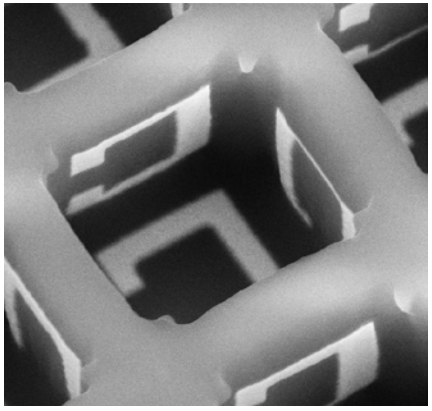
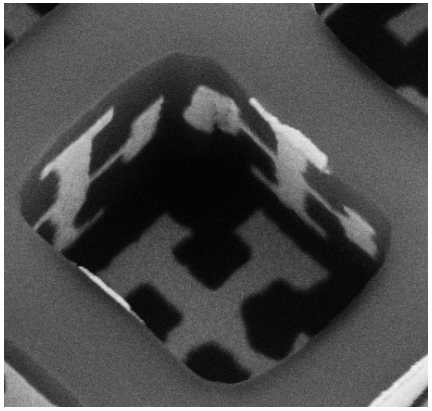
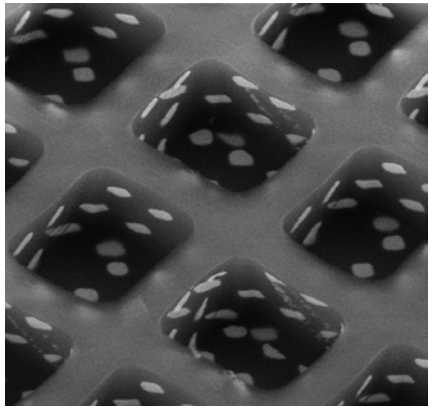
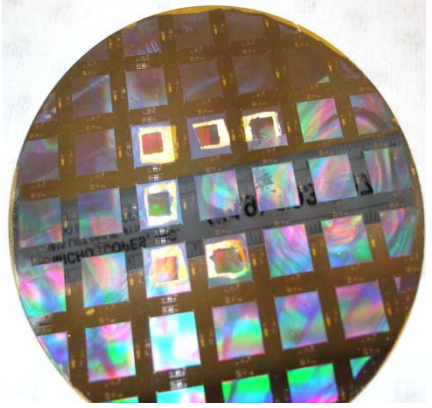
SAND2011-3798C

Resonant and Nonresonant 3D Metallic Metamaterials: Membrane Projection Lithography

Bruce Burckel

Joel Wendt, James Ginn, Robert Ellis, Sally Samora, John Anderson, Larry Warne, Lori Basilio, Igal Brener, Mike Sinclair

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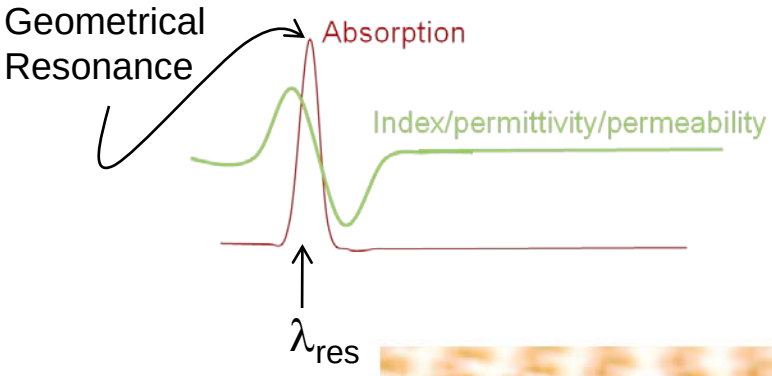
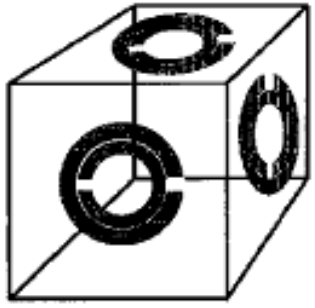
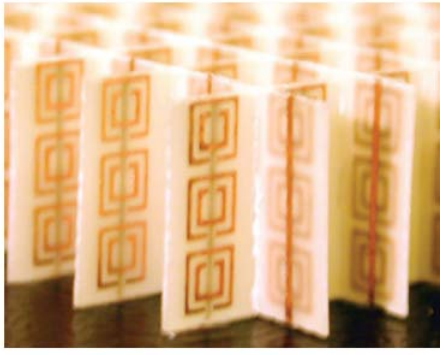
3D Metallic Metamaterial Strategies

Resonant Structures



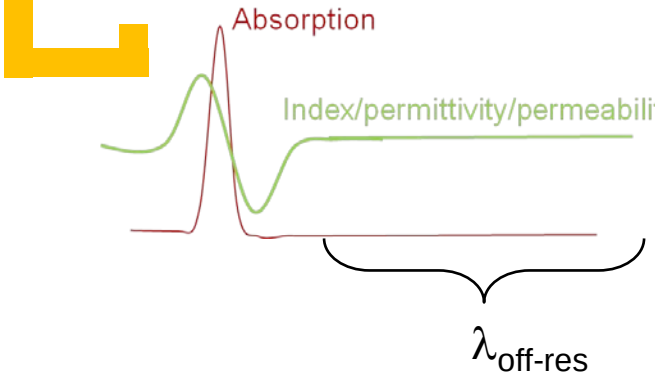


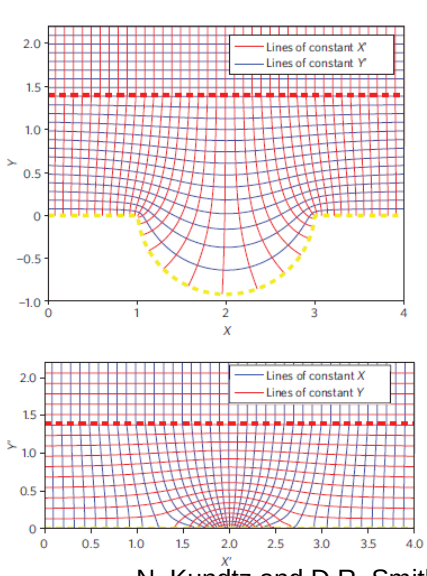
Pendry, IEEE Trans on Microwave Theory and Techniques **47**, #11, 2075 (1999)

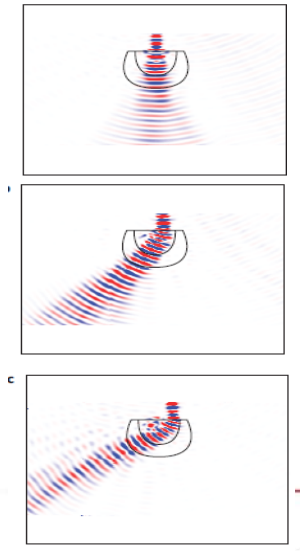


Schultz, Science **292**, 77, (2001)

