Establishing and Verifying the Fundamental Optical and Material Capabilities and Limitations of Metasurfaces

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Senior Researcher

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An opportunity

Metasurface solution

Bulky AR/VR system

Lightweight AR/VR glasses

What is a metasurface?

Metasurfaces (Definition varies, but similar features):

- Planar arrays of subwavelength electromagnetic structures
- Near-uniform height profile, thickness on an order of wavelength
- Flexible light-field modulation (phase, wavelength, polarization etc.)

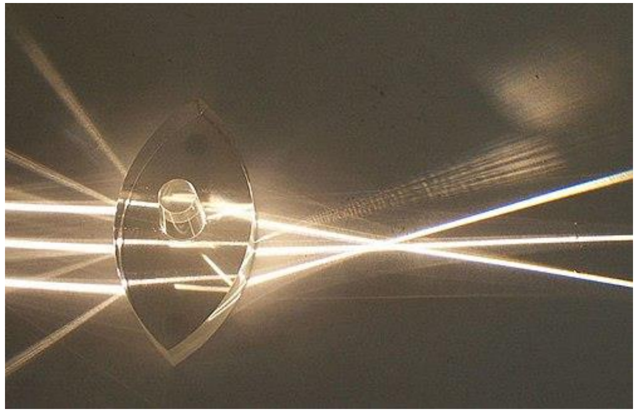
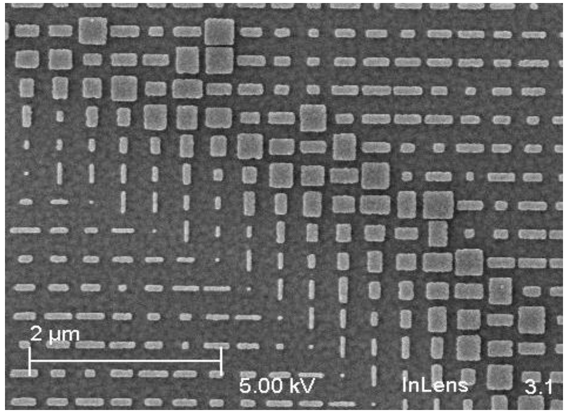
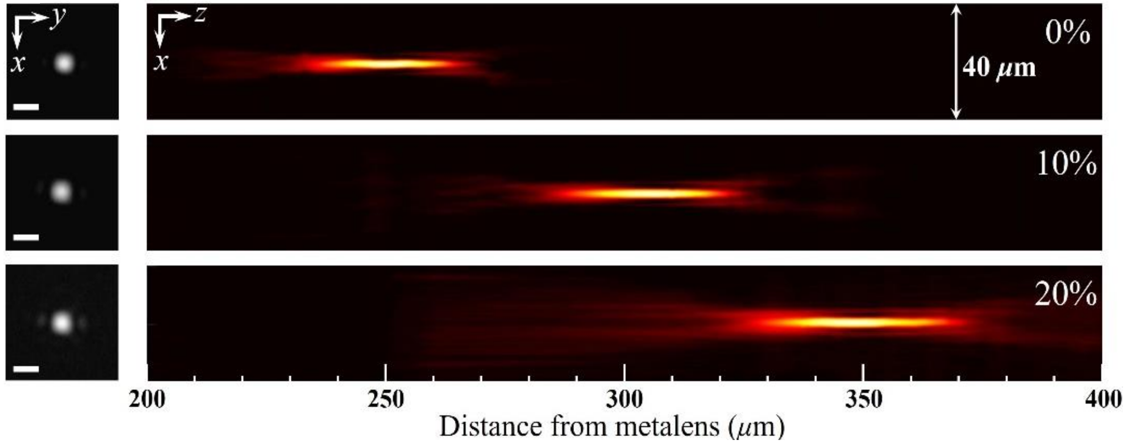


Figure from Wikipedia





Cheng et al., *Opt. Express* (2019), 27, 15194
(published by Senior Researcher and PIs)

Project Goals

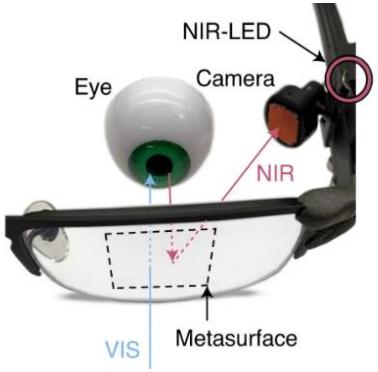
1. Develop an understanding of the properties and limitations of metasurfaces based on a robust understanding of the theoretical fundamentals and experimental evaluations
2. Create a robust metasurface taxonomy, thus creating a library of design examples, which can be used to teach students and new designers and establish performance metrics for these experimentally verifiable metasurfaces

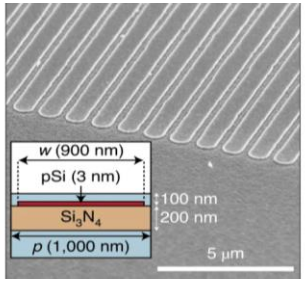
Deliverables:

- A categorization scheme of metasurfaces with example designs (2023-2024)
- An experimental setup for metasurface metrology (2024)
- Fabricated and evaluated metasurface samples (2024-2025)

Applications

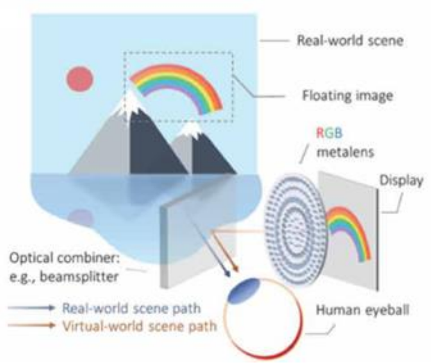
Steering

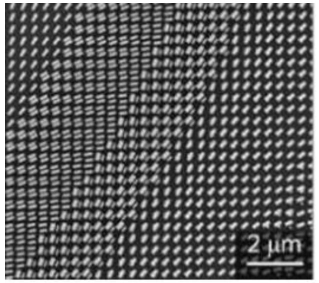




Song et al., Nat. Nanotechnol. 16, 1224–1230 (2021)

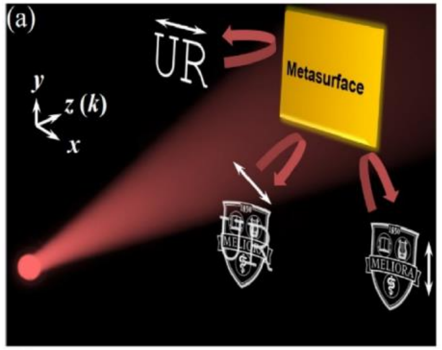
Lensing

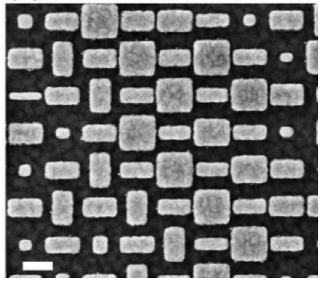




Li et al., Sci. Adv. 7, eabe4458 (2021)

