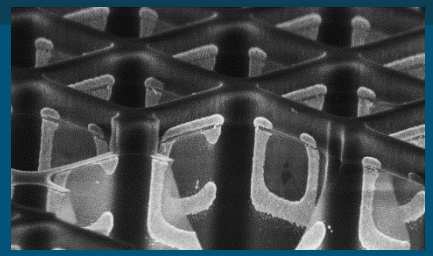
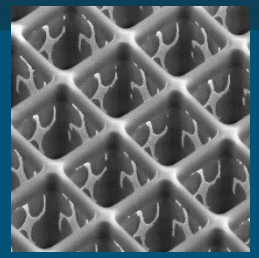
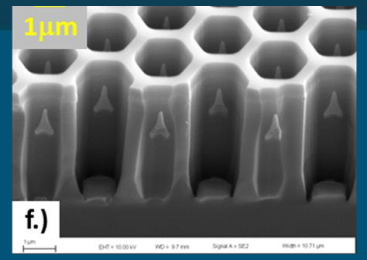
SAND2022-14231C

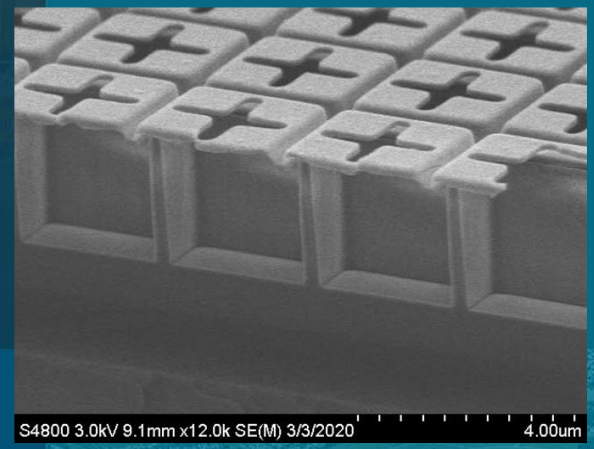
Sandia National Laboratories

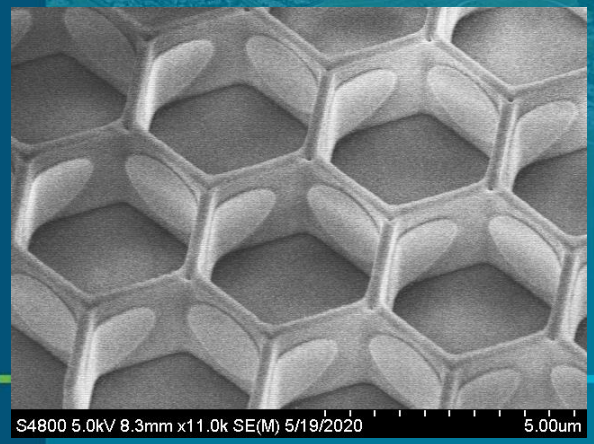
Fabrication and Characterization of Large Area Plasmonic Metasurface Lenses











Katherine M. Musick and D. Bruce Burckel

dbburck@sandia.gov

Frontiers in Optics 2022

Rochester, NY

October 17, 2022

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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SAND2022-7216 C

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Outline

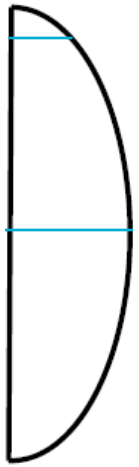
1. Lenses
2. Membrane Projection Lithography
3. Genetic Algorithm Design
4. Metal-dependent Defects
5. Preliminary Lens Characterization

Lenses

Creating Lenses

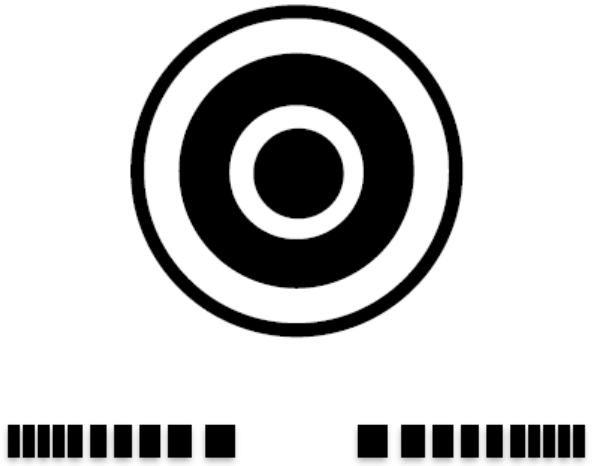
Phase due to propagation through high index medium

Refractive Lens



Isaac Newton

Binary Zone Plate



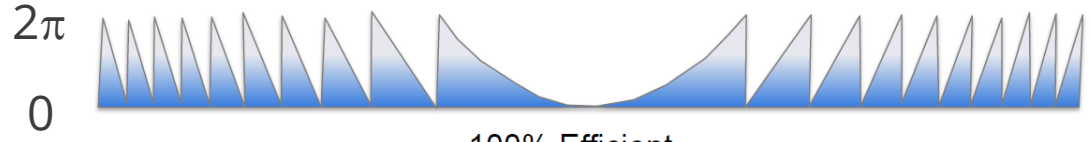
August-Jean Fresnel

40.4% Efficient

Phase Reversal Zone Plate

Wood (Lord Rayleigh)

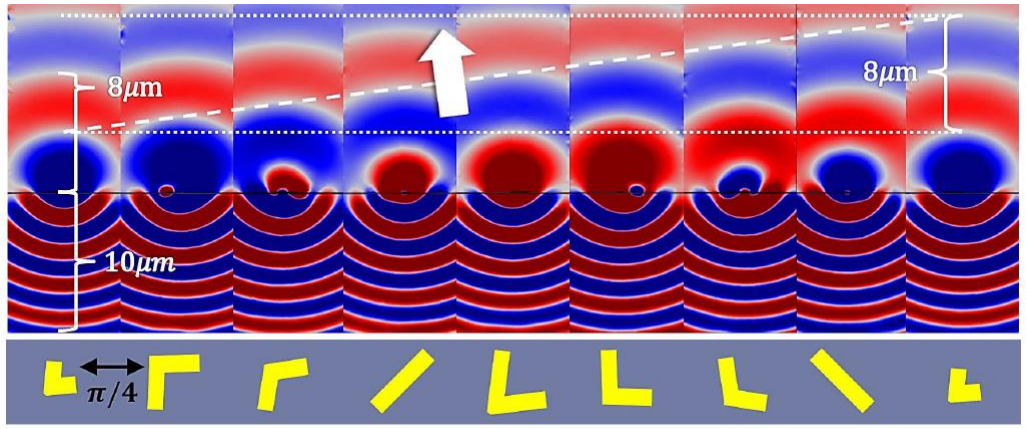
Continuous Phase Distribution

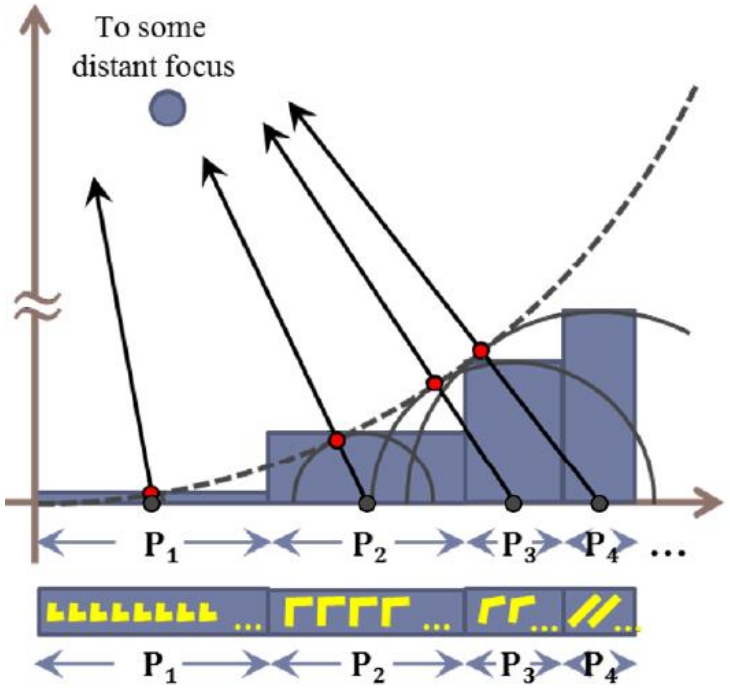


100% Efficient

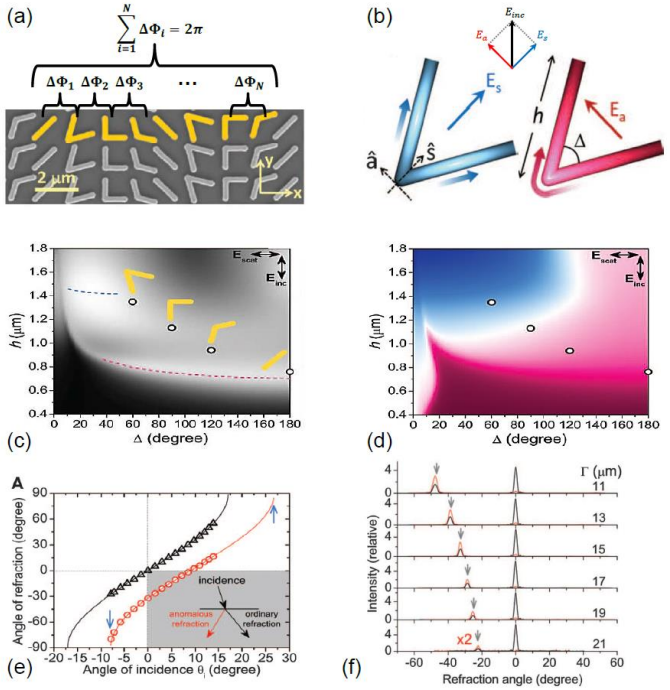
Discrete Approximation Phase Distribution