Non-Resonant Structures



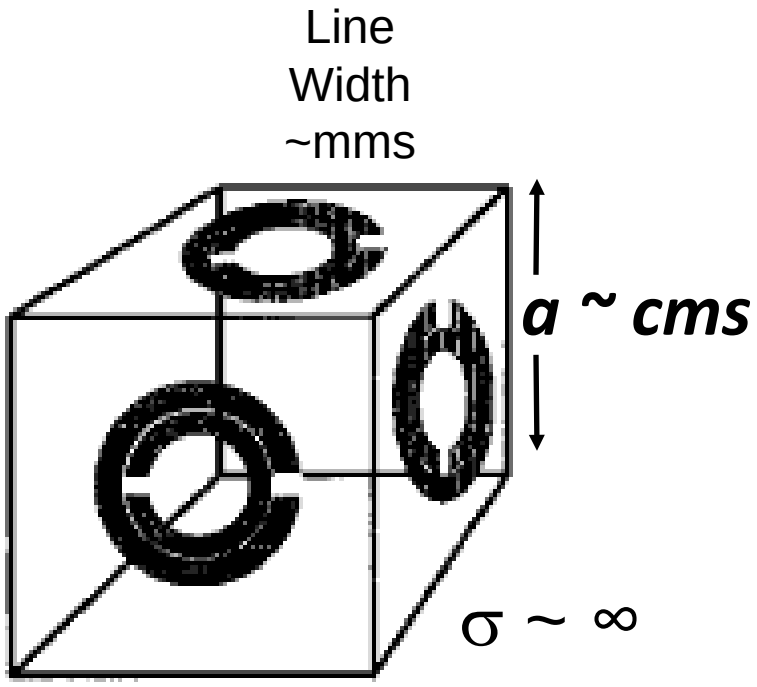




N. Kundtz and D.R. Smith, Nat. Mater. 129-132 (2010).

Translating 3D metamaterials from RF to IR : MM Grand Challenge Goal

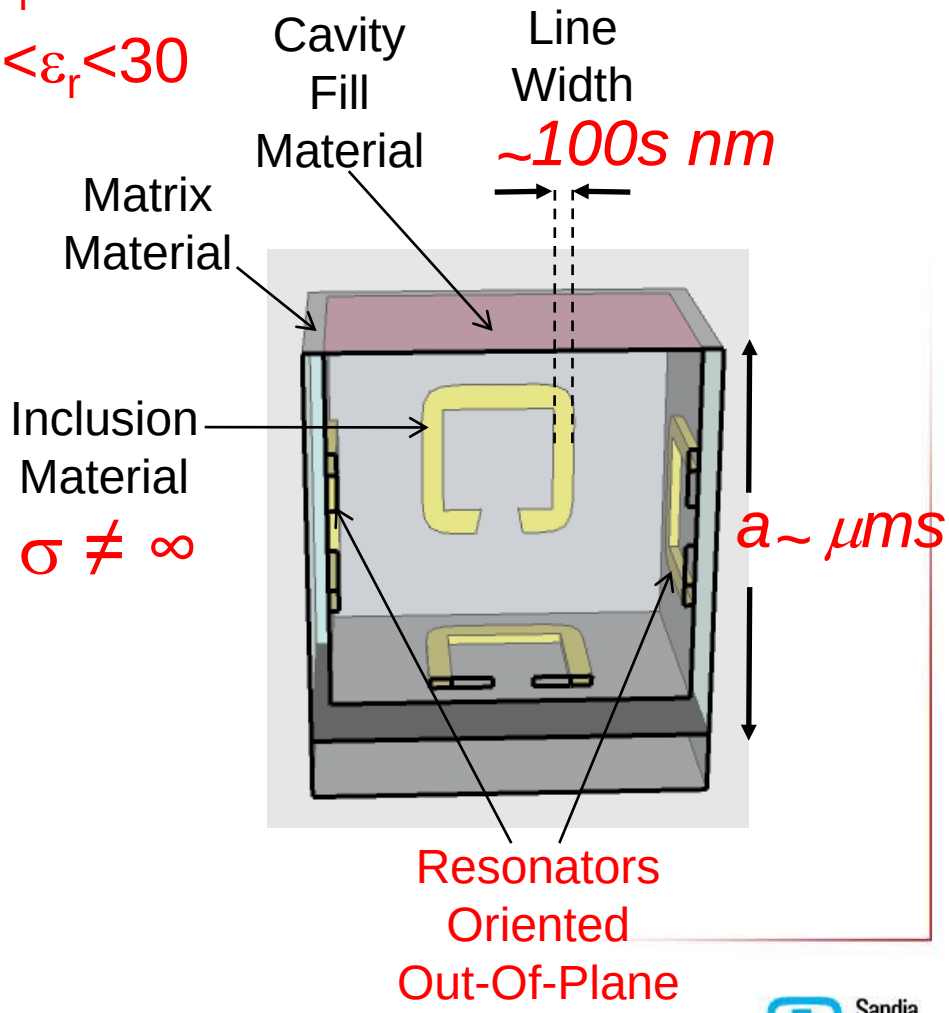
RF/Microwave



Infrared

$\mu_r \sim 1$

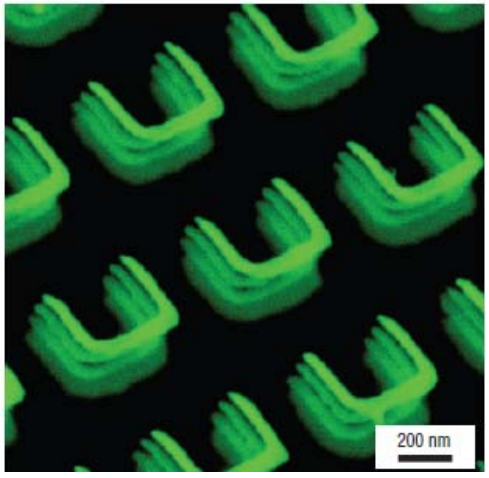
$1 < \varepsilon_r < 30$



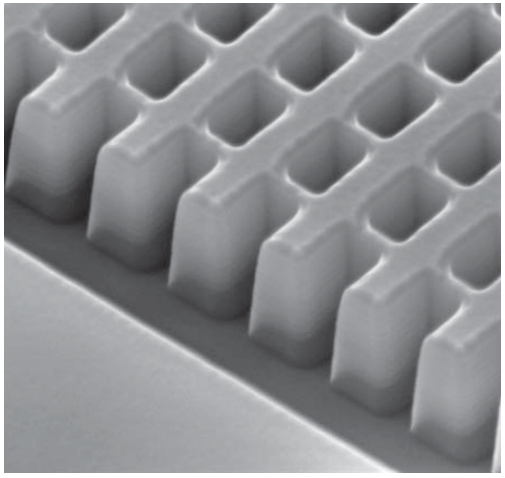
Current State of the Art in IR 3D MM fabrication

Metamaterials Science & Technology

Stacked Planar

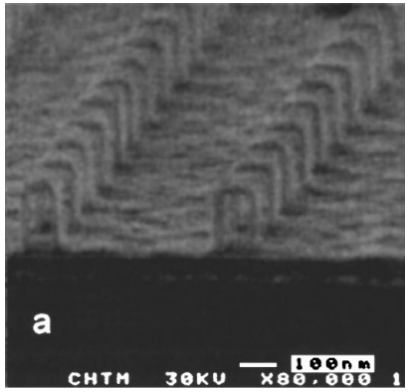


Giessen- Nature Mat **7**, 31, (2008)

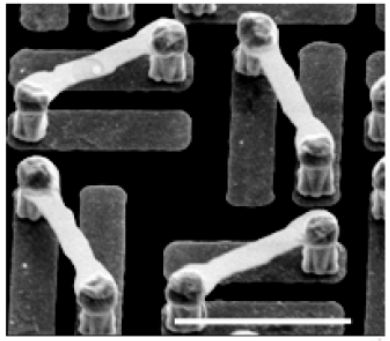


Zhang, Nature **455**, 376 (2008)

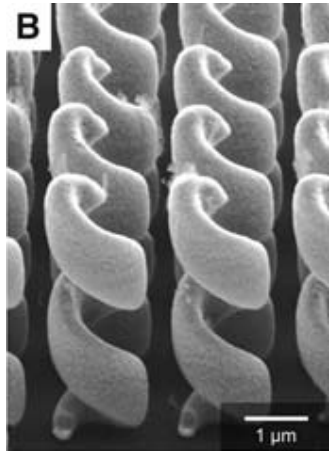
Out-of-Plane Current



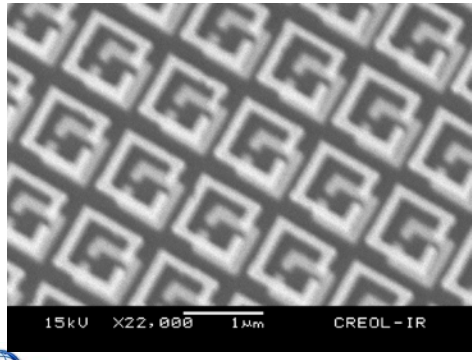
Brueck - JOSA B **23**, #3, 434, (2004)



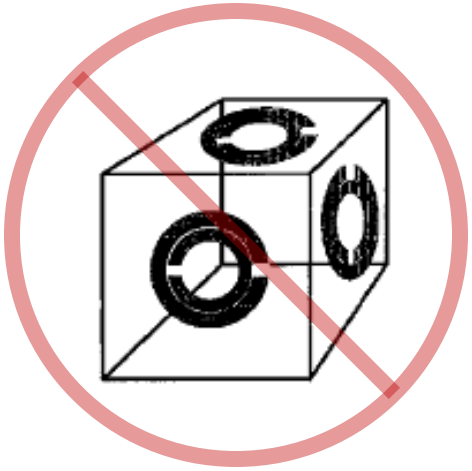
Zhang, PRL **102**, 023901, (2009)



Wegener, Science **325**, 1513-1515, (2009)



SANDIA+CREOL



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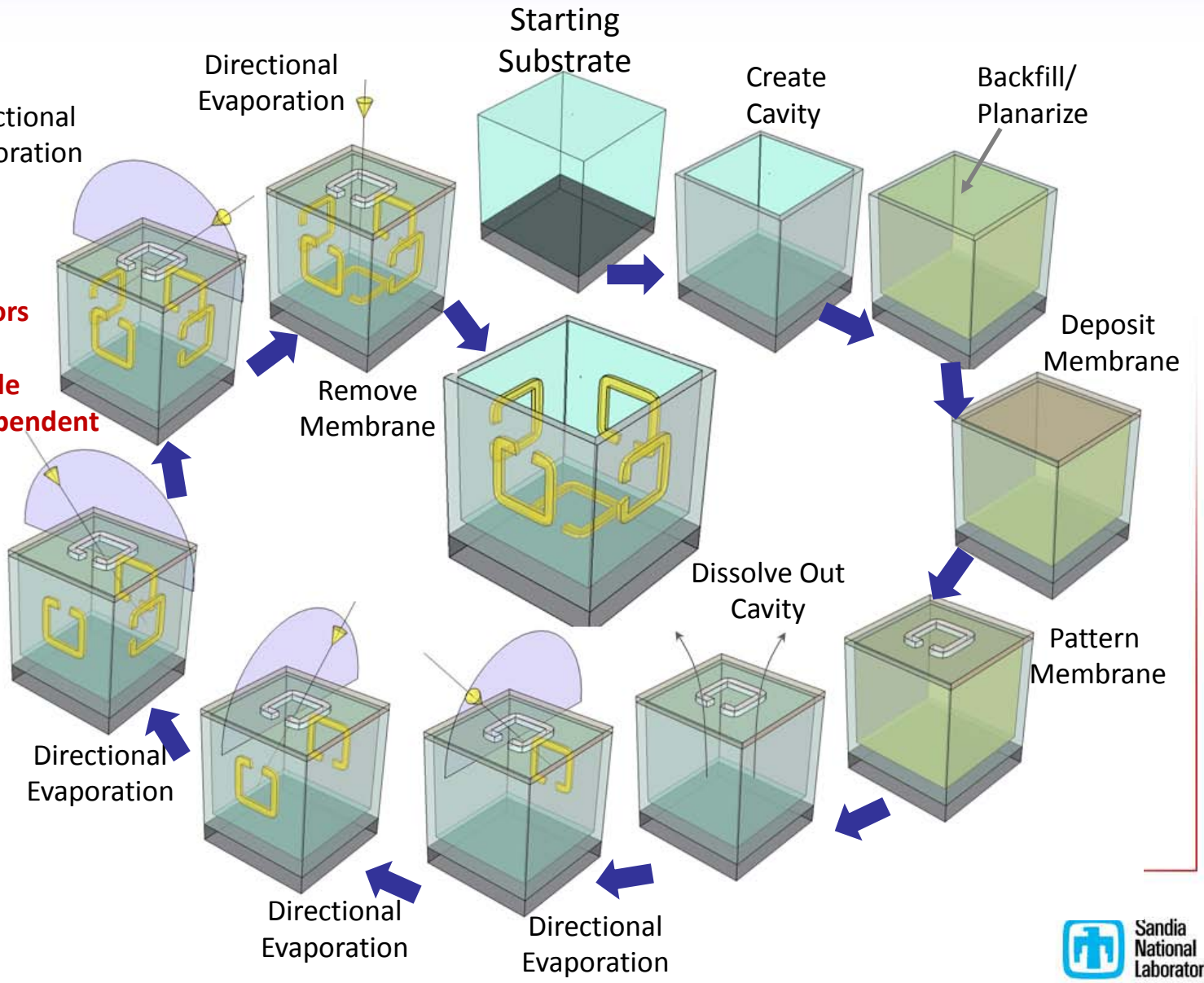
Membrane Projection Lithography: MPL

- **Out-of-plane resonators**
- **Planar lithography**
- **Many patterns possible**
- **Cavity geometry independent of resonator pattern**
- **Scalable**
- **Layer-by-layer → 3-D**