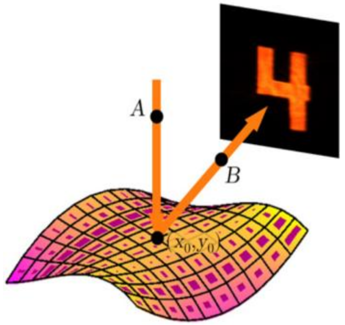
Holography

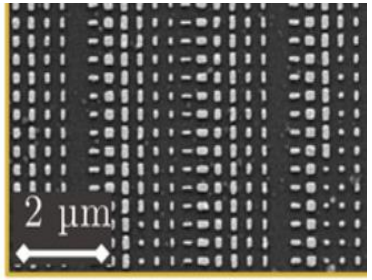




Cheng et al., Opt. Express 26(23), 30678–30688 (2018) (published by Senior Researcher and PIs)

Imaging

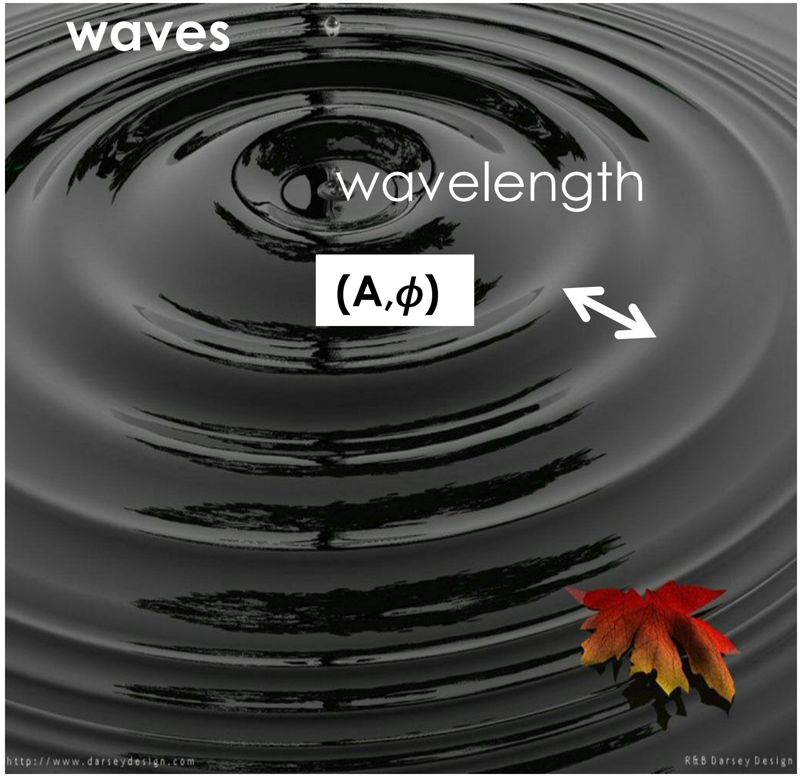




Nikolov et al., Sci. Adv. 7, eabe5112(2021) (published by Senior Researcher and PIs)

