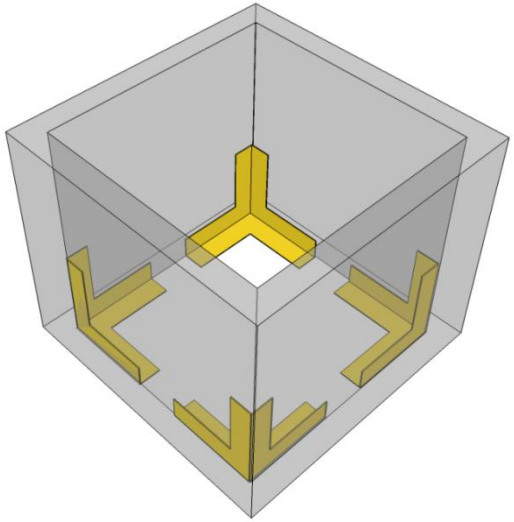
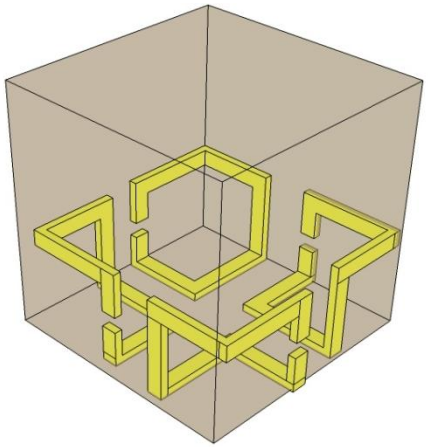
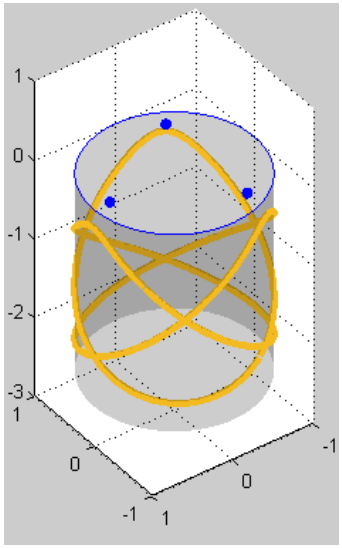
SAND2012-6862C

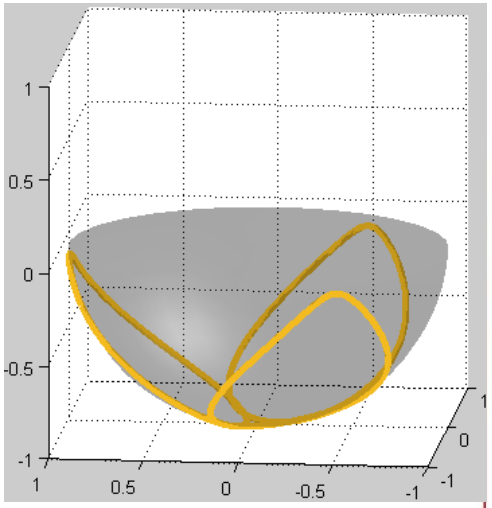
SPIE Optics and Photonics 2012
San Diego, CA August 14, 2012

3-Dimensional Plasmonic and Metamaterial Structures









Bruce Burckel (dbburck@sandia.gov)

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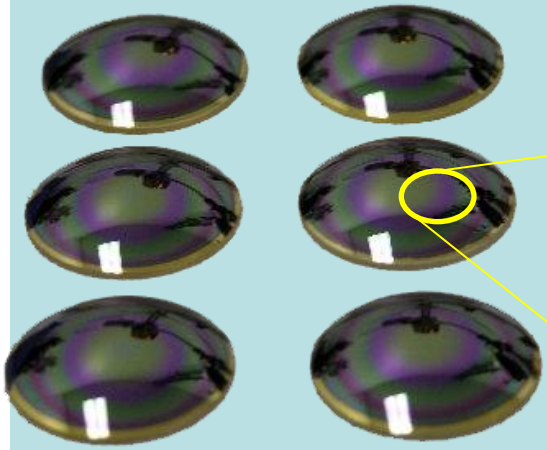
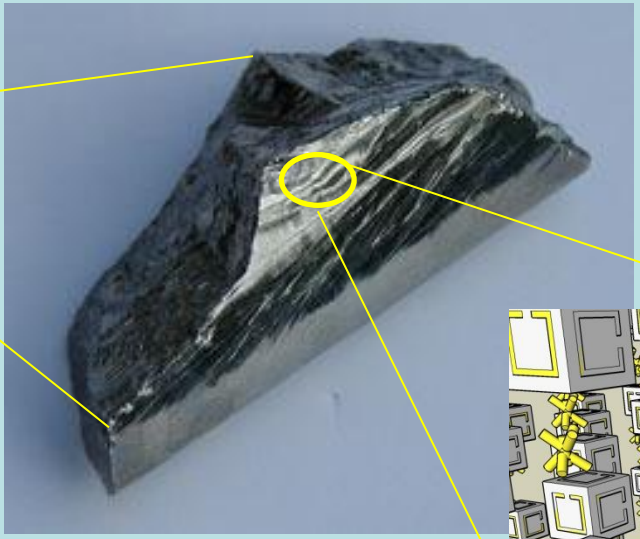
3D in the Macroscopic Sense

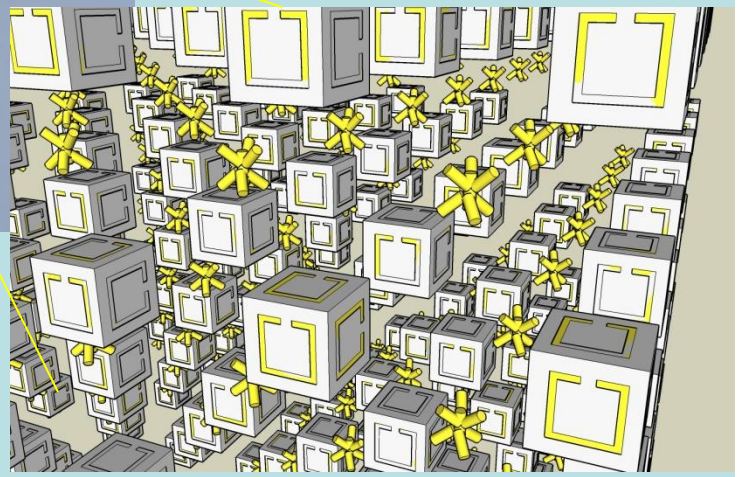
Application



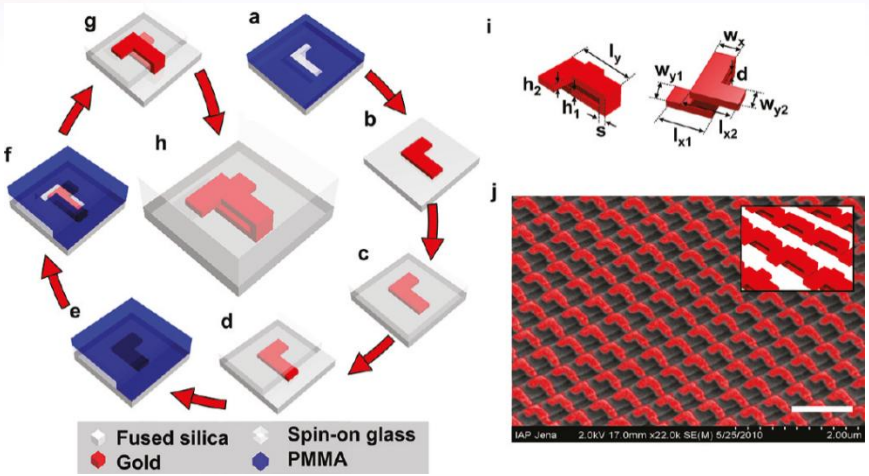
Bulk Material



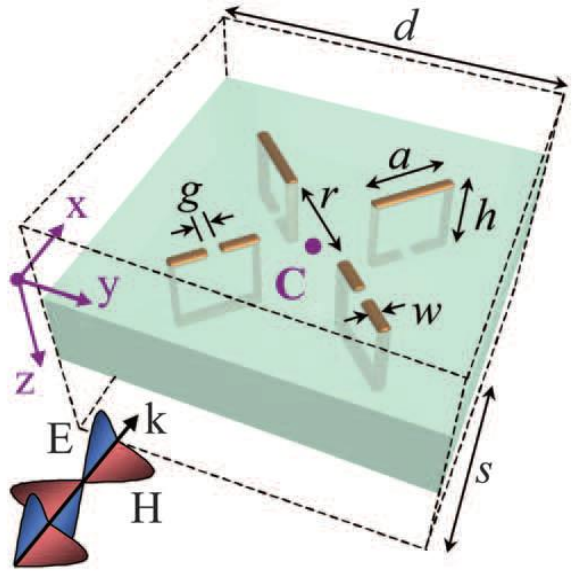
“Atomic” Structure



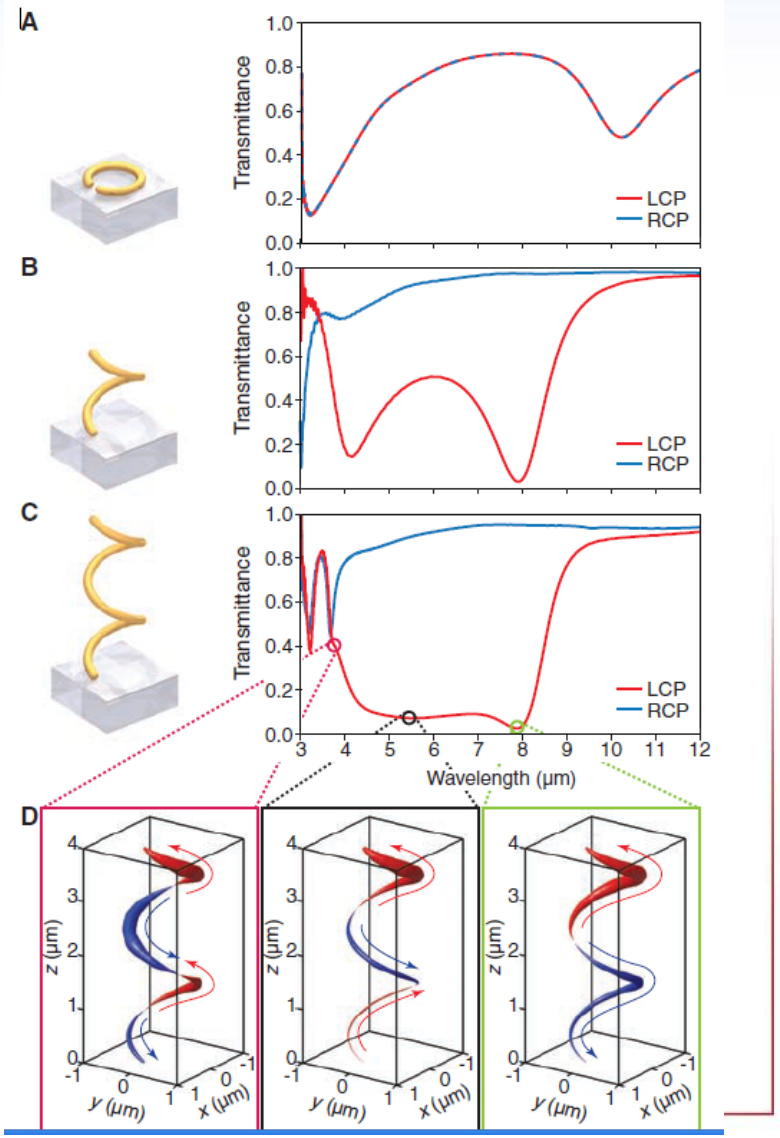
3D in the MetaAtomic Sense



Helgert, et al. Nano Letters **11**, 4400 (2011)

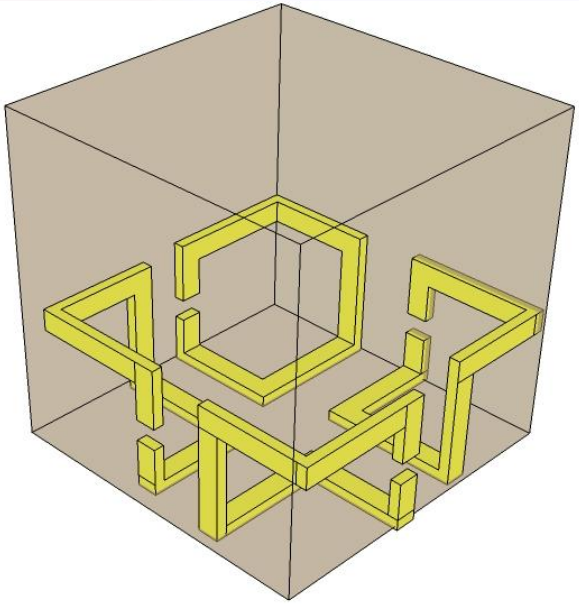


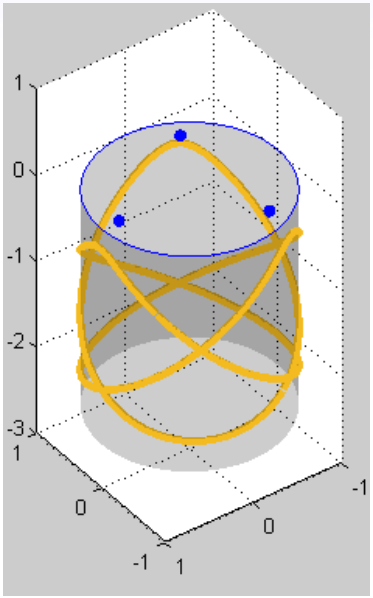
Kaelberer, et al. Science **330**, 1510 (2010)

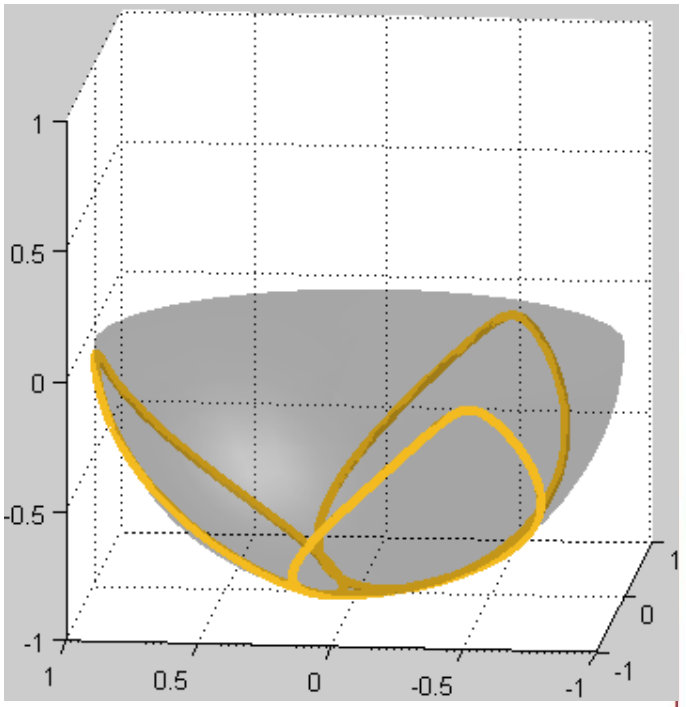


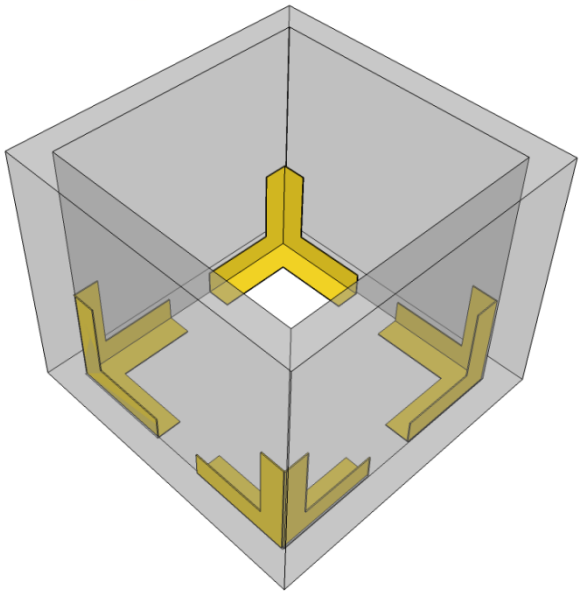
Gansel, et al. Science **325**, 1513 (2009)

