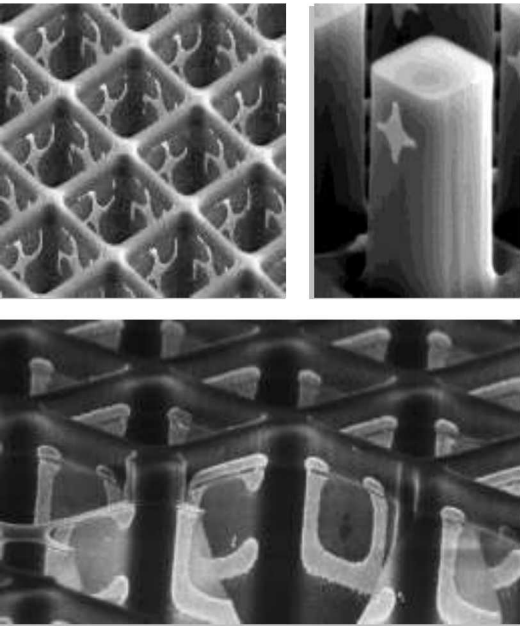




This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

SAND2018-3391C



Challenges and Opportunities in Modeling and Optimization of 3D Optical Metasurfaces

March 29, 2018

Bruce Burckel

dbburck@sandia.gov

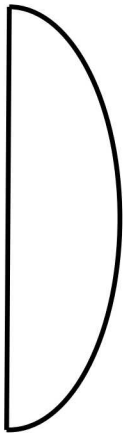


*Exceptional
service
in the
national
interest*



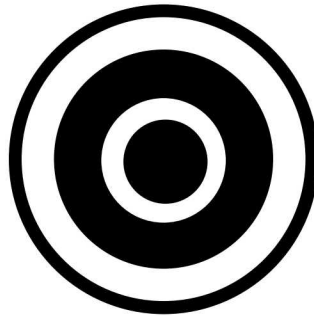
Sandia National Laboratories is a multi mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525

**Refractive
Lens**



Isaac Newton

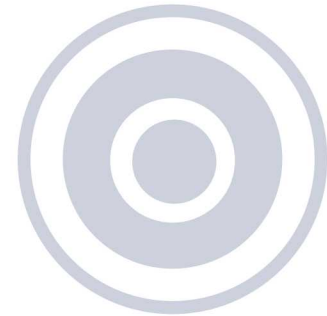
**Binary Zone
Plate**



August-Jean Fresnel

40.4% Efficient

**Phase Reversal
Zone Plate**



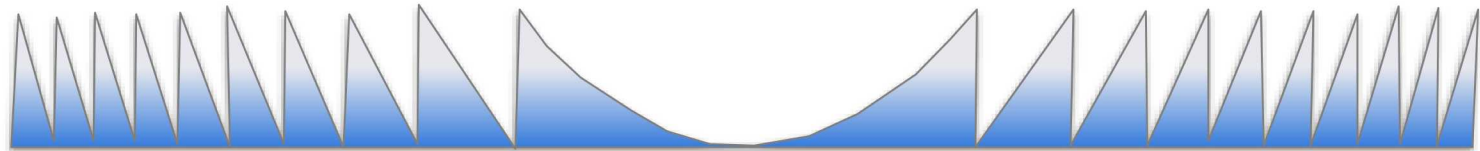
Wood (Lord Rayleigh)



How to Make a Lens



Continuous Phase Distribution



100% Efficient

Discrete Approximation Phase Distribution



81% Efficient

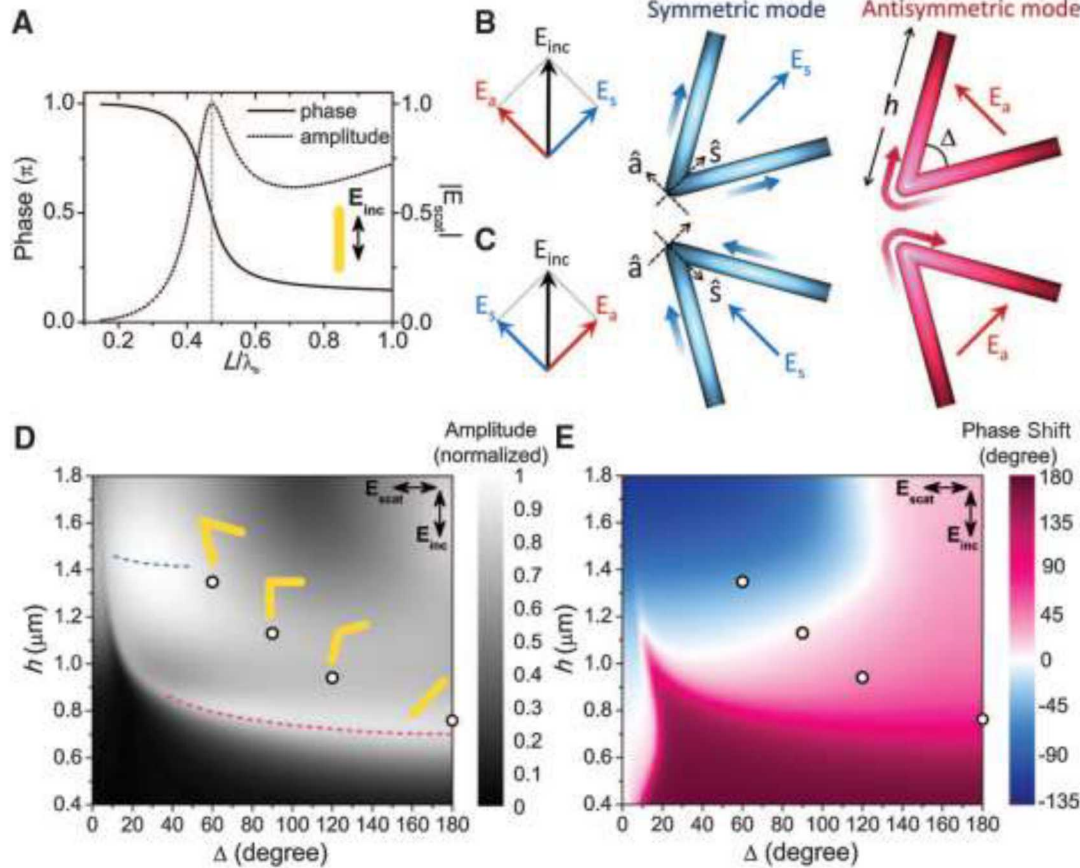


Outline



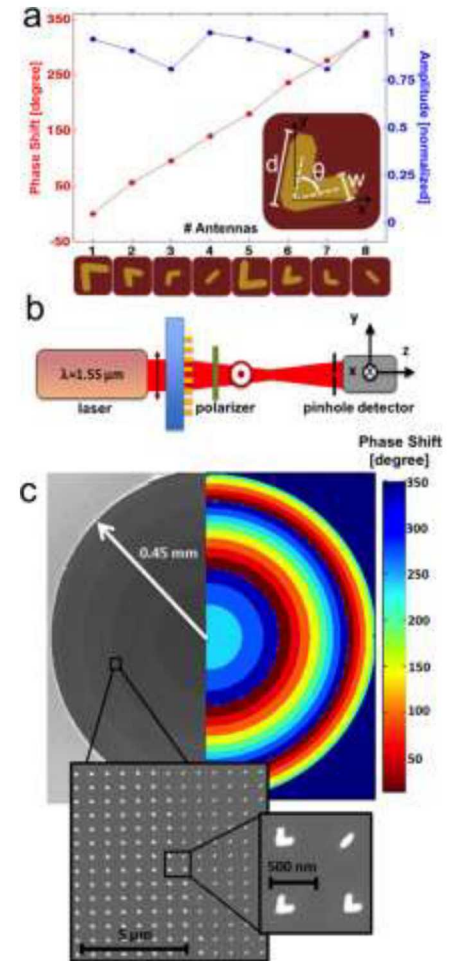
1. Generalized law of reflection and refraction – planar meta-surfaces
2. 3D Metamaterial Atoms – unique coupling and scattering response
3. MPL Fabrication – 3D meta-films
4. Unique behaviors for 3D meta-atoms

V-Antenna Amplitude/Phase Relationship



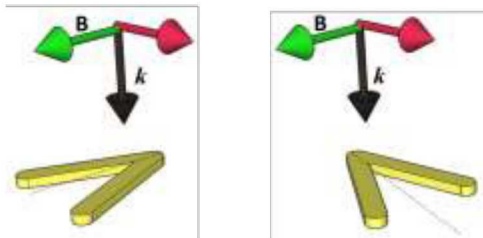
Yu, et al, Science, **334**, pp 333-337 (2011)

Lens Design

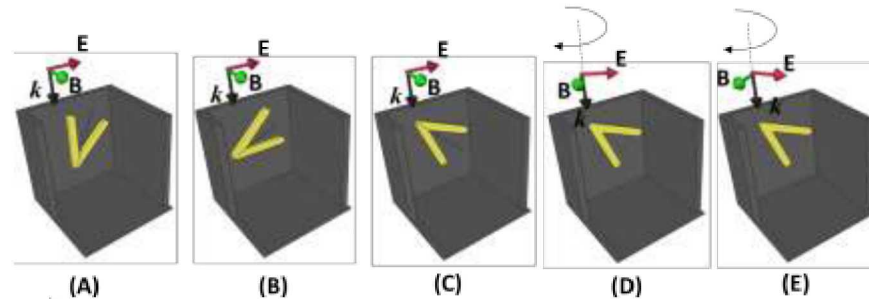


Aieta, et al, Nano Letters, **12**, pp 4932-4936 (2012)

