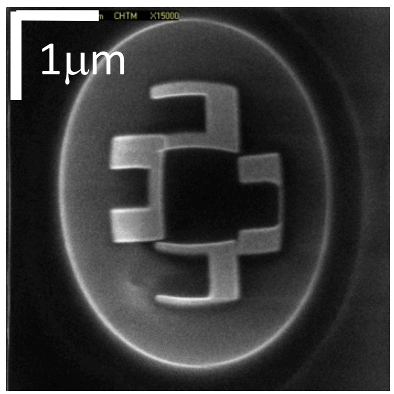
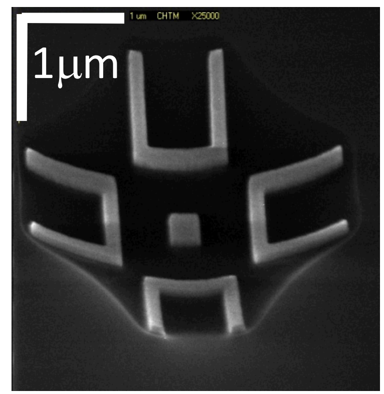
SAND2010-0217C

3-D Metamaterial Fabrication Using Membrane Projection Lithography





D. Bruce Burckel, P. Davids, I. Brener, G. A. Ten Eyck, A. R. Ellis, J. R. Wendt, and M. B. Sinclair

dbburck@sandia.gov

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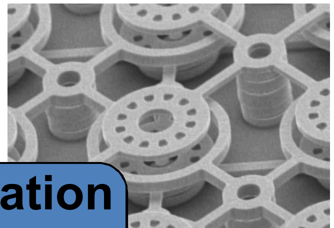
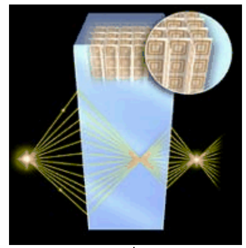
Sandia's MST Program at a Glance

Metamaterials Science & Technology



fabrication & testing

•DUVL, EBL, PnP, NIL
•spectroscopic phase meas.



•<0.1 db/Wave
•perfectly absorbing structures

theory & modeling

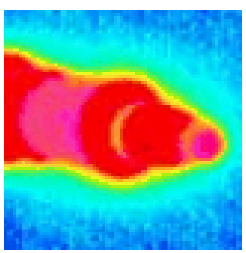
•loss fundamentals
•MPP HPC design environment
•full anisotropic optimization

Metamaterials

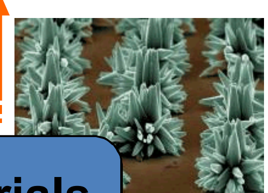
low loss

IR 8-12 μm

3D

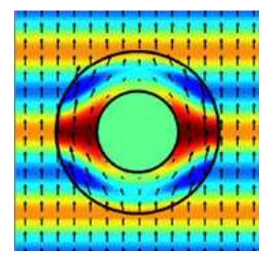


• thermal IR
• limits to shorter-λ



materials science

•dielectrics/composites/alloys
•low-n polymer 3D matrix materials



university Partners

•volumetric energy flow, large area
•multiple directions
•multiple polarizations

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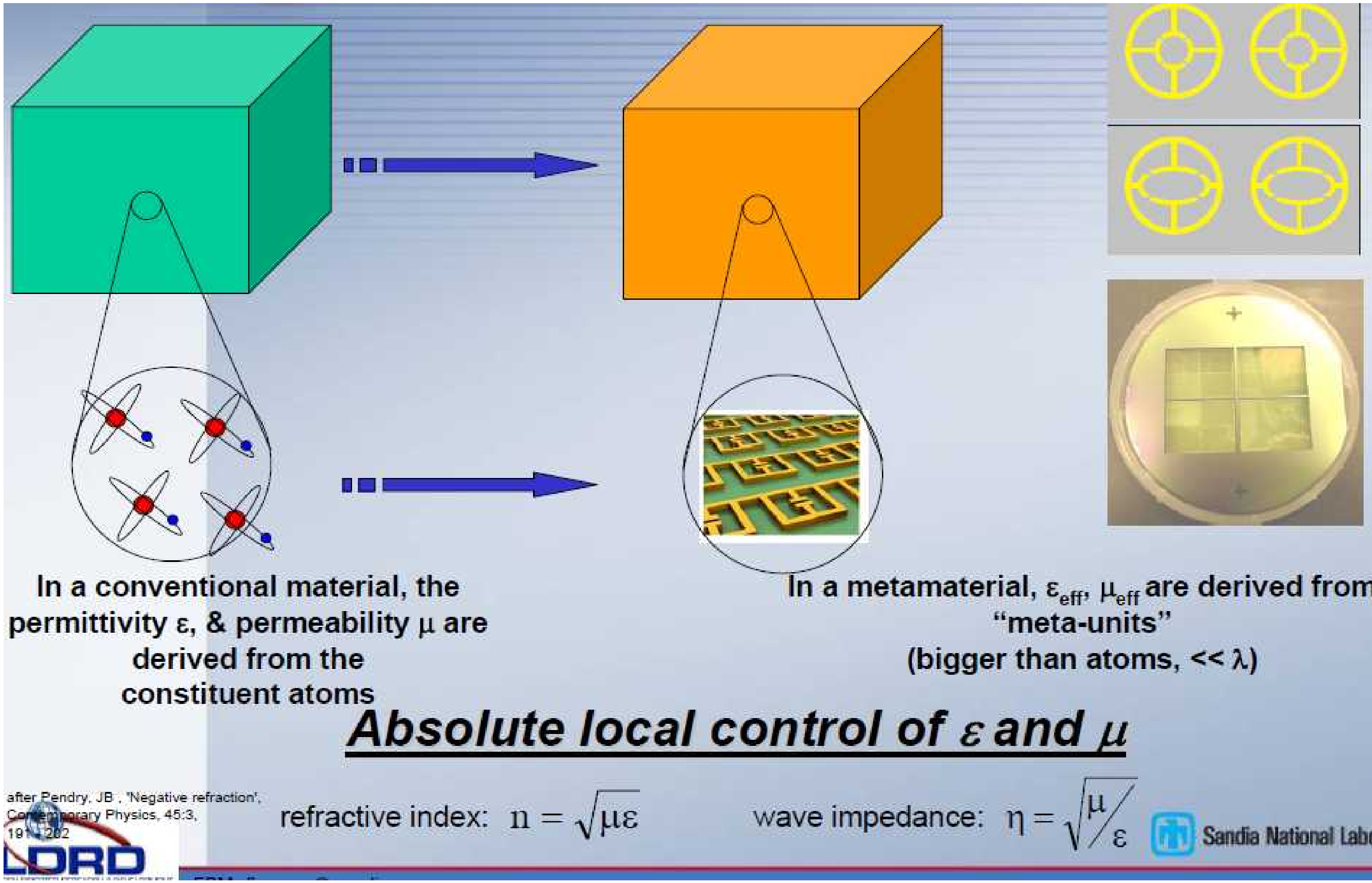
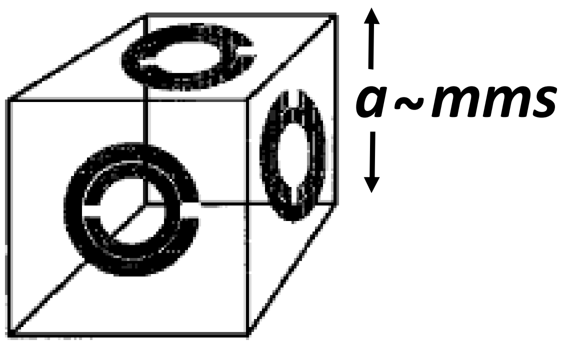
Concept of Metamaterials



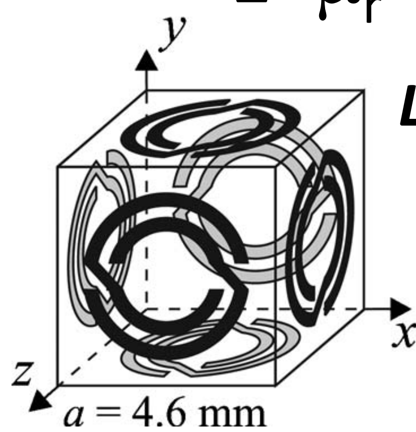
RF/Microwave Metamaterials

$1<\varepsilon_r<300$ $1<\mu_r<30$

Notional Design



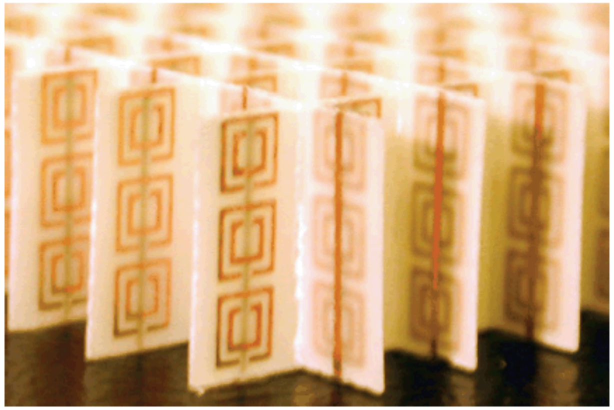
Pendry, IEEE Trans on Microwave Theory and Techniques **47**, #11, 2075 (1999)



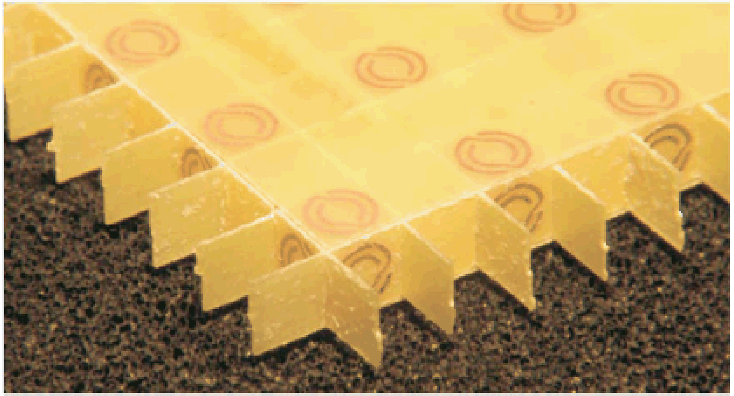
Linewidth ~mms

Baena, APL **91**, 191105, (2007)

Experiment



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



Baena, APL **91**, 191105, (2007)

