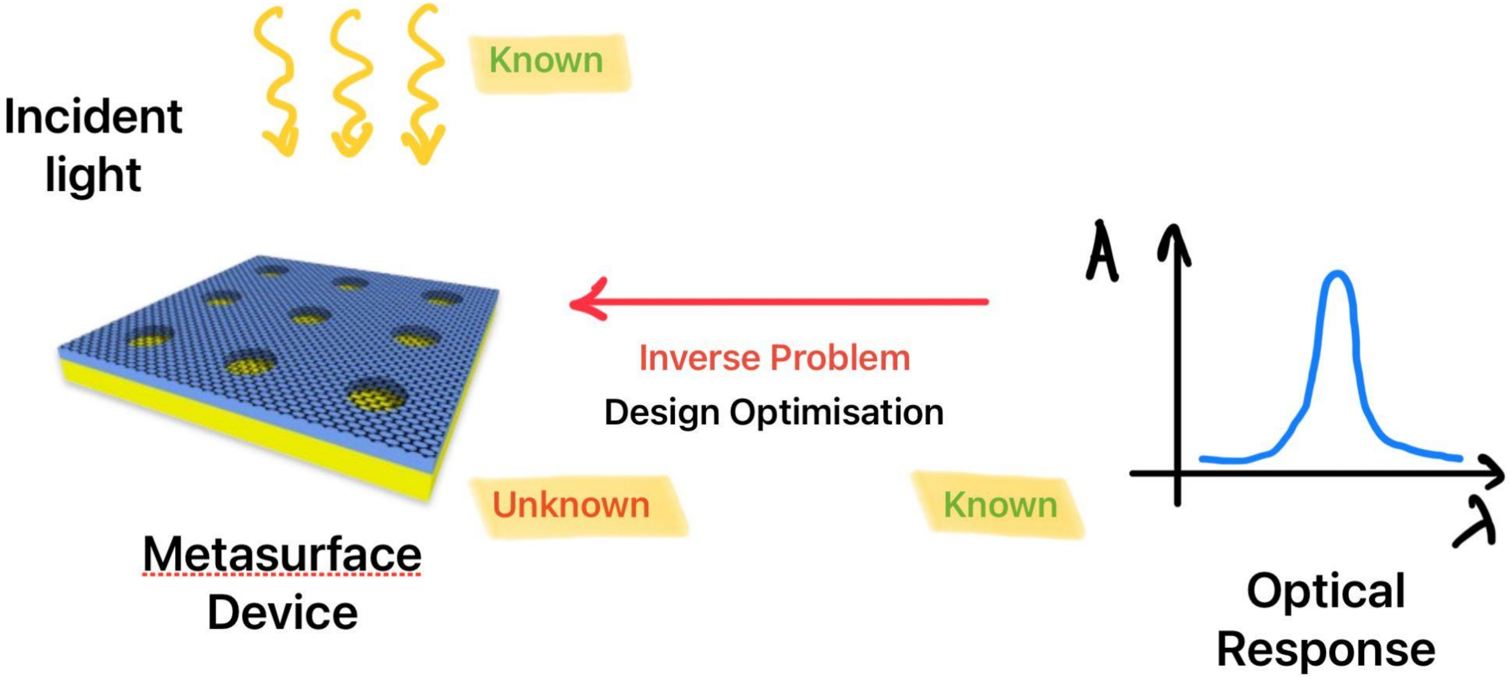
- Can we devise a well-defined method to optimize metasurface geometry?
- Hence, can we design structures that perfectly absorb any chosen wavelength?
- Why just absorption, can we also tailor transmission and reflection?