Sources of MPL Pattern Distortion

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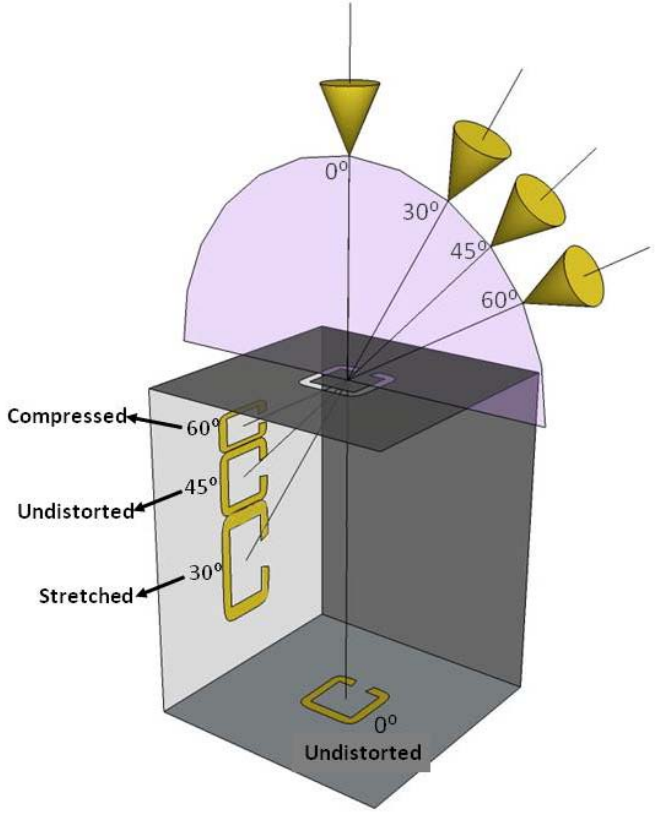
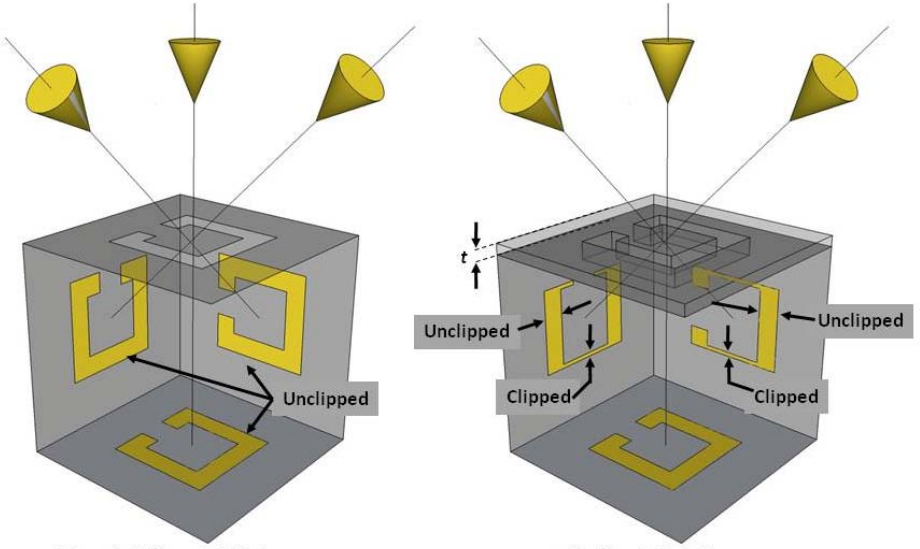
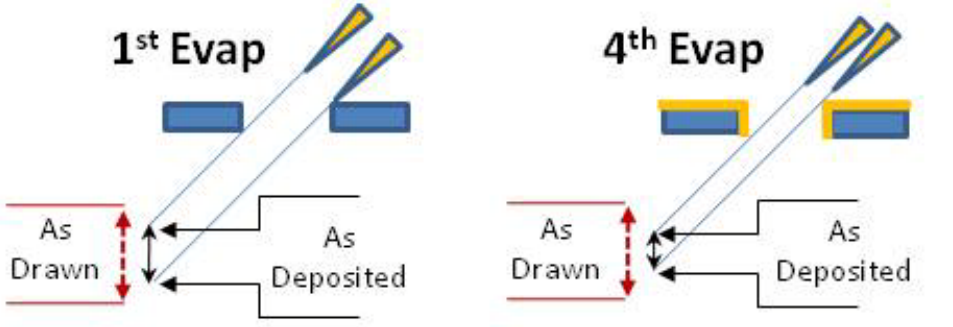
Projection at 45^0
Preserves Pattern
Shape in Cubic Geometries



Real Membranes result in Linewidth Clipping



Multiple Evaporations result in Linewidth Thinning



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MPL Fabrication Degrees of Freedom

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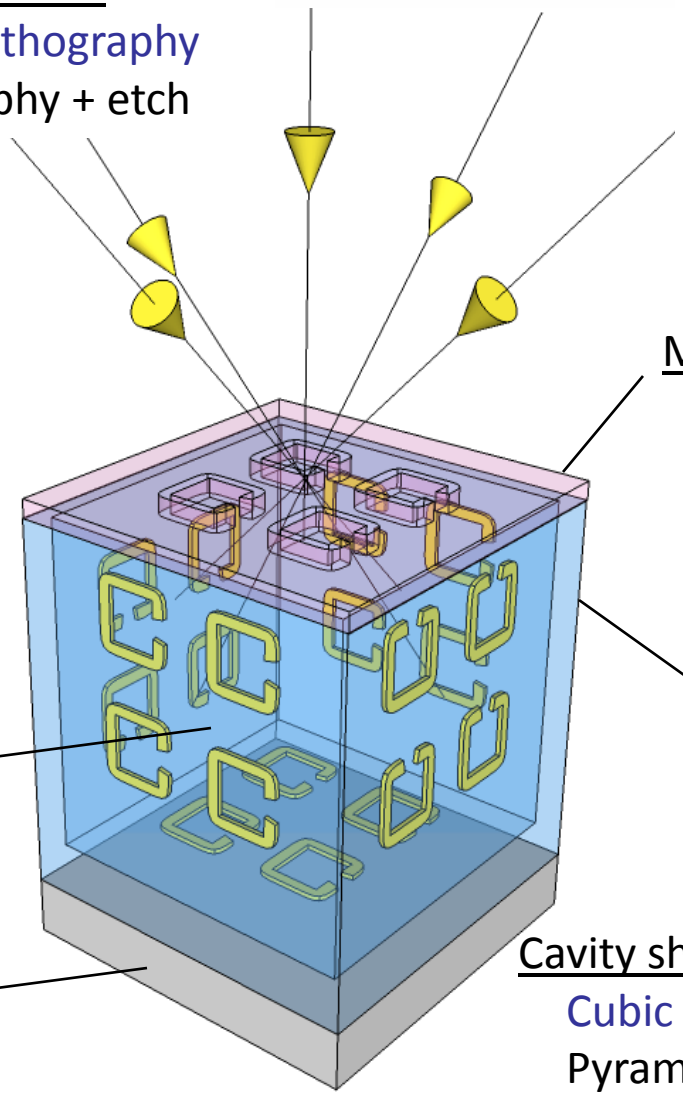
Cavity formation
- Optical lithography
- Lithography + etch

Pattern
- SRRs
- Any non-closed loop, structurally stable design

Evaporations
- One to Five (Normal + 4 Angled)

Membrane Lithography
- E-beam (JBX-9300FS)
- Optical
- Interferometric Lithography



Membrane
- PMMA
- Photoresist
- Patterned hardmask

Backfill
- Polyimide
- Oxide

Lattice material
- SU-8
- Polyethylene
- Tellurium

Substrate
- Silicon
- GaAs
- BaF

Cavity shape
- Cubic
- Pyramidal
- Hemispherical

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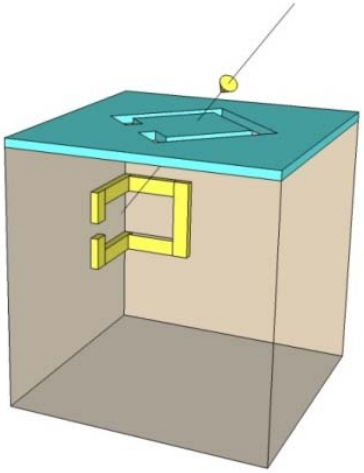
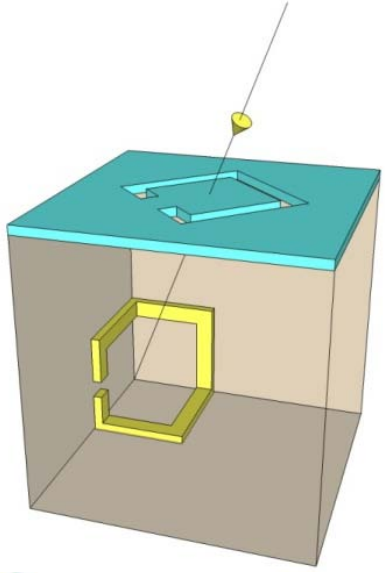
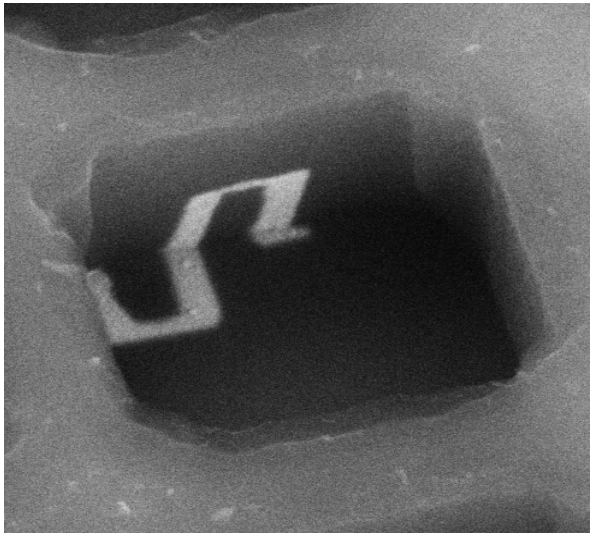
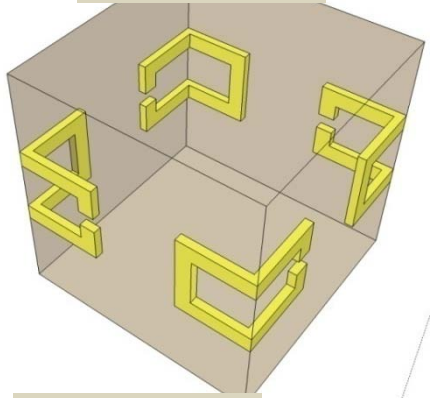
MPL Enables a Rich Variety of 3-D Metamaterial Resonator Topologies



