3D (passive) and 2D (active) Metamaterials at Infrared Optical Frequencies

Igal Brener

Sandia National Labs &
Center for Integrated Nanotechnologies (CINT)

ibrener@sandia.gov, **(505) 844-8097**

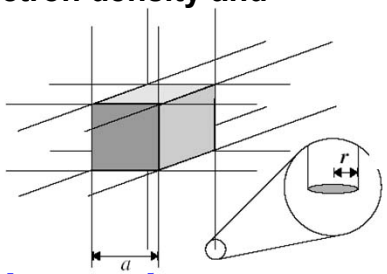
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

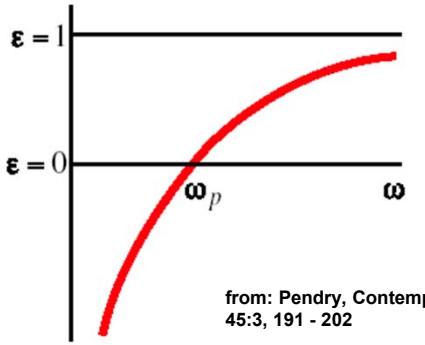
How to make a "Metamaterial"

Wire grid designs provide control over the electric permittivity (ε)

- Wire diameter and spacing << operating wavelength
- Can tune the plasma frequency by diluting the electron density and also varying the electron effective mass.
- Negative values of ε are obtained below

$$\omega_p = \sqrt{\frac{ne^2}{m^* \varepsilon_o}}$$

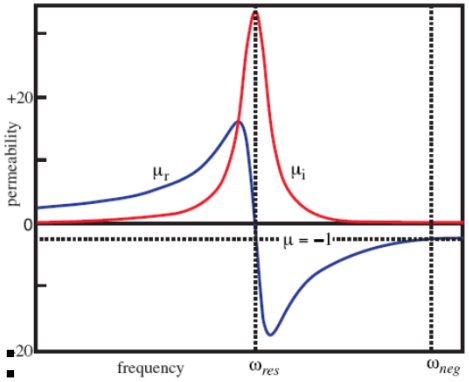


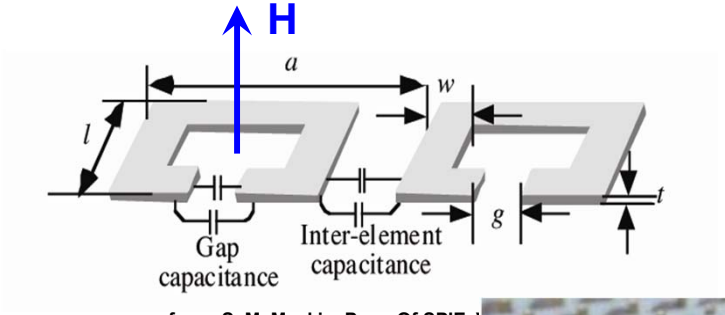


from: Pendry, Contemporary Physics, 45:3, 191 - 202

Split-ring resonator designs provide control over the magnetic permeability (μ)

- Can be viewed as resonant RLC circuit
- Negative values of μ are possible

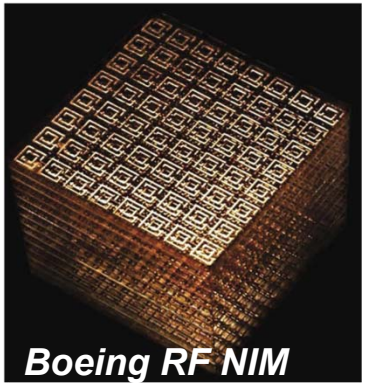


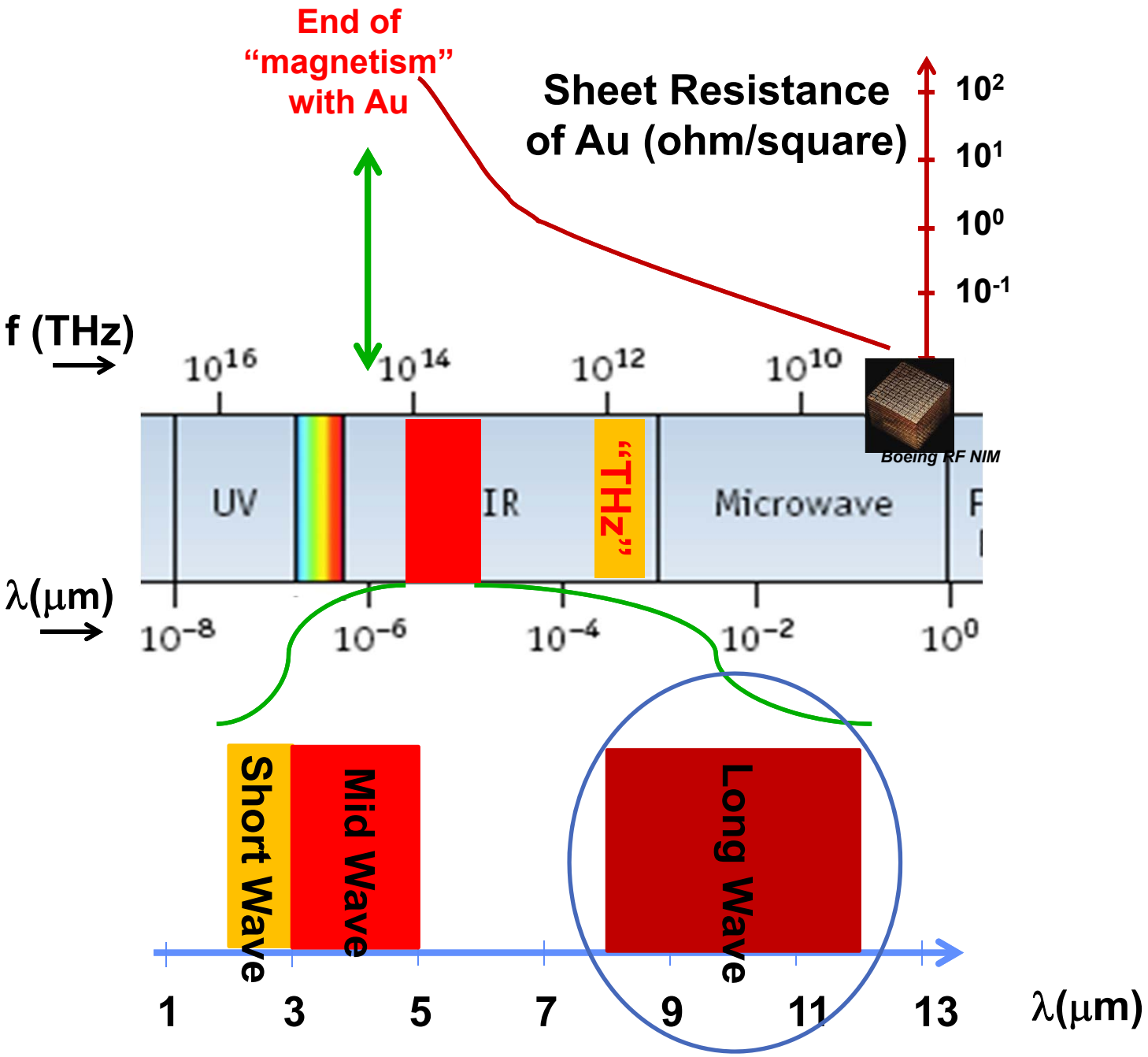


from; S. McMeekin, Proc. Of SPIE, V

Combine the two:

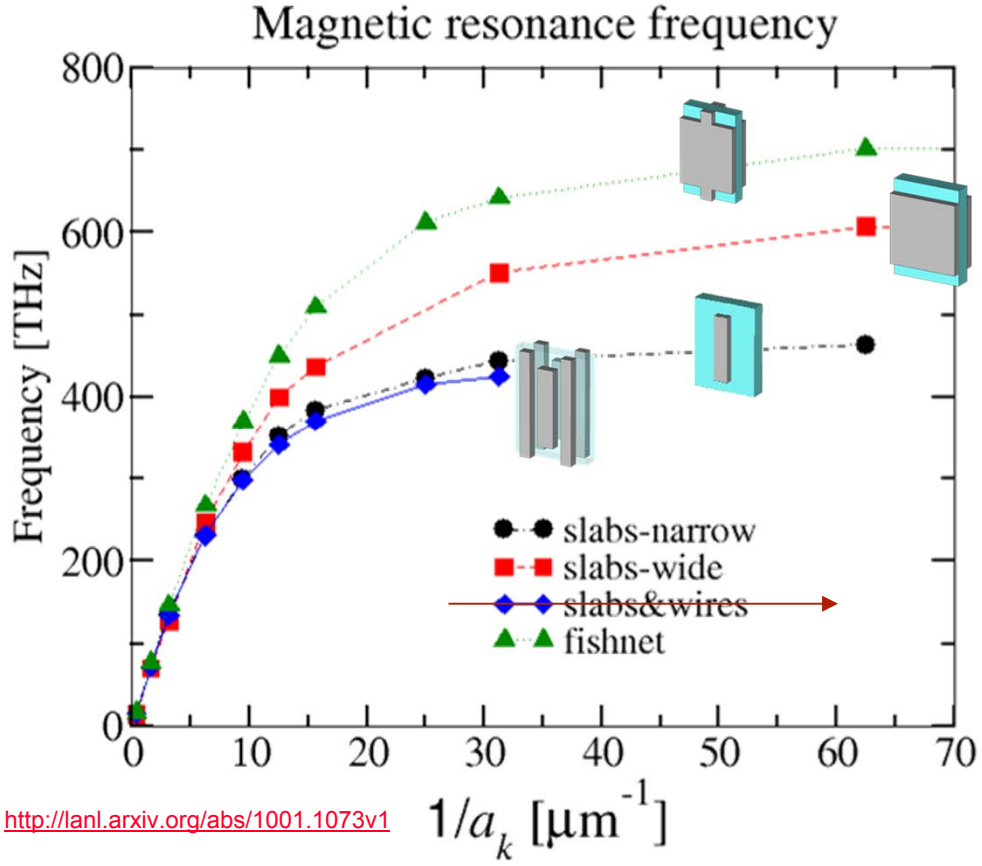
http://www.multitel.be/newsletter/mn72005/images/nl3_Metamaterials_type1.jpg



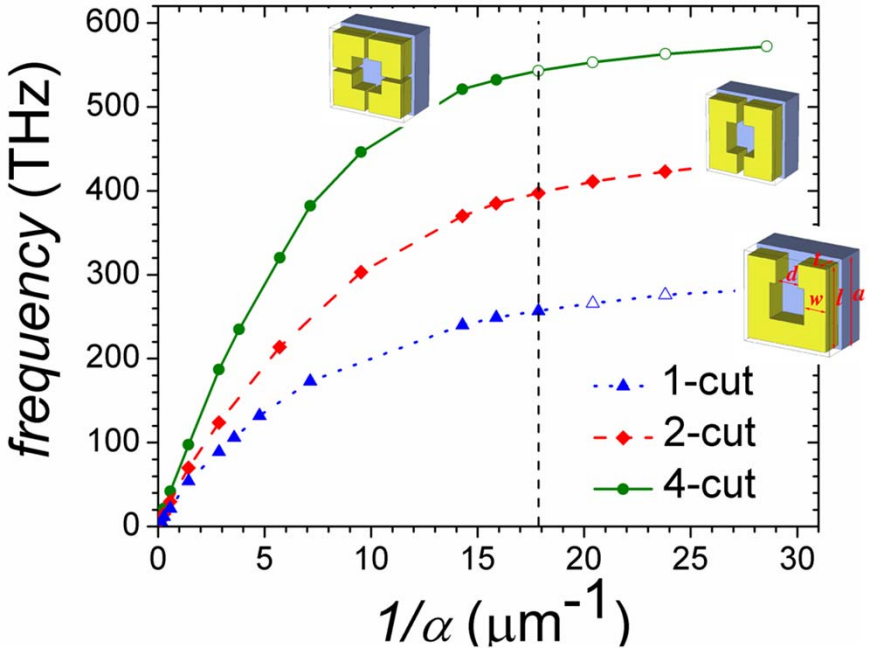

End of
"magnetism"
with Au
Sheet Resistance
of Au (ohm/square)
10^2
10^1
10^0
10^{-1}
f (THz)
10^{16}
10^{14}
10^{12}
10^{10}
Boeing RF NIM
UV
IR
"THz"
Microwave
λ(μm)
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^0
Short Wave
Mid Wave
Long Wave
1
3
5
7
9
11
13
λ(μm)

Scaling issues: saturation of magnetic behavior

Saturation of magnetic resonance frequency for small length scales (*a*<500 nm)



http://lanl.arxiv.org/abs/1001.1073v1



Zhou et alPhys. Rev. Lett. 95, 223902 (2005).

$$\sigma = i\varepsilon_0 \frac{\omega_p^2}{\omega + i\gamma_m}$$

$$R_{tot} = \frac{1}{\sigma}\frac{l}{S} = \frac{\gamma_m}{\varepsilon_0\omega_p^2}\frac{l}{S} - i\omega\frac{1}{\varepsilon_0\omega_p^2}\frac{l}{S} = R - i\omega L_e$$

"Inductive" term

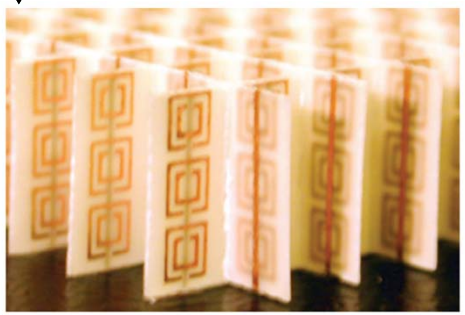
Zhou et. al., 2005, Tretyakov, 2007, Solymar, 1976, Shvets et. al., 2005

Outline

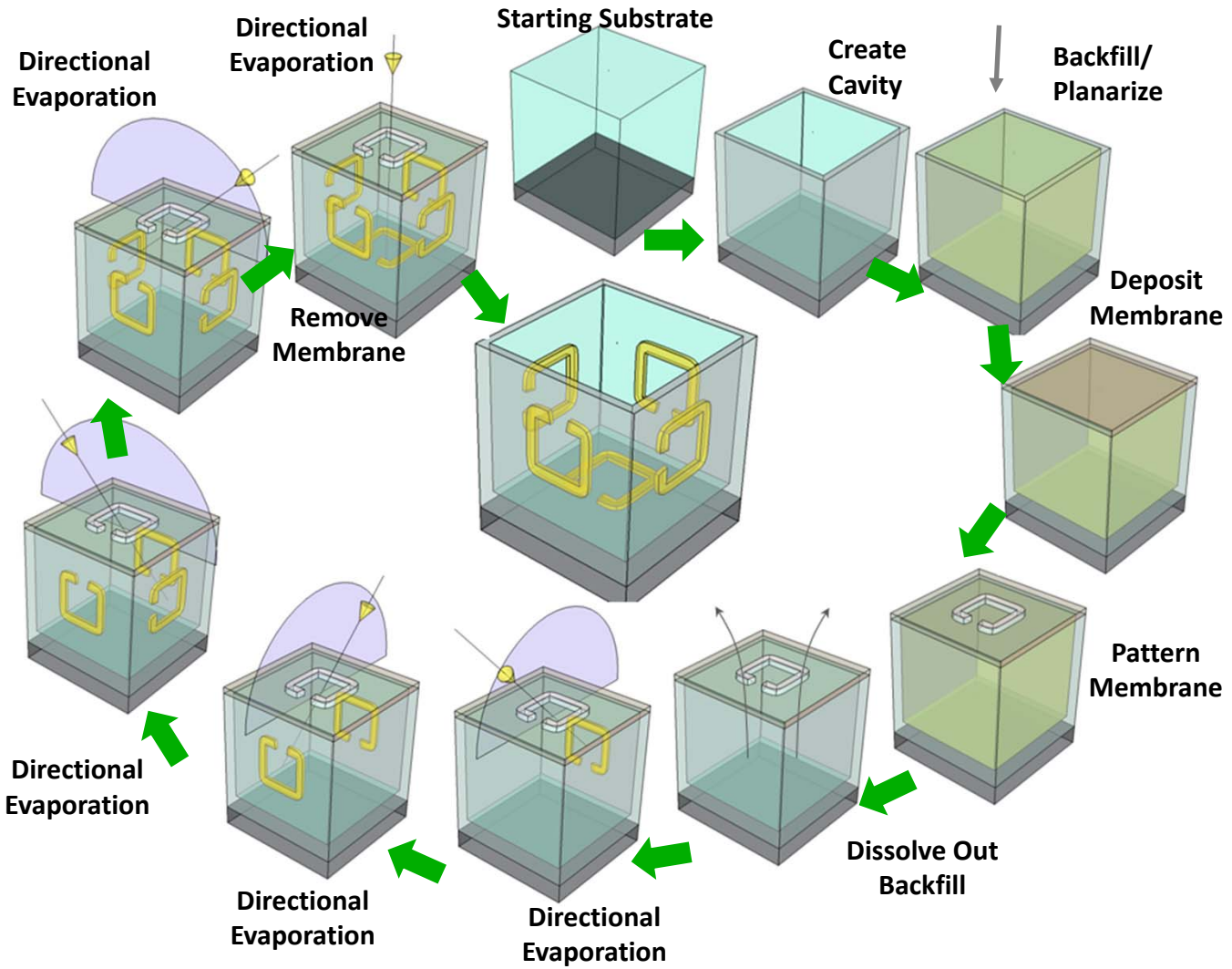
- **3D Passive Metamaterials**
  - **With Metals: Membrane Projection Lithography**
  - **Without Metals: Dielectric Resonators**
- **2D Active Metamaterials**

3D MMs: Membrane Projection Lithography (MPL)

Goal: achieve this at optical frequencies

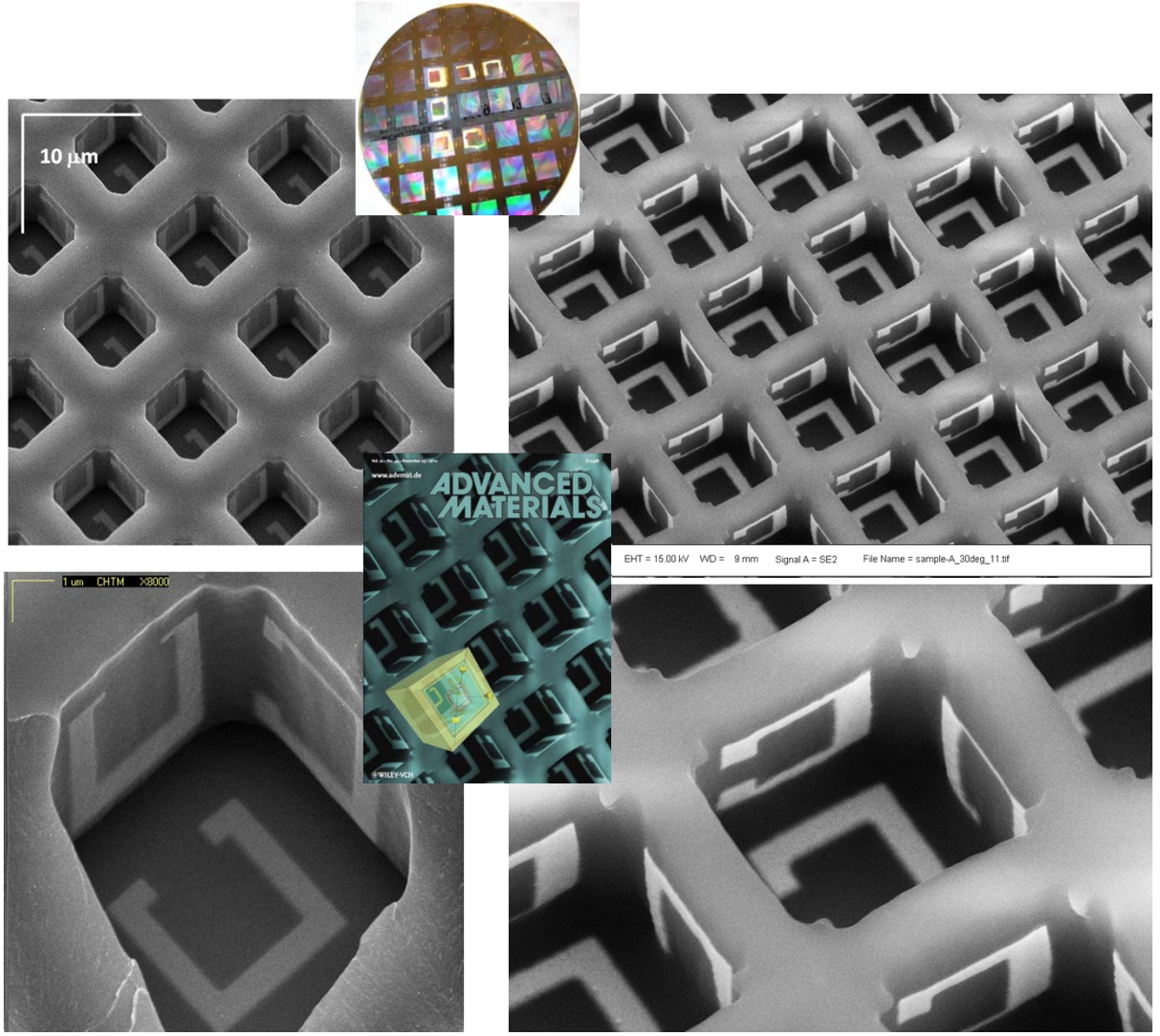


- Out-of-plane resonators
- Planar lithography
- Many patterns possible
- Cavity geometry independent of resonator pattern
- Scalable
- Layer-by-layer → 3-D

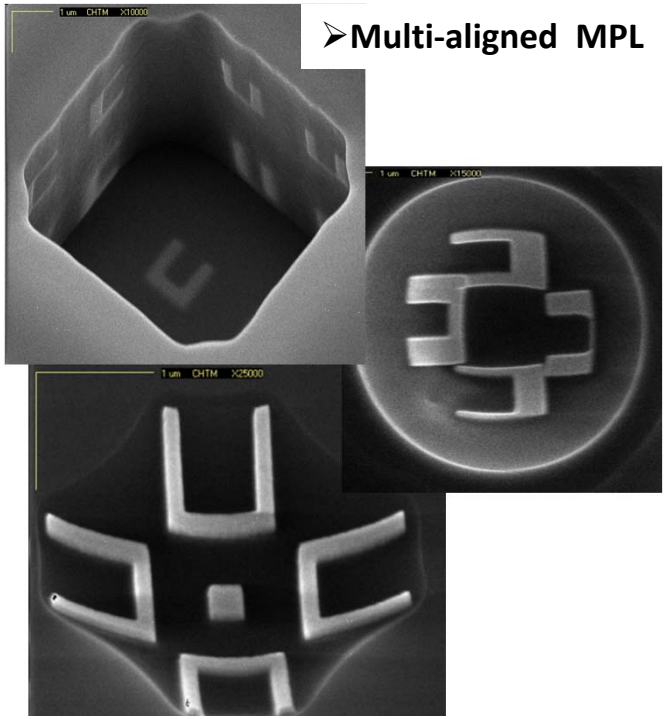


D. B. Burckel, et al (2010), Advanced Materials, 22: 5053–5057.

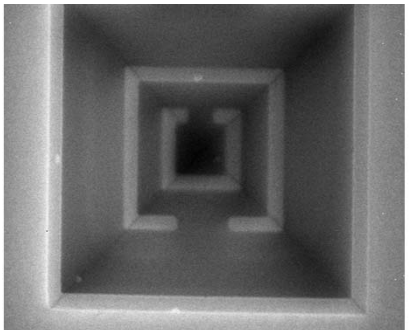
3D Metamaterials via MPL



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



- Multi-aligned MPL
- Self-aligned MPL: spherical cavities

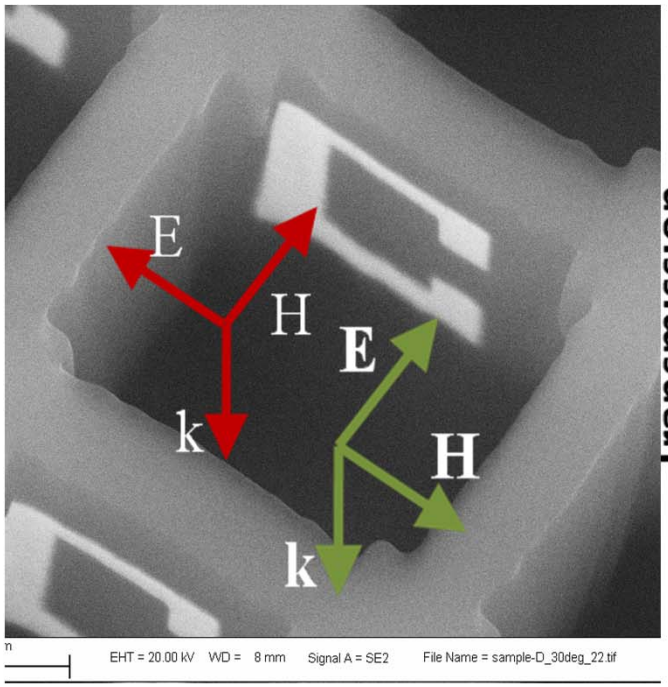


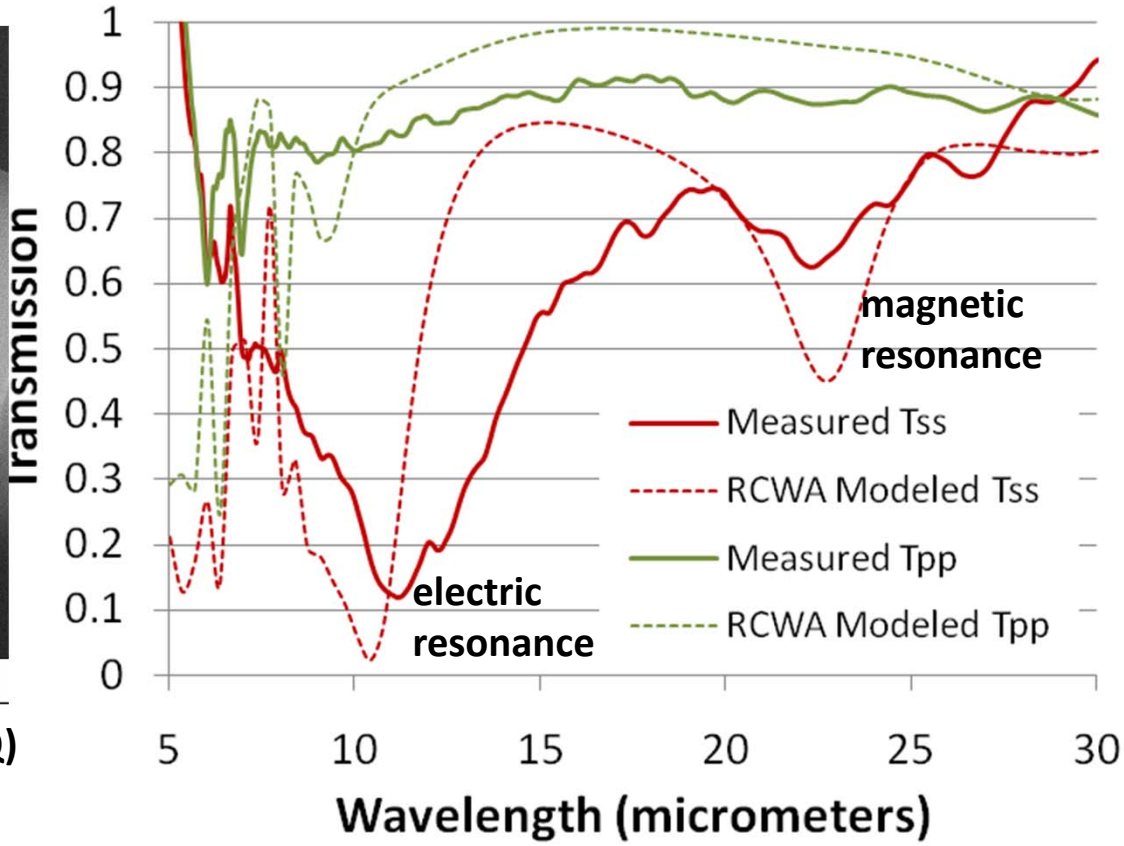
- Pyramidal 3D metamaterials in Si

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

I. Brener, D. B. Burckel, et al, SPIE Newsroom, 8 September 2010, SPIE Newsroom; Adv. Mat 2010

Polarized Transmission of Magnetically Excited SRR Array





RCWA: m=0.36+0.56i (fill factor, low-Q)

S-polarization

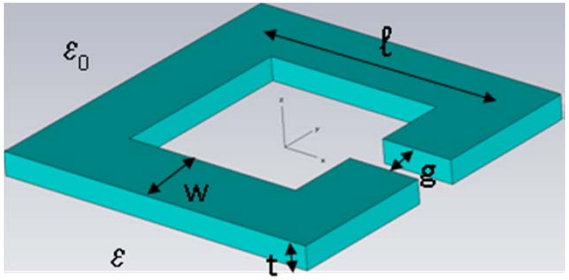
- **B-field excites lowest SRR resonance --- magnetic excitation**
- **E-field excites second order resonance --- electric excitation**

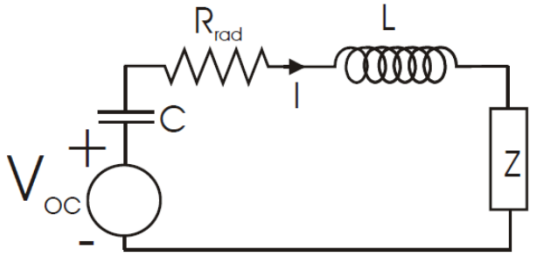
P-polarization

- **can't couple to any SRR resonances**

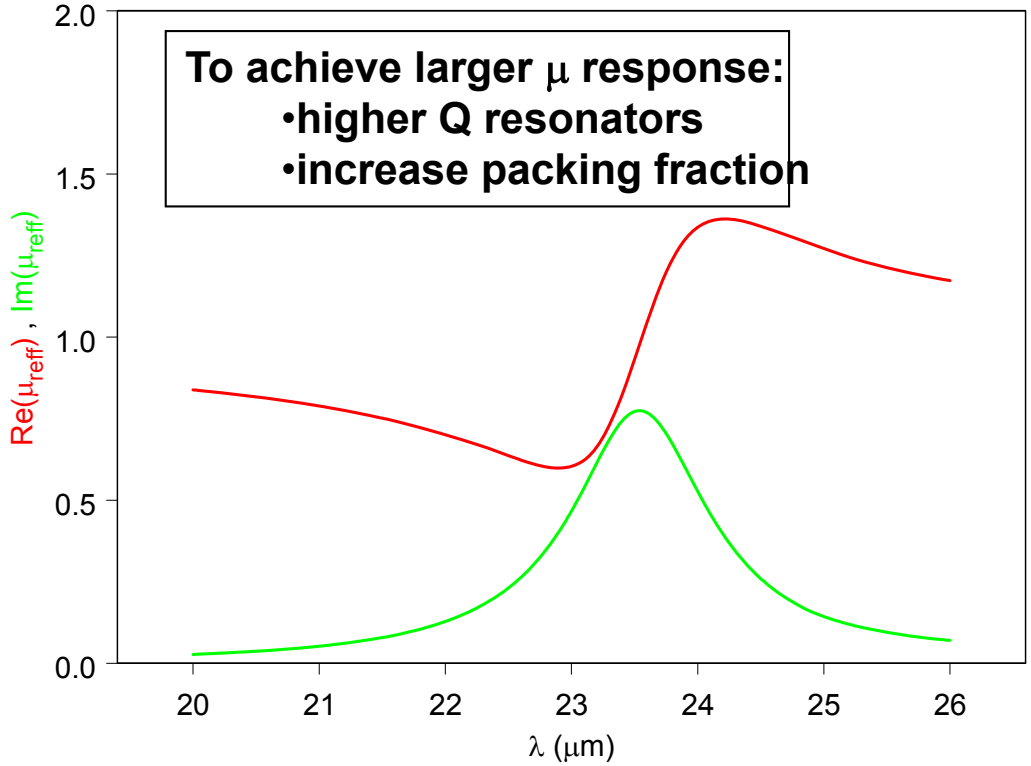
D. B. Burckel, et al (2010), Advanced Materials, 22: 5053–5057.

Predicted permeability: bulk array with SRRs on single wall



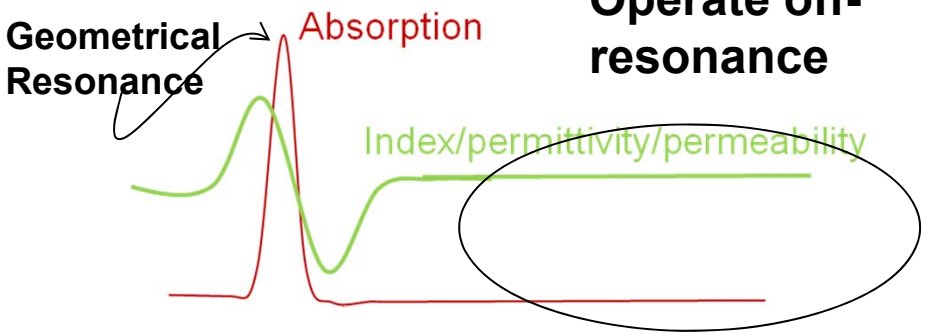


Bulk Magnetic Permeability



Analytic Circuit Model (L. Warne) + larger scale simulations

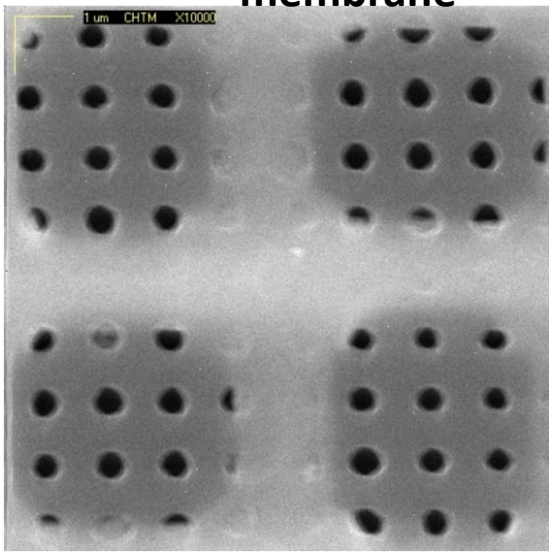
Non-Resonant MPL: Artificial Dielectrics

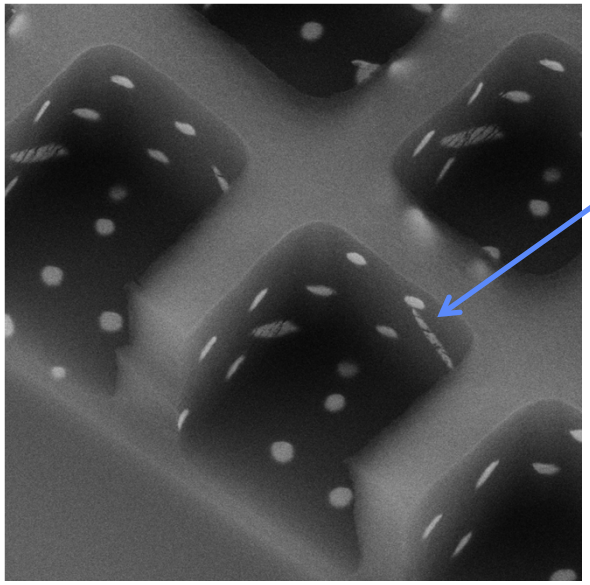


Operate off-resonance

We need:
Electrically Polarizable Inclusions

Perforated photoresist membrane

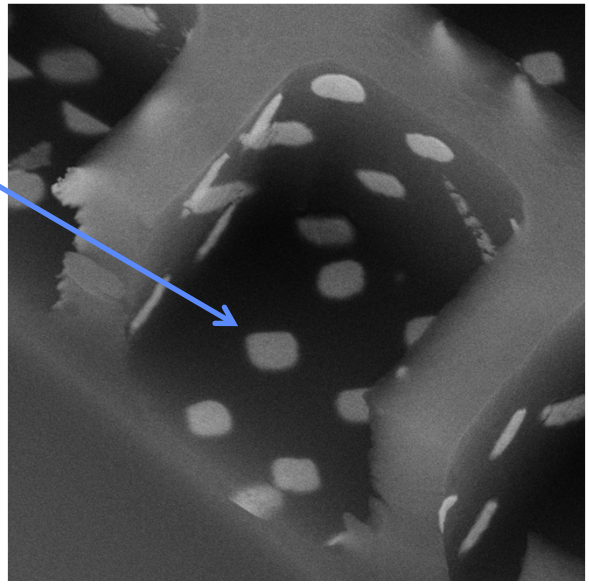




Exposure dose controls inclusion size

~ 200 nm inclusions

~ 400 nm inclusions

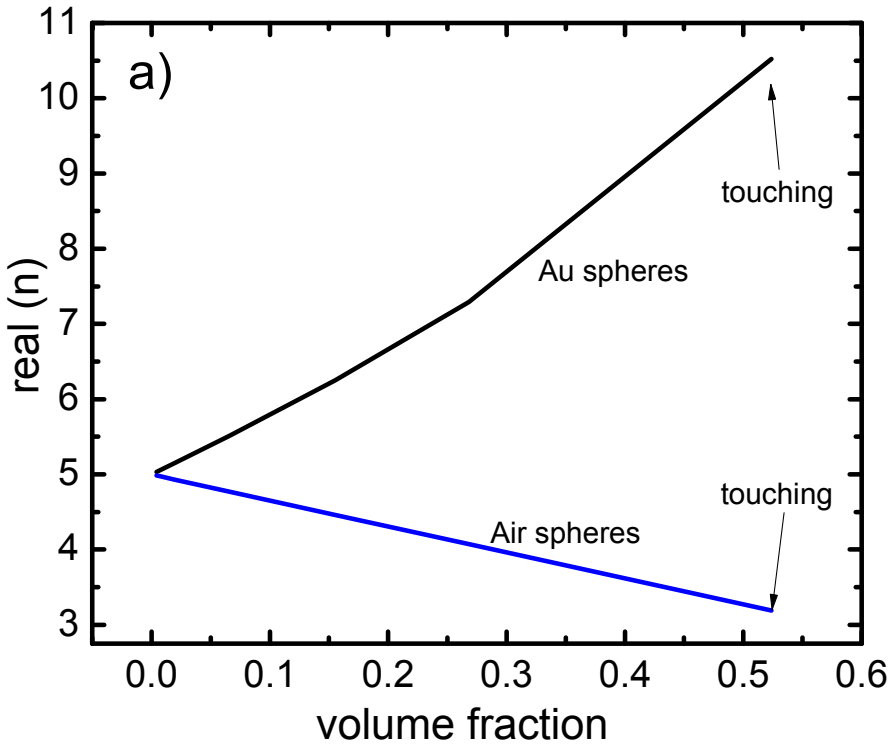


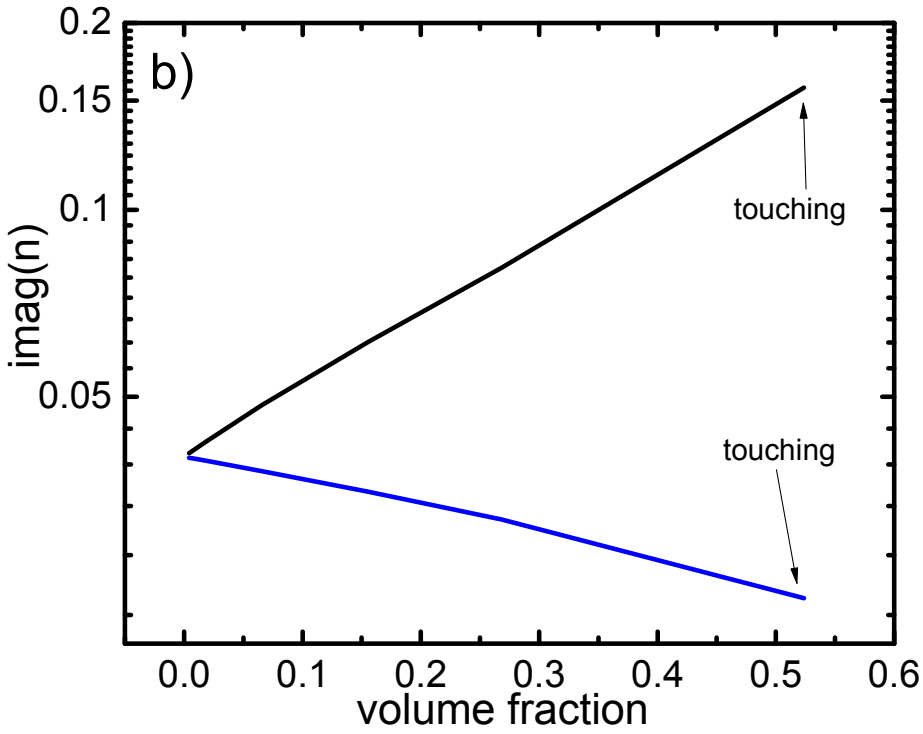
Opt. Mat. Exp. 2011

Non-Resonant MPL: What is the Range of n?

Claussius Mossotti:

- **Air voids & Au spheres in Te (n=5+i*0.04)**
- **radius=0.1 um**





Voids in high ε matrix: Δn~2-3

Metallic Inclusions in high ε matrix: Δn~5-6!

Outline

- **3D Passive Metamaterials**
  - With Metals: Membrane Projection Lithography
  - **Without Metals: Dielectric Resonators**
- 2D Active Metamaterials

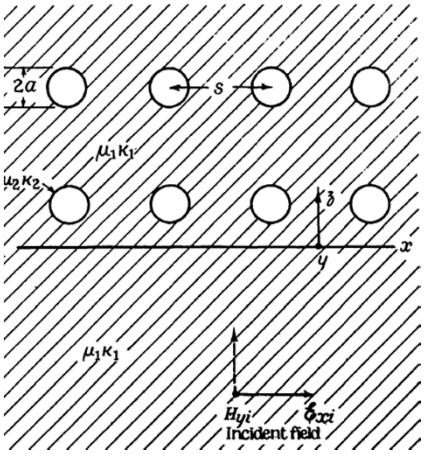
A Non-Metallic Path to Low Loss Metamaterials: Dielectric Resonators

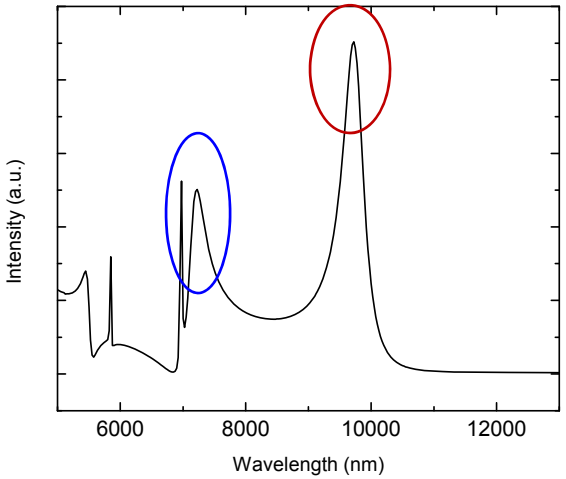
$$a_n = \frac{m\Psi_n(mx)\Psi_n'(x) - \Psi_n(x)\Psi_n'(mx)}{m\Psi_n(mx)\xi_n'(x) - \xi_n(x)\Psi_n'(mx)}$$

$$b_n = \frac{\Psi_n(mx)\Psi_n'(x) - m\Psi_n(x)\Psi_n'(mx)}{\Psi_n(mx)\xi_n'(x) - m\xi_n(x)\Psi_n'(mx)}$$

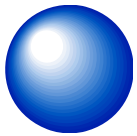
$$\Psi_n(p) = pj_n(p) \qquad \xi_n(p) = ph_n^{(1)}(p)$$

$$x = ka_s \qquad m = \frac{n_{sphere}}{n_{host}}$$





http://www.philiplaven.com/mieplot.htm



Gustav Mie

First (Primary) resonance is magnetic for most materials; Secondary is electric

THE ELECTRICAL CONSTANTS OF A MATERIAL LOADED WITH SPHERICAL PARTICLES*

By L. LEWIN.†

(*The paper was first received 4th March, and in revised form 27th September*, 1946.)

$$F(\theta) = \frac{2(\sin\theta - \theta\cos\theta)}{(\theta^2 - 1)\sin\theta + \theta\cos\theta}$$

$$\mu'_{re} = \mu_{r1}\left(1 + \frac{3v_f}{\frac{F(\theta)+2b_m}{F(\theta)-b_m} - v_f}\right)$$

$$\epsilon'_{re} = \epsilon_{r1}\left(1 + \frac{3v_f}{\frac{F(\theta)+2b_e}{F(\theta)-b_e} - v_f}\right)$$

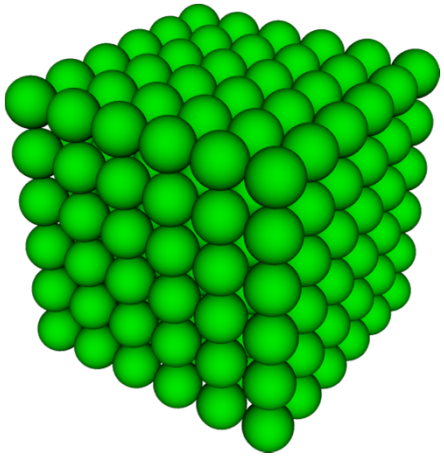
$$\theta = k_0 a\sqrt{\epsilon'_{r2}\mu'_{r2}}$$

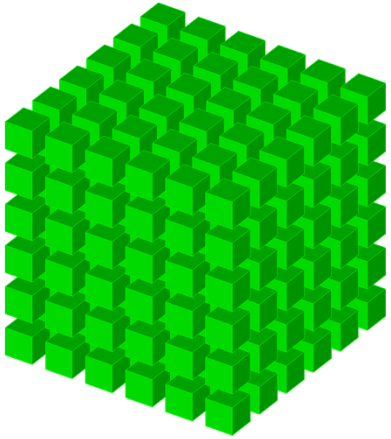
$$b_e = \frac{\epsilon_1}{\epsilon_2}, \qquad b_m = \frac{\mu_1}{\mu_2}$$

ε<0 if $\dfrac{3v_f}{\frac{F(\theta)+2b_e}{F(\theta)-b_e} - v_f} < -1$

and a similar condition for μ<0

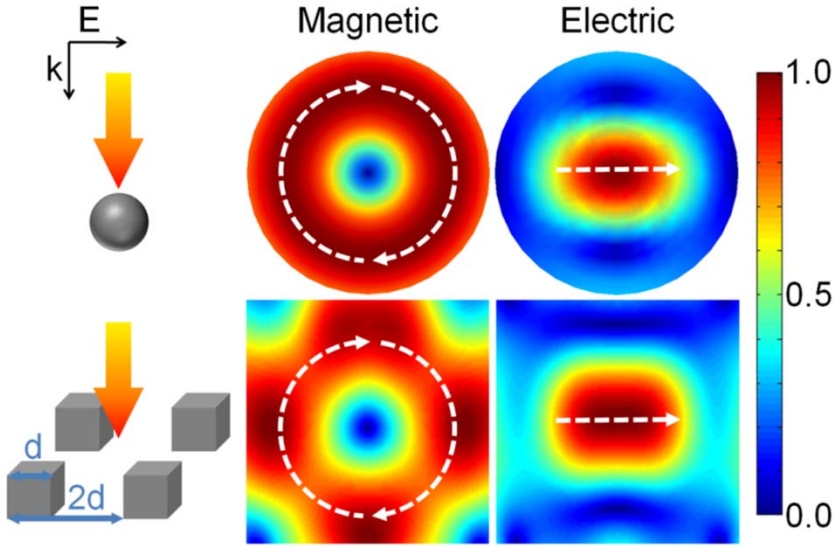
Arrays of High ε Resonators: Low Loss Metamaterials





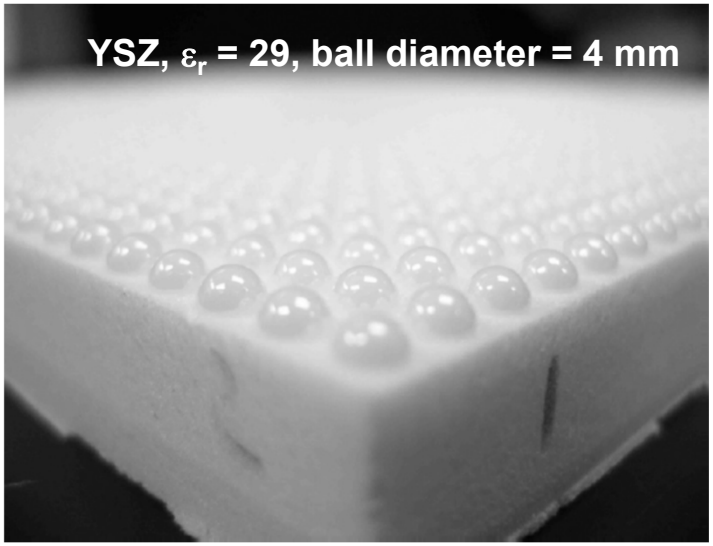
Spherical

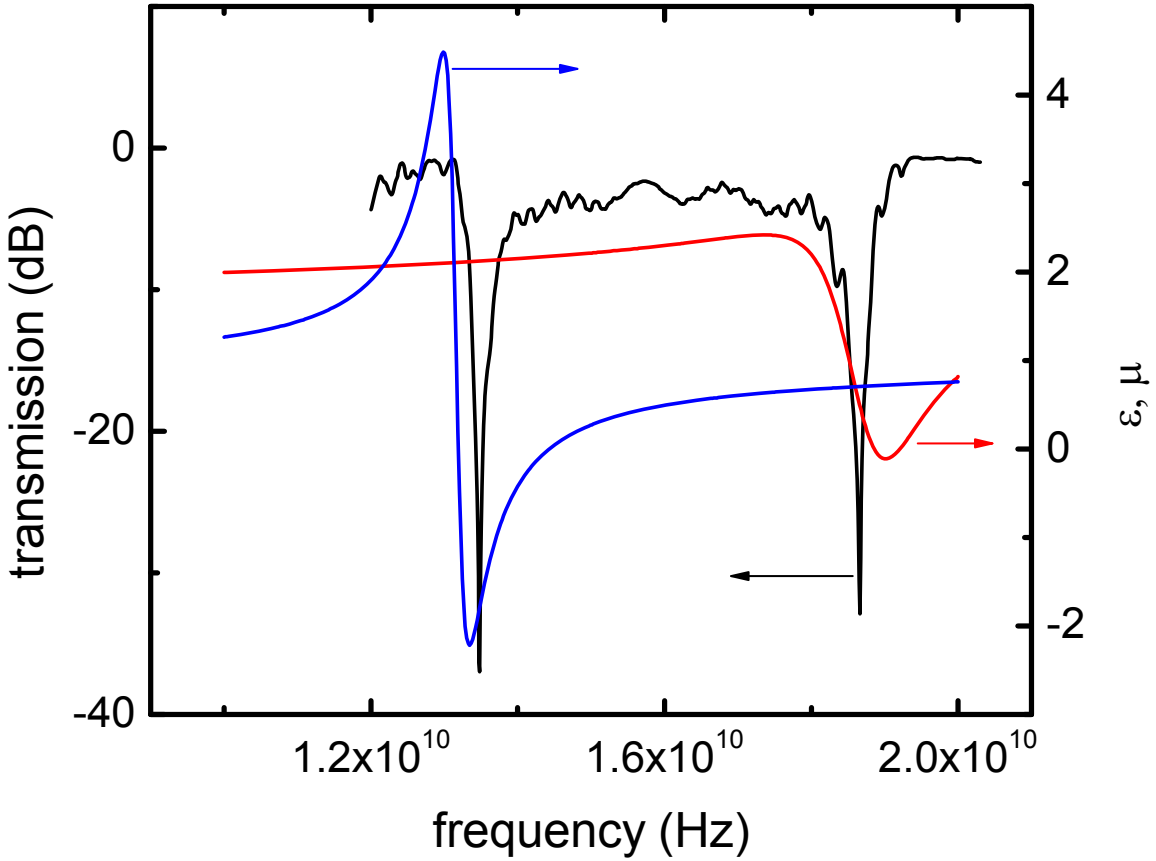
Cubic



RF Demonstration: YSZ Spheres

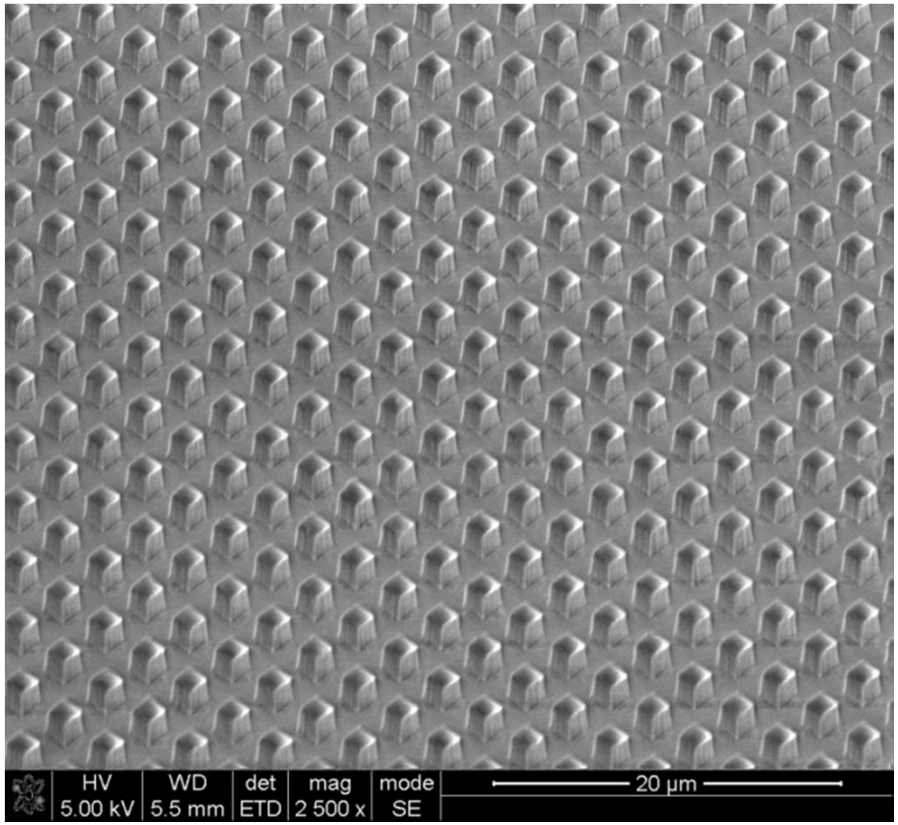
ε_r = 29, ball diameter = 4 mm

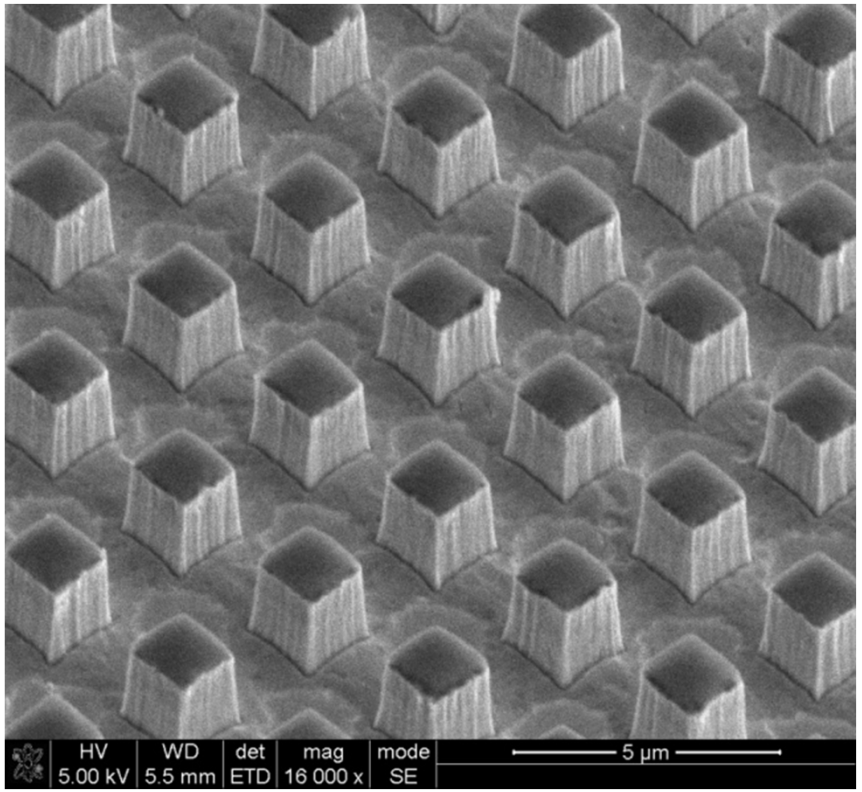




Low transmission band coincides with negative ε, μ spectral ranges.

Dielectric Resonator IR Metamaterial: Te/BaF_2

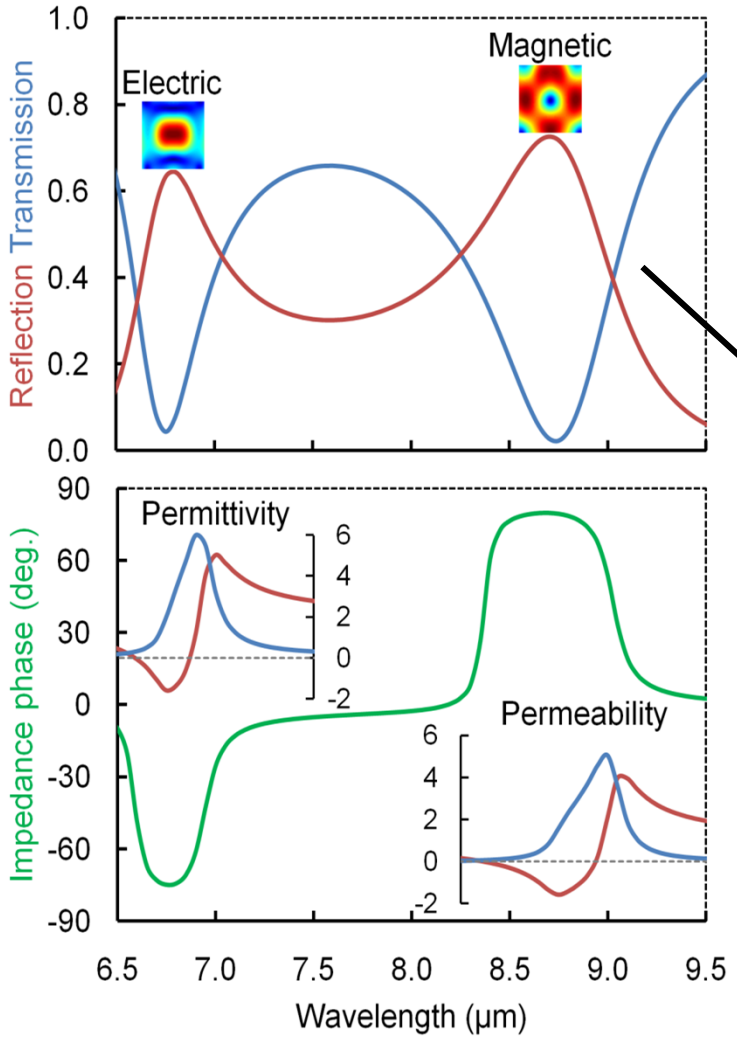


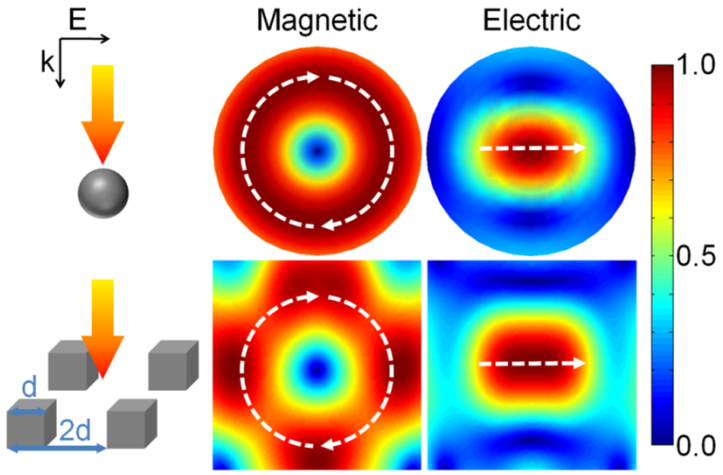


$1.53x1.53x1.7mm^3$
10 deg wall slope

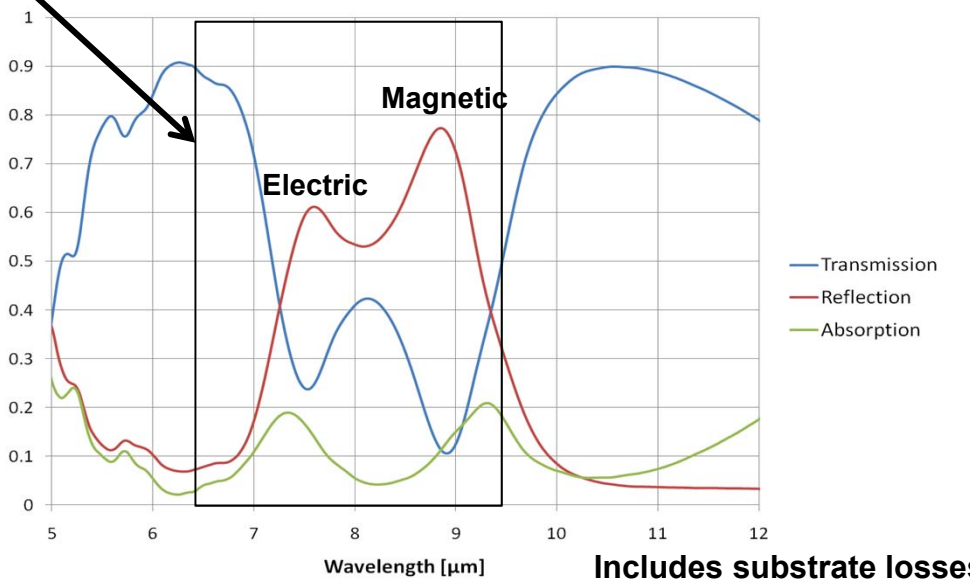
J. C. Ginn, et al, arXiv 2011, PRI 2012 (accepted)

Dielectric Resonator IR Metamaterial: Te/BaF_2





Te on BaF2: Full Reflection/Transmission



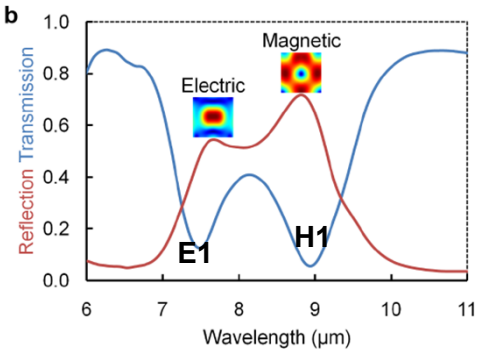
Includes substrate losses

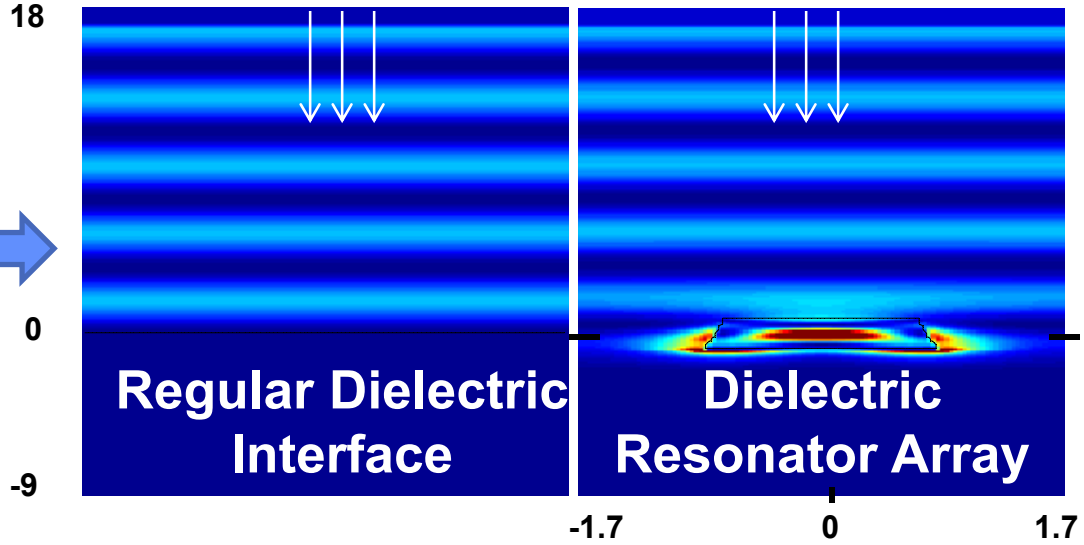
J. C. Ginn, et al, arXiv 2011, PRI 2012 (accepted)

Te Cubic Resonators:
FDTD Simulation of the Reflected Wave

Simulated using as-made dimensions and measured optical constants

Electric Resonance λ=7.4μm

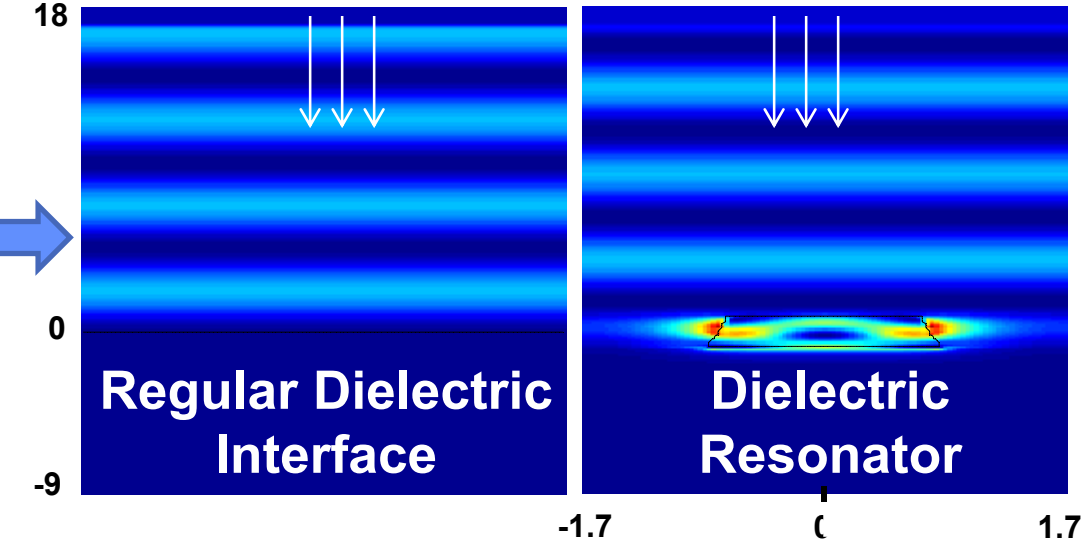




$$E_r \propto -E_i$$

H1 (λ=9.5μm)

Magnetic Resonance λ=9.5μm

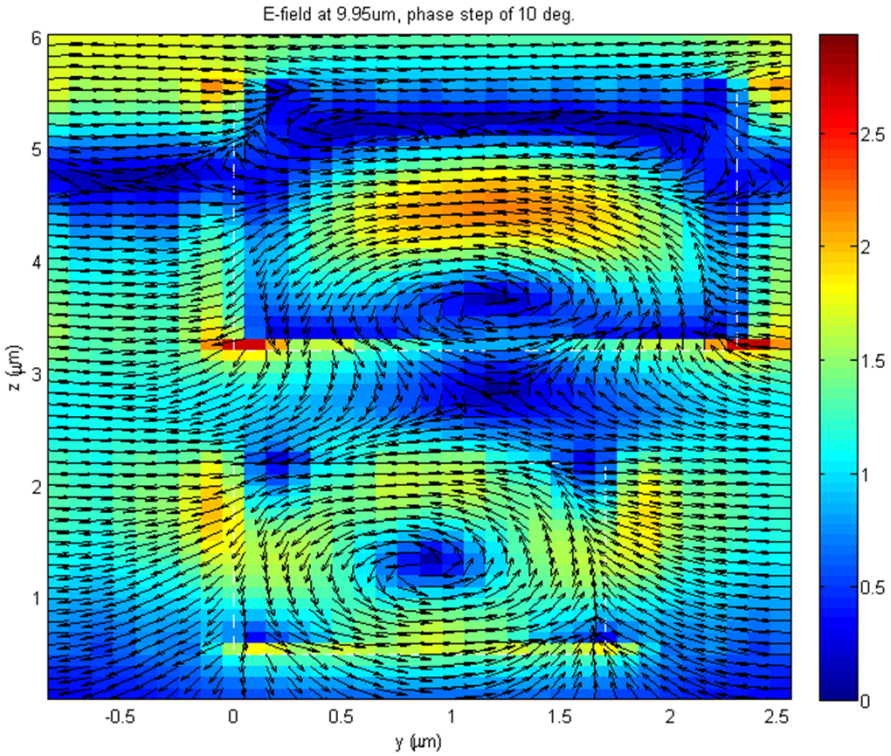


$$E_r \propto +E_i$$

"magnetic mirror"

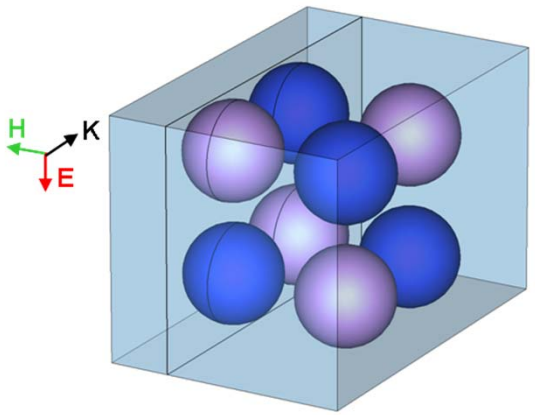
Tailoring both ε and μ: Dual Species Unit Cell Designs

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

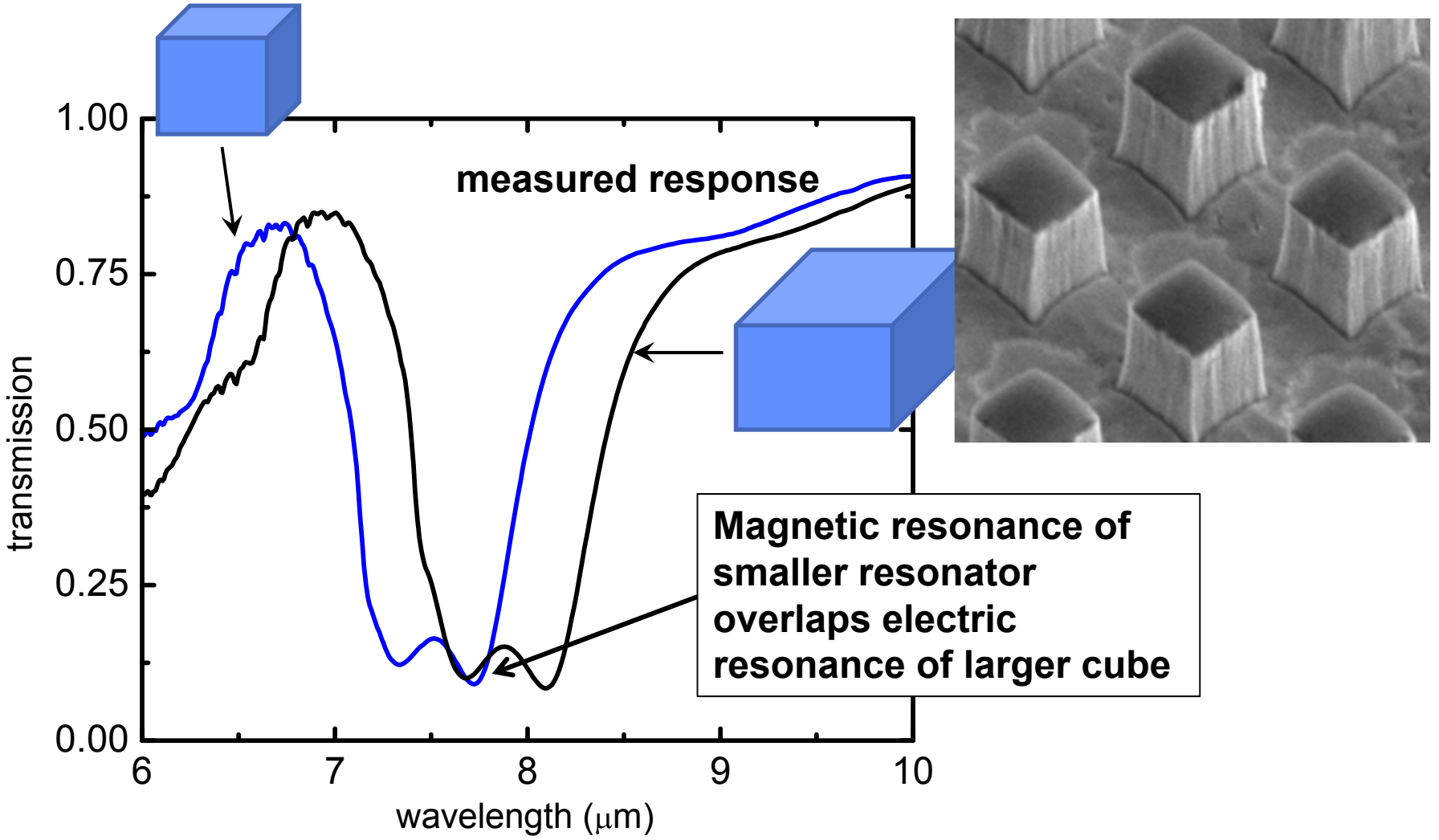


Primary Drawbacks:

- **Doubling of the unit cell size**
- **Difficult to stay within the effective medium regime**
- **Can't achieve high index metamaterials due to cut-off**

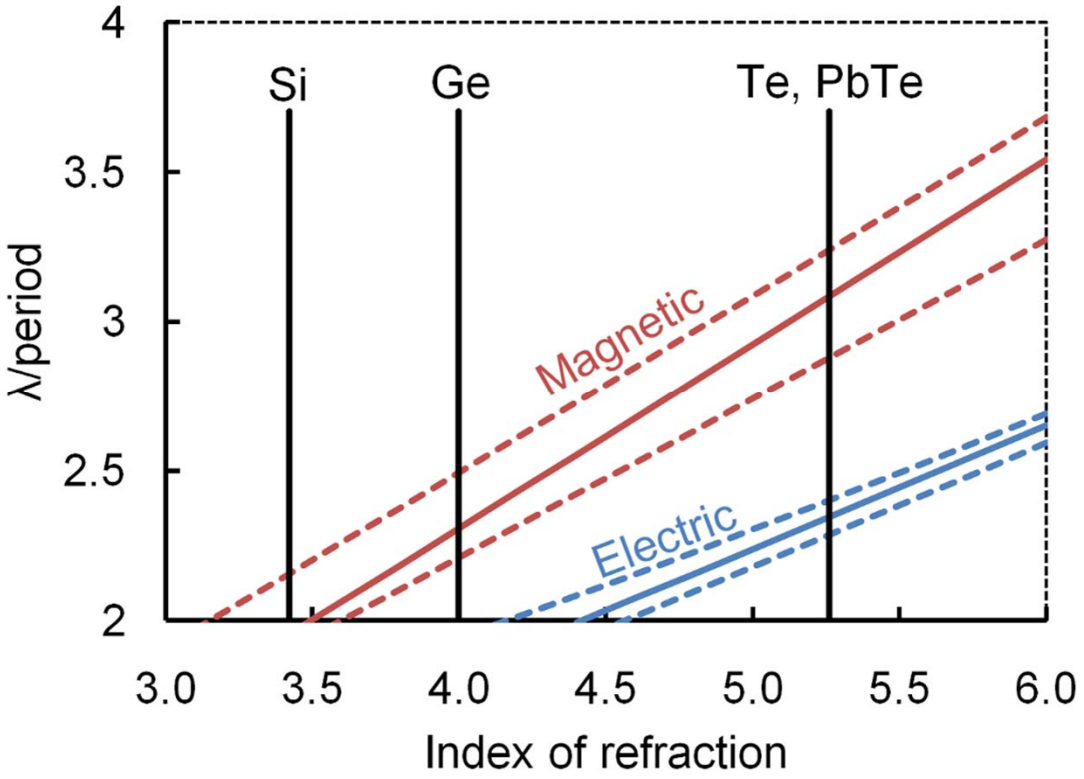


Te Resonators: Electric and Magnetic Mode Overlap



We have begun fabrication of multi-species Te-cube metamaterials

What DR MMs are achievable at optical frequencies?

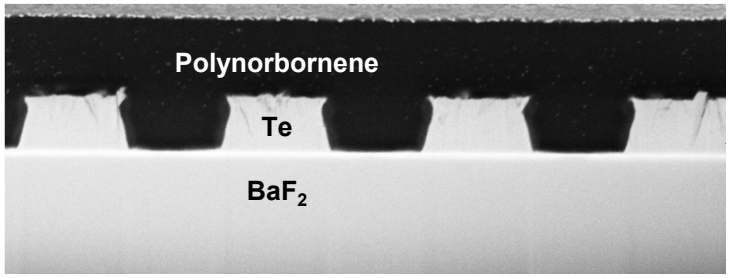


Solid lines: the lowest-order magnetic (red) and electric (blue) resonances.
Top dashed line: transition to a band-gap regime (peak of mu or eps)
Bottom dashed line: effective parameter has its zero crossing.

DR Metamaterials: Current Status

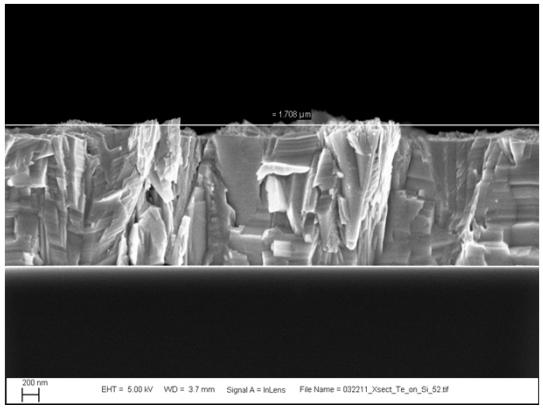
Extension to multilayer

- **Polynorbornene overcoat**
- **Ready for second Te layer**



Te film quality and residual loss

- **roughness**
- **crystallographic texturing**
- **residual loss (doping?)**



Moving to degenerate resonator designs

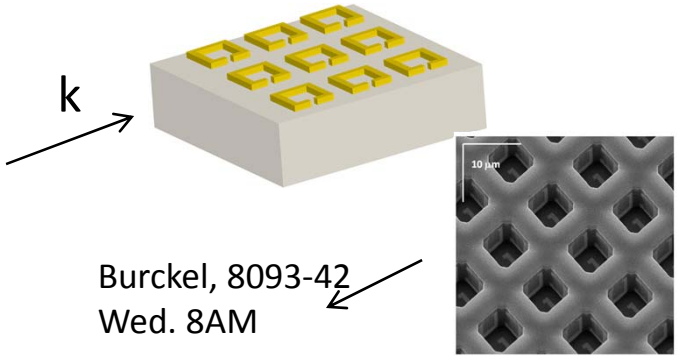
- **overlap ε and μ resonances**

Outline

- 3D Passive Metamaterials
  - With Metals: Membrane Projection Lithography
  - Without Metals: Dielectric Resonators
- **2D Active Metamaterials**

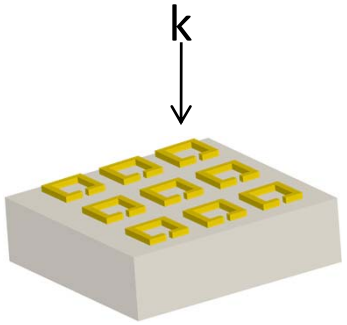
What's Attractive in Planar Metamaterials for Device Applications

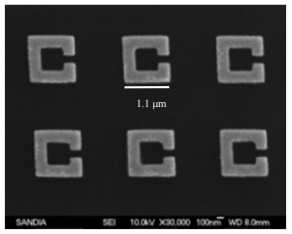
Magnetic Resonance



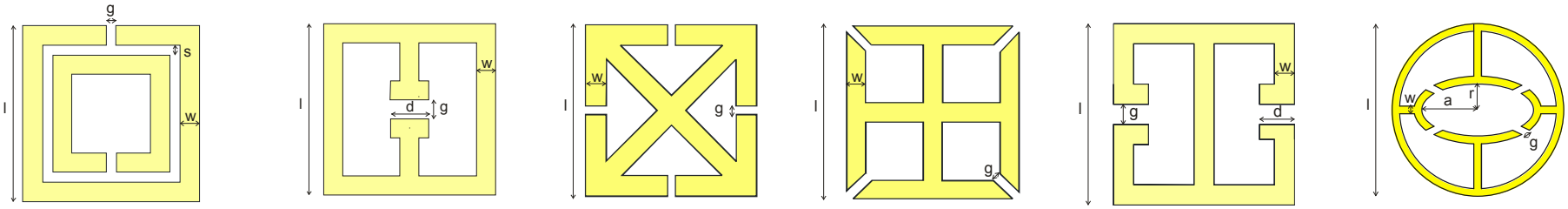
Burckel, 8093-42
Wed. 8AM

Electric Resonance (mostly)





Planar Metamaterial resonators come in many shapes

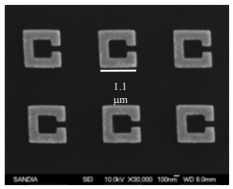


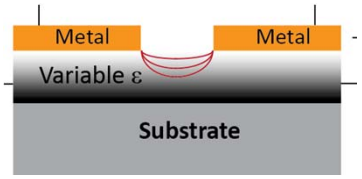
Common properties:

- They are (usually) subwavelength
- They provide a large cross section
- The spectral response is extremely sensitive to local changes in ε
- The field decays from the metal surface exponentially into the substrate

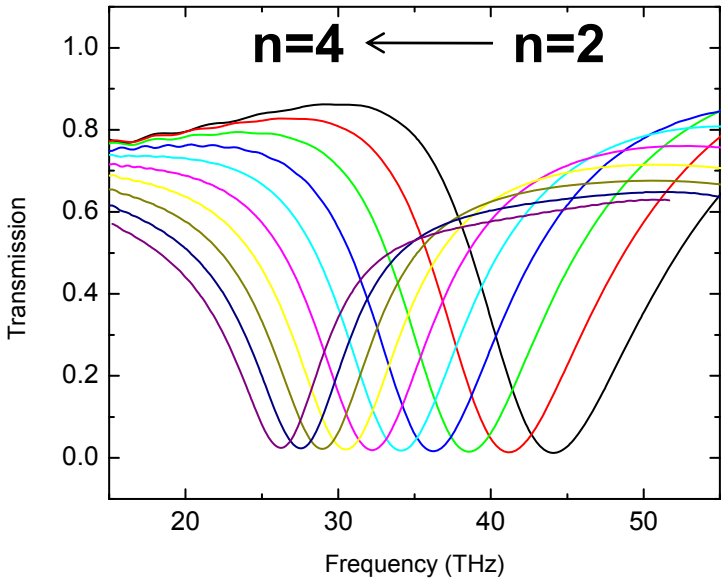
Modulating MM Response by Changing ε
Importance of *Interactions*

Example, SRRs at 10um
Thin "tunable" ε underneath

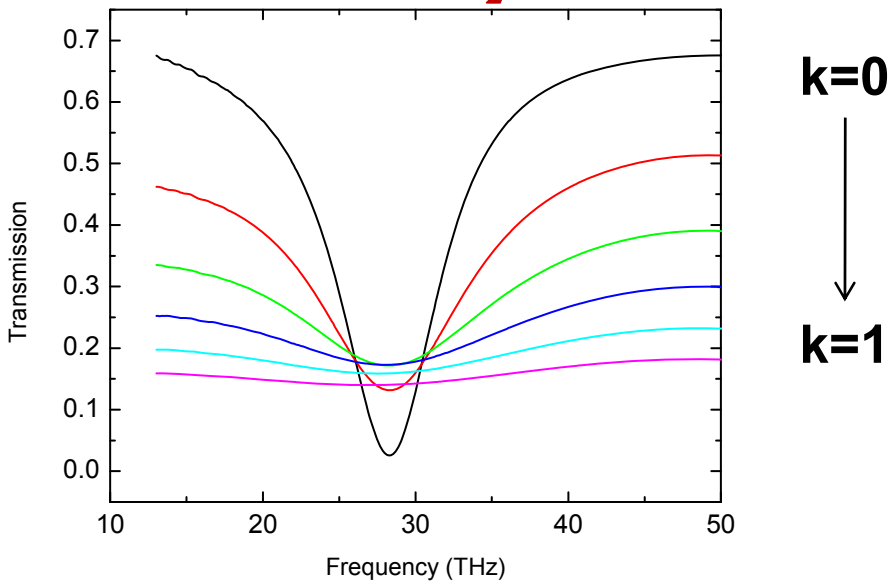




Modulating ε_1 (n)



Modulating ε_2 (k)

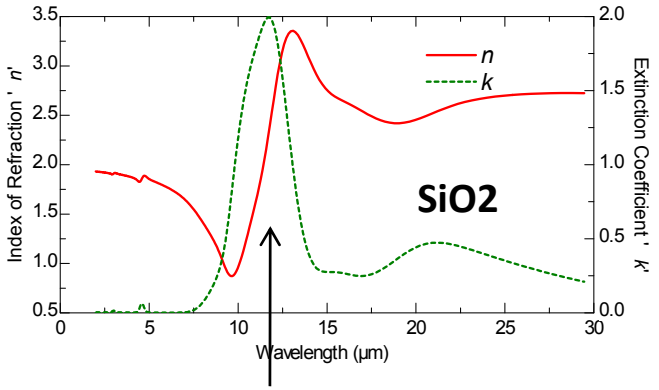


- **If we can modulate the local permittivity around the resonators then we can modulate its spectral response.**
- **Can be done in a number of ways (phase change, optical doping, electrical, etc)**
- **We need to understand these interactions (devices, fundamentals)**

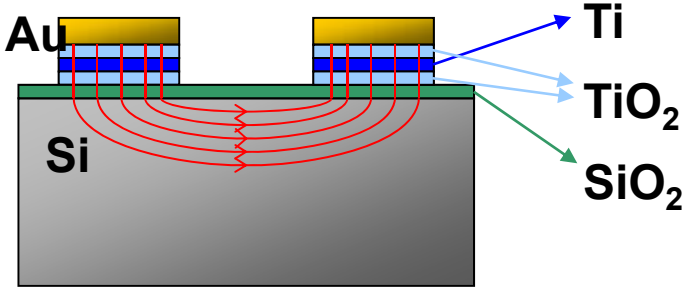
Interaction between SRRs and Phonons in Oxide Layers

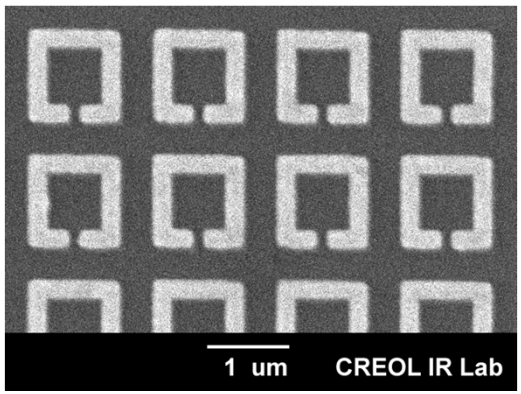
- Oxides with strong IR phonon modes are always present in fabricated samples.

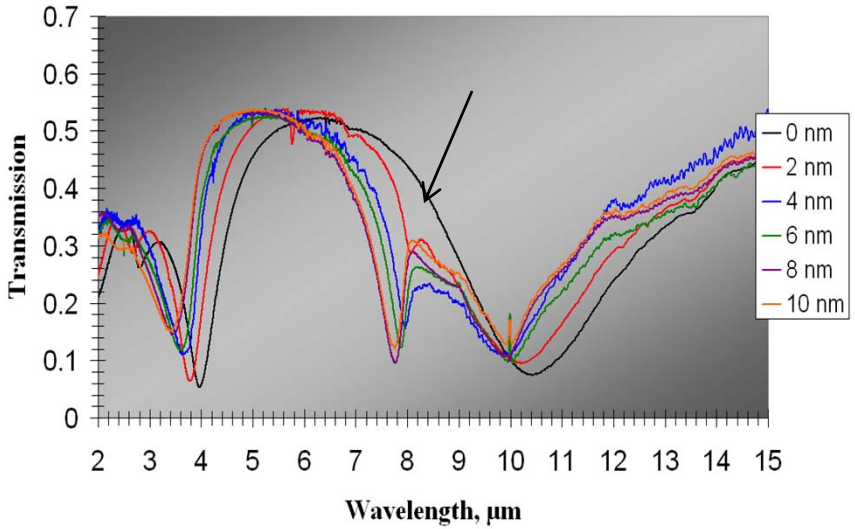
- We realized that even extremely thin layers (~5nm) would show up in the spectra of planar metamaterials.



Si-O stretch



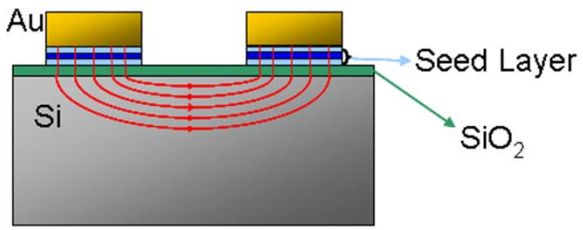


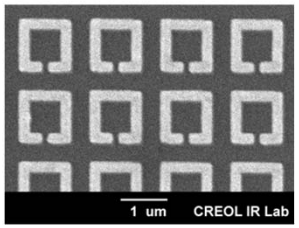


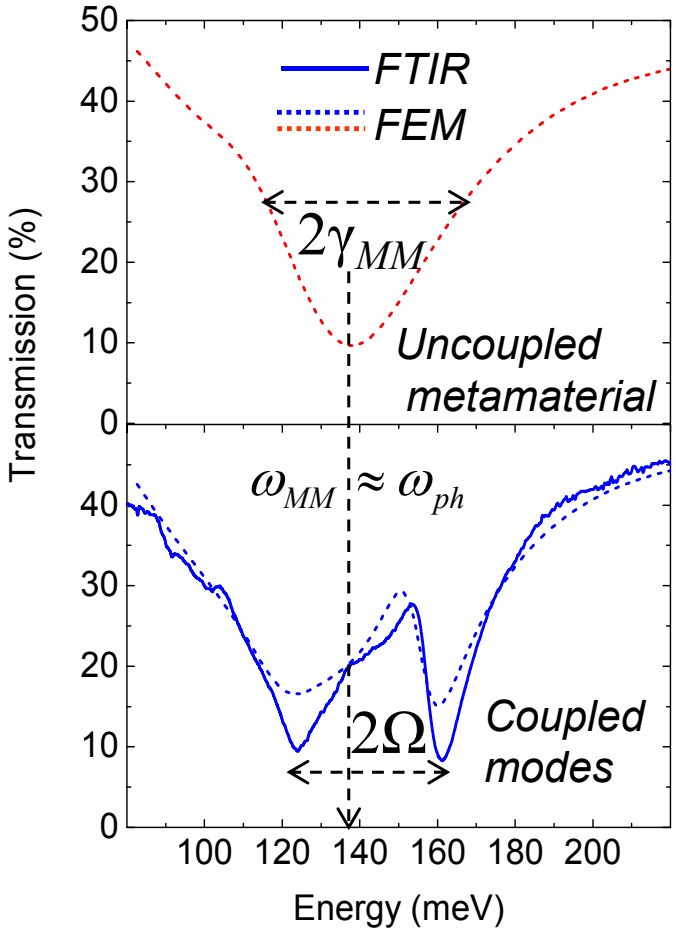
Optics Express 18, 1085 (2010)

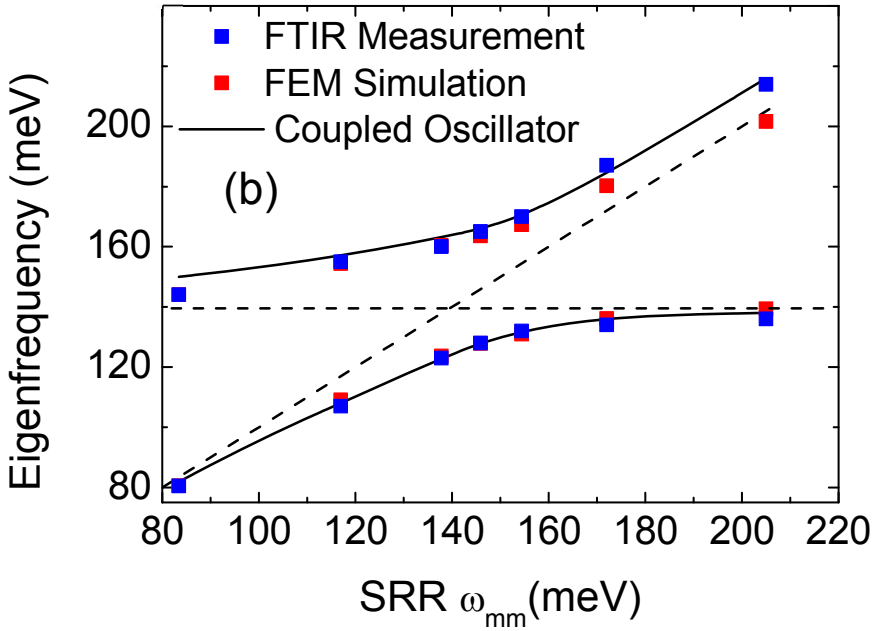
Strong Coupling: MM & Phonons

Oxide is only 10nm!









$$V^2 = (\omega_{MM} - \omega - i\gamma_{MM}\omega)(\omega_{ph} - \omega - i\gamma_{ph}\omega)$$

Linewidth of phonon is comparable to MM

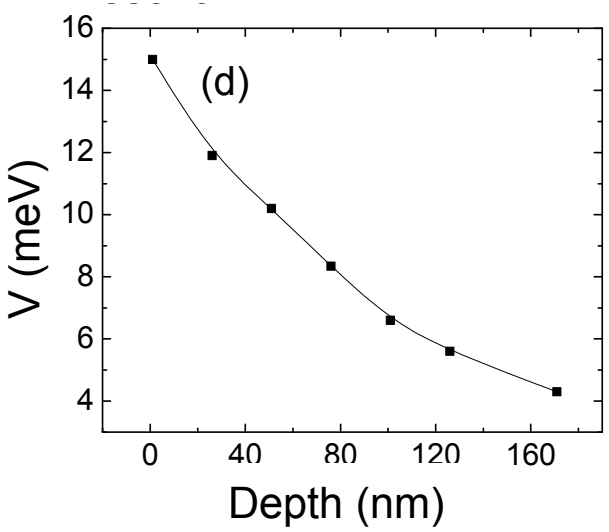
$$\Omega = \sqrt{4V^2 - (\gamma_{MM} - \gamma_{ph})^2}$$

Nano Letters 11, 2104 (2011)

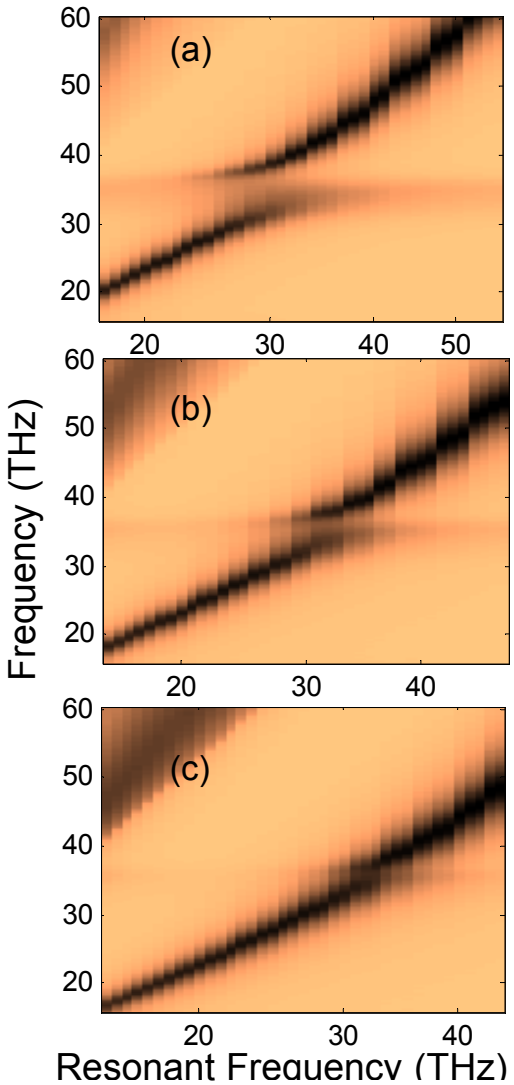
Dependence of Coupling with Depth

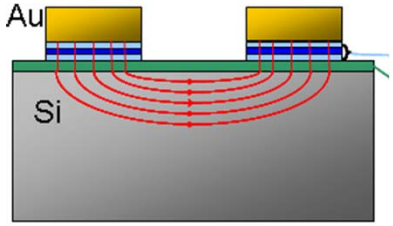
$$V^2 = \left(\omega_{MM} - \omega - i\gamma_{MM}\omega\right)\left(\omega_{ph} - \omega - i\gamma_{ph}\omega\right)$$

$$\Omega = \sqrt{4V^2 - \left(\gamma_{MM} - \gamma_{ph}\right)^2}$$



The "interaction strength" can be controlled by the location of the dielectric layer

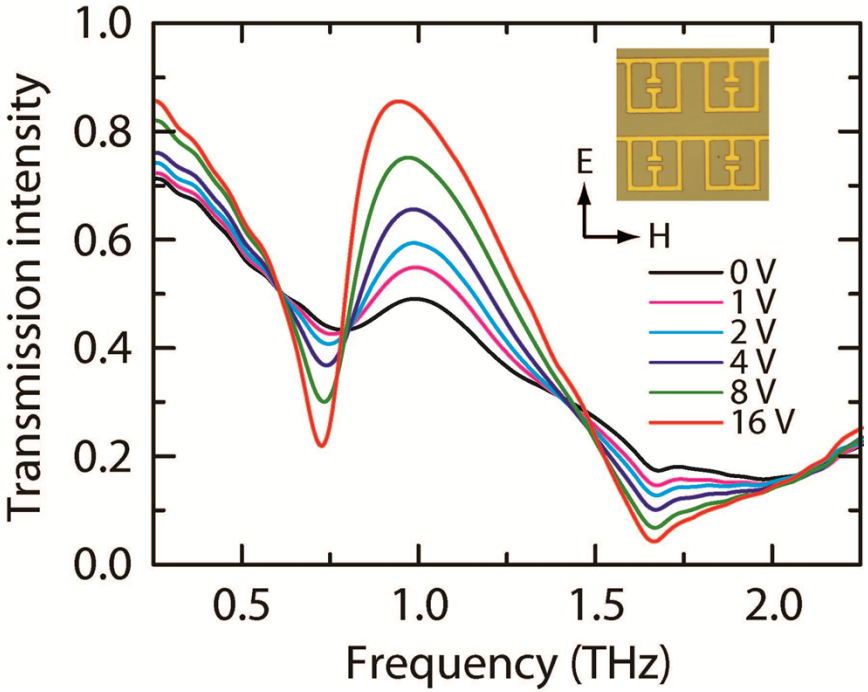




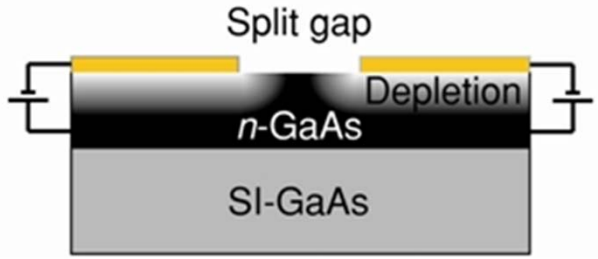
(simulation)

Nano Letters 11, 2104 (2011)

Interaction With Electrons: Electrically Switchable THz Metamaterials

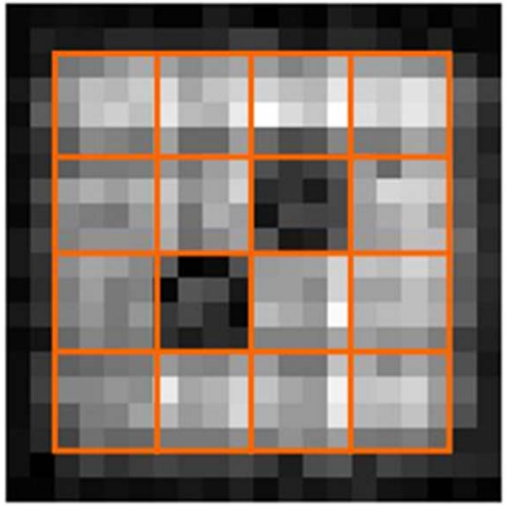


Nature 444, 597 (2006).

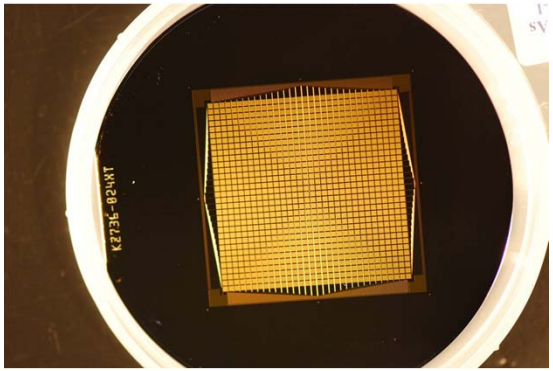


This works by increasing the damping (ε_2). Plasma frequency of doped layer needs to match the MM resonance frequency

0.36 THz,4x4 SLM



16 mm

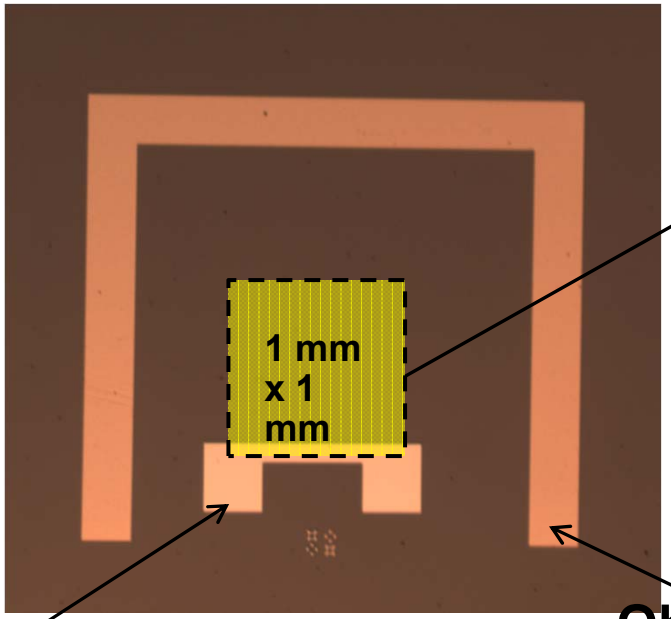


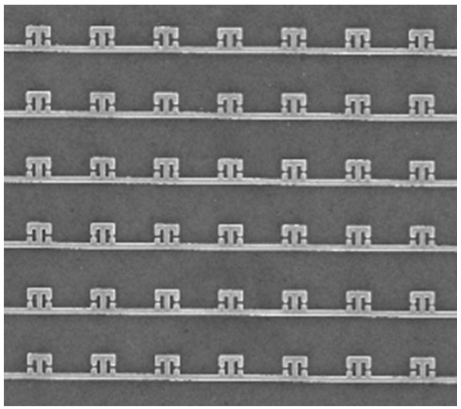
Bigger arrays

Appl. Phys. Lett. 94, 213511 (2009)

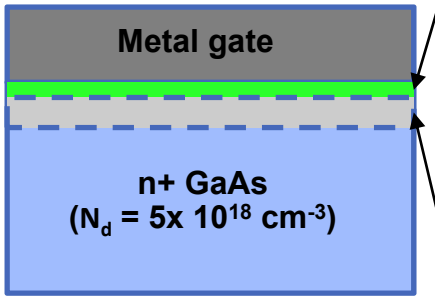
An Attempt to Scale These Active MMs to the mid-IR (from 1THz to 30Thz)

* Metal contacts patterned by optical lithography





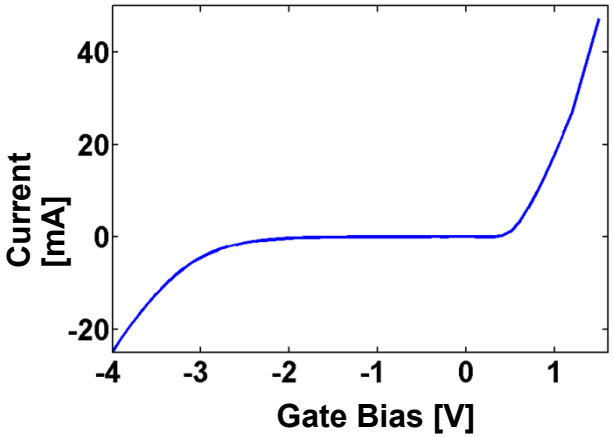
$Al_{0.3}Ga_{0.7}As$ (30 nm)

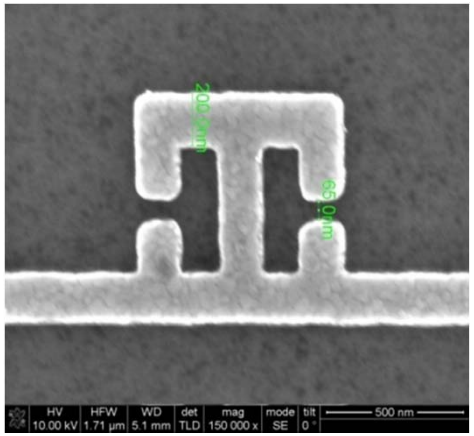


Depletion region

Ohmic contact

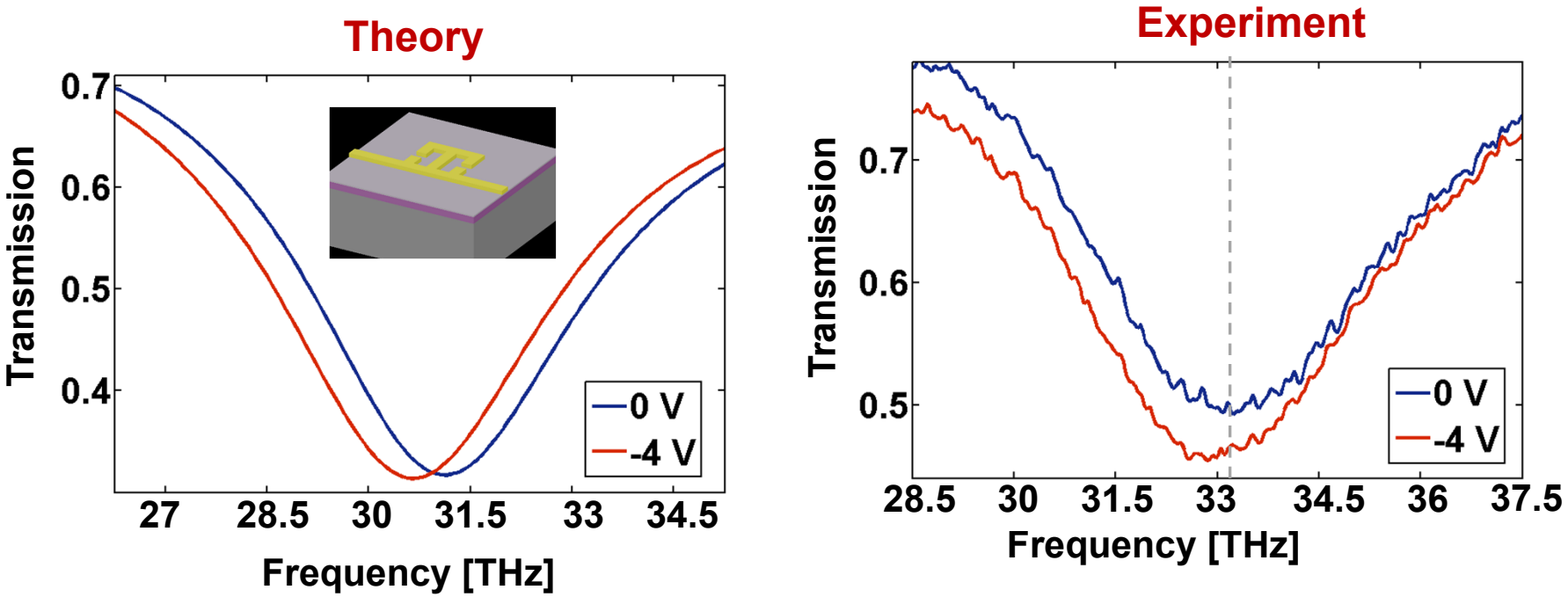
Metal gate





* SRR array patterned by E-beam lithography (connected to Metal gate)

Experimental Results



- **Metamaterial transmission spectrum red-shifts with external bias (small..)**

Optics Express 20, 1903 (2012)

Lesson #2:
Depletion Region is Thin (because we work in IR)

Large changes in ε happen near the plasma frequency

$$\omega_P \propto \sqrt{\frac{N_e}{m^*}}$$

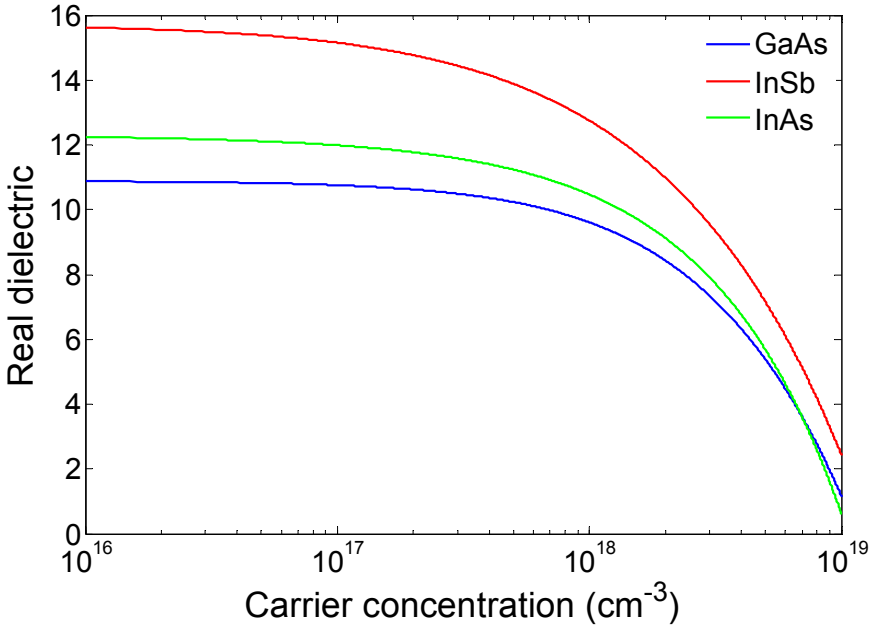
$$W_{depletion} = \left[\frac{2\varepsilon_{GaAs}\varepsilon_0}{qN_D}(-\phi_s) \right]^{1/2}$$

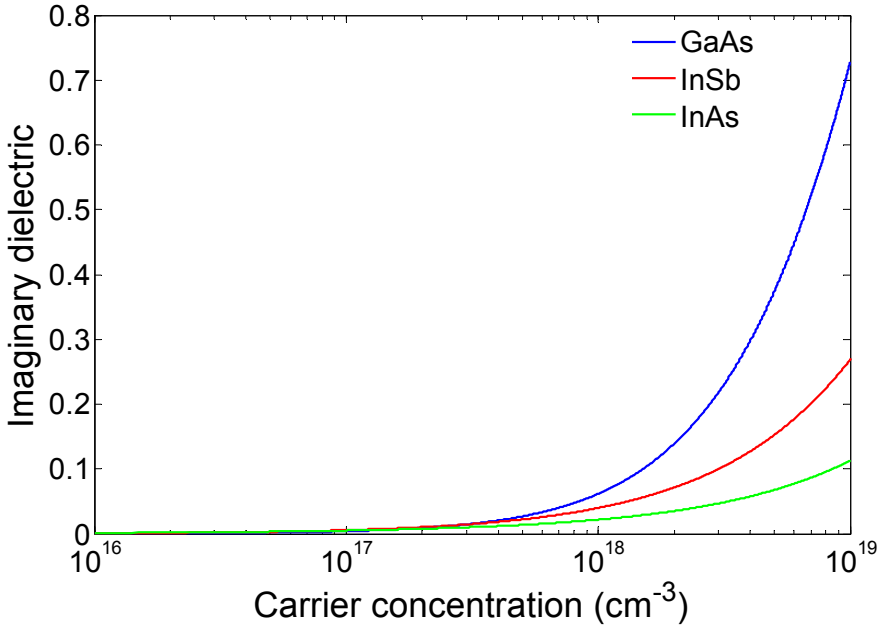
- **Large N implies thin $W_{depletion}$, *Interaction* ↓**

Where φ_s is a surface potential which is related to the gate voltage:

$$V_G = \phi_s - \frac{\varepsilon_{GaAs}}{\varepsilon_{AlGaAs}} W_{barrier} \left[\frac{2qN_D}{\varepsilon_{GaAs}\varepsilon_0} |\phi_s| \right]^{1/2}$$

InSb is a Better Semiconductor for Tuning in the Mid IR



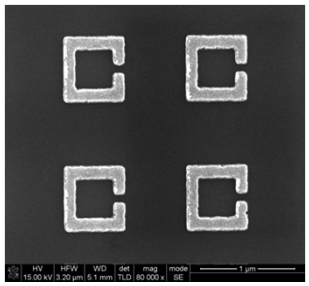


InSb has the largest dependence of real dielectric on doping level

[2] Litwin- Staszewska et al, Physica Status Solidi (b), 1981

[1]Zawaski et al, Advances in Physics, 1974

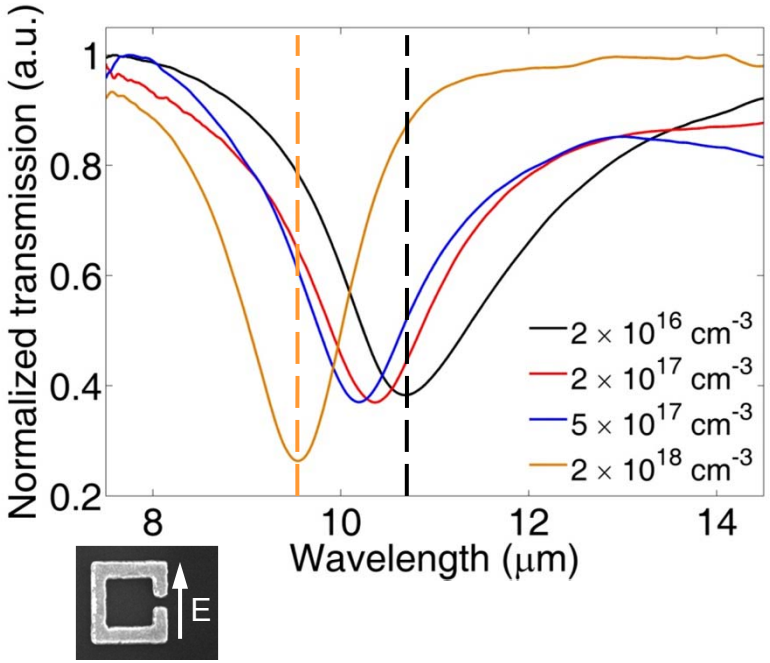
Tuning of IR Metamaterials: InSb

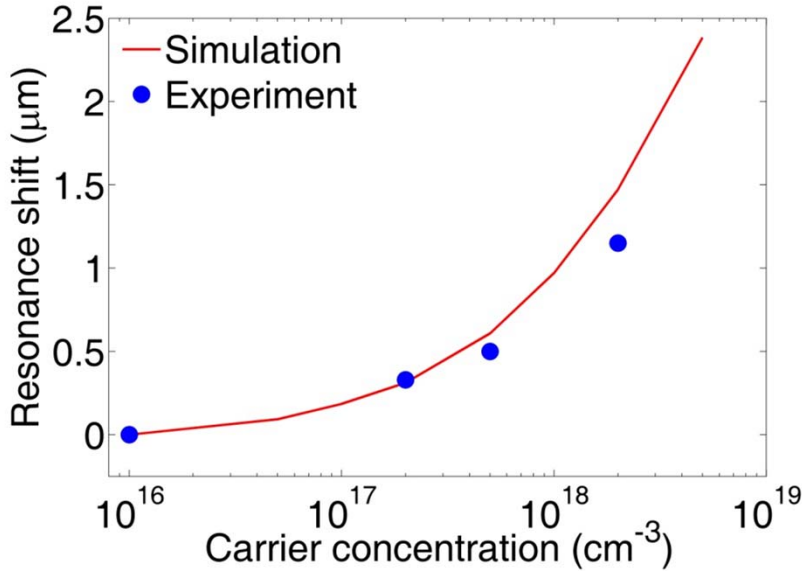


- Thin n-type doped layer grown on semi-insulating InSb wafer.
- SRRs are made by EBL+liftoff, Au/Ti

$\Delta \lambda = 1.15\ \mu m$

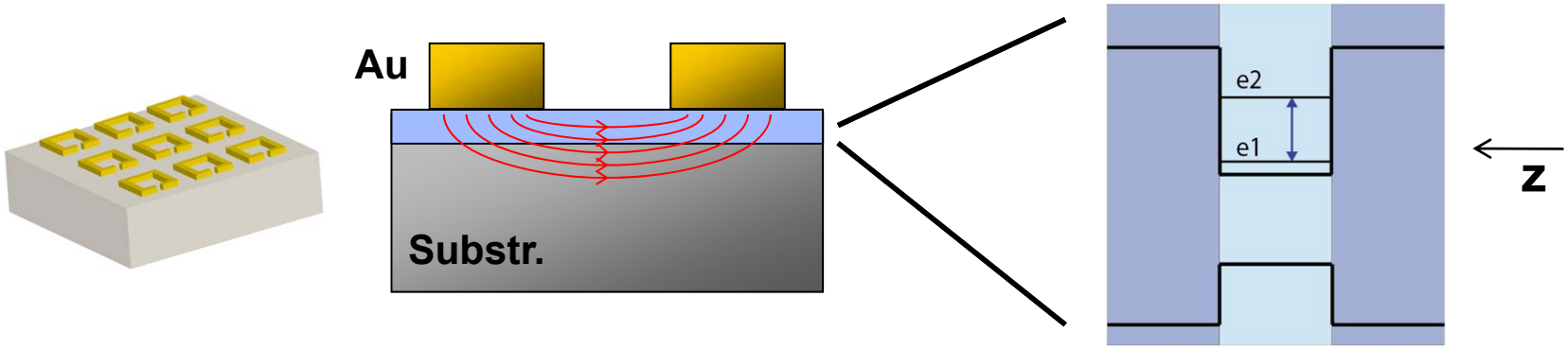
Appl. Phys. Lett. 96, 1 (2010)





- Resonance shift of 1.15 μm is achieved by varying the carrier concentration of InSb epilayer from 1×10^{16} cm^{-3} to 2×10^{18} cm^{-3} with no appreciable damping.

More Tunability: Semiconductor Heterostructures Meet Metamaterials



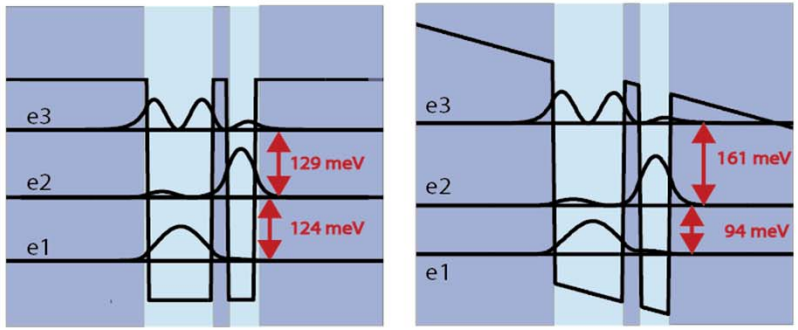
- We can "engineer" voltage dependent optical transitions (3-60 THz)
- Huge design space (QWs, QDs) & mature technology (MBE, MOCVD, etc)
- Material Versatility (GaAs, GaN, InGaAsP, GaSb Heterostructures…)

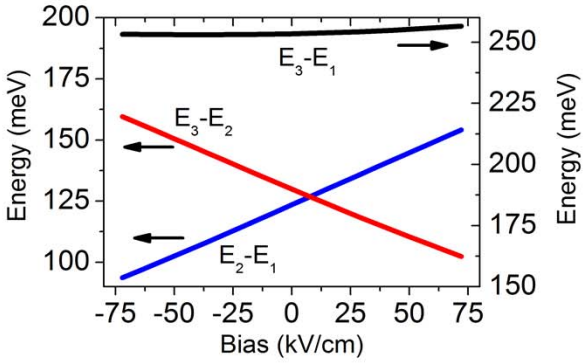
For example, GaAs/AlGaAs

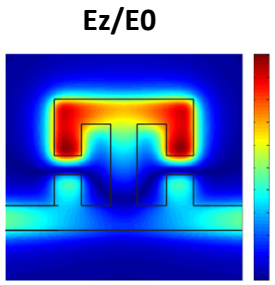
$$\varepsilon_{GaAs}^{QW}(\omega)=\begin{pmatrix}\varepsilon_{GaAs}^{b}(\omega) & 0 & 0\\ 0 & \varepsilon_{GaAs}^{b}(\omega) & 0\\ 0 & 0 & \varepsilon_{GaAs}^{b}(\omega)\end{pmatrix}+\begin{pmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & \chi_0(\omega)\end{pmatrix}$$

$$\chi_0(\omega)=-\frac{Ne^2}{\varepsilon_0\hbar}\frac{|z_{21}|^2}{(\omega-\omega_{21}+i\gamma_{21}/2)}$$

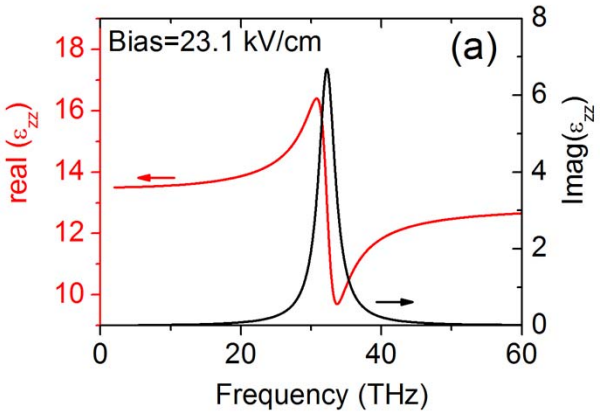
How to Achieve Electrical Modulation by Coupling to Inter-Subband Transitions



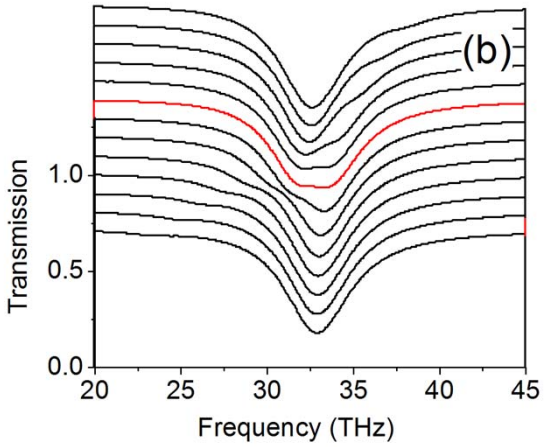


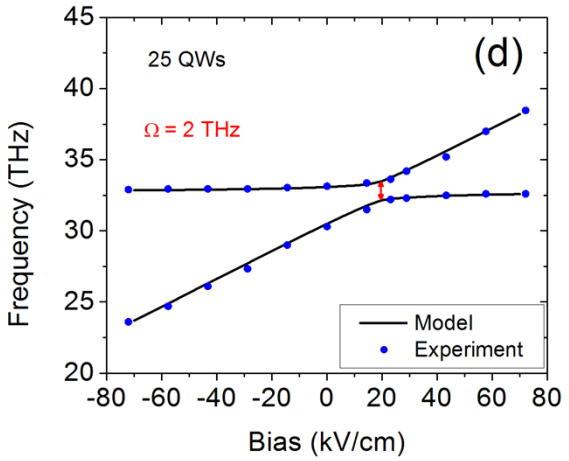


At any given bias, ε_{zz} looks like a Lorentzian

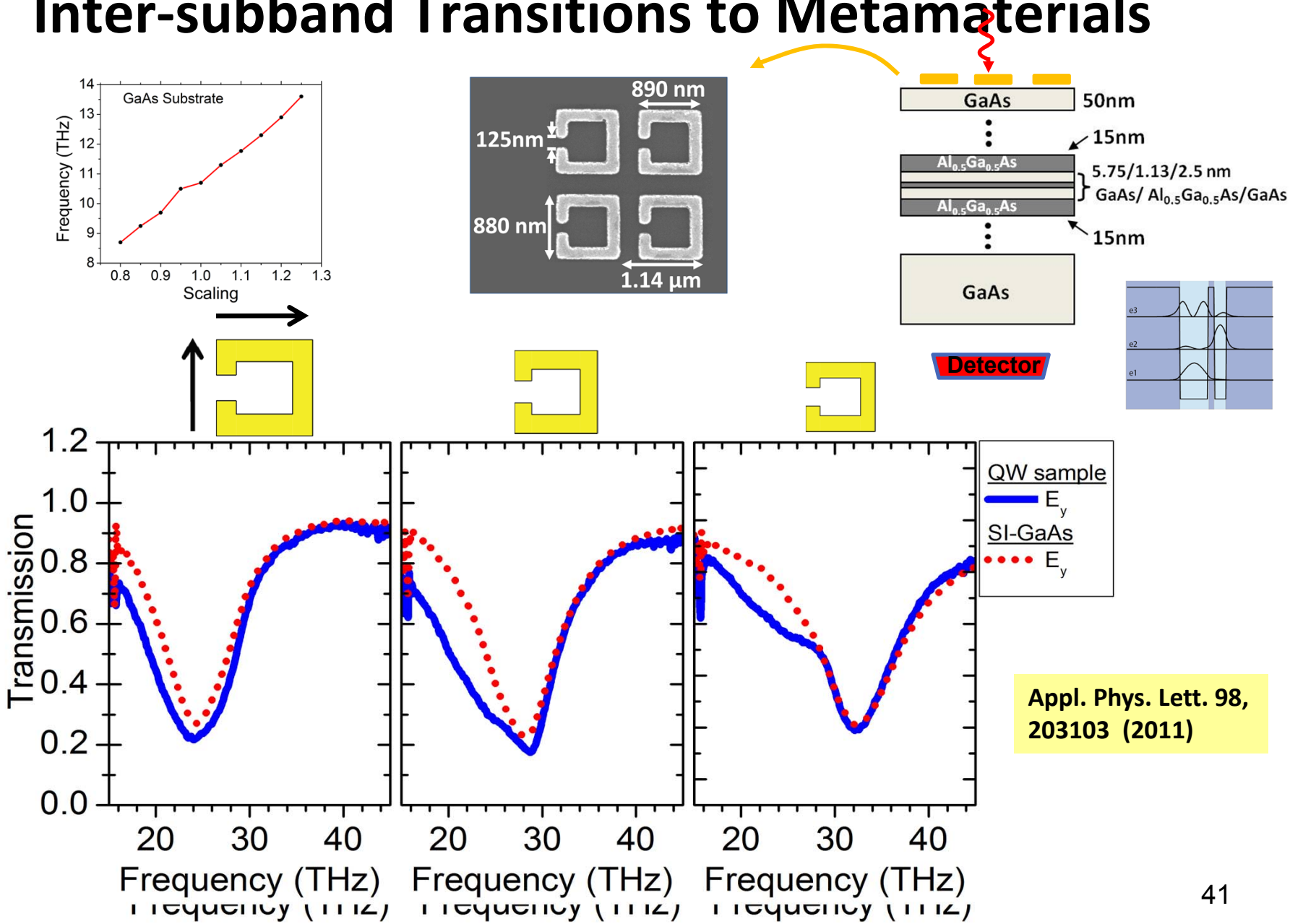


We then change the bias voltage to tune the IST.
Anticrossing behavior with bias
Coupling → Tuning

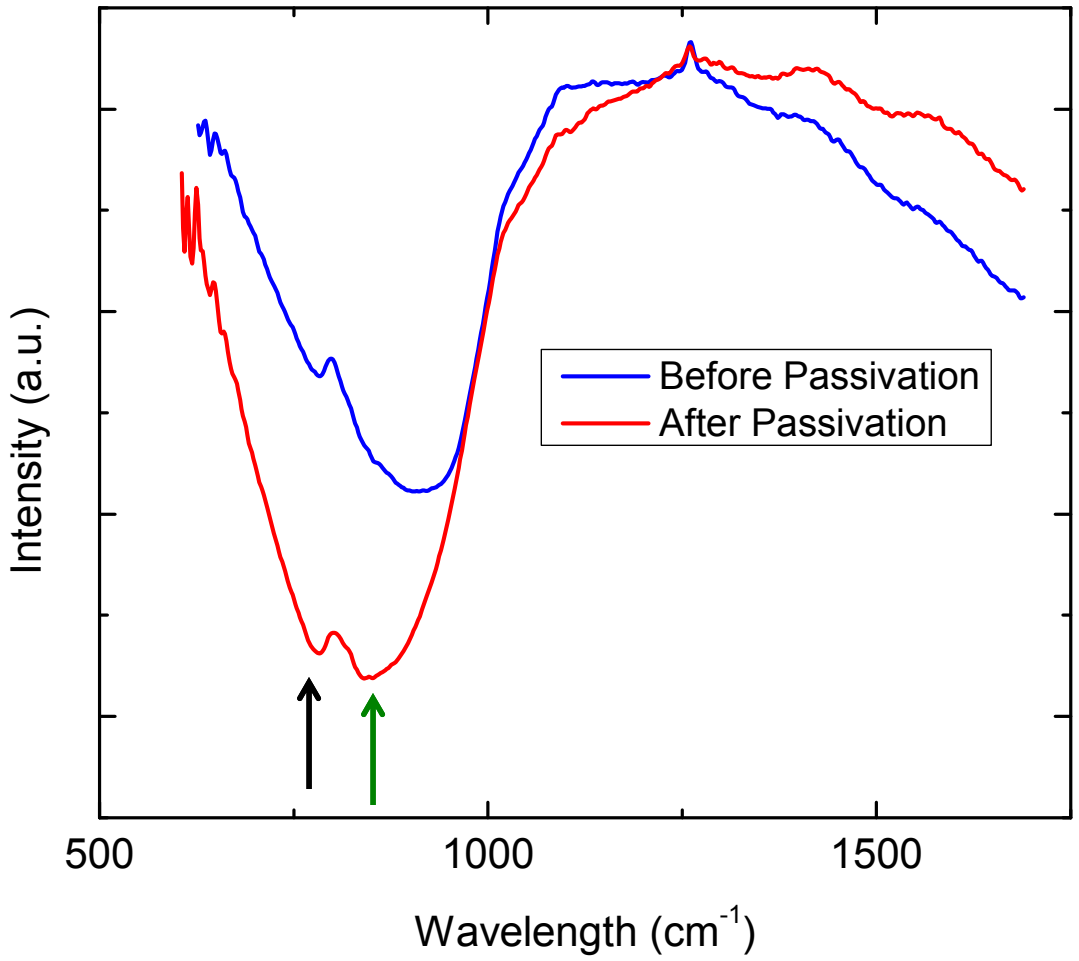


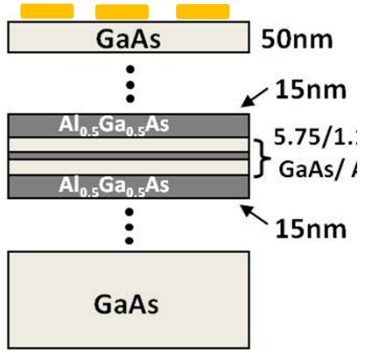


Experimental Demonstration of Coupling of Inter-subband Transitions to Metamaterials

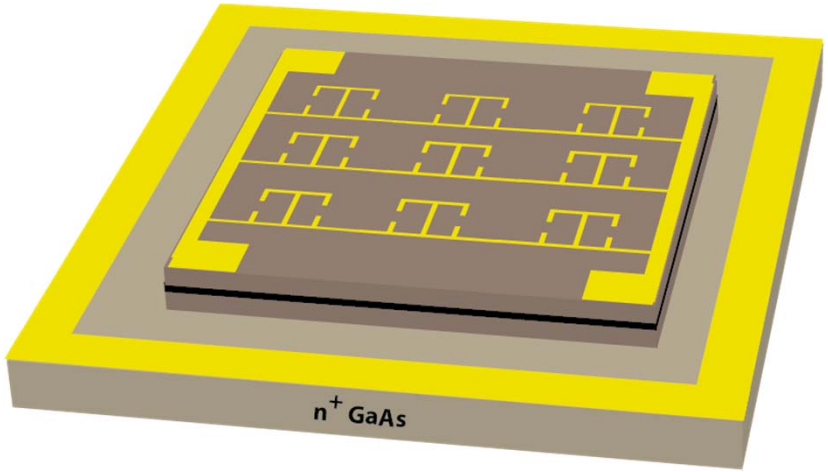


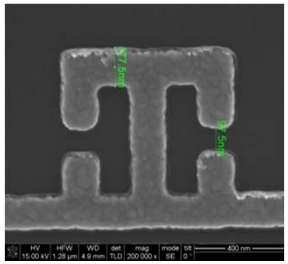
Appl. Phys. Lett. 98, 203103 (2011)

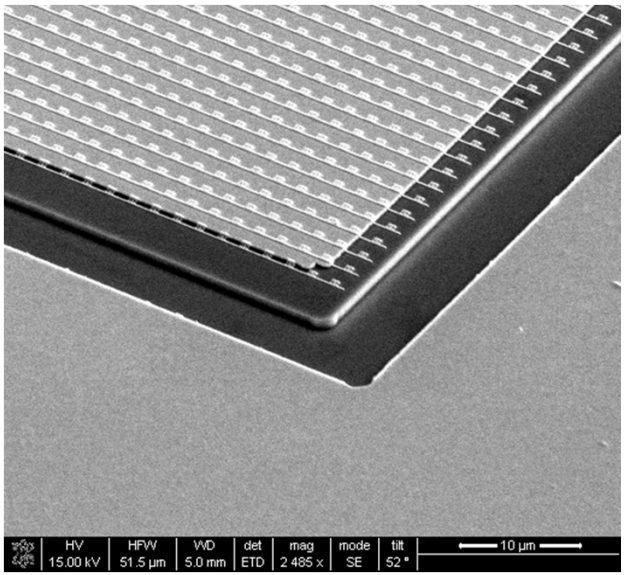

Intensity (a.u.)
500
1000
1500
Wavelength (cm-1)
Before Passivation
After Passivation

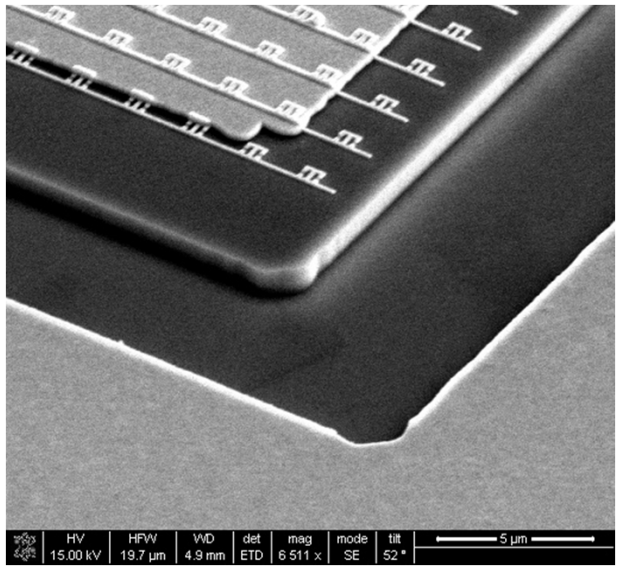

GaAs
50nm
15nm
Al0.5Ga0.5As
5.75/1.
GaAs/
Al0.5Ga0.5As
15nm
GaAs

Metamaterial-IST Coupled Device









Experiments currently under way

Acknowledgments

Postdocs: Alon Gabbay, Young Chul Jun, Xiaoyu Miao*, Brandon Passmore*, James Ginn*

CINT + Sandia: Mike Sinclair**,** John Reno, Aaron Gin*, Eric Shaner, Mike Wanke, Joel Wendt, Paul Clem, Jon Ihlefeld, Bruce Burckel,

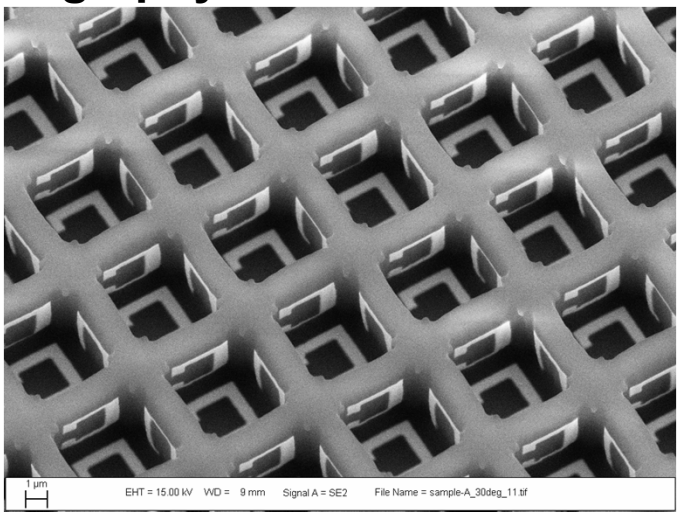
UCF (MM-Ph): G. Boreman, D. Shelton, J. Ginn

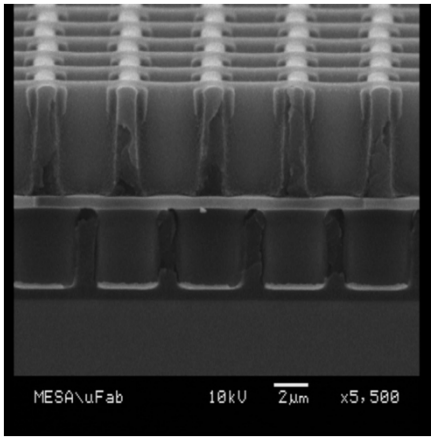
THz work: Xomalin Peralta (UTSA)
Hou-Tong Chen, Toni Taylor, John O'Hara* (LANL),
Willie Padilla (BC), Rick Averitt (BU)
Liam Chen*, Dan Mittleman (Rice)

IR Fishnet: Slava Smolev, Steve Brueck (UNM)

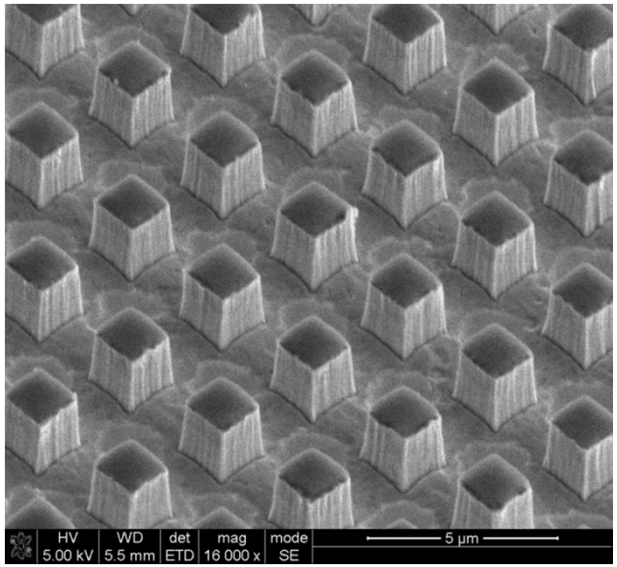
Summary 1: 3D (Passive)

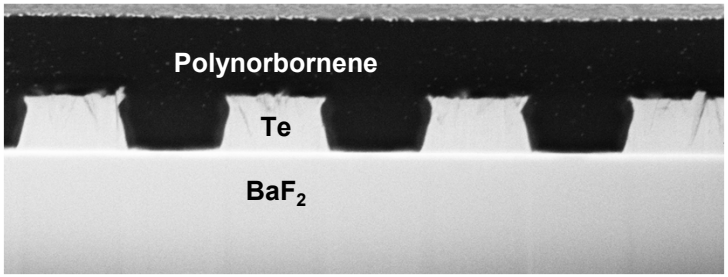
Metallic: Membrane Projection Lithography





Non-Metallic: Dielectric Resonators

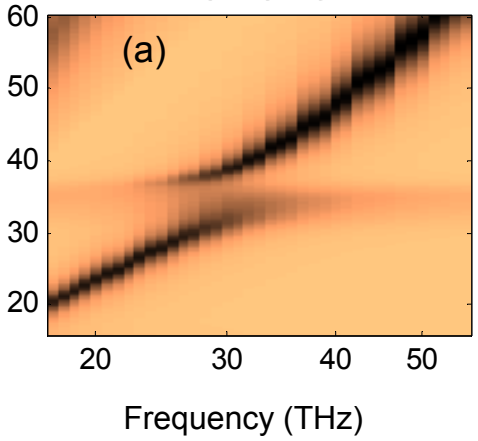




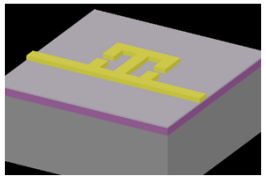
Summary 2: 2D (Active)

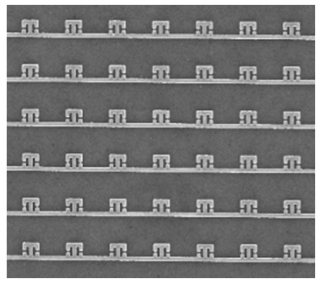
Interactions with Planar Metamaterials in the Mid-Infrared.

Phonons

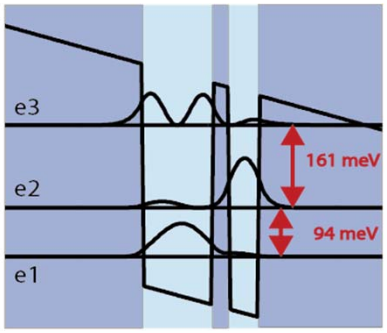


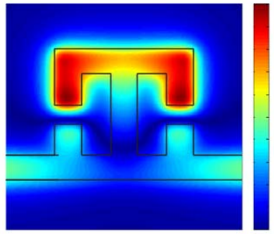
Electron Sheets





Semiconductor Heterostructures





Fundamentals: phonons, phonon-dynamics, sensing
Devices: electrically tunable filters, modulators