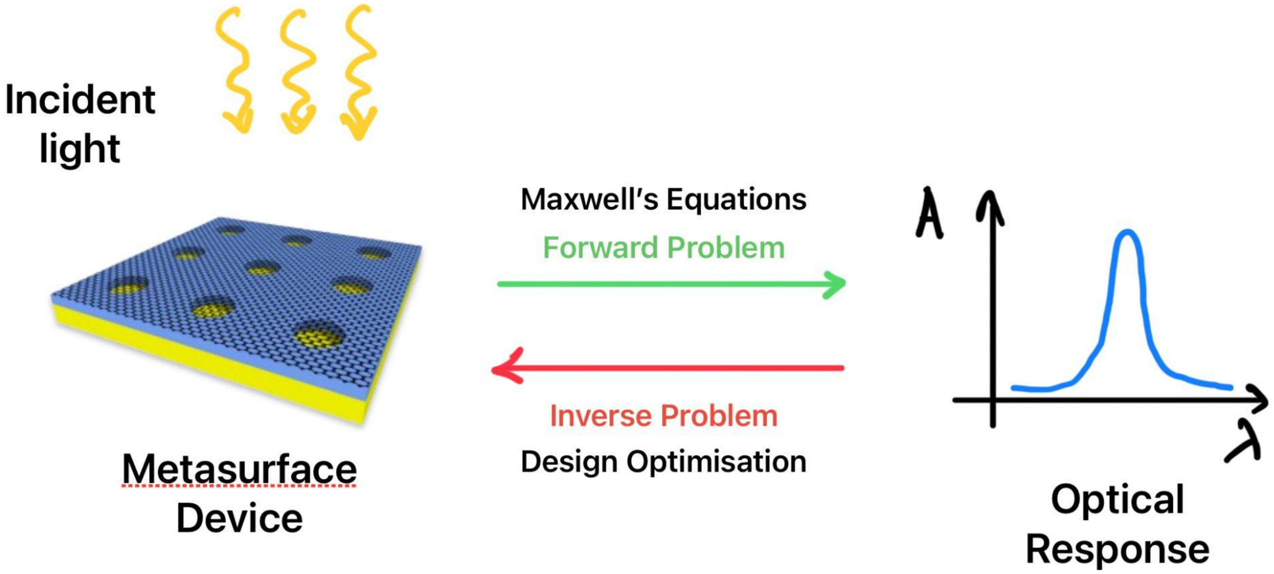
Framing the ‘Inverse’ Problem



Framing the ‘Inverse’ Problem



Framing the ‘Inverse’ Problem



This study presents a general technique to *inverse* design resonance at one or multiple desired optical modes - wavelengths, angle, polarization, etc.

Simulation and Optimization

Absorption $\mathbf{A}$ is a function of

- wavelength $\boldsymbol{\lambda}$
- metasurface geometry $\mathbf{X}$
- material refractive indices $\boldsymbol{\Theta}$

For a set of wavelengths $\boldsymbol{\Lambda}$, find the best absorber with optimal $\mathbf{X}^*$ such that

$$\boxed{\mathbf{X}^* = \arg\max_{\mathbf{X}\in\Omega} \sum_{i=1}^{|\Lambda|} A(\lambda_i, \mathbf{X}, \Theta)}$$

Simulation: Rigorous Coupled Wave Analysis (RCWA)

- **Computationally efficient tool to solve Maxwell's equations in the Fourier domain.**
- **Method of choice for 2D photonic crystals - invariant along z-axis**

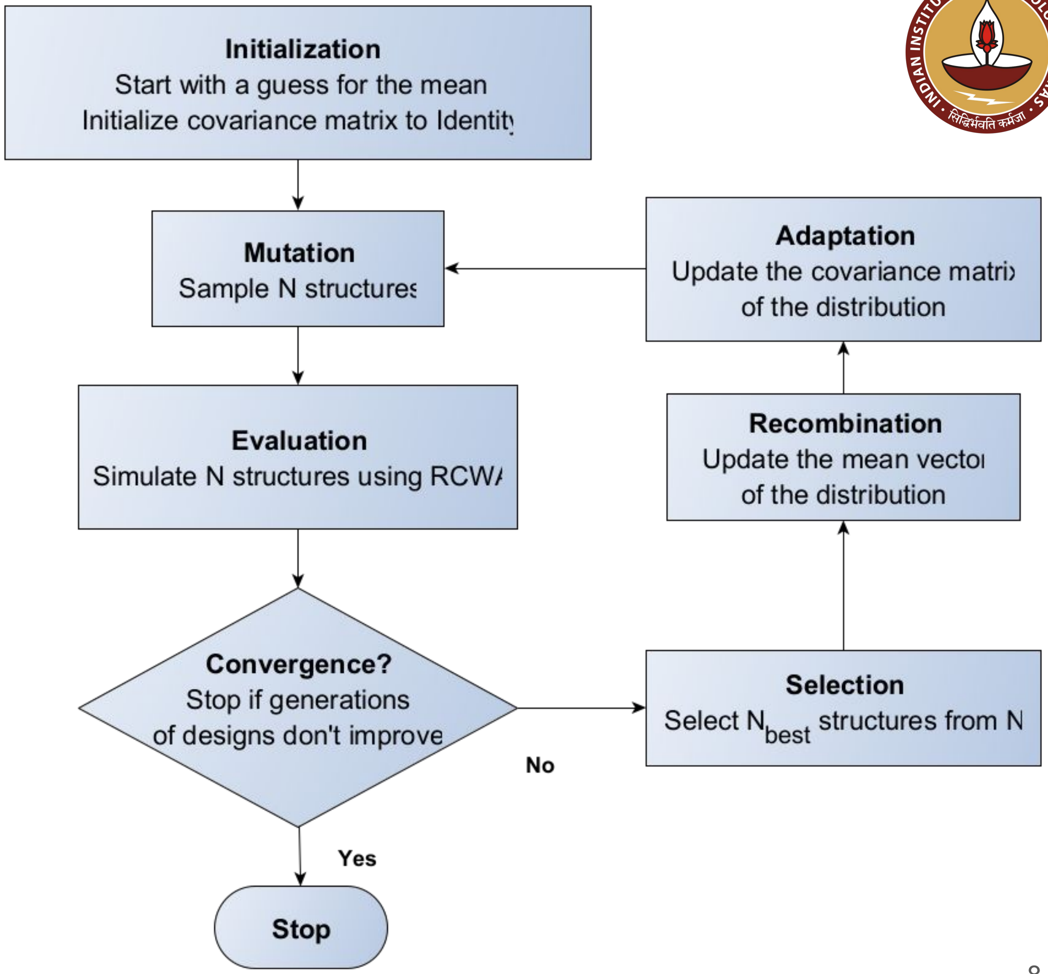
- $\mathbf{A}$: non-separable, non-convex, and noisy
- Required: a stochastic numerical optimization

Covariance Matrix Adaptation - Evolutionary Strategy **(CMA-ES)**

- Treat metasurface parameters as random variables sampled from a multivariate Gaussian distribution.
- Characterized by
  - Mean - best solution
  - Covariance Matrix - direction of search
- Iteratively adapt the distribution to the absorption objective function