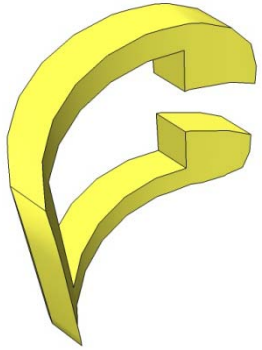




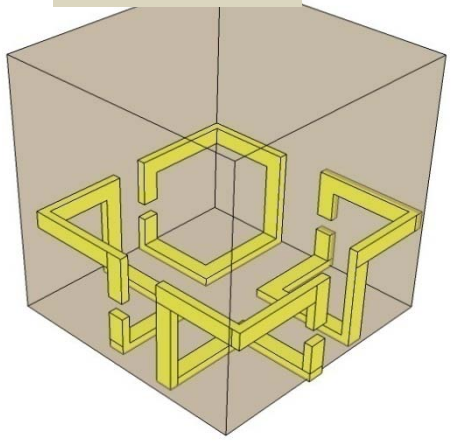
3-D Array of 2-D SRRs



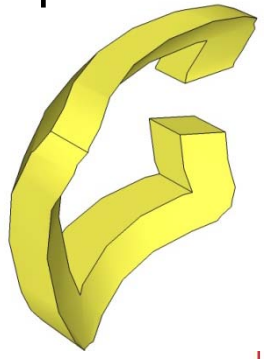
Cylindrical



3-D Array of 3-D SRRs



Spherical



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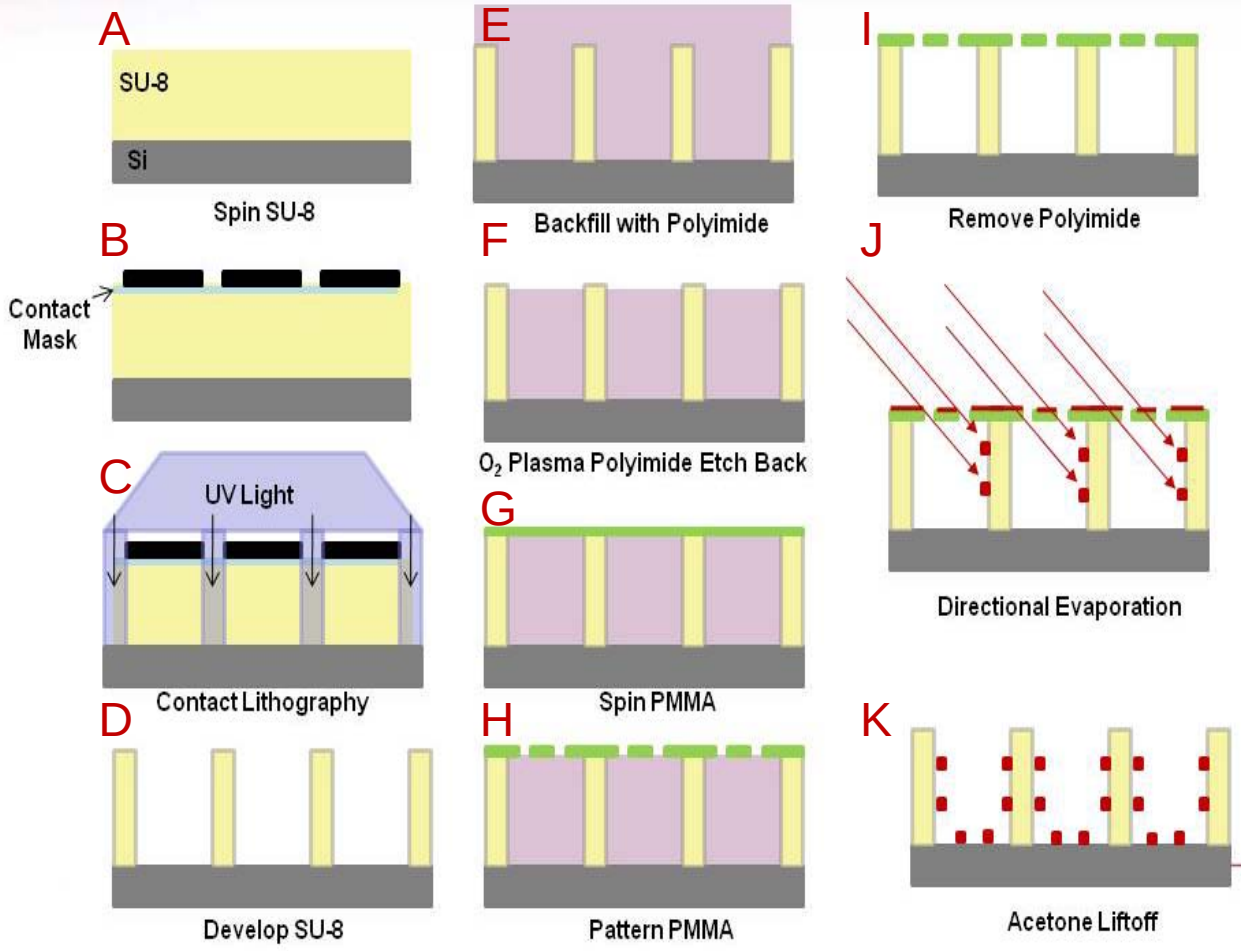
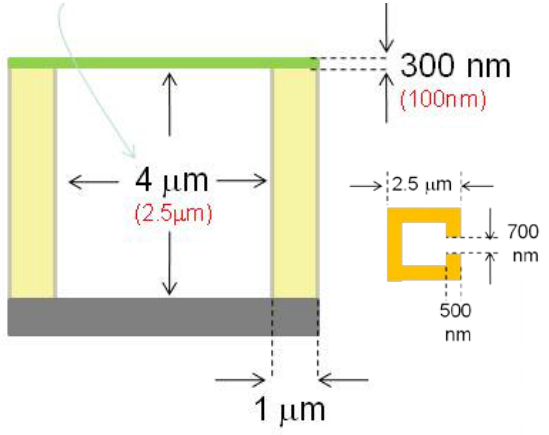
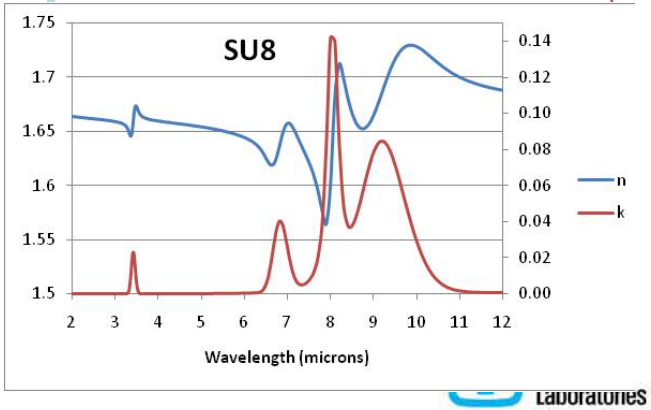
Specific MPL Process Flow



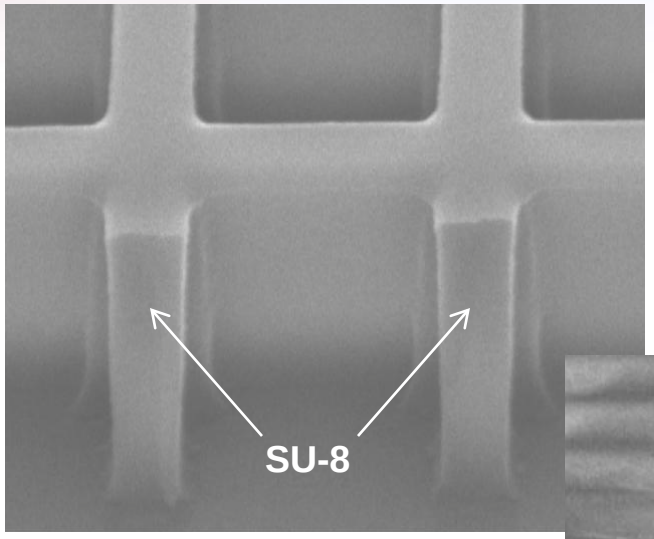
Current MPL Process Node

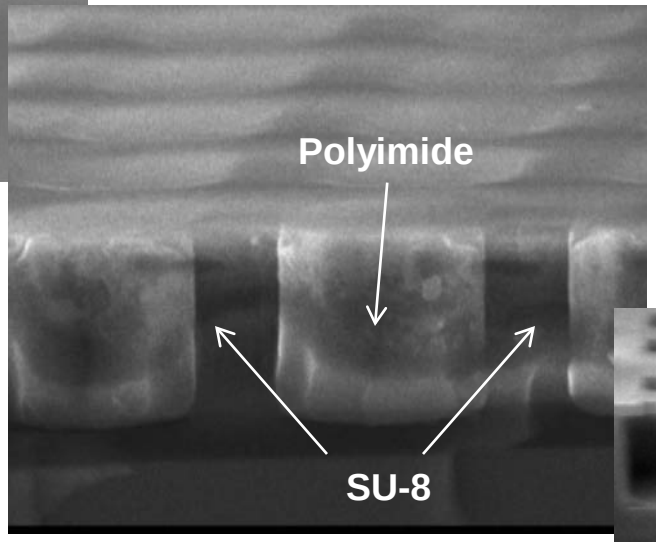
4x4 μm cubic cavity
1 μm SU-8 walls
300 nm PMMA membrane
Polyimide backfill

