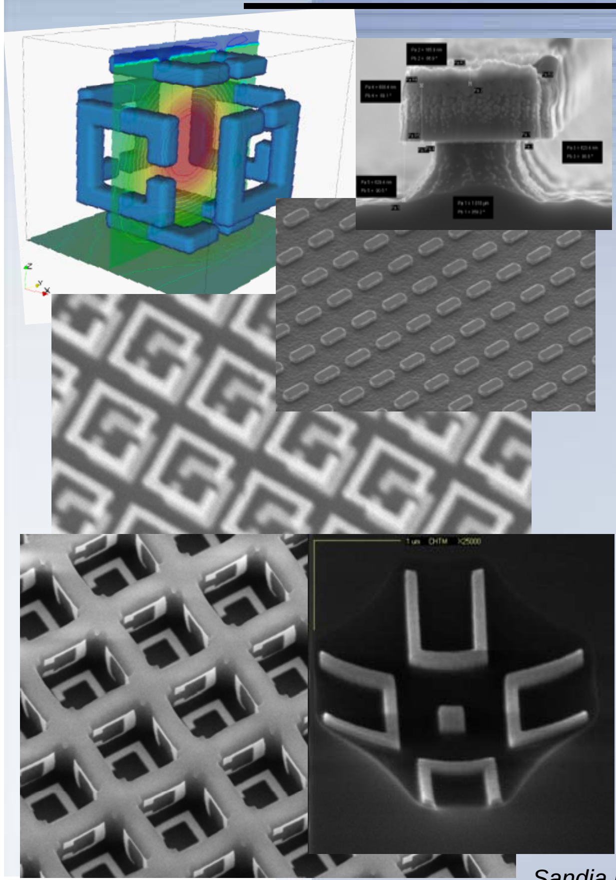
SAND2011-0038C

The 3rd International Topical Meeting on Nanophotonics and Metamaterials
3 - 6 January, 2011 Seefeld, Tirol, Austria

Metamaterials Science and Technology at Sandia National Laboratories



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- **Metamaterials: Background, Promise, Challenges**
- **Sandia & Sandia's Metamaterials Program**
- **MST Progress & Potential Applications**

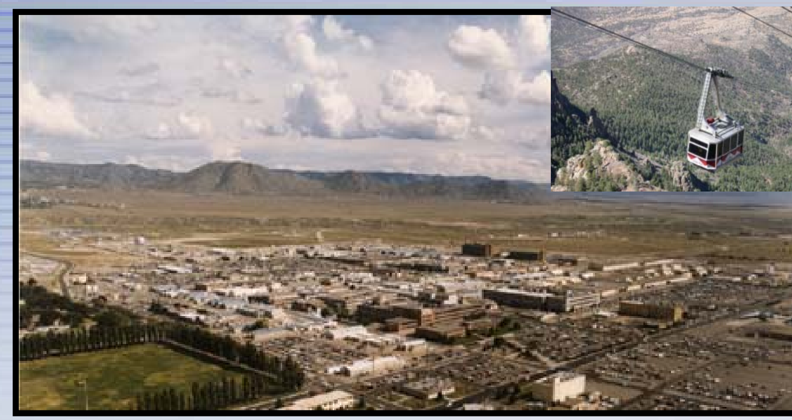
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

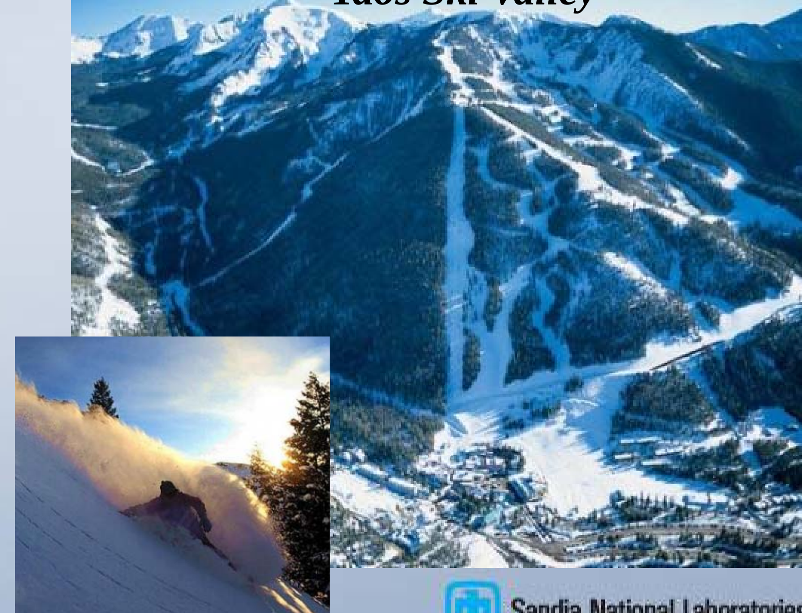
Sandia National Laboratories

Sandia and Nanophotonics

- **Sandia (<u>not "watermelon" national lab</u>→ DOE): national <u>security</u>, <u>energy</u>, & <u>infrastructure</u> technologies: ~ 8000 staff, $2B/year, 6 locations**
- **Large investments in Rad.-Hard <u>CMOS</u> and <u>Nanofab</u> at Sandia**
- **Production R&D rigor applied to nanophotonics can rapidly develop science and applications**
- **Nanophotonic technologies are poised to have major impacts on <u>energy</u>, <u>sensing</u>, <u>information processing</u>, and <u>communication</u> applications**



Taos Ski Valley

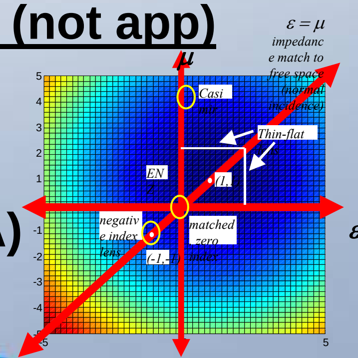


Sandia Optical Metamaterials "Landscape"

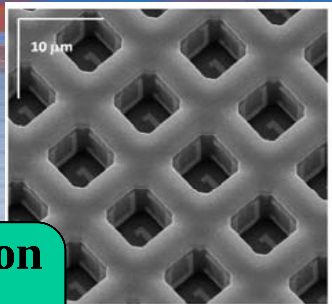
- **Strong links to our fundamental Nanoscience programs**
- **Good leverage of our Modeling/High Performance Computing, Materials, NanoFab, and Test capabilities**
- **Many hypothetical applications in Energy, Sensing, & National Security**

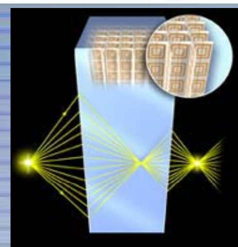
BUT…..

- **Critical challenges in both <u>tech fundamentals</u> (theory, loss, bandwidth), and <u>tech adoption</u> (application engineering, design & manufacturing infrastructure)**
- **Sandia systems groups (and others) want <u>specific & compelling application advantages</u>, *they don't care what the technology is called***
- **MST research program ➔ addressing <u>sci & tech fundamentals (not app)</u>**
- **Advice of internal and external Advisory Boards:**
  - **develop "<u>proxy apps</u>" survey**
  - **specific <u>impact and requirements</u> (compare to current SOA)**
  - **Flow-down to specifics μ, ε, & tunability requirements**



Metamaterial Science & Technology Program





- *<0.1 db/wave low loss*
- *"perfect" absorption/emission structures*

fabrication & testing

- **DUVL, EBL, PnP, NIL**
- **spectroscopic phase meas.**

theory & modeling

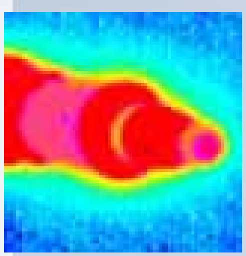
- **loss fundamentals**
- **MPP HPC design environment**
- **full anisotropic optimization**

loss engr.

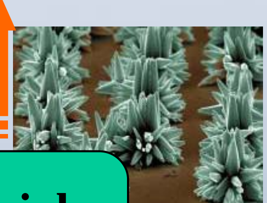
Metamaterials

IR 8-12 μm

3D

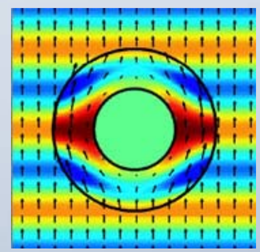


- *thermal IR*
- *limits to shorter-λ*



materials science

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



university partners

- *volumetric energy flow, large area*
- *multiple directions & polarizations*

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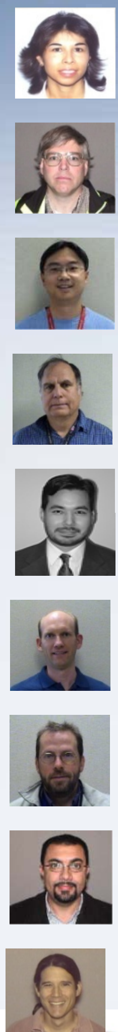
The MST Team

Mike Sinclair, PI

Rick McCormick, PM



Design:
- *Lori Basilio*
- *Larry Warne*
- *Dave Peters*
- *William Langston*
- *Jacques Loui*
- *William Johnson*
- *Ihab El-Kady*
- *Paul Davids*
- *Jonathon Hu*

Materials:
- *Paul Clem*
- *Shawn Dirk*
- *James Carroll*
- *Jon Ihlefeld*
- *Alex Lee*

Fabrication:
- *Igal Brener*
- *Bruce Burckel*
- *Greg Ten-Eyck*
- *Joel Wendt*
- *James Ginn*
- *Eric Shaner*
- *Brandon Passmore*
- *Daniel Bender*
- *Rob Ellis*

Penn University of Pennsylvania

UMASS

Mark Lee

University of Central Florida
CREOL - The College of Optics

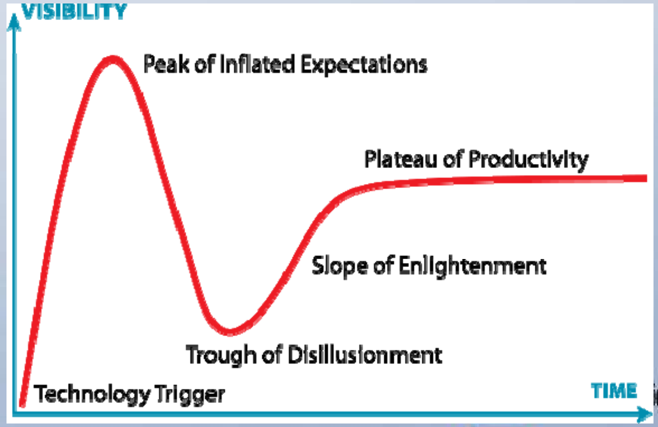
Linda Wood, Administration

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Where do we see opportunities for MMs?

- **<u>Infrared!</u>**
- **Wavefront Control and engineering, dispersion management**
- **Lightweight IR optics using transformation optics (i.e., large FOV)**
- **Sub-λ Field Concentration (ex: lead to smaller, less noisy FPA pixels)**
- **Absorption / Emission engineering**
  - **Thermophotovoltaic (TPV) micro-power generation**
  - **IR projectors: scene generation & calibration**
  - **IR DOS engineering (efficient LEDs, better PV cells)**
  - **Passive/Active thermal control (satellite)**
  - **Camouflage**
- **Agile/tunable Metamaterials:**
  - **dynamic filters**
  - **limiters**
  - **phase & amplitude modulators**

(ex: $\varepsilon=\mu=0$ metamaterial)



Status of Metamaterial Applications

RF Metamaterials are starting to appear in commercial products (usually in antenna applications)

LG Electronics Chocolate BL40

Netgear RangeMax wireless router

<u>Optical</u> Metamaterials face significant challenges:

- *Optical losses must be reduced at least 100x for many applications*
  - *dielectric resonator based metamaterials (Sandia Labs & others)*
  - *other metamaterial groups are pursuing gain-enhanced metamaterials*
- *Difficult to achieve unit cell sizes much smaller than the wavelength*
- *3D isotropic metamaterials difficult to fabricate at shorter wavelengths*
  - *Membrane projection lithography (Sandia Labs)*
- *Bandwidth must be increased (1% to 5-10%)*
  - *researchers now pursuing non-resonant ε-only metamaterials for broadband transformation optics designs (full circle back to artificial dielectrics)*
- *Active tuning and modulation methods must be developed*
  - *integration of active materials in metamaterials is a hot topic*

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Optical Metamaterials Demonstrations?

(more difficult at optical frequencies)

Clever ideas, rapid progress, but demos are much less mature:

- **2D: IR "Nantennae": FPAs, SERS substrates/sensors**
  - Promising -- some commercialization
- **2.5D Negative Index Perfect / Super / Hyper Lenses**
  - But high loss, narrowband, anisotropic
- **2D & 3D "Carpet cloaks"**
  - GRIN with "effective index" > 1

Why limited demonstrations? Need a new "Engineering Infrastructure":
➔ theory, design, simulation, materials, fab, & test

To enable a wide application space, we need:

- **Low loss (reduce from 100 dB/λ to 0.1 dB/λ**
- **Isotropic materials (metamaterials not "metafilms")**
- **Wider bandwidth (1% to 5-10%)**
- **3D structural integration, conformal integration**
- **Tunable, dynamic metamaterials**

What is Sandia doing?

Challenges Associated with LWIR Metamaterials

- **Infrared optical properties of component materials can present problems**
  - **metal conductivity**
    - ohmic losses limit metamaterial performance
    - can't use PEC limit
    - fine mesh required for convergence
  - **IR transparent substrate materials**
    - GaAs, Si: high-ε materials, oxide layers
    - BaF_2: low thermal conductivity, fragile
  - **transparency of IR matrix materials**
    - absorptions can complicate & degrade performance
    - processibility of IR matrix materials
- **Unit cell size not << λ for metals or DRs**
  - **significant radiation resistance for metafilms**
  - **spatial dispersion**
- **Lithography more forgiving than for visible metamaterials, but …**
  - **how do we make fully 3D structures??**

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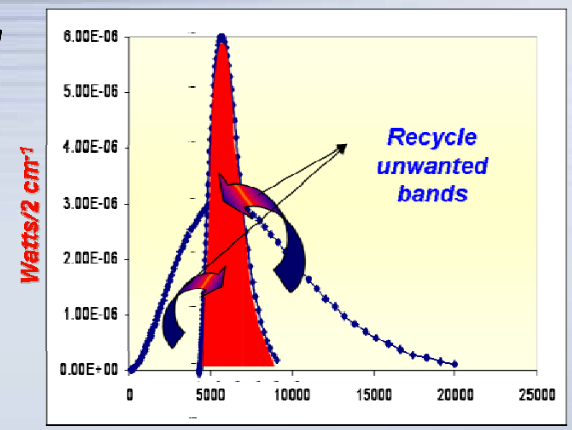
What Applications?