Genetic Algorithm inspired by Natural Selection

CMA-ES Algorithm



Results | Designing a Photodetector for 1.55 um

Structure

1. Black Phosphorus[2] **4 nm**
2. Si Metasurface **130 nm**
3. Metallic Mirror

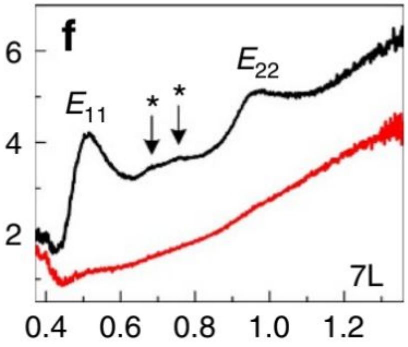


Fig. BP Extinction % plotted against photon energy[2]

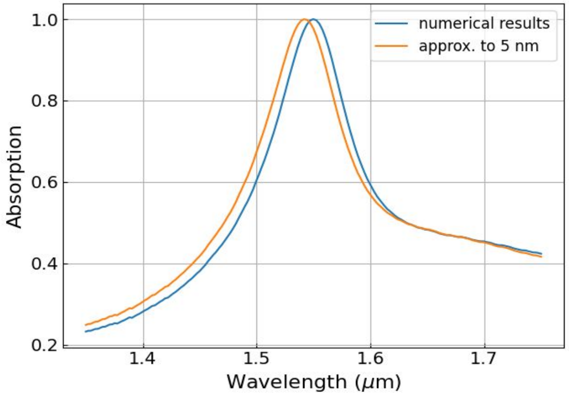
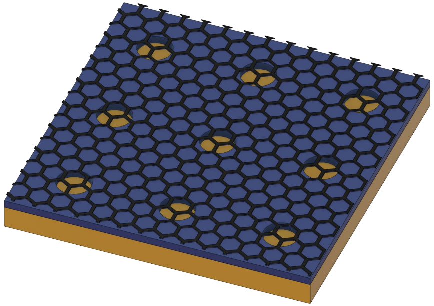
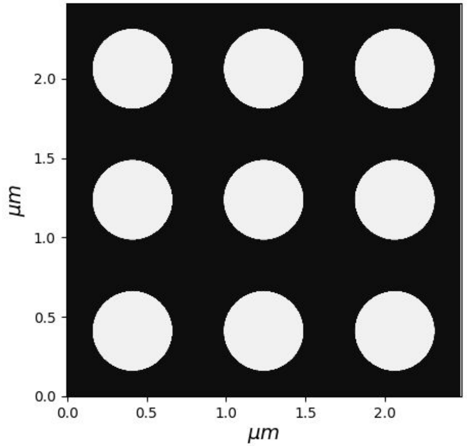


Fig 1. Absorption in BP



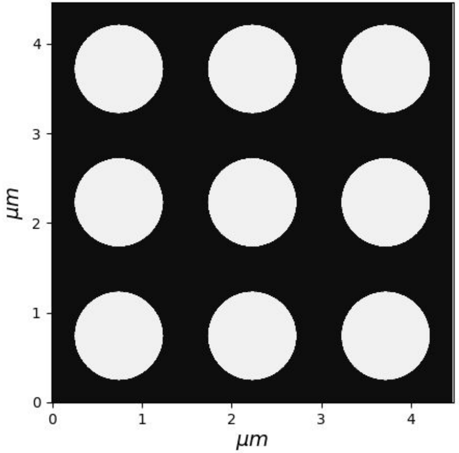


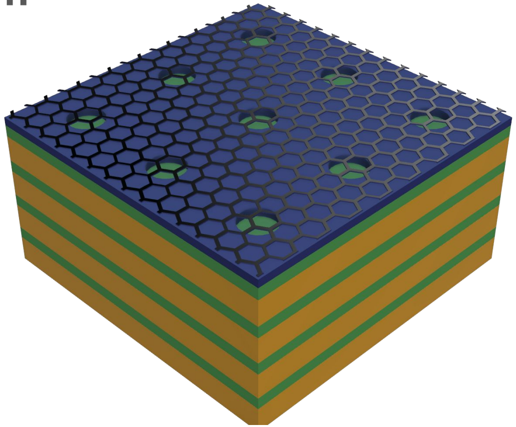
[2] Zhang, Guowei, et al. "Infrared fingerprints of few-layer black phosphorus." *Nature communications* 8.1 (2017): 14071.