Understanding wave optics

$$U = A\cos\phi$$



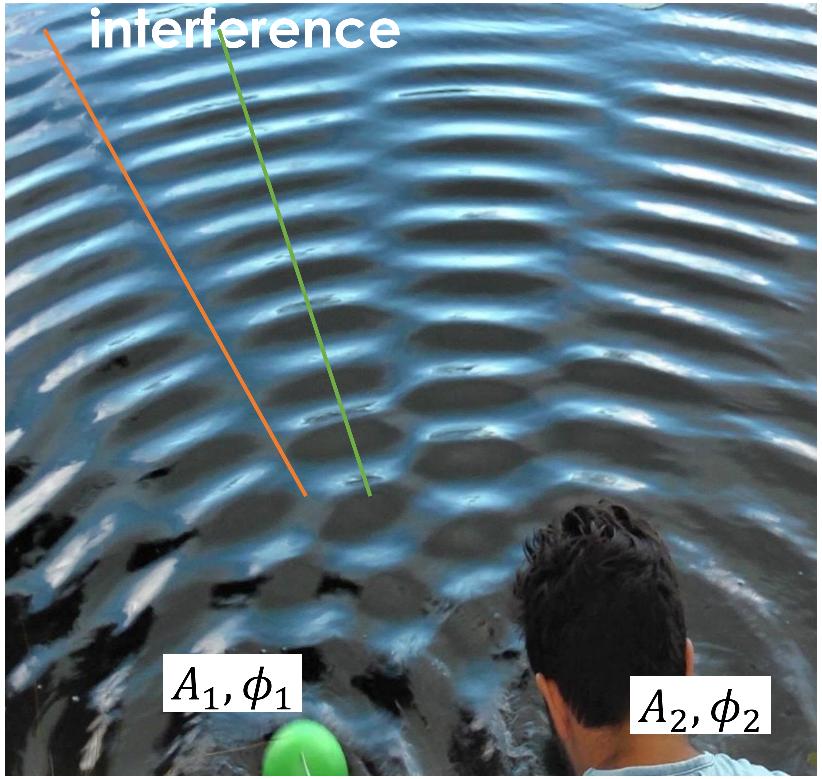


Figure from:
https://youtu.be/Iuv6hY6zsd0?si=TrVIFhpFT_TOTb6A

Understanding wave optics

$$U = A\cos\phi$$

$$U = A\cos\phi \rightarrow \bar{U} = \hat{\sigma}A\cos\phi$$

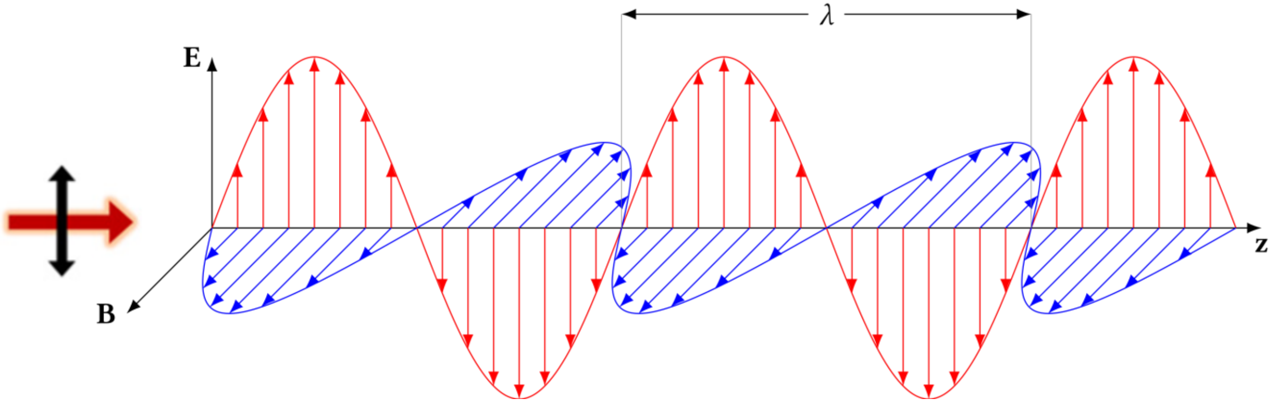
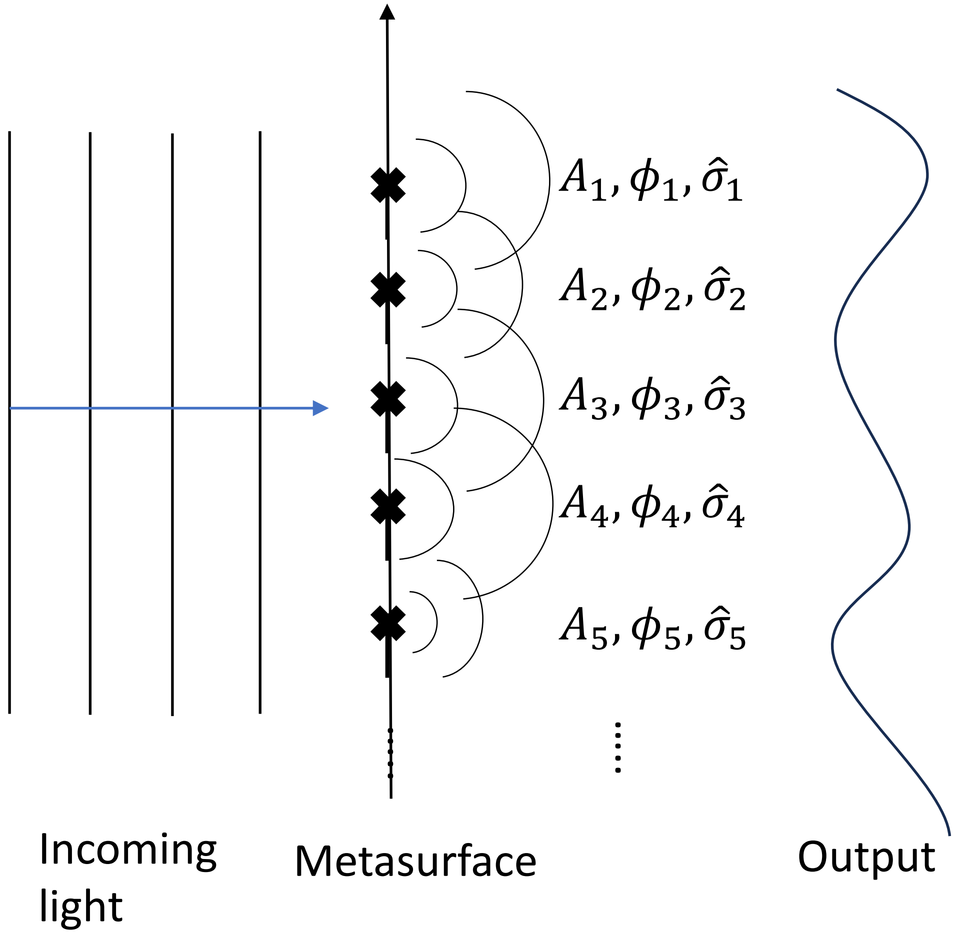


Figure from Wikipedia: Polarization

Metasurface as array of antennas

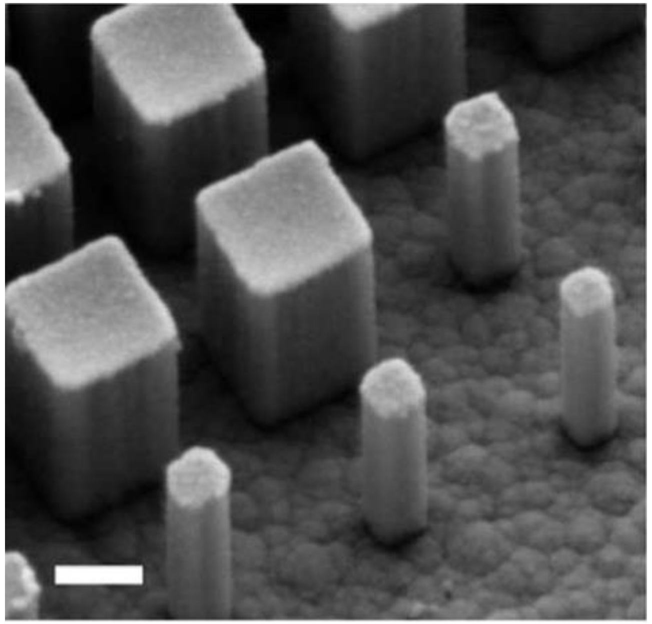
- Incoming wave actuates the meta-atom (“antenna”) array
- Each “antenna” radiates new waves
- New waves superpose to form the output wave

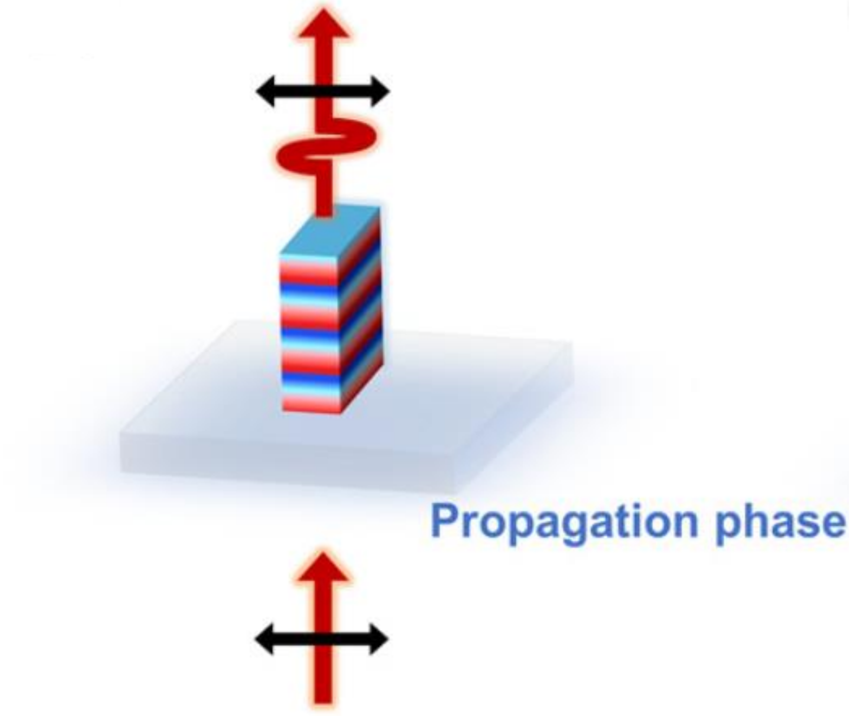


Phase modulation via propagation phase

- Transmissive meta-atoms (ex. dielectric nanopillars) act like truncated waveguides
- Phase is accumulated by propagation inside the nanopillars