What optical functions can metamaterials perform?

1. Wavefront Control and engineering
2. Sub-λ Field Concentration
3. Absorption / Emission engineering
4. Active Tunability for 1-3

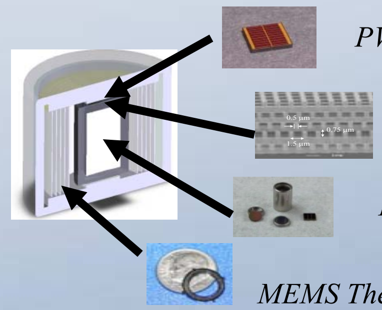
Recycling Action



Micro-TPV

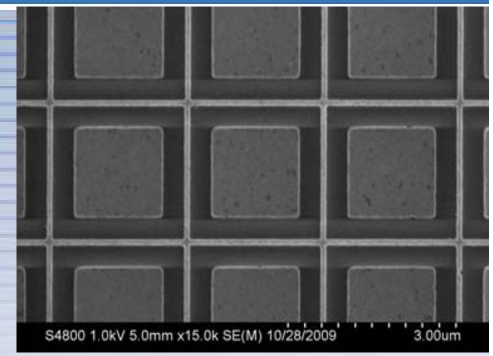
Absorption / Emission engineering

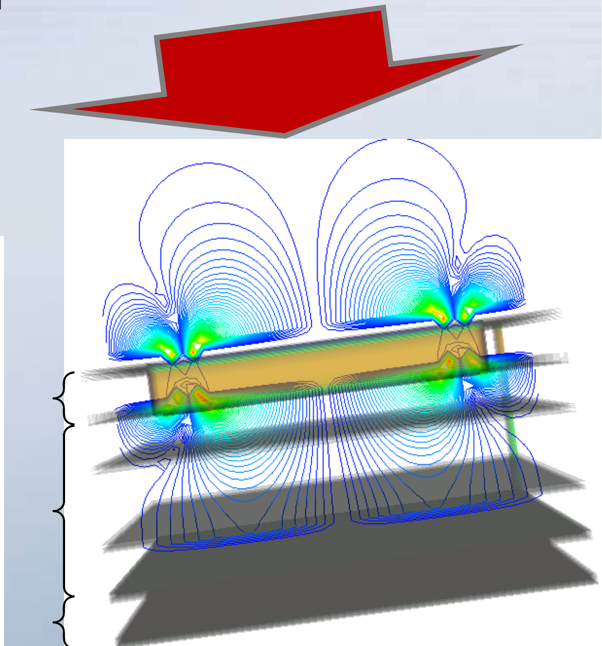
- Thermophotovoltaic (TPV) micro-power generation
- IR projectors: scene generation & calibration
- Low power IR spectroscopy
- IR DOS engineering (efficient LEDs, better PV cells)
- Passive/Active thermal control (satellite)
- Camouflage

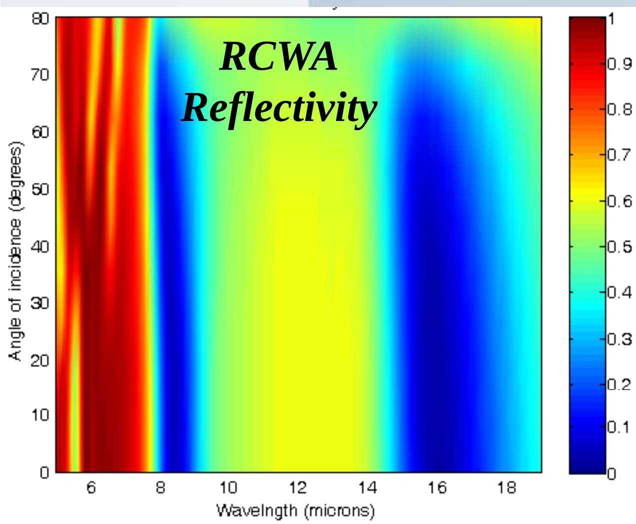


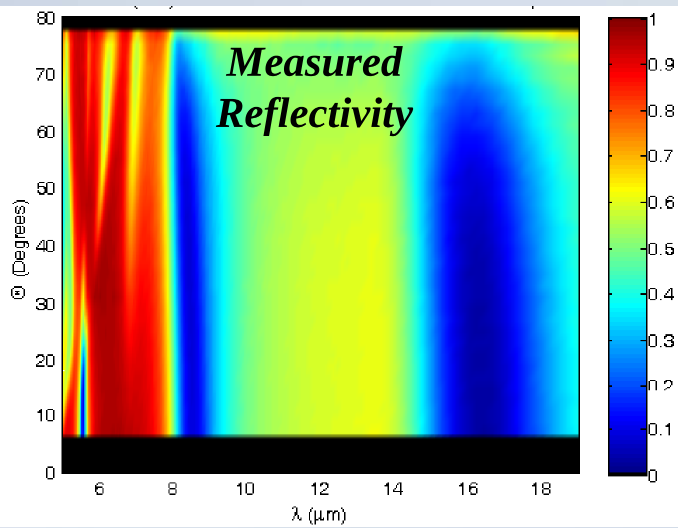
Past Sandia Research: PARC

- *Sandia has previously developed an all-angle absorber based on a slot-loop FSS*
  - *Gold trace above a 1.71 μm silicon nitride thin film*
  - *Absorption occurs in the nitride layer*
  - *Near unity absorption*
  - *Largely angularly independent*
- *Compact nature of surface waves leads to efficient absorption in a small volume.*







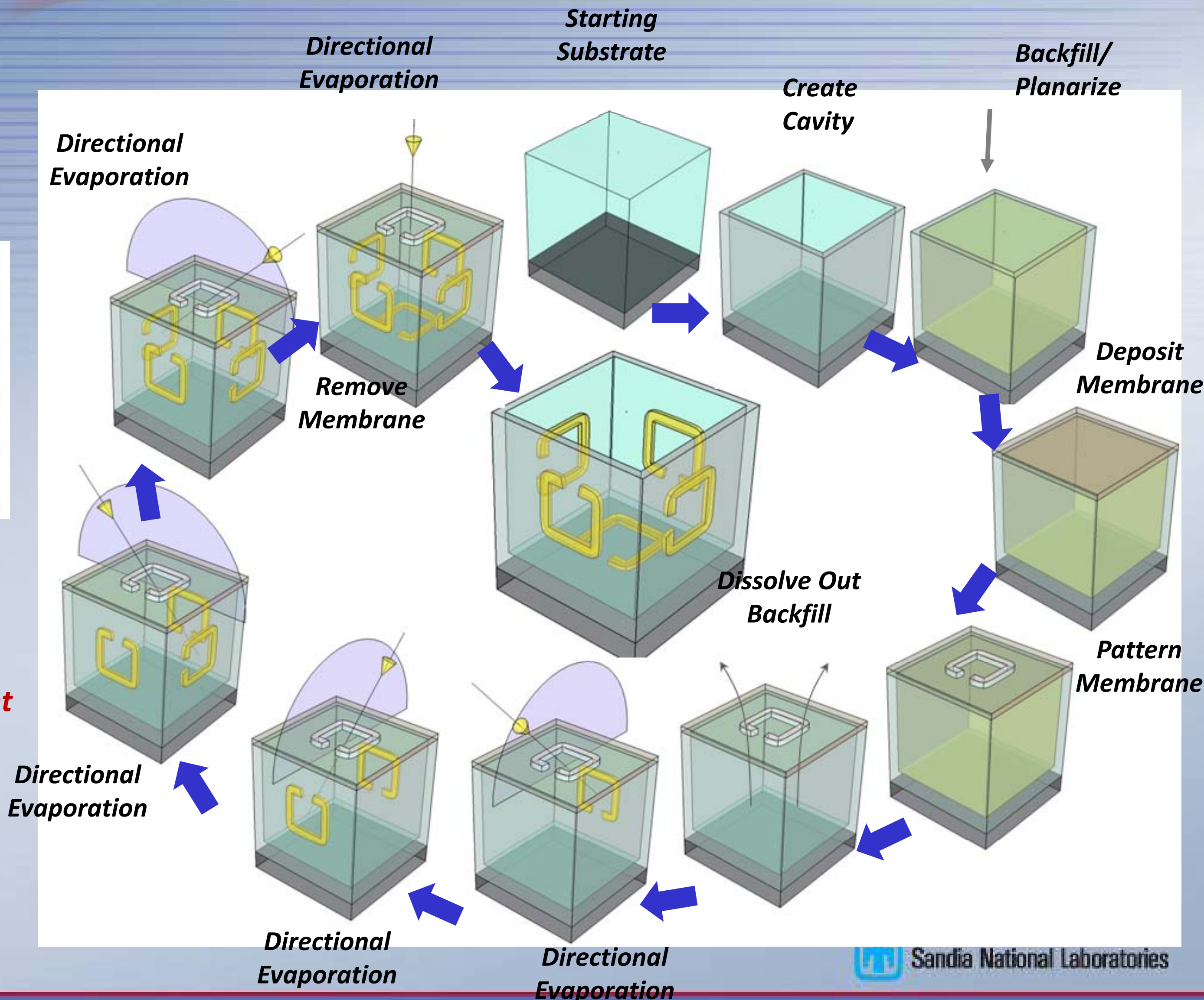


D. Peters, et al., Sandia Report, SAND2009-6012 (2009).

3D MMs: Membrane Projection Lithography: MPL

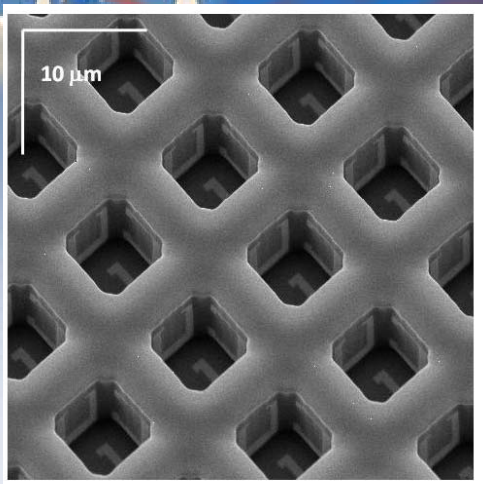
Goal: achieve this at optical frequencies

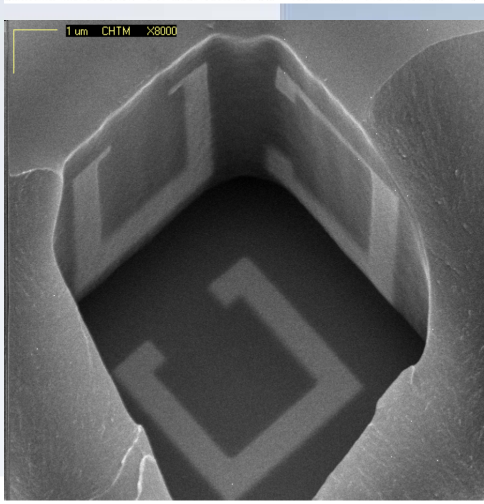
- *Out-of-plane resonators*
- *Planar lithography*
- *Many patterns possible*
- *Cavity geometry independent of resonator pattern*
- *Scalable*
- *Layer-by-layer → 3-D*