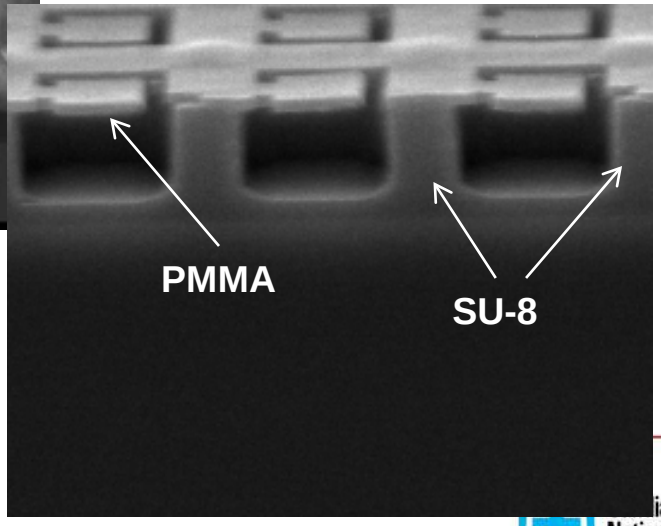




Specific MPL Process Flow

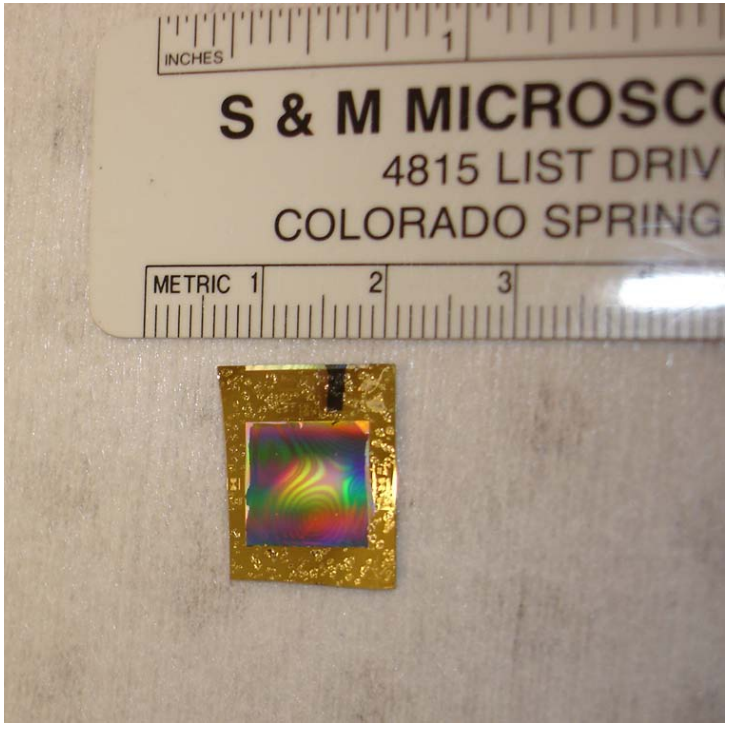




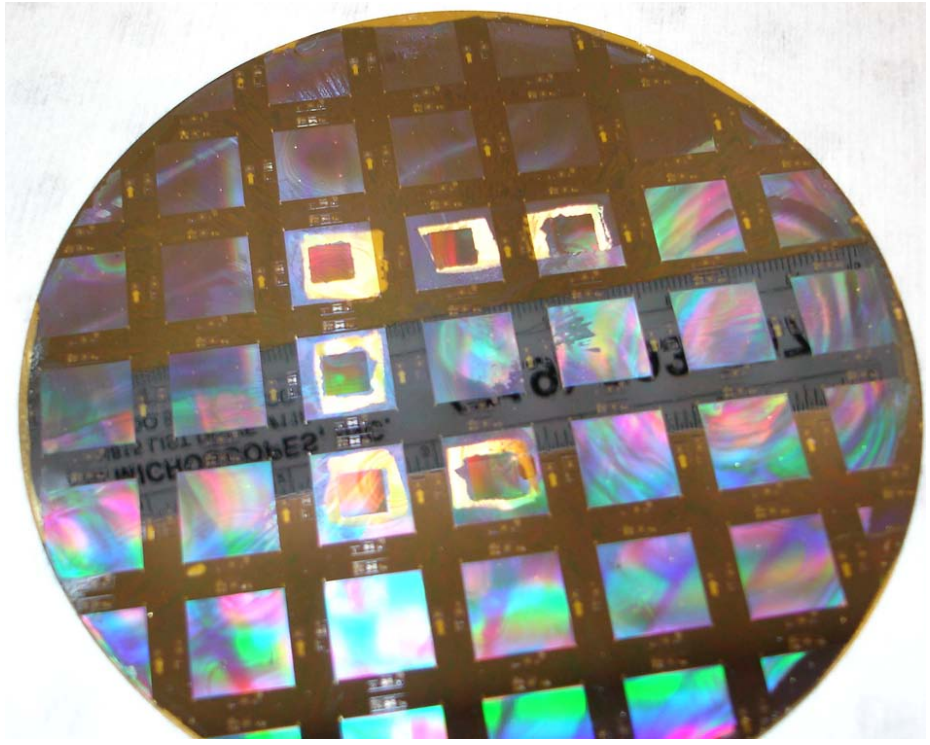


MPL : Large Area Fabrication Method

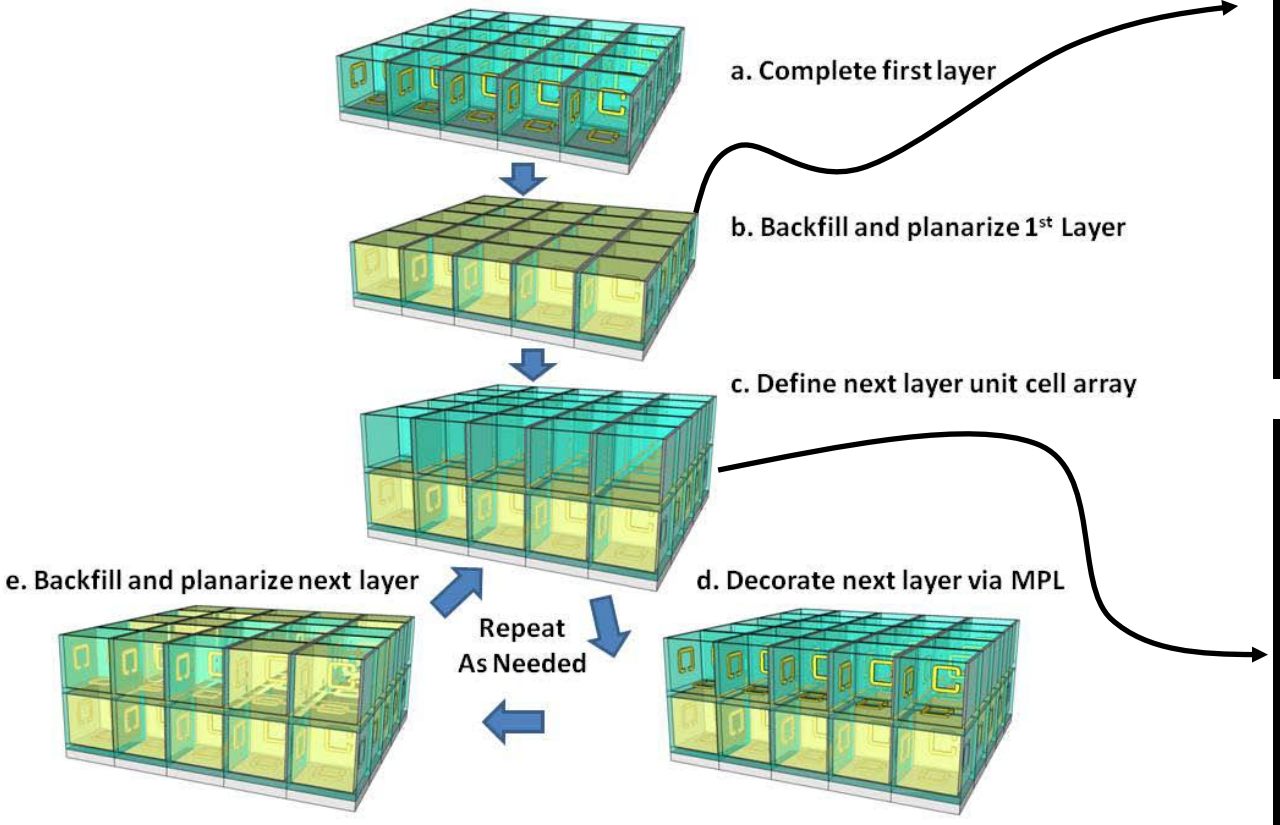
1 cm^2 die

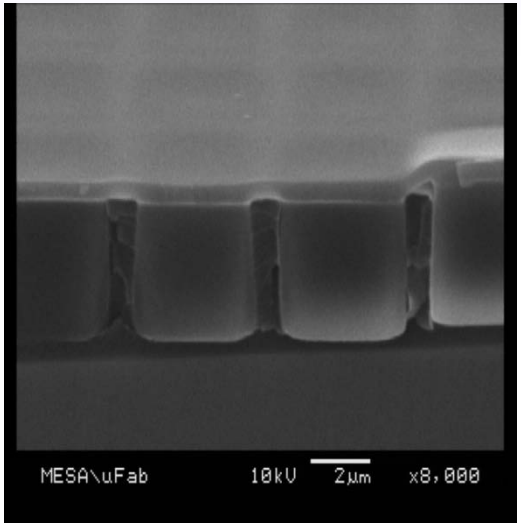


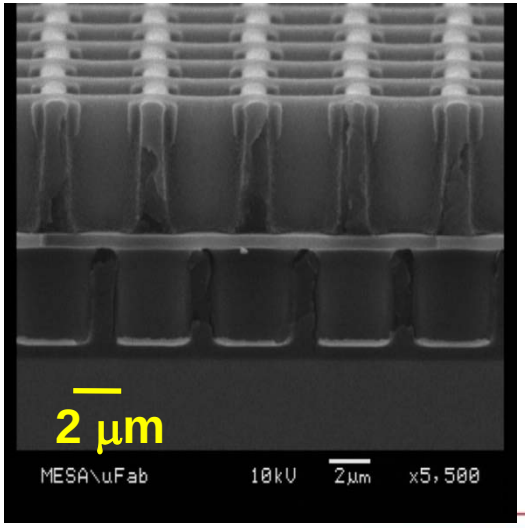
4” wafer



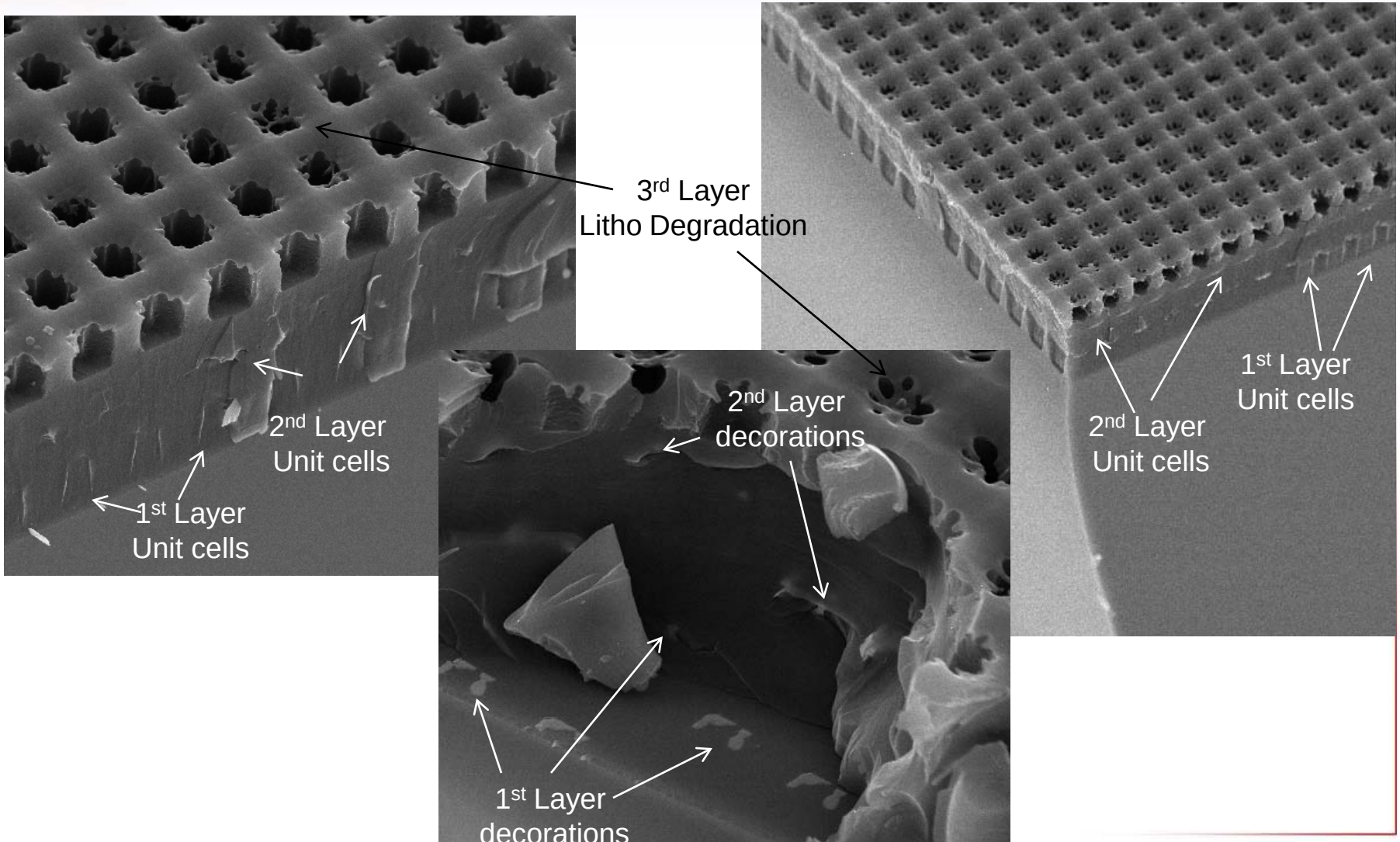
Extending MPL to MultiLayers



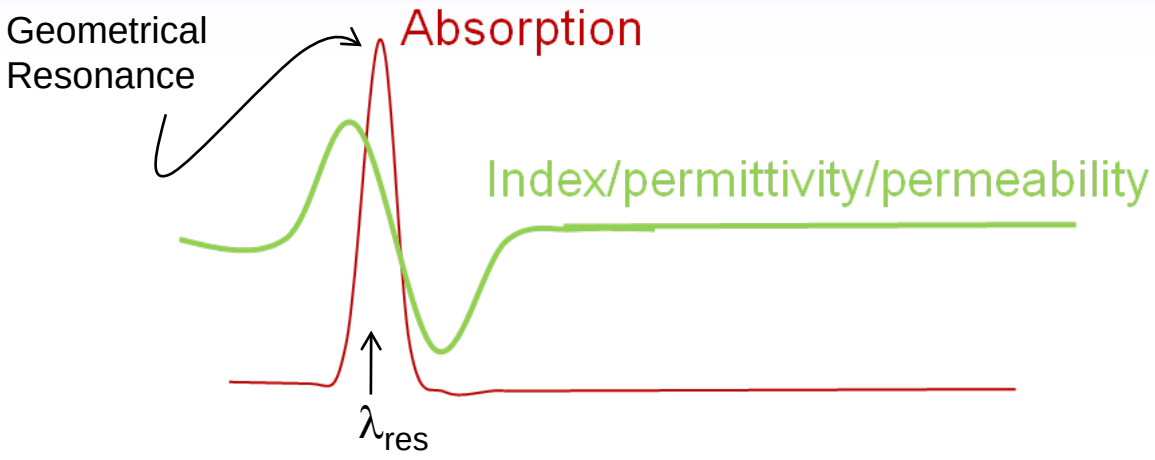




MultiLayer Decorated MPL



MPL For Fabrication of Resonant Metamaterial Strategies



To access:	We need:	Inclusion Type:
Negative Permittivitty	Electrically Excited Resonators	Dipole-like metallic inclusions