Khorasaninejad et al., *Nano Lett.* (2017), 17, 3, 1819–1824



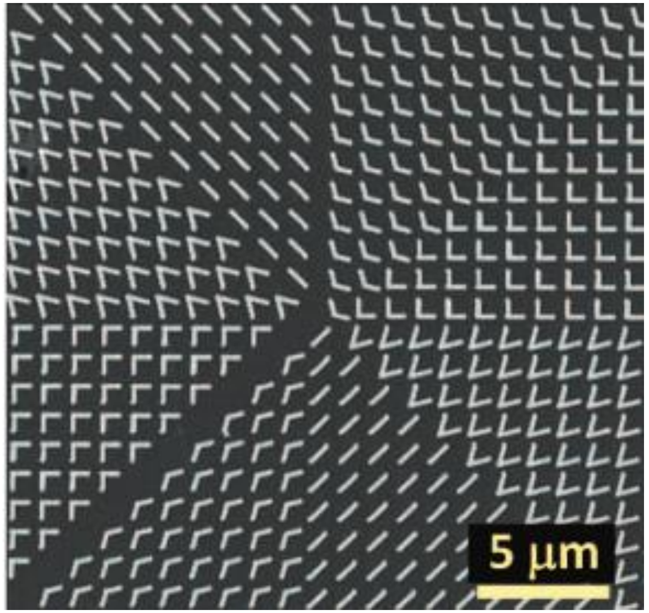


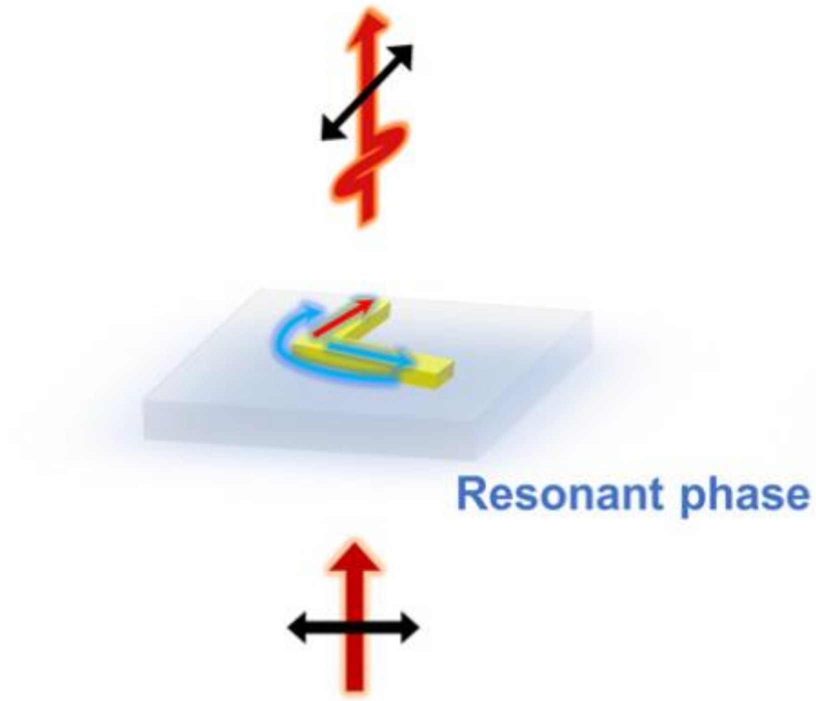
Liu et al., *Adv. Photon.* (2023) Vol. 5, Issue 3, 034001

Phase modulation via resonant phase

- The incident light excites a resonant mode of the metallic meta-atom
- The cross-polarized transmitted light will experience a phase shift modulation.