3D MetaAtoms Created With MPL

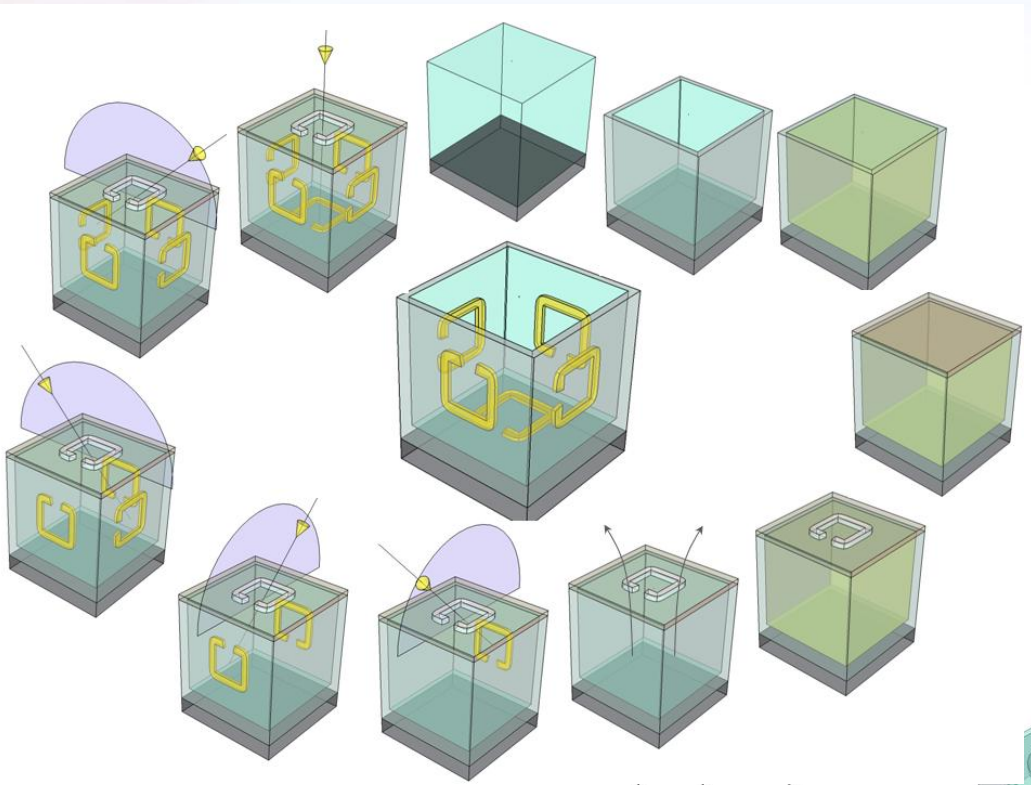


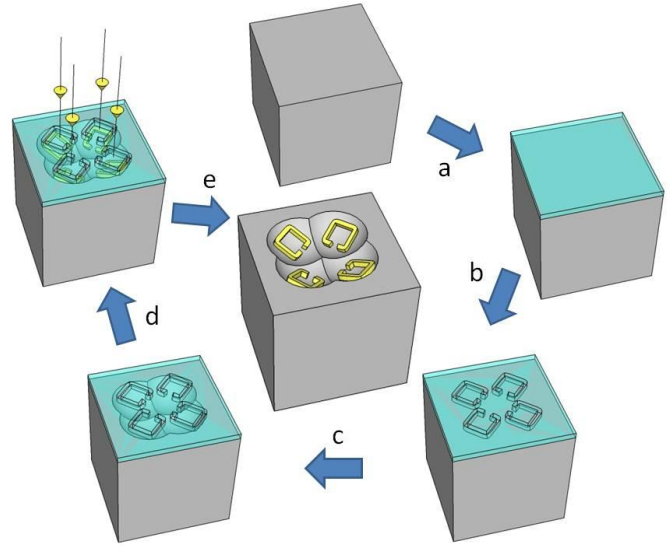


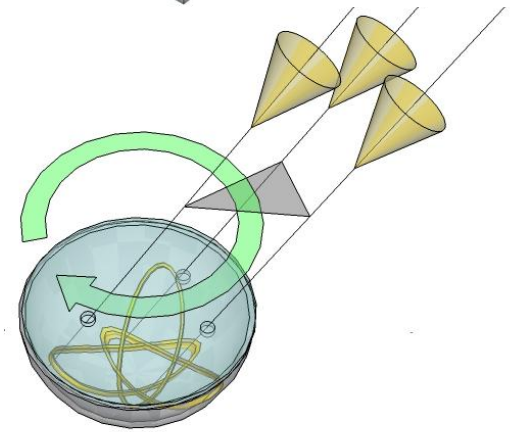


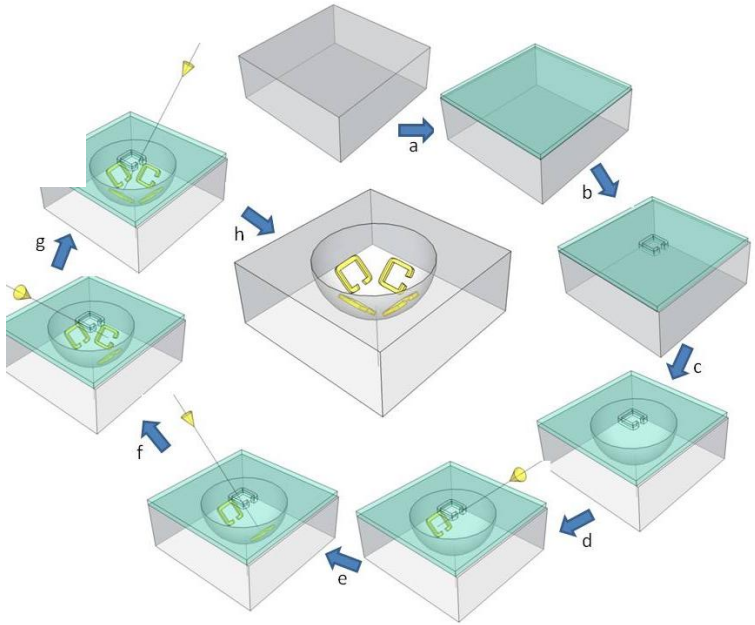


MPL At A Glance

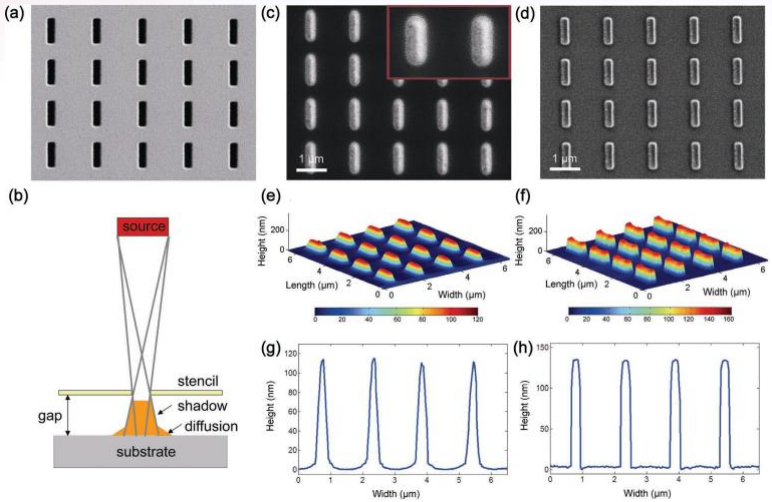




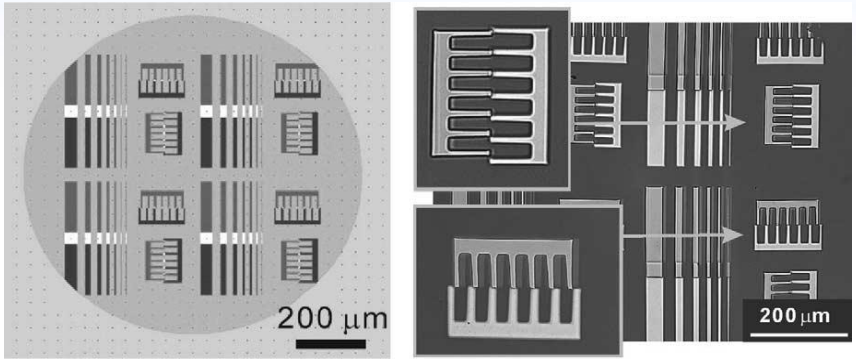




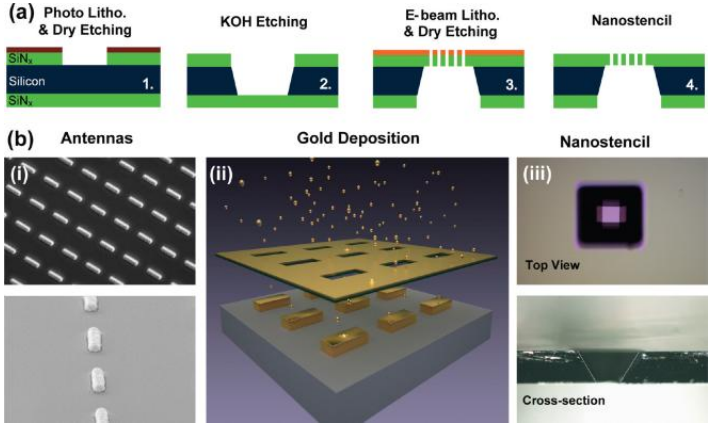
Nano Stencil Lithography



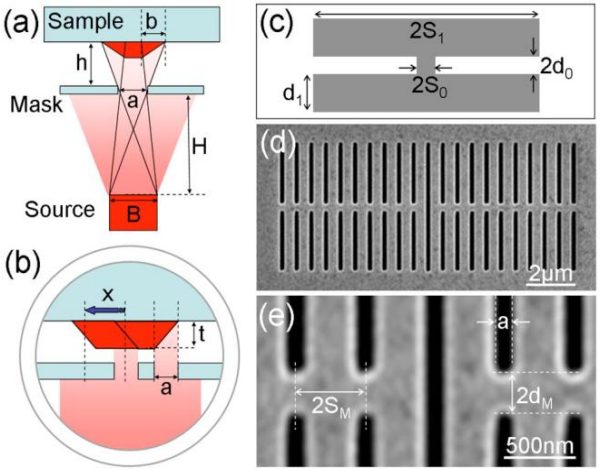
S. Aksu et. al. Adv. Mater, **23**, pp. 4422-4430 (2011)



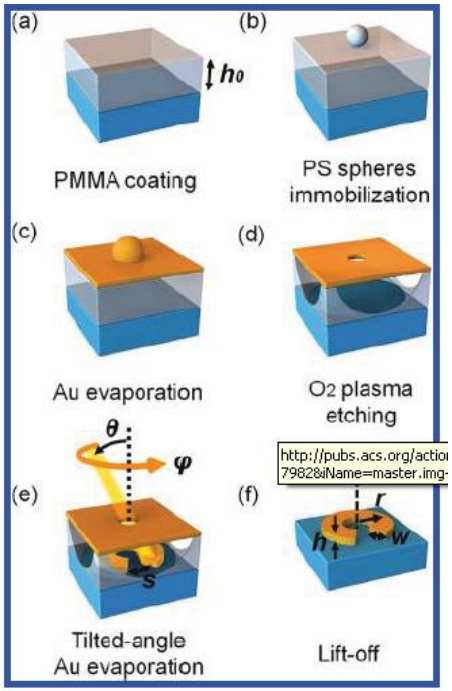
G. Kim et. al. Sensors and Actuators A, **107**, pp. 132-136 (2003)



S. Aksu et. al. Nano Lett, **10**, pp. 2511-2518 (2010)

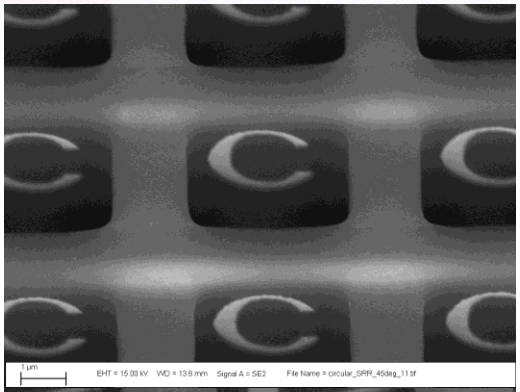


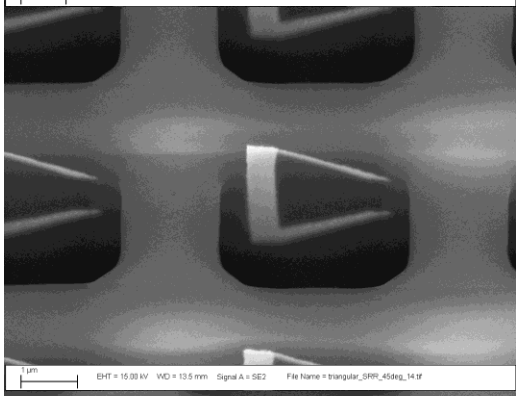
L. Gross et. al. Applied Phys Lett, **90**, 093121 (2007)

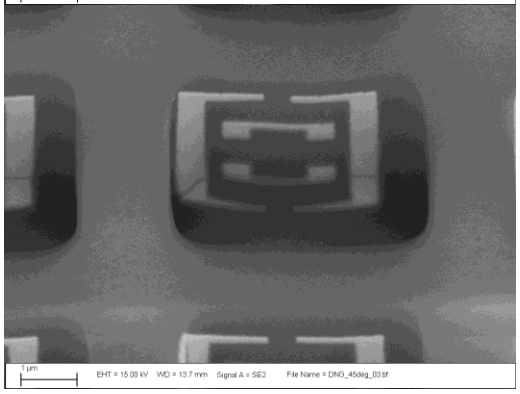


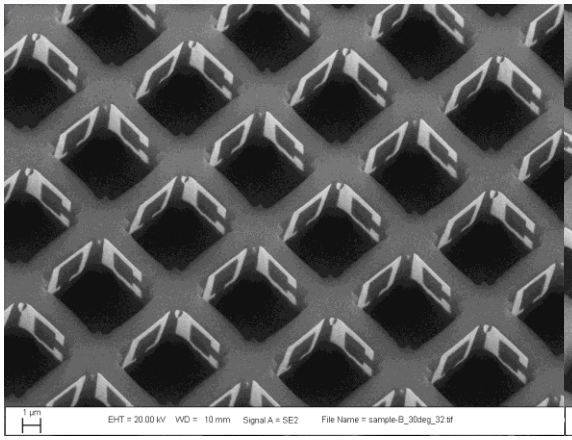
Giessen et. al. ACS Nano, **6**, 979-985, (2012)

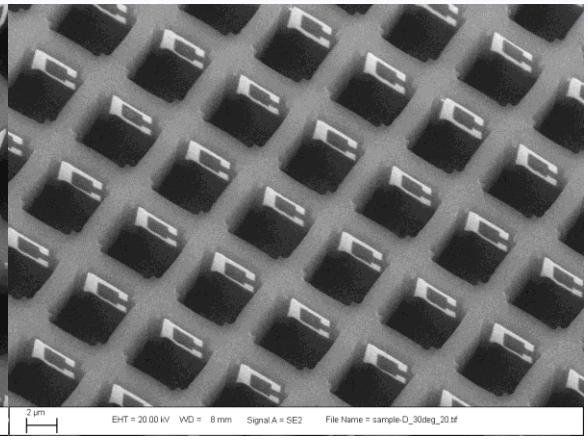
Micron-Scale Cubic Metamaterial Layers

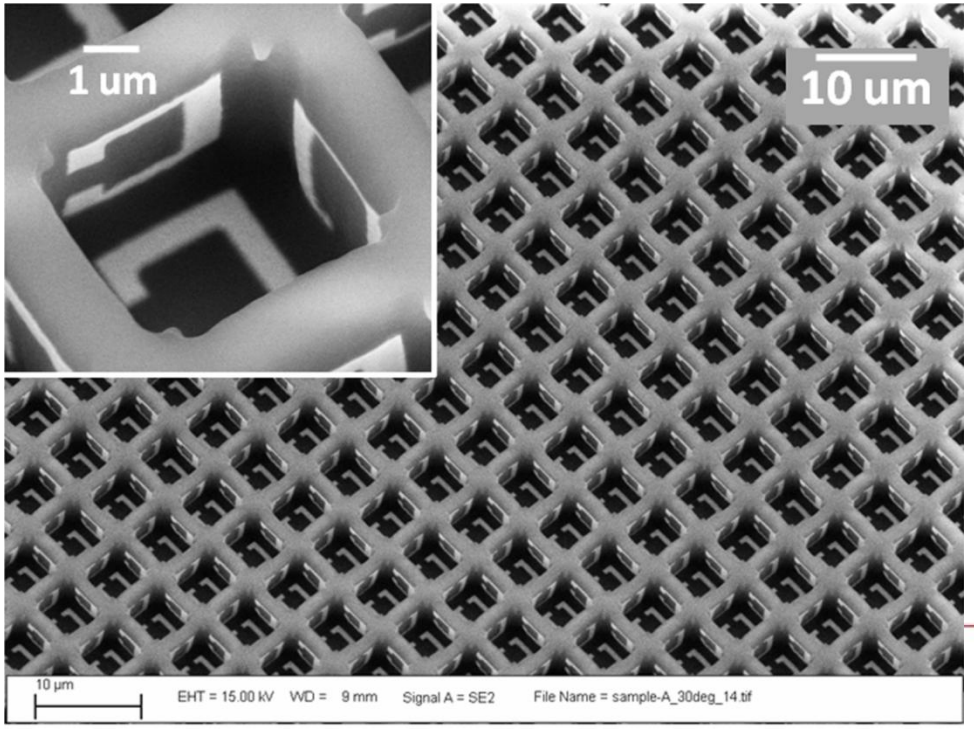




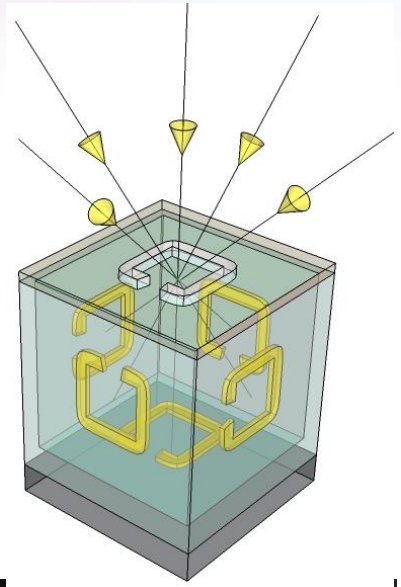


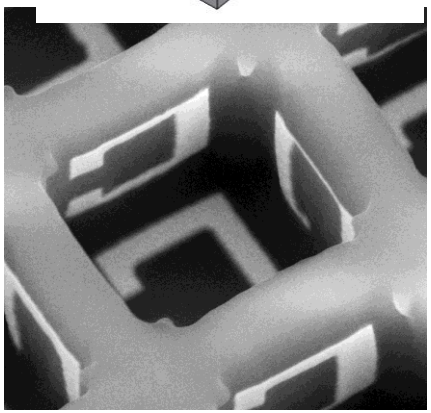




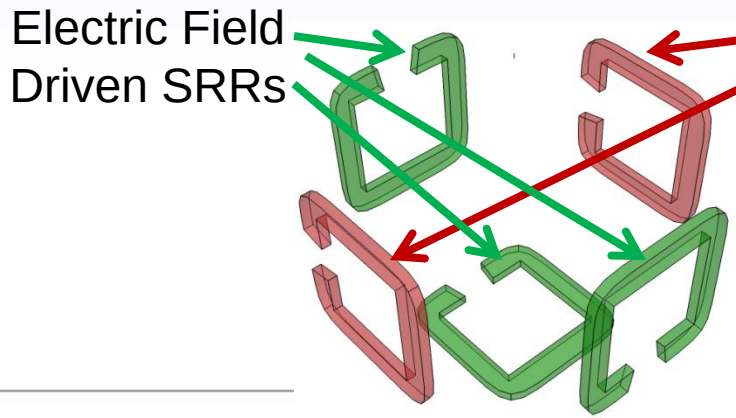


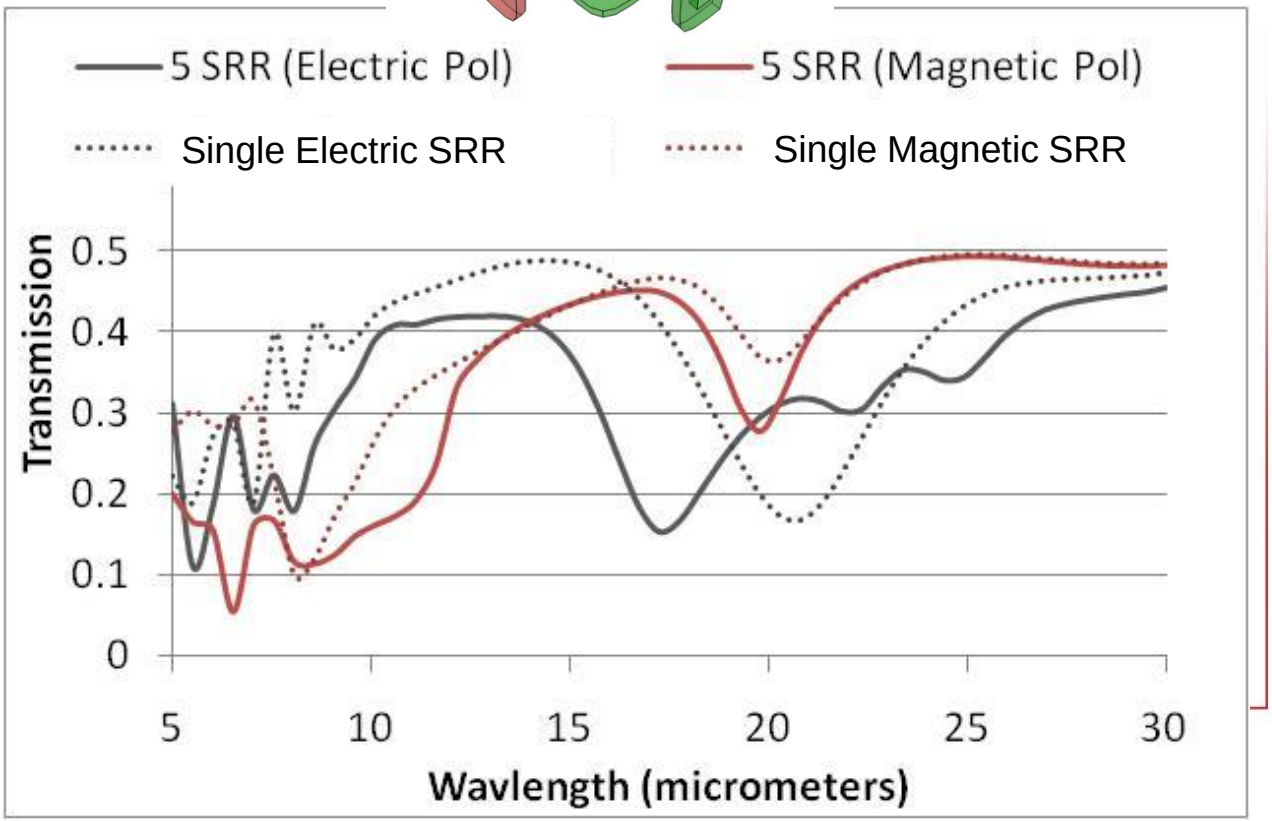
Composite 5 SRR Unit Cell Response



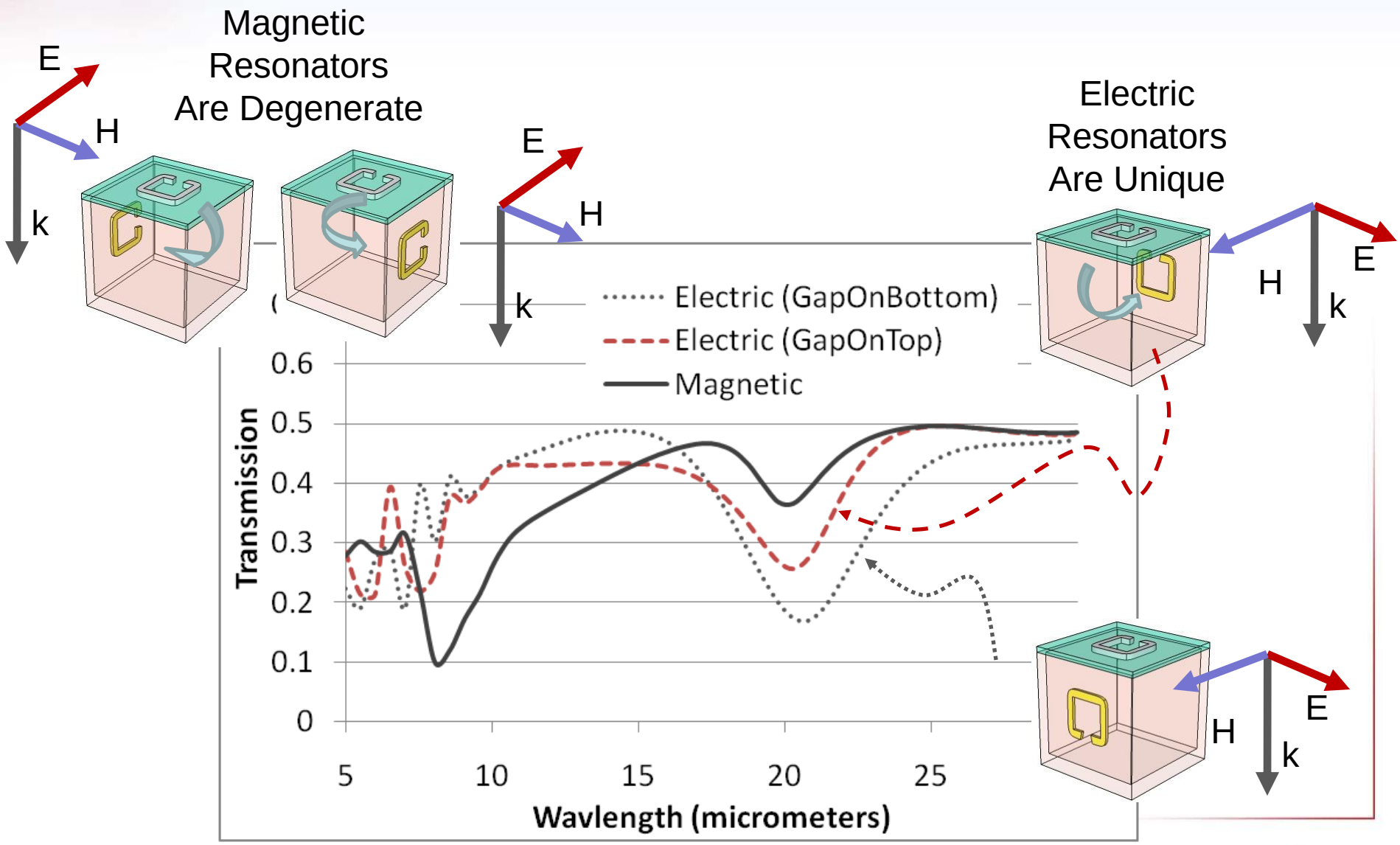


6 micron pitch
1 micron SU-8 walls



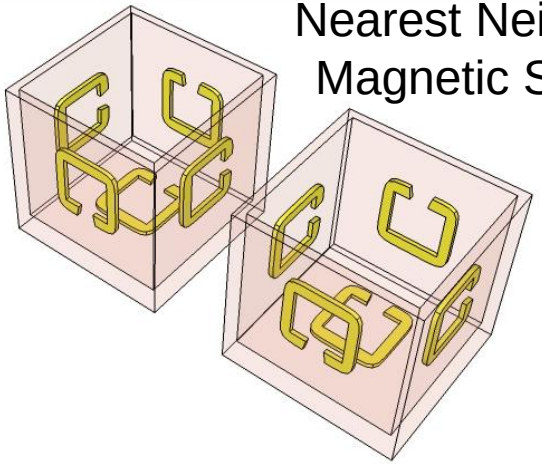


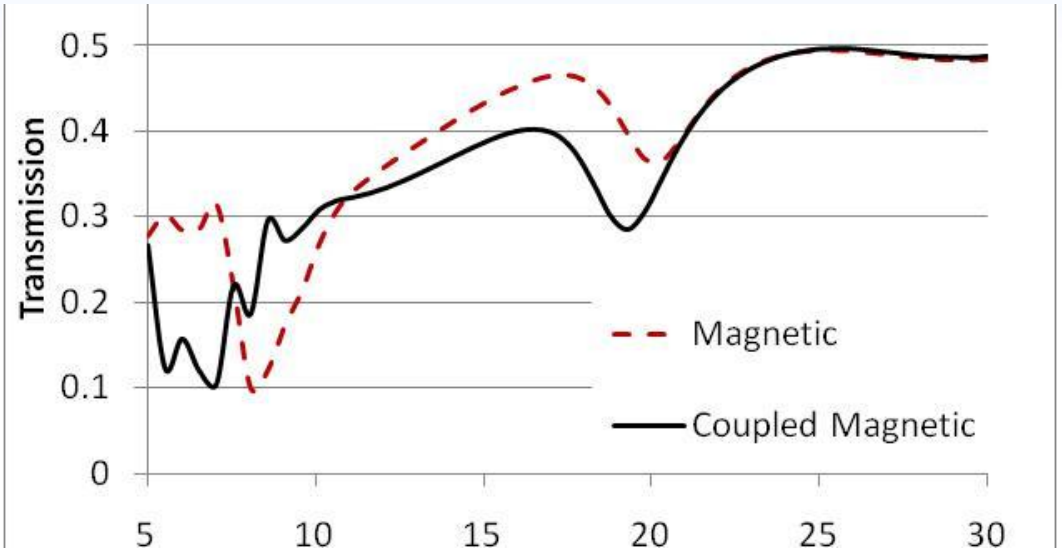
Pattern Symmetry vs. Projection Symmetry



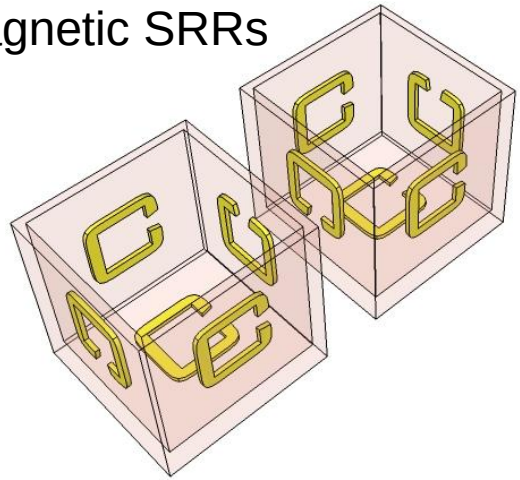
Impact of NNN Coupling

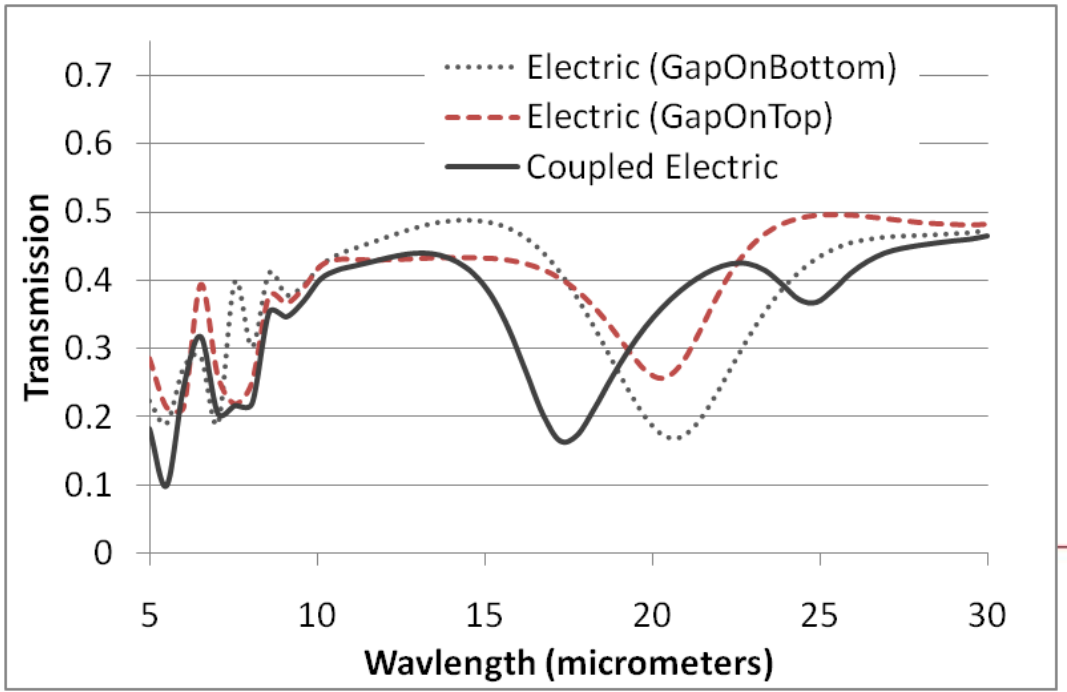
Aligned
Nearest Neighbor
Magnetic SRRs



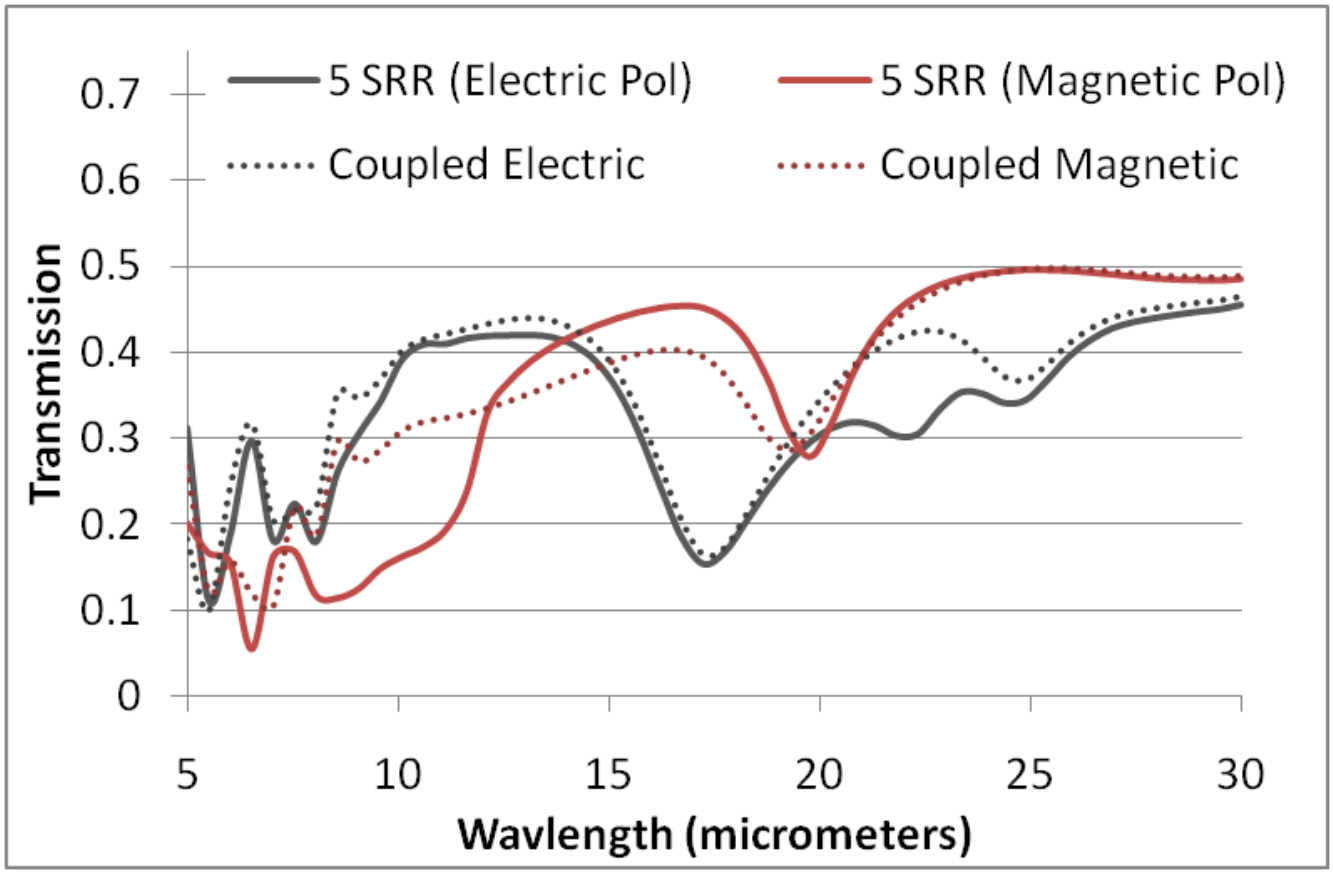


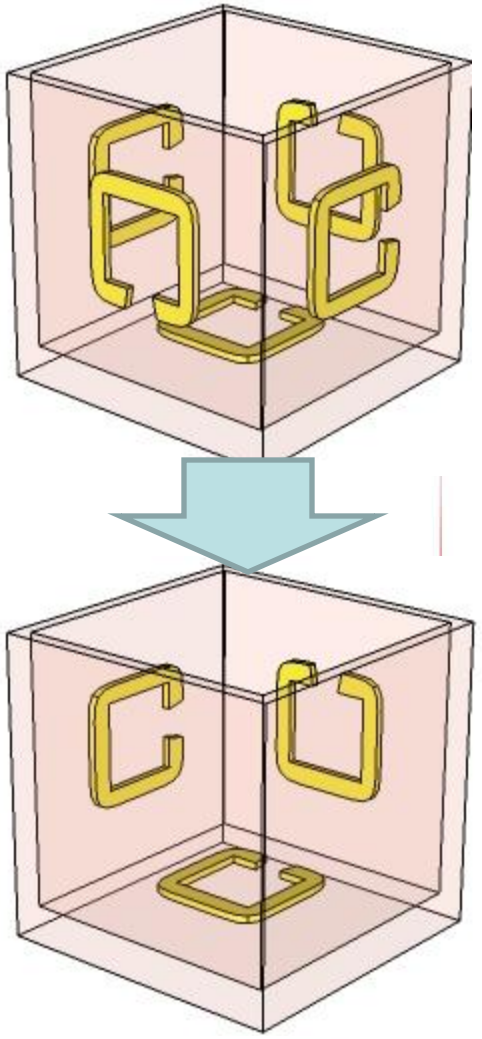
Anti-Aligned
Nearest Neighbor
Magnetic SRRs





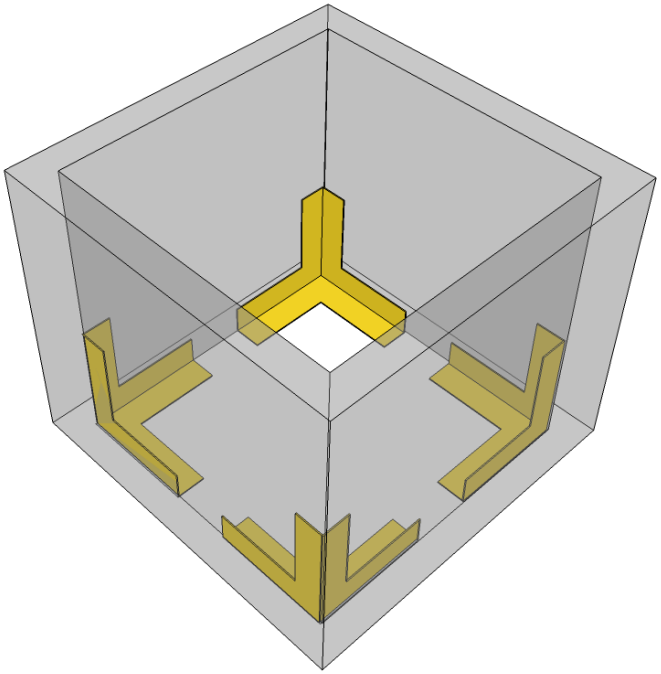
Composite Unit Cell Response Mimics Coupled Resonators

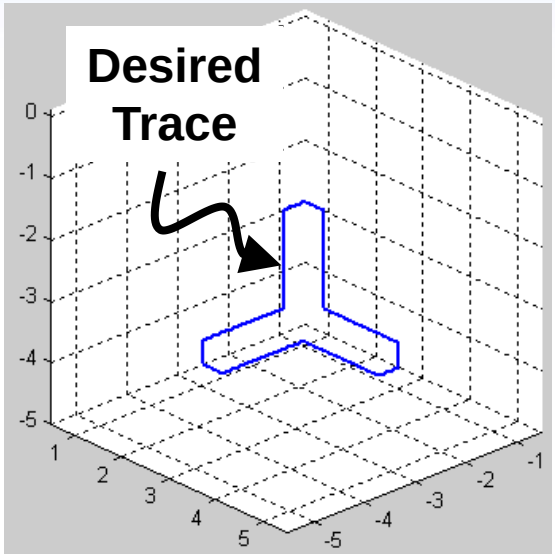


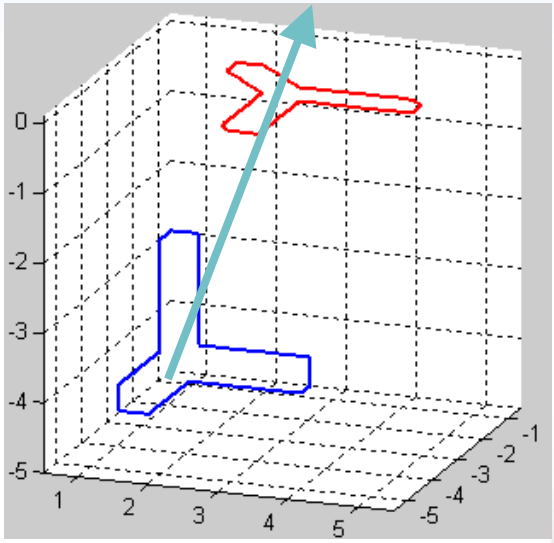


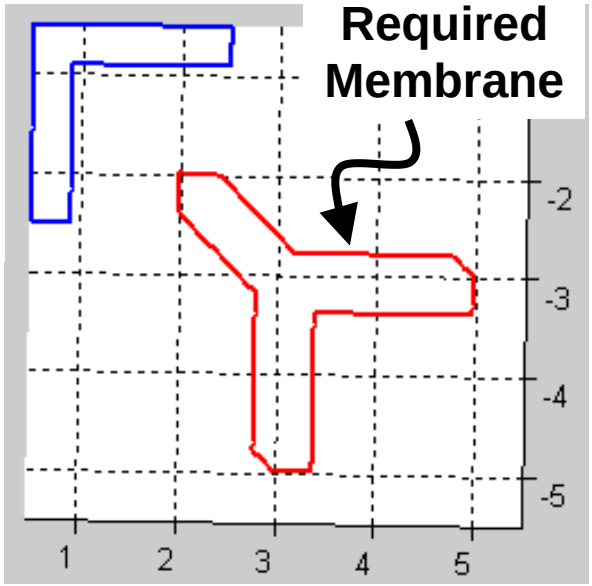
Creating Non-Planar Inclusions

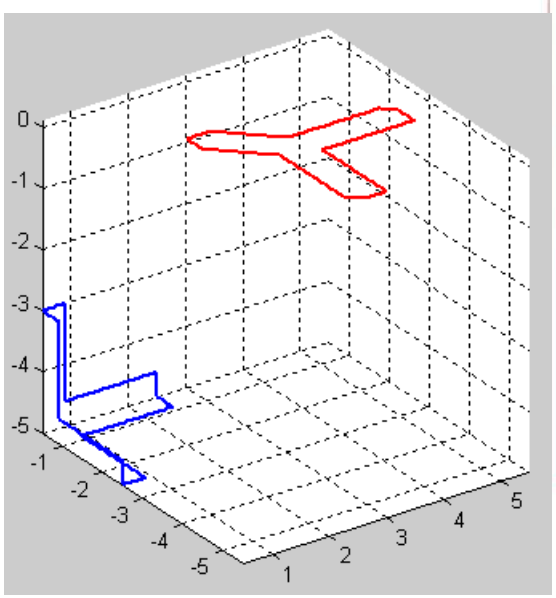
Bottom Half of A Split Cube



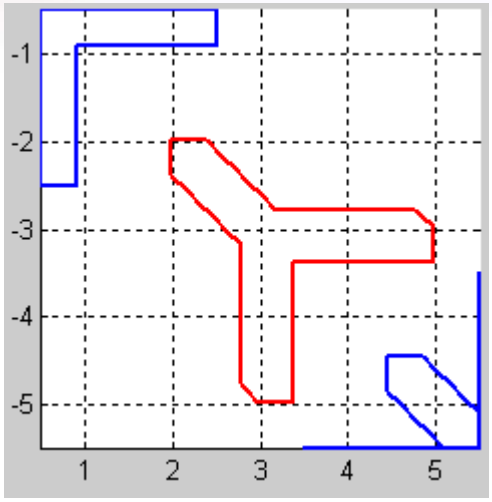


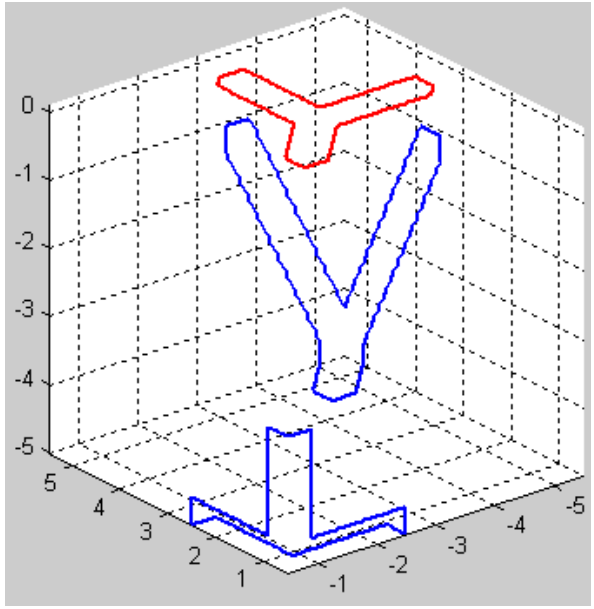


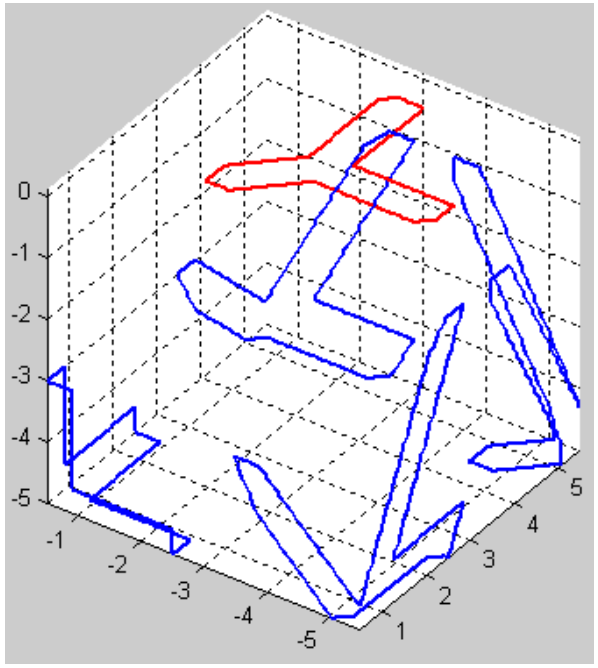




High Symmetry Inclusions Do Not Imply High Symmetry Membrane Patterns

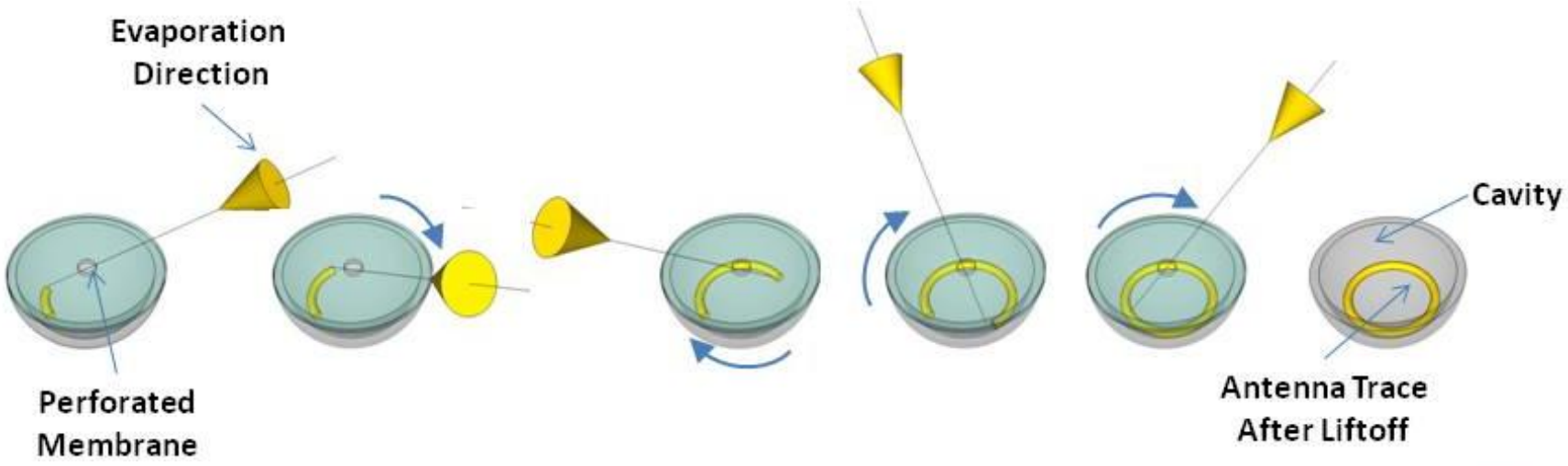




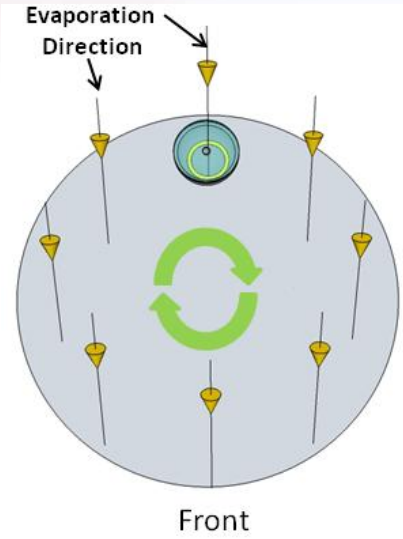


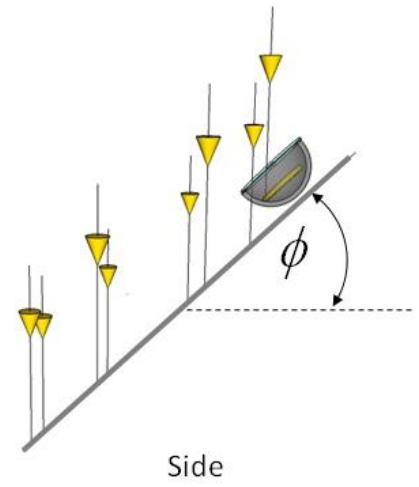
Dynamic Membrane Projection Lithography:

What happens if we move during deposition?



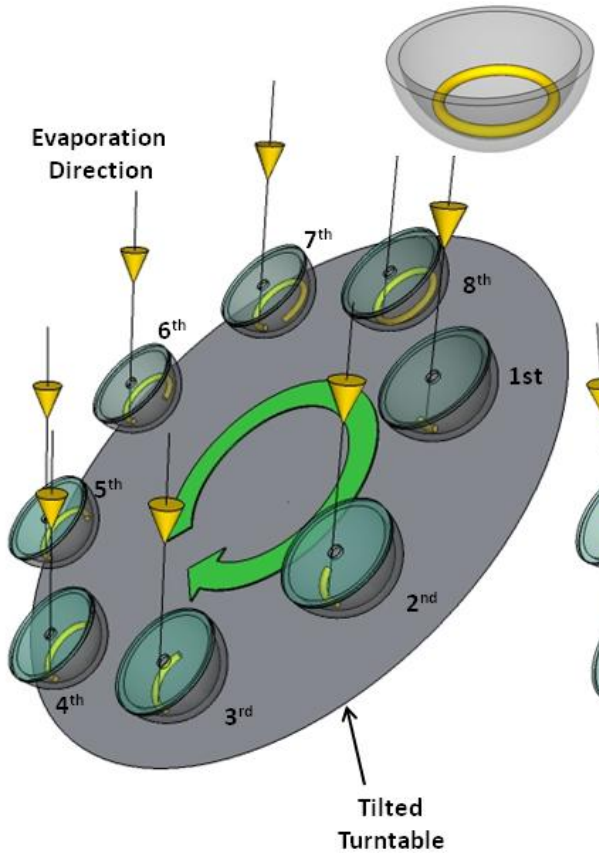
A More Practical Fabrication Approach

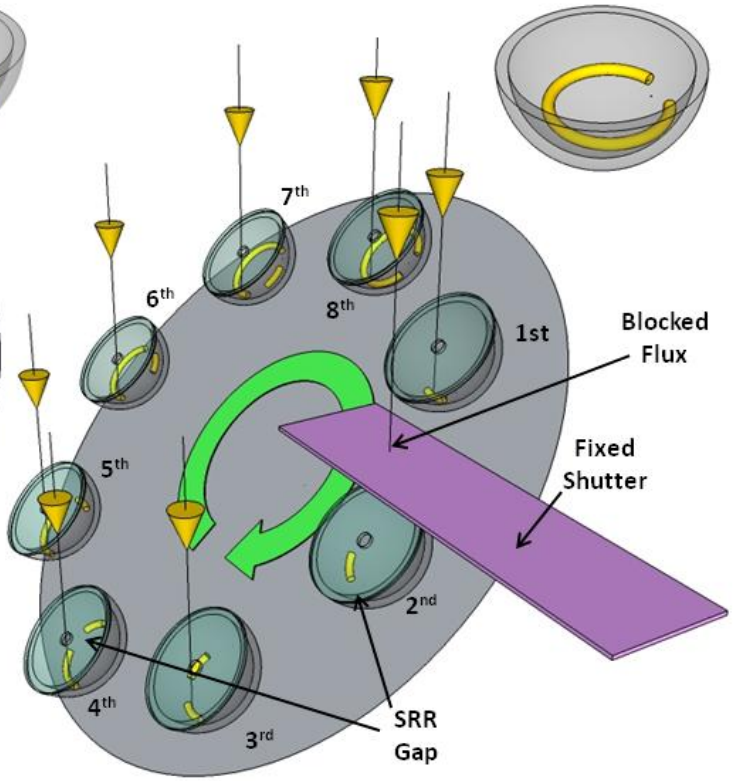




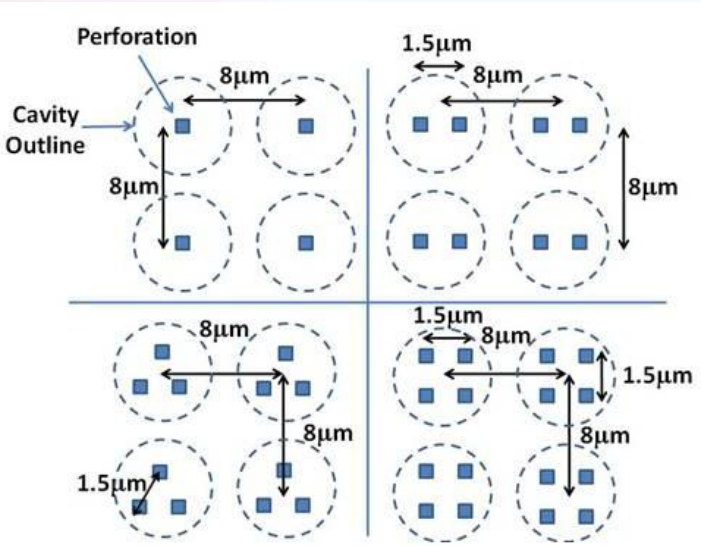
Closed Loops

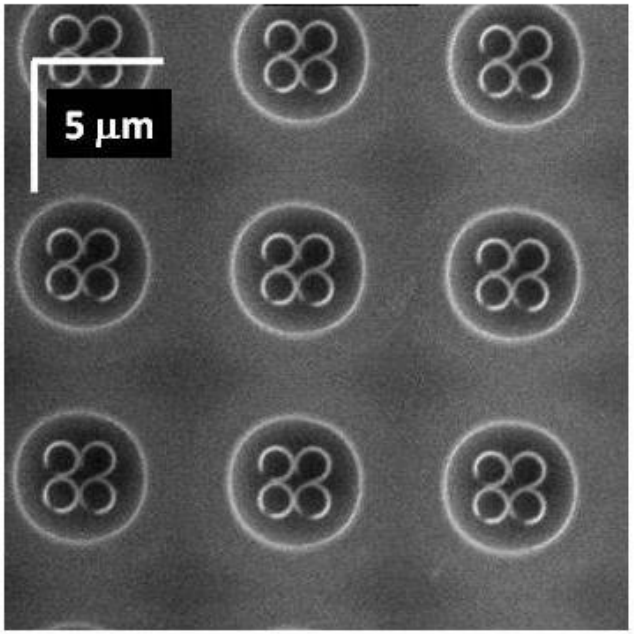
Split Loops



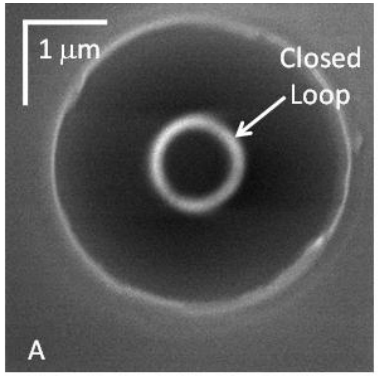


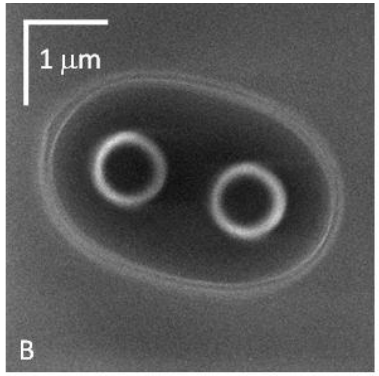
Preliminary Self- Aligned Fabrication Results

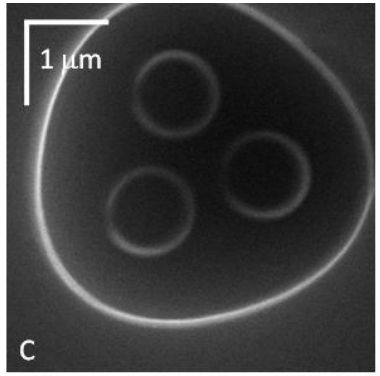


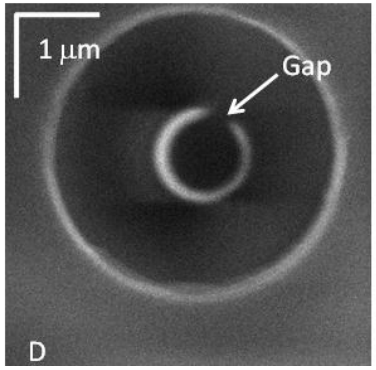


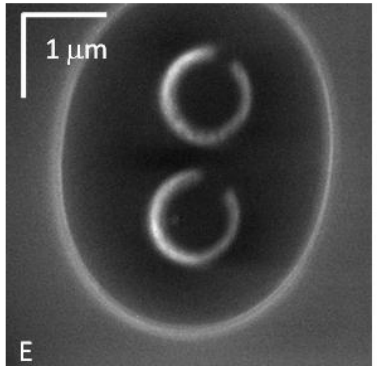
Self-aligned process flow – trace dependent cavity shape

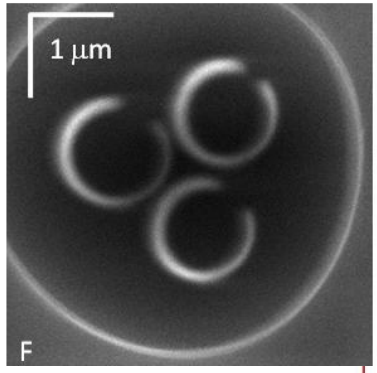










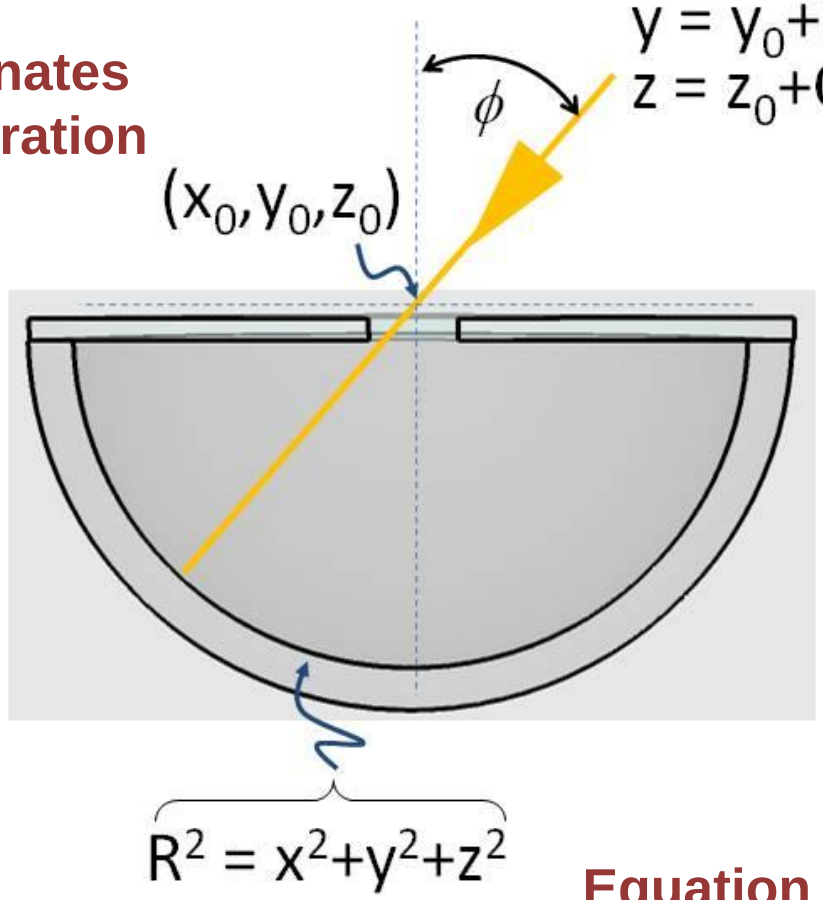


Designing 3D Antenna Geometries

Parametric description of evaporation line

$$x = x_0 + At$$
$$y = y_0 + Bt$$
$$z = z_0 + Ct$$

Coordinates of perforation

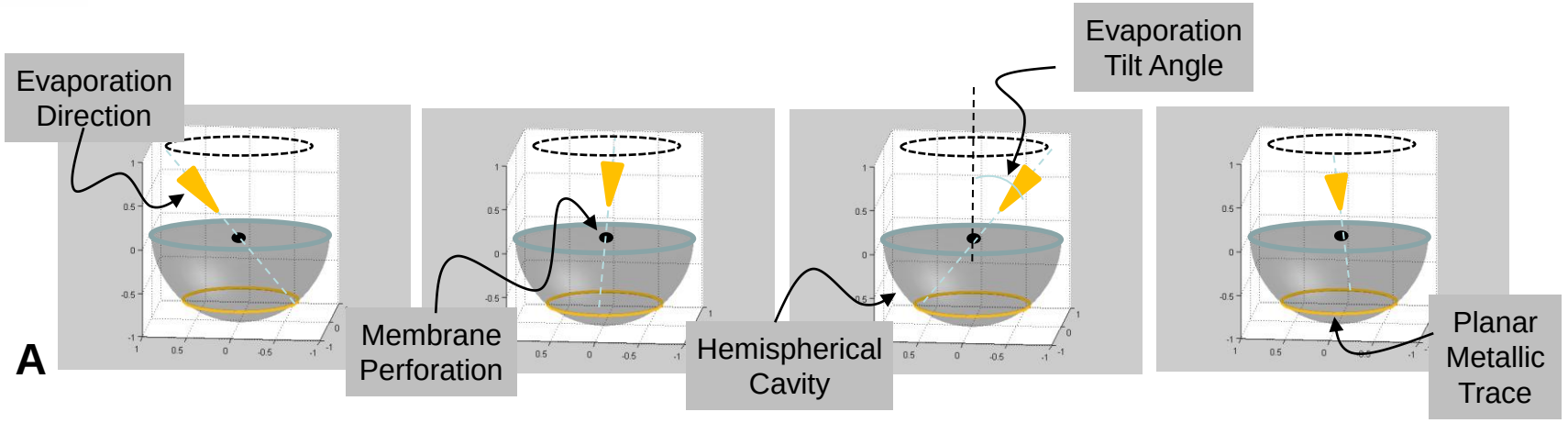


$$A = \sin\phi\cos\theta$$
$$B = -\sin\phi\sin\theta$$
$$C = \cos\phi$$

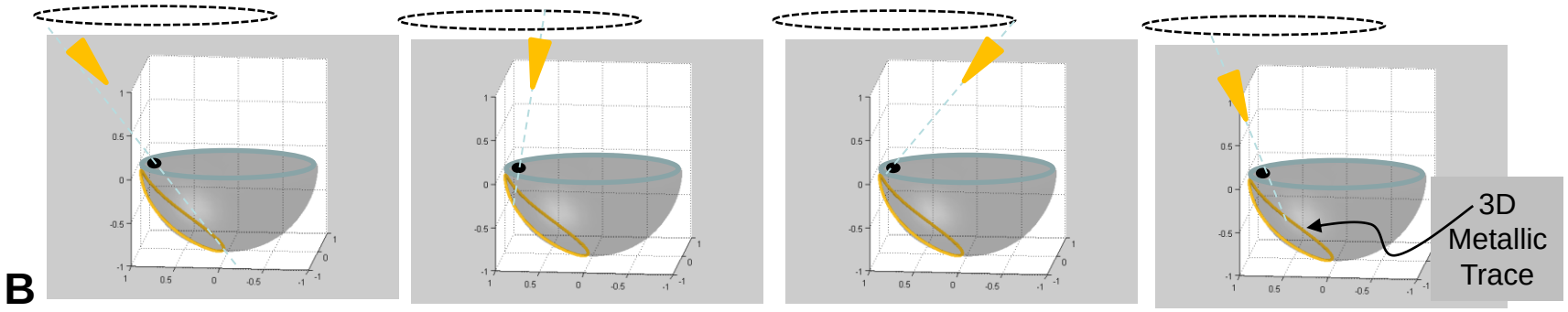
Equation describing cavity surface

Impact of Perforation Position

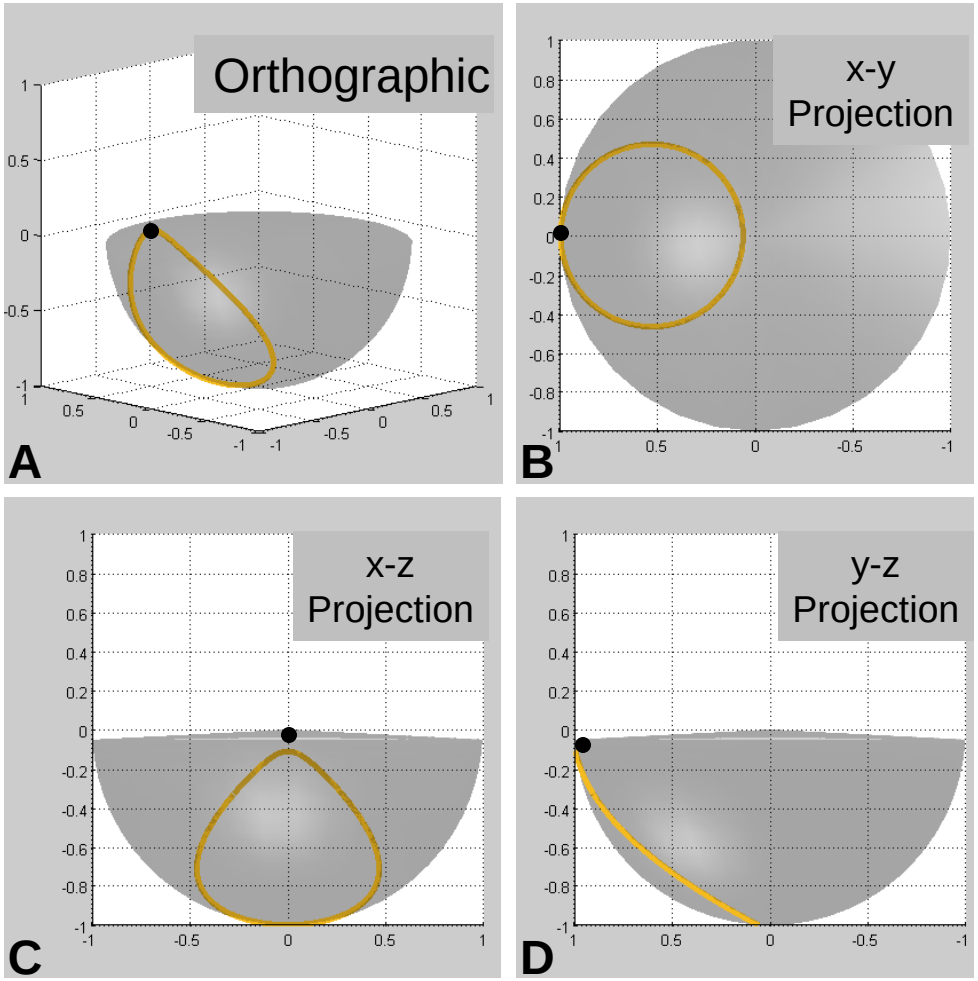
Centered Perforation Generates Planar Trace



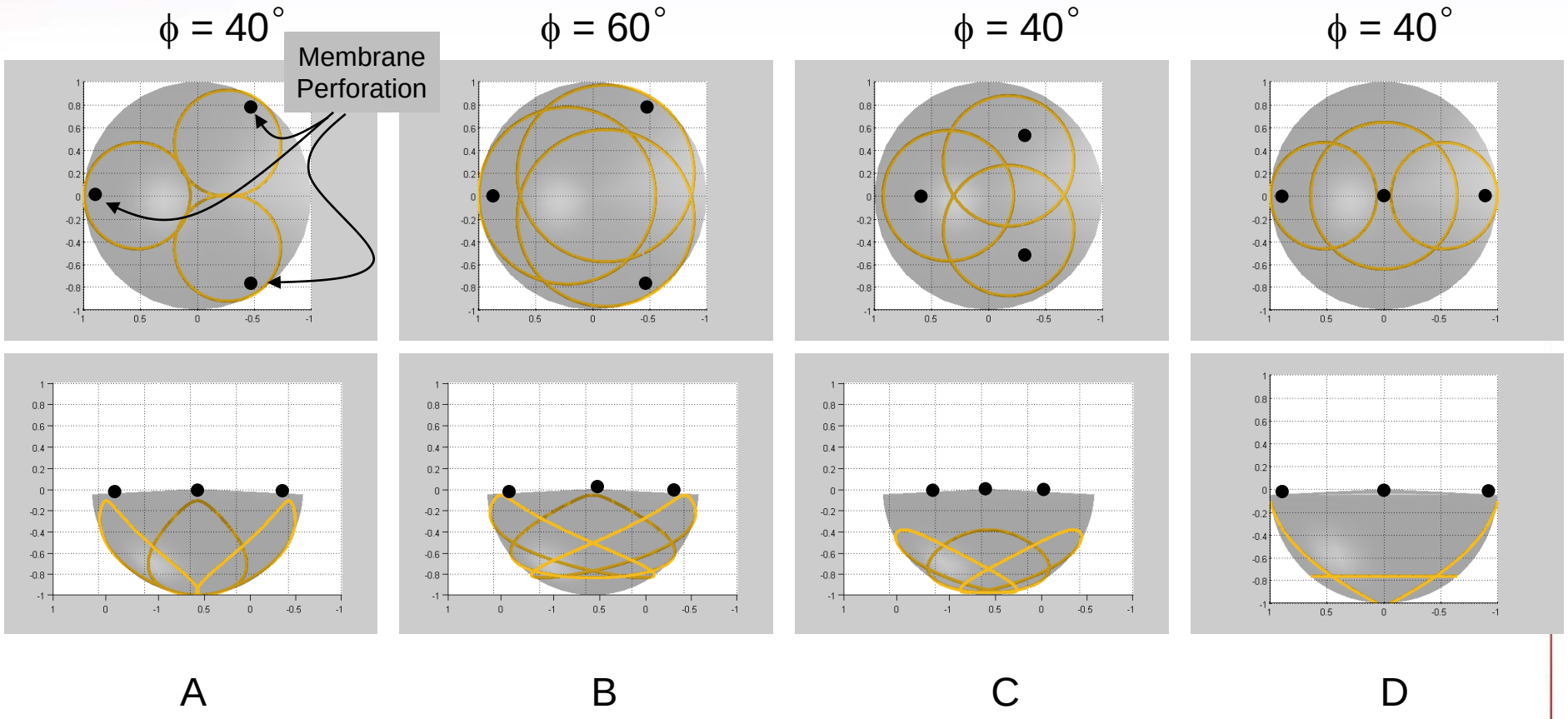
Off-Center Perforation Generates 3D Trace