Results | Designing a Photodetector for 2.1 um

Structure

1. Black Phosphorus **4 nm**
2. Si Metasurface **110 nm**
3. DBR Mirror





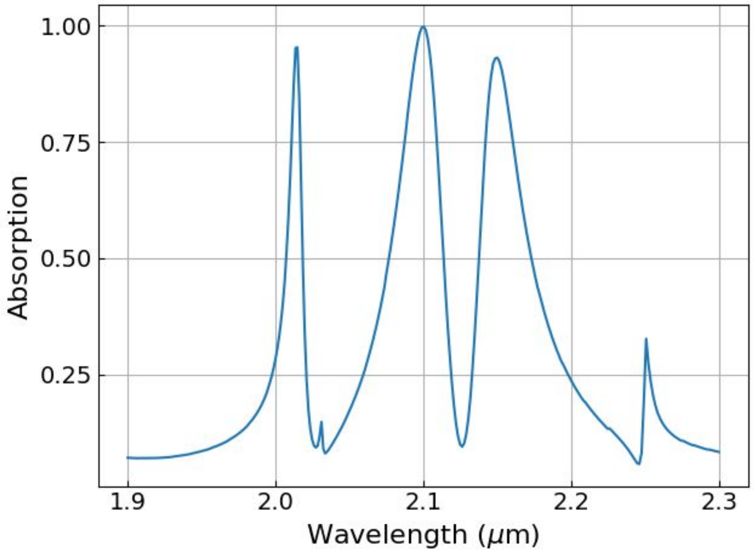


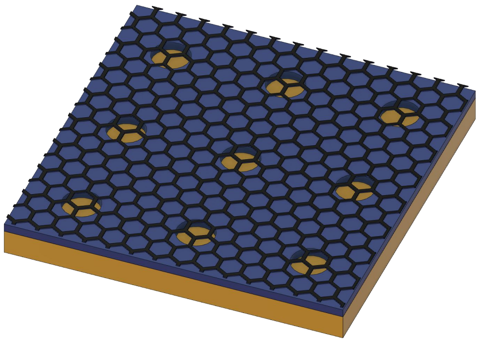
Fig 2. Absorption in BP

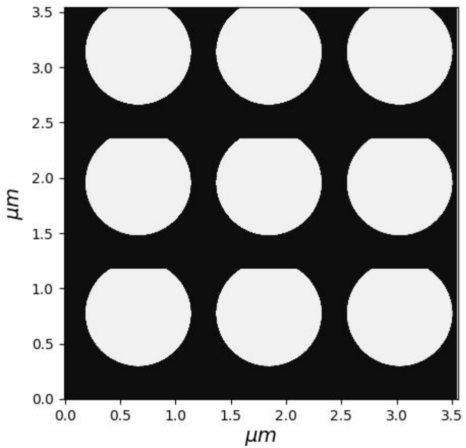
Results | Designing Double Resonance at 1.3 & 1.55

Structure

1. Black Phosphorus **4 nm**
2. Si **110 nm**
3. Metallic Mirror

- Notice the partial holes





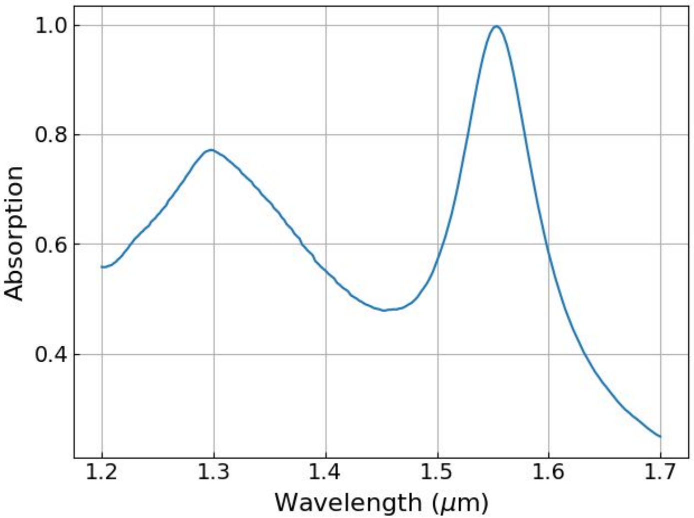
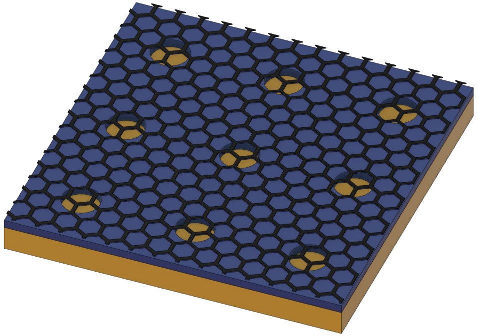


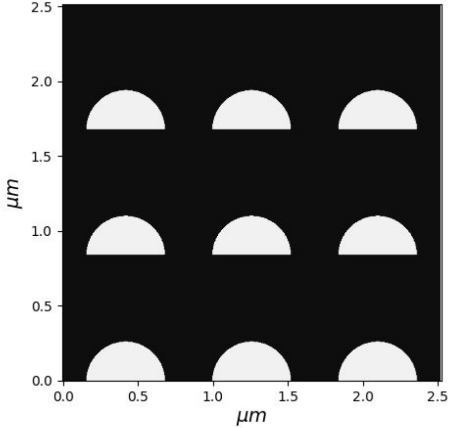
Fig 3. Absorption in BP

Results | Wide-angle Absorption at **1.55 um**

Structure

1. Black Phosphorus **4 nm**
2. Si Metasurface **130 nm**
3. Metallic Mirror





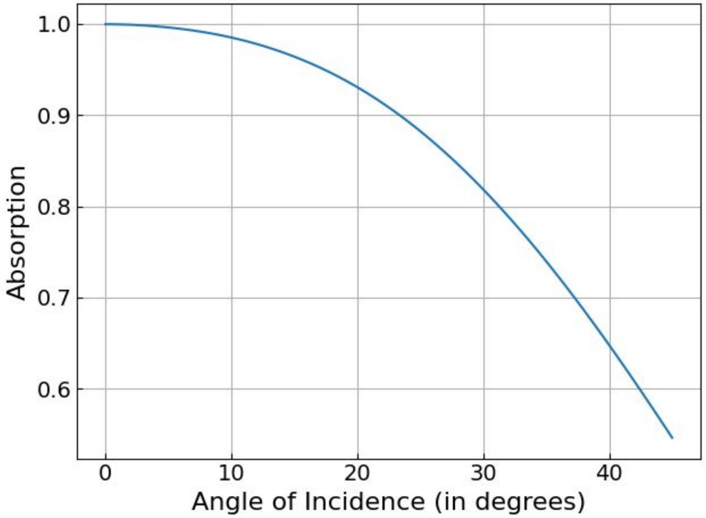


Fig 4. Absorption in BP

From Mathematics to Physics - Aryan

Understanding Photonic Band Structures

The Problem

- Detectors- less responsive for large angles of incidence (upto 10-15 degrees)
- Design a system of graphene+PCS+mirror for broad-angle absorption