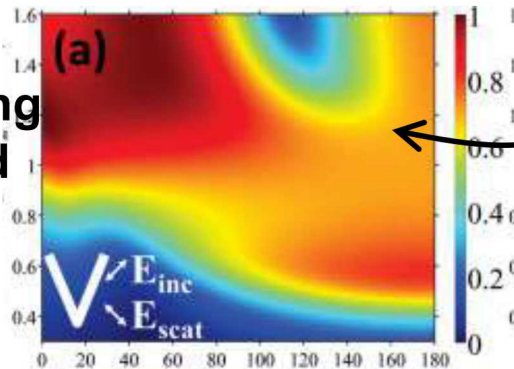
Planar V-Antennas



Vertical V-Antennas



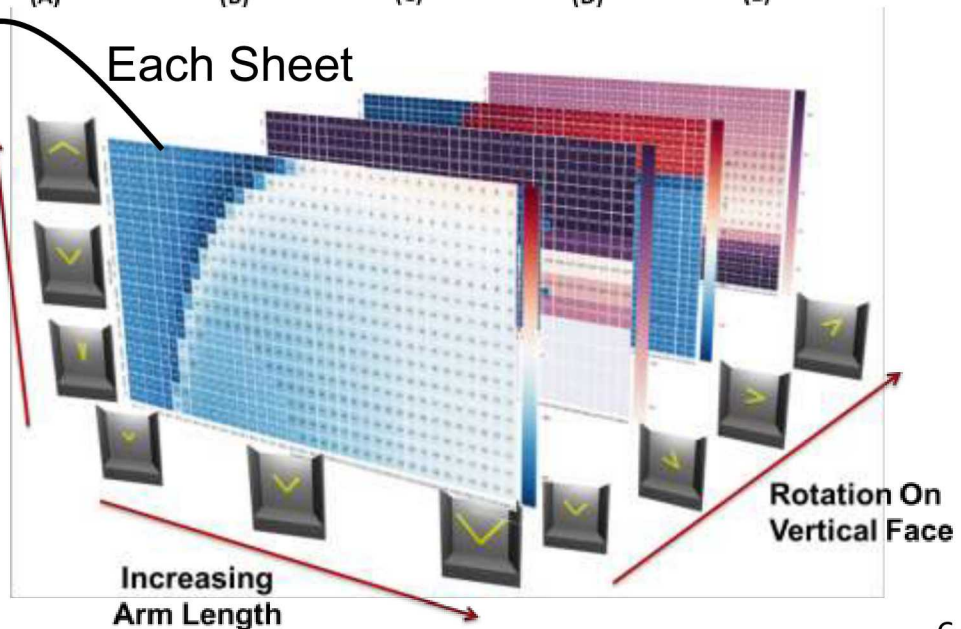
Increasing
Spread
Angle



Increasing
Arm Length

Each Sheet

Increasing
Spread
Angle

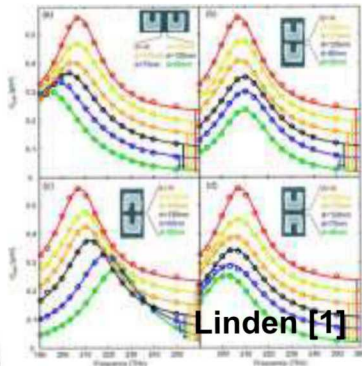
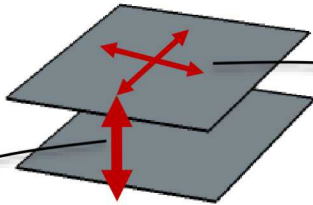




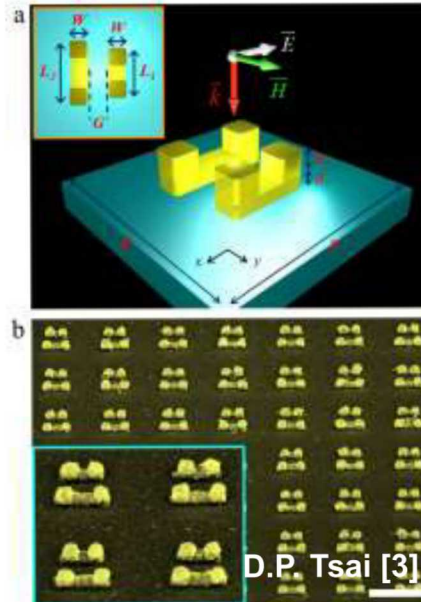
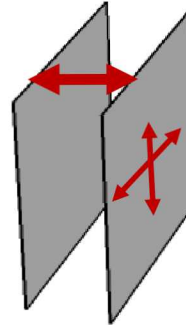
Comparing Coupling Mechanisms in Planar and Vertical Structures



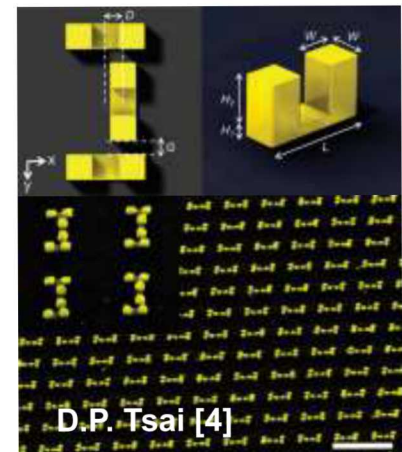
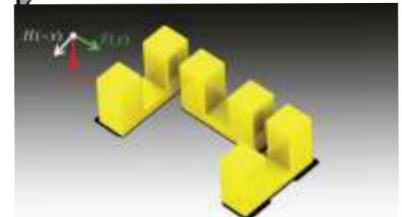
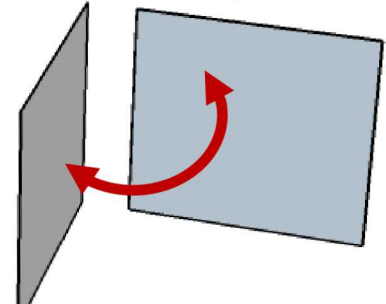
Stacked Planar Geometry



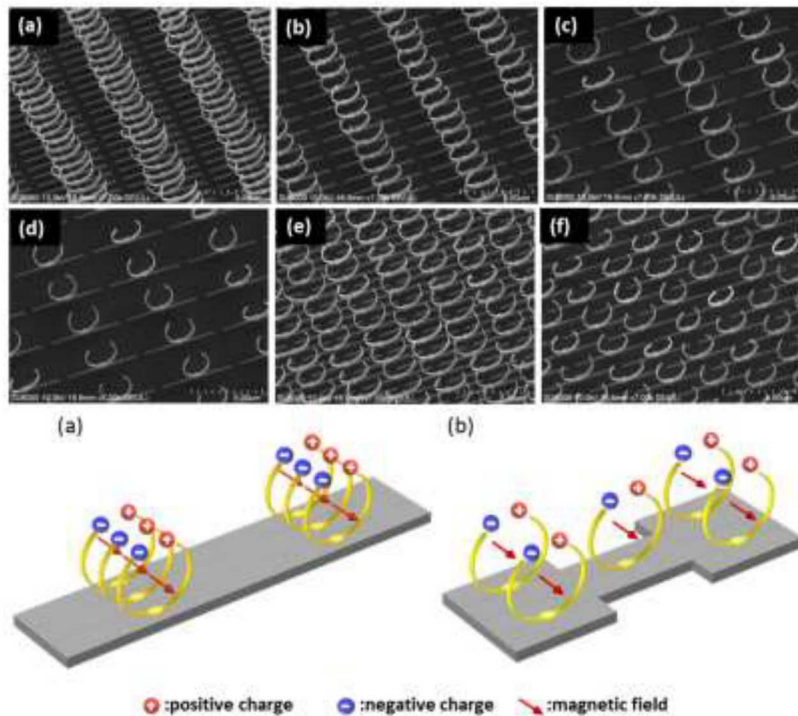
Back-to-back Vertical Geometry



Orthogonal Vertical Geometry

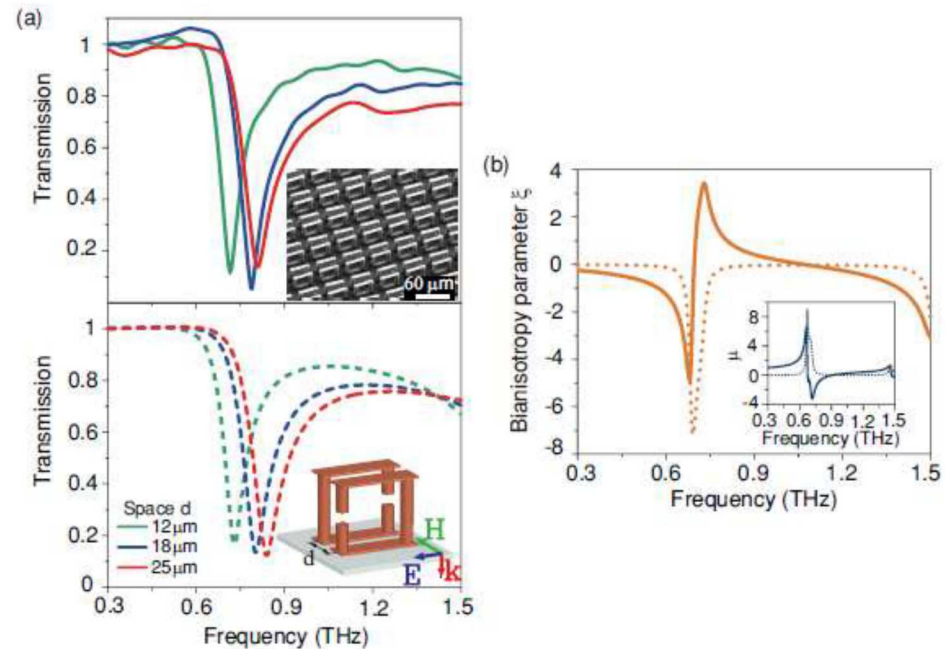


Horizontally Oriented Magnetic Dipole



Tanaka and Chen [5]