RF/μWave Designs → IR/Optical

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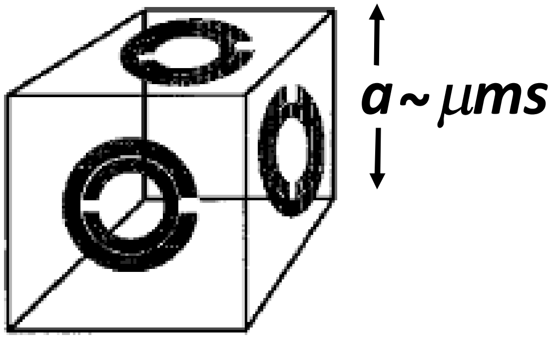
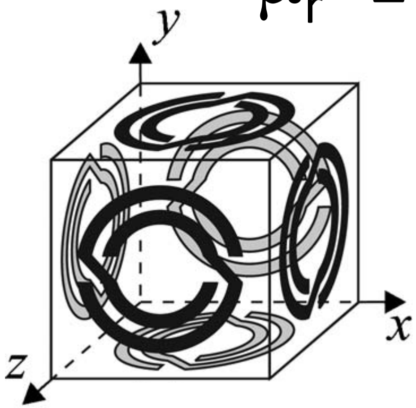
$1<\varepsilon_r<40$ $\mu_r=1$





Linewidth ~100nm

Material Challenges
- Maximum ε_r and μ_r are OOM smaller than for RF frequencies
- Metals become lossy at IR and optical frequencies

Fabrication Challenges
- Linewidths require advanced lithography
- Most advanced lithography techniques have short depth of focus – can only form planar patterns
- Post processing assembly not possible at these size scales – Full resonator must be fabricated in place
- Out-of-plane features are limited in aspect ratio by typical etch/deposition methods

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IR and Optical Metamaterials

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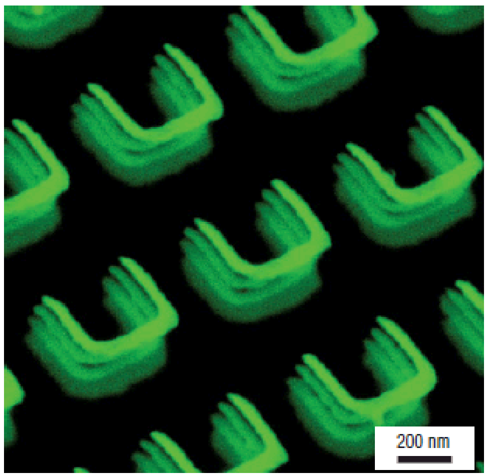
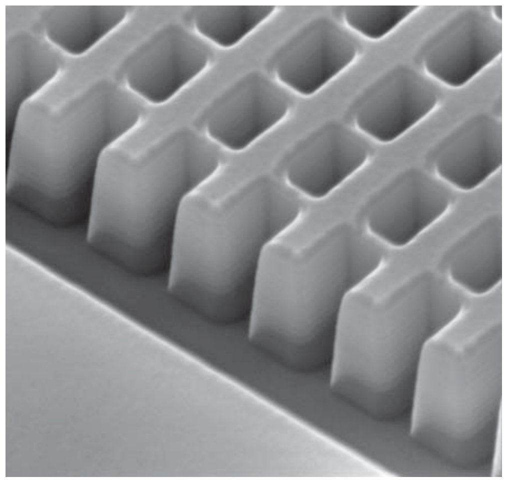
Stacked Planar

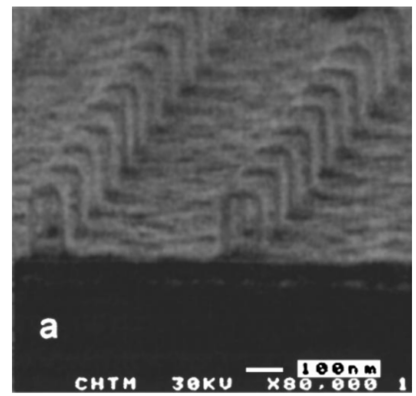


Giessen- Nature Mat **7**, 31, (2008)

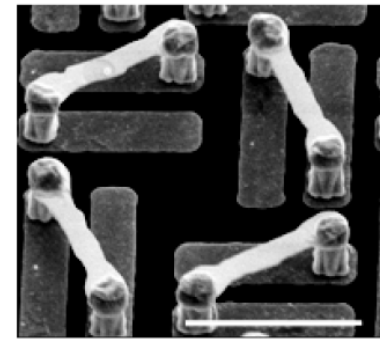


Zhang, Nature **455**, 376 (2008)

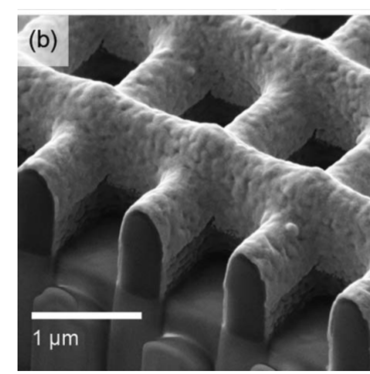
Out-of-Plane Current



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



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



Wegener, Optics Lett **34**, 16, (2009)

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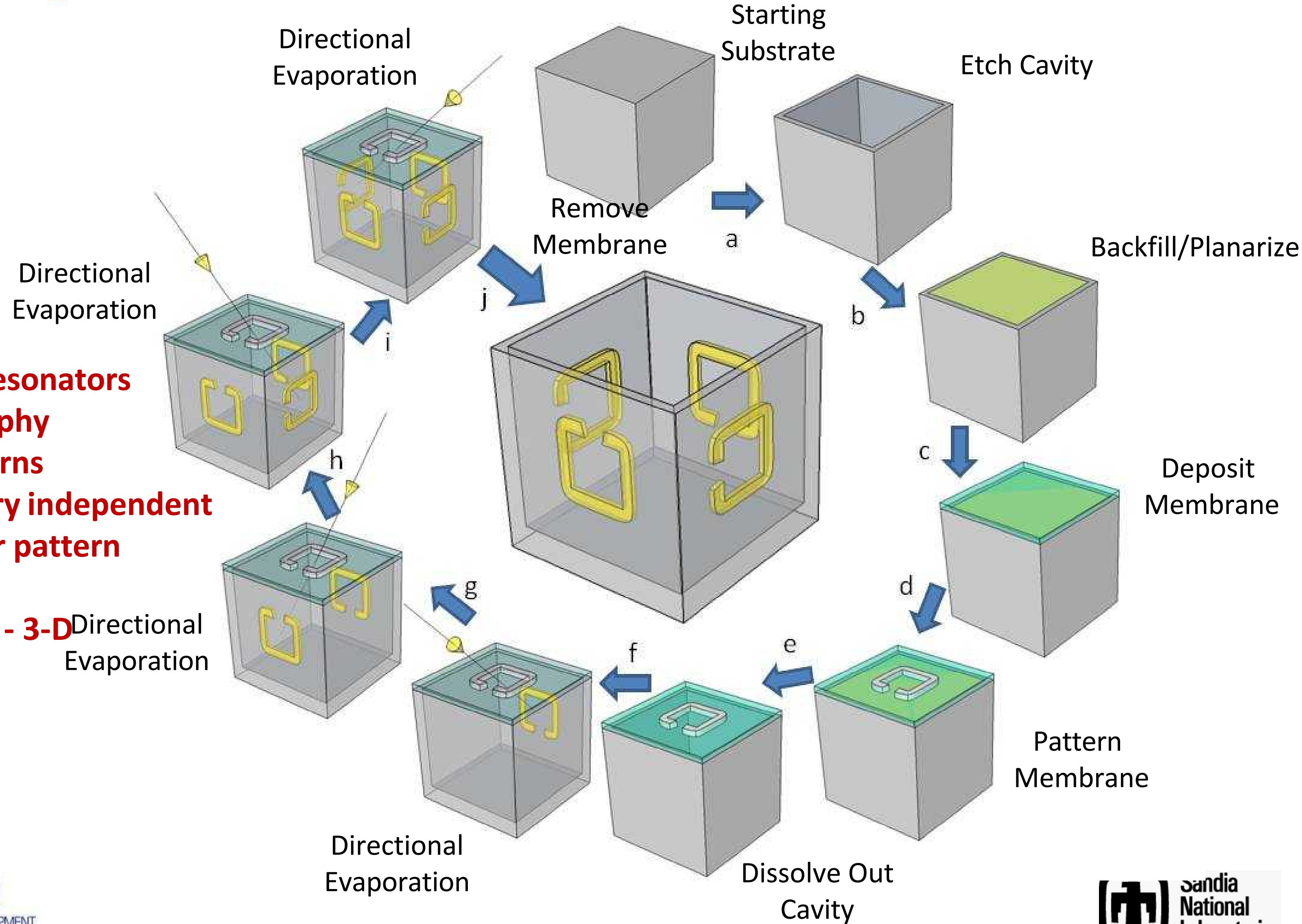
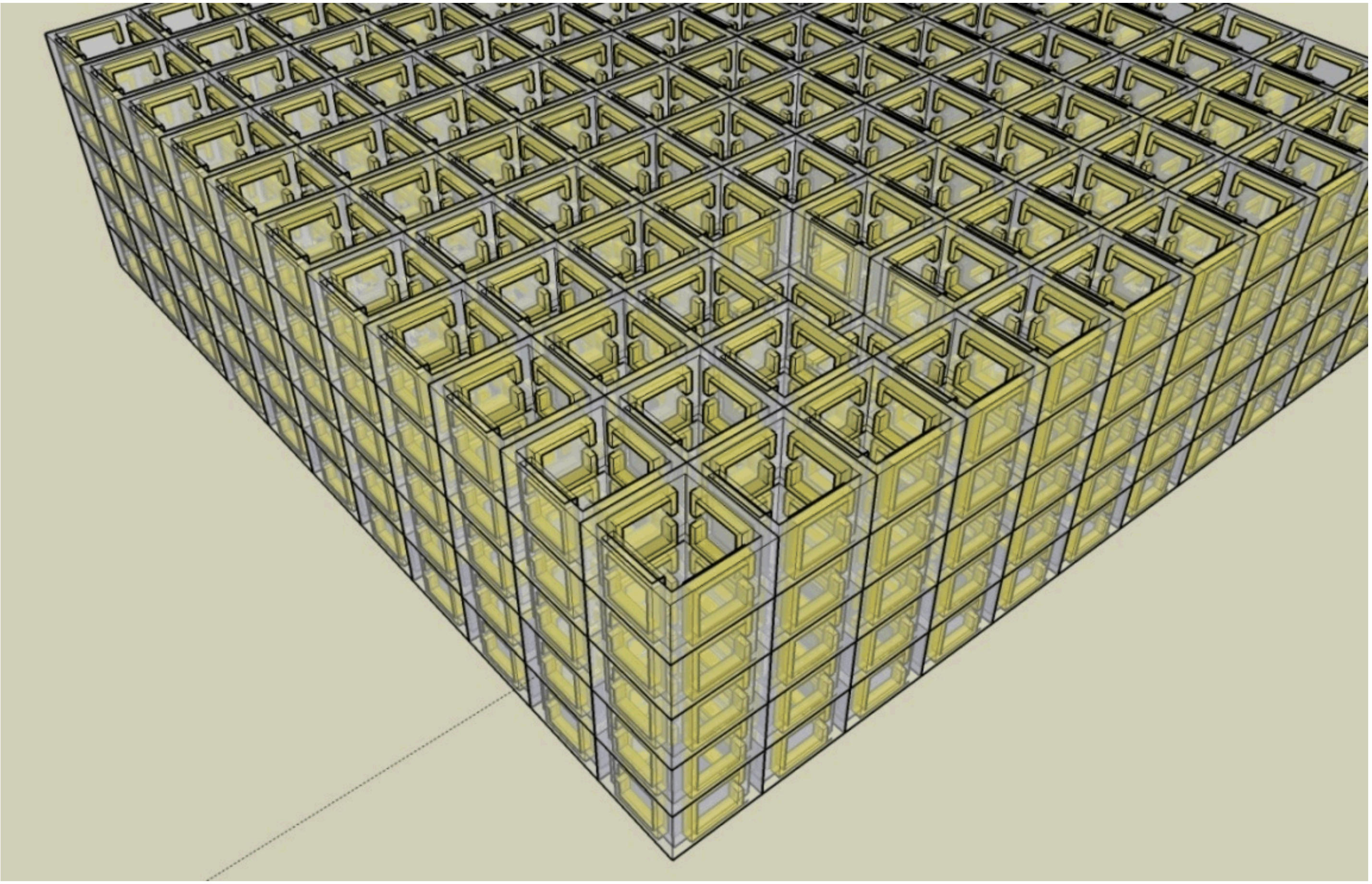
Membrane Projection Lithography