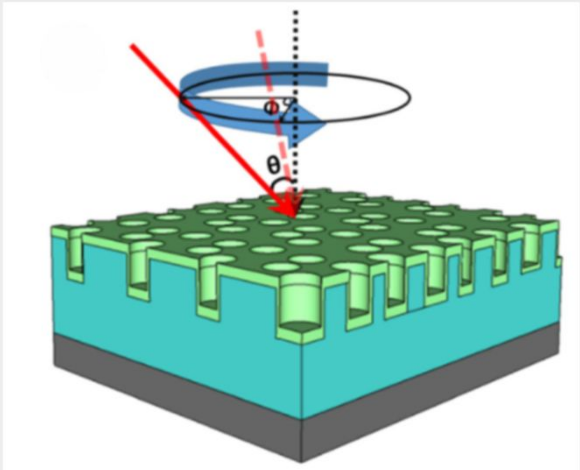


Image:Ding H.,Lalouat L.,Gonzalez B. “Design rules for net absorption enhancement in pseudo-disordered photonic crystal for thin film solar cells” *Optics Express 24(6):A650*

A Physics Approach

Using **band diagrams** of the photonic crystal

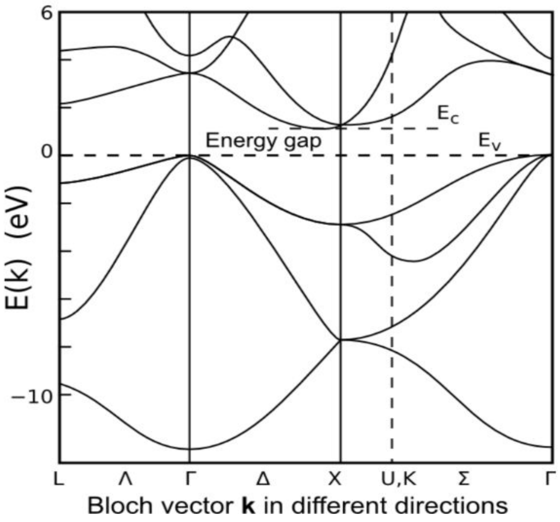
- Solutions, in frequency, to the eigenvalue Maxwell's equation for the photonic crystal

	Quantum Mechanics	*Electrodynamics*
Field	$\Psi(\mathbf{r},t) = \Psi(\mathbf{r})e^{-iEt/\hbar}$	$\mathbf{H}(\mathbf{r},t) = \mathbf{H}(\mathbf{r})e^{-i\omega t}$
Eigenvalue problem	$\hat{H}\Psi = E\Psi$	$\hat{\Theta}\mathbf{H} = \left(\frac{\omega}{c}\right)^2 \mathbf{H}$
Hermitian operator	$\hat{H} = -\frac{\hbar^2}{2m}\nabla^2 + V(\mathbf{r})$	$\hat{\Theta} = \nabla \times \frac{1}{\varepsilon(\mathbf{r})}\nabla \times$

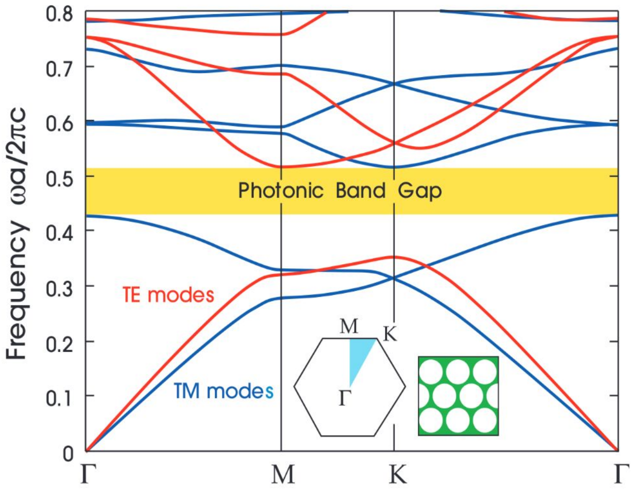
Analogy With Quantum Mechanics

A Physics Approach

- Electronic band diagrams- familiar counterpart from solid state physics



Electronic band diagram of Si



Photonic band diagram
Triangular lattice of air columns in dielectric

Images:[Left] Wacker A., “An Introduction to the Concept of Band Structure”
[Right] Johannopalous J.,” Photonic Crystals:Molding the flow of light”

Band diagram of a photonic crystal

- The **light cone** represents a continuum of states (radiation modes) in the band diagram
- Region inside the light cone corresponds to **propagating waves** that can exist outside the photonic crystal-extend into the surrounding material