Unambiguous Coupling to Normally Incident Magnetic Field

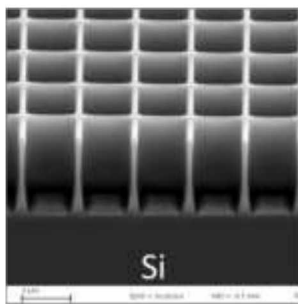
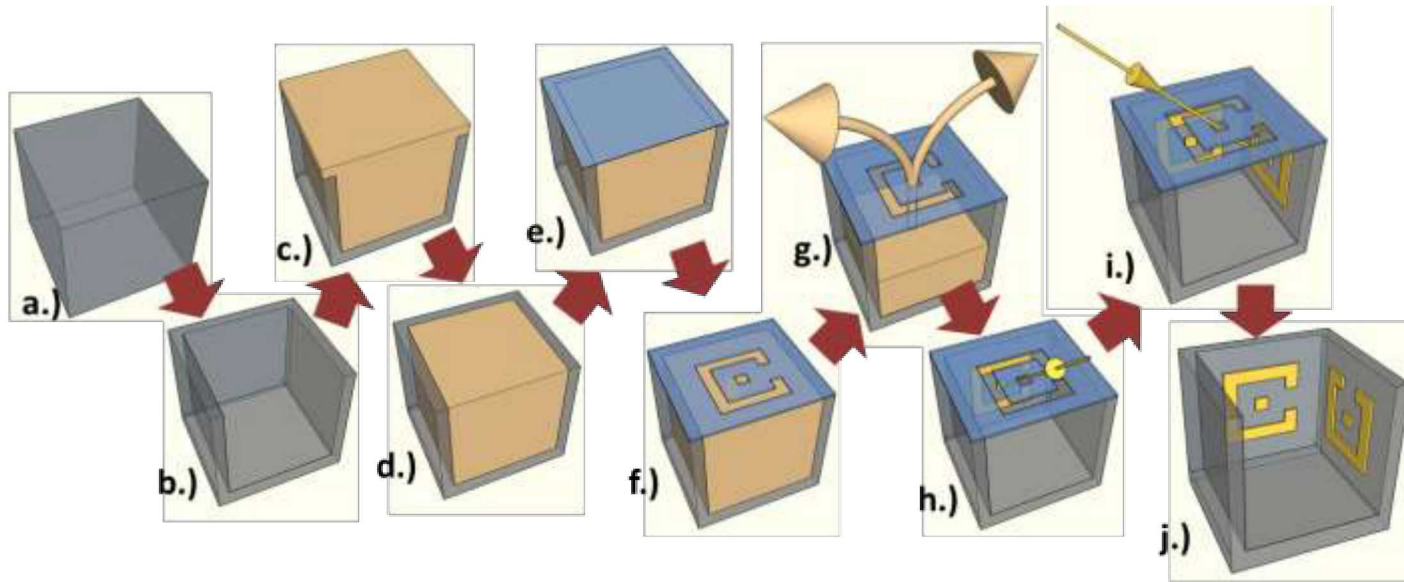


Averitt [6]

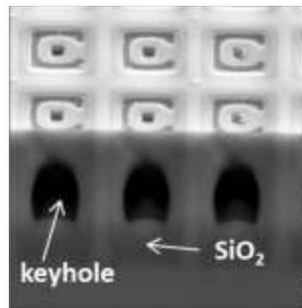


Membrane Projection Lithography (MPL)

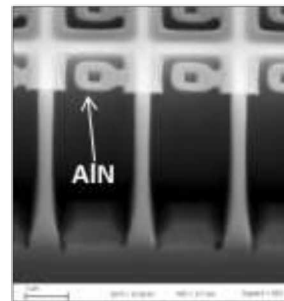
3D Micron-scale Fabrication Approach



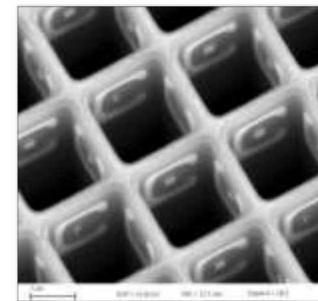
k.)



l.)



m.)



n.)

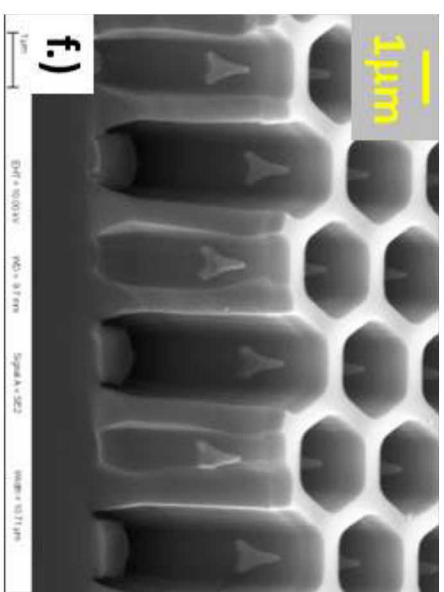
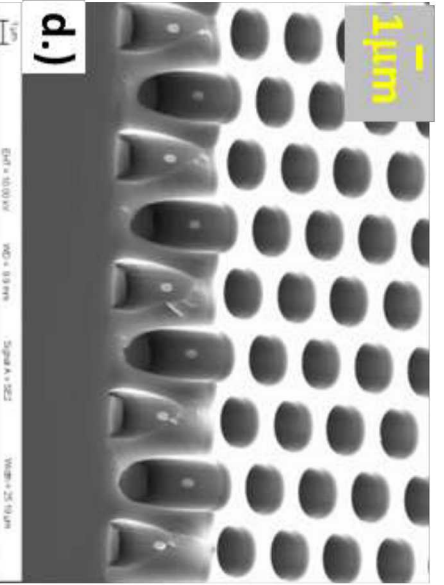
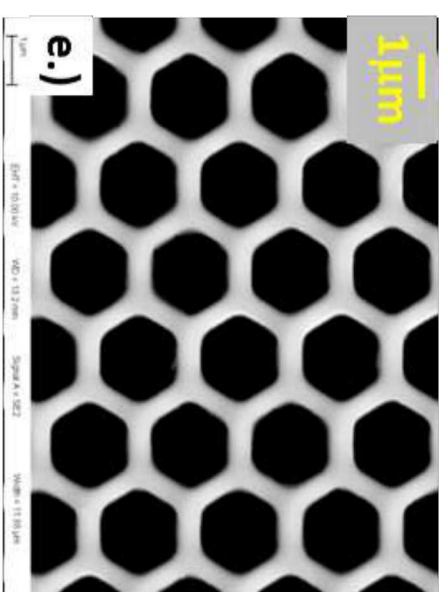
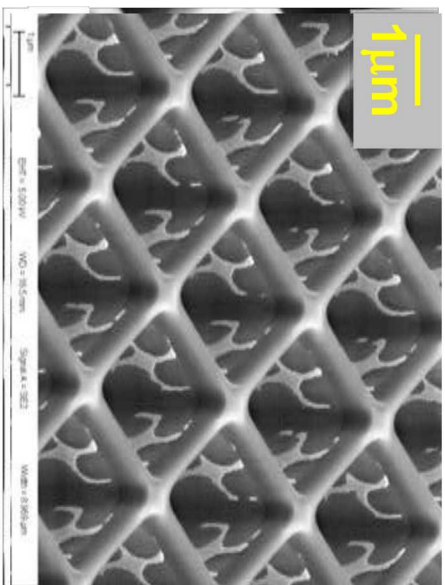
D. Bruce Burckel, Paul J. Resnick, Patrick S. Finnegan, Michael B. Sinclair and Paul S. Davids “Micrometer-scale fabrication of complex three dimensional lattice+basis structures in silicon,” *Optical Materials Express*, 5, 2231-2239, (2015).