3D Metallic Trace: A Closer Look

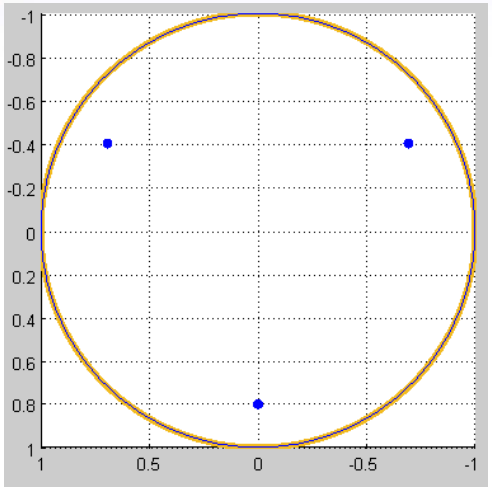


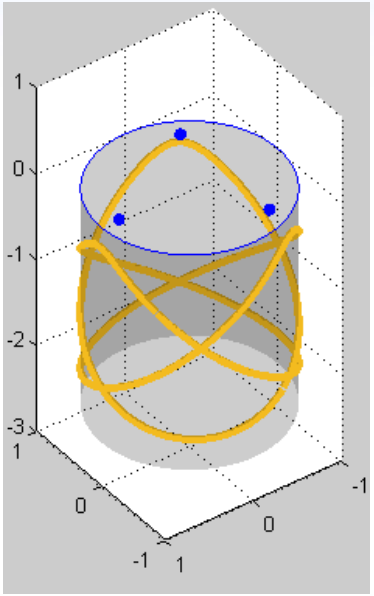
3D Multi-loop Traces

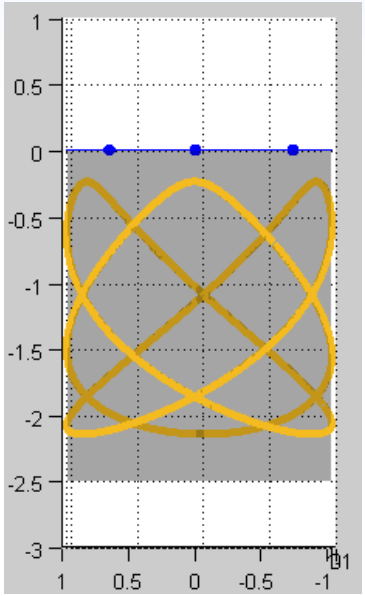


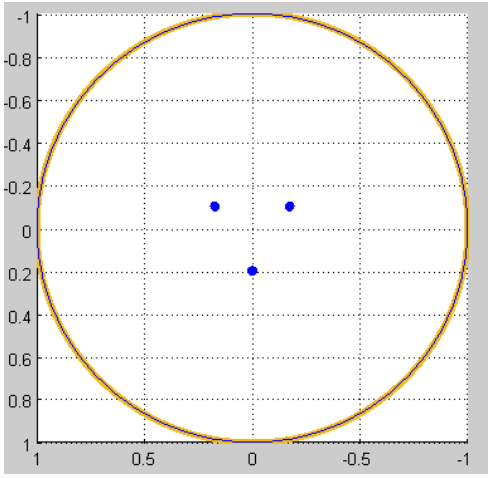
Simple geometrical variations lead to highly diverse 3D trace geometries

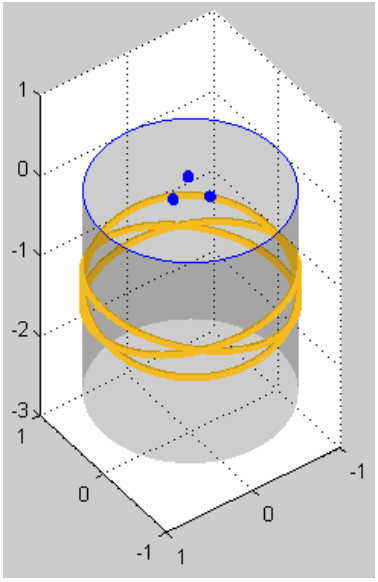
Dynamic MPL in a Cylindrical Cavity

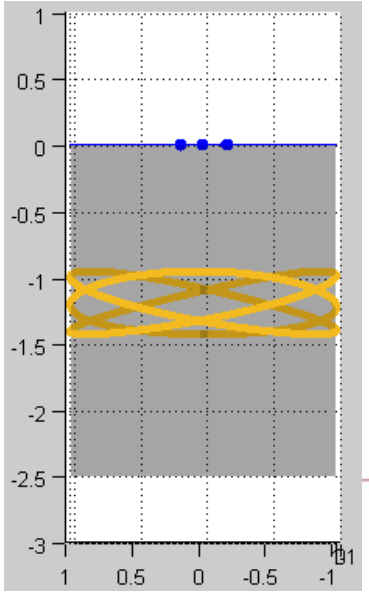




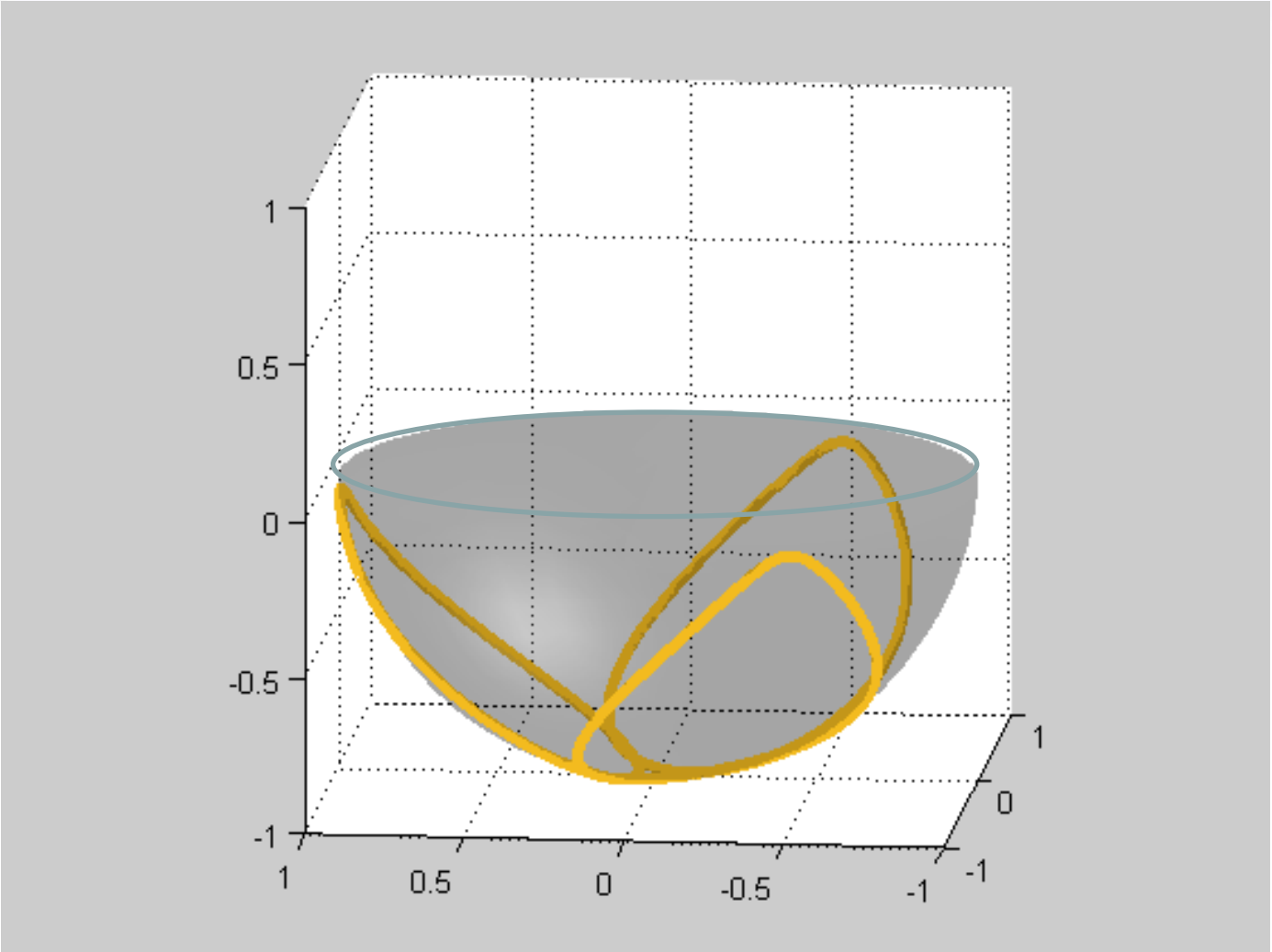




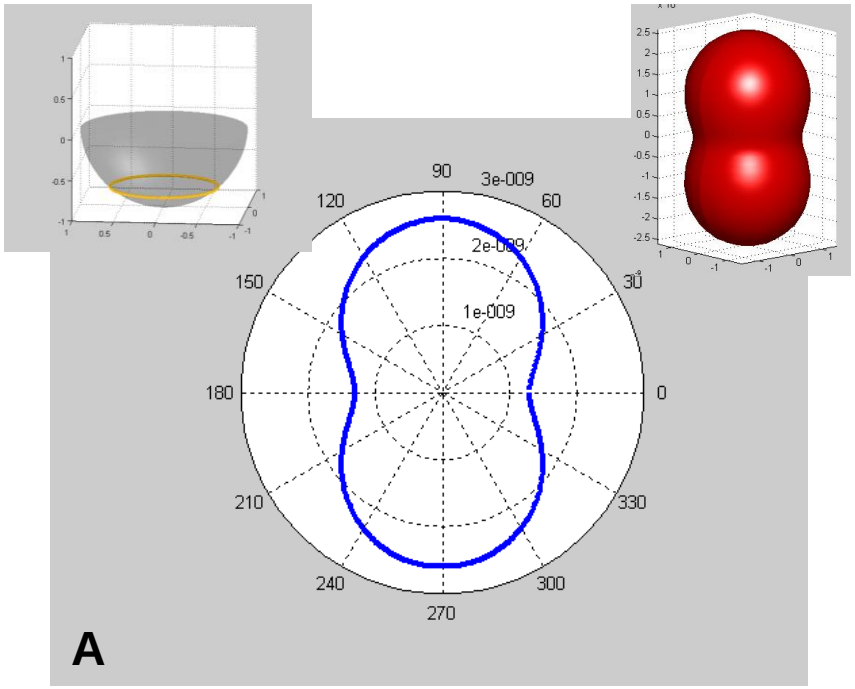


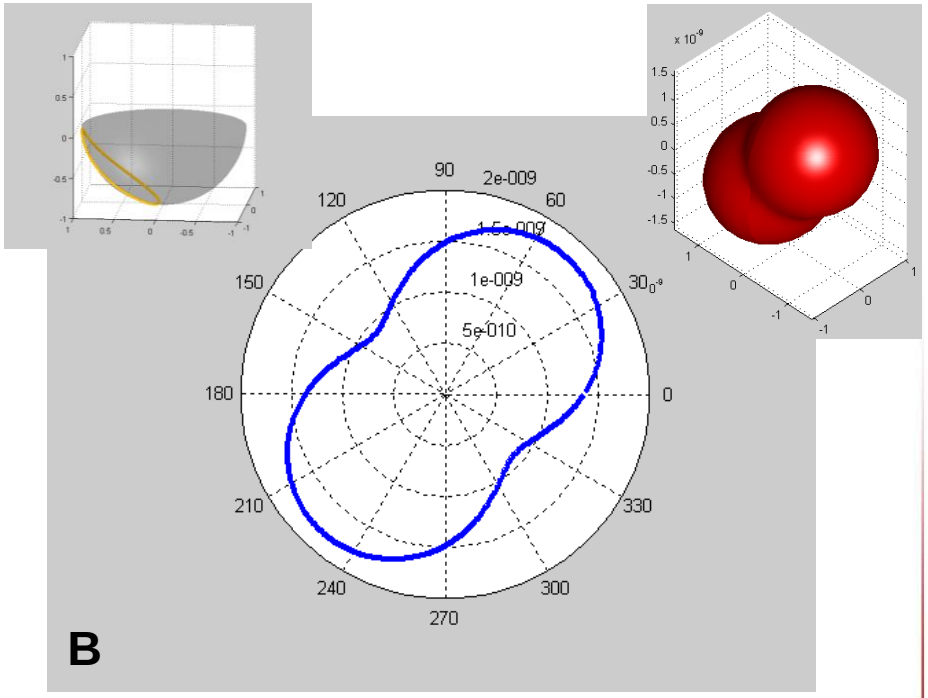


3D Metallic Trace: A Closer Look

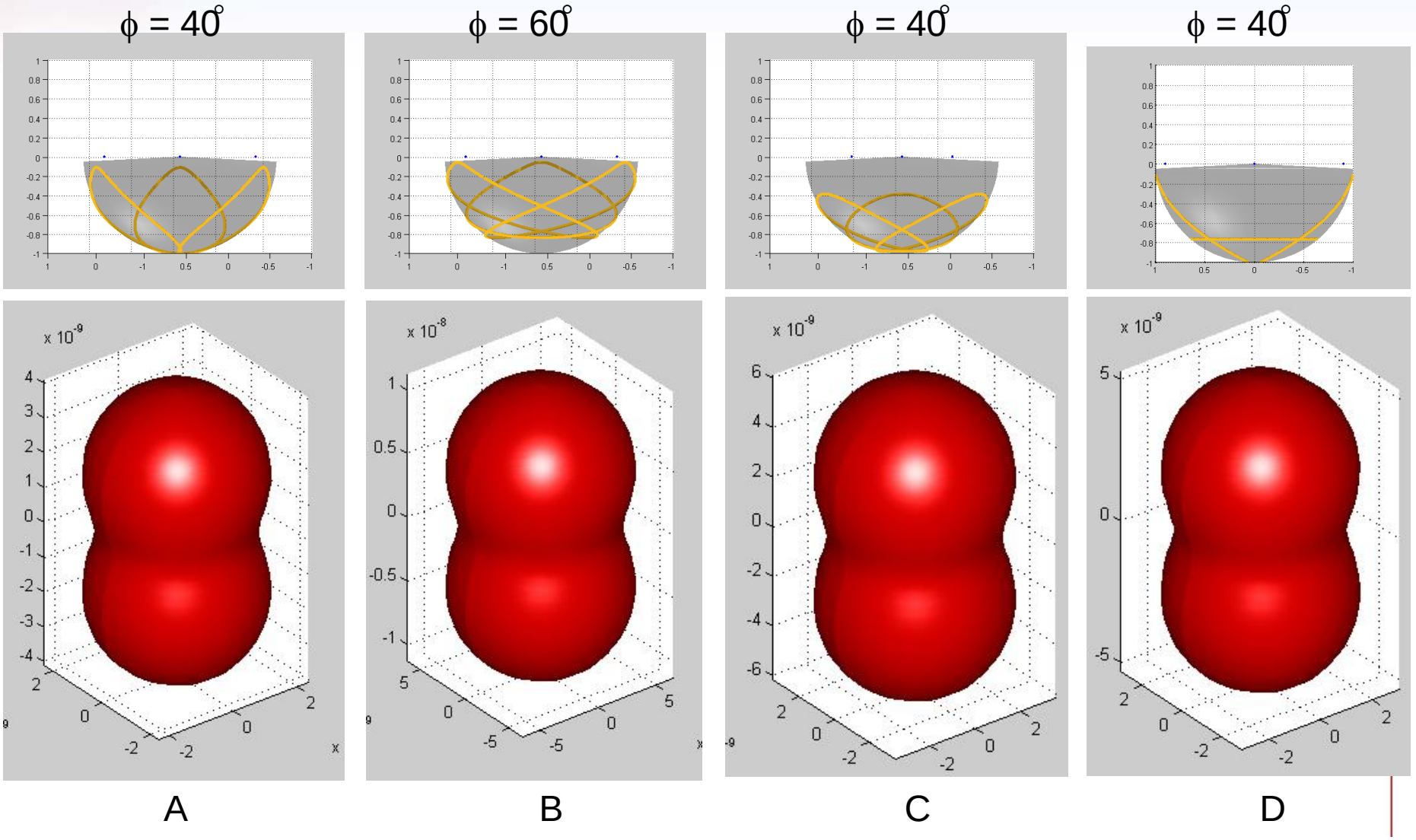


Planar loop vs. 3D trace





Localized Current Distribution : Farfield Magnetic Dipole



“Far away from any localized current distribution, the magnetic induction is that of a magnetic dipole.” Classical Electrodynamics, Jackson Ch. 5. p. 147

Conclusions

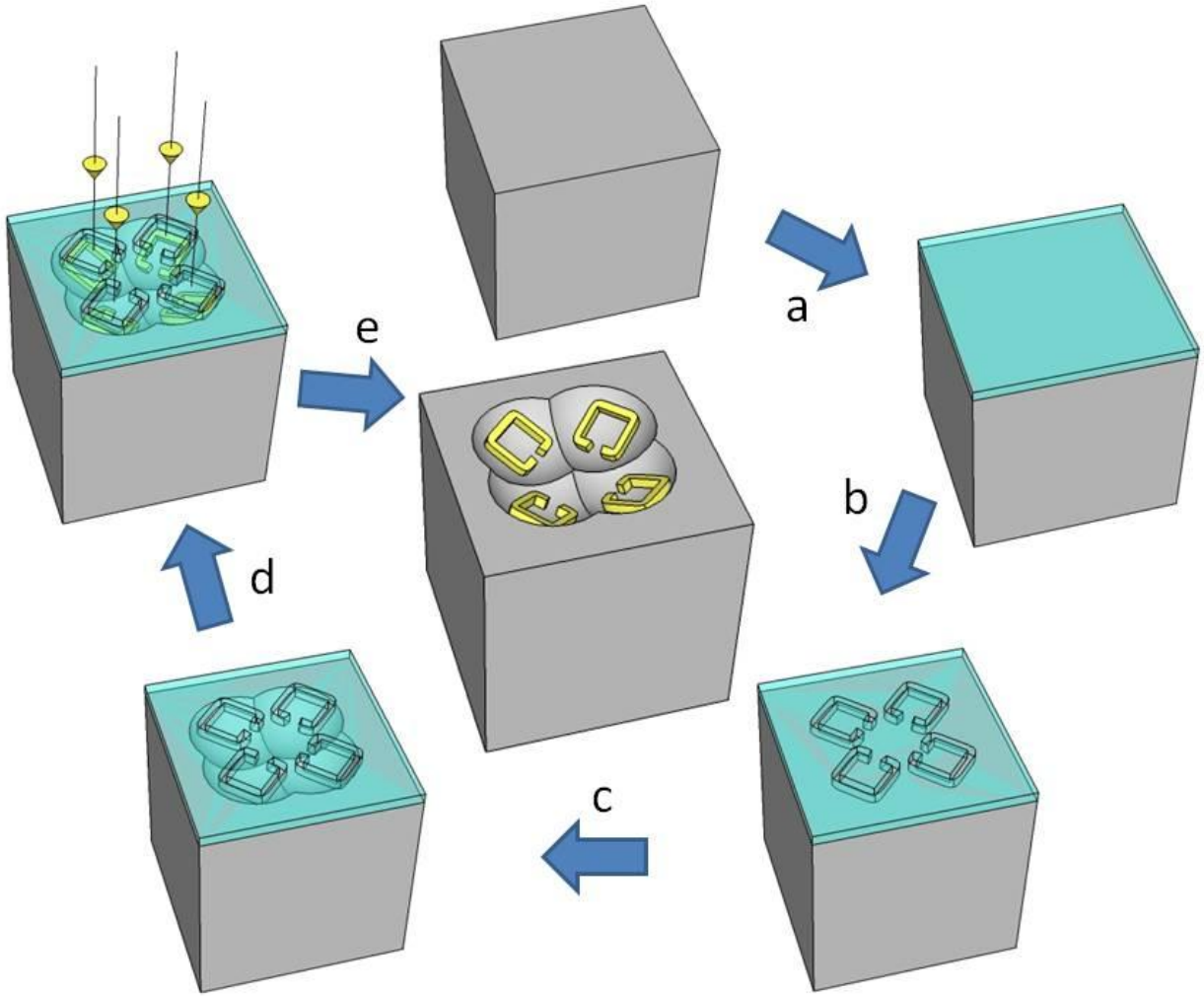
- MPL is proving to be a manufacturable approach to complex 3D electromagnetic structures.
- Dynamic-MPL offers a unique fabrication approach to realize highly non-planar 3D micro/nano antennas with and without split gaps.
- Localized current distributions create magnetic dipole farfield magnetic field patterns, however the nearfield behavior can be quite different depending on geometry.
- Next step – full wave simulations to begin assessing the radiative performance of these 3D traces as multifunctional antennas

dbburck@sandia.gov

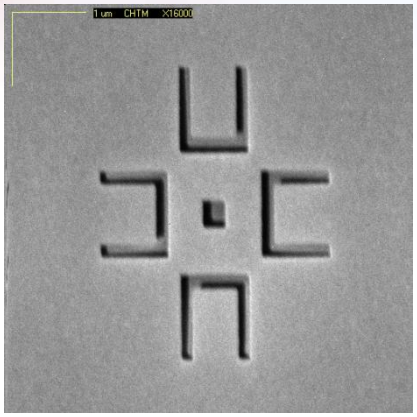
Backup Slides

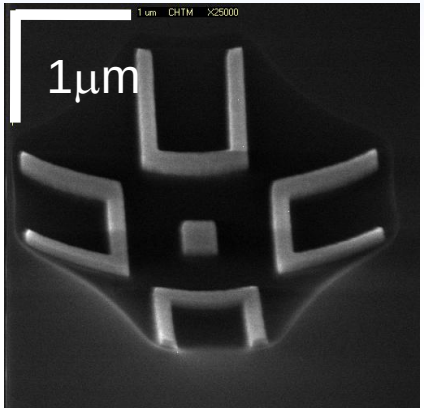
Single Evaporation MPL

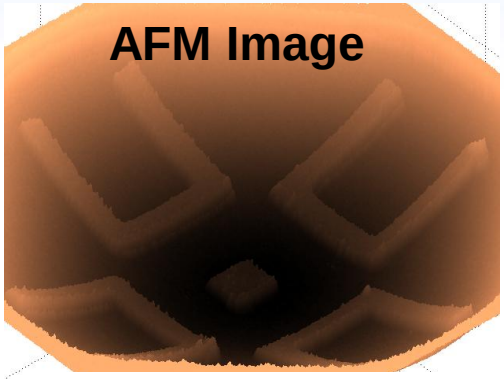
1.) Pattern membrane with entire suite of unit cell features.
2.) Use patterned membrane to dissolve out substrate to create cavity.
3.) Perform single evaporation to decorate unit cell.

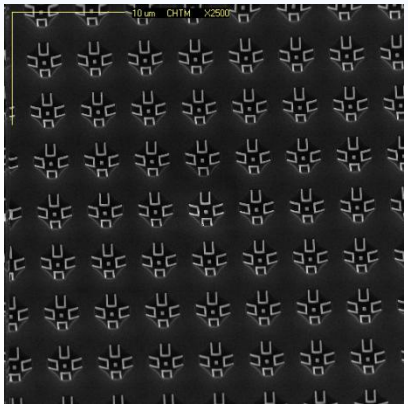


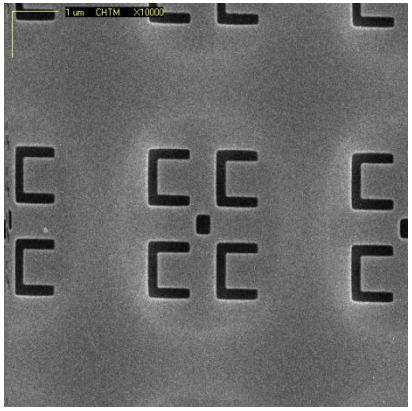
Examples of Single Evaporation SAMPL

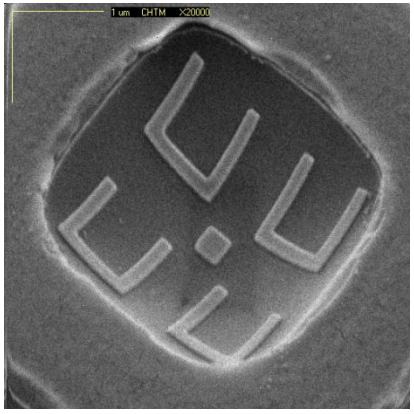


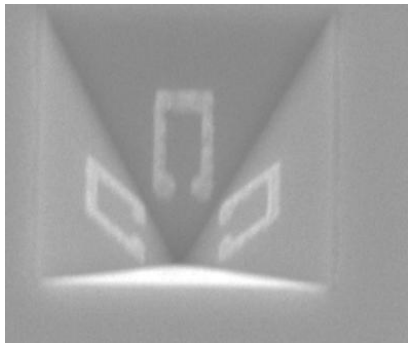


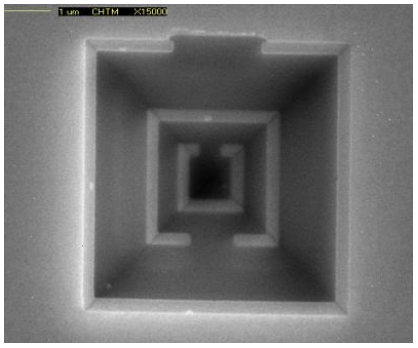




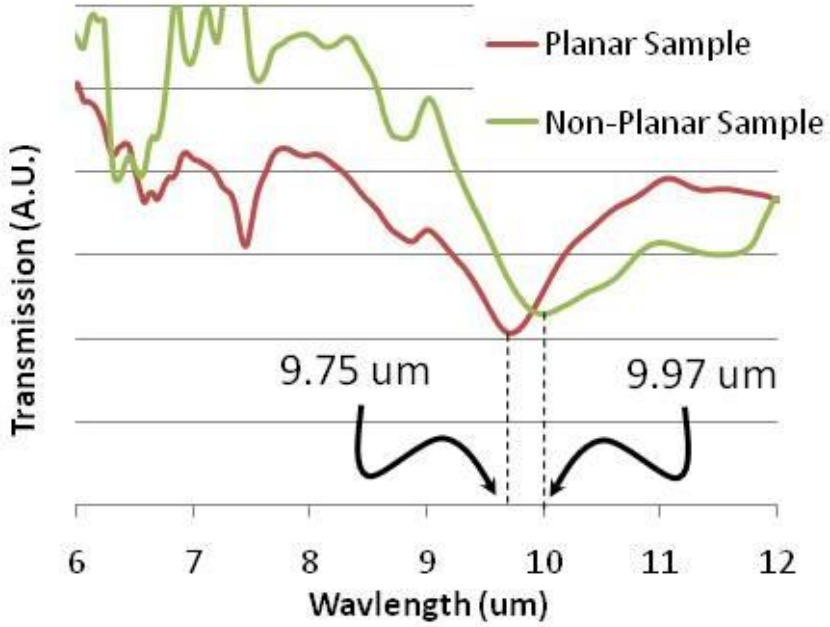






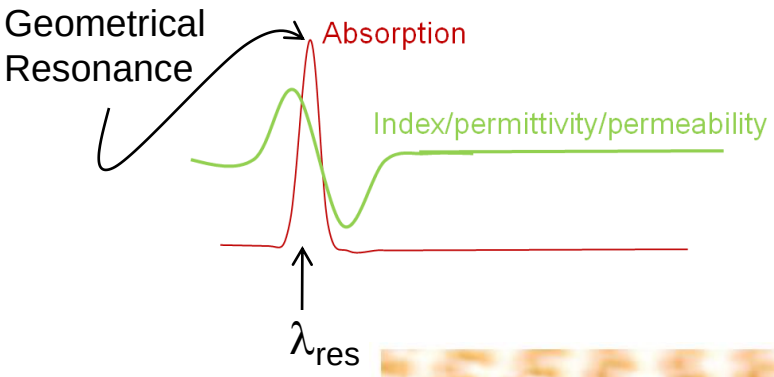


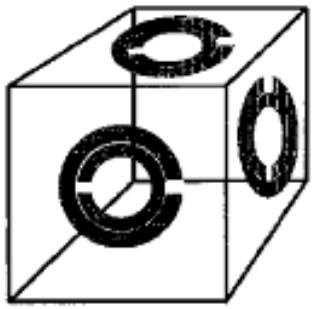
Resonators ~ 20^0 out-of-plane



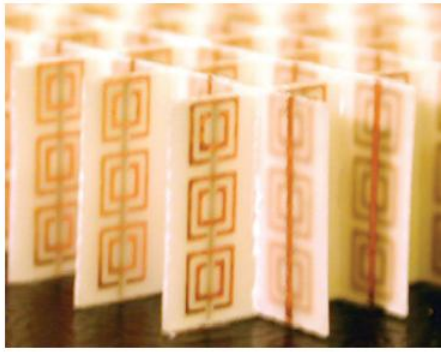
3D Metallic Metamaterial Strategies

Resonant Structures



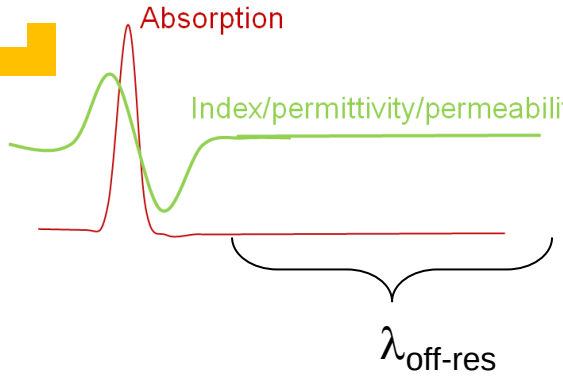


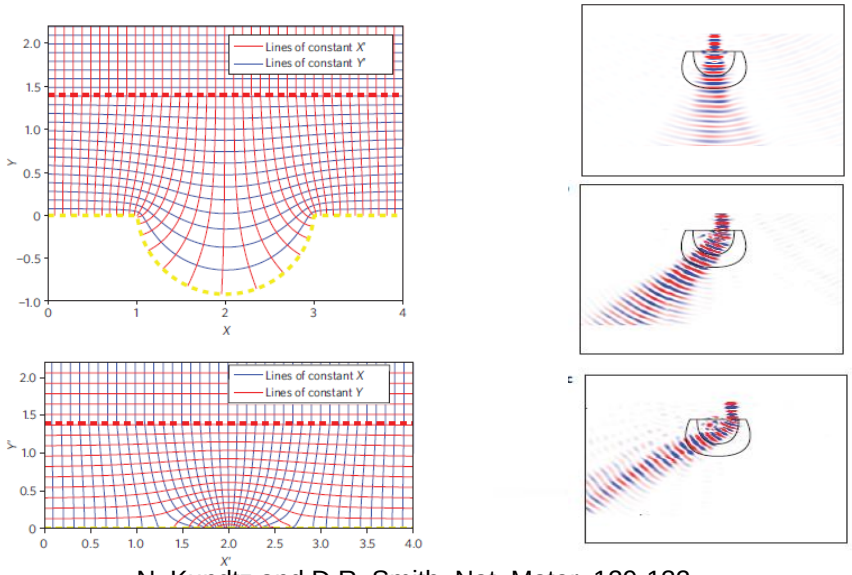
Pendry, IEEE Trans on Microwave Theory and Techniques **47**, #11, 2075 (1999)



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

Non-Resonant Structures

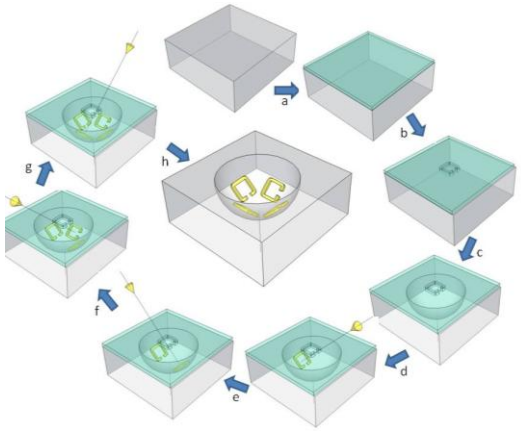


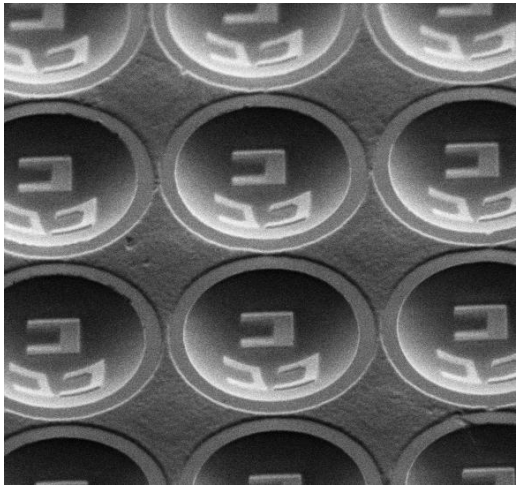


N. Kundtz and D.R. Smith, Nat. Mater. 129-132 (2010).

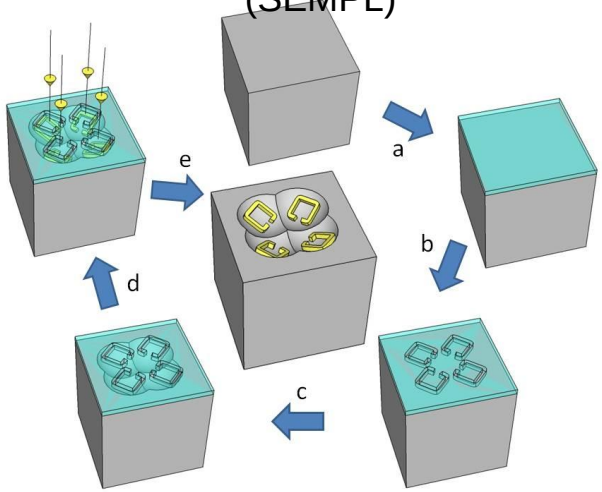
MPL Variants

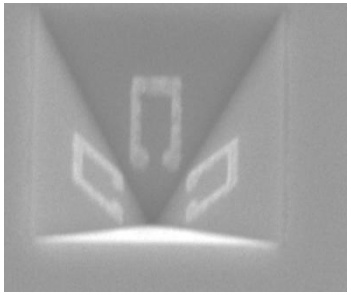
Self Aligned
Membrane Projection Lithography
(SAMPL)

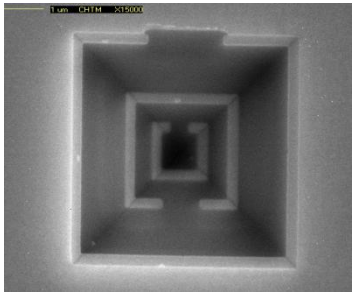


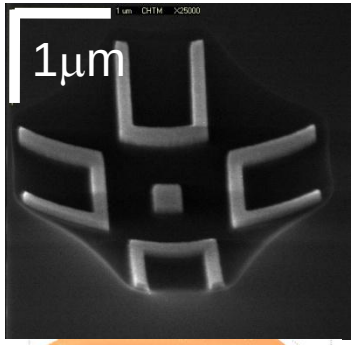


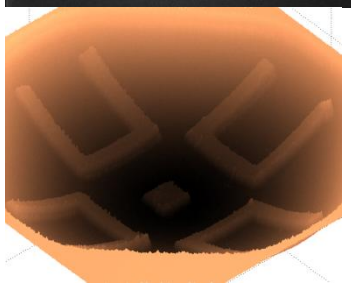
Single Evaporation
Membrane Projection Lithography
(SEMPL)



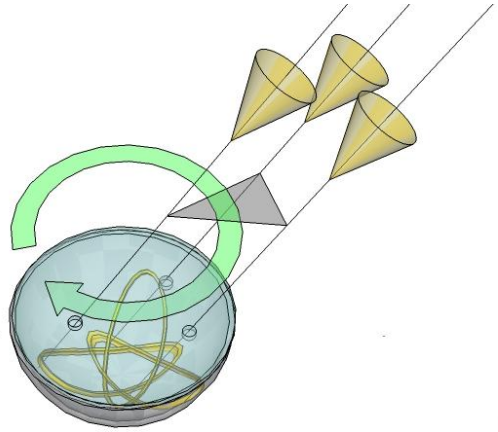


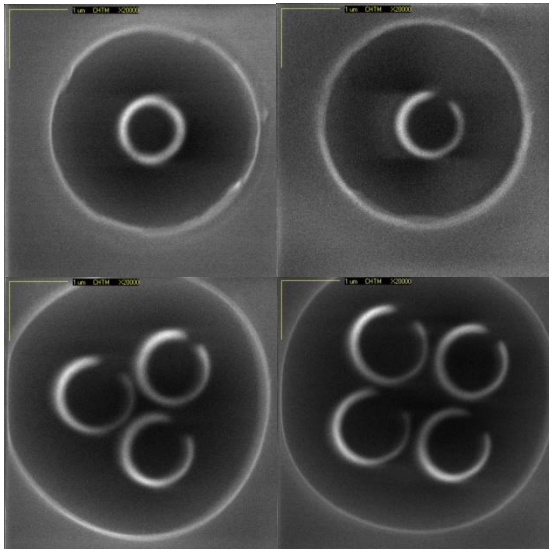




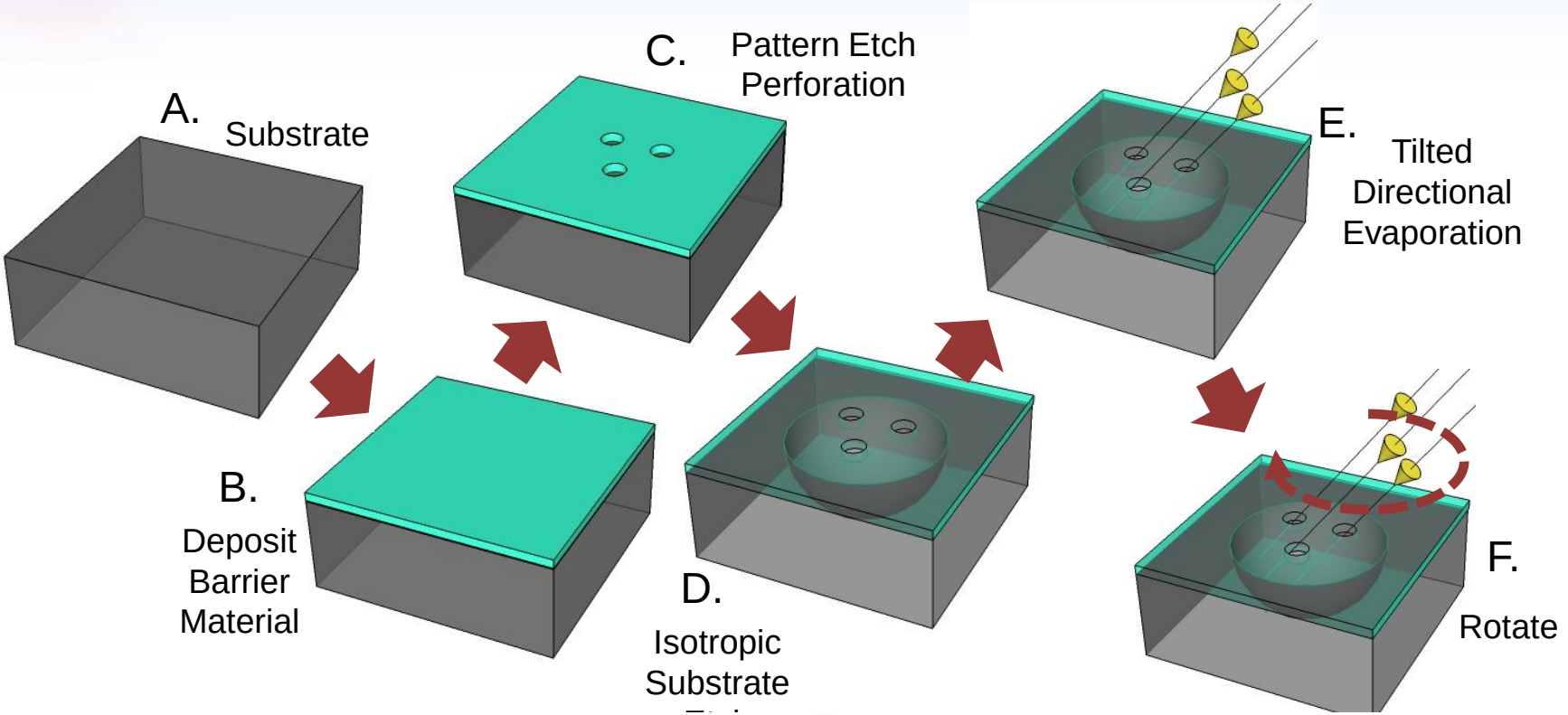


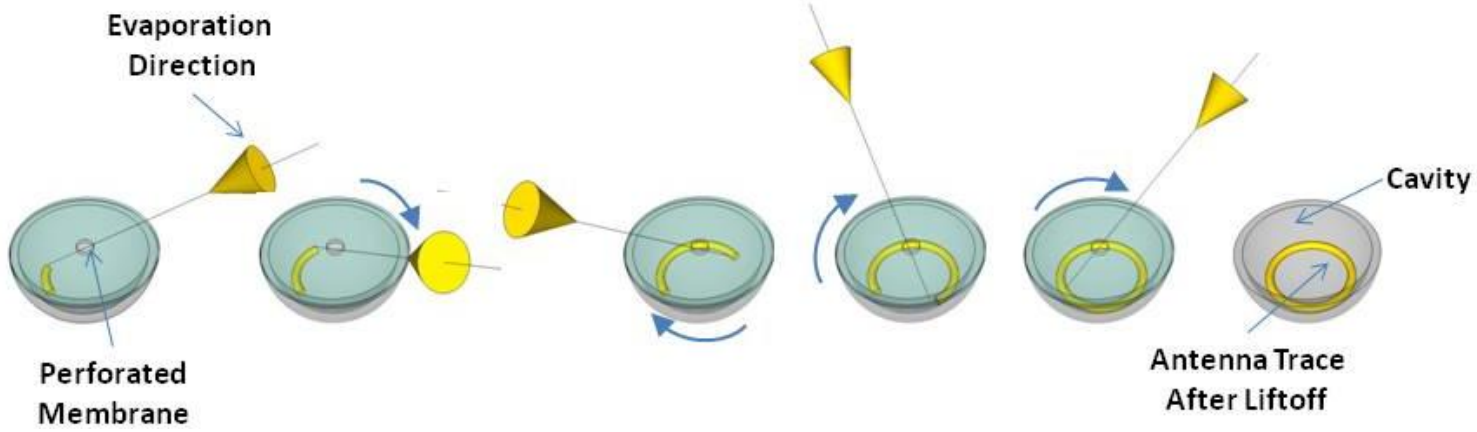
Dynamic Membrane
Projection Lithography



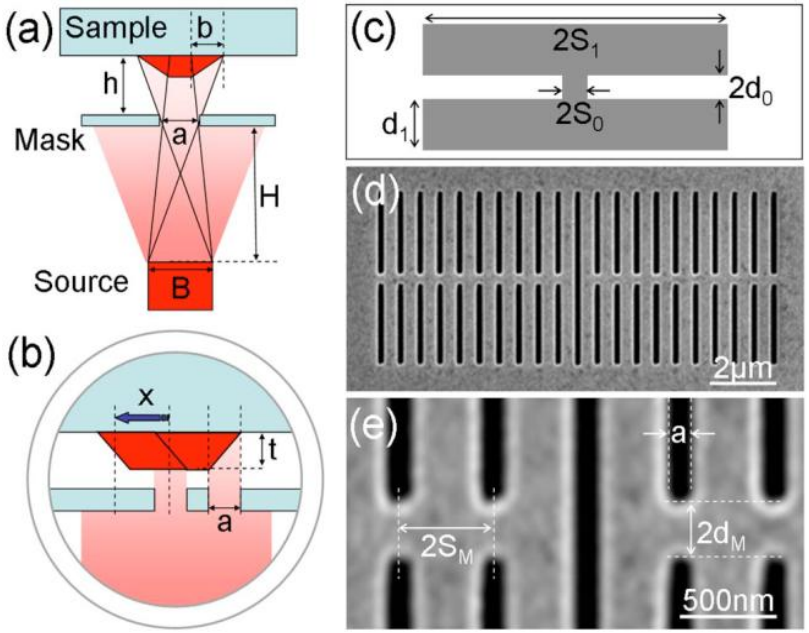


Self-Aligned Process Flow

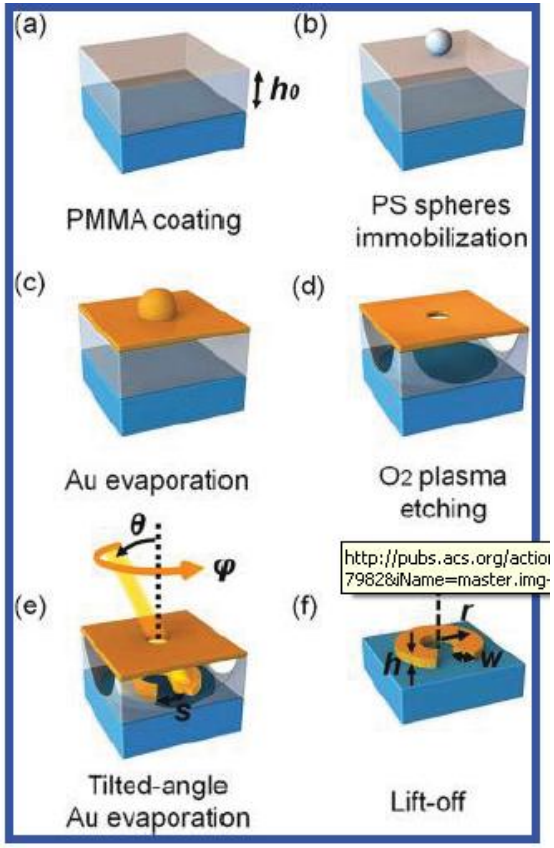




Dynamic Nano Stencil Lithography
Hole-Mask Lithography



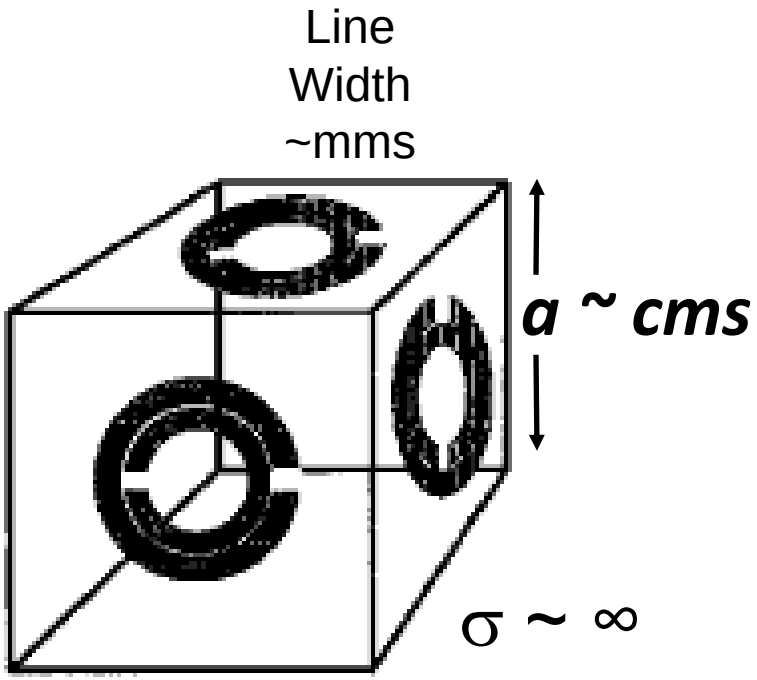
L. Gross et. al. Applied Phys Lett, **90**, 093121 (2007)



Giessen et. al. ACS Nano, **6**, 979-985, (2012)

Translating 3D metamaterials from RF to IR: Achieving $\mu \neq 1$

RF/Microwave

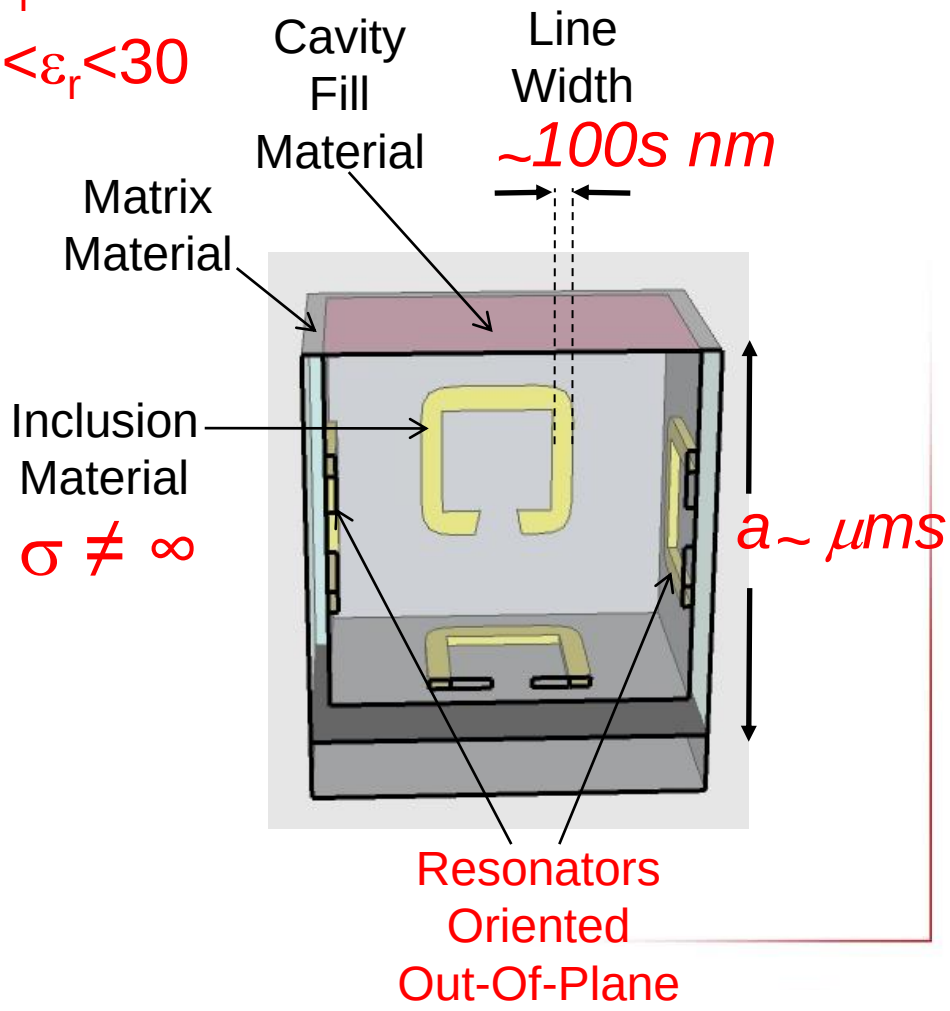


Pendry - 1999

Infrared

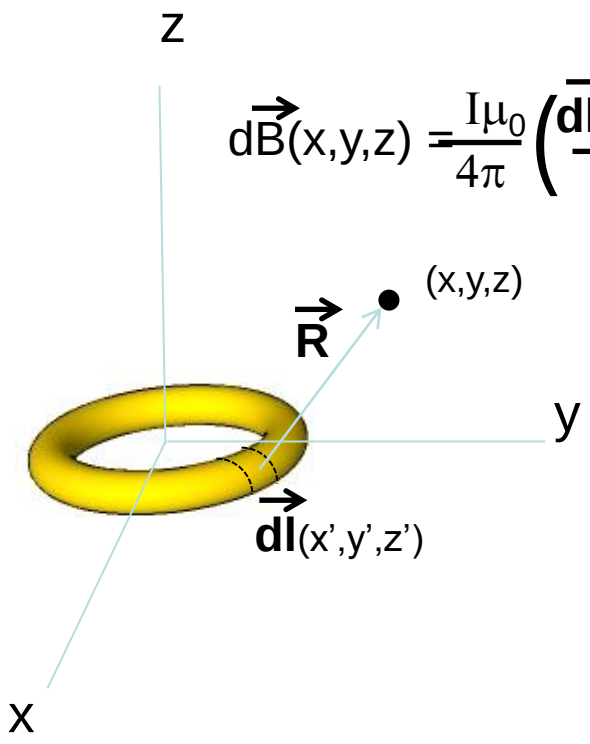
$\mu_r \sim 1$

$1 < \varepsilon_r < 30$

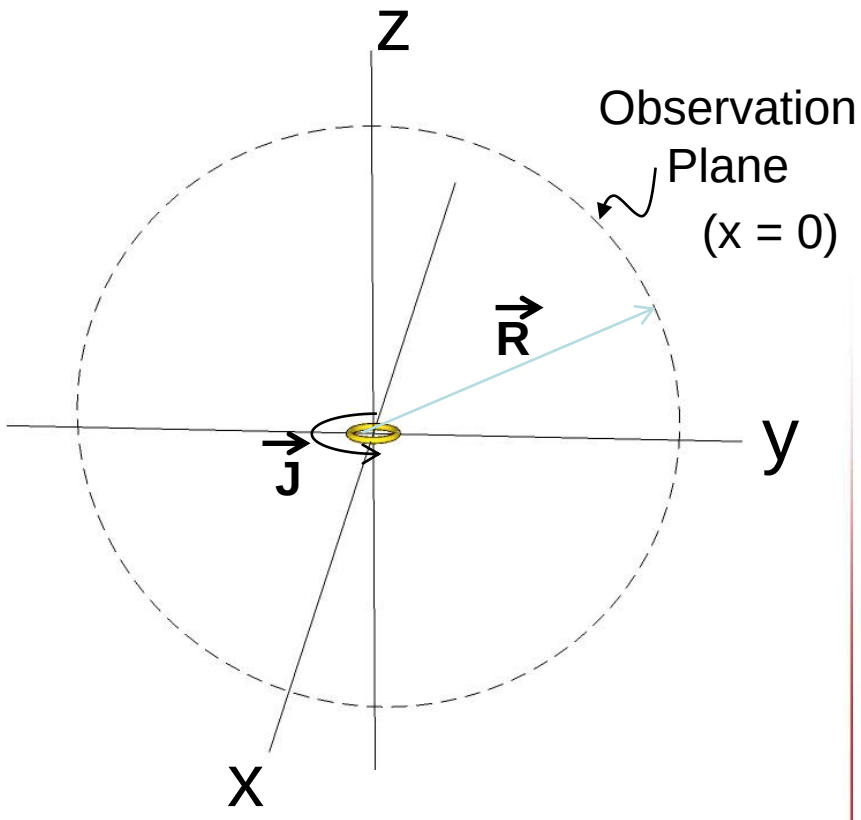


Magnetostatic Behavior : Biot-Savart Law

$$d\vec{B}(x,y,z) = \frac{I\mu_0}{4\pi}\left(\frac{\vec{dl'} \times \vec{R}}{R^3}\right)$$



A



B

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**