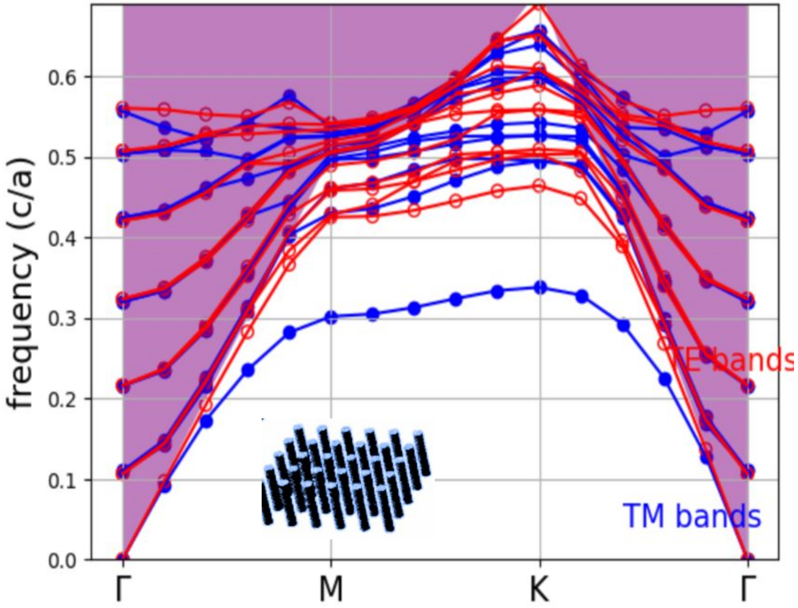
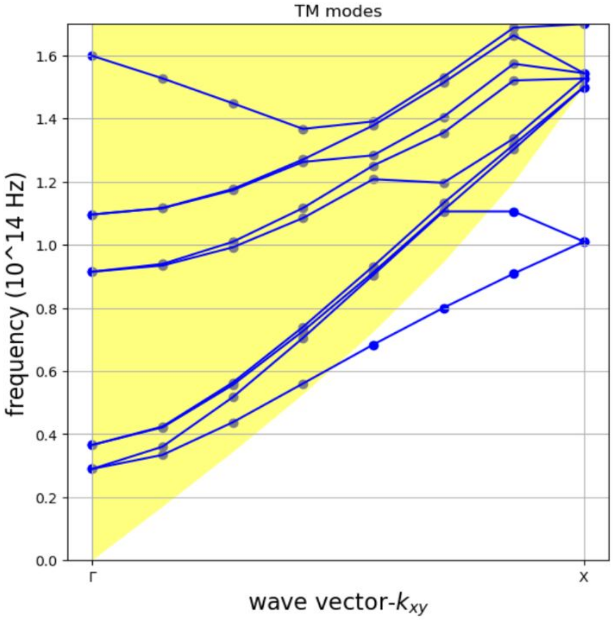
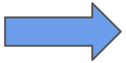


Fig 1. Band dispersion curve
Cylindrical Si rods in a square lattice
Inset: Johannopalous J. ,"Photonic crystals: Molding the flow of light "

Bands & Transmission

Our hypothesis:





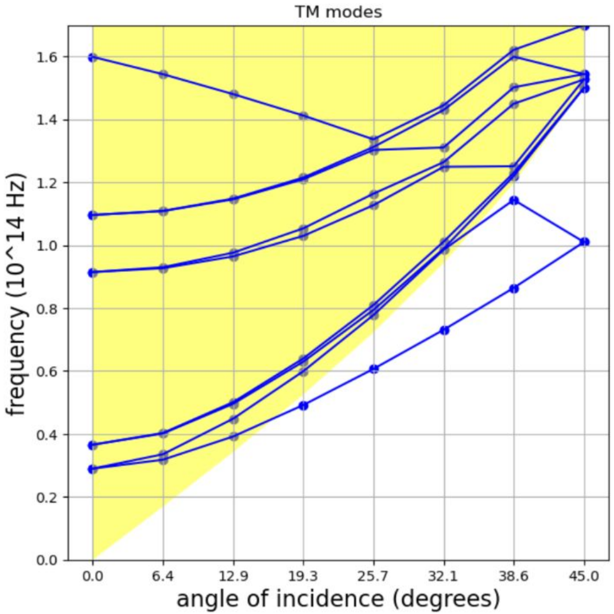


Fig 2. Comparison of band diagrams of Si slab

Bands & Transmission

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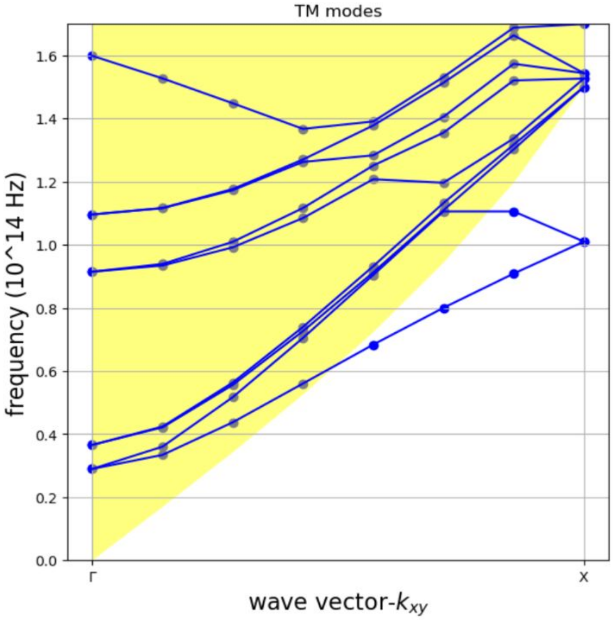