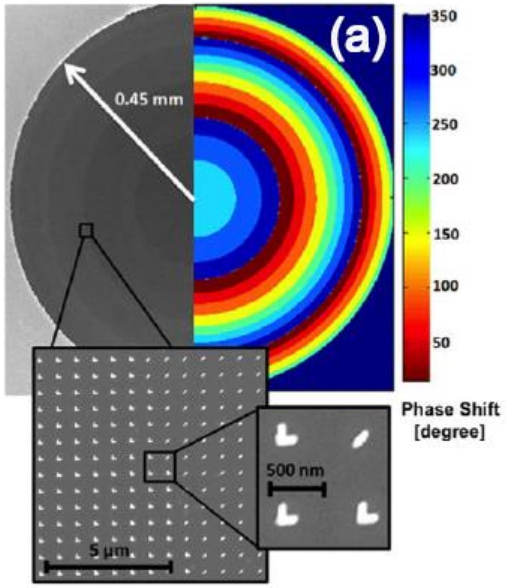
81% Efficient

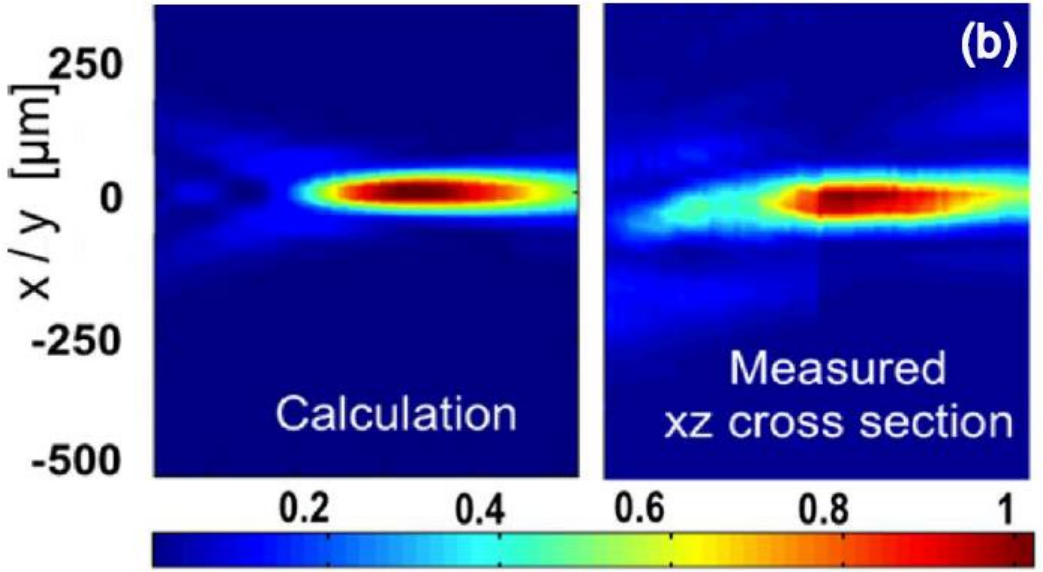




Creating Lenses Using a Metasurface



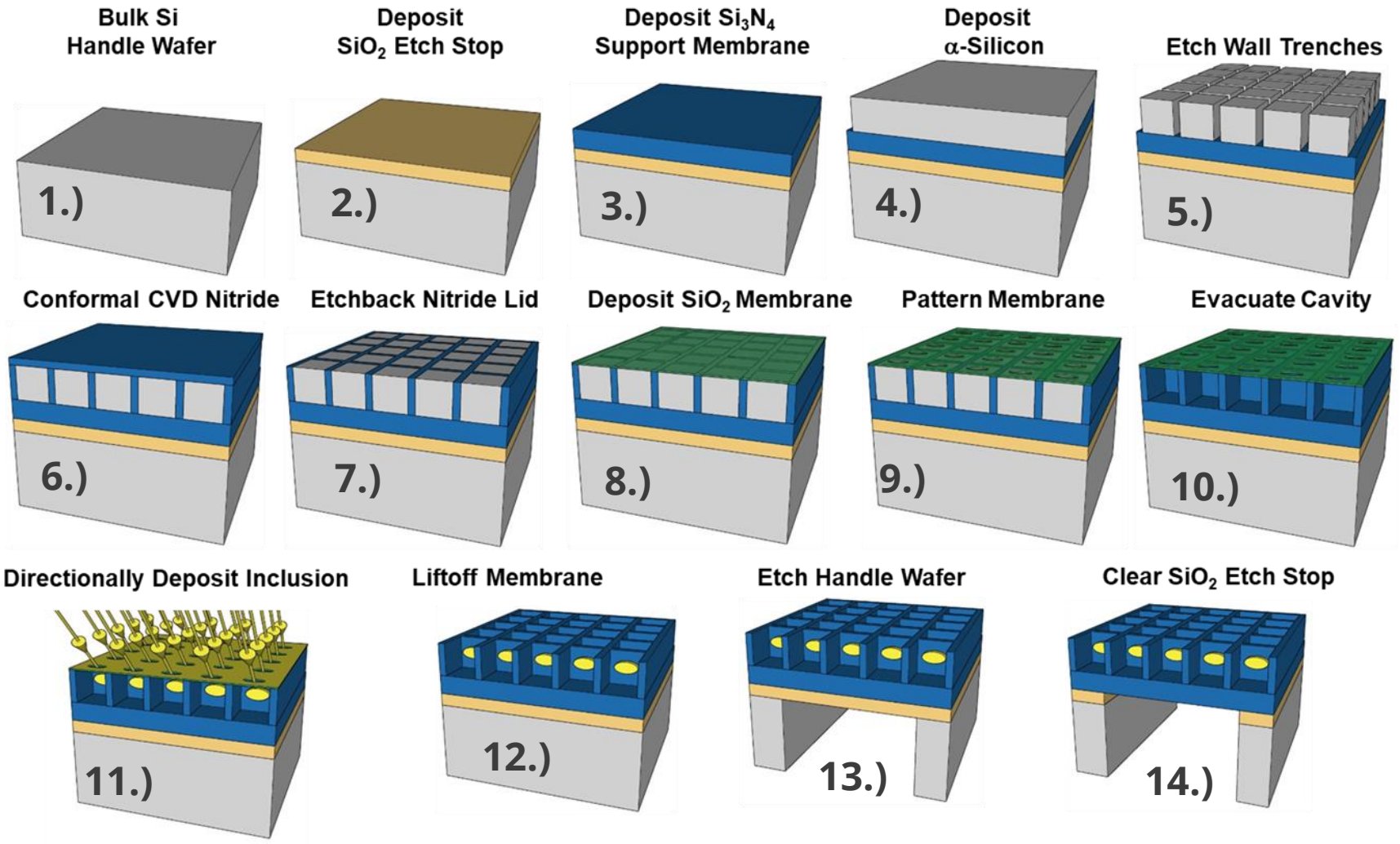


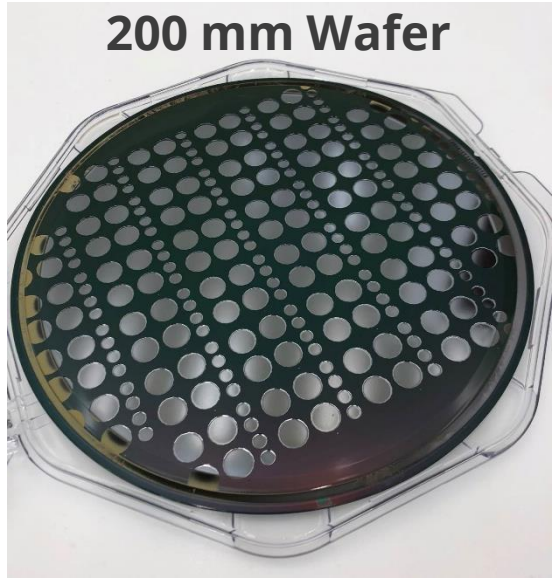


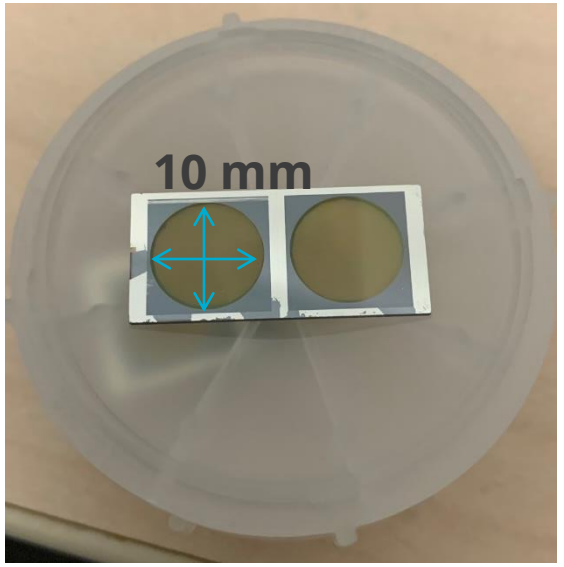
Membrane Projection Lithography

DB Burckel et. al., “Micrometer-scale cubic unit cell 3D metamaterials” Adv. Mater. **22** 5053-5057 (2010).

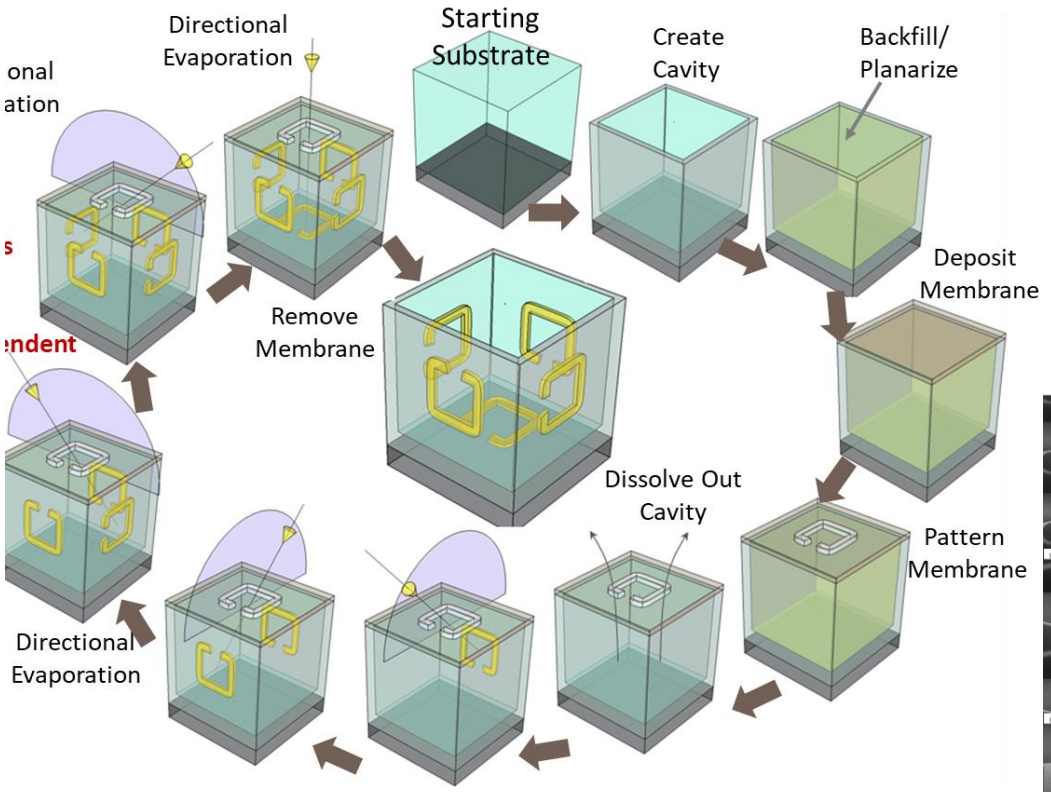
Wall-First Membrane Projection Lithography Process Flow (2020)

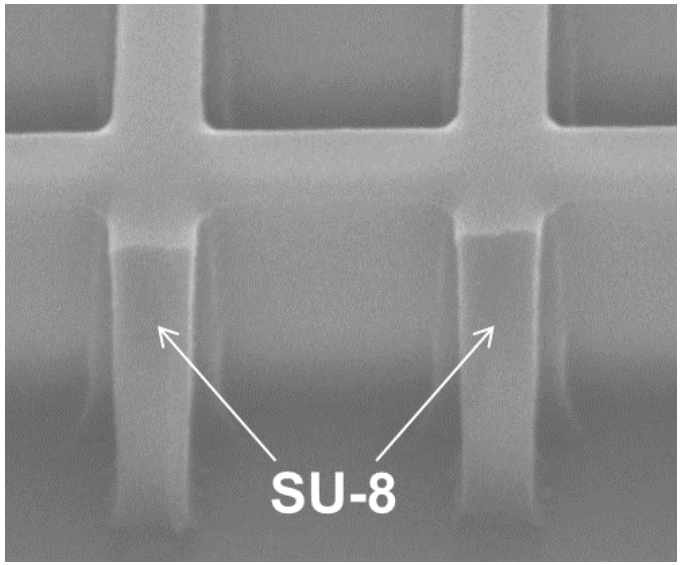


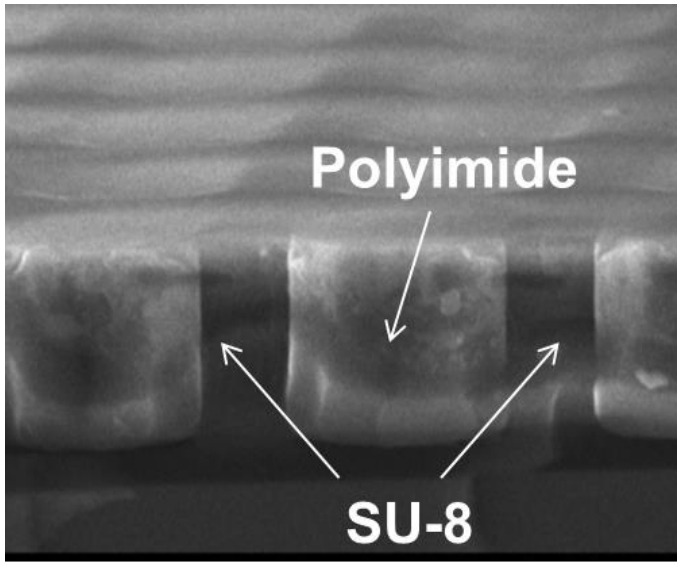


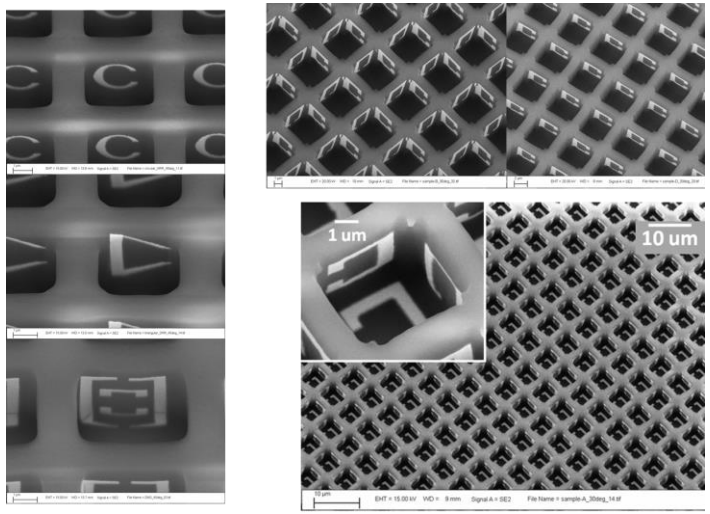


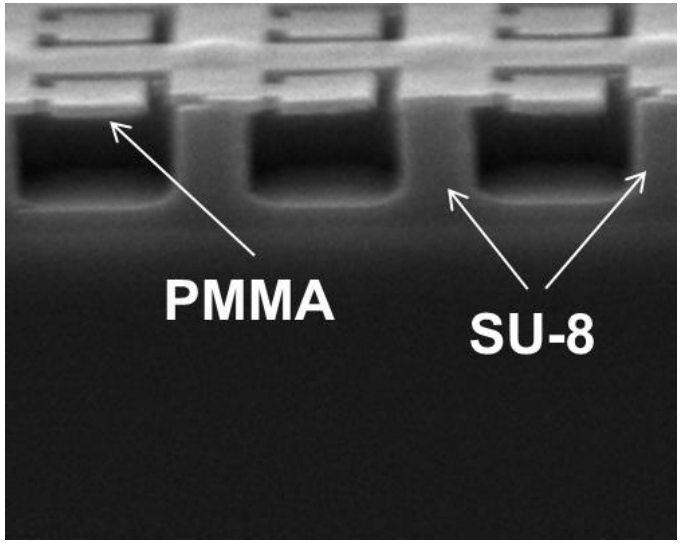
Polymer-Based Membrane Projection Lithography (2009)





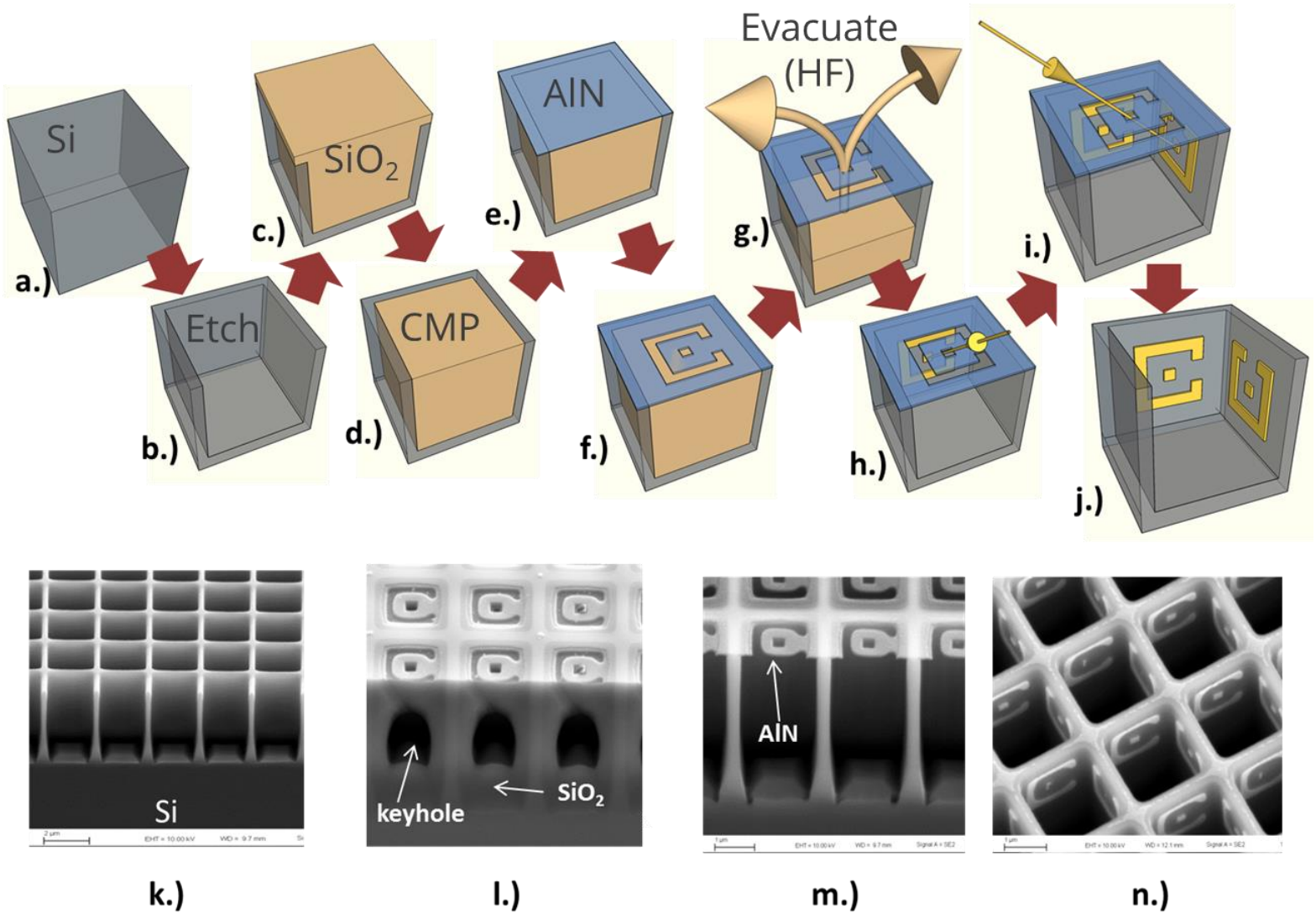






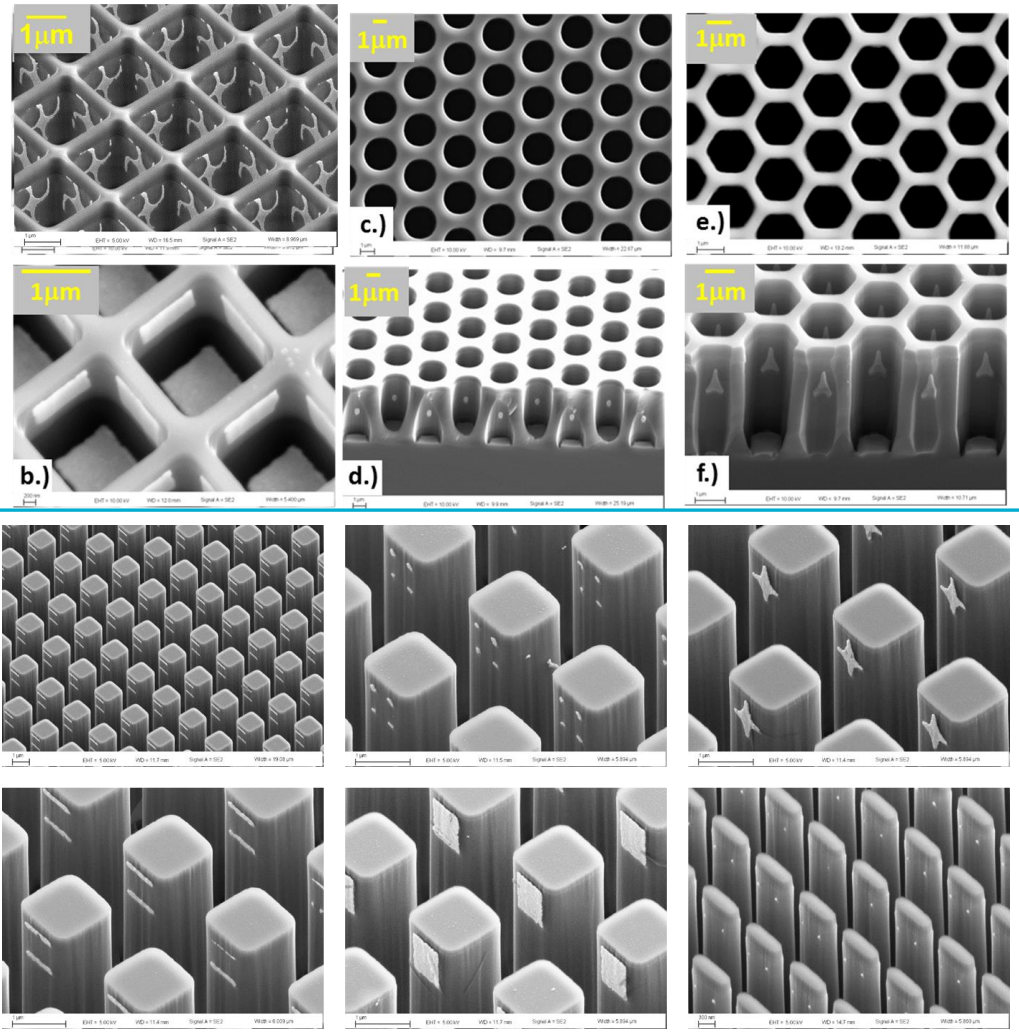
DB Burckel et. al., "Micrometer-scale cubic unit cell 3D metamaterials" Adv. Mater. **22** 5053-5057 (2010).