Yu et al., *Science* (2011) **334**, 333–337

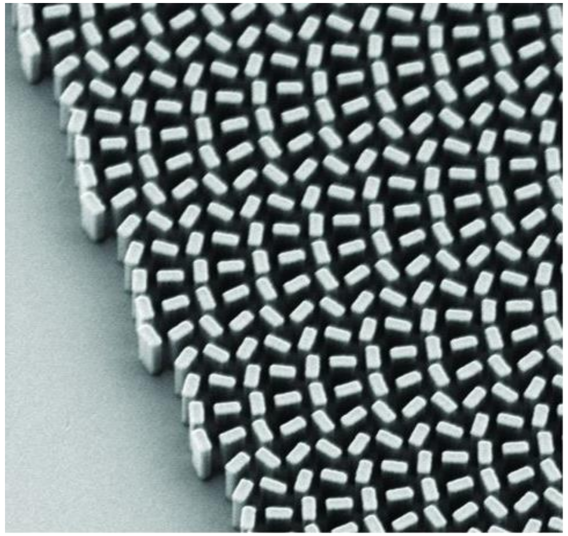




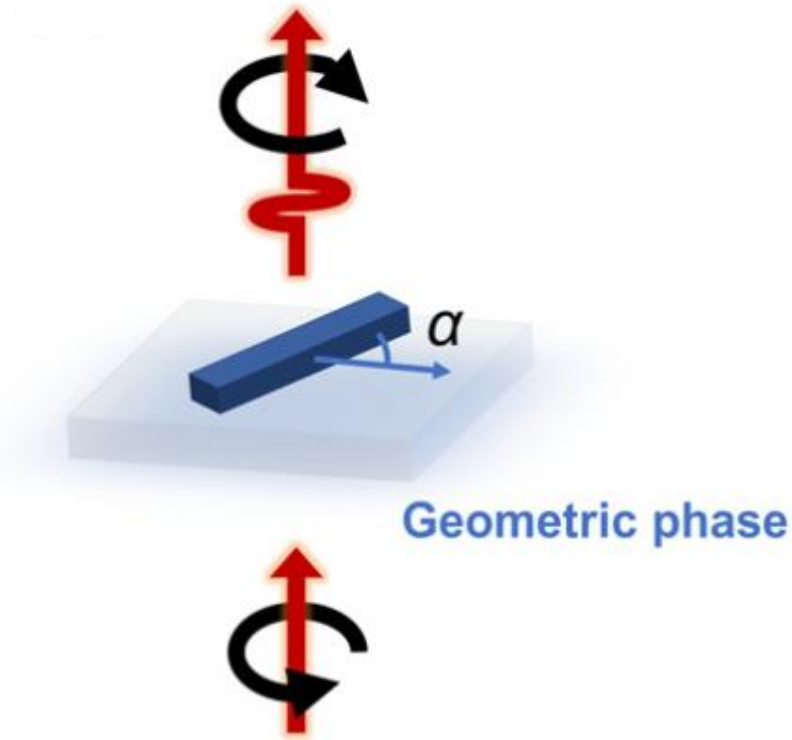
Liu et al., *Adv. Photon.* (2023) Vol. 5, Issue 3, 034001

Phase modulation via geometric phase

- An array of anisotropic meta-atoms of constant size but different in-plane orientation
- Incoming light is circularly polarized
- The cross-circularly polarized component will be imparted a phase shift modulation that is twice the meta-atom orientation angle



Khorasaninejad et al., *Science* (2016) **352**,1190-1194



Liu et al., *Adv. Photon.* (2023) Vol. 5, Issue 3, 034001

Example metasurface fabrication procedure

Fabrication for Silicon nanorods

a. Deposit silicon layer onto SiO2 using Plasma-Enhanced Chemical Vapor Deposition (PECVD)
b. EBL to create the pattern
c. Metal (high etch resistance) deposition
d. Then lift off the resist to create an etch mask so that the Si pillar under the metal layer won't be etched
e. Etch the Silicon layer
f. Wet etch to remove the metal

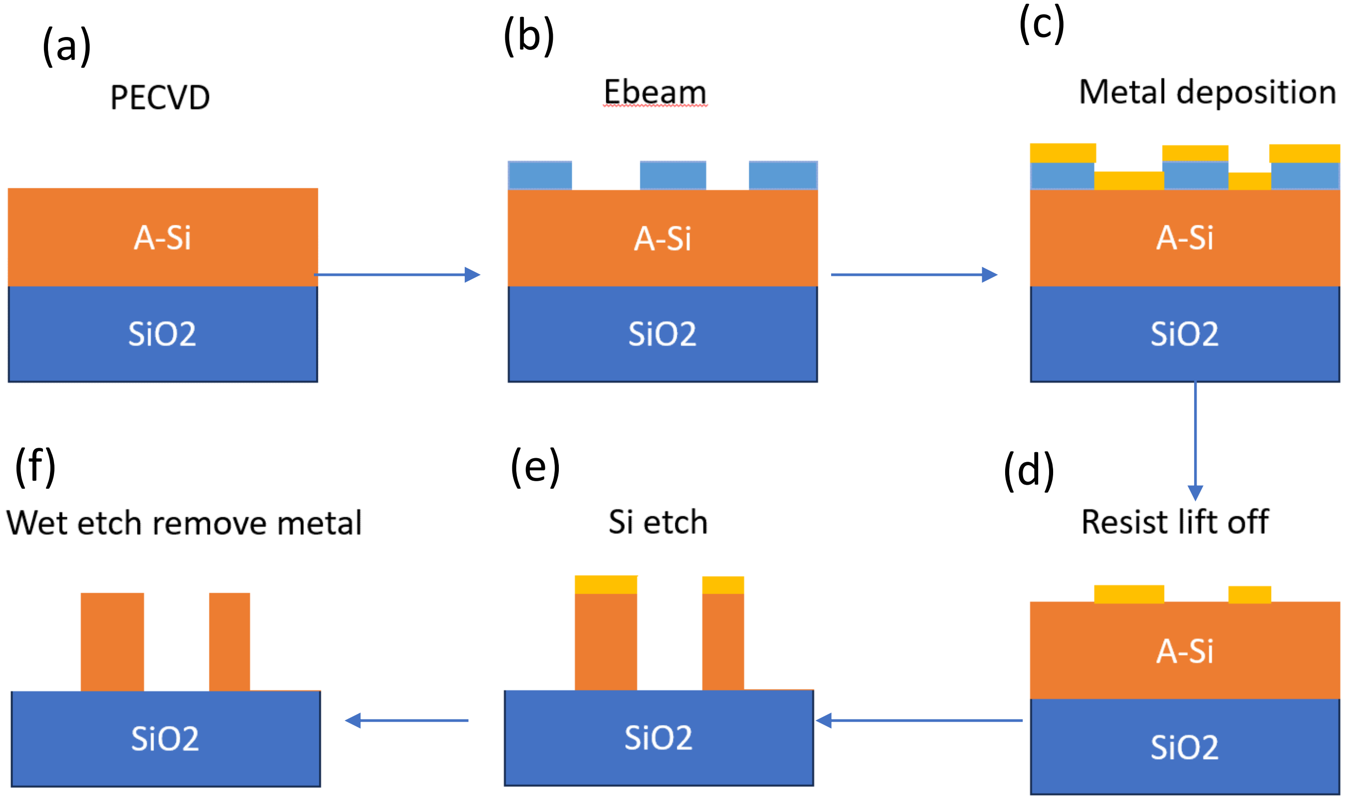
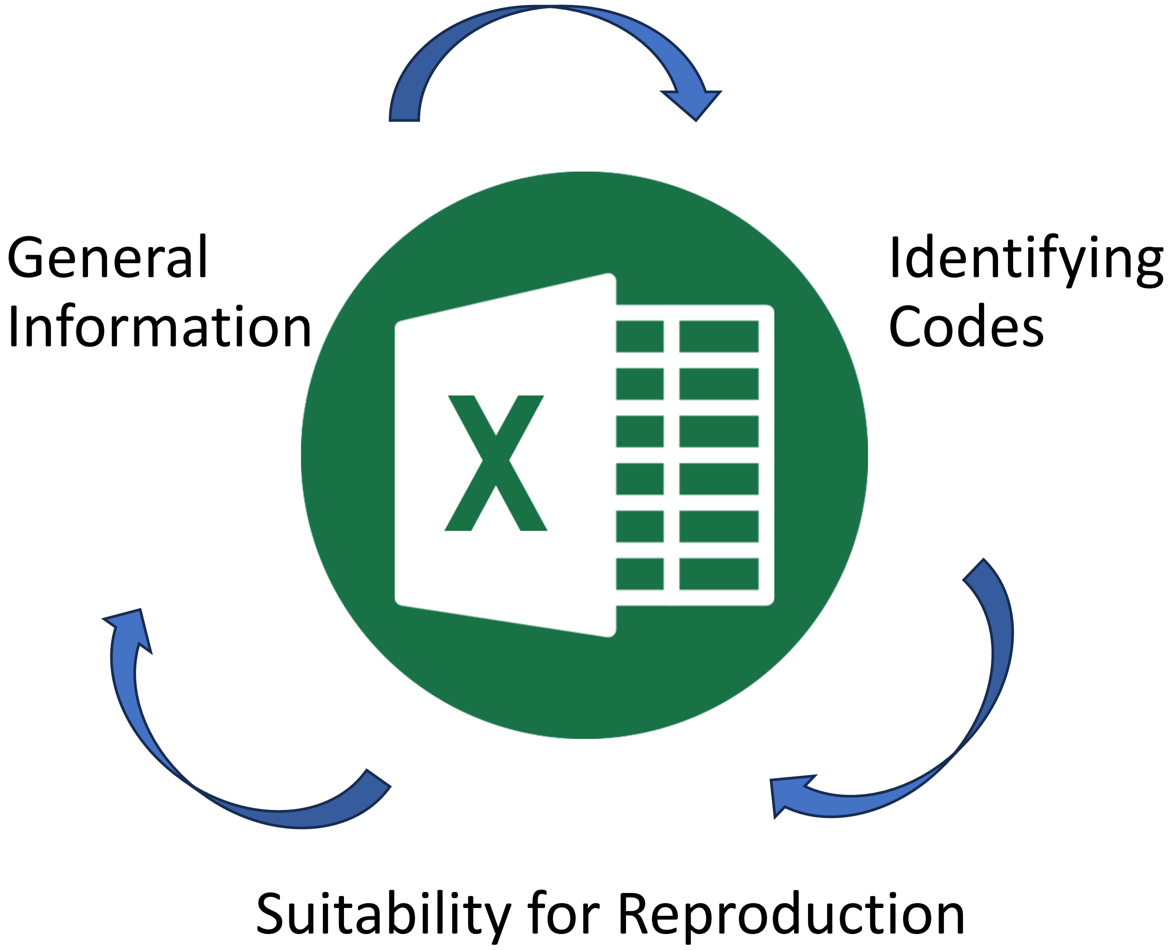