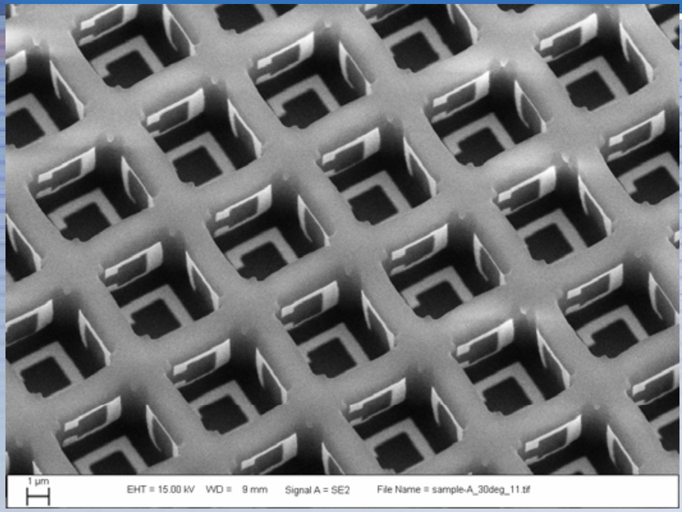


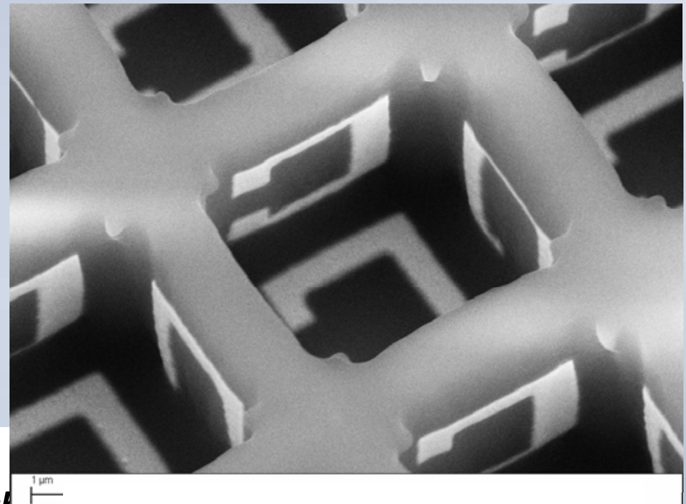
D. Bruce Burckel

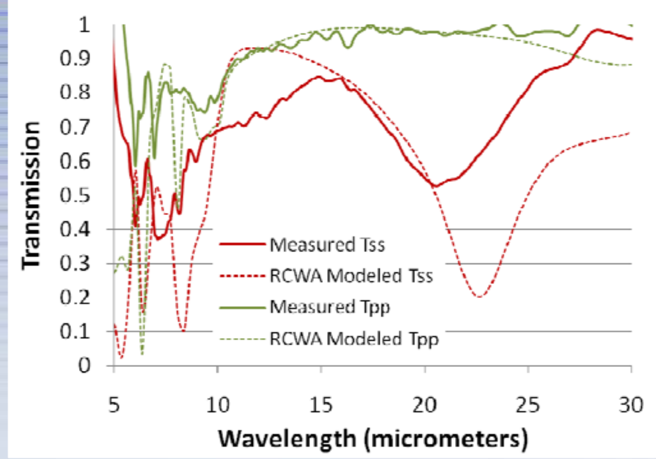
Cubic 3D Metamaterials via MPL

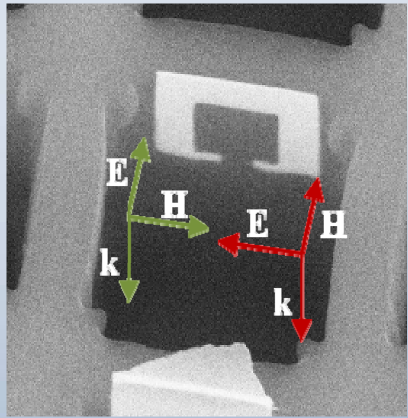








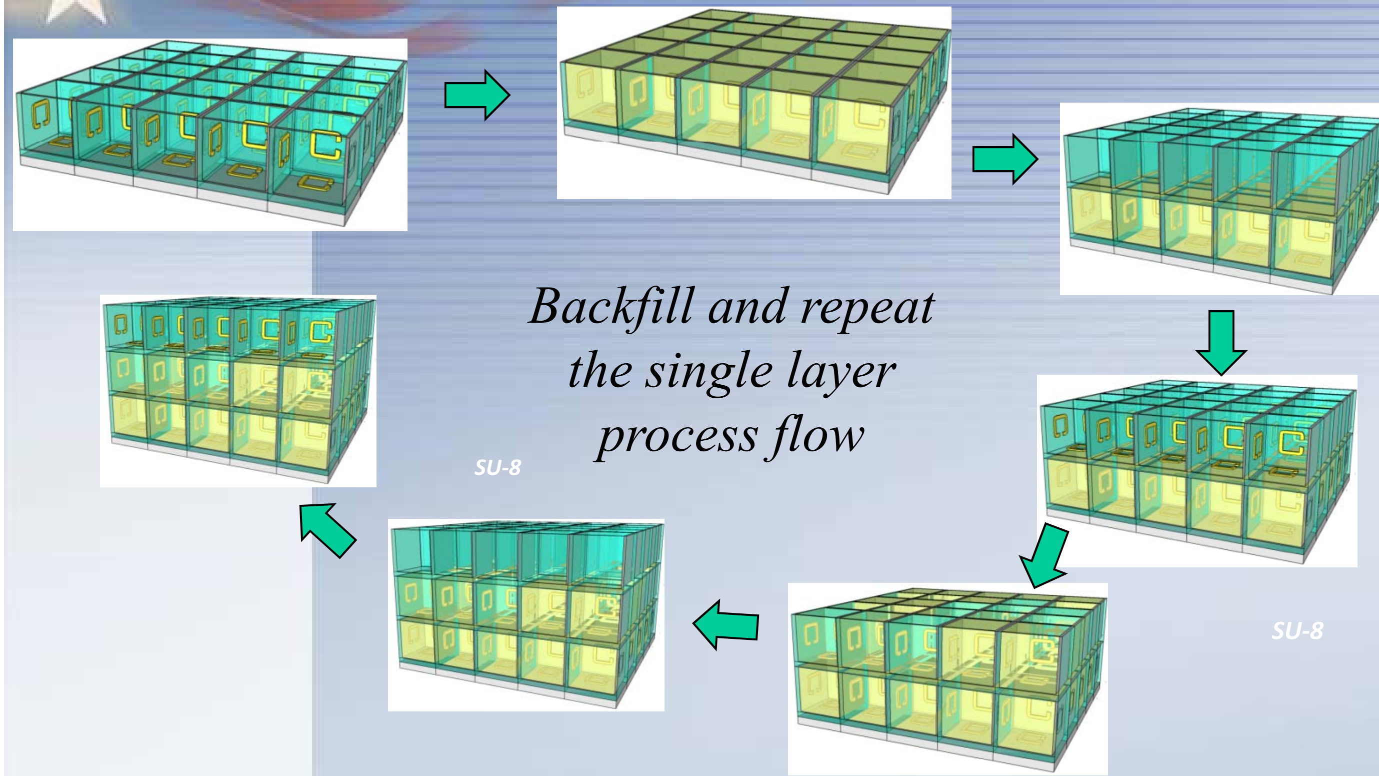


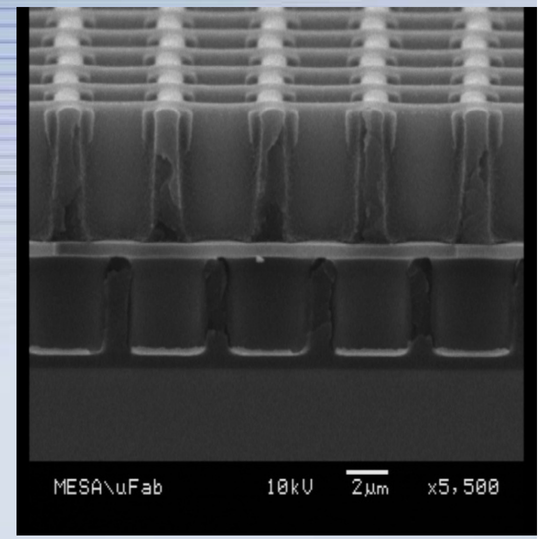


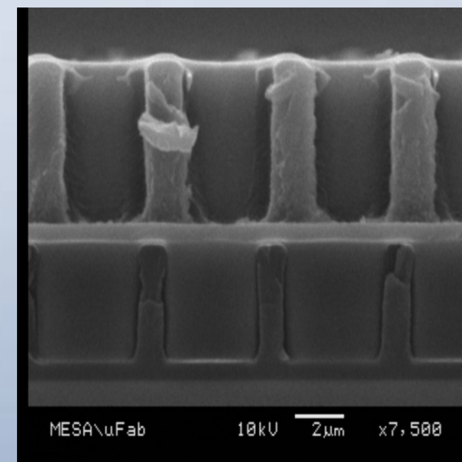
- ➢*Unit Cell Dimension = 14 μm pitch*
- ➢*SRR Dimension = 8 μm*
- ➢*Resonance wavelength ~ 50 μm*

- ➢*Unit Cell Dimension = 6 μm pitch*
- ➢*SRR Dimension = 3 μm*
- ➢*Resonance wavelength ~ 22 μm*

Route to Multilayer 3D Materials



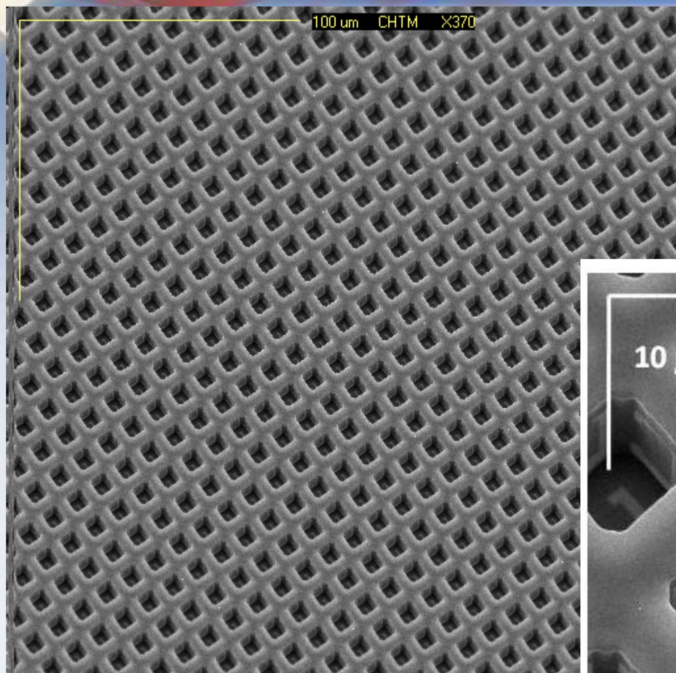




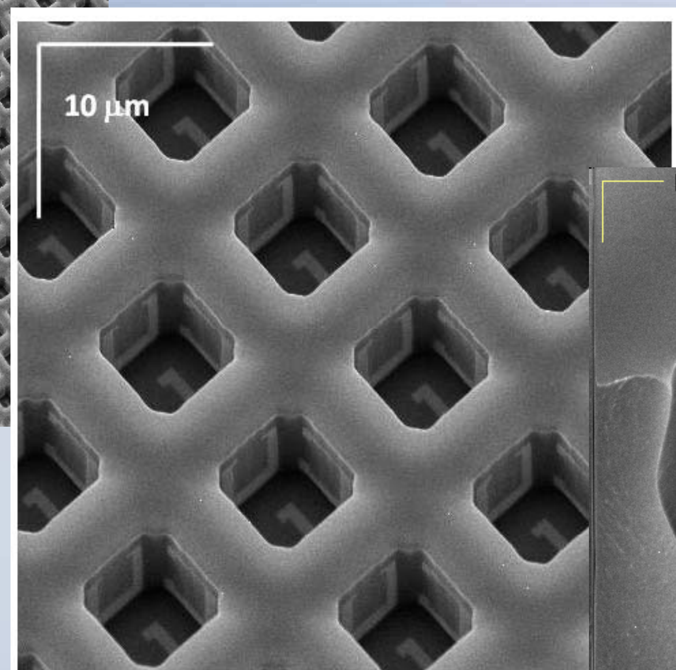
Membrane projection lithography is a promising route for fabrication of IR selective absorbers and emitters.

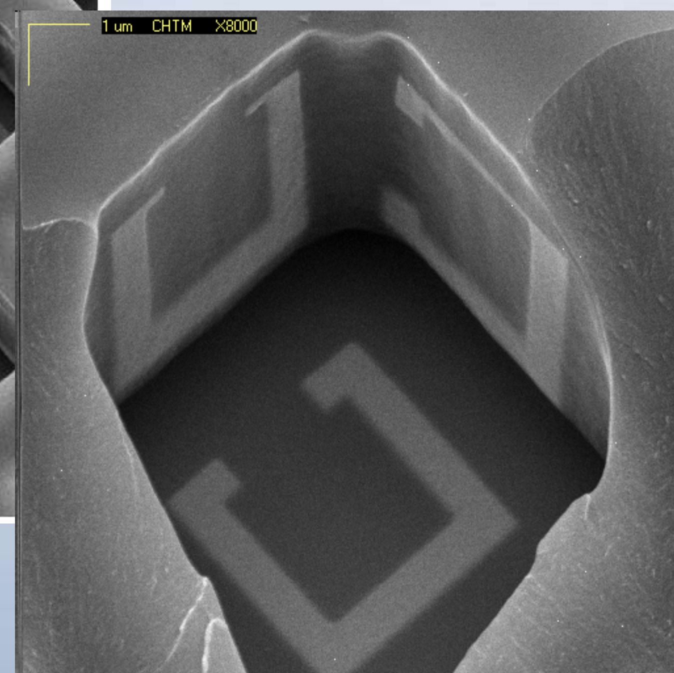
Another path: non-resonant metallic inclusions. Avoids loss issues and only controls ε. (with Smith, Duke)

3D Metamaterials via MPL



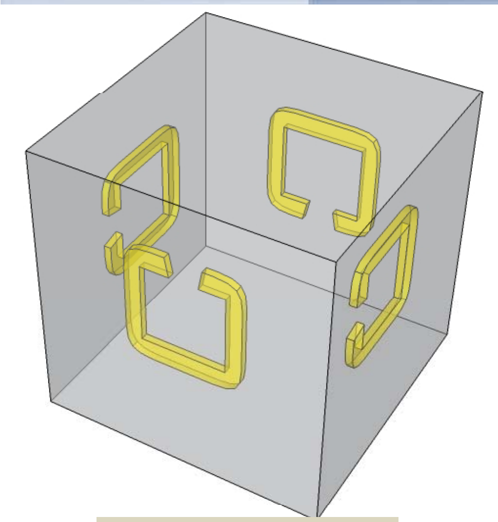
Proof of concept demonstration



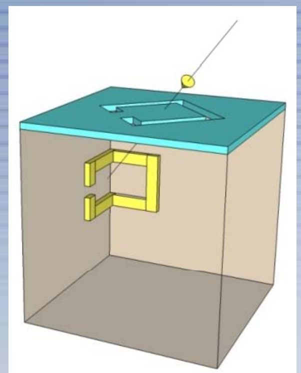


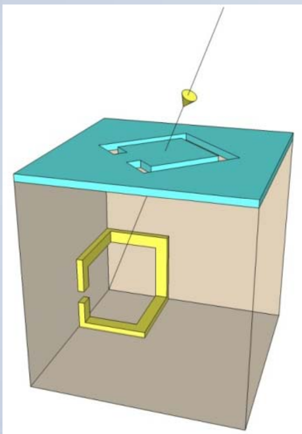
- *Cubic resonators --- 14 µm pitch*
- *Ti/Au SRRs on 4 sides and bottom*
- *Resonance wavelength ~ 40 µm*