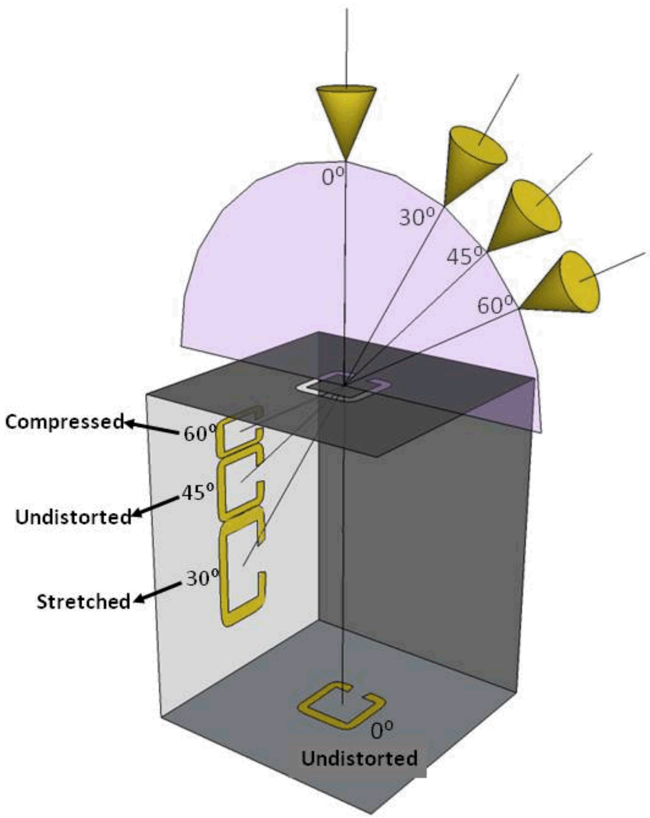
- **Out-of-plane resonators**
- **Planar lithography**
- **Arbitrary patterns**
- **Cavity geometry independent from resonator pattern**
- **Scalable**
- **Layer-by-layer - 3-D**

Layer-by-layer Route To 3D Material

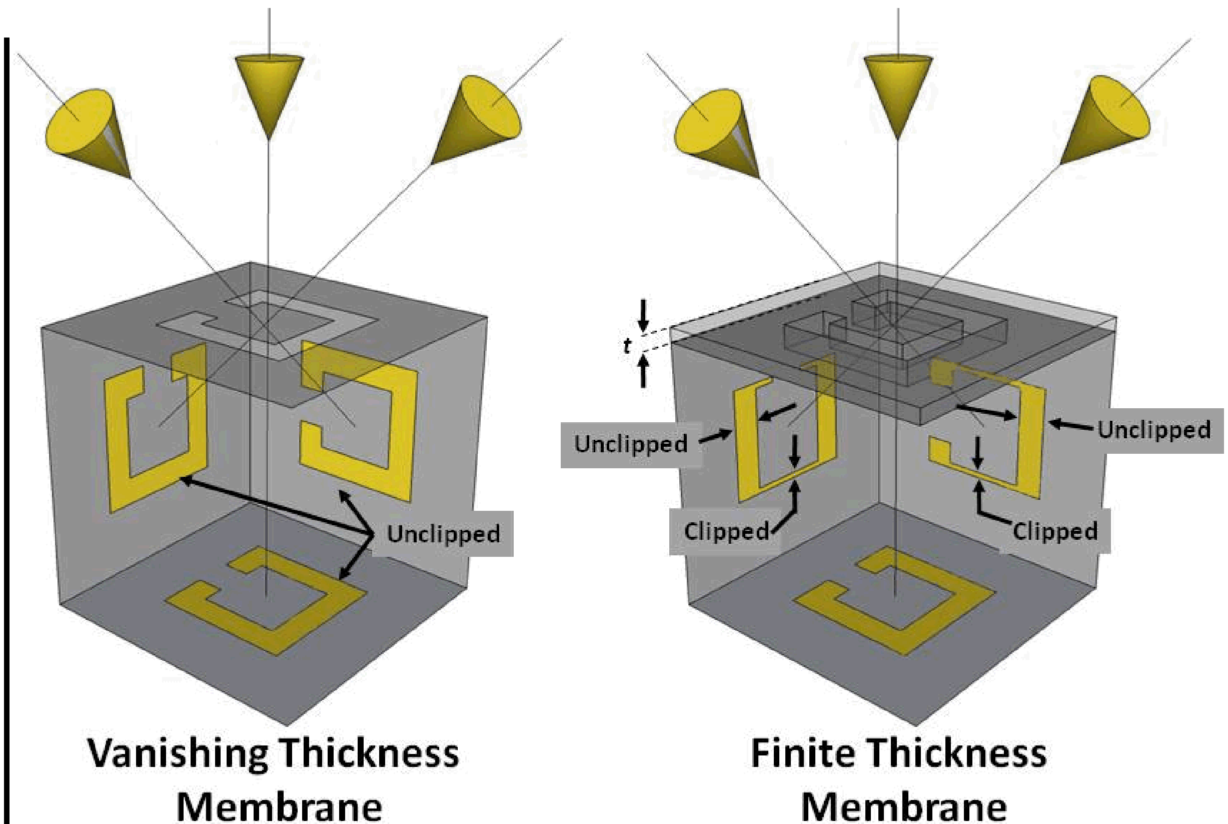


Real Membranes result in Linewidth Clipping

Projection at 45° Preserves Pattern Shape



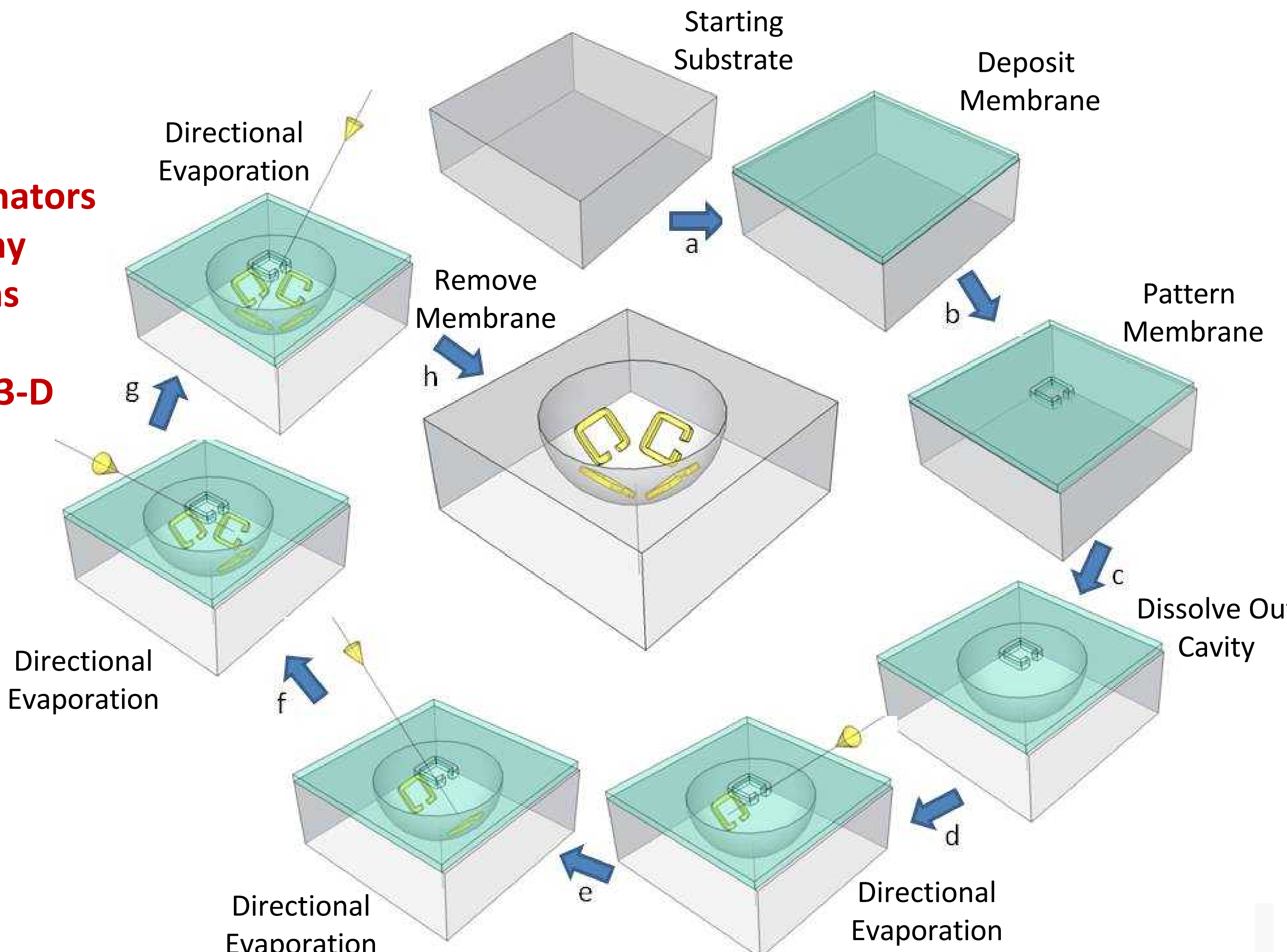
Real Membranes result in Linewidth Clipping