Negative Permeability	Magnetically Excited Resonators	Real or virtual-loop metallic inclusions
Negative Index	Both	Both

- Applications must be loss-tolerant.
- Inclusions should be significantly sub-wavlength to be in the effective medium limit.

Magnetically Excited Resonator: Tuning the Effective Permeability

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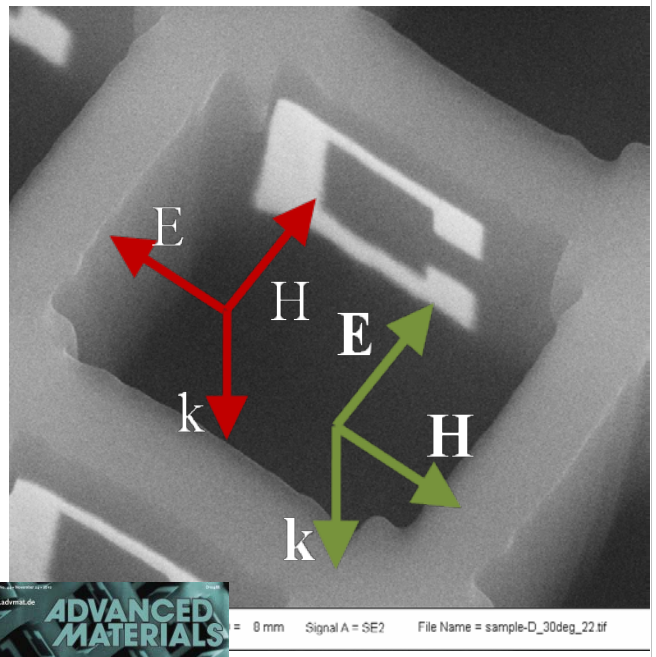
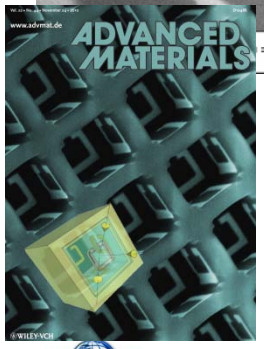
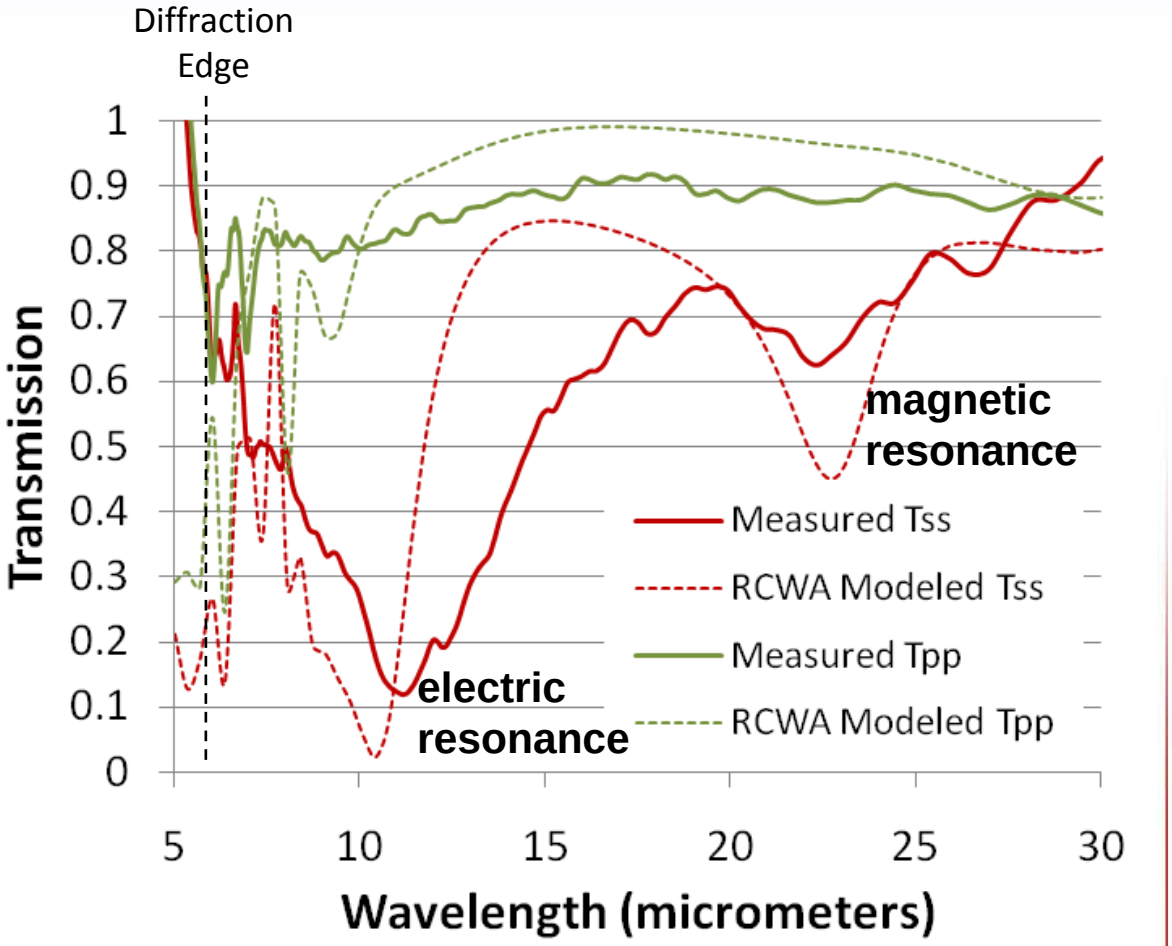
λ_{res} = 22 μm
Unit Cell= 6 μm ~ λ/4
Inclusions= 3 μm ~ λ/7







S-polarization

- B-field excites lowest SRR resonance --- magnetic excitation
- E-field excites second order resonance --- electric excitation