MPL enables a rich variety of 3-D metamaterials

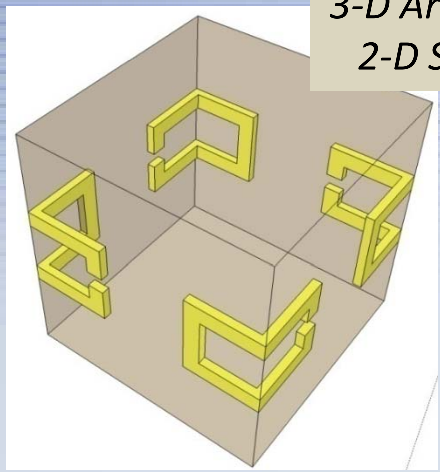


3-D Array of Planar SRRs

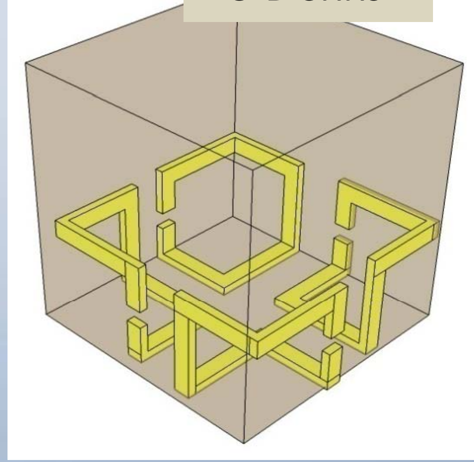




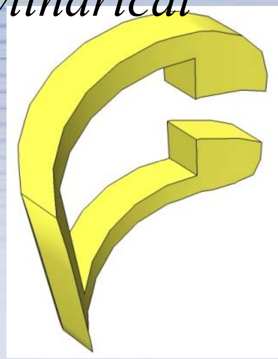
3-D Array of 2-D SRRs



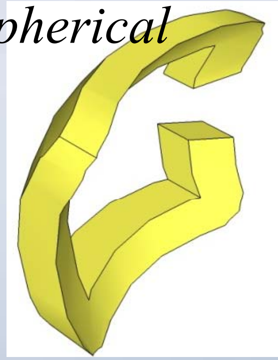
3-D Array of 3-D SRRs

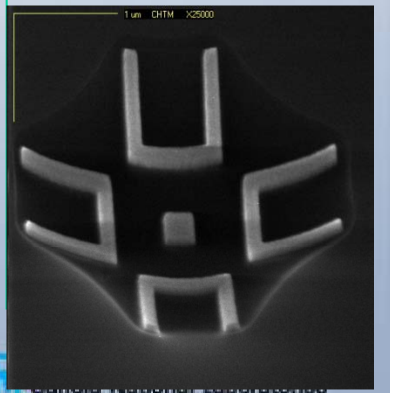


Cylindrical



Spherical

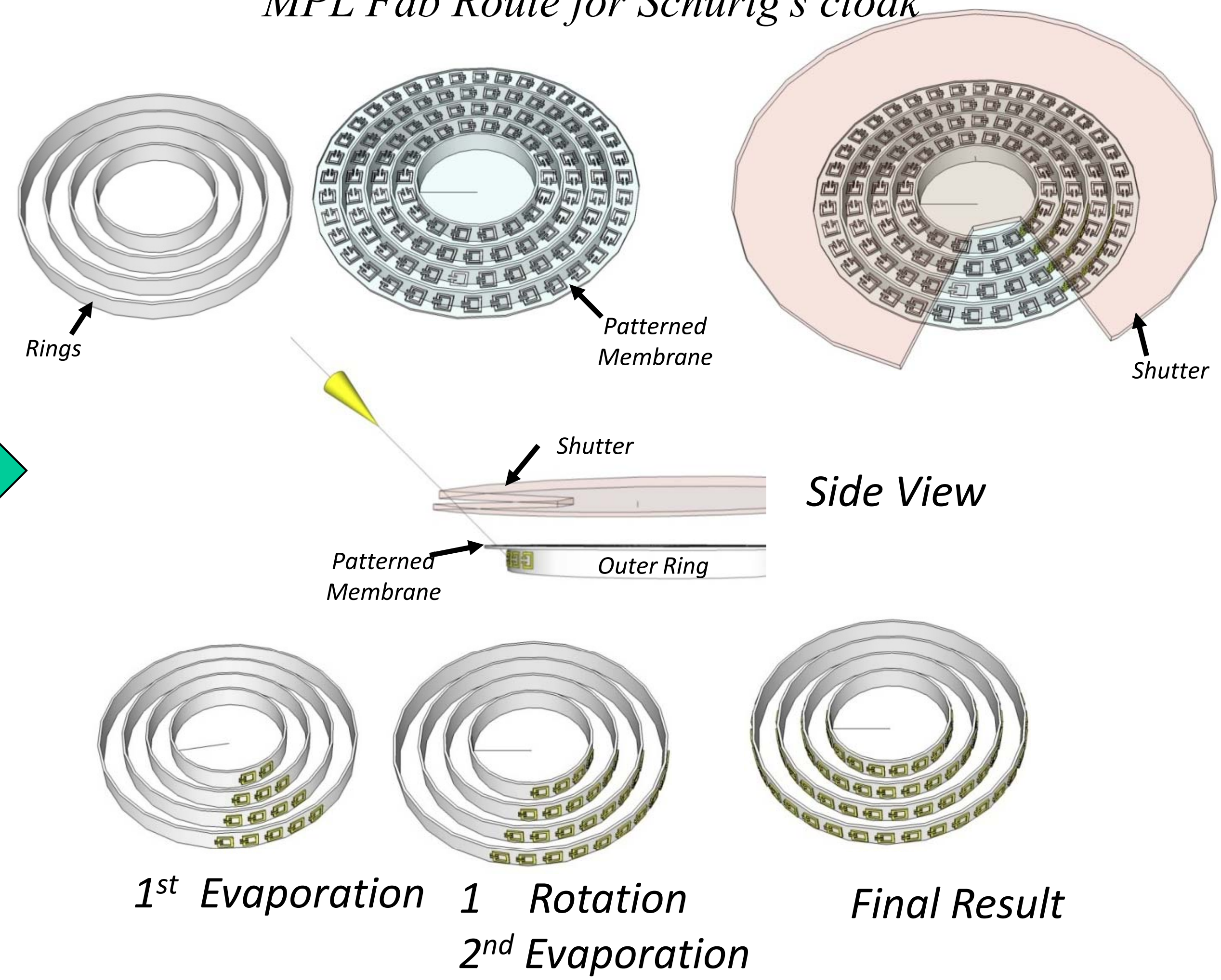




Beyond Homogeneous Metamaterials: Direct Fabrication of IR Metamaterial Devices

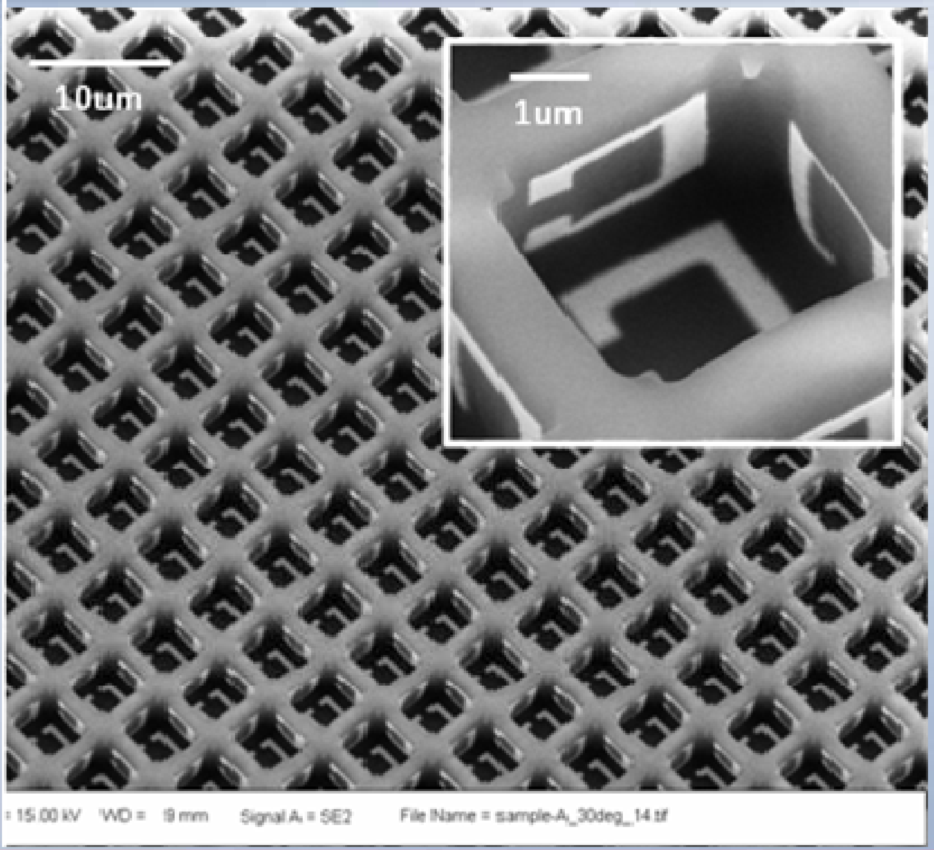
- ***MPL is not restricted to rectangular geometries***
- ***Multilayer devices possible***

MPL Fab Route for Schurig's cloak

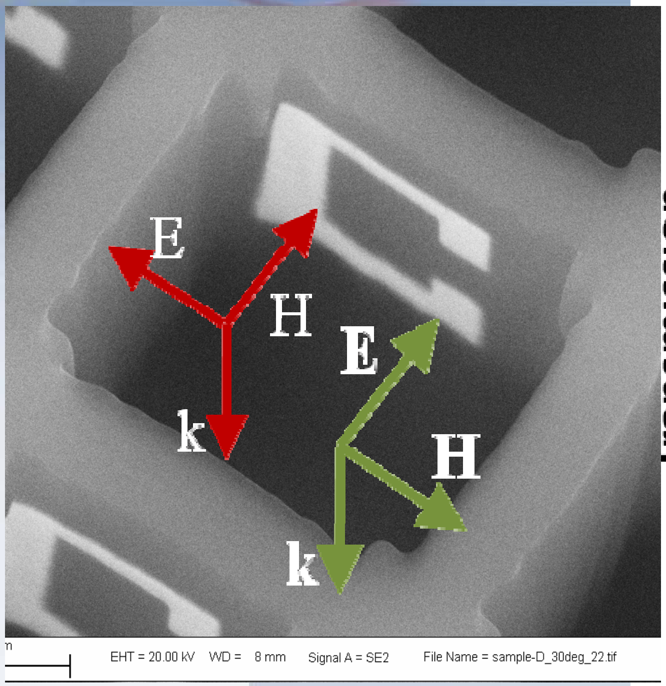


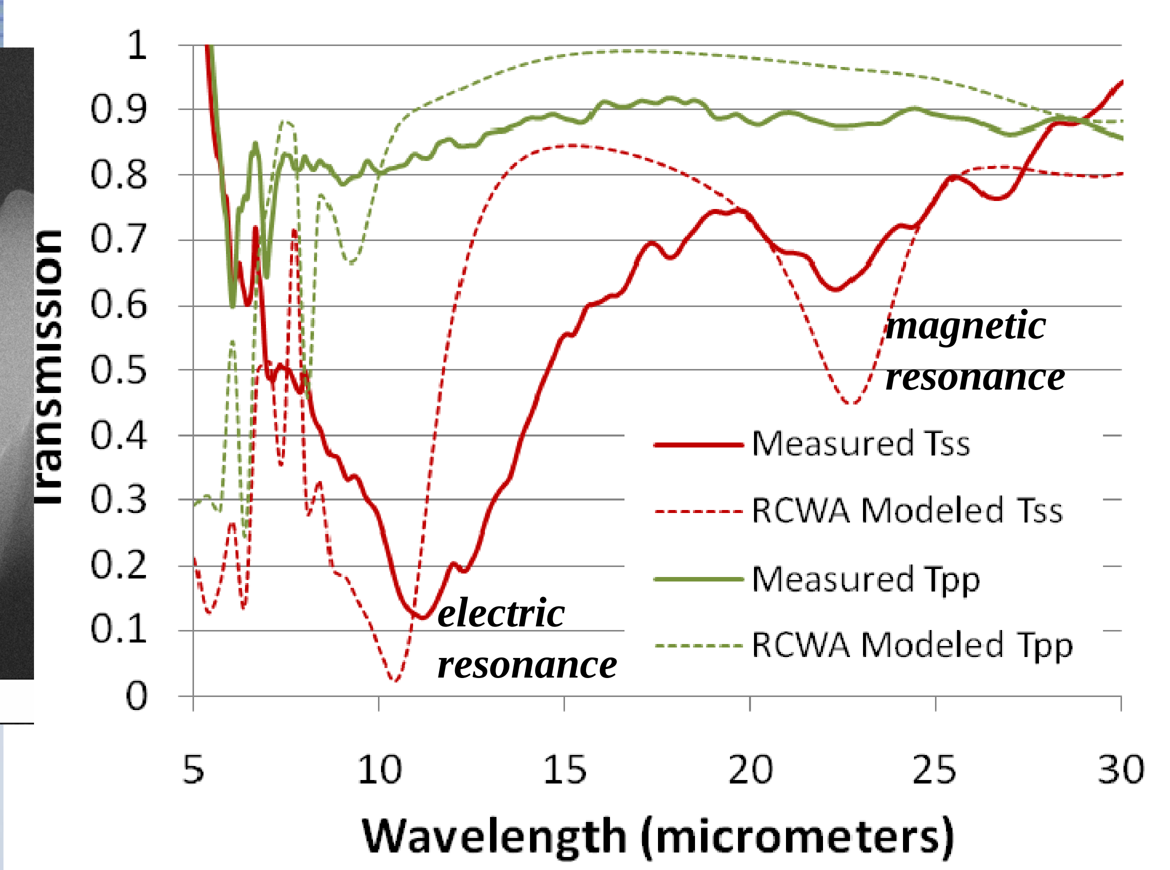
Cubic SRR Metamaterial Operating at 22 mm

- ***SU8 boxes, Ti/Au resonators (10/50 nm)***
- ***Box Pitch = 6 μm***
- ***Wall thickness = 1 μm***
- ***SRR side length = 3 μm***
- ***Resonators deposited on 1 wall, or 4 walls and bottom***



Polarized Transmission of Magnetically Excited SRR Array





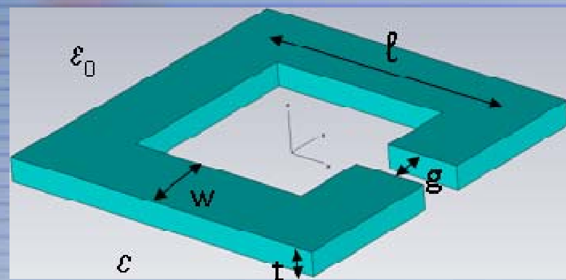
S-polarization

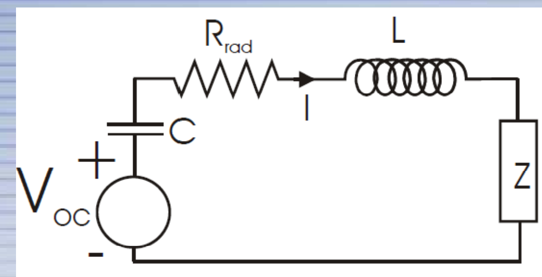
- *B-field excites lowest SRR resonance --- magnetic excitation*
- *E-field excites second order resonance --- electric excitation*

P-polarization

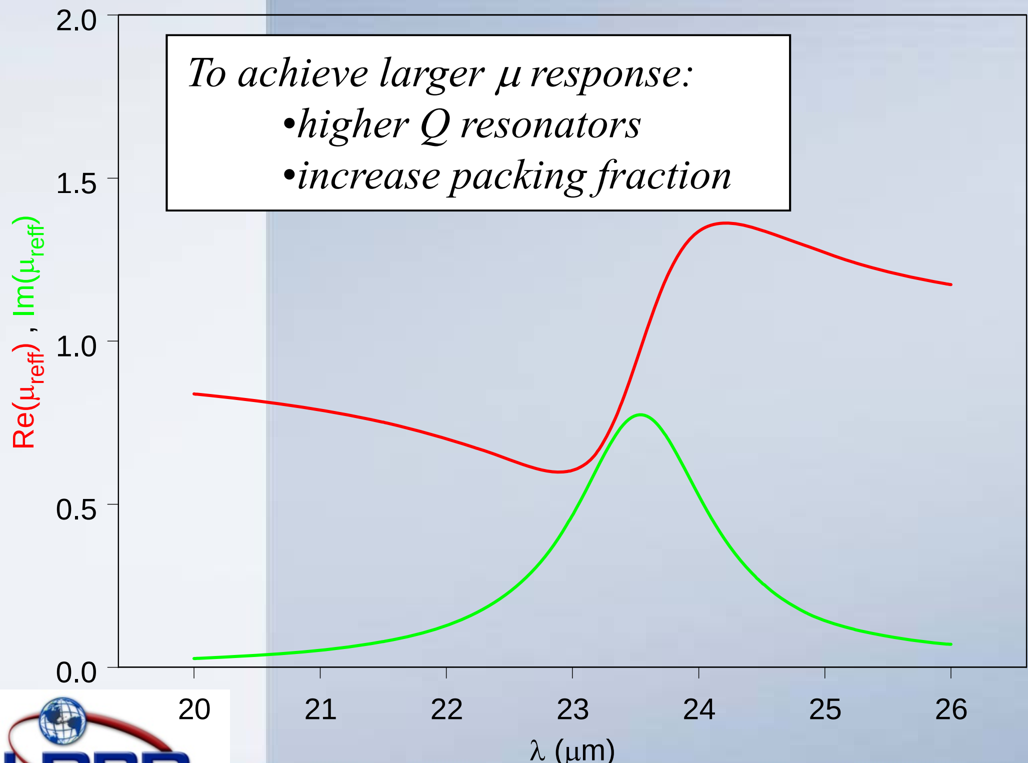
- *can’t couple to any SRR resonances*

Predicted permeability: __bulk__ array with SRRs on single wall





Bulk Magnetic Permeability



Analytic Circuit Model (L. Warne)

- *Inductance (Grover)*
- *Internal impedance*
- *Capacitance (Schelkunoff, King)*
- *Dielectric half space*
- *Substrate effects*
- *Magnetic excitation*
- *Dipole moments (Tretyakov, Schelkunoff)*
- *Radiation from surface (Kuester, Simovski)*
- *Effective media*

Full Wave Models

- *CST, HFSS, RCWA, EIGER*

What Applications?

What optical functions can metamaterials perform?

1. Wavefront Control and engineering
2. Sub-λ Field Concentration
3. Absorption / Emission engineering
4. Active Tunability for 1-3

Wavefront Control:

- *Conformal optics: air frames, missile seekers*
- *Automobile headlights & backup cameras*
- *Computational/Compressive imaging*
- *Novel illuminators*

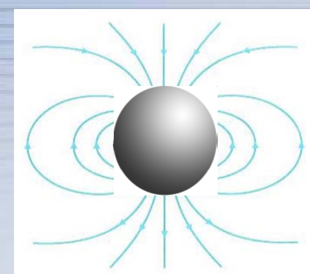
www.optics-online.com/Profile/technology.asp#TailoredSecurity

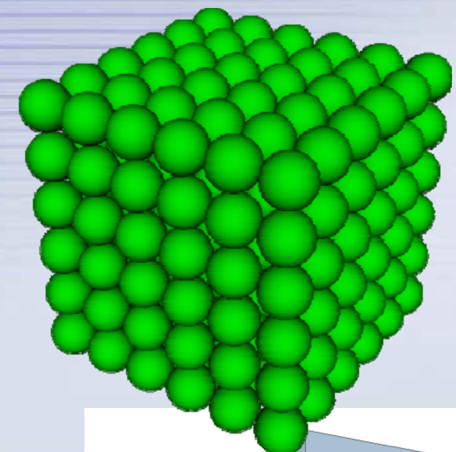
Lower Loss: Dielectric Resonator Metamaterials

Electromagnetic scattering by arrays of high-ε resonators can lead to low loss electric and magnetic metamaterials.

Dielectric Spheres → Mie scattering

- *electric & magnetic dipole resonances*
- *occur at different frequencies*



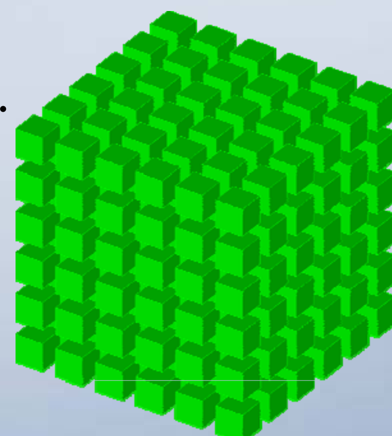


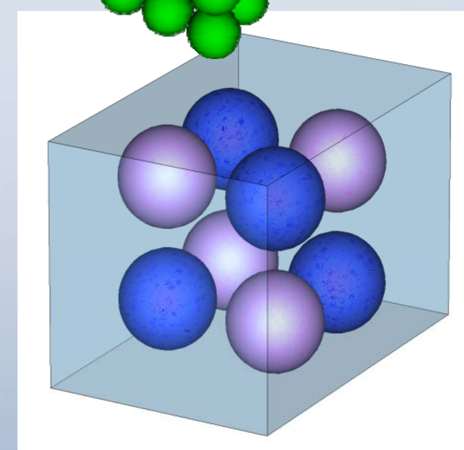
Array of resonators in a host matrix:

- *effective ε and μ values*
- *Claussius-Mossotti equation or beyond*

Overall loss depends on loss tangents of resonators and host

- *can be significantly lower than metal based metamaterials.*





Other resonant scattering structures can be employed

- *cubes*
- *wires*
- *anisotropic structures*
- *readily extendible to IR metamaterials*

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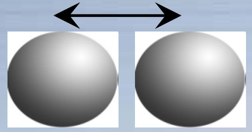
Limits to effective medium parameters with dielectric resonators

- *Largest identified ε in thermal IR is not as high as is desired*
  - *extending effective medium theory to account for finite size effects*
- *Minimum resonator size & pitch ~ λ_0/N_{res}*

$$p \sim \frac{\lambda_0}{N_{res}}$$

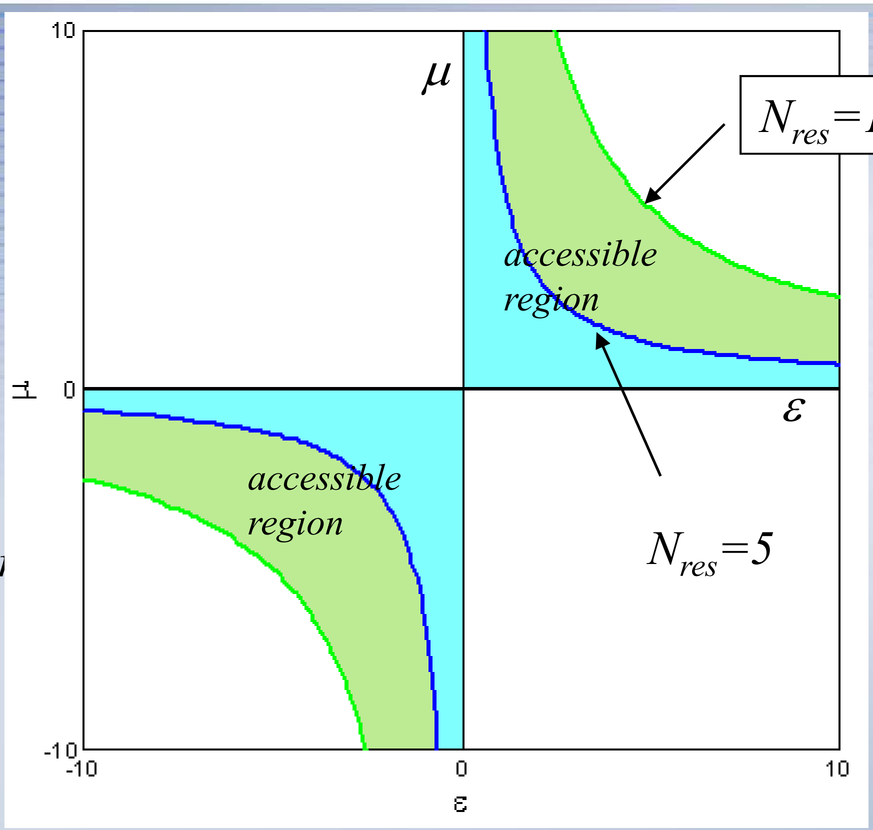


- *Effective medium wavelength must be greater than twice the pitch*

$$\lambda_{eff} > 2 \cdot p \Rightarrow \frac{\lambda_0}{N_{eff}} > 2 \cdot \frac{\lambda_0}{N_{res}}$$

- *Accessible region of μ-ε space for propagating waves correspond to:*

$$N_{eff} \le \frac{N_{res}}{2}$$

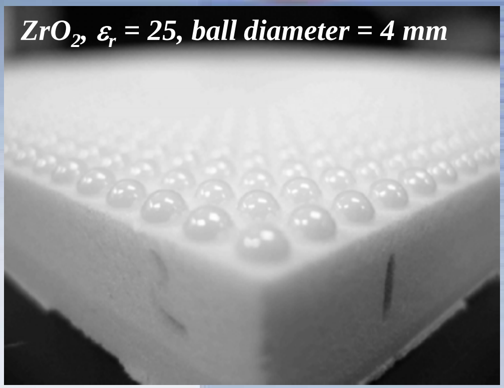


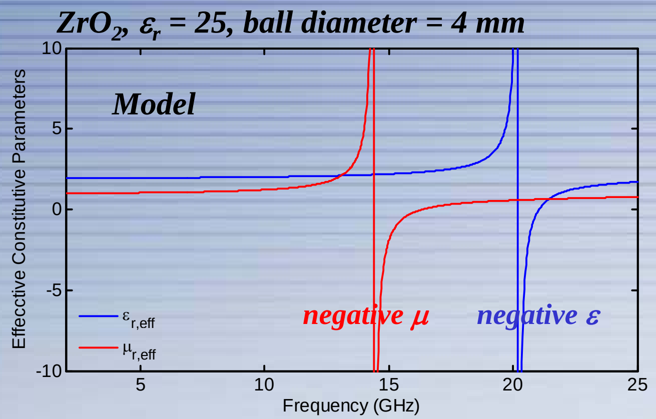
- *Larger values of N_{res} give access to more μ-ε space*
- *ENZ, MNZ accessible*
- *N_{eff} = -1 accessible*

DR Metamaterials: RF & IR

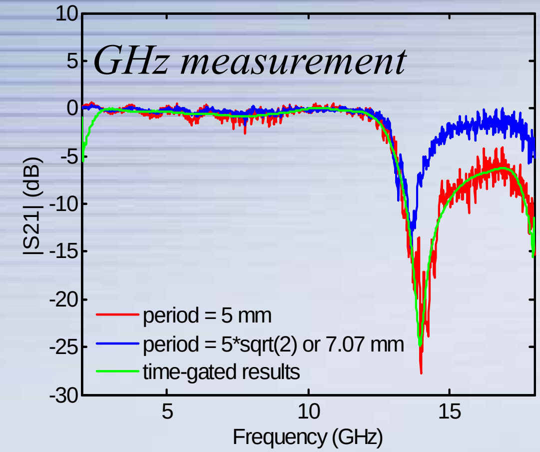
RF

Example: Negative μ metamaterial.



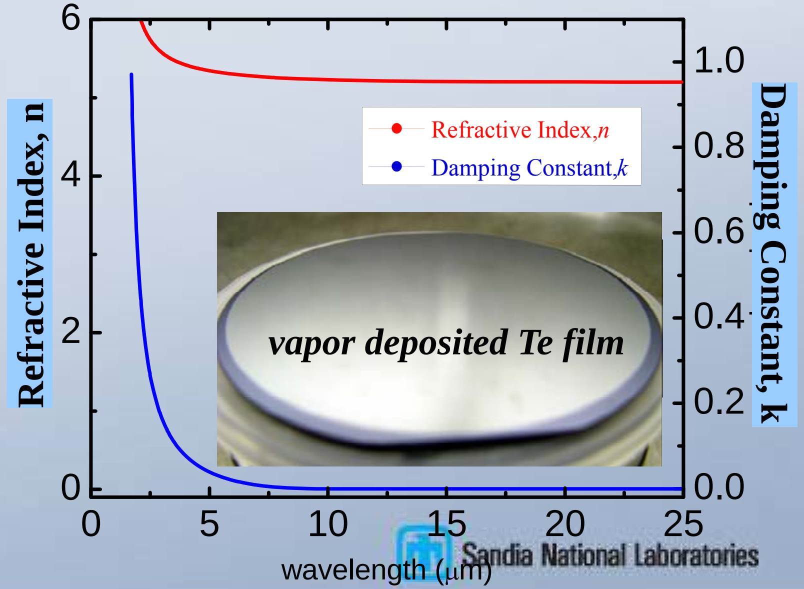


Expt.



IR

- *What is required is a very low loss, high index material that can be patterned. Ex: PbTe, Te*
  - *PbTe IR properties measure using IR VASE*
    - *refractive index ~ 5–6 (would prefer larger)*
    - *damping is small (difficult to measure)*
  - *electro-deposition, vapor deposition*



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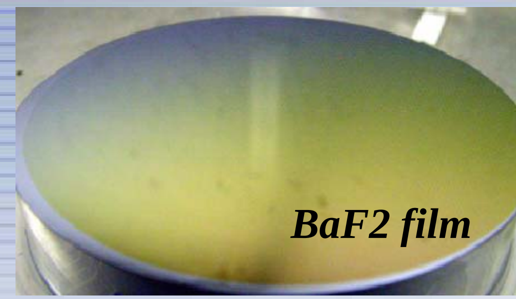
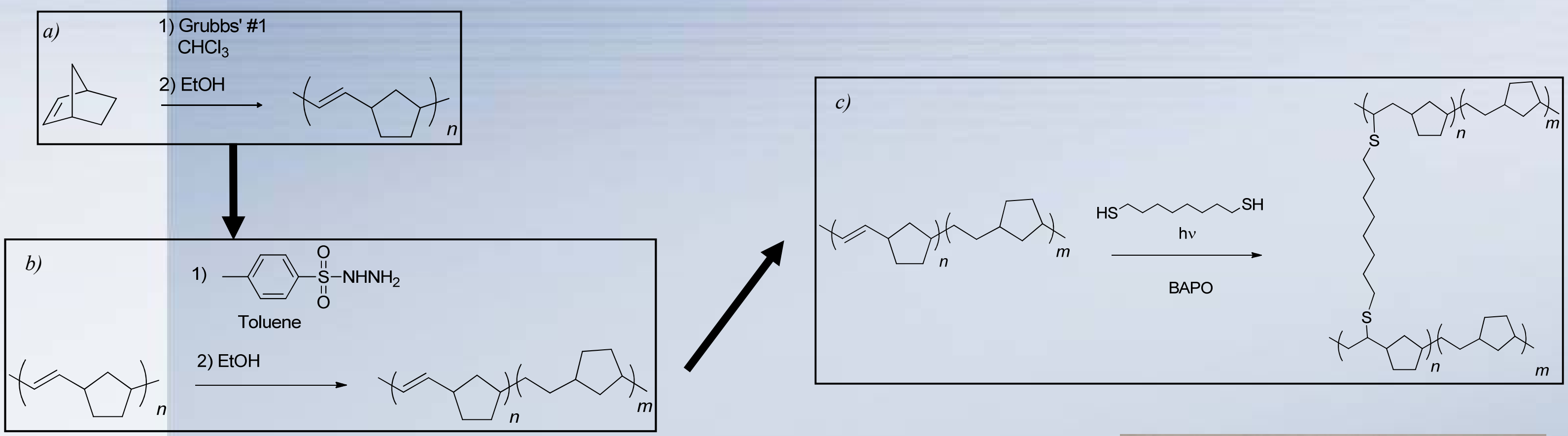
Host Materials for the thermal IR

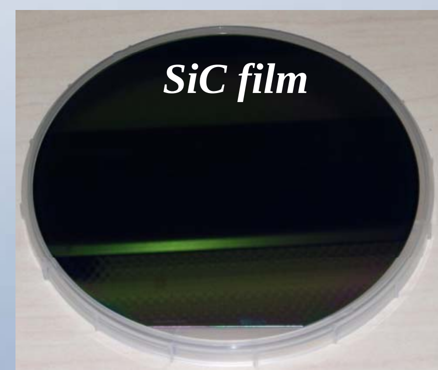


- *Passive Materials:*
  - *polynorbornene (low loss polymer)*
  - *BaF2, YF3 (sol-gels & vapor deposited)*
  - *IRX (vapor deposited)*

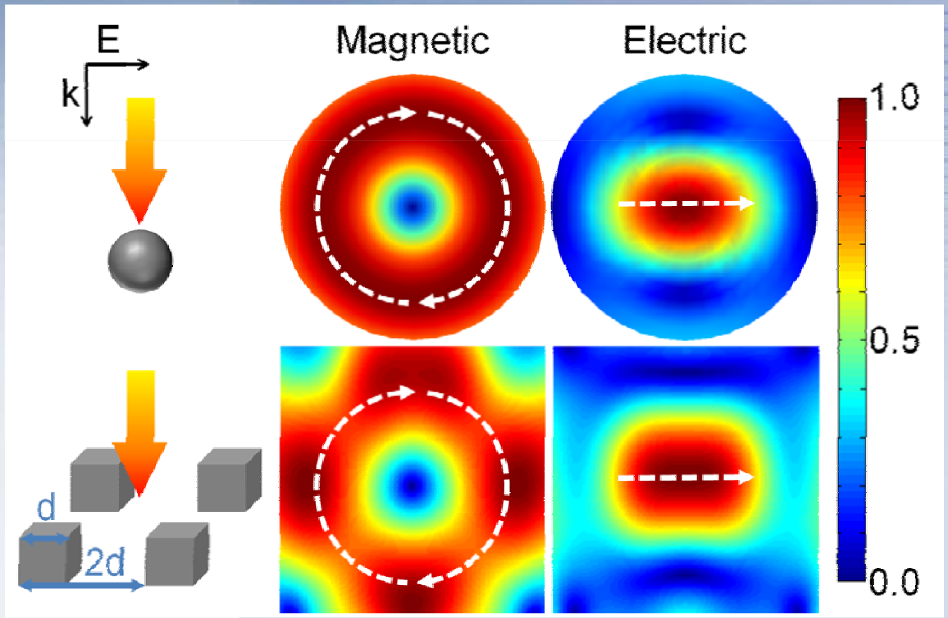
Polynorbornene Synthesis

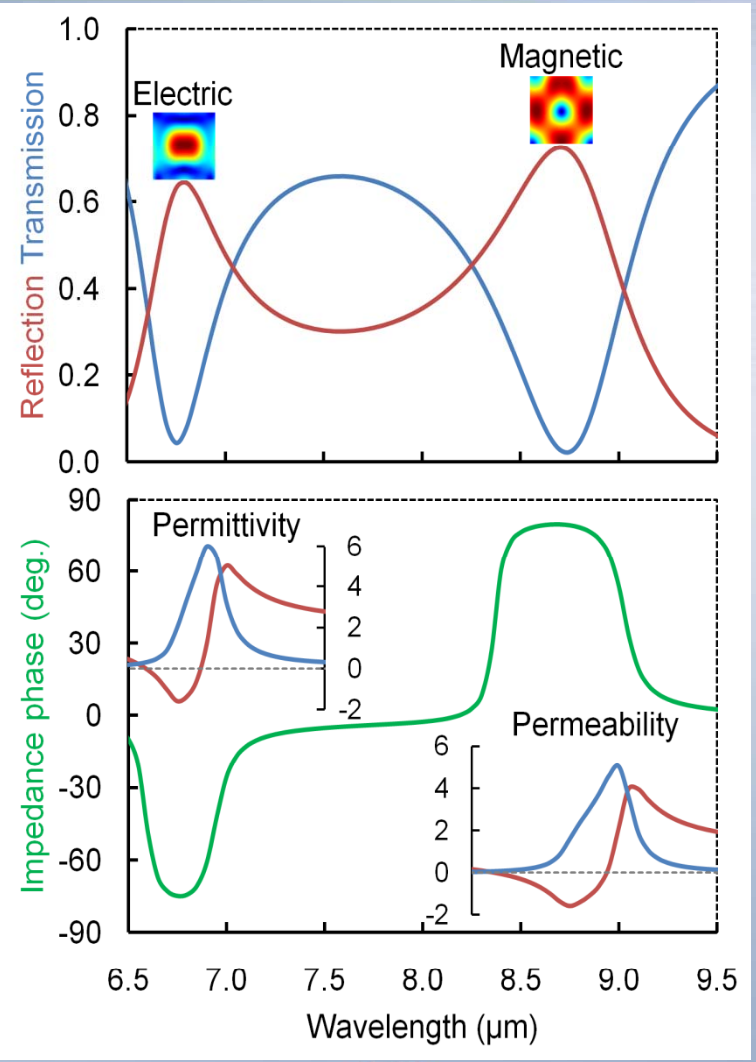


- *"Active" Materials (contribute to ε behavior):*
  - *SiC*
    - *CVD in the MDL*
  - *Oxide glasses*
    - *being looked at by materials team*

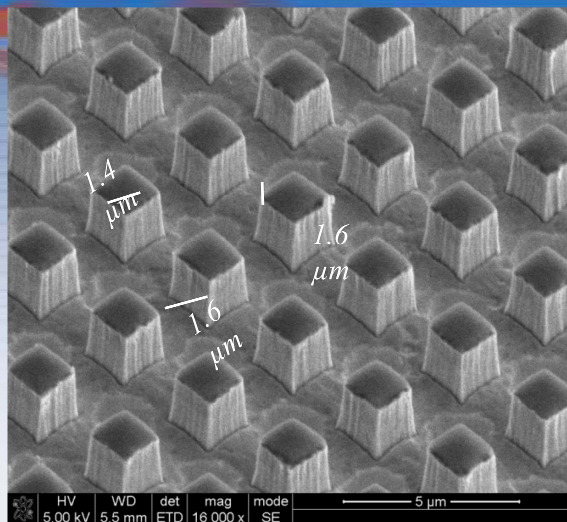


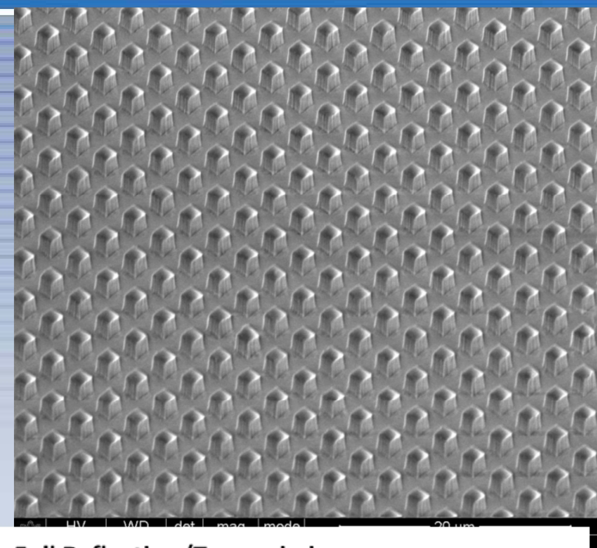
DR Infrared Metamaterial: Te/BaF_2

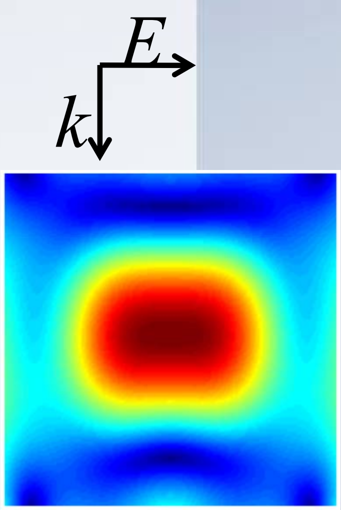


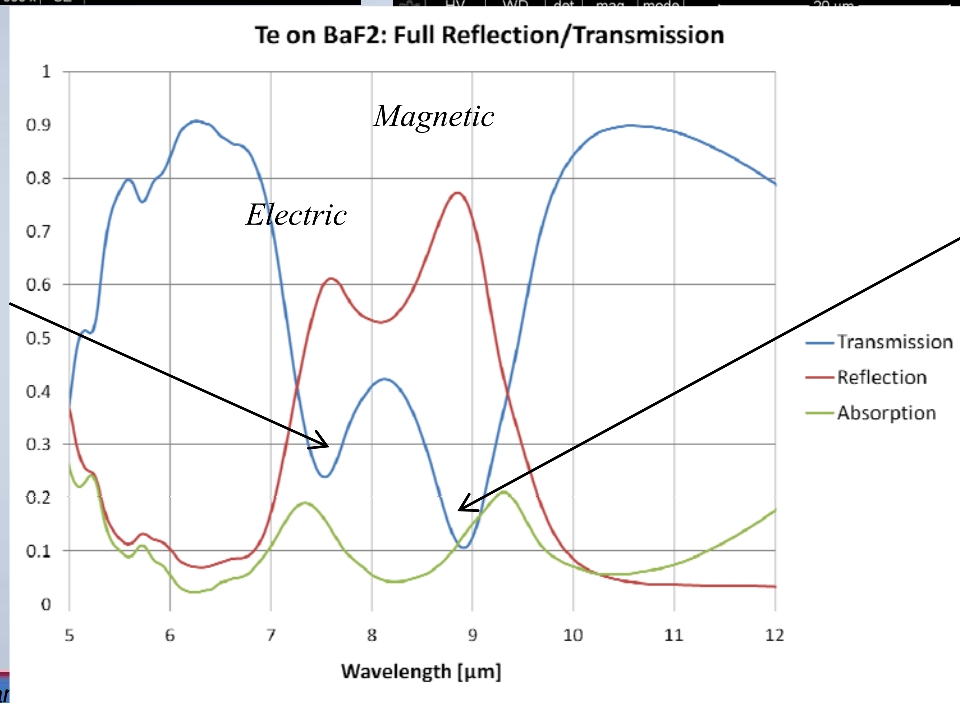


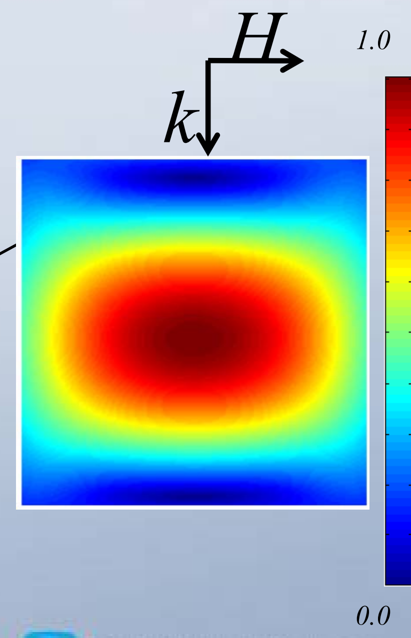
DR Infrared Metamaterial: Te/BaF_2





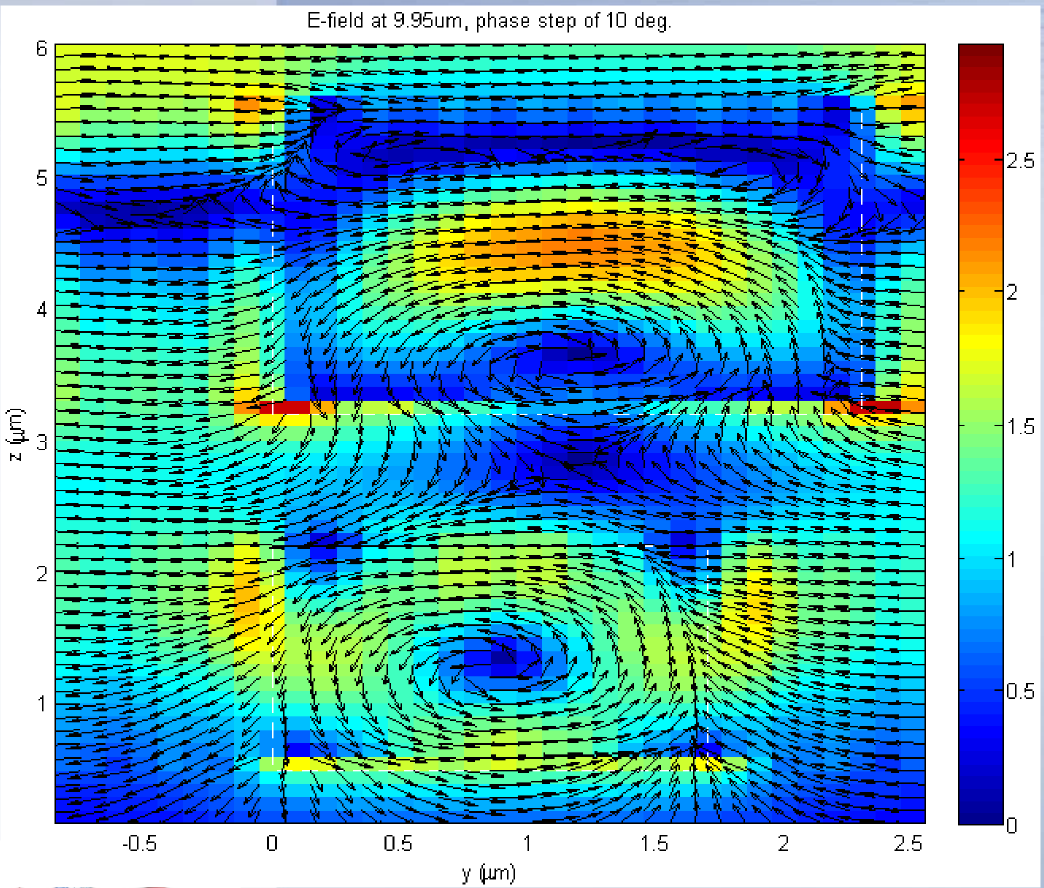






Tailoring both ε and μ: Dual Species Unit Cell Designs

- *Strategy: utilize two different resonators in the unit cell to separately adjust ε and μ*
  - *same material different sizes*
  - *different materials*
- *Has been experimentally demonstrated at RF frequencies (Sandia)*



Primary Drawbacks:

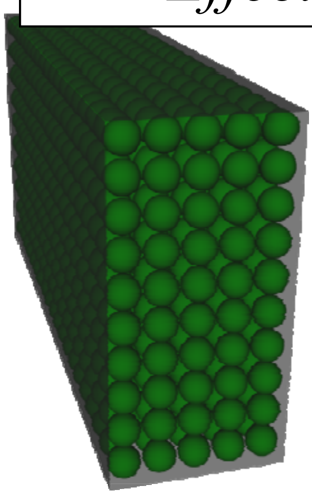
- *Doubling of the unit cell size*
- *Difficult to stay within the effective medium regime (without extremely high permittivity building blocks)*
- *Can't achieve high index metamaterials due to cut-off*

Tailoring e & m: high-Q resonators in e<0 matrix

- ***Simple spheres***
- ***Small unit cell***
- ***Sphere resonance contributes magnetic response, host material contributes electric response***
- ***Disadvantage***
  - ***loss in host contributes to overall loss***

PbTe Spheres in SiC Host Layer

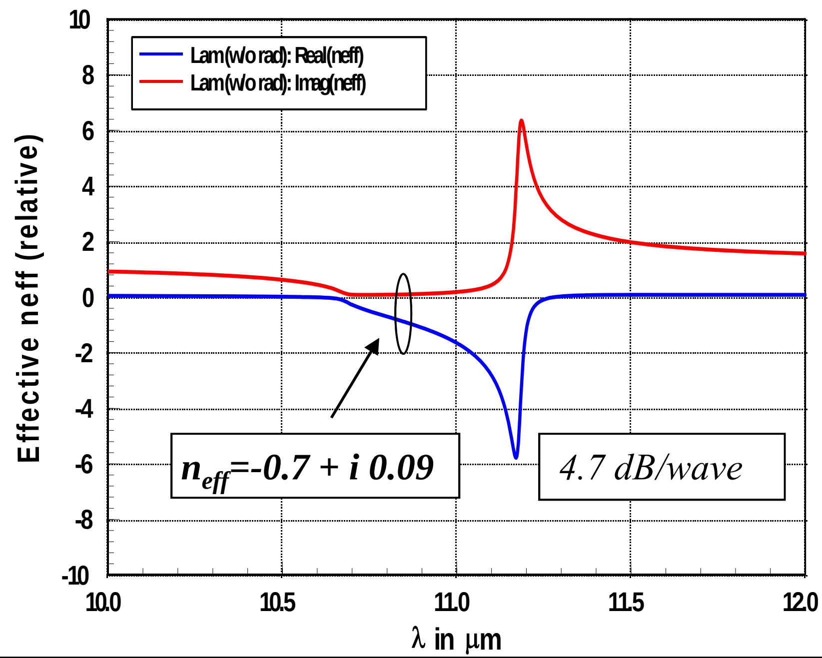
Effective Media Design



- *Palik values for PbTe*
- *SiC dispersion*

$$a = 0.997\,\mu m, b = 3.467\,\mu m, \mu_1 = \mu_2 = \mu_o$$

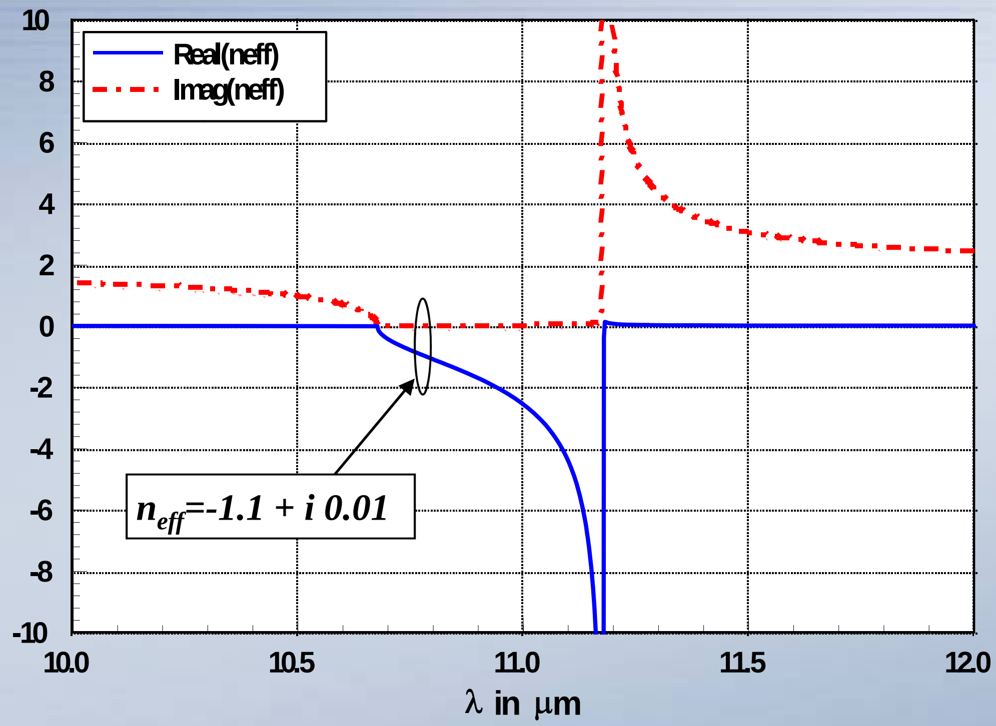
$$\varepsilon_{r1} = \varepsilon_{r1}(f), \varepsilon_{r2} = 30.5 + i0.0734$$



Reducing tan(δ) for PbTe by ~ 700 only reduces overall loss by ~2
Loss dominated by matrix loss

Optimizing the host leads to better performance

- *Keeping the resonator fixed at low loss PbTe and optimizing the host yields n_{eff}=-1.1+ i 0.01 for a host with ε=-2.82+ i 0.04.*
- *Might be achievable with a suitably doped conducting oxide.*



FOM~100 ➔ ~0.5 dB/wave

What Applications?

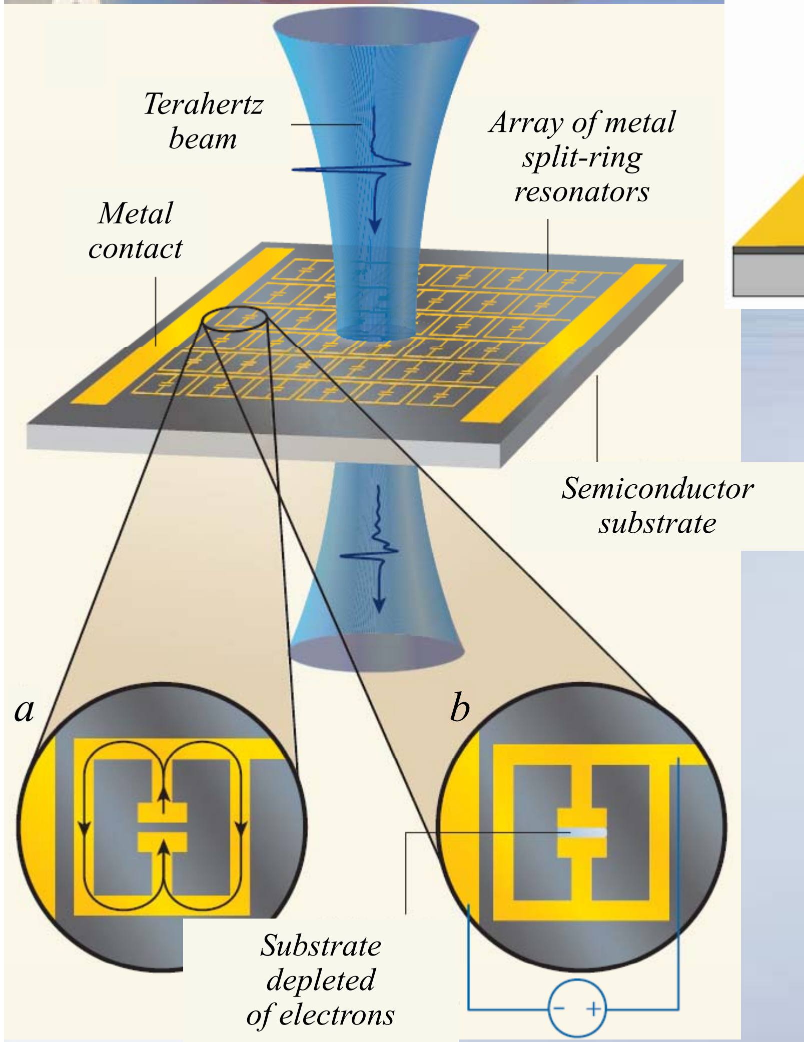
What optical functions can metamaterials perform?

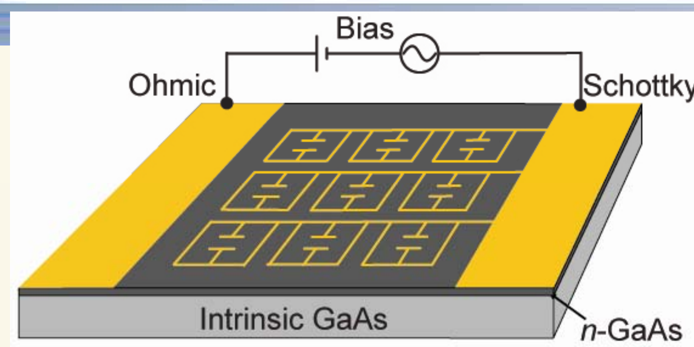
1. *Wavefront Control and engineering*
2. *Sub-λ Field Concentration*
3. *Absorption / Emission engineering*
4. *Active Tunability for 1-3*

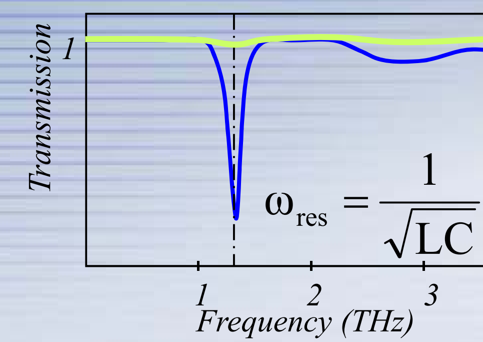
Tunability / Gain:

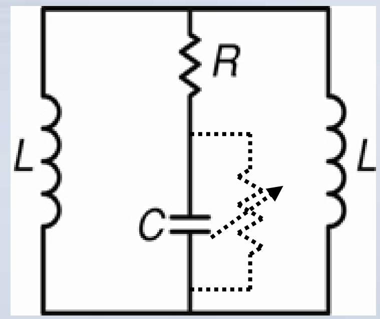
- **Loss compensation, novel lasers**
- **Communication, tunable filters, laser protection filters**
- **Vari-focal or "zoom" optics**
- **Spatial light modulators, Optical phased array beamsteering**

Electrically Tunable THz Metamaterials

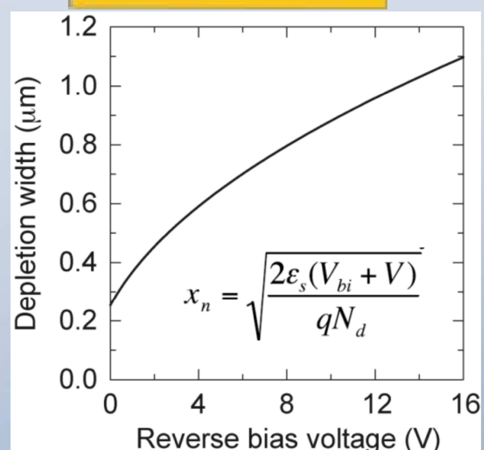


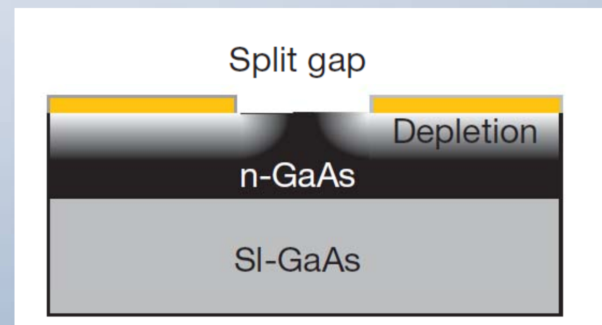






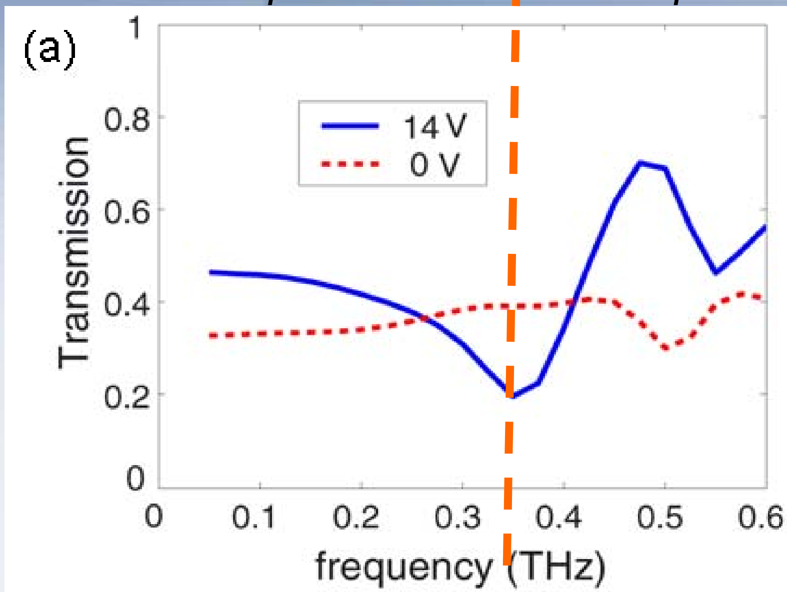
Modulate transmission by depleting carriers in GaAs (Chen et al, Nature, 2006)



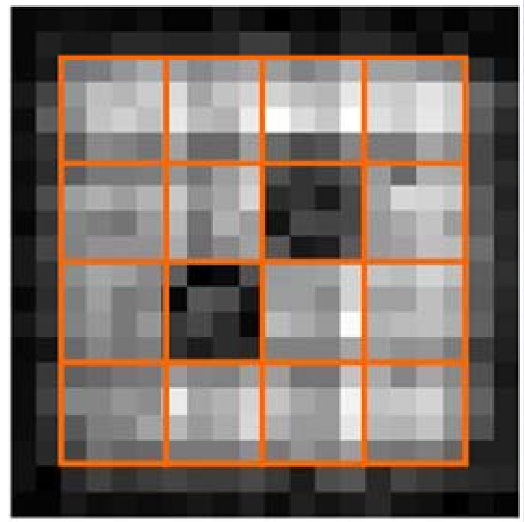


Performance of Metamaterial SLM

Typical on/off transmission spectra of a THz-SLM pixel



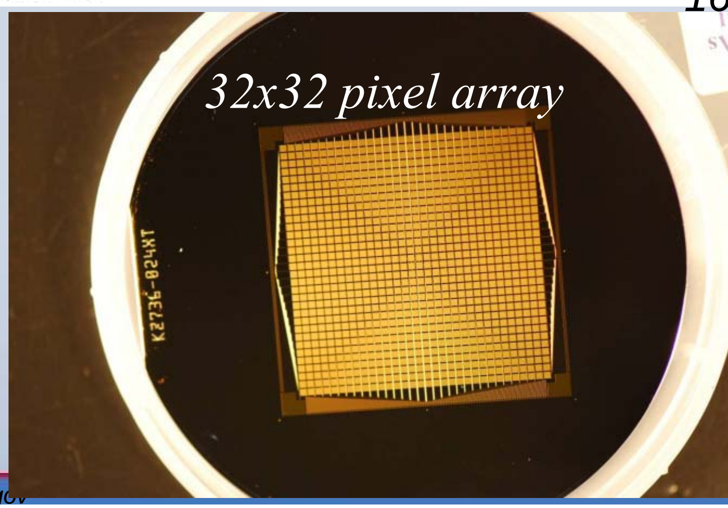
Transmission image of THz-SLM at 0.36 THz

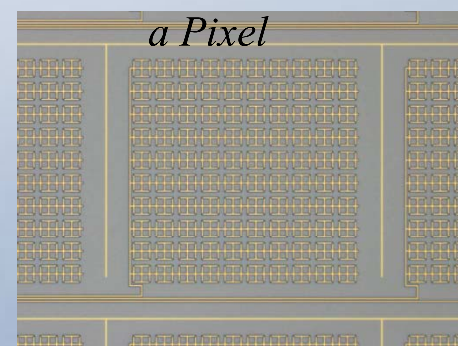


16 mm

- *~40% modulation*
- *Uniform across 16 pixels*

Chan et al, APL 94, 213511 (2009)





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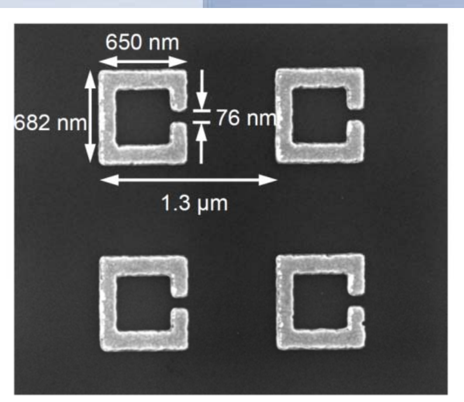
Scaling Tunable MM's to the Thermal IR

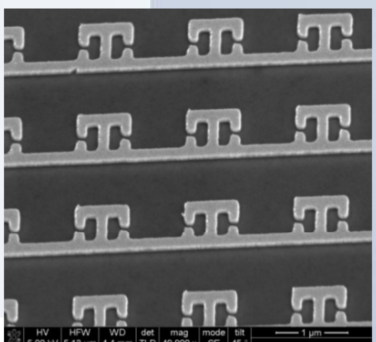
A semiconductor with higher plasma frequency needs to be chosen: InSb

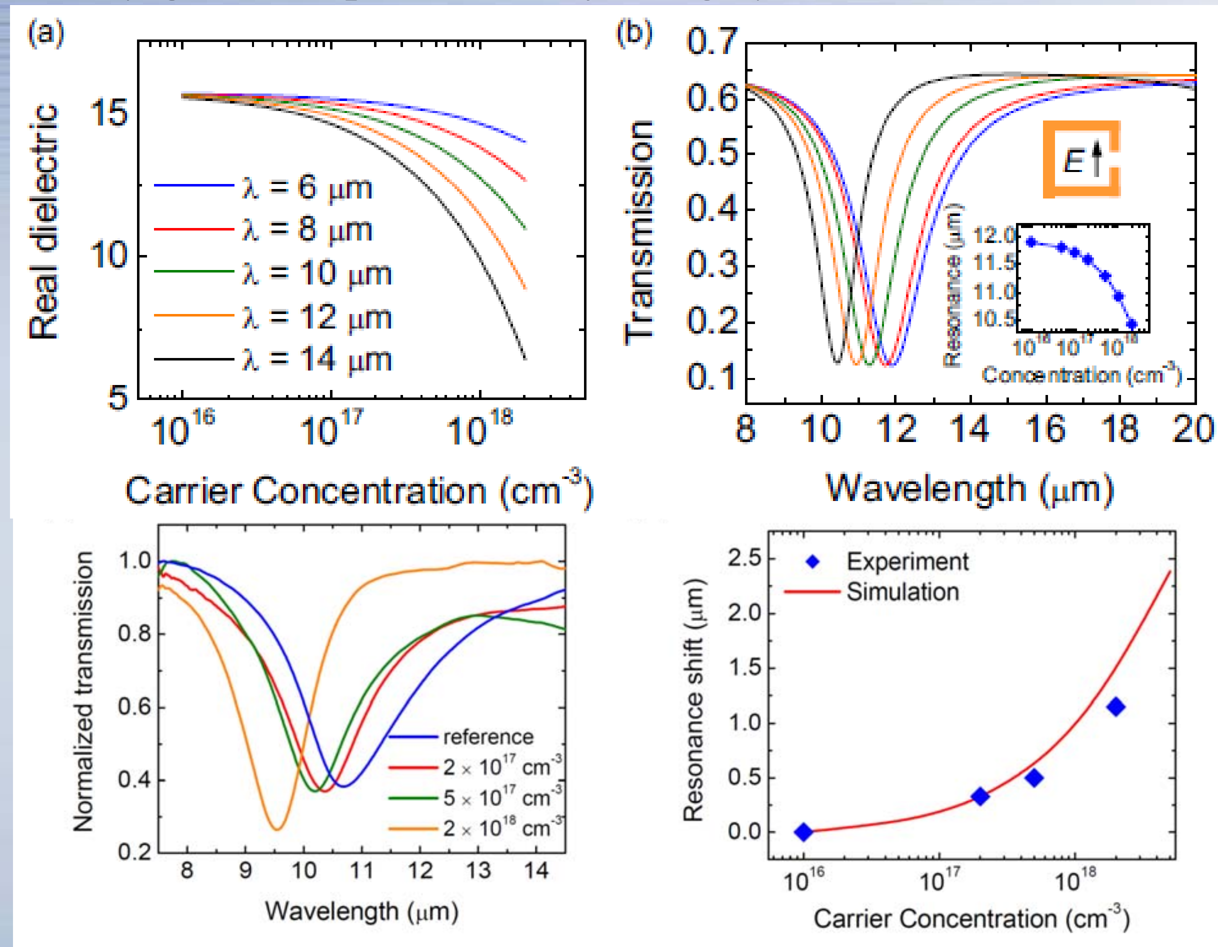
Demonstrated tuning of resonance with doping.

Working towards MOS structure (Schotky gates are problematic for highly doped InSb

"Blocking" filter

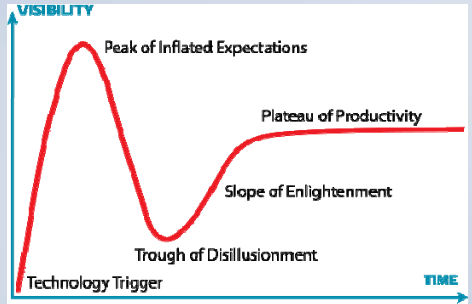




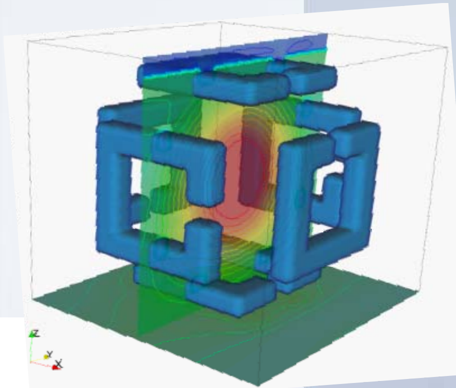


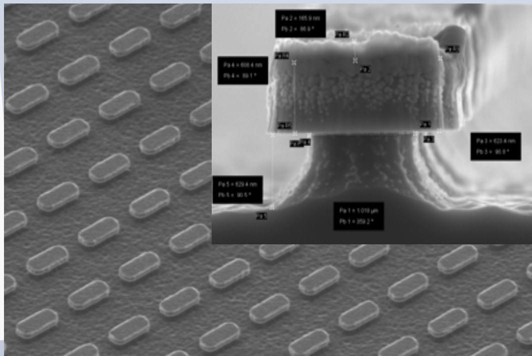
Conclusions

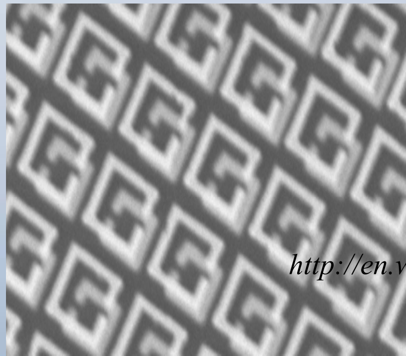
- **Current high interest in Metamaterials is a double-edged sword: <u>the “clock is ticking” for a compelling application</u>**
- **A critical mass of “nano-EM” expertise and <u>Full-cycle (Des/Fab/Test) capabilities are coming on-line</u> around the world**
- **“A<u>pplication-Engineering</u>” is becoming as important as Physics**

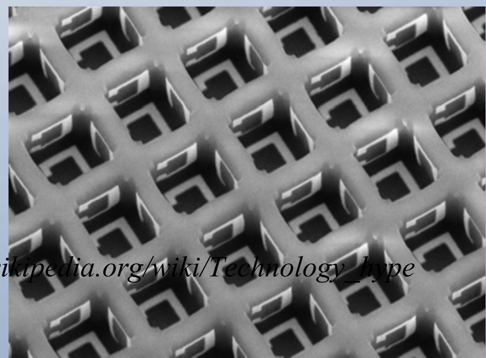


<u>Gartner, Inc. “Hype-Cycle”</u>









http://en.wikipedia.org/wiki/Technology_hype

The MST Team

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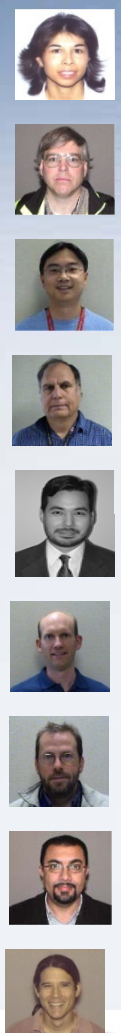

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