Self-Aligned MPL

Advantages

- Self-Aligned
- Non-planar resonators
- Planar lithography
- Arbitrary patterns
- Scalable
- Layer-by-layer - 3-D



SAMPL – Patterned Membranes

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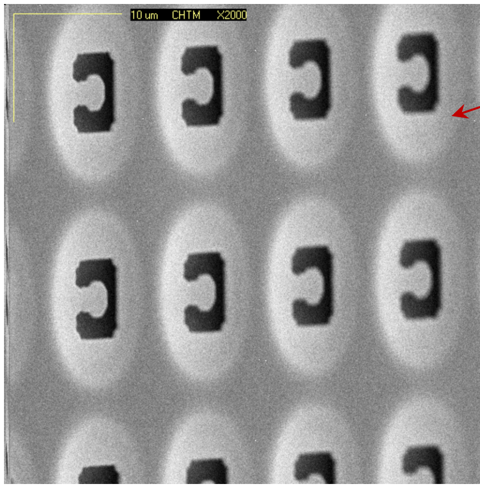
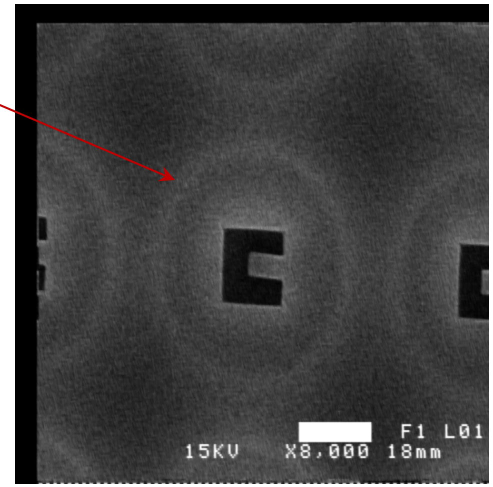
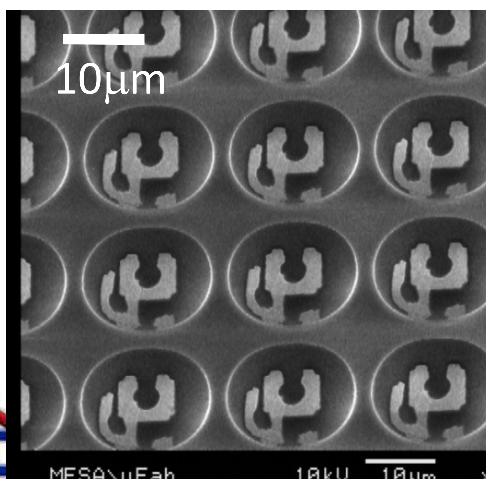
Contact Lithography | **E-Beam Lithography**

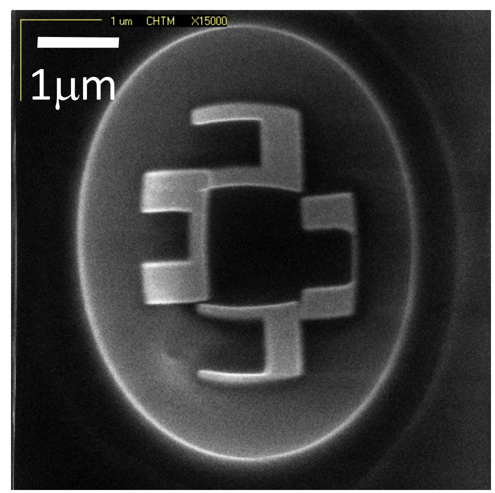


Halos show extent of cavity



Suspended Patterned Membrane





Au-SRRs After Liftoff

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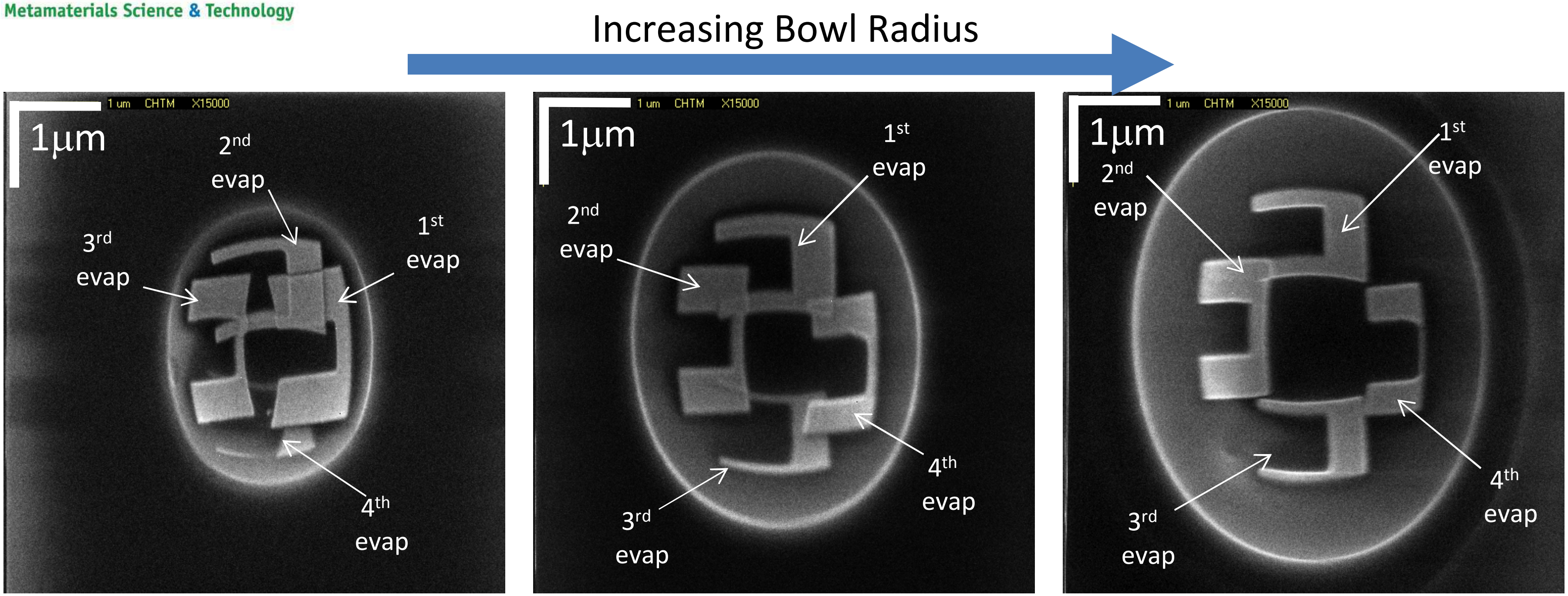
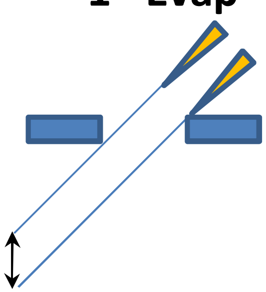
Curved SRRs via MPL

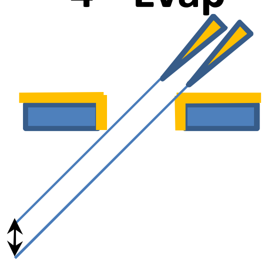


1^{st} Evap



1^{st} Evap linewidth inhomogeneity due to membrane thickness

4^{th} Evap



4^{th} Evap linewidth inhomogeneity due to membrane thickness + accumulated deposition

240nm total deposition through ~340 nm clear aperture

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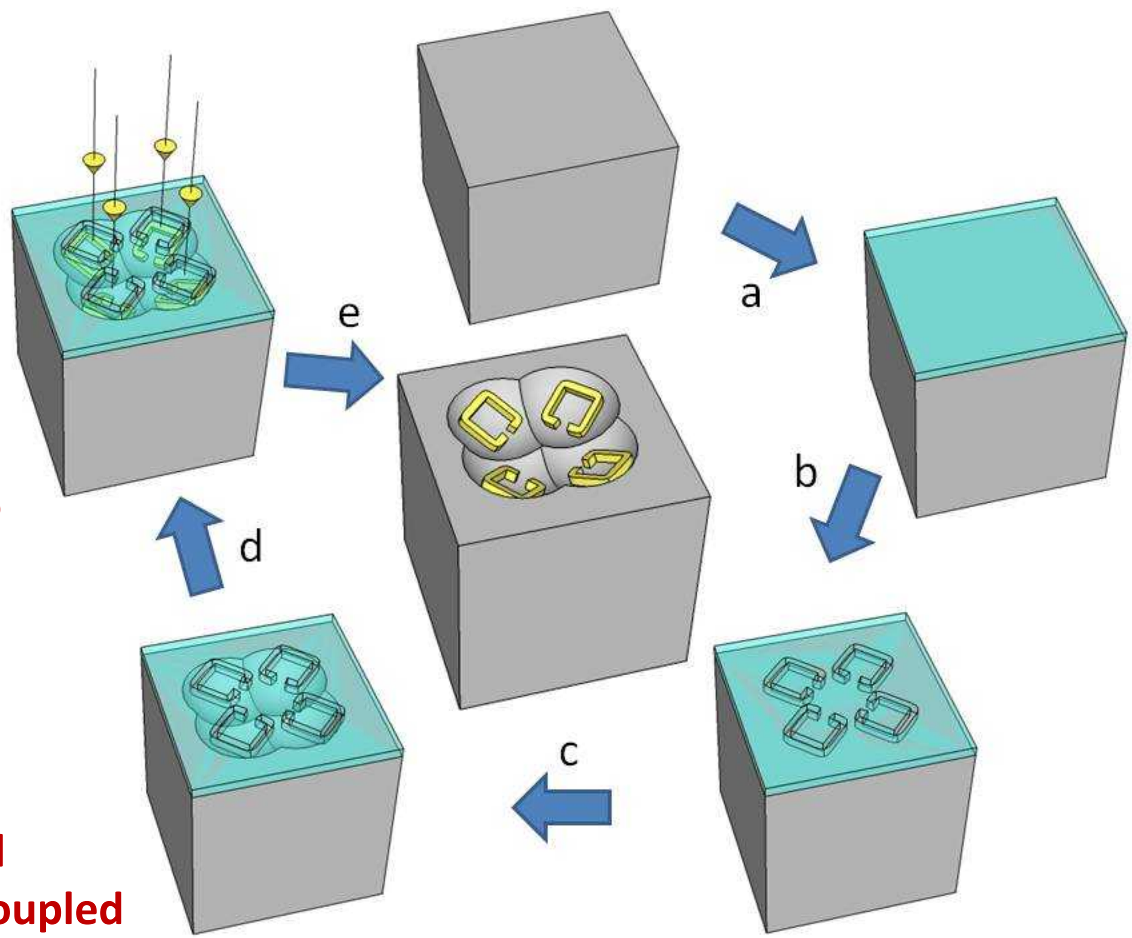
Single-Evaporation MPL