3D micron-scale Metamaterials

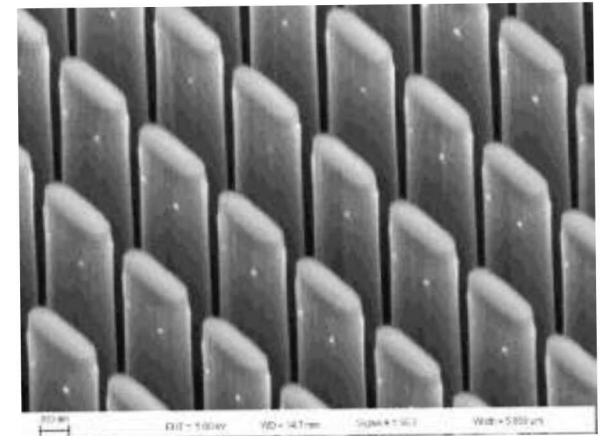
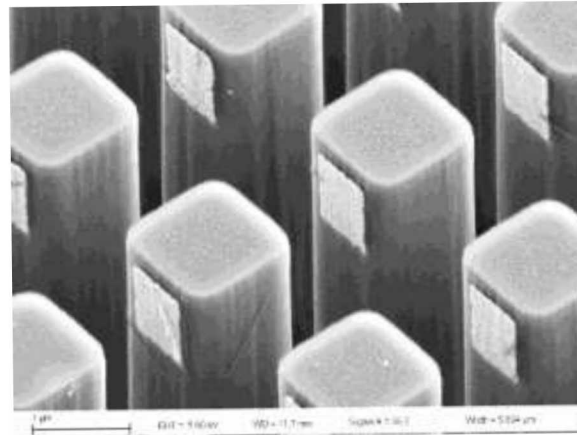
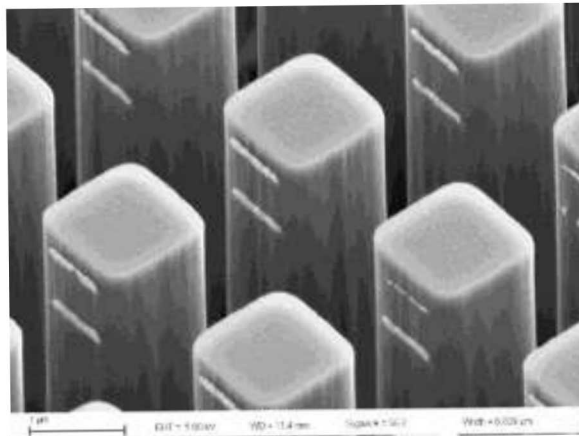
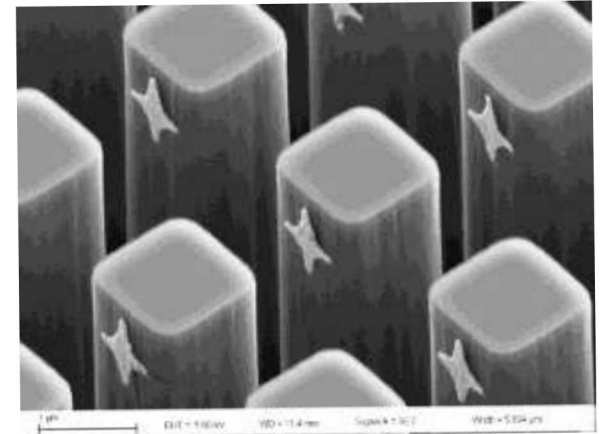
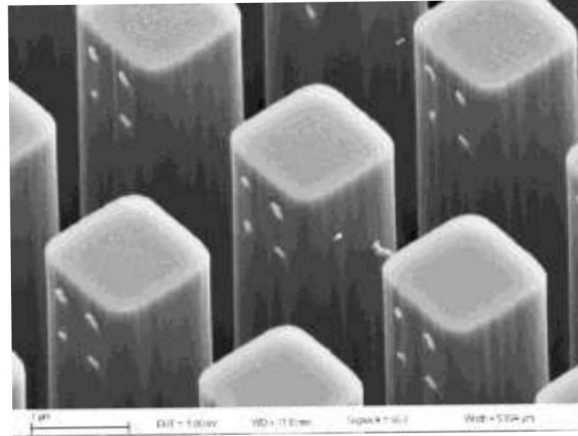
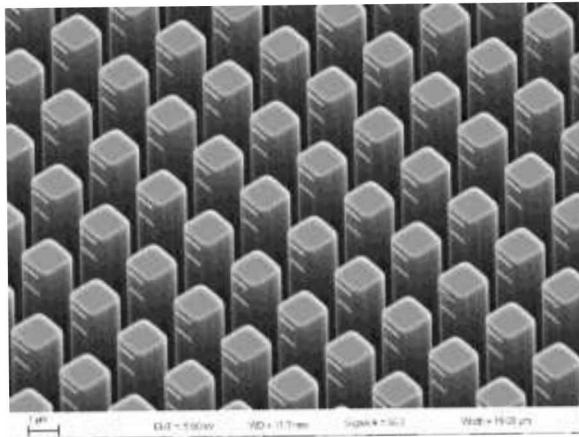


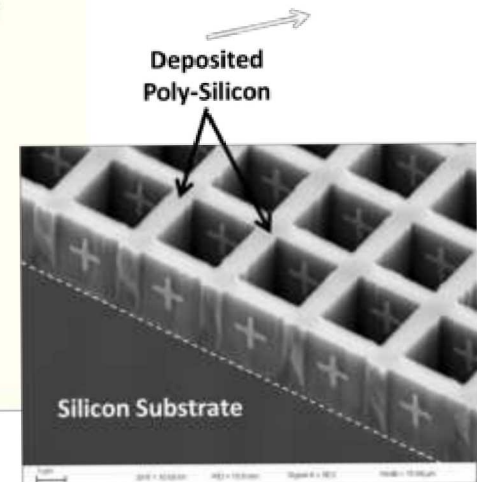
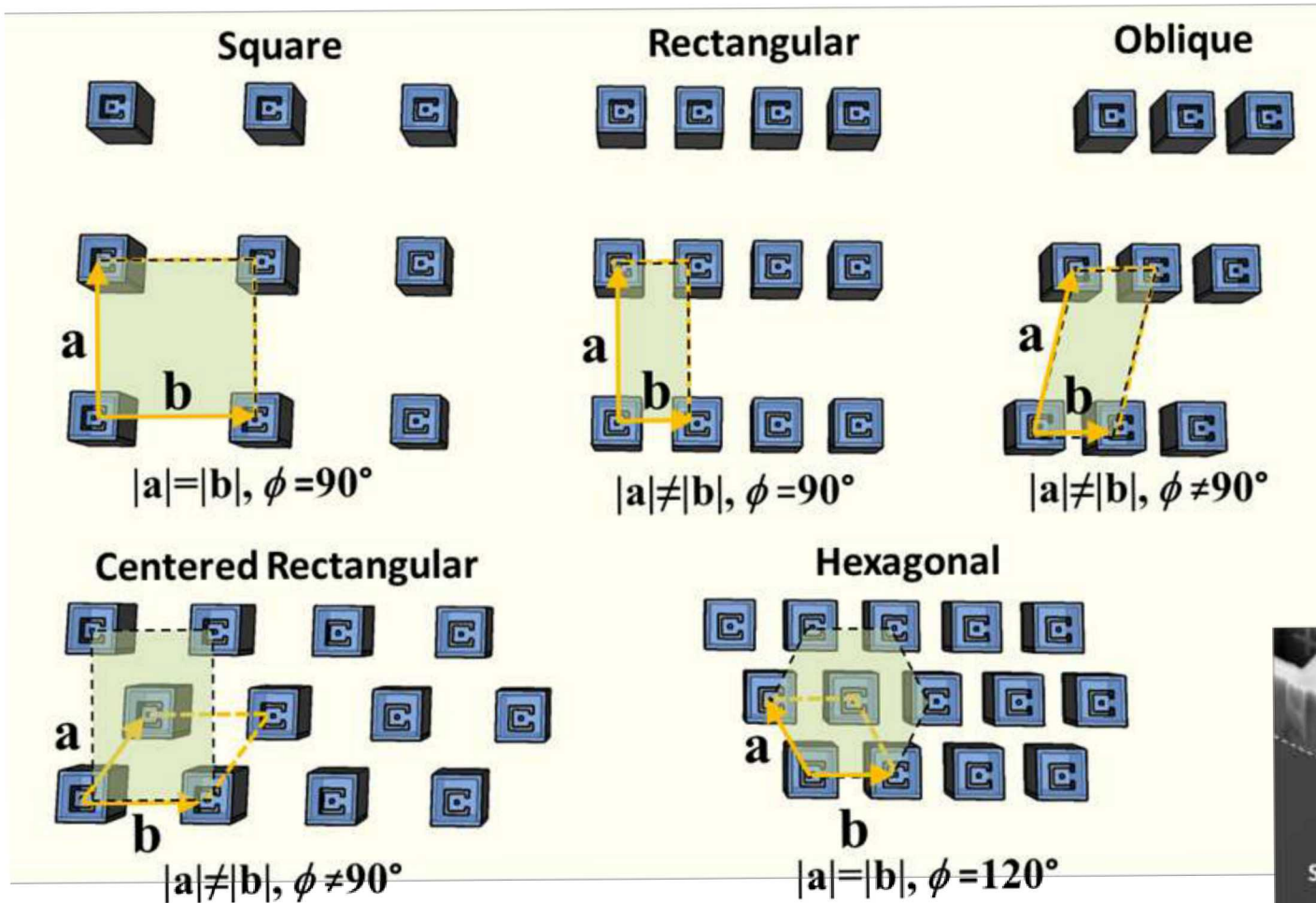
Sandia
National
Laboratories