CMOS Compatible MPL (2015)

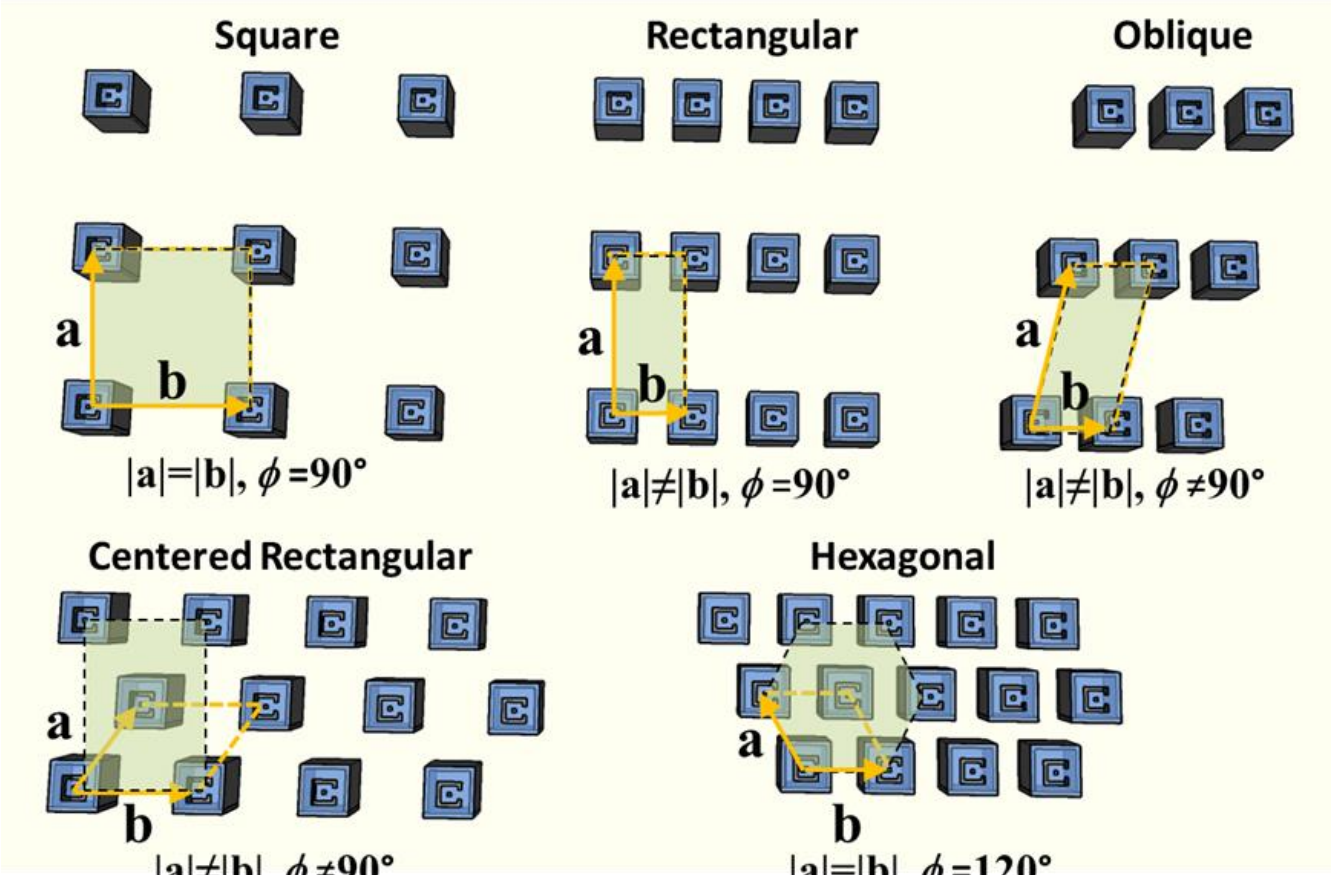


DB Burckel et. al., “Micrometer-scale fabrication of complex 3D lattice + basis structures in silicon” Opt Mat.. Exp. **10** , 2231-2239 (2015).

3D micron-scale Metamaterials



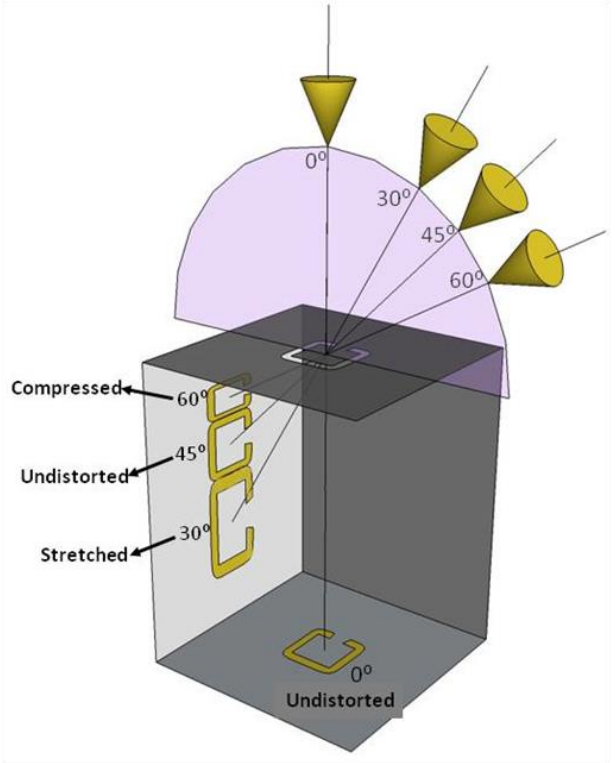
Any In-plane Lattice



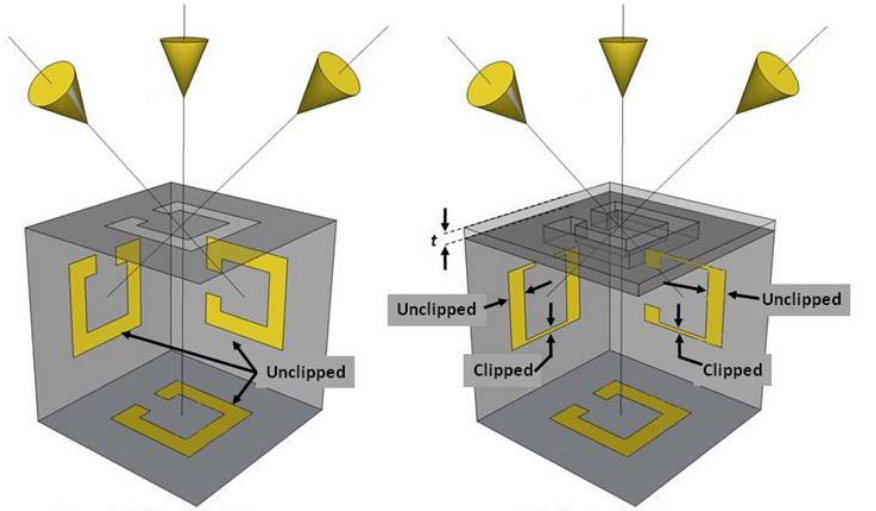
DB Burckel et. al., "Micrometer-scale fabrication of complex 3D lattice + basis structures in silicon" Opt Mat.. Exp. **10** , 2231-2239 (2015).

Sources of MPL Pattern Distortion

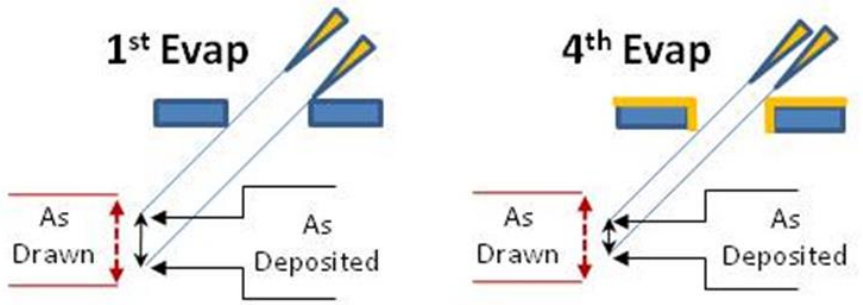
Projection at 45º
Preserves Pattern
Shape in Cubic Geometries



Real Membranes result in Linewidth Clipping



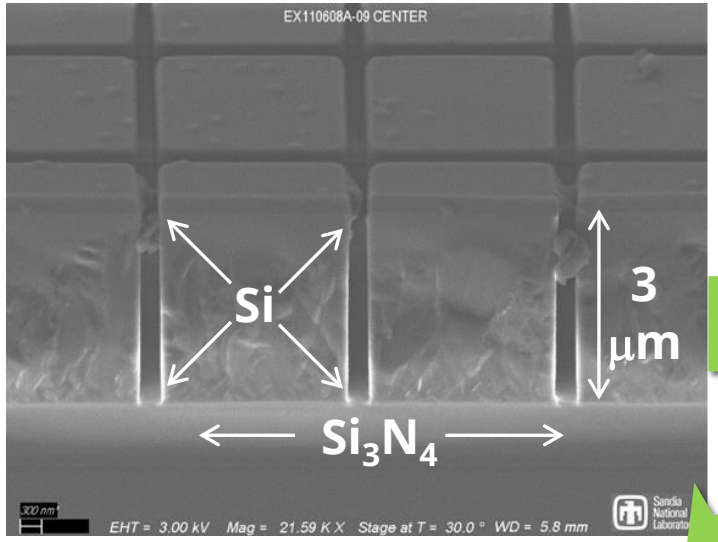
Multiple Evaporations result in Linewidth Thinning

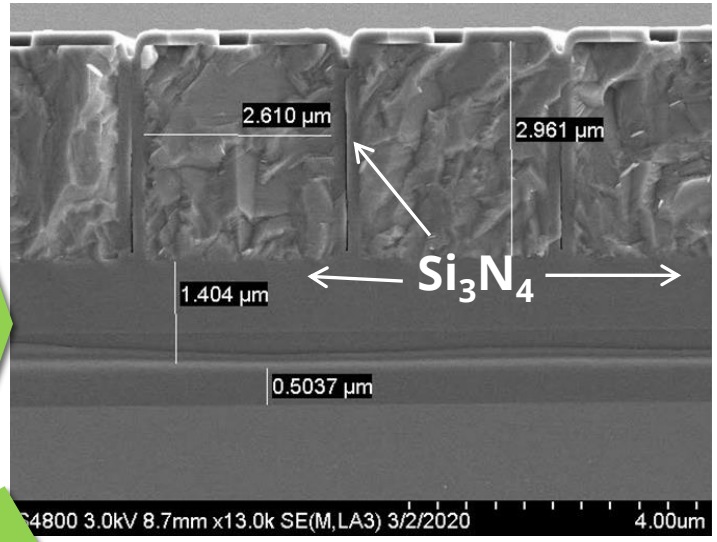


DB Burckel et. al., "Micrometer-scale cubic unit cell 3D metamaterials" Adv. Mater. **22** 5053-5057 (2010).