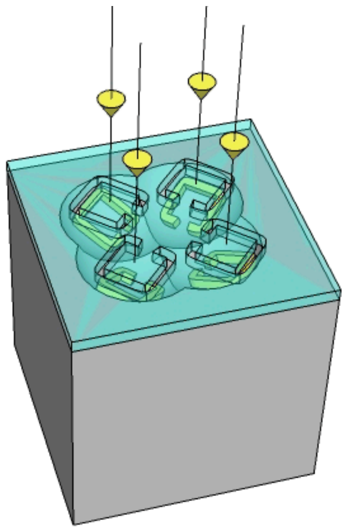
Advantages

- Self-Aligned
- Non-planar resonators
- Planar lithography
- Arbitrary patterns
- Single Evaporation Step
- Scalable
- Layer-by-layer - 3-D

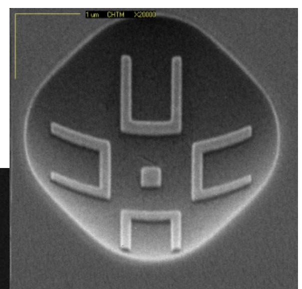
Caveats

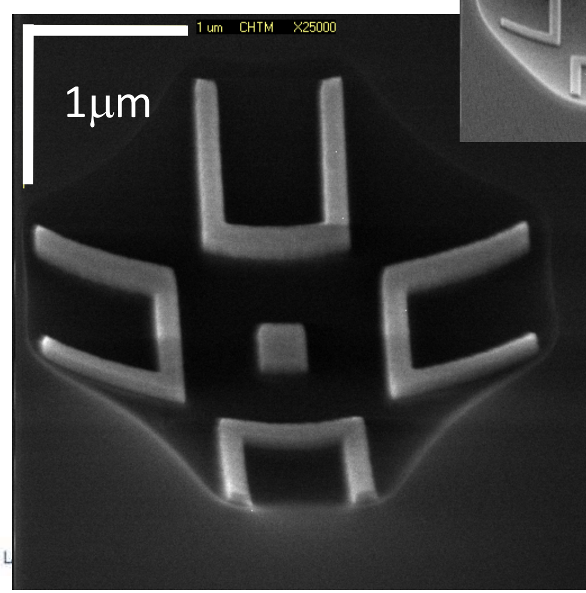
- resonator cavity and pattern are tightly coupled

Fabrication of Out-of-Plane MM Resonators

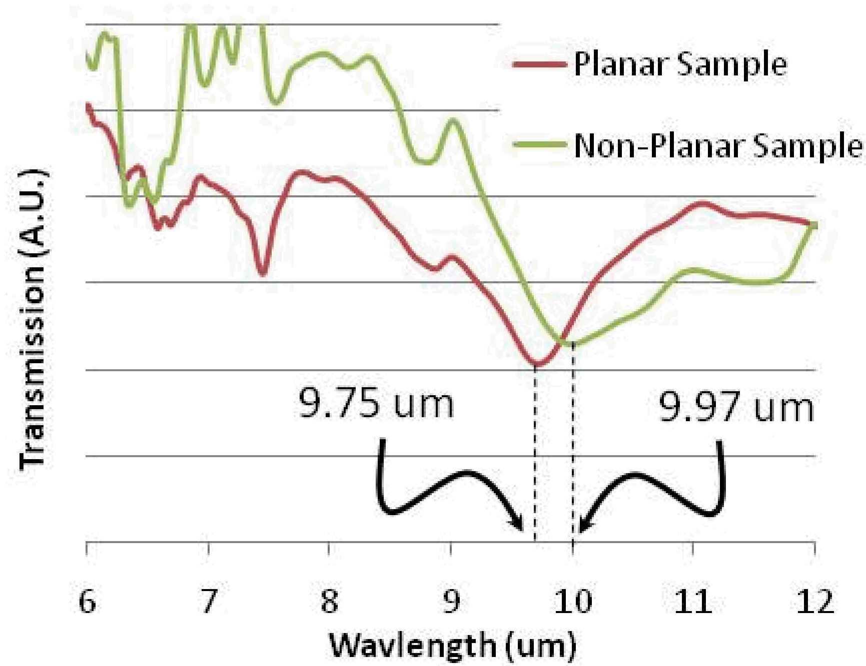


Single Evaporation
Self-Aligned
Membrane
Projection
Lithography





Un-Normalized Normal Incidence
FTIR Transmission Data



Impact of Out-Of-Plane Resonators

1. Resonance shift due to projection of pattern out of plane
2. Resonance broadening.

Calculating Induced Magnetism For A Planar Current Stripe

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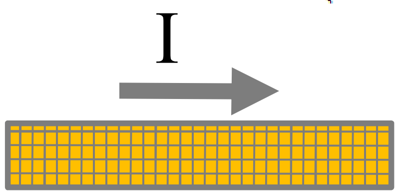
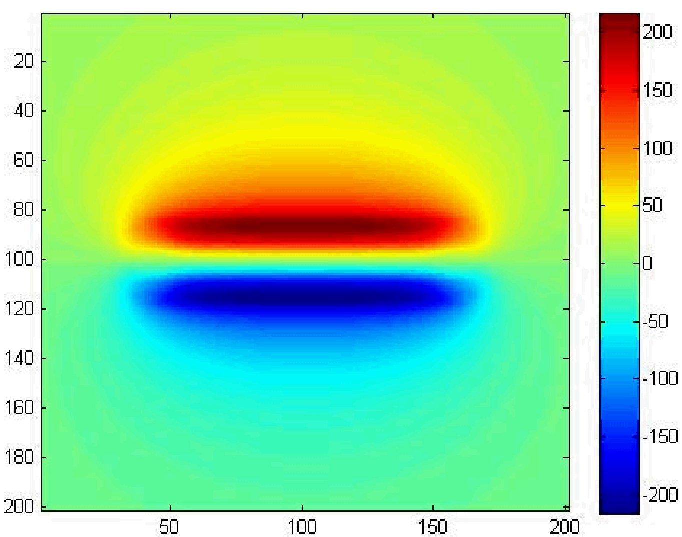
Magnetic Field

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

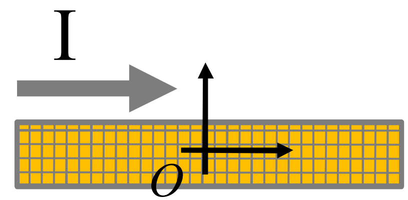




Magnetization Vector

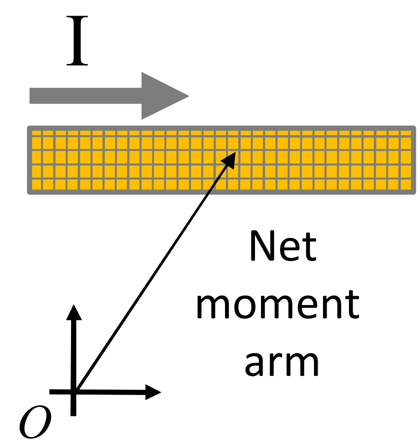
$$\vec{M} \equiv \frac{1}{2c}\sum \vec{r}_i \times \vec{J}_i$$

Origin A:



$$\vec{M} = 0$$

Origin B:



$$\vec{M} \neq 0$$

We will always choose the center of mass coordinate as the origin in this work

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Computation Cell for Single Stripe Geometry

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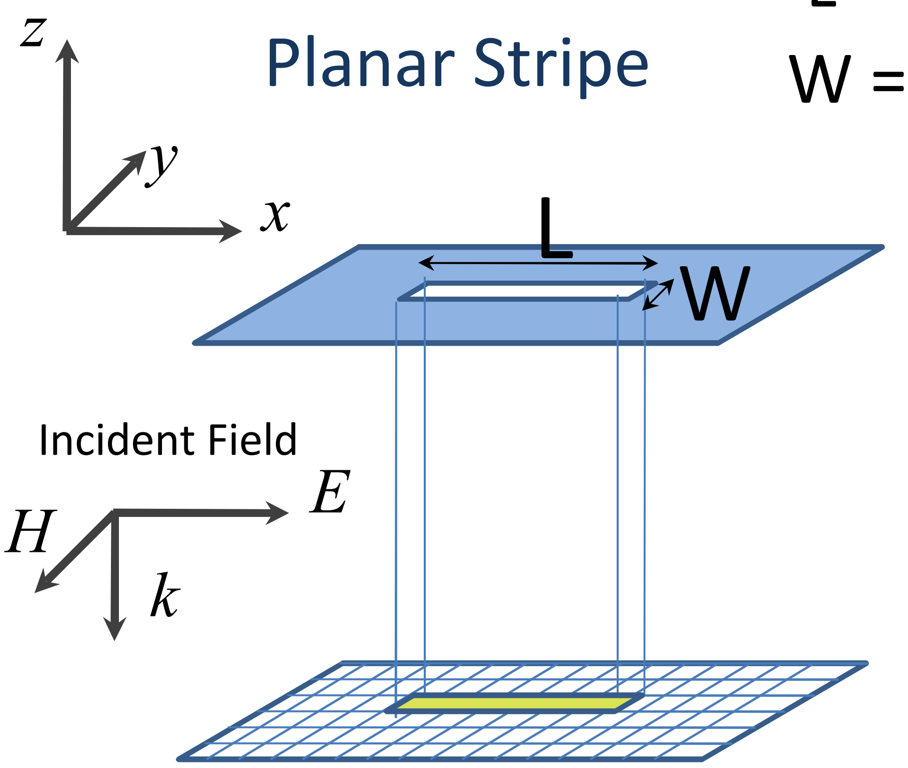
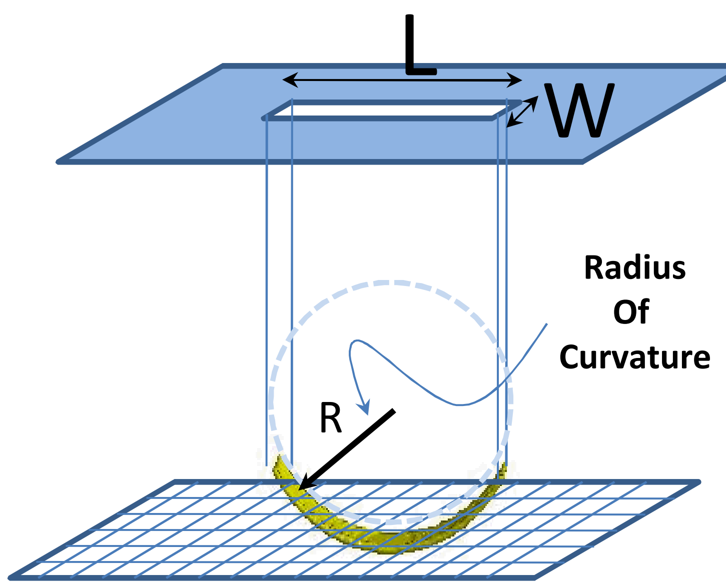
$L = 1\ \mu m$

$W = 0.2\ \mu m$

Planar Stripe



Curved Stripe



Simplified Current Model:

Assume E-field induces a constant current with only an x-component.

Simplified Current Model:

Assume E-field induces a constant current with only an x-component – curvature of metal also creates z-component.

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Effect of Adding Curvature: Single Stripe

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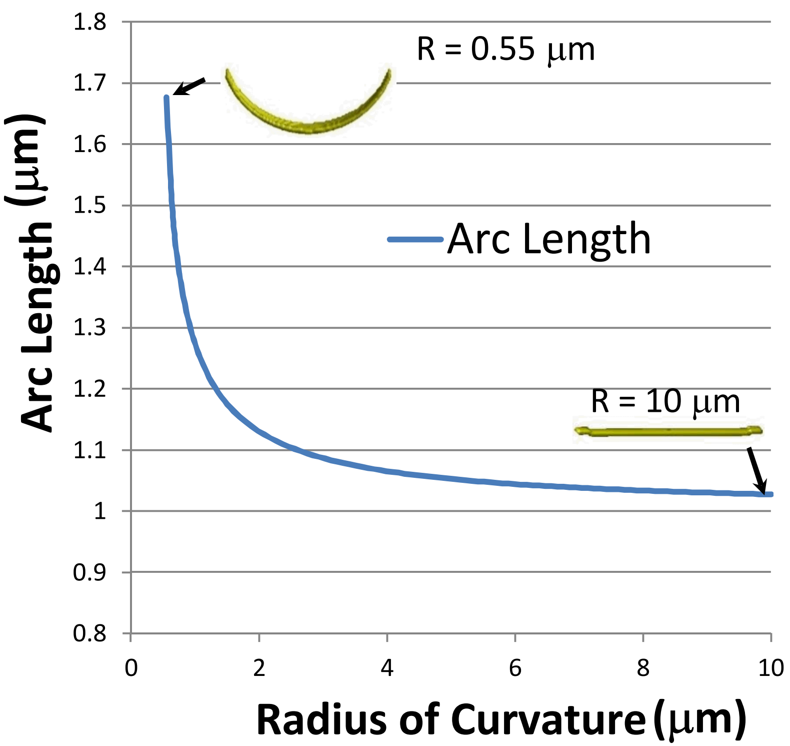
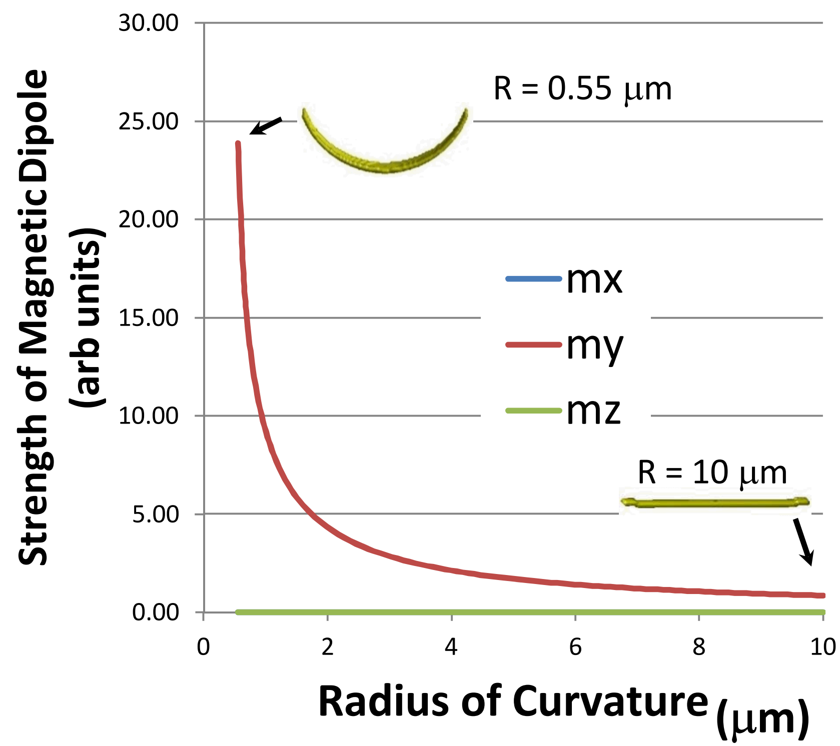
Arc Length Dilation



Non-Zero Magnetization



Mask Dimensions:

- L = 1 μm
- W = 0.2 μm

m_x, m_z are identically 0

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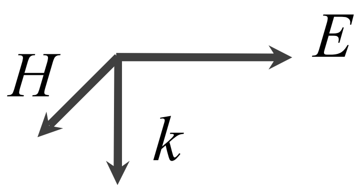
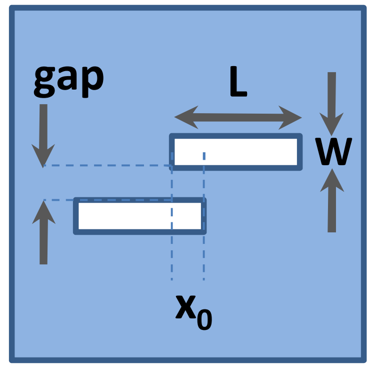
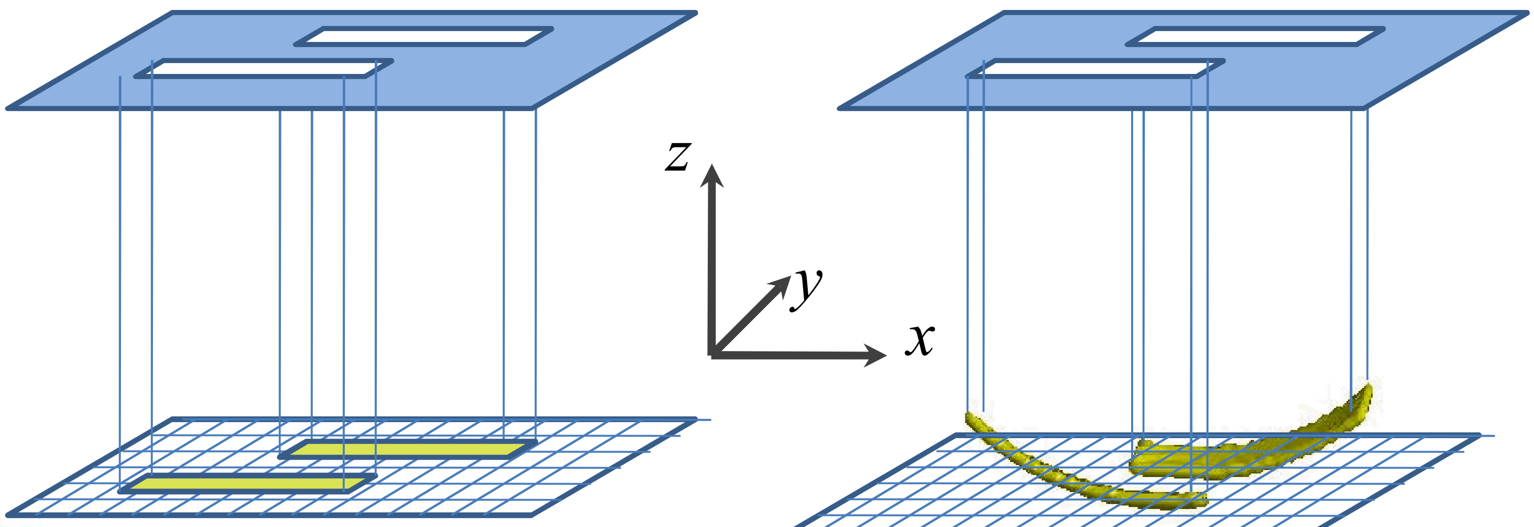
Computation Cell for Split Wire Pair Geometry

Incident Field





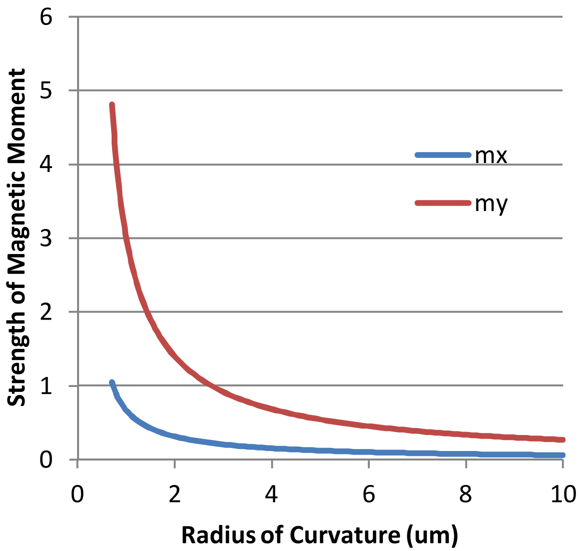
Top-Down Schematic of SWP Membrane



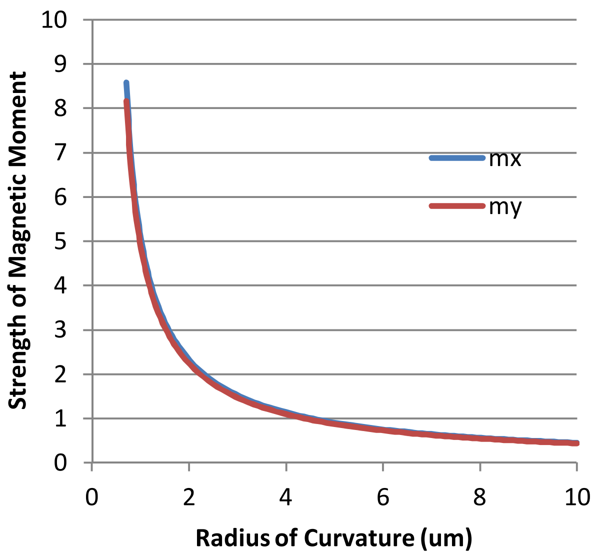
Effect of Adding Curvature: SWP

Metamaterials Science & Technology

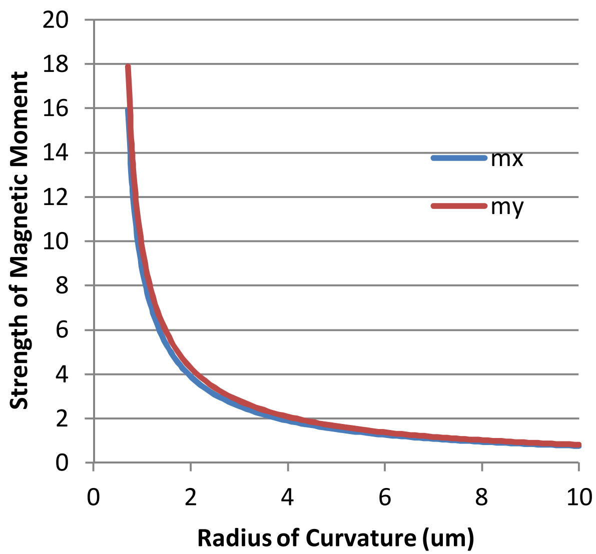
Tunable Non-Zero m_x and m_y



$L = 0.5\ \mu m$
$W = 0.1\ \mu m$
$x_0 = 0.0\ \mu m$
$gap = 0.05\ \mu m$



$L = 0.5\ \mu m$
$W = 0.3\ \mu m$
$x_0 = 0.2\ \mu m$
$gap = 0.3\ \mu m$



$L = 0.5\ \mu m$
$W = 0.3\ \mu m$
$x_0 = 0.0\ \mu m$
$gap = 0.3\ \mu m$

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Simplified Current Model
Biot-Savart vs FDTD

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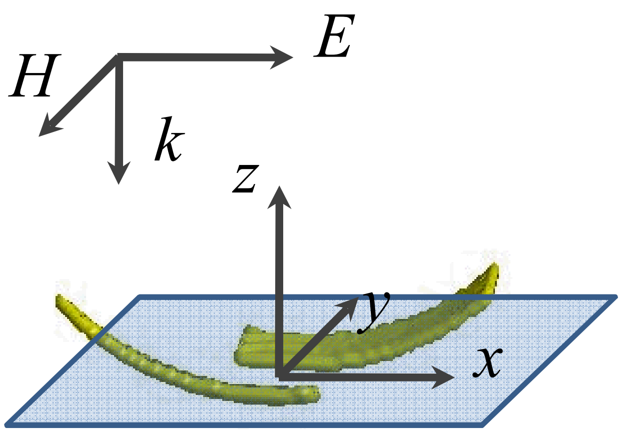
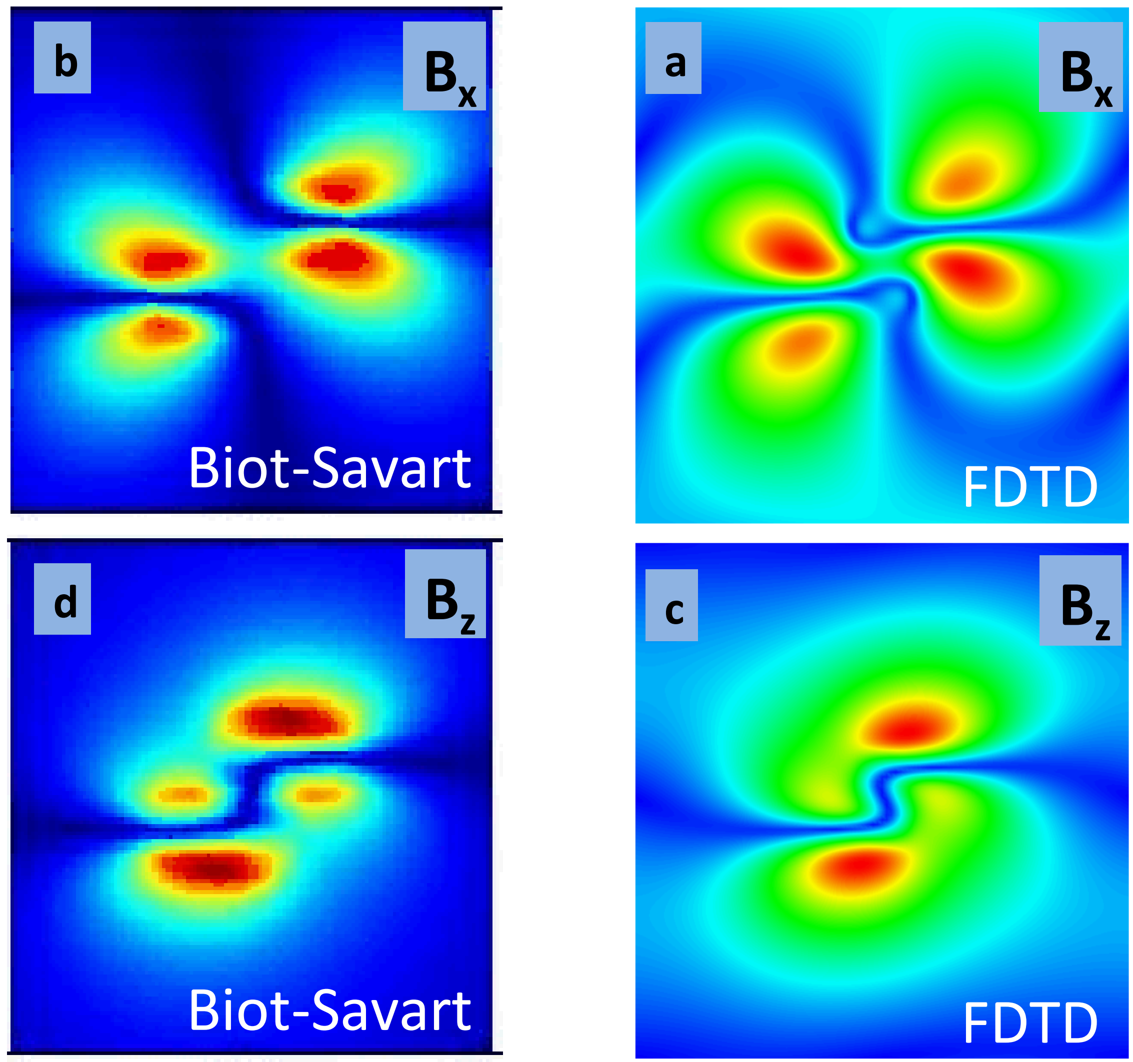
Incident Field



Calculated B-Field
At z = 0



Run Time ~ s

Run Time ~ hrs

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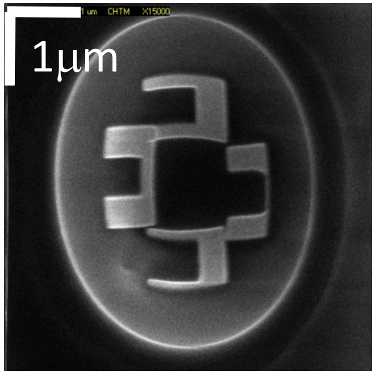
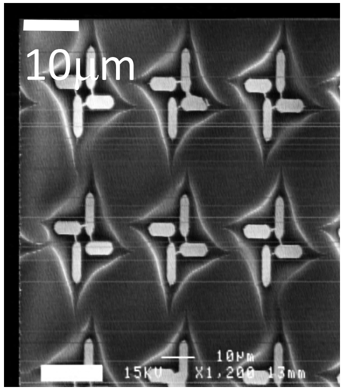
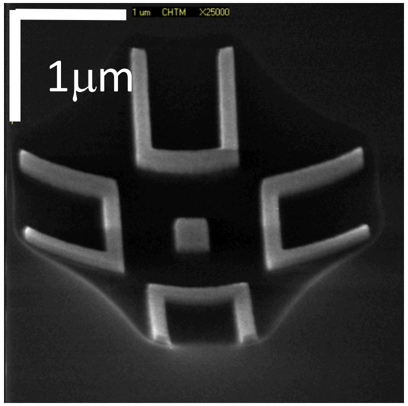
Closing Thoughts

1. MPL offers a fabrication route to 3-D IR/Optical Metamaterials.
2. Vision → Hand crafted unit cells with fully 3-D current flow – leveraging symmetry, geometry and material.
3. Expand modeling and simulation capabilities to develop intuition for design space using MPL.

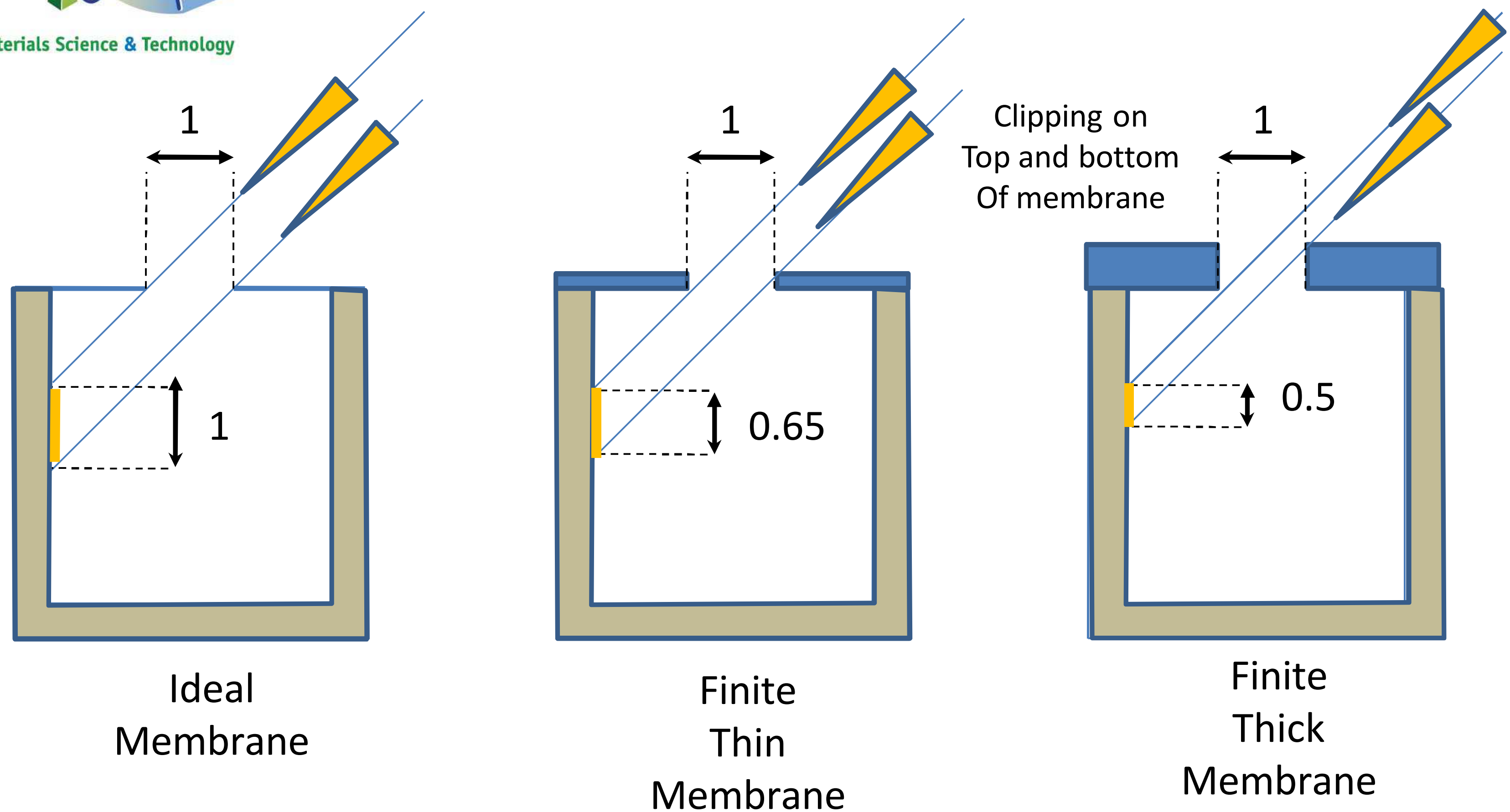






Backup Slides

Impact of Membrane Thickness



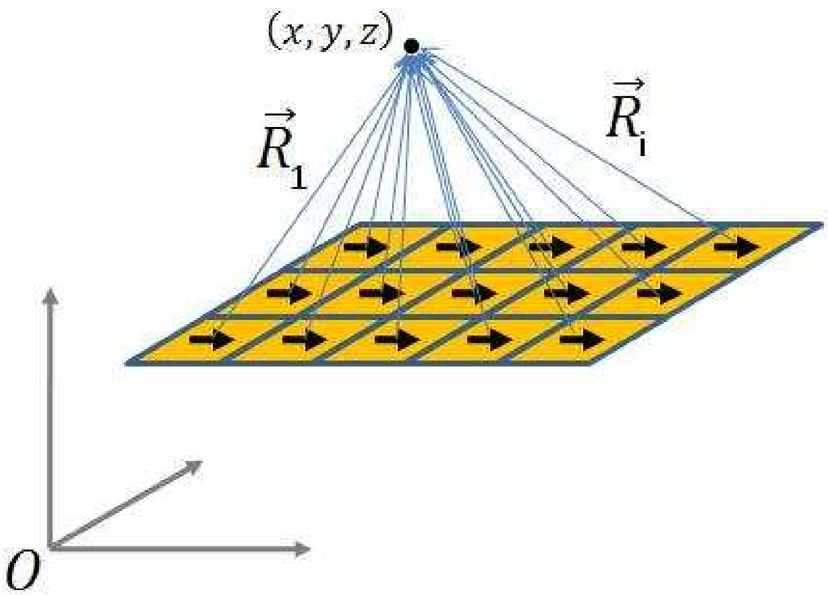
For evaporation at 45^{o}, projected linewidth is decreased by the thickness of the membrane.

Induced Magnetic Response

Metamaterials Science & Technology

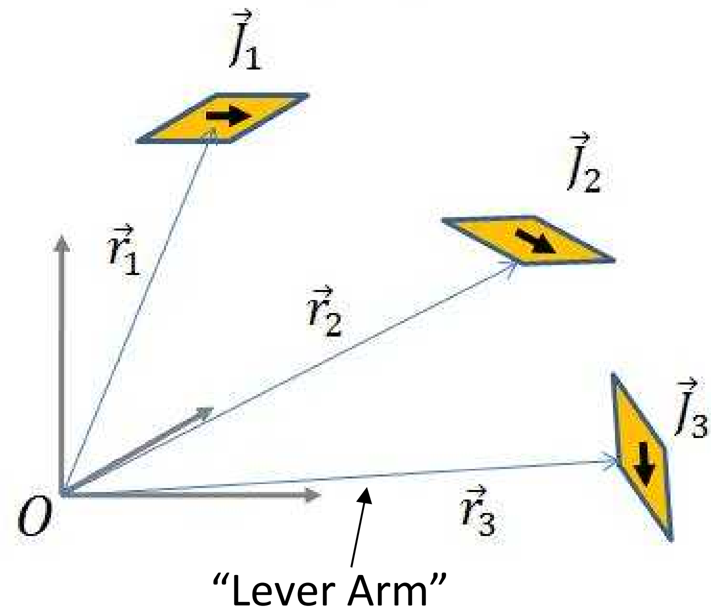
Magnetic Field

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



Magnetization Vector

$$\vec{M} \equiv \frac{1}{2c} \sum \vec{r}_i \times \vec{J}_i$$



LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Sandia National Laboratories

Metamaterials Science & Technology

Magnetization Vector

$$\vec{M} \equiv \frac{1}{2c}(\vec{r} \times \vec{J})$$

Bulk Material Property

$$\vec{H} = \frac{1}{\mu}\vec{B}$$

$$\vec{H} = \vec{B} - 4\pi\vec{M}$$

Nano Antenna Property

$$A(\vec{r}) = Dipole\ Term + C\int J(\vec{r})(\vec{n}\cdot\vec{r})$$

Electric Quadrupole Term

Magnetic Dipole Term

$$\frac{1}{2c}[(\vec{n}\cdot\vec{r})\vec{J} + (\vec{n}\cdot\vec{J})\vec{r}] + \frac{1}{2c}(\vec{r}\times\vec{J})\times\vec{n}$$

$$\vec{M}$$

Both the material parameter μ and the far-field scattering behavior depend on the magnetization vector of the meta – "atoms".

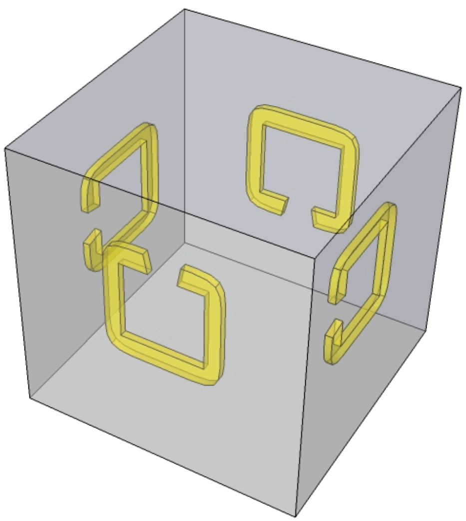
LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

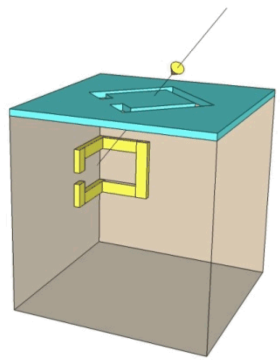
Sandia National Laboratories

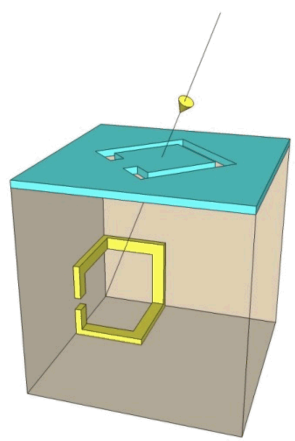
MPL Enables Truly 3-D Resonators

3-D Could Be or 2.5-D

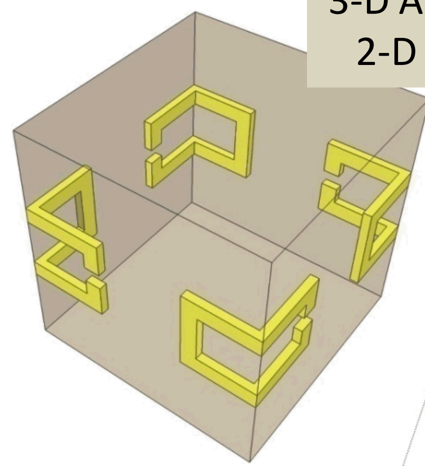
3-D Array of Planar SRRs



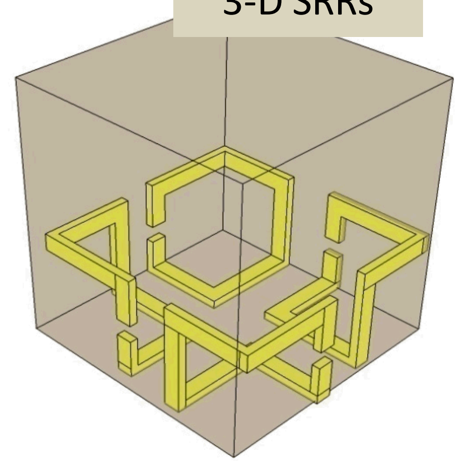




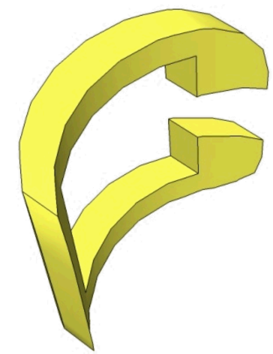
3-D Array of 2-D SRRs



3-D Array of 3-D SRRs



Cylindrical



Spherical