3D micron-scale Artificial Dielectrics



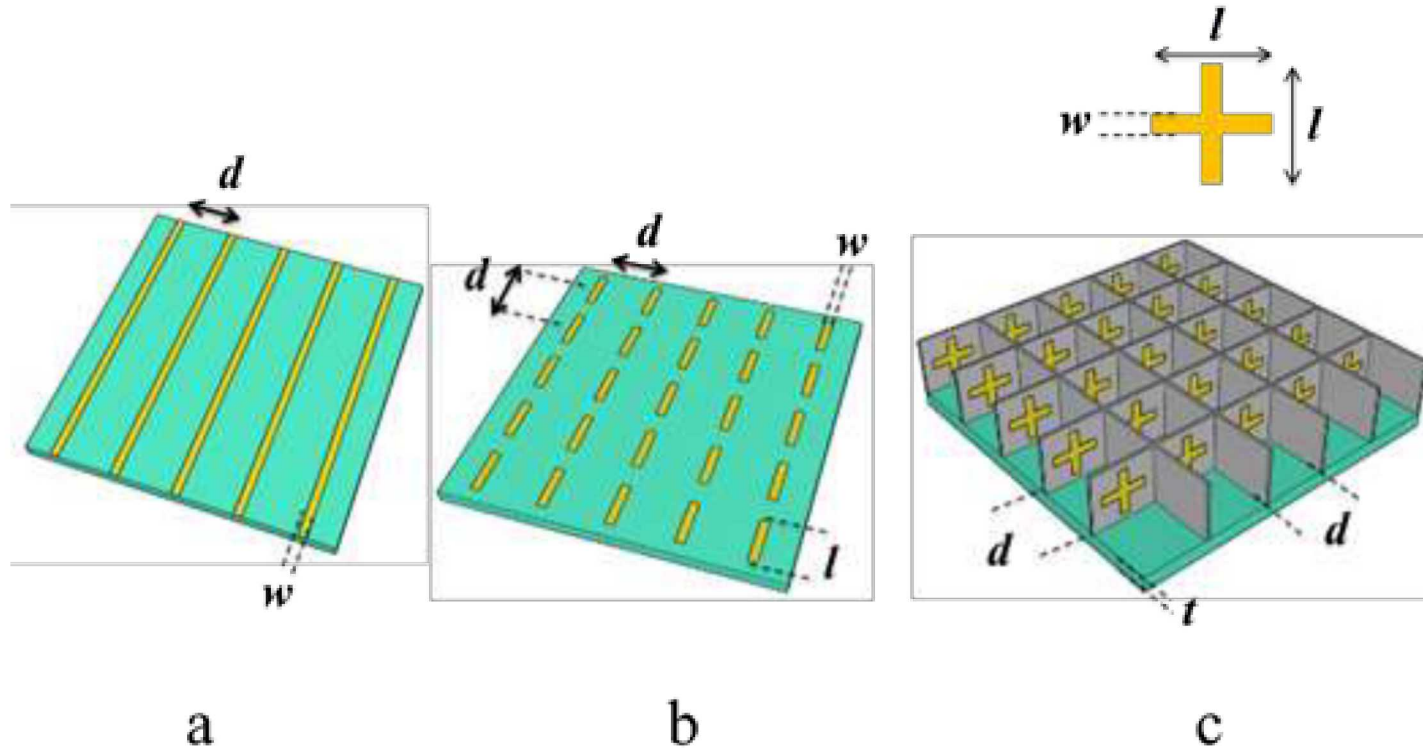


Path to all 14 3D Bravais Lattices?



Vertical Back-To-Back Wire Grid Polarizers

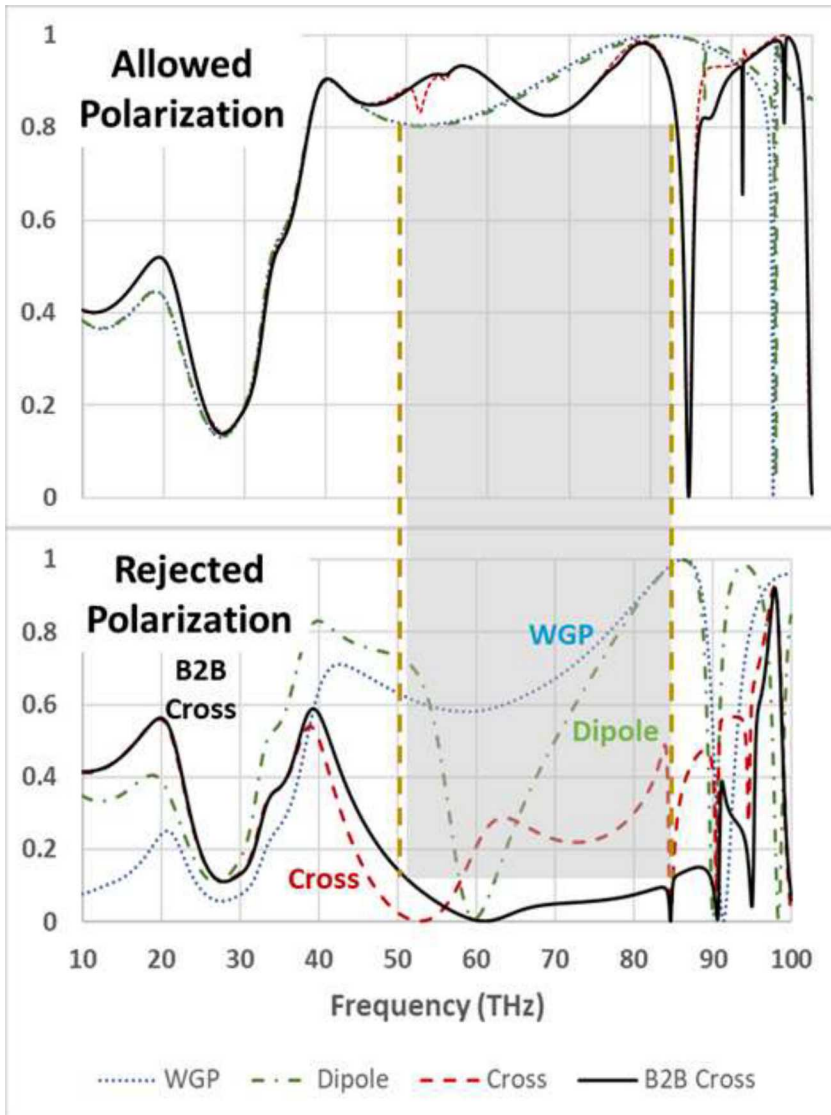
Planar and Vertical Wire Grid Polarizer Geometries



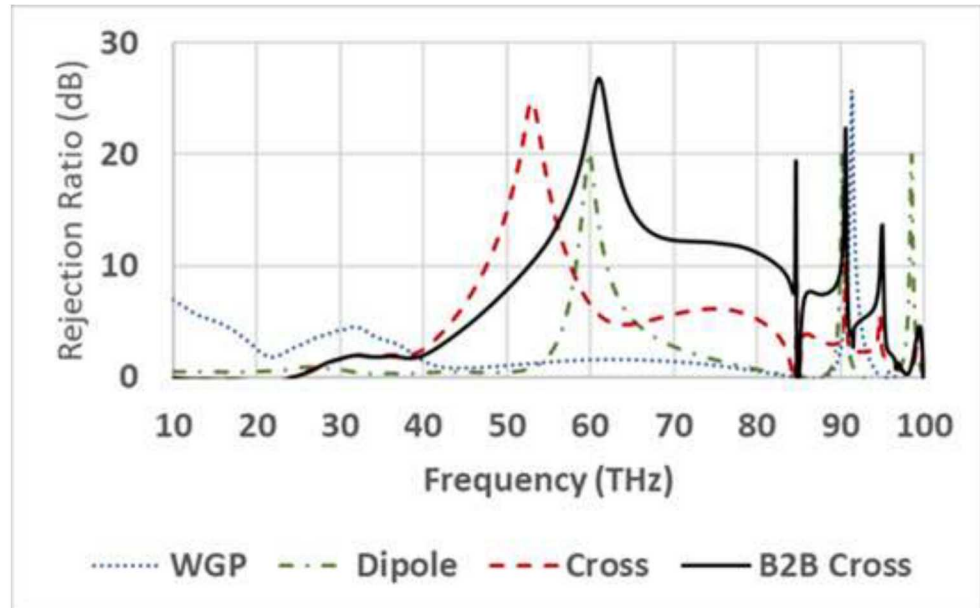
Submitted for publication



Back-to-Back Vertical Cross WGP



$$\text{Rejection Ratio} = 10 \cdot \text{Log}(T_{\text{passed}}/T_{\text{rejected}})$$