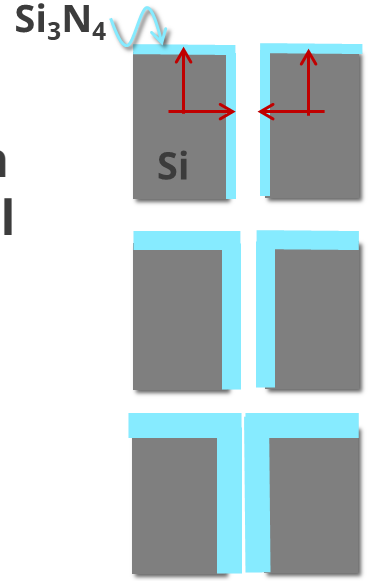
Process Flow Snapshot SEMs

Trench Etch

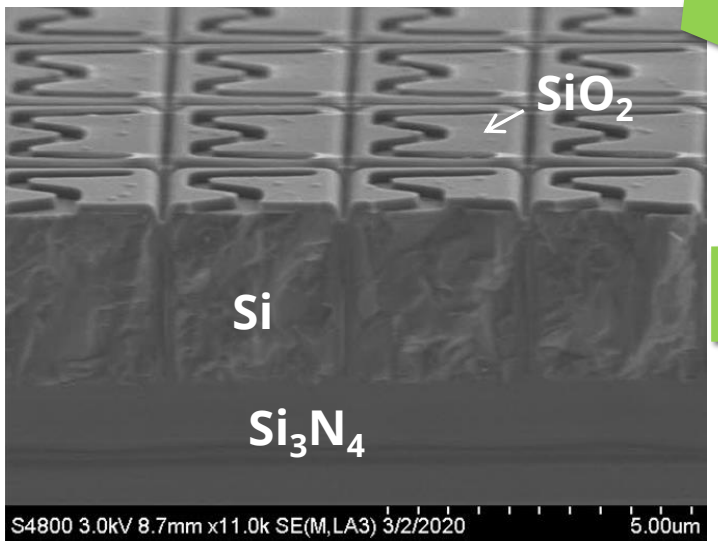


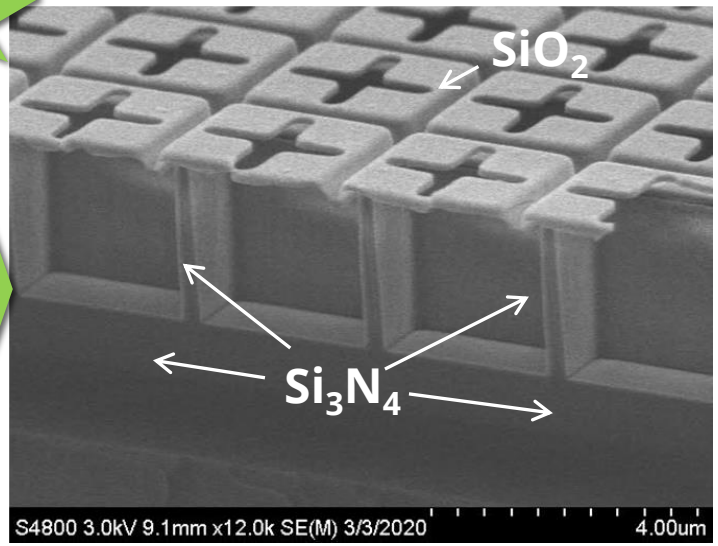


Trench Backfill



Membrane Patterning

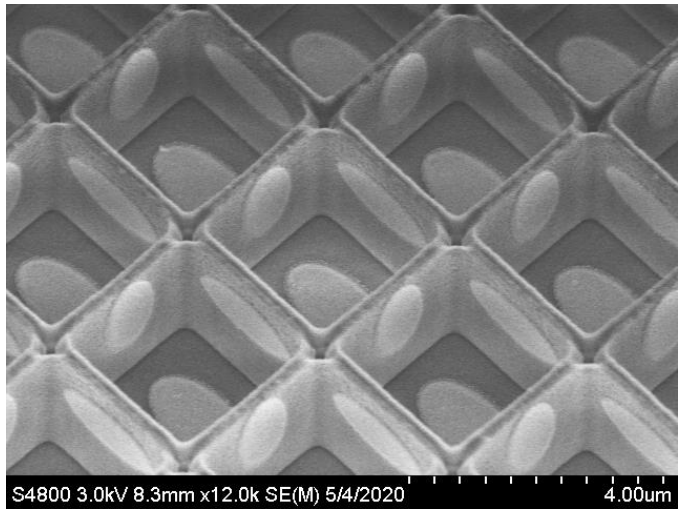


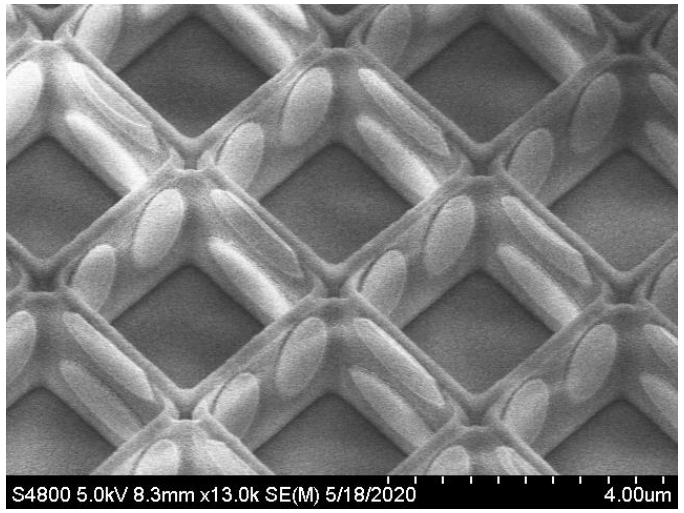


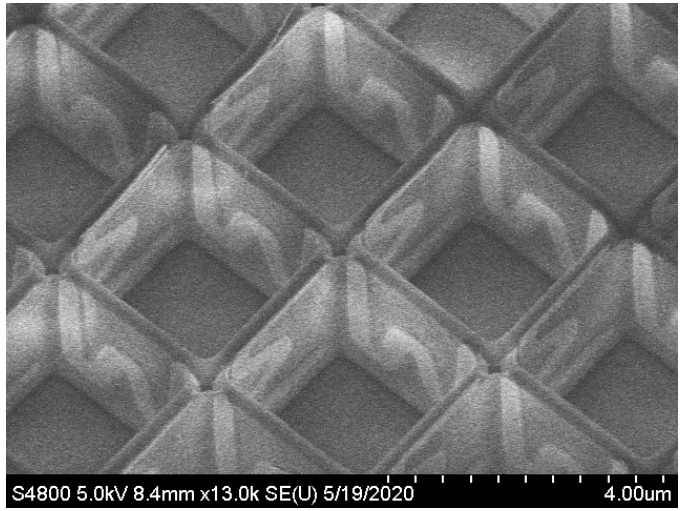
Cavity Evacuation (XeF_2)

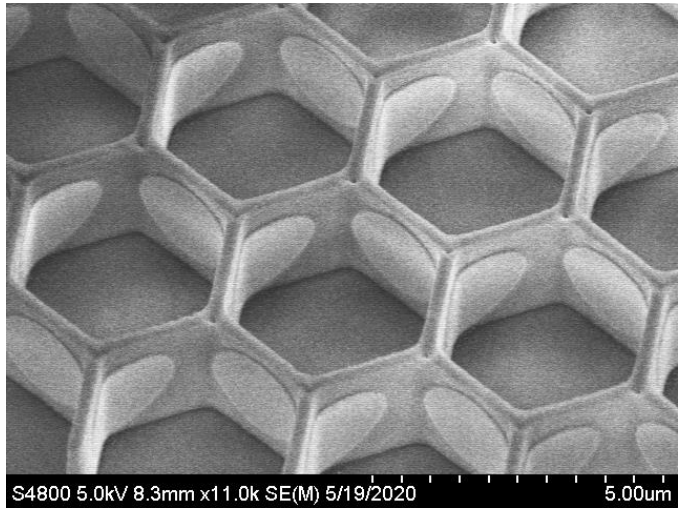
DB Burckel et. al., "Coupling between plasmonic and photonic crystal modes in suspended three-dimensional meta-films" Opt. Exp. **28** (8), 10836-10846 (2020).

Decorated Unit Cells – 3D Metafilms

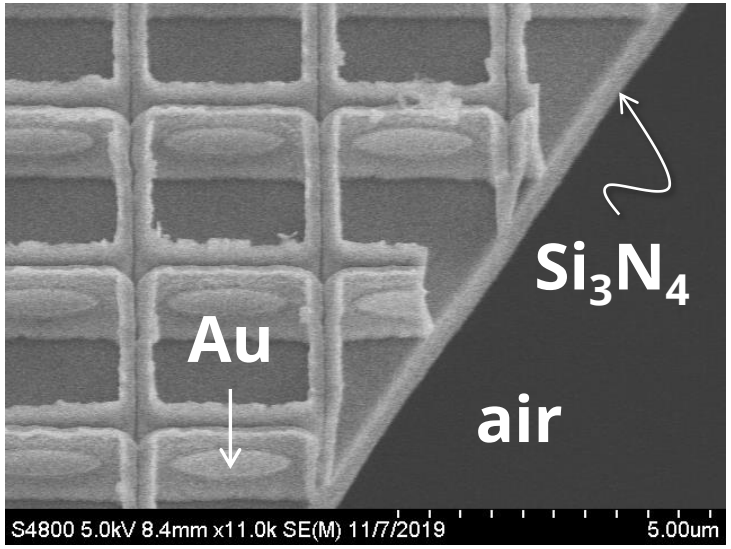








Handle Wafer Removed



DB Burckel et. al., "Coupling between plasmonic and photonic crystal modes in suspended three-dimensional meta-films" Opt. Exp. **28** (8), 10836-10846 (2020).

Genetic Algorithm Unit Cell Design

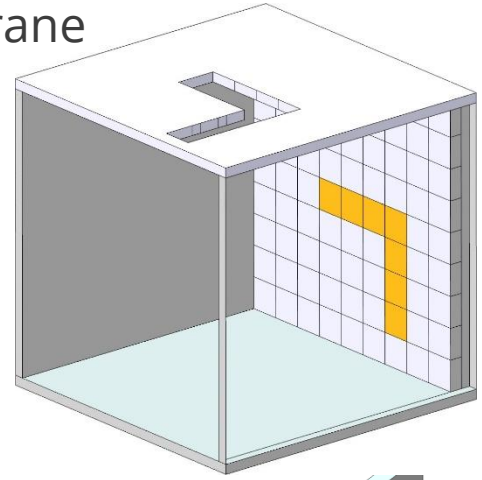
B. Adomanis et. al., “3D plasmonic design approach for efficient transmissive Huygens metasurfaces” Optics Express **27** 20928-20937 (2019).

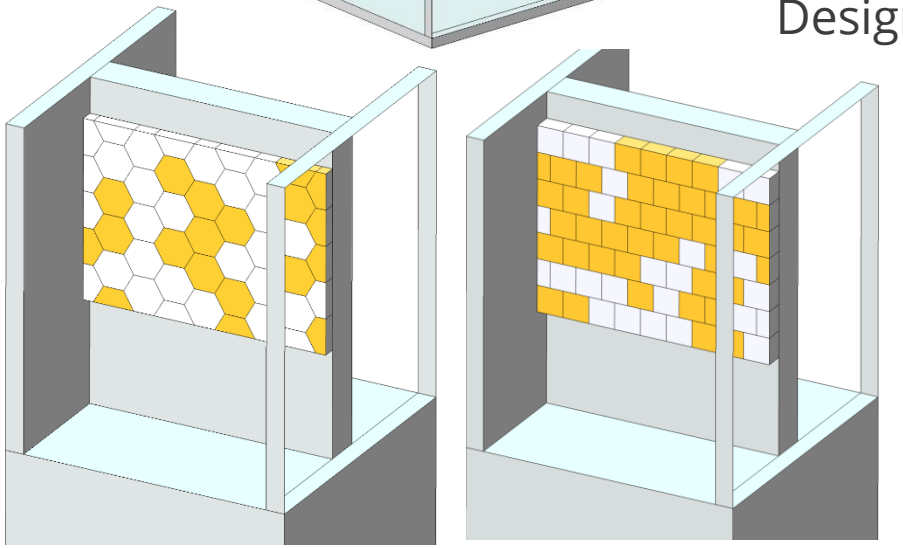
DZ Zhu et. al., “Optimal high efficiency 3D plasmonic metasurface elements revealed by lazy ants” ACS Photonics **6**, 2741-2748 (2019).

EB Whiting et. al., “Broadband asymmetric transmission of linearly polarized mid-infrared light based on quasi 3D metamaterials” Adv. Func. Mater. **32**, 2109659 (2022).

Genetic Algorithm Design of Phase Structures

Optimization can be performed by pixelating the wall or the membrane





Gold – “1”

Blank – “0”