P-polarization

- can't couple to any SRR resonances

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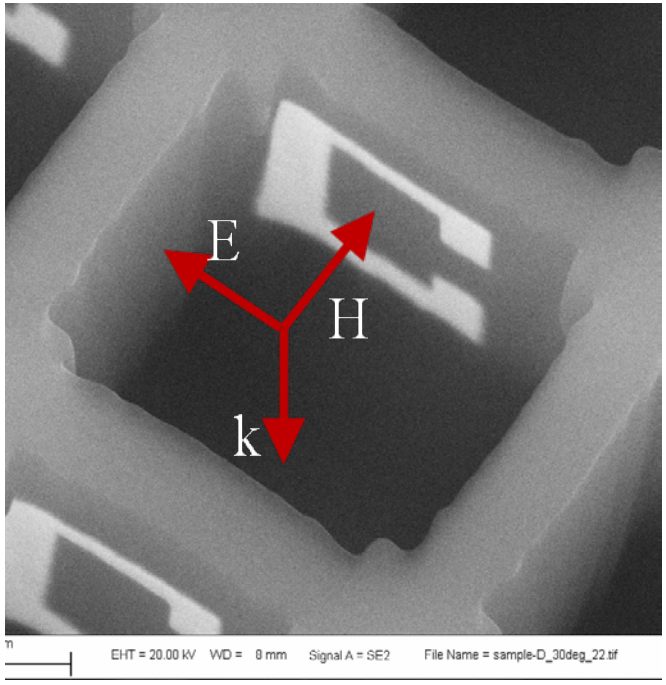
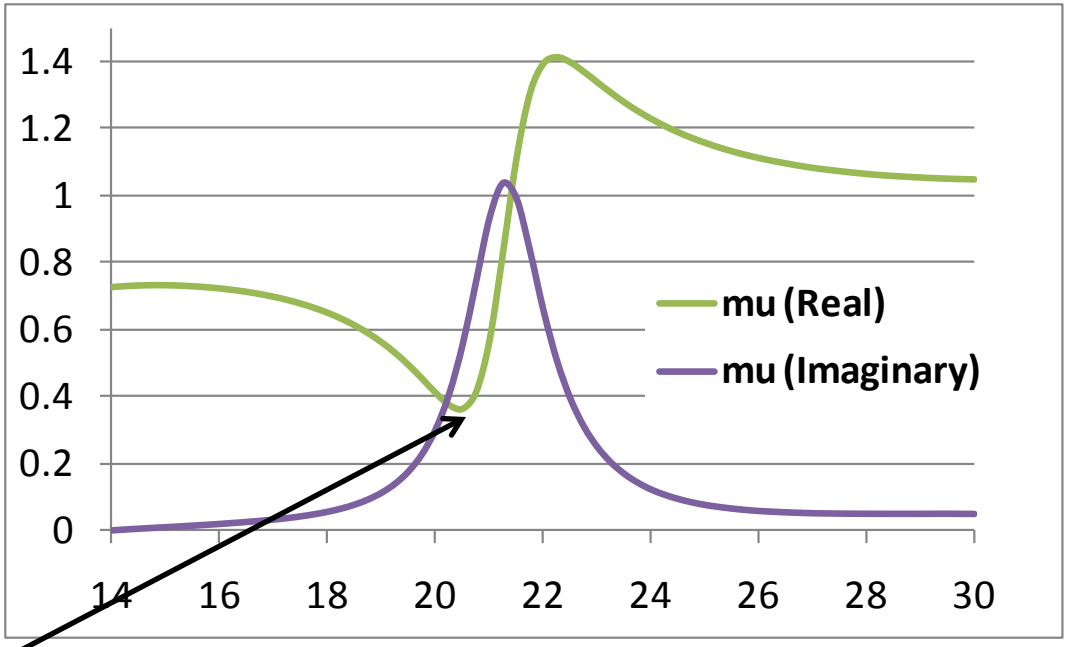
Extracted Permeability for Magnetically Excited SRR Array

Successfully tuned permeability away from 1.

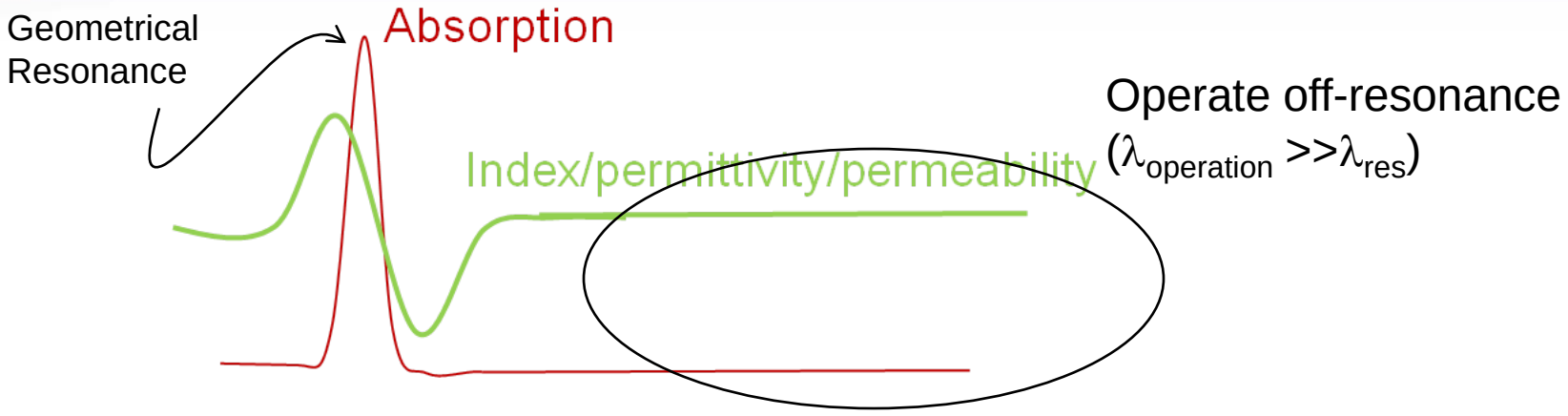




$\mu = 0.37 + i\,0.56$

Need to optimize resonator Q and packing Fraction to achieve negative permeability

MPL For Fabrication of Non-Resonant Metamaterial Strategies



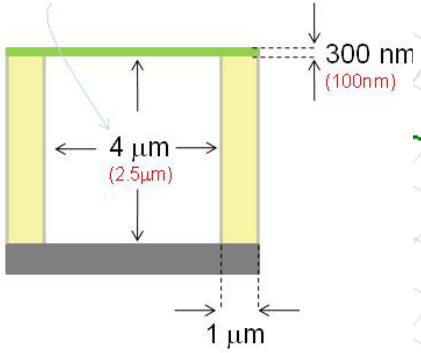
To access:	**We need:**
Permittivitty > 1	Electrically Polarizable Inclusions

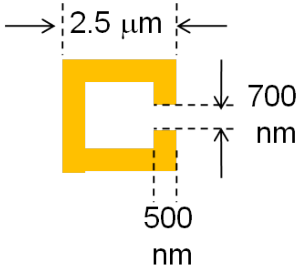
- Materials can have significantly lower loss than resonant metamaterials
- In order to operate off-resonance and avoid spatial dispersion, inclusions must be even smaller relative to the operation wavelength.
- Create artificial dielectrics for IR applications – graded, and spatially inhomogeneous designs provided via transformation optics.

Non-Resonant Metamaterials with MPL

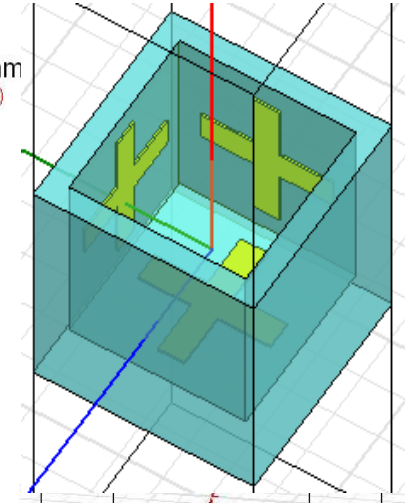
Metamaterials Science & Technology

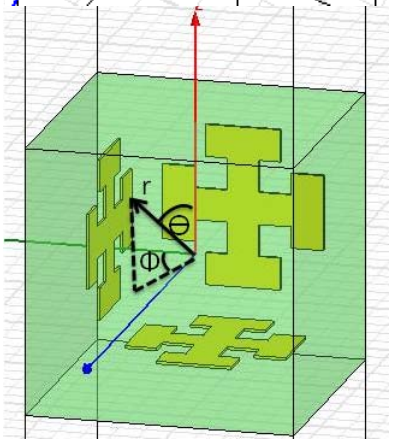
MPL Design Rules



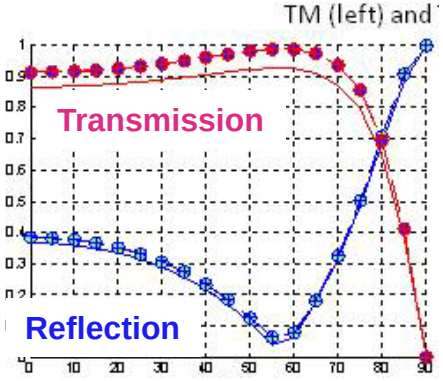


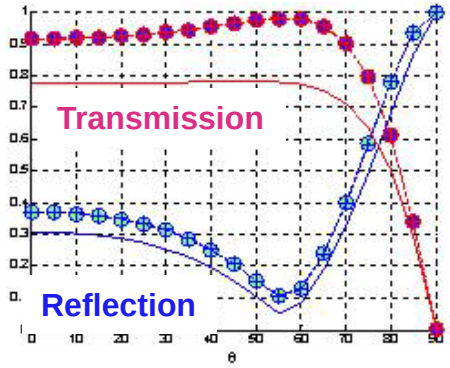
Duke Unit Cell Designs



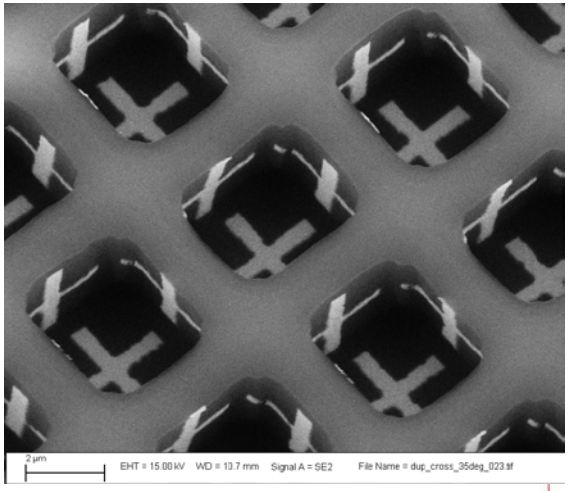


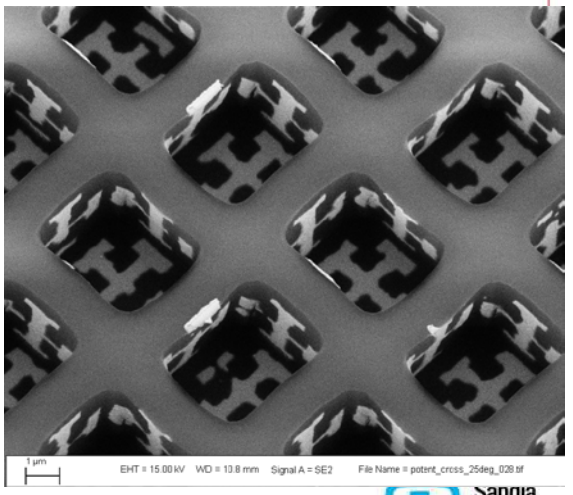
Modeled R&T





MPL Fabricated Material





Work performed in collaboration with David R. Smith (Duke)