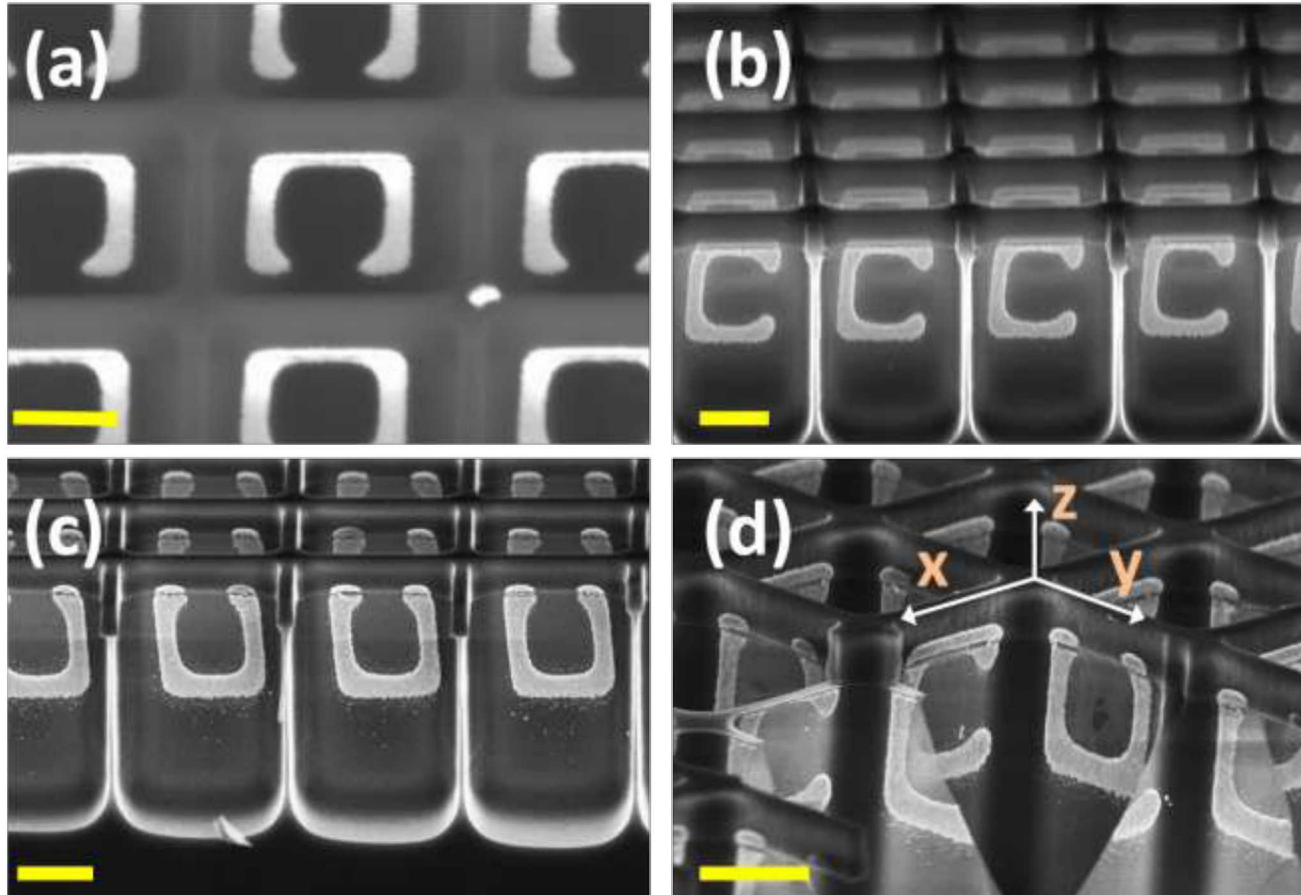




Vertical Split Ring Resonators

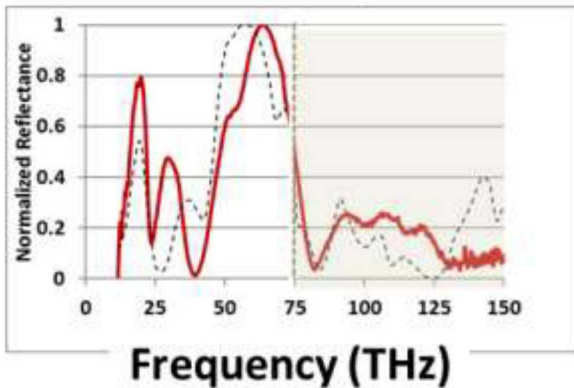
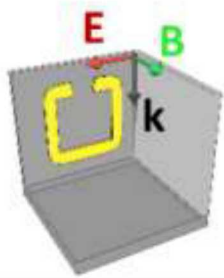


Cubic Unit Cells with 1-SRR and 2-SRR Bases



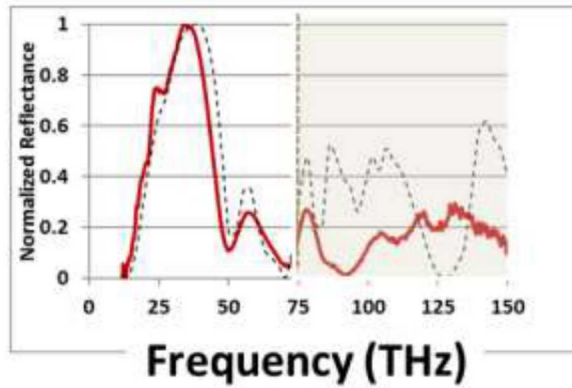
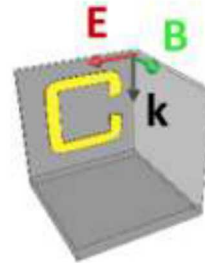
D. Bruce Burckel, Salvatore Campione, Paul S. Davids, and Michael B. Sinclair, "Three dimensional metamaterials with dual channel unit cells," *Applied Physics Letters*, 110, 143107, (2017).

**Gap
Up**



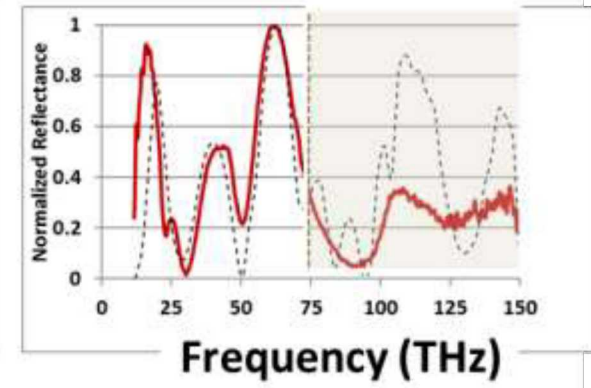
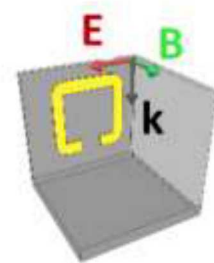
(a)

**Gap
Right**



(b)

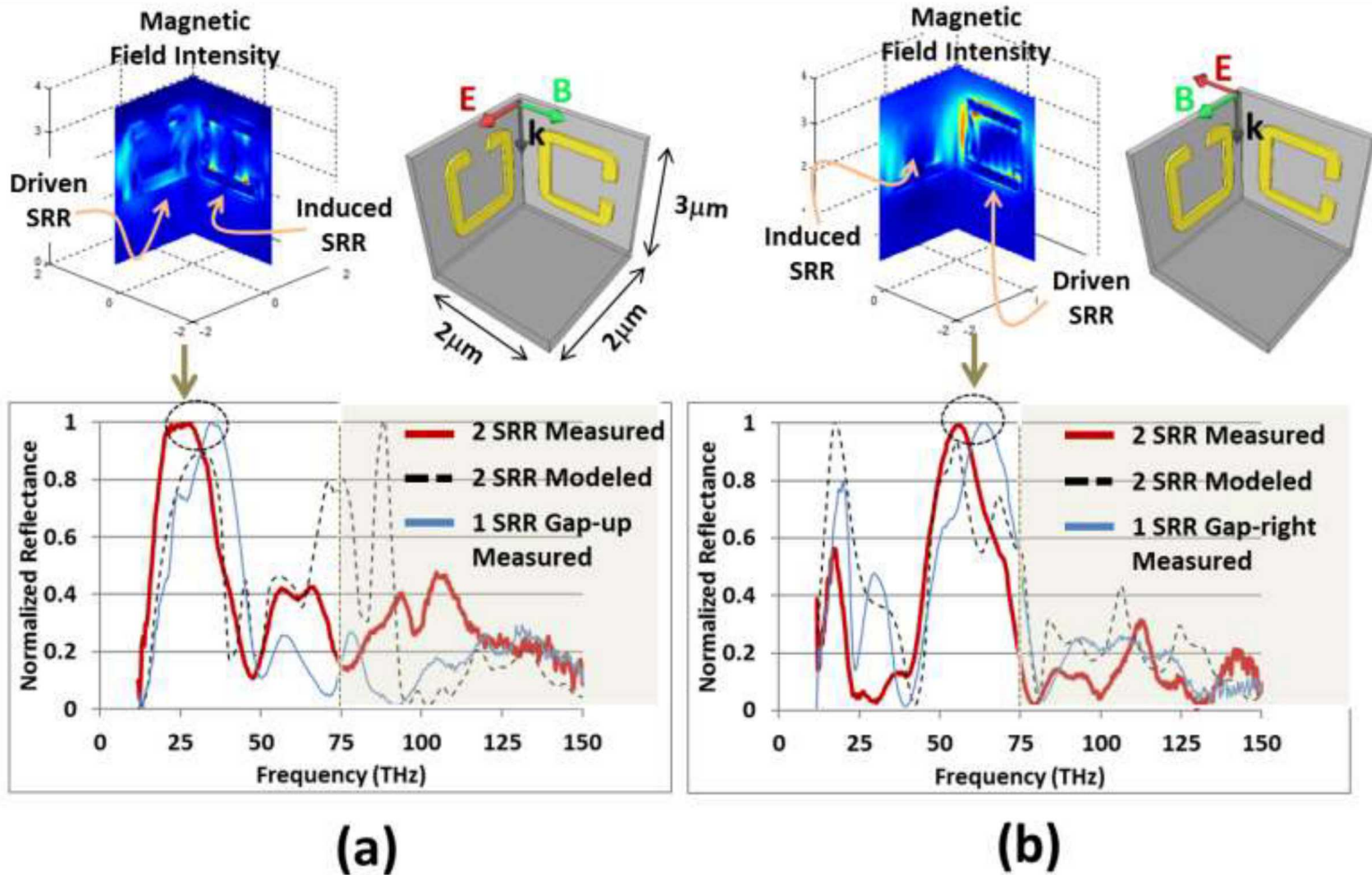
**Gap
Down**



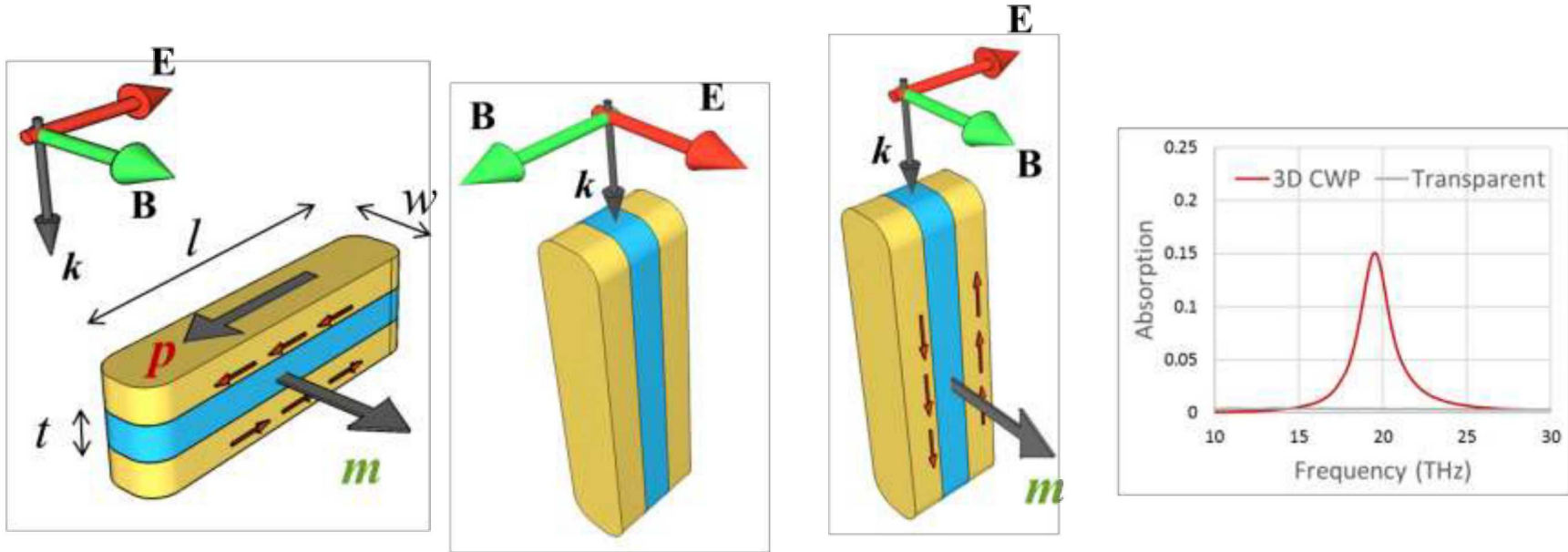
(c)