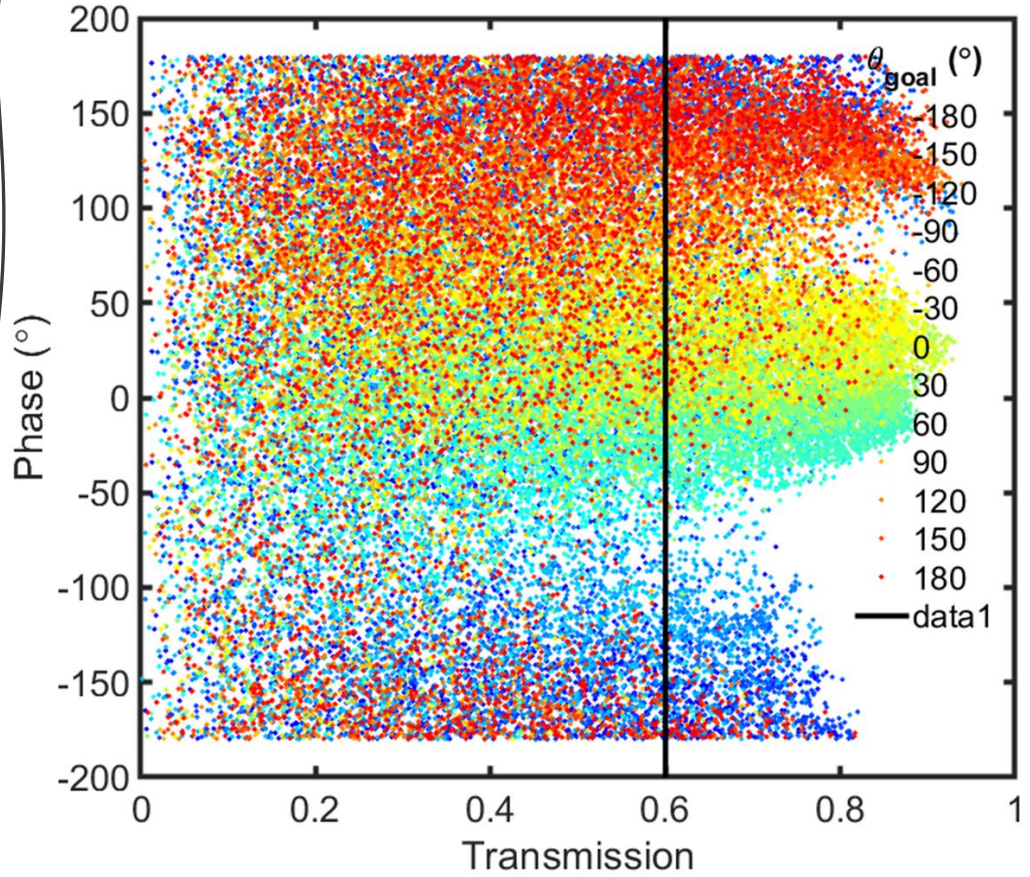
Form population

Evaluate ϕ and T

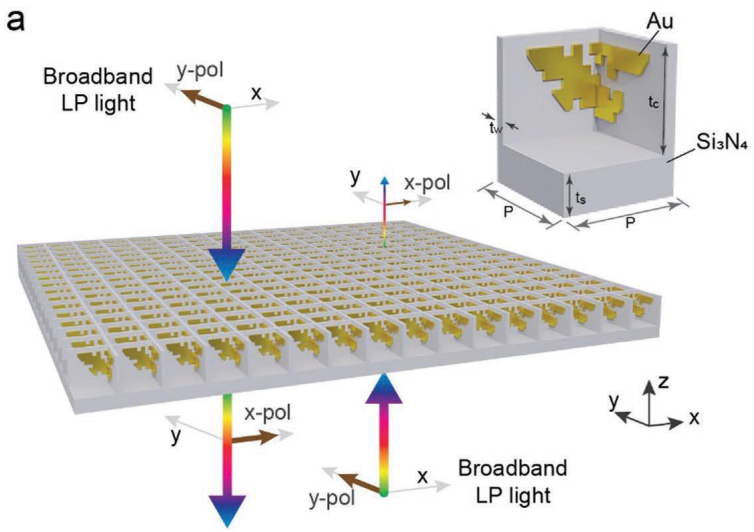
Report Results

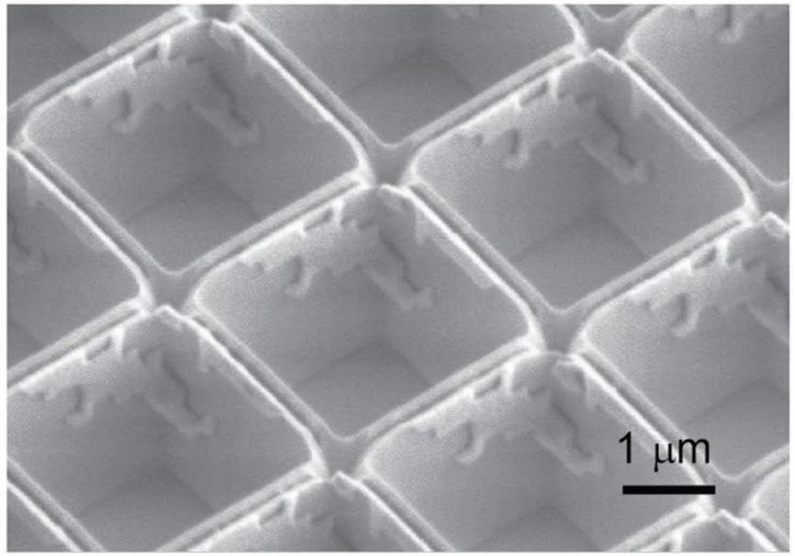
Mate Successful Designs +mutation

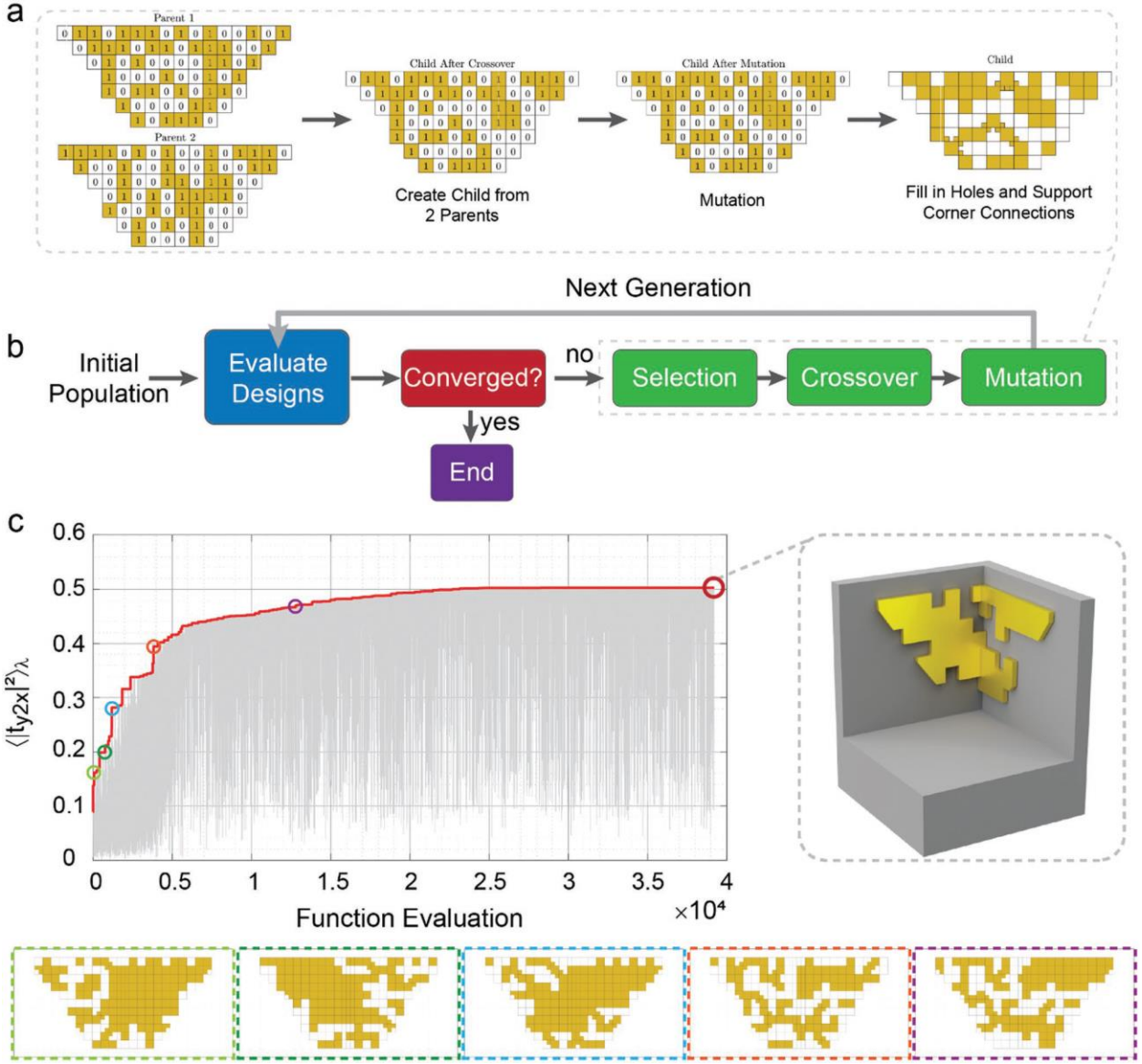
Threshold Transmission



Design of Asymmetric Transmission Metasurface

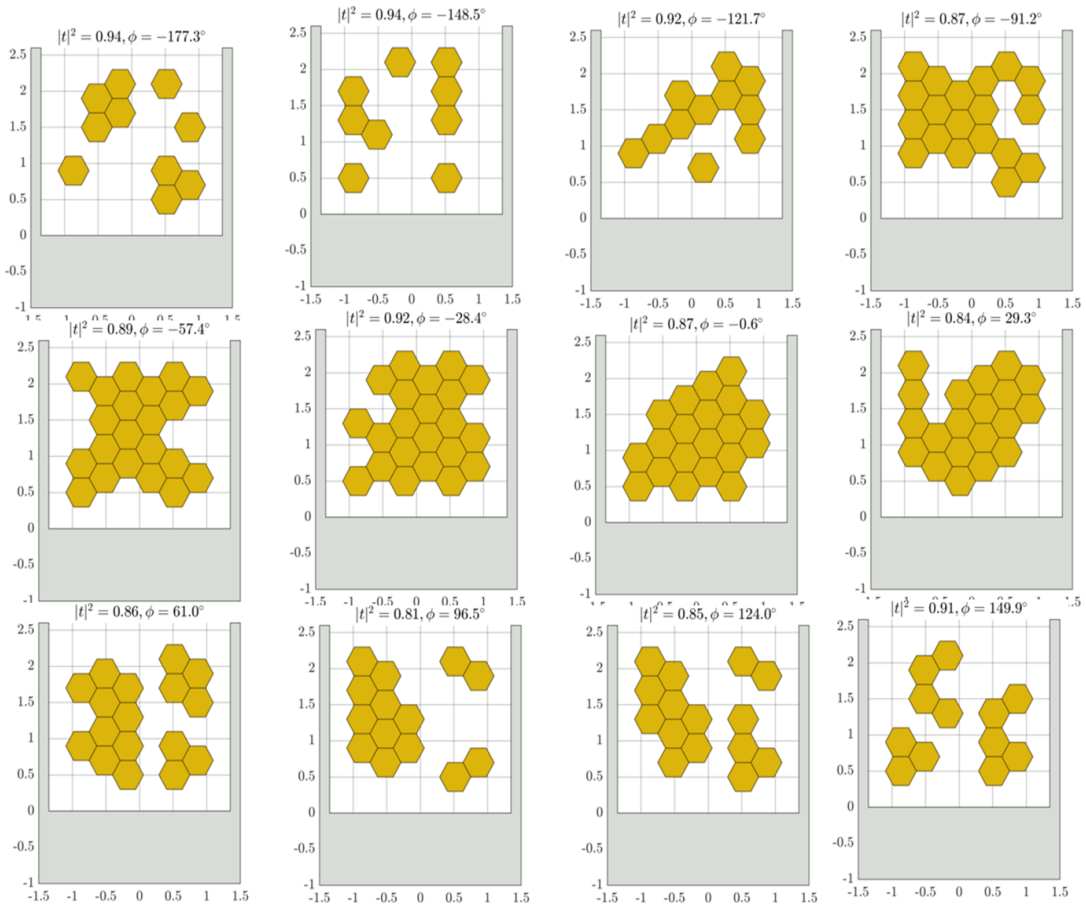




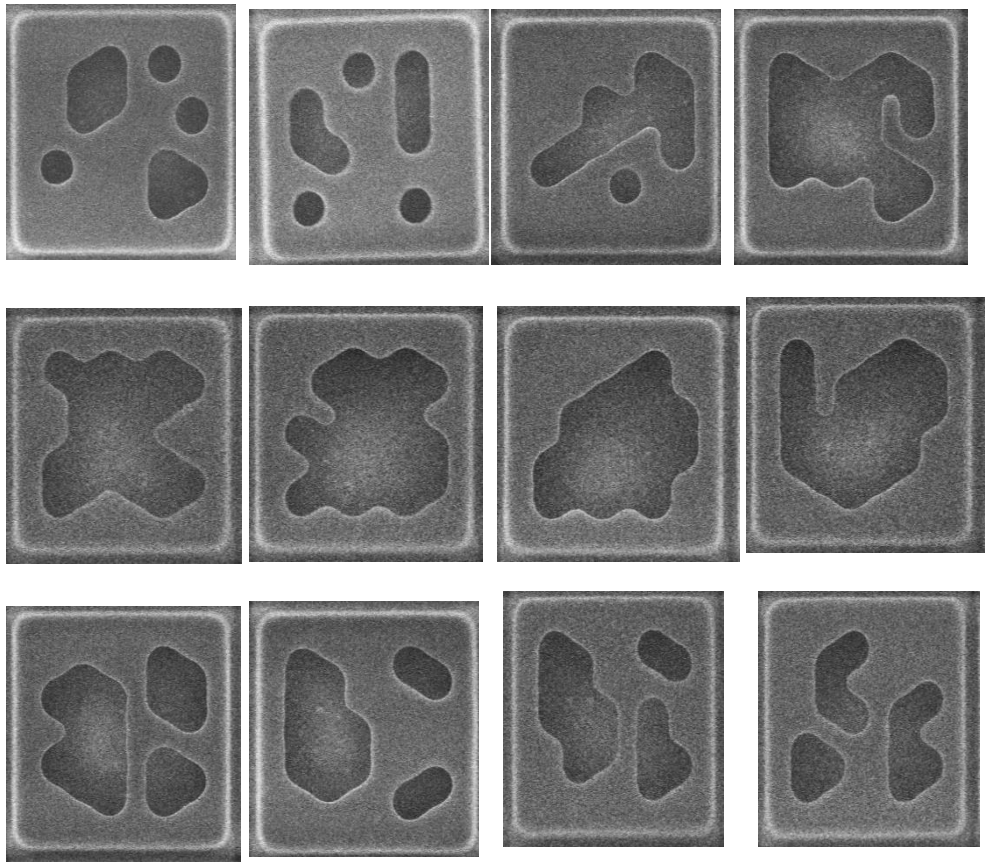


GA Designed Phase Elements – 4um Design wavelength

Phase Elements from Penn State



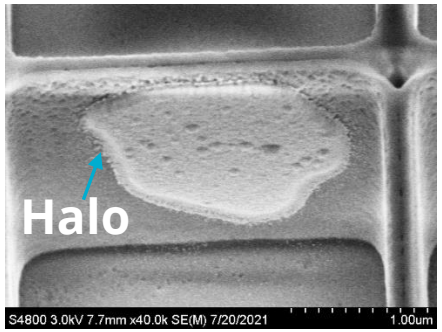
Membrane patterns prior to evaporation

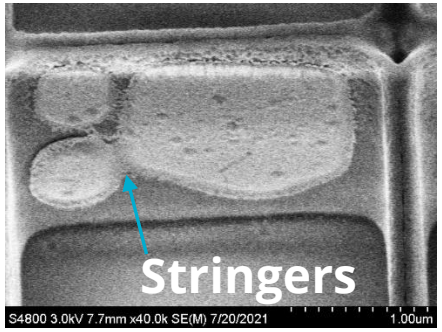


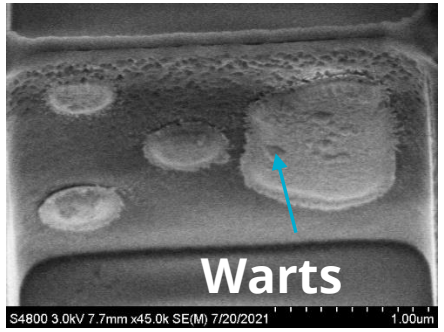
Metal-dependent Defects

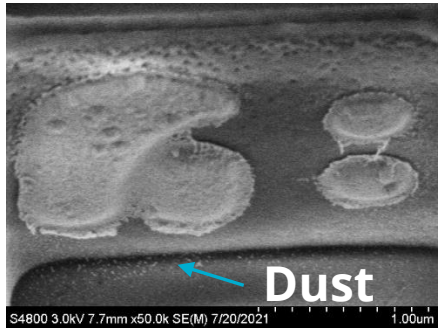
Houston, we have a problem,…

Gold

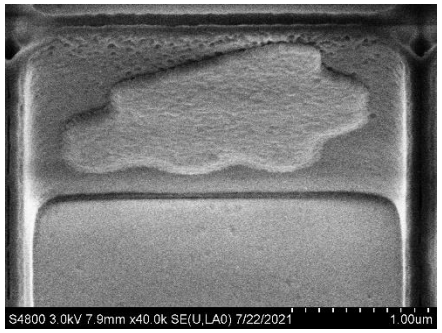


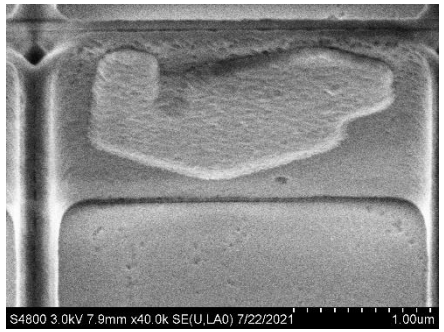


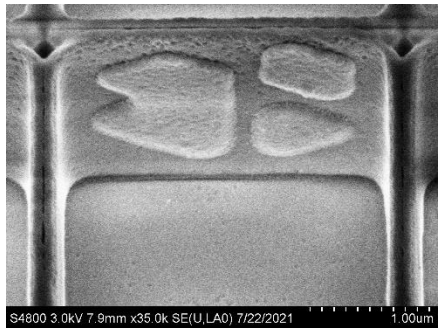


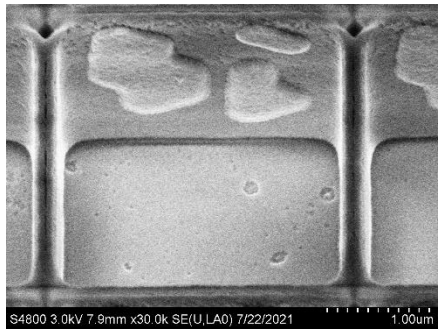


Aluminum



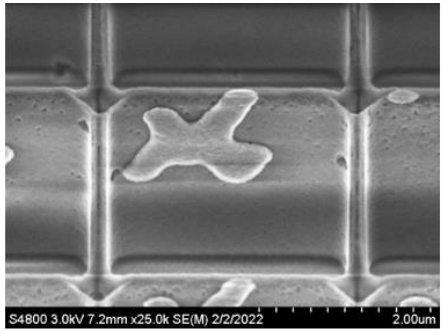


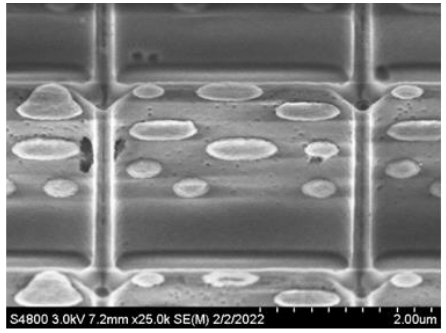


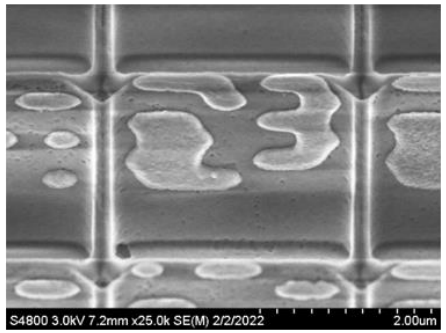


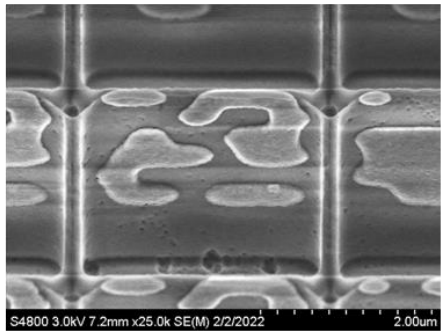
Metal Choice Affects Meta-atom Shape

Al









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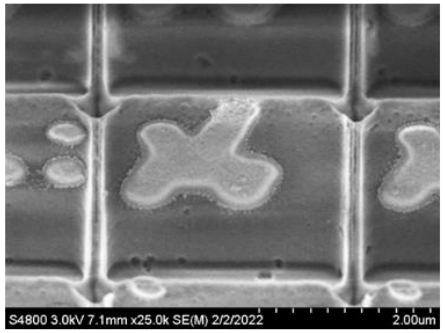