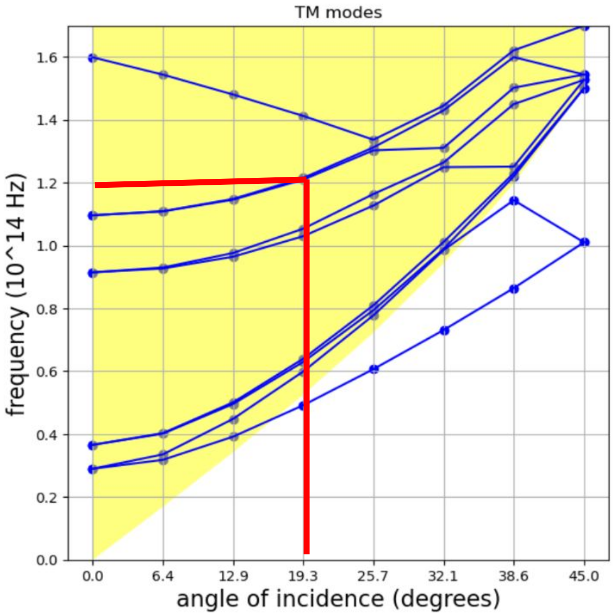

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Bands & Transmission

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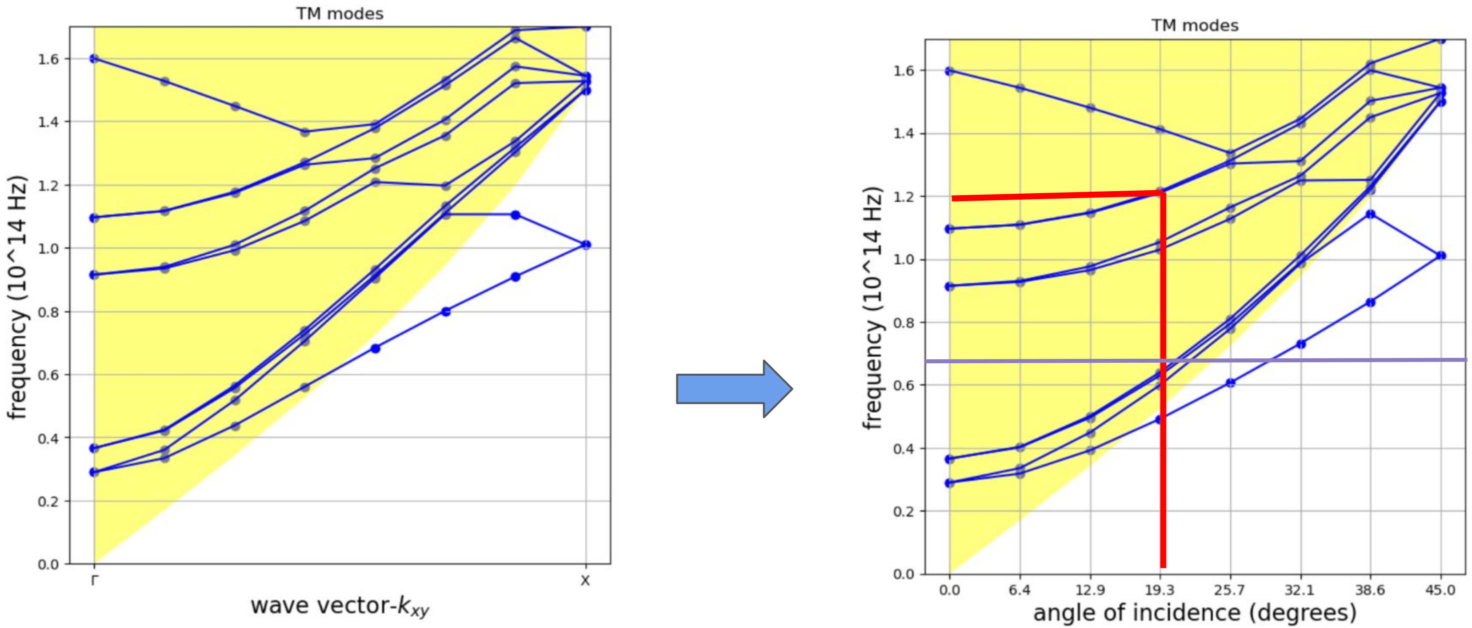