— Measured - - - RCWA-Modeled

2-SRR Basis Unit Cell – Two Channels



Comparing Planar CWPs to Vertically Oriented CWPs



a)

Planar CWP

b)

**Transparent
Polarization**

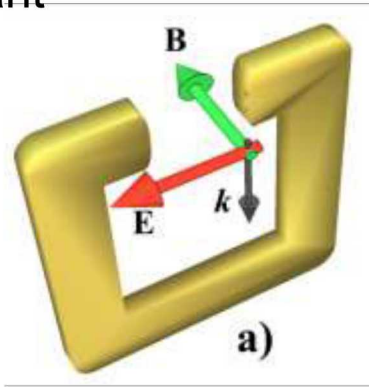
c)

**3D
CWP**

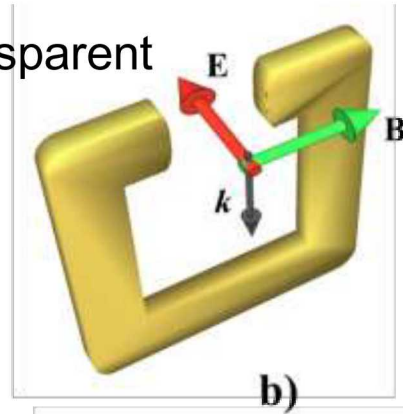
d)

**Calculated
Absorption Spectra**

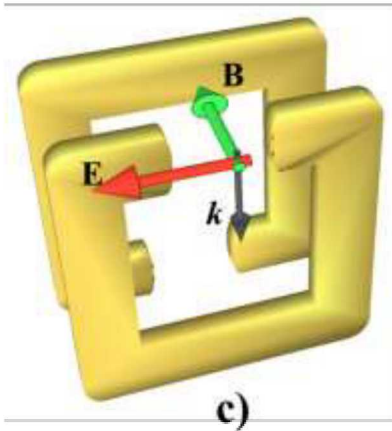
Resonant



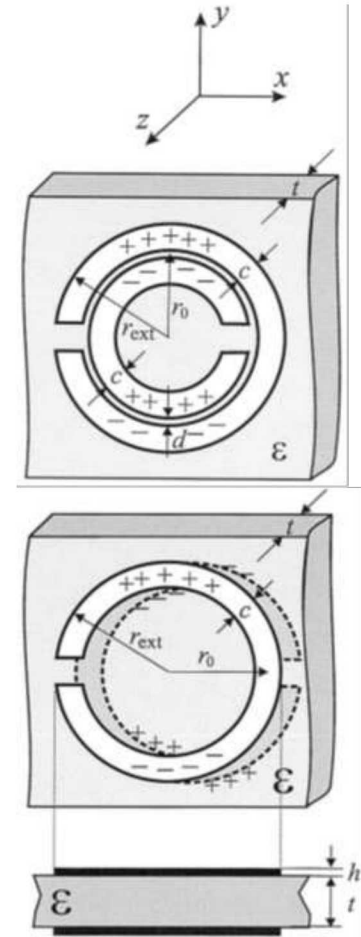
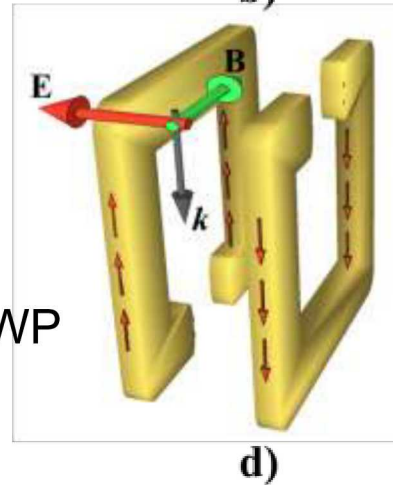
Transparent



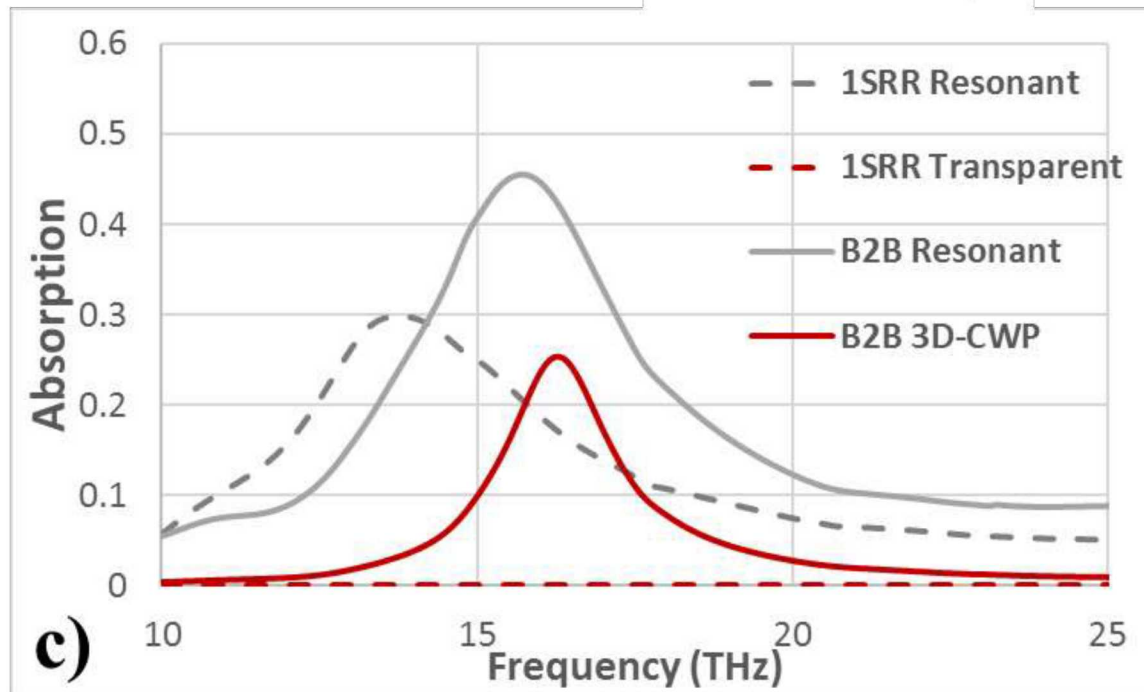
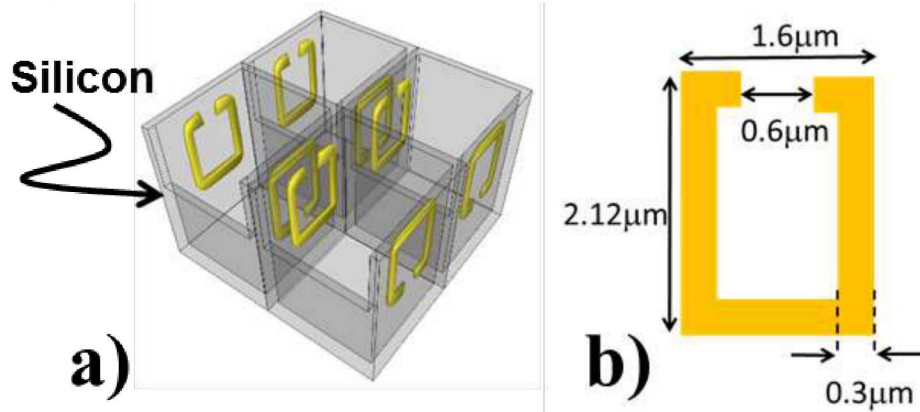
Resonant