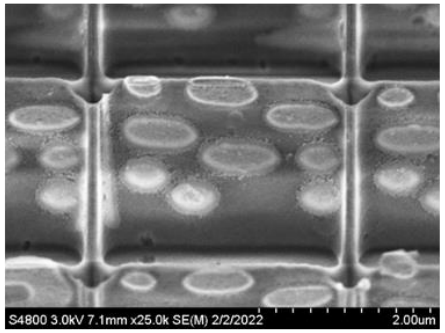

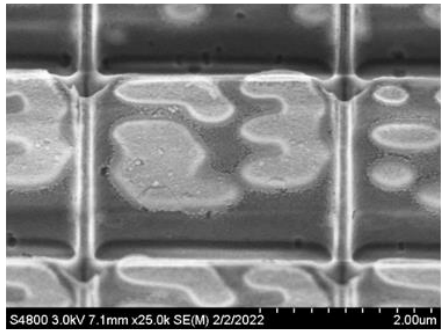

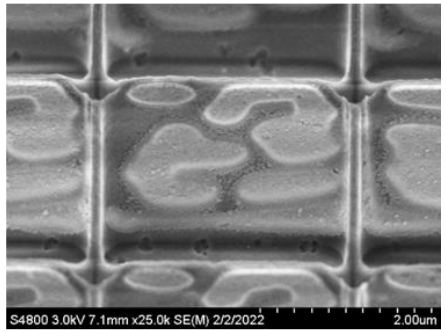

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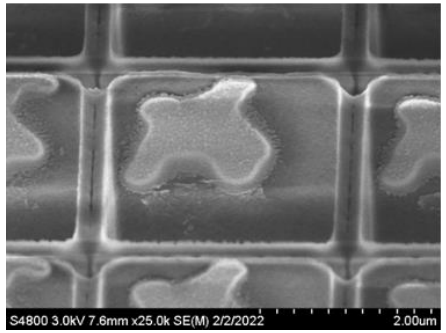
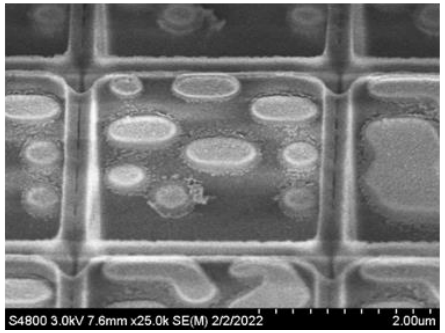
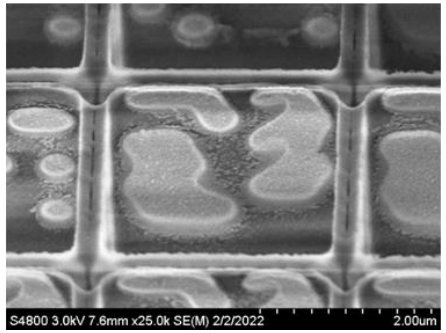
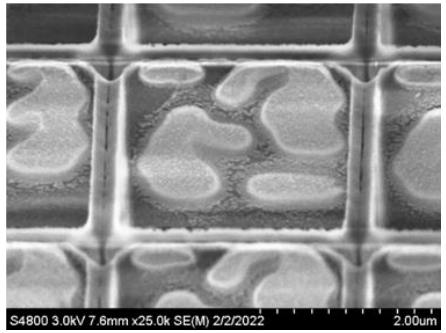
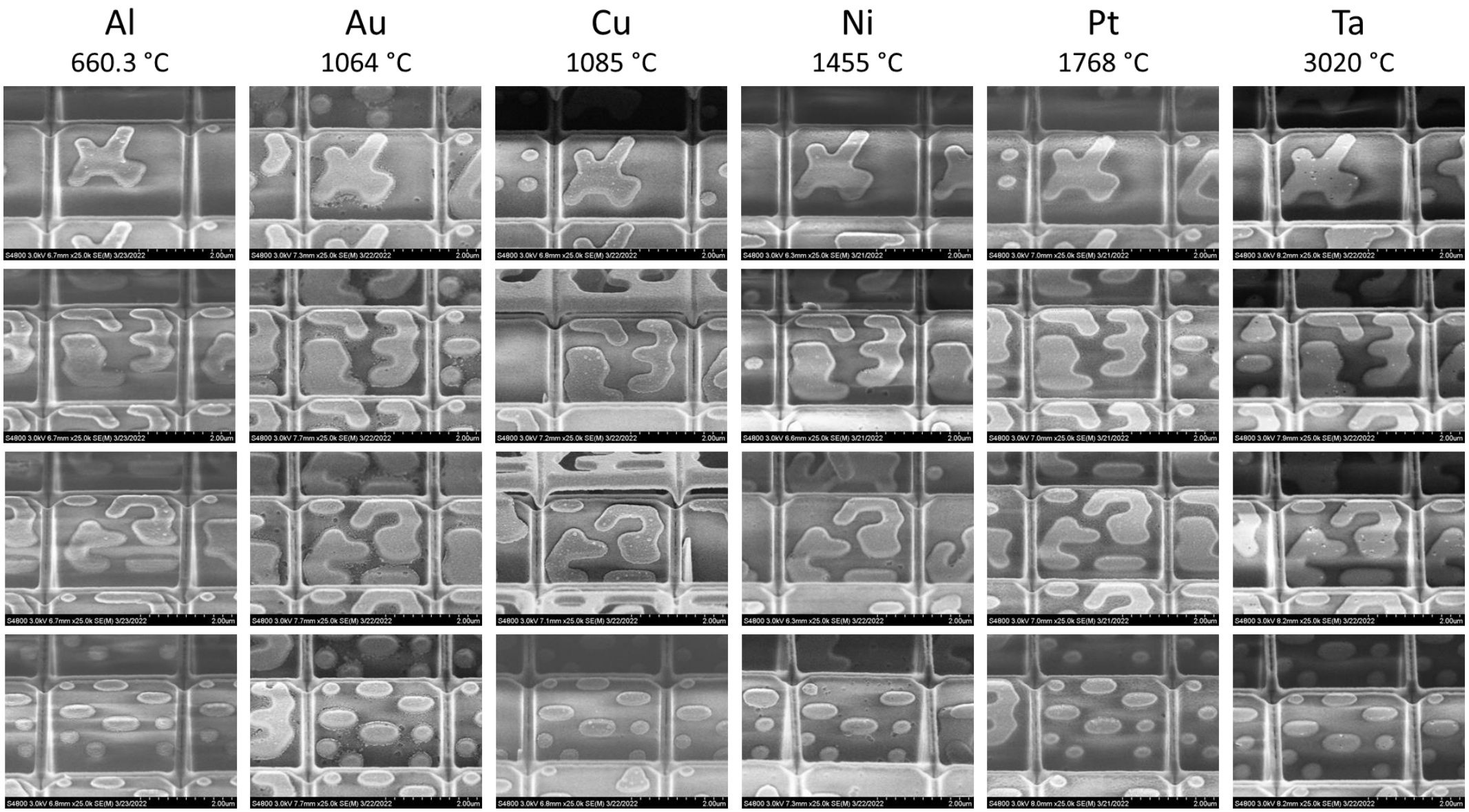






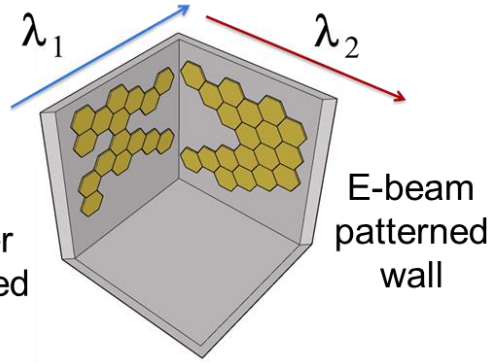


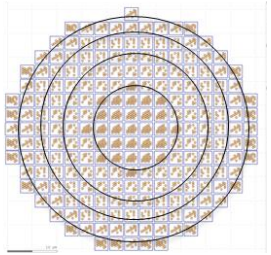
Pattern fidelity vs melting point



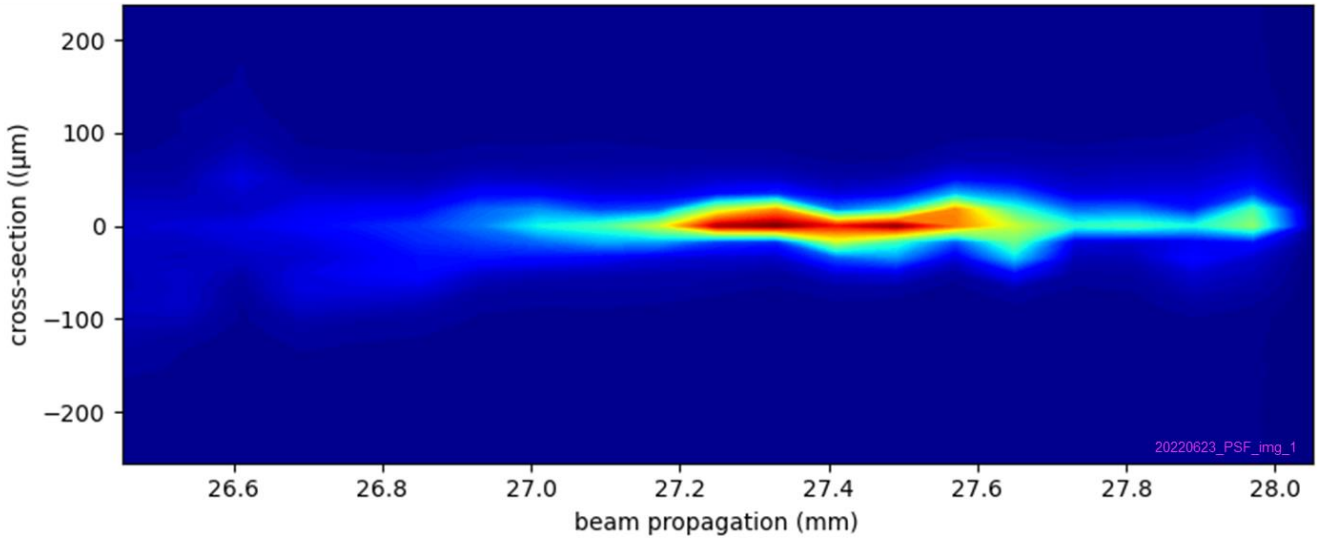
Preliminary Characterization of 2-color MPL – Metasurface Lens

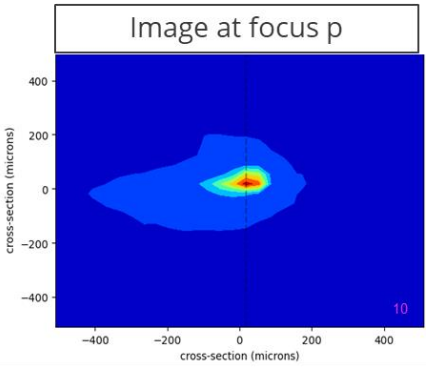
Functionality Enabled at the Unit Cell Level

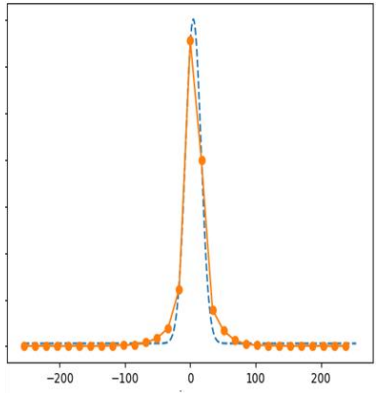




Lens created by populating aperture with phase elements



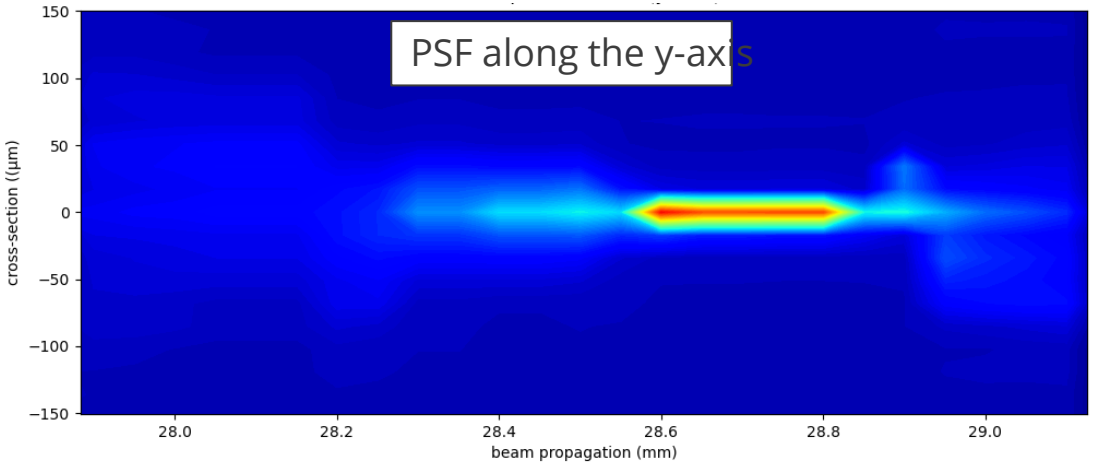


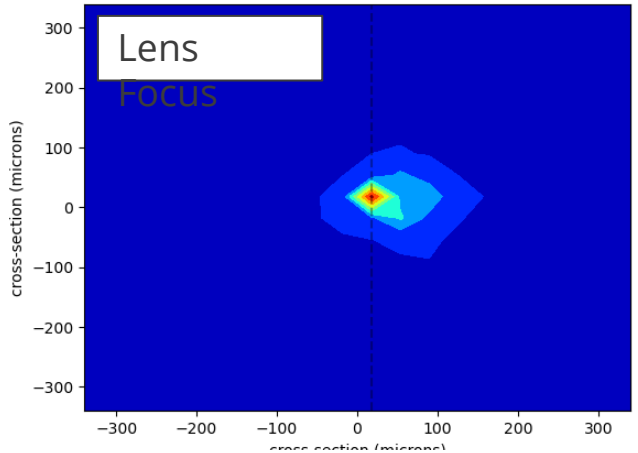


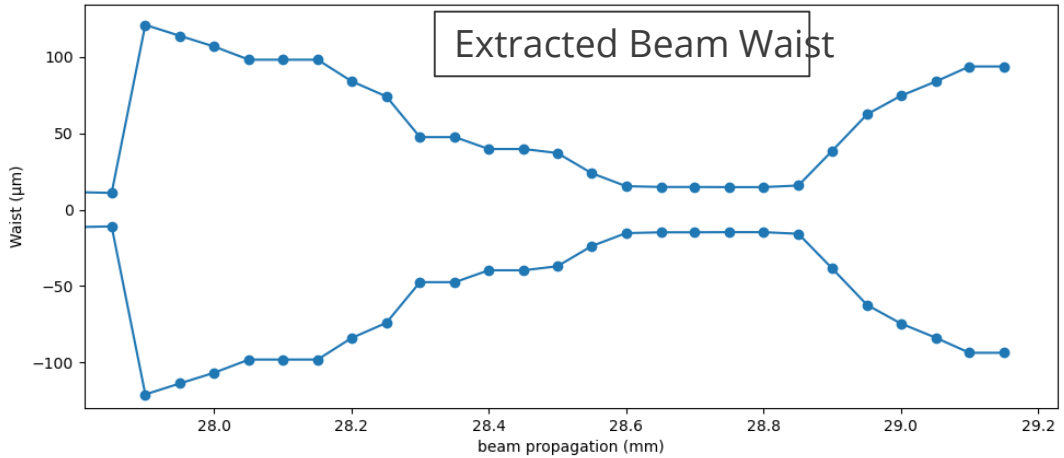
Measured Beam waist = 47.24 µm (DL = 16.98 µm)
Measured FL = 27.25 mm

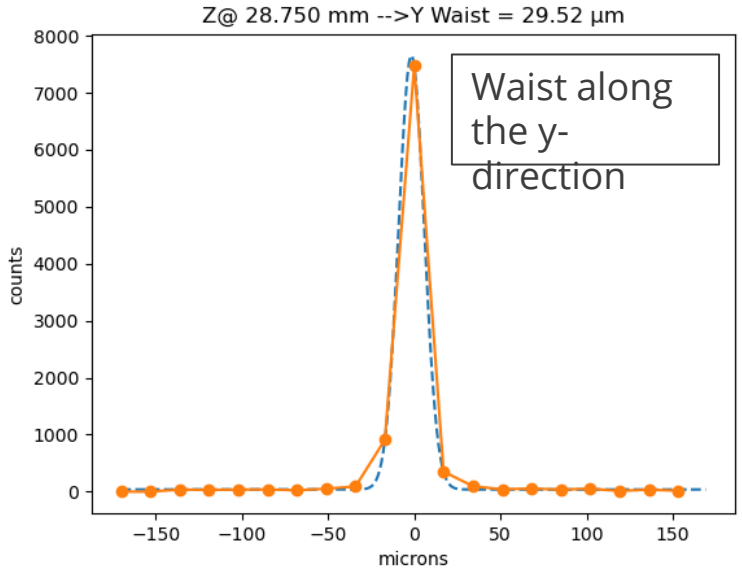
Worked performed by Augustine Urbas and Joel Leger AFRL

Preliminary Characterization of 1-color MPL – Metasurface Lens



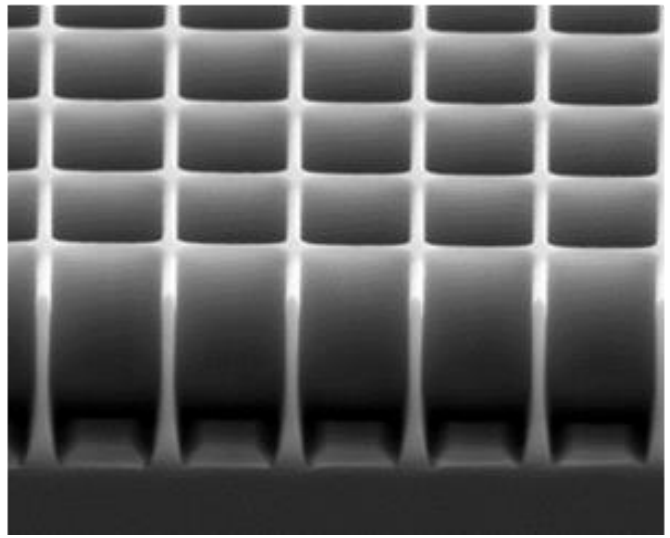


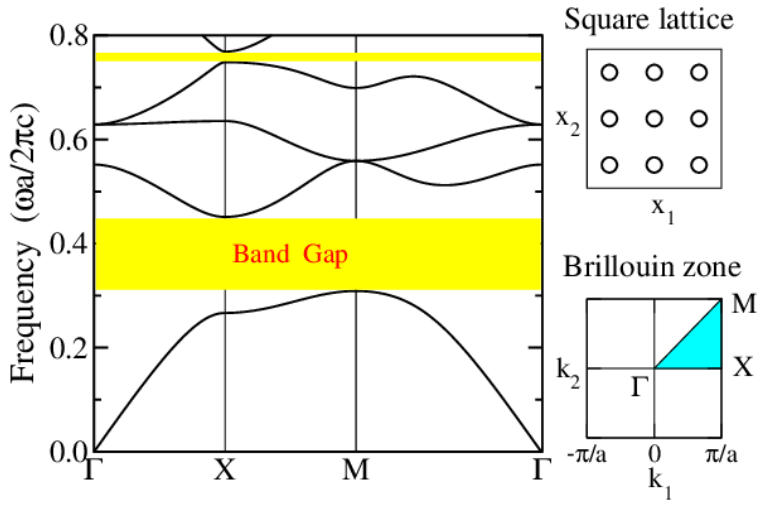




Note the px pitch is 17 and fail to resolve the focus for a couple a points.