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

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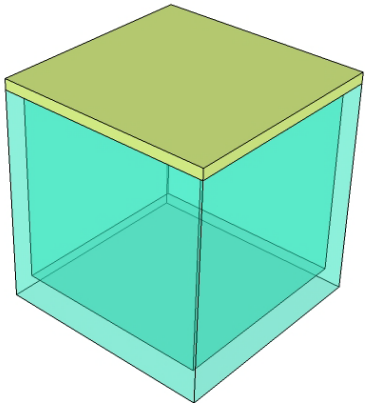
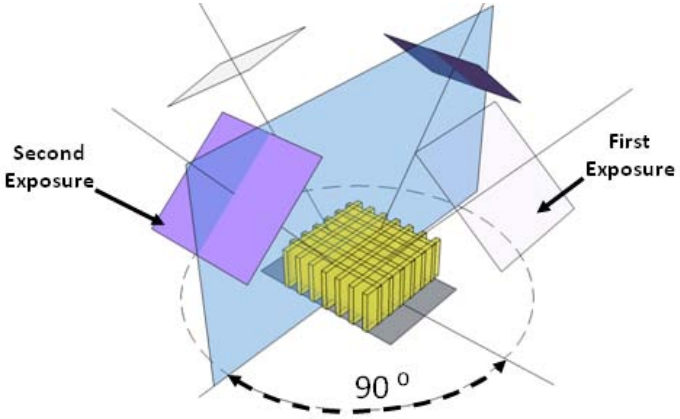
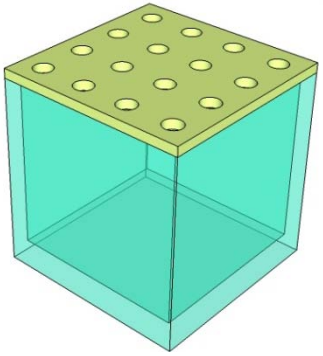
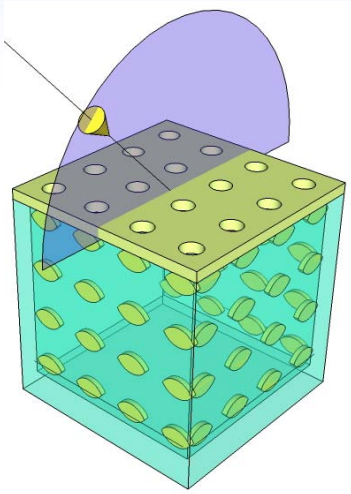
Interferometric Lithography + MPL: Route to Large Area Non-Resonant MMs





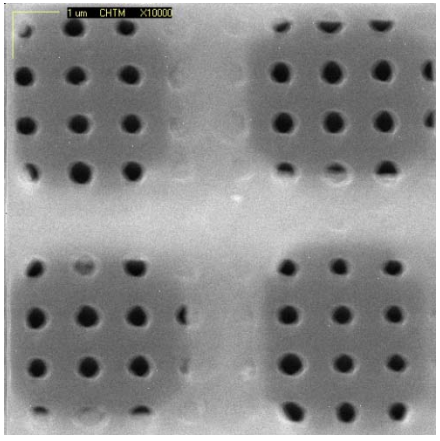


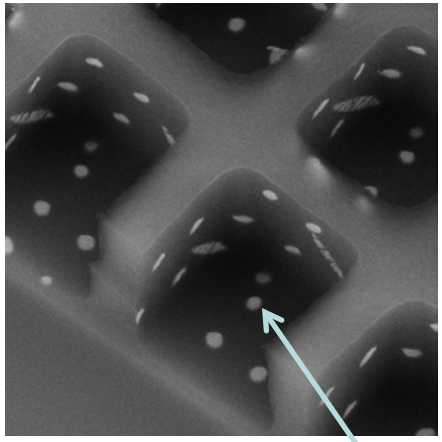


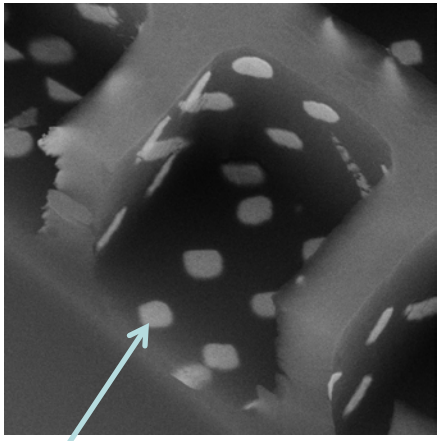
~ 200 nm inclusions

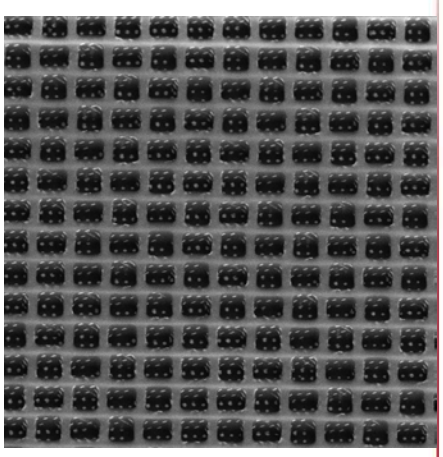
~ 400 nm inclusions

IL exposures cover entire1cm^2 die in 10 sec





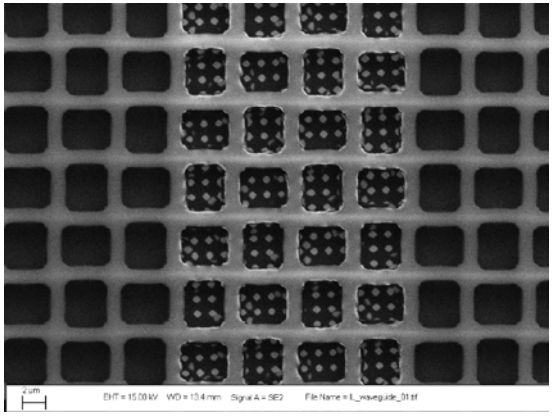


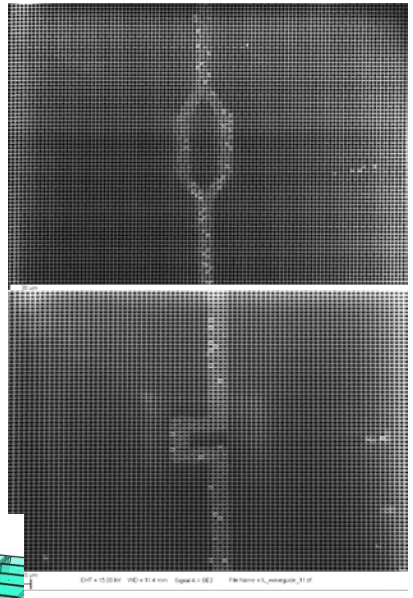


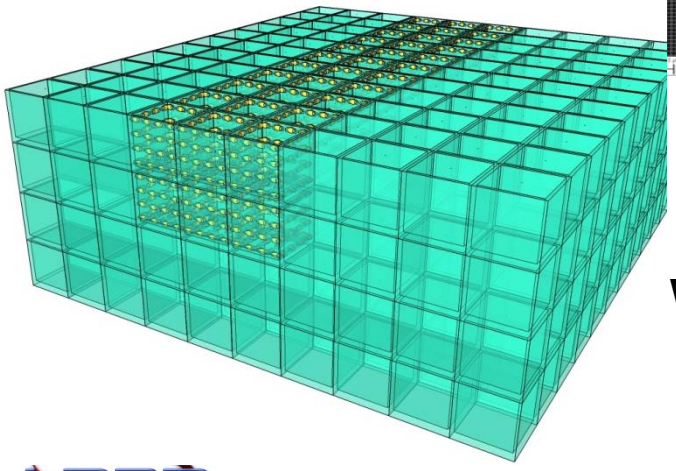
Exposure dose controls inclusion size

Applied MPL: Artificial Dielectric Waveguides, Lenses and Transformation Optics

Combining IL and contact lithography yields structures with controllable in-plane variation in inclusion size/density.

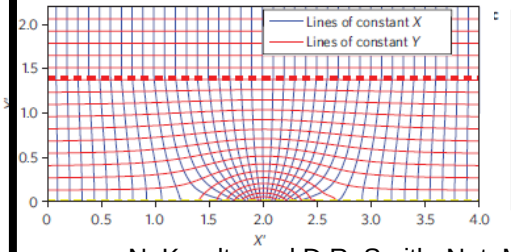


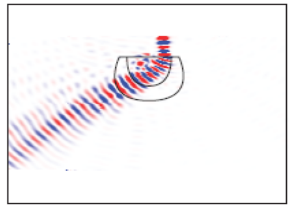




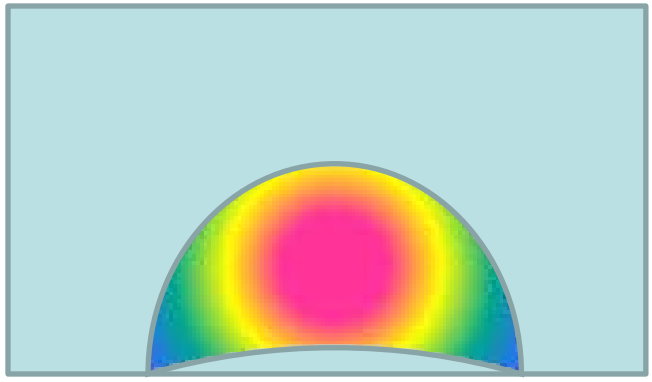
Waveguides

Can we realize thick TO designed IR optics?





N. Kundtz and D.R. Smith, Nat. Mater. 129-132 (2010).



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Conclusions and Future Work

Conclusions

- MPL is proving to be a manufacturable approach to 3D metamaterial fabrication
- We have demonstrated IR scale fabrication in both dielectric and metallic metamaterial structures

Future Work

- Fabricated Multi-layer impedance matched absorber
- Explore artificial dielectric waveguides and TO designed structures
- Investigate the possibility of directional thermal emission from MPL structures