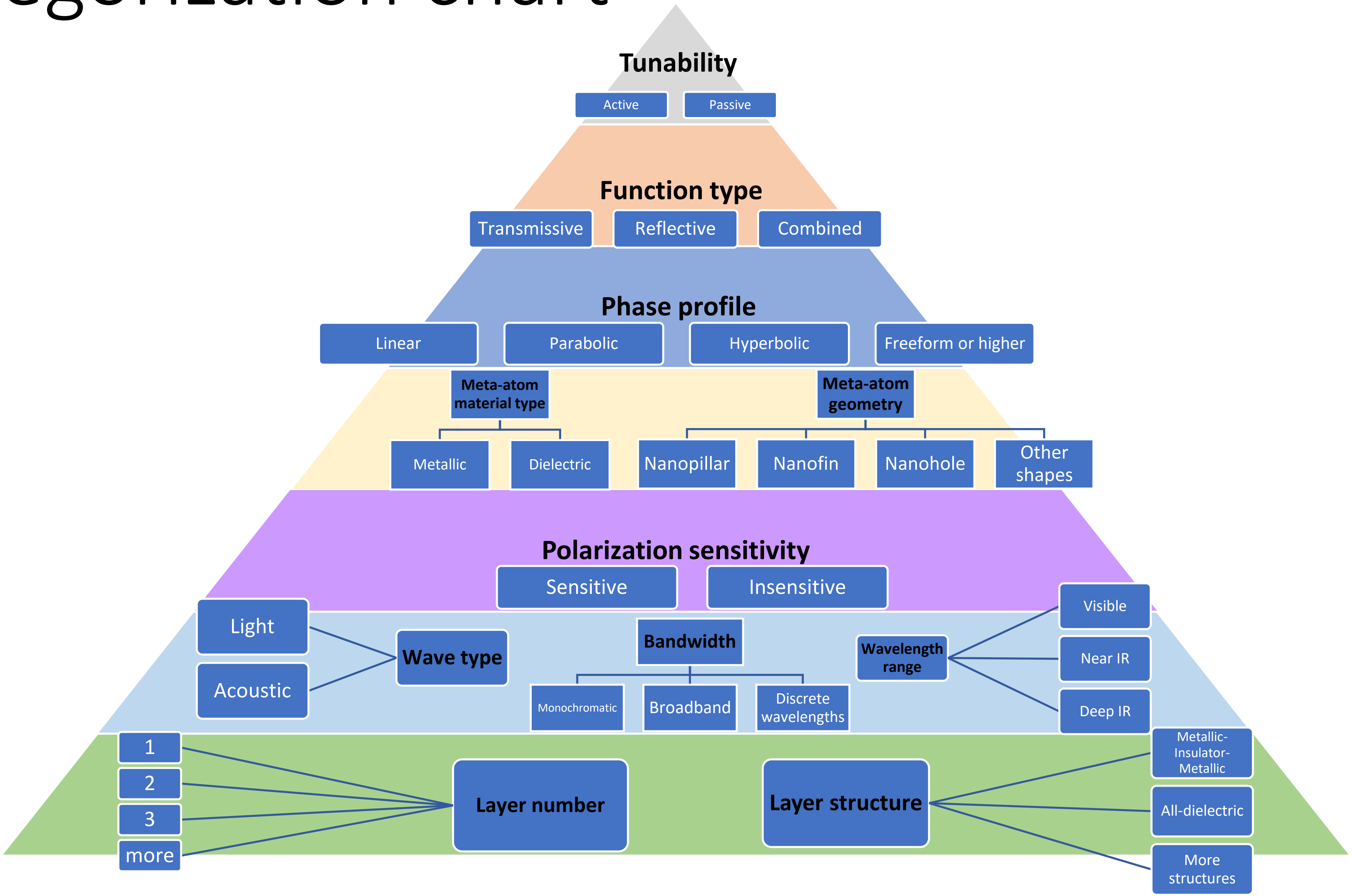
Figure credit to Pei Xiong, a PhD student in Vamivakas' Group

Literature review

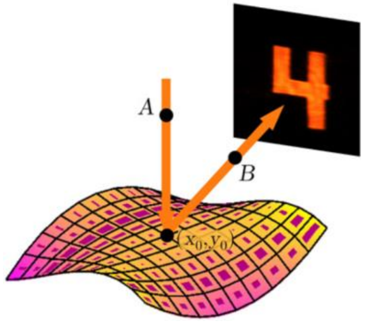
- Reviewed over 130 papers related to metasurface.
- Topics include physics, designs, material properties, manufacturing.
- Functions include metalenses, metagratings, antennas, waveguide couplers, bandpass filters, holography, AR/VR etc.