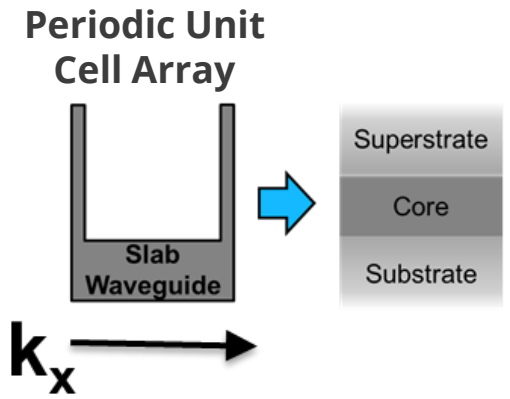
Photonic Crystal Slab Modes

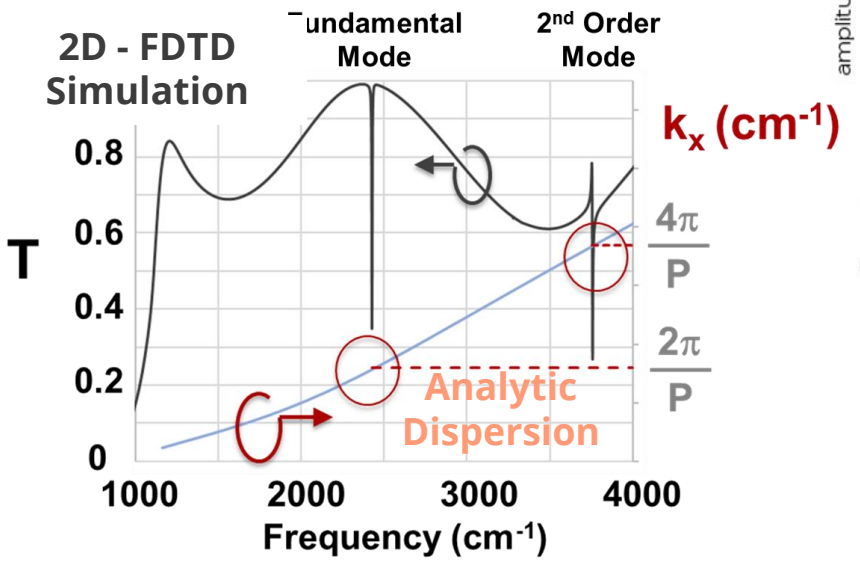




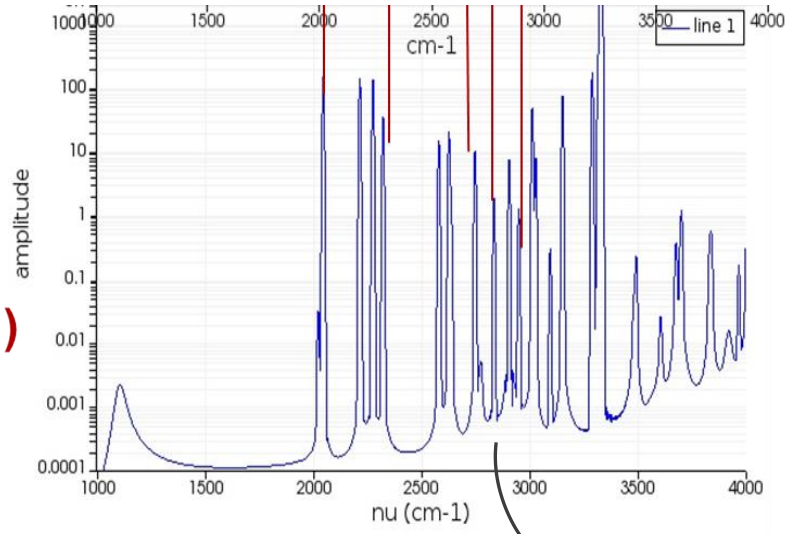
DB Burckel et. al., "Coupling between plasmonic and photonic crystal modes in suspended three-dimensional meta-films" Opt. Exp. **28** (8), 10836-10846 (2020).

Analyzing the Scattering Spectrum : Empty Boxes



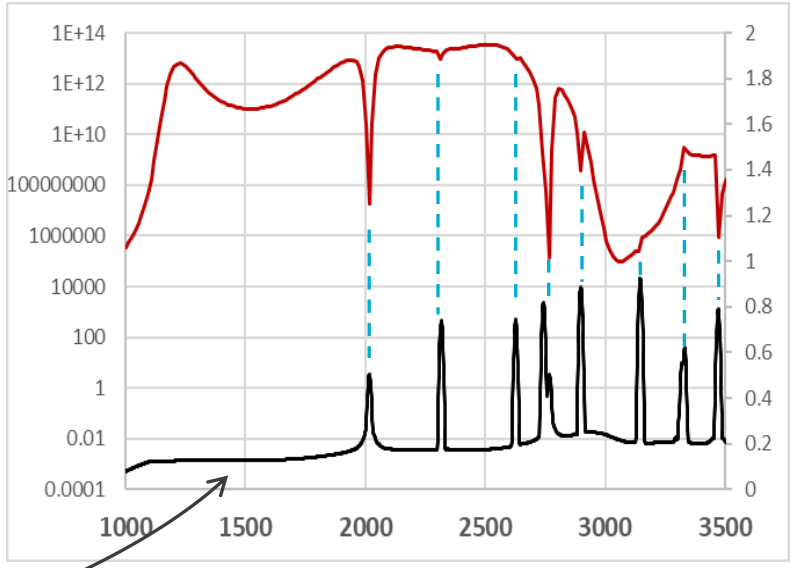


PSD – all allowed modes in matrix



Subset of all allowed modes

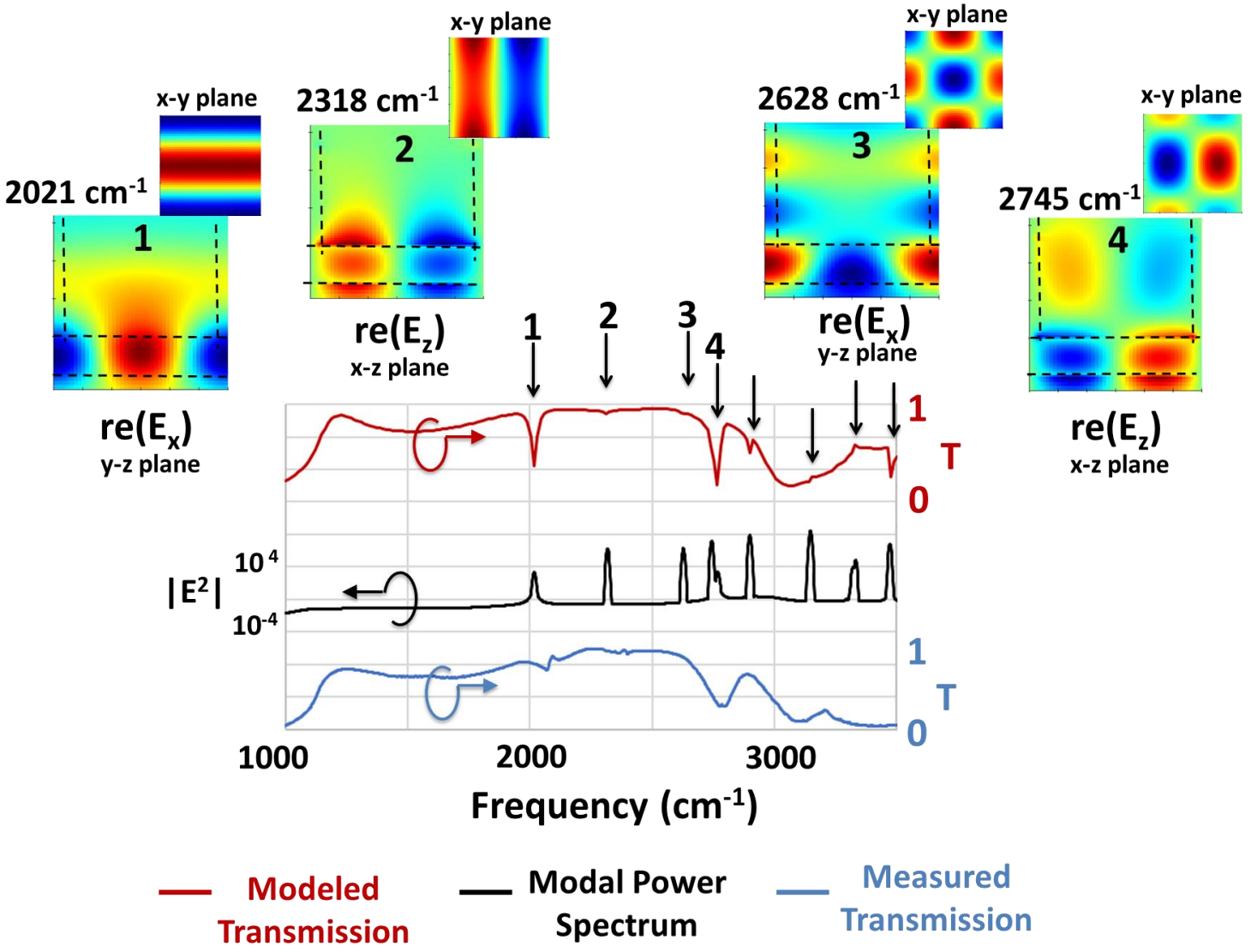
3D - FDTD Simulation



PSD – modes coupled to external plane wave excitation

DB Burckel et. al., "Coupling between plasmonic and photonic crystal modes in suspended three-dimensional meta-films" Opt. Exp. **28** (8), 10836-10846 (2020).

Analyzing the Scattering Spectrum: Empty Boxes



DB Burckel et. al., "Coupling between plasmonic and photonic crystal modes in suspended three-dimensional meta-films" Opt. Exp. **28** (8), 10836-10846 (2020).

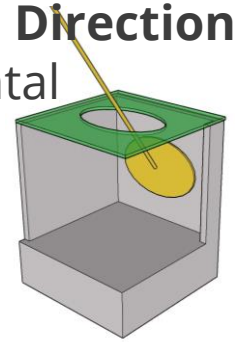
Coupling between Photonic Crystal Slab Modes and 3D Plasmonic Meta-atoms

DB Burckel et. al., “Coupling between plasmonic and photonic crystal modes in suspended three-dimensional meta-films” Opt. Exp. **28** (8), 10836-10846 (2020).

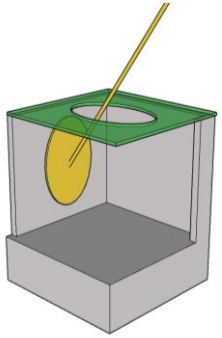
Decorating with plasmonic meta-atoms

Same Membrane Pattern
Different Evaporation Direction

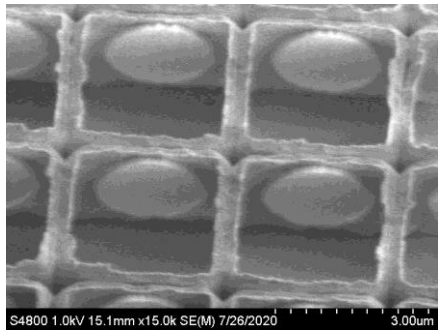
Horizontal Ellipses

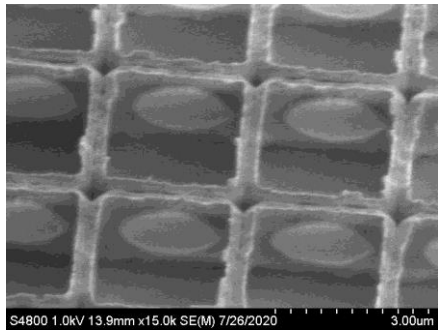


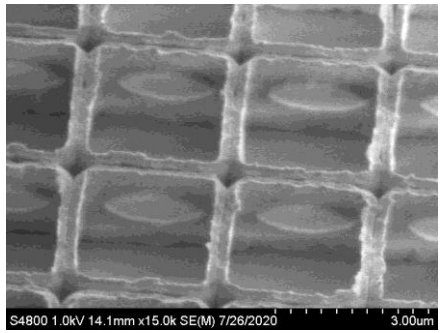
Vertical Ellipses

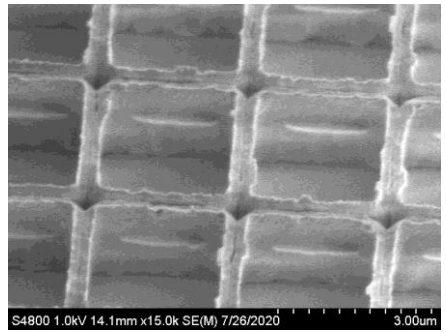


North wall evaporations

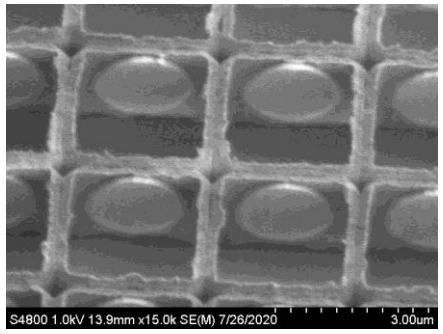


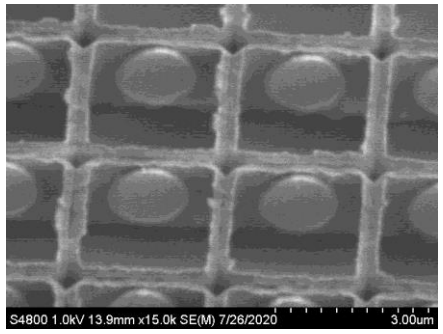


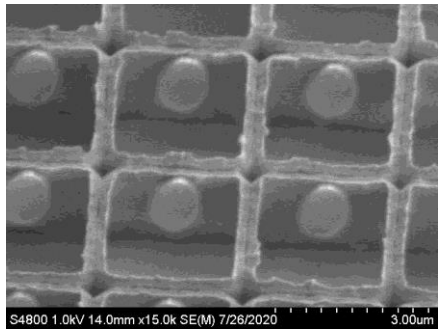


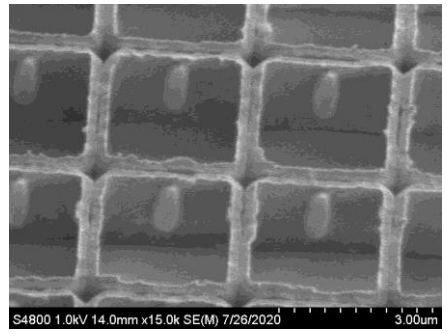


East wall evaporations



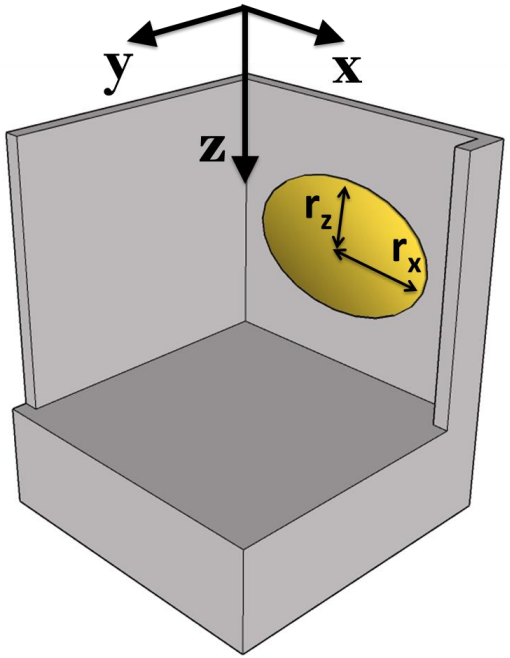




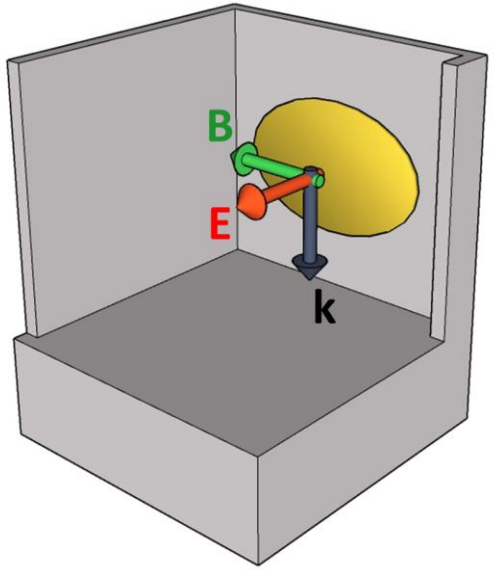


DB Burckel et. al., “Coupling between plasmonic and photonic crystal modes in suspended three-dimensional meta-films” Opt. Exp. **28** (8), 10836-10846 (2020).

Polarization in 3D Metafilms

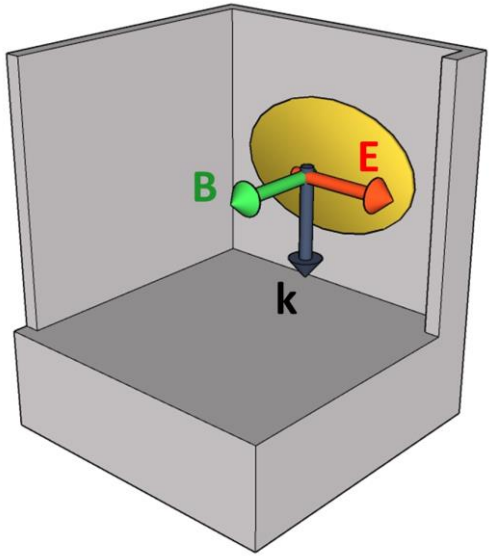


Transparent Polarization



Electric field normal to plane of ellipse

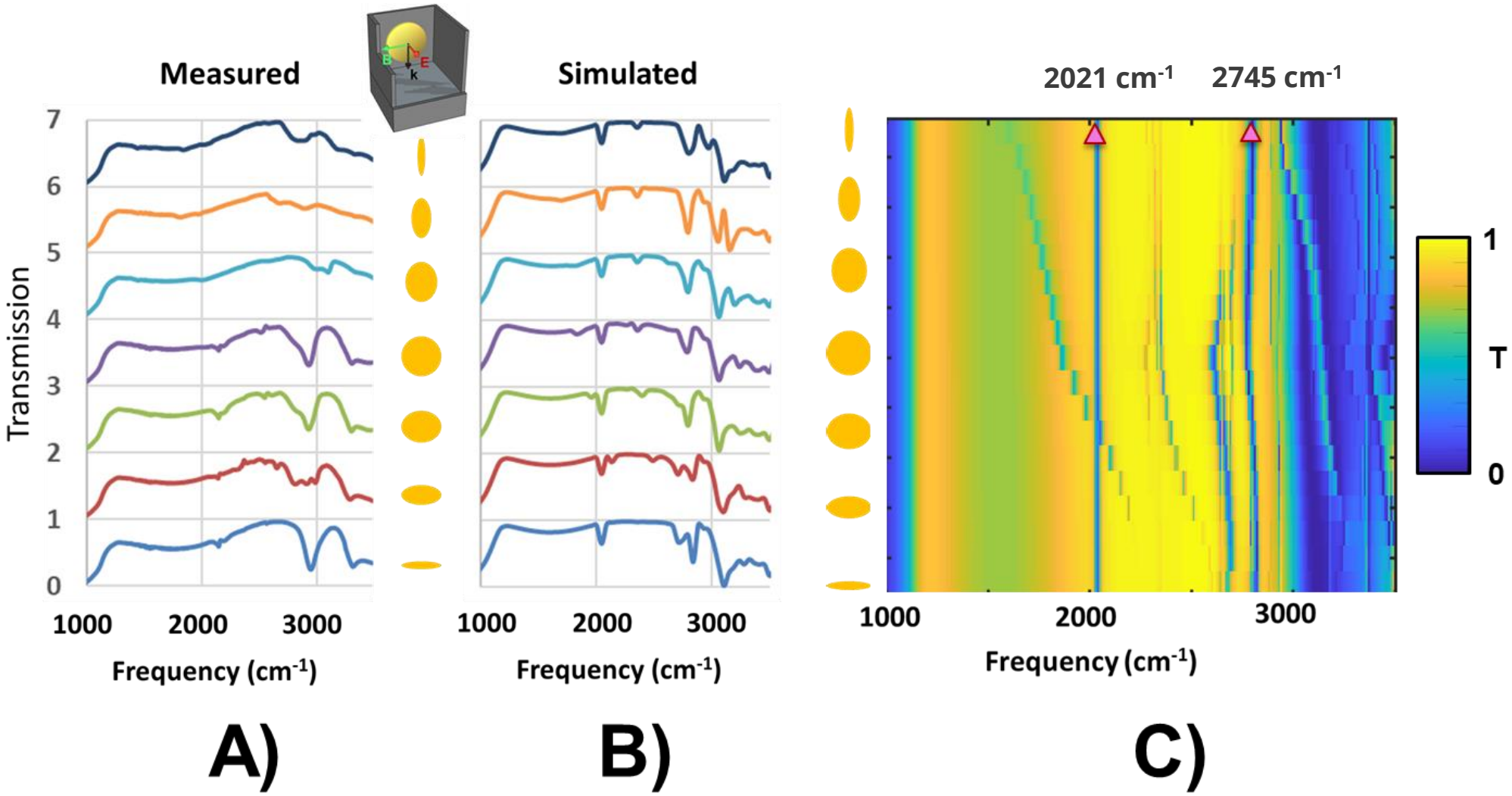
Resonant Polarization



Electric field in the plane of ellipse

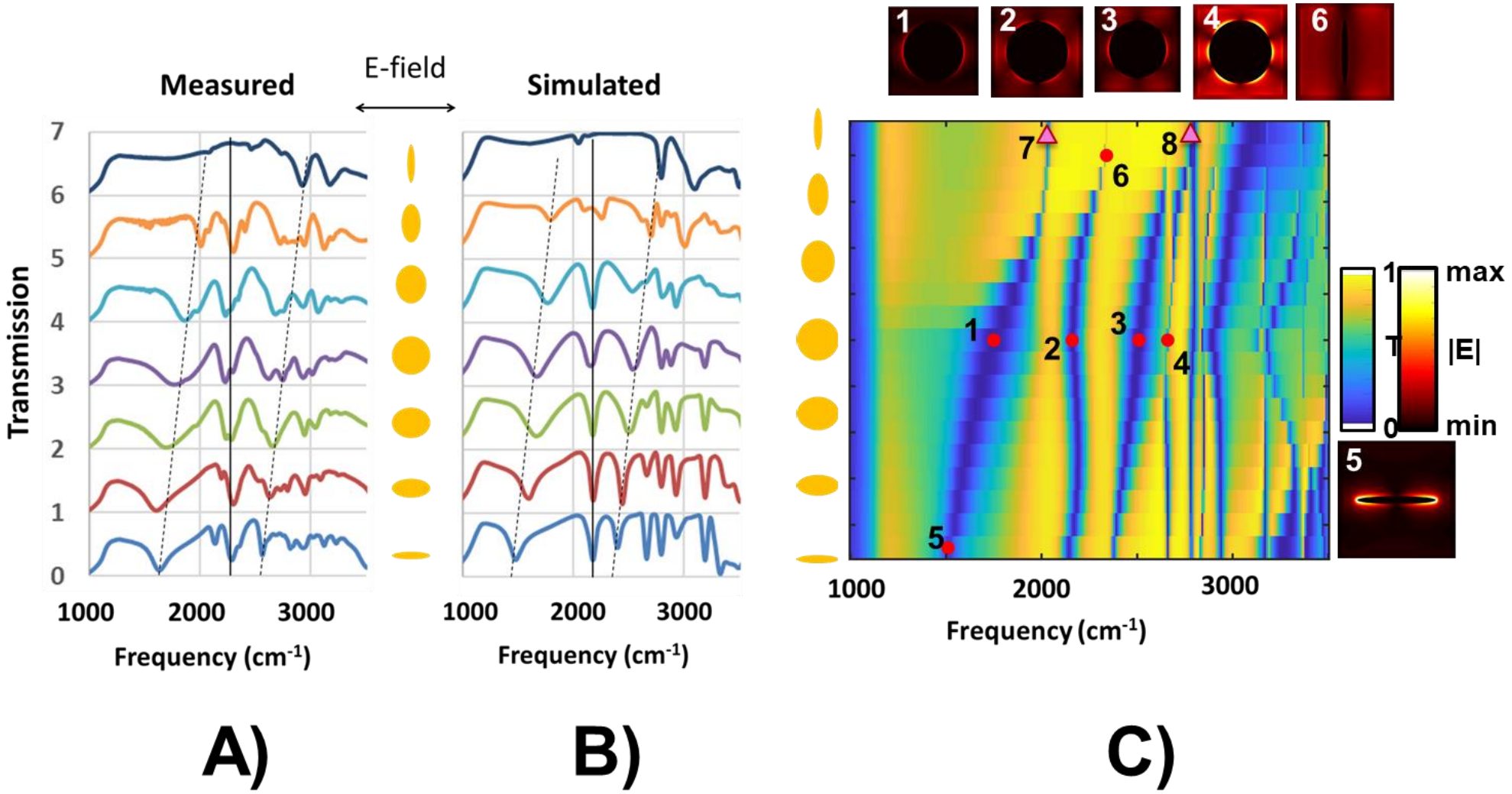
DB Burckel, M Goldflam, KM Musick, PJ Resnick, G Armelles, and MB Sinclair, “Coupling between plasmonic and photonic crystal modes in suspended three-dimensional meta-films” Optics Express **28** (8), 10836-10846 (2020).

Transparent Polarization



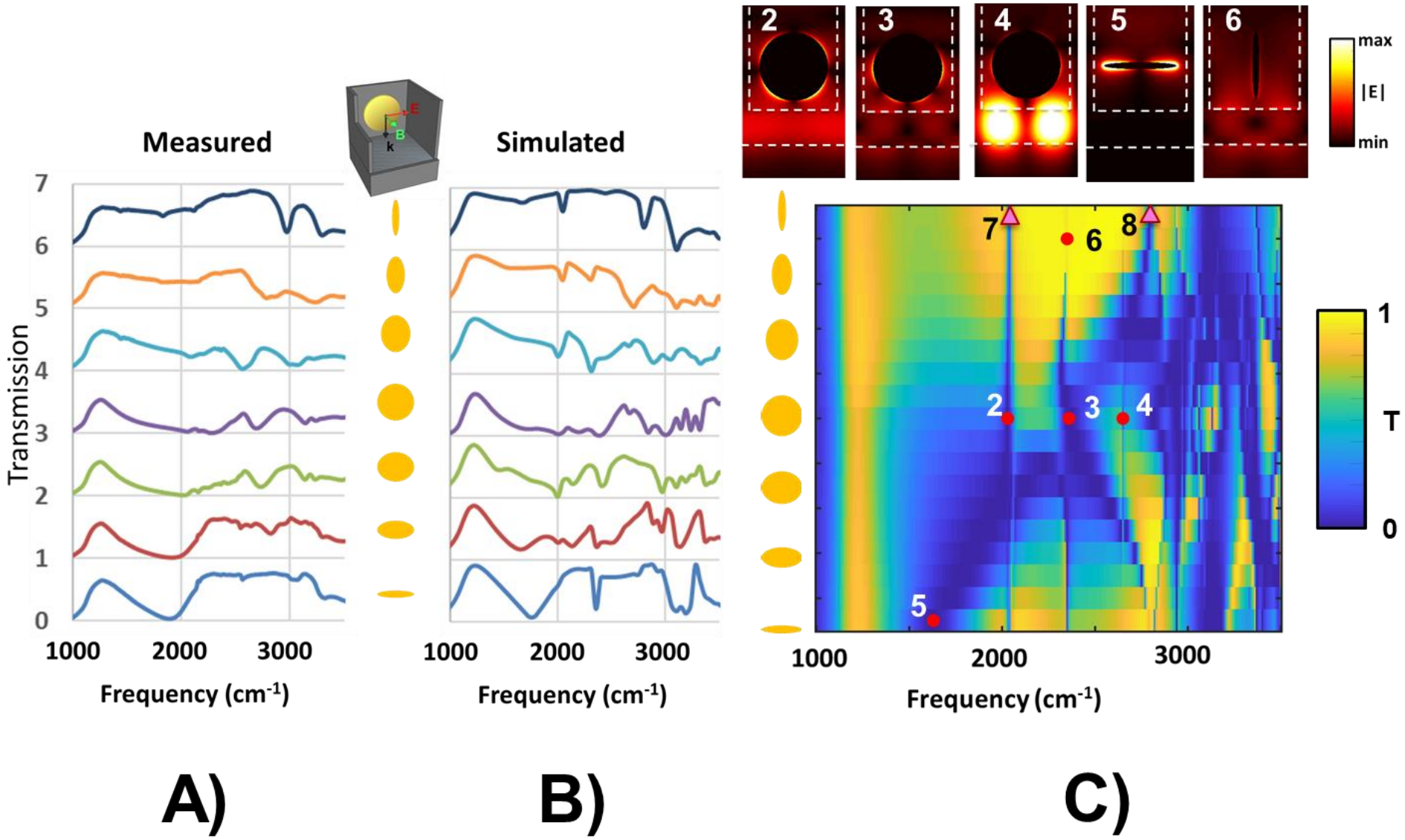
DB Burckel et. al., "Coupling between plasmonic and photonic crystal modes in suspended three-dimensional meta-films" Opt. Exp. **28** (8), 10836-10846 (2020).

Ellipses on the Floor



DB Burckel et. al., "Coupling between plasmonic and photonic crystal modes in suspended three-dimensional meta-films" Opt. Exp. **28** (8), 10836-10846 (2020).

Resonant Polarization



DB Burckel et. al., "Coupling between plasmonic and photonic crystal modes in suspended three-dimensional meta-films" Opt. Exp. **28** (8), 10836-10846 (2020).

Conclusions

1. Wall-first membrane projection lithography fabrication approach is a robust method for creation of infrared 3D metafilms

2. 3D metafilms can be used to create macroscopic lenses with unique characteristics due to their geometry.

3. 3D metafilms combine and couple photonic crystal slab modes and plasmonic particle modes

4. Planar ellipses on the floor respond to both incident polarizations

5. Vertical ellipses exhibit a resonant response to linear polarization with e-field in the plane of the ellipse, while being largely transparent to the orthogonal polarization

6. Retardation effects broaden the spectral width of resonances for vertically oriented ellipses.

Funding and Collaboration

- Funding : DARPA Extreme, NGA, SNL-LDRD

- SNL Collaborators: Michael Goldflam (Systems and Technology Research, San Diego, CA), Kate Musick, Michael Sinclair, Paul Resnick, Rob Jarecki

- External Collaborators: Gaspar Armelles -Microelectronic Institute of Madrid (IMM-CNM, CSIC) ;