Fig 2. Comparison of band diagrams of Si slab

Results | Square lattice of circular holes in Si slab

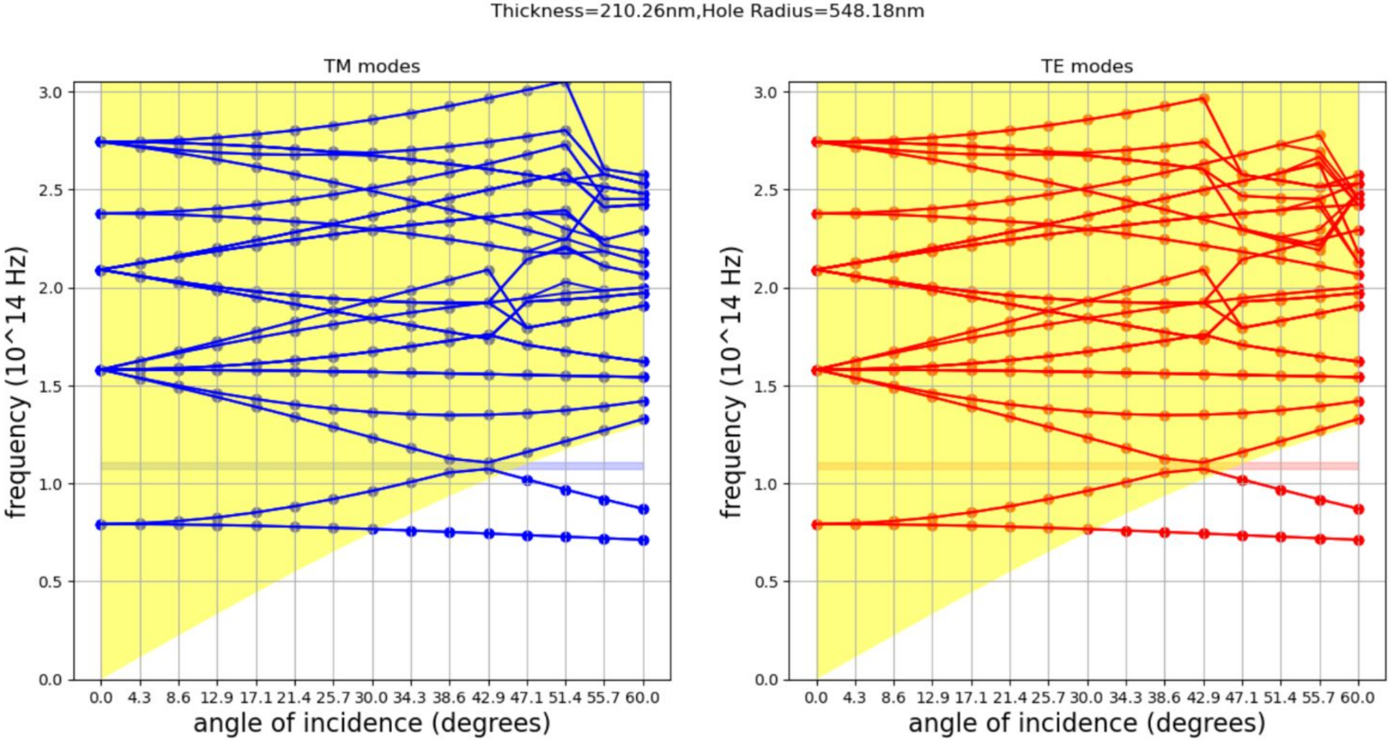


Fig3. Band diagrams of Si slab with circular air holes in a square lattice

Results and Follow-up

- Yet to explain all features in the transmittance plots through band diagrams and quantify correlation
- Vary parameters - lattice constant, thickness, radius to achieve nearly flat bands
- Using these parameters to reduce bounds of exploration in CMA-ES

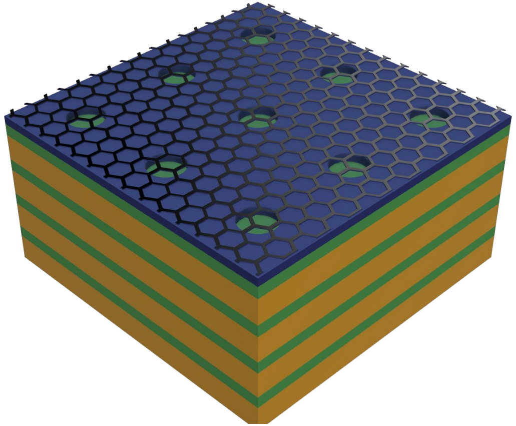
Future Work

- Hyperspectral Sensitivity - tailoring transmission (Sourav)
- Biphoton Generator Devices - pump in and pump out at different wavelengths
- Experimenting with different objective functions

$$\boxed{\mathbf{X}^* = \arg\max_{\mathbf{X}\in\Omega} \sum_{i=1}^{|\Lambda|} A(\lambda_i, \mathbf{X}, \Theta)}$$

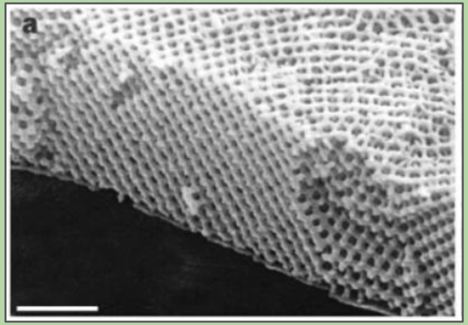
Conclusion

- The method presents an assistive tool to design metasurface devices
- We can thus, tailor absorption, reflection, and transmission.
- Moreover, the tool can be extended to general optical modes - angle, polarization, etc.
- Improvements can be made by drawing inferences from the photonic crystal band diagrams



Acknowledgement

We sincerely our guides thank **Prof. Srini Krishnamurthy** and **Prof. Rituraj** for their support and advice in this study. We would also like to thank our project advisor **Prof. Sivarama Krishnan**



Photonic Crystals in Nature - *Parides sesostris*
Right image scale 1.2 microns

Image Courtesy: Vukusic, P., Sambles, J. Photonic structures in biology. *Nature* 424, 852–855 (2003) and R. Prum, Yale University

Questions?