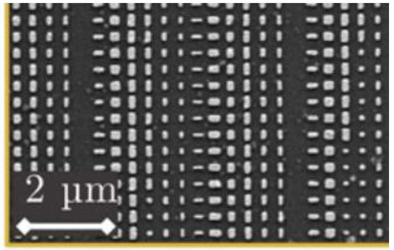


Categorization chart



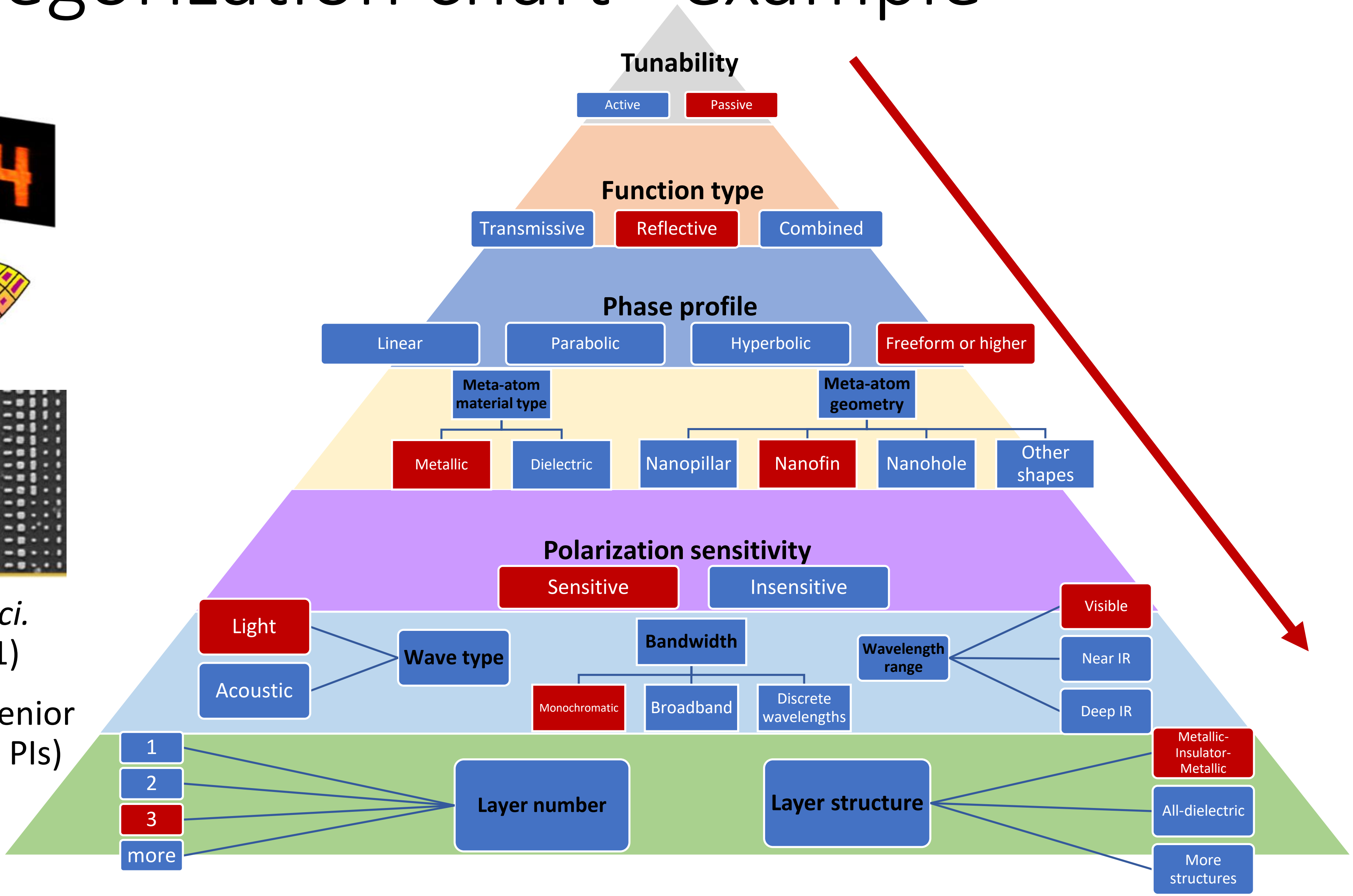
Categorization chart - example





Nikolov et al., *Sci. Adv.* 7, 10 (2021)

(published by Senior Researcher and PIs)



Photonics simulation

- Main simulation algorithm: FDTD (Finite-Difference Time Domain)
- Solves Maxwell Equations on a discrete grid in space and time

- No assumption is made, so the solution is highly versatile
- Only one approximation is made (finite-sized mesh and finite-sized time step), highly accurate
- Typically used when structure features is on the order of wavelength
- Time-domain method, so FDTD can solve a broadband problem in a single simulation

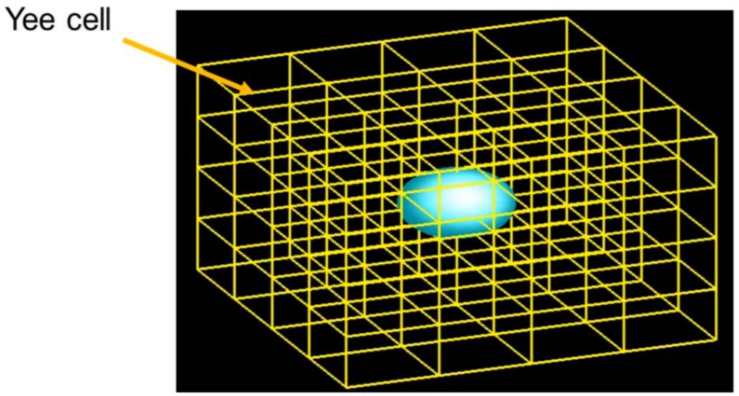
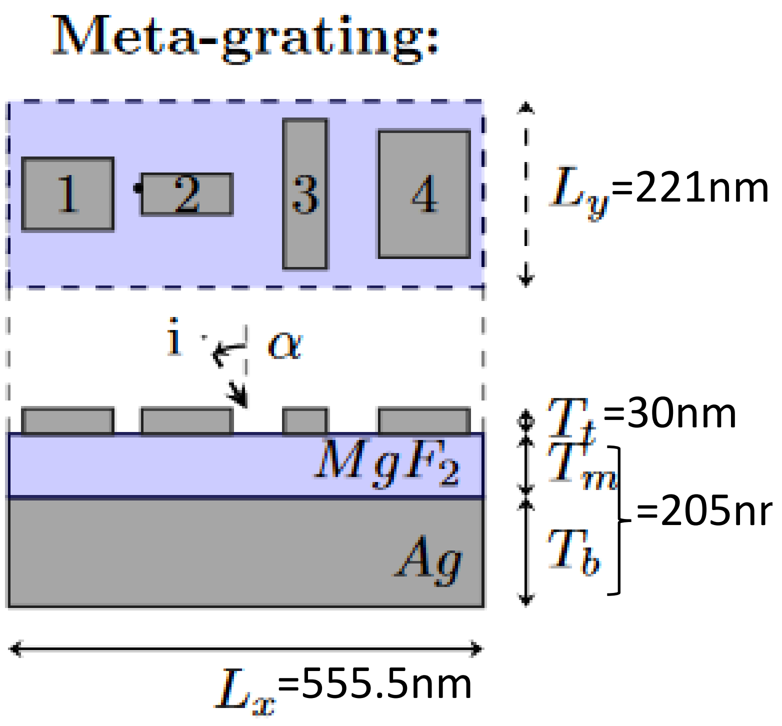


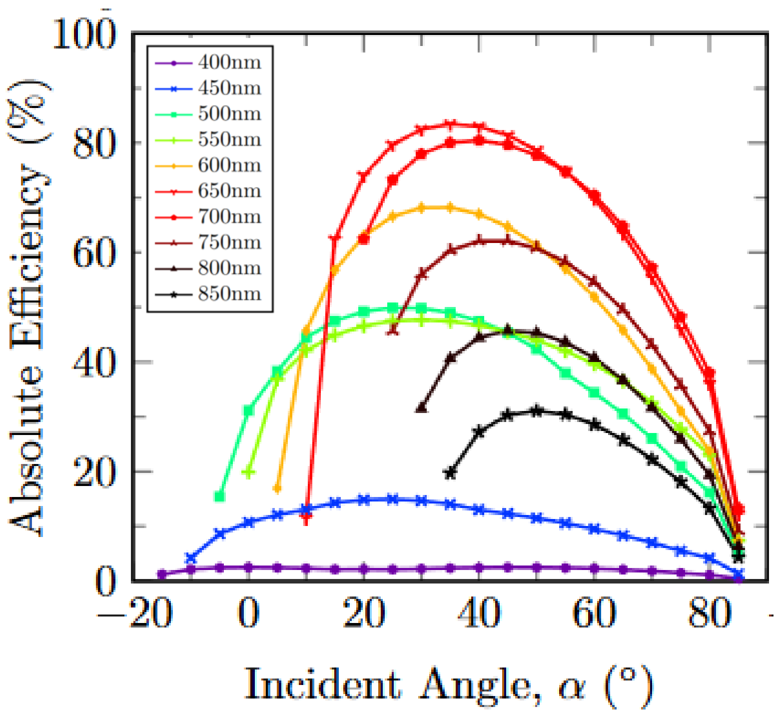
Figure from: Ansys Lumerical FDTD Method — Lesson 1, Part 2 https://www.youtube.com/watch?v=NvRu65R-Tmw

An example FDTD simulation

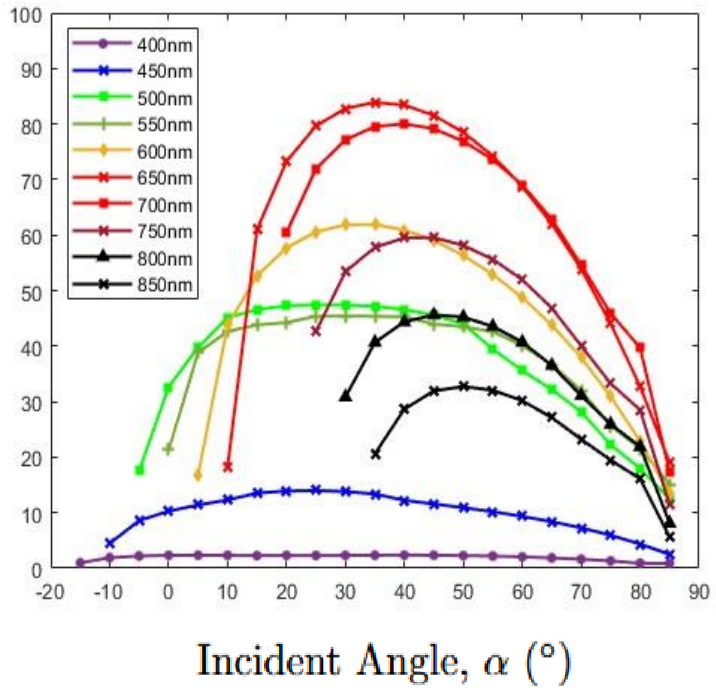
Metasurface structure



Simulation results in the paper

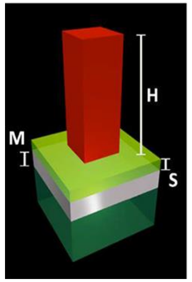


My simulation results



Kitt et al., *Opt. Mater. Express* **5**, 2895 (2015)
(published by PIs)

Year 1 (2023-2024) ongoing work



Khorasaninejad et al., *Nano Lett.* (2017), 17, 3, 1819–1824

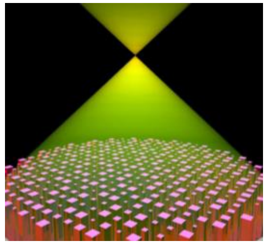
1. Identify the meta-atom parameters relationships and the regions in the parameter space that we will perform simulations over

2. Perform parameter sweeps for the chosen parameter space regions

3. Develop an organization and data access system for the simulation results

4. Milestone: complete an initial meta-atom simulation library

Year 2 (2024-2025) tasks



Khorasaninejad et al., *Nano Lett.* (2017), 17, 3, 1819–1824

1. Populate example designs for each metasurface category. Organize all the designs and simulations using JSON (JavaScript Object Notation) structures

2. Summarize the results from Year 1 of the program in a review manuscript

3. Establish the best metrics and metasurface optical responses

4. Design and begin building a benchtop experimental setup capable of measuring the metrics and optical responses

5. Begin fabricating some metasurface example designs and evaluate them using the experimental setup

Year 3 (2025-2026) tasks

1. Continue expanding the design library and the experimental setup as needed and will fabricate and test more of the example design

2. Start developing mathematical relationships connecting various parameters of metasurfaces and their optical functions

3. Continue discovering new fundamental relationships and limitations for the metasurface parameters and their optical functions

By the end of Year 3: Complete analysis of fundamental optical and material capabilities and limitations of metasurfaces

Thank you!