3D CWP



Scattering Response for B2B SRRs

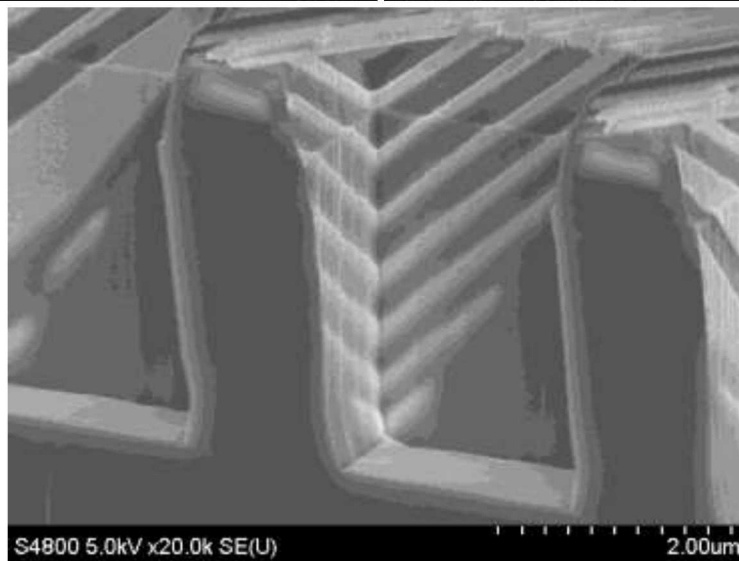
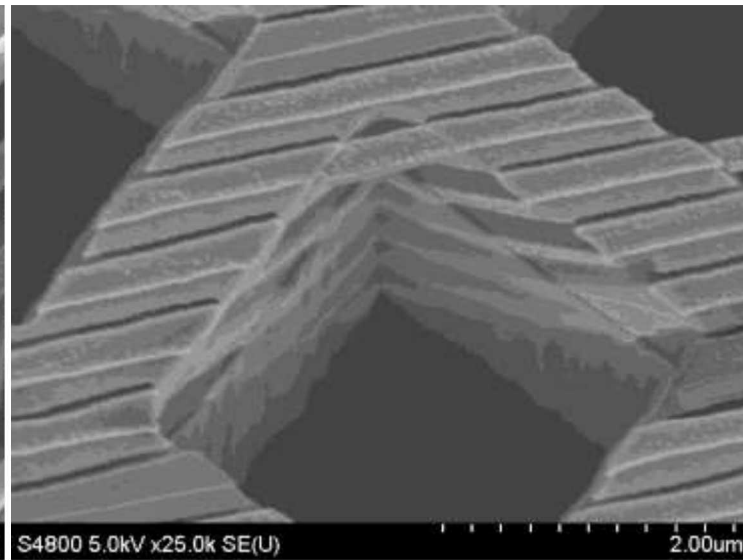
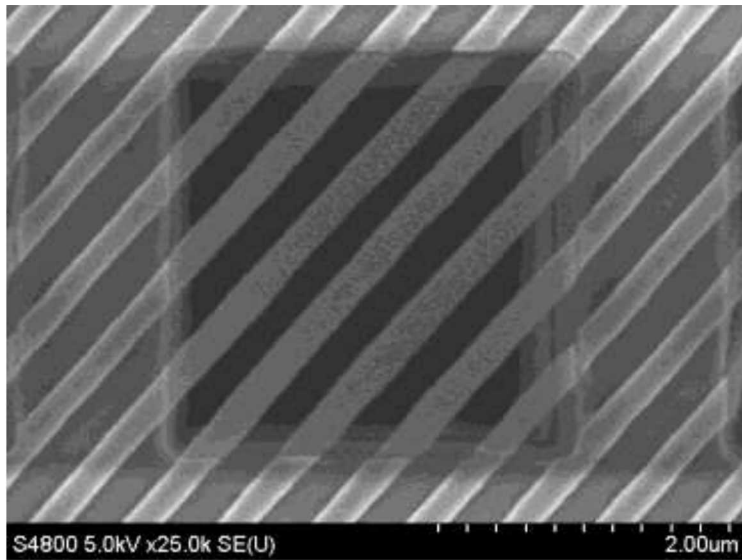


Submitted
for
publication



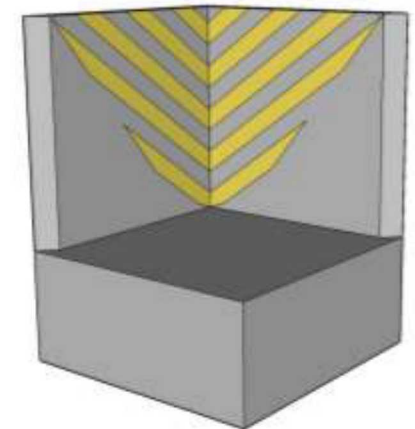
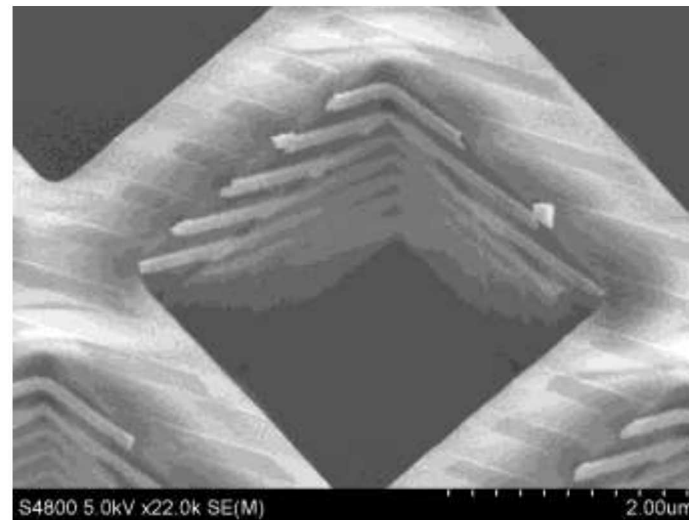
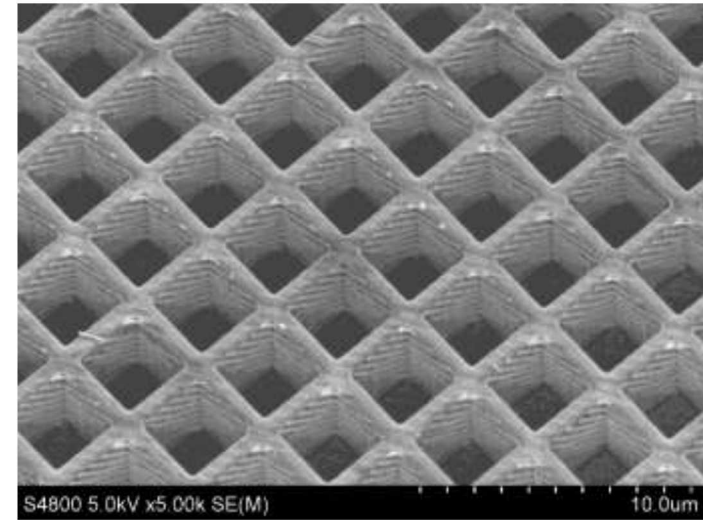
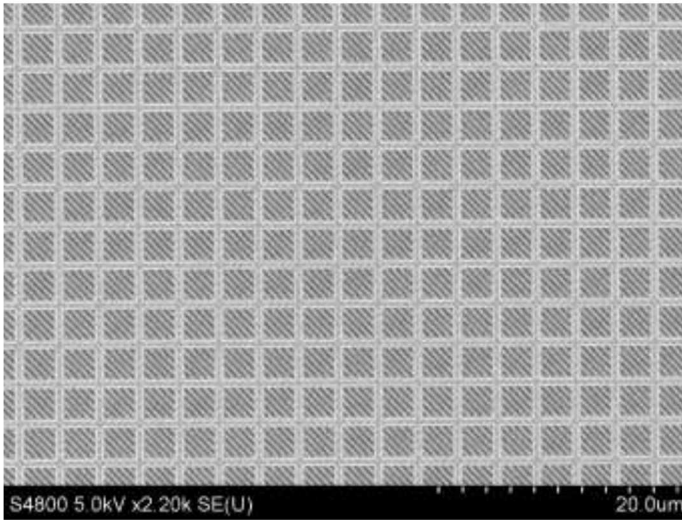
Truly 3D Meta-atoms - Chevrons

IL – 3D Chevrons





Improved Removal from Wall Tops – Ge zipper layer





Summary



1. Membrane projection lithography is a versatile fabrication approach capable of fabricating a wide range of 3D metamaterial structures in CMOS compatible material systems.
2. Vertically oriented inclusions demonstrate coupling behaviors which cannot be duplicated by planar structures.
3. Even though CWP and SRRs have been studied for more than 10 Years, there are still subtleties to their scattering behavior which will impact how they perform in next-generation 3D metamaterial components.



Collaborators



SNL (theory and modeling) – Salvatore Campione, Aaron Pung, Mike Sinclair, Igal Brener, Paul Davids

SNL (fabrication) – Paul Resnick, Kate Musick, Patrick Finnegan

Penn St. – Danny Zhu, Sawyer Campbell, Doug Werner

AFIT – Capt. Bryan Adomanis, Mike Marciniak



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2. Na Liu, et. al., "Stereometamaterials," *Nature Photonics*, **3**, 157-162, (2009).
3. Pin Chieh Wu, et. al., "Plasmon coupling in vertical SRR metamolecules," *Scientific Reports*, **5**, 9726 (2015).
4. Pin Chieh Wu, et. al., "Magnetic plasmon induced transparency in 3D metamolecules," *Nanophotonics*, **1**, 131-138 (2012).
5. Yi-Hao Chen, et. al., "Interplay of mutual electric and magnetic couplings between 3D SRRs," *Optics Express*, **25**, 2909 (2017).
6. Kebin Fan, et. al., "Stand-up magnetic metamaterials at THz frequencies," *Optics Express*, **19**, 12619 (2011).
7. D. Bruce Burckel, Paul J. Resnick, Patrick S. Finnegan, , Michael B. Sinclair and Paul S. Davids "Micrometer-scale fabrication of complex three dimensional lattice+basis structures in silicon," *Optical Materials Express*, , **5**, 2231-2239, (2015).
8. D. Bruce Burckel, Salvatore Campione, Paul S. Davids, and Michael B. Sinclair, "Three dimensional metafilms with dual channel unit cells," *Applied Physics Letters*, **110**, 143107, (2017).
9. D. Bruce Burckel and Salvatore Campione, "Vertically oriented metamaterial broadband linear polarizer," *Electronics Letters*, (submitted 2017).
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11. Cai, et. al., "Metamagnetics with rainbow colors," *Optics Express*, **15**, 3333-3341 (2007).
12. Shvets, et. al., "Negative index meta-materials based on two-dimensional metallic structures," *J. of Opt. A: Pure Appl. Opt*, **8**, S122-S130 (2006).
13. G. Dolling, et. al., "Cut-wire pairs and plate pairs as magnetic atoms for optical metamaterials," *Optics Letters*, **30**, 3198-3200 (2005).
14. Ricardo Marques, et. al., "Comparitive analysis of Edge- and Broadside- coupled SRRs for metamaterial design – theory and experiment," *IEEE Trans. On Ant. And Prop*, **51**, 2572-2581 (2003).