SAND2010-0873C

Metamaterials Science & Technology

Active and Passive Metamaterials for the Infrared

2/18/2010

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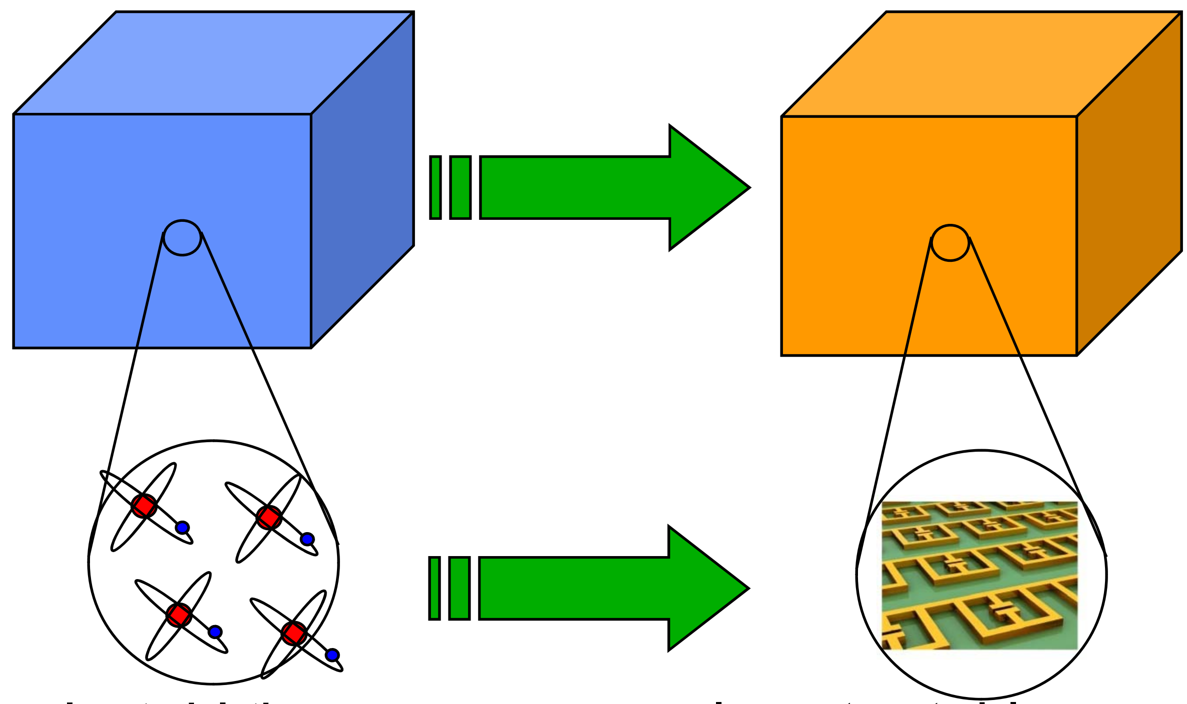
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline

- Introduction, metamaterials, scaling, etc
- Fabrication of IR 3D Metamaterials
- Optical modulators based on single layer metamaterials
- Hybridization between metamaterial resonances and material dielectric resonances

What is a metamaterial?

***μετα* = meta = "beyond"**



In a conventional material, the permittivity ε, & permeability μ are derived from the constituent atoms

In a metamaterial, ε_{eff}, μ_{eff} are derived from "meta-units" (bigger than atoms, << λ)

<u>Absolute local control of ε and μ</u>

after Pendry, JB , 'Negative refraction', Contemporary Physics, 45:3, 191 - 202

refractive index: $n = \sqrt{\mu\varepsilon}$ wave impedance: $\eta = \sqrt{\mu/\varepsilon}$

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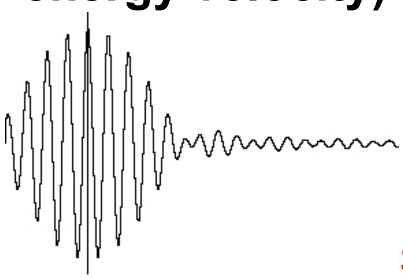
What is possible with Metamaterials?

- **Rigorous solutions to Maxwell's Equations**

$$n = -\sqrt{\varepsilon\mu}$$

negative

Backwards propagation (opposite phase & energy velocity)

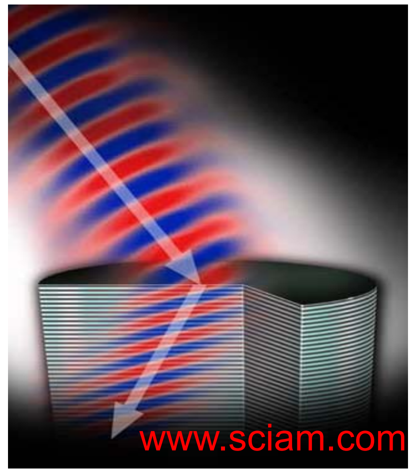


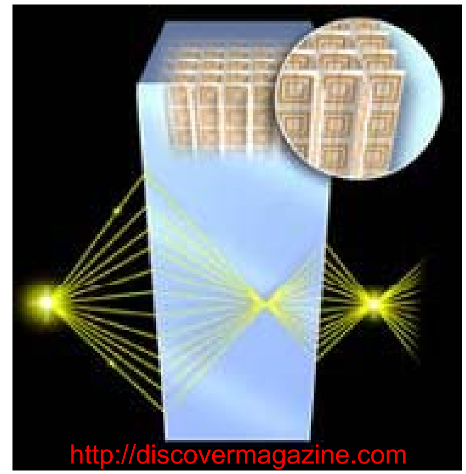
$$\mathbf{k}\times\mathbf{E} = \frac{\omega}{c}\mu\mathbf{H}$$

S=E×H

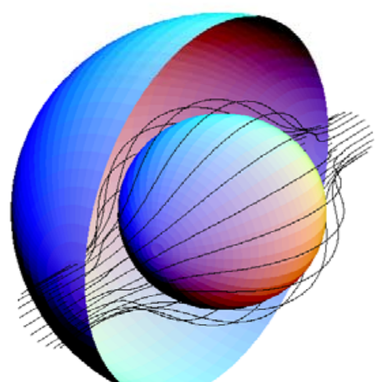
- **active optical devices**
- **nonlinear components**
- **concentrators**
- **perfect absorbers**
- **photon funnels**
- **electromagnetic wormholes (LPI)**

Negative Refraction & Perfect Lensing

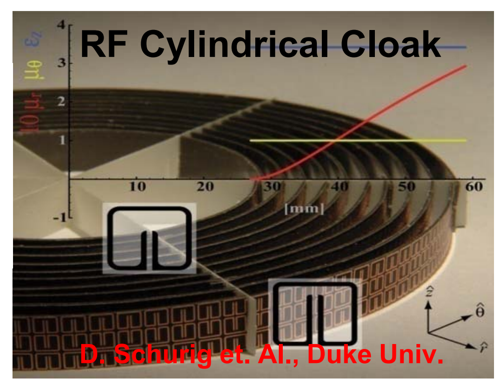




Electromagnetic Cloaking



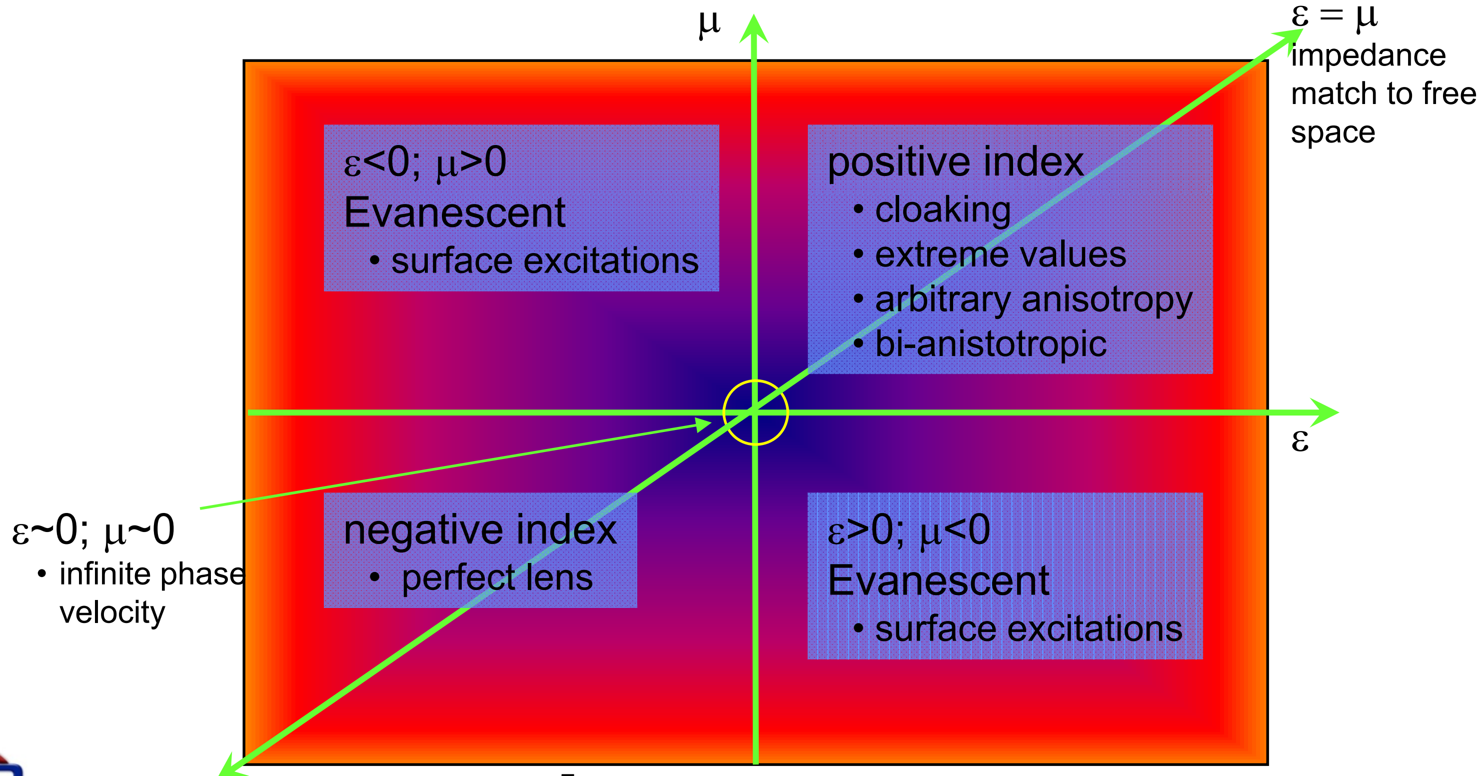
from: Schurig, et al, OPTICS EXPRESS Vol. 14, 9794 2006



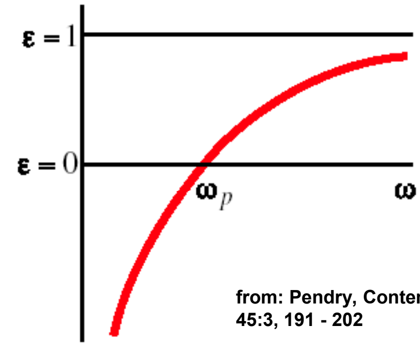
What ranges of ε and μ are interesting?

Can adjust ε , μ , and magneto-electric couplings (and their anisotropies) independently: highly multidimensional design space!

- Interesting applications occur in many regions of the ε – μ space.
    - negative index
    - impedance match line
    - regions with ε and/or μ near zero
- Losses increases as we move away from ε=μ=1



How to make a "Metamaterial"

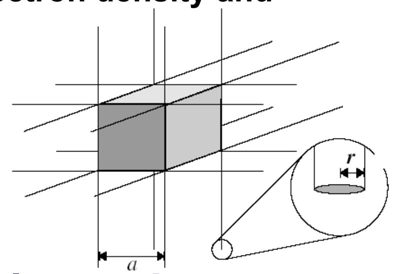


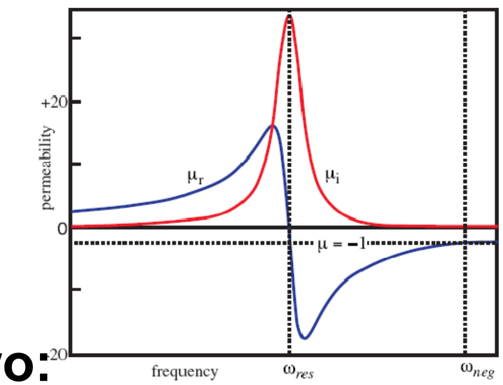
from: Pendry, Contemporary Physics, 45:3, 191 - 202

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

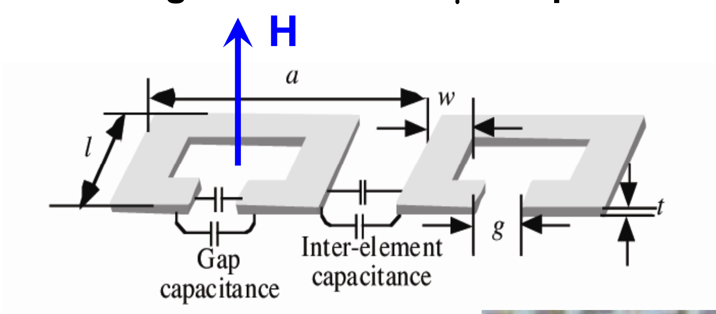
$$\omega_p = \sqrt{\frac{ne^2}{m^* \varepsilon_o}}$$





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

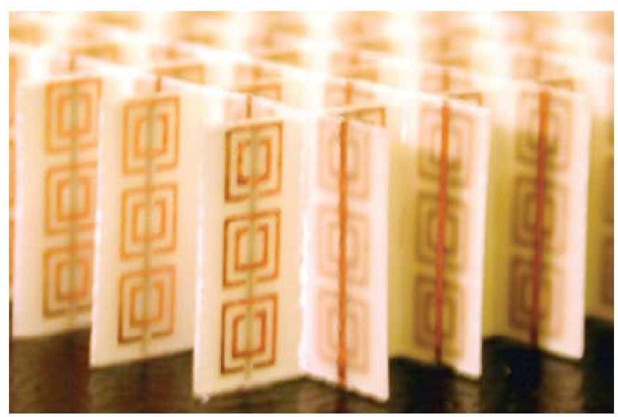
- Can be viewed as resonant RLC circuit
- Negative values of μ are possible

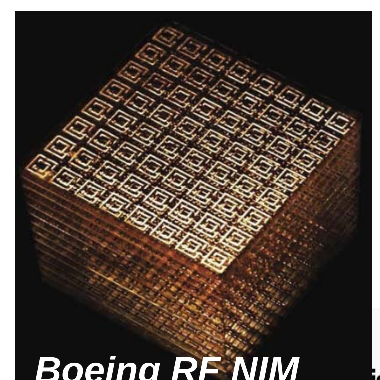


from; S. McMeekin, Proc. Of SPIE, V

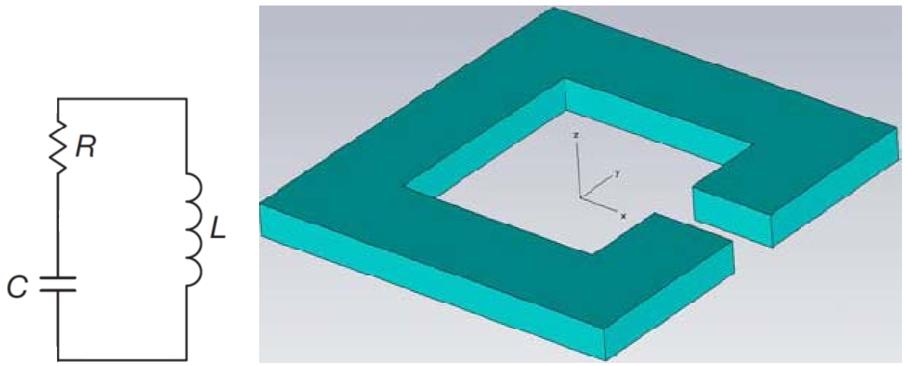
http://www.multitel.be/newsletter/mn7 2005/images/nl3_Metamaterials_type 1.jpg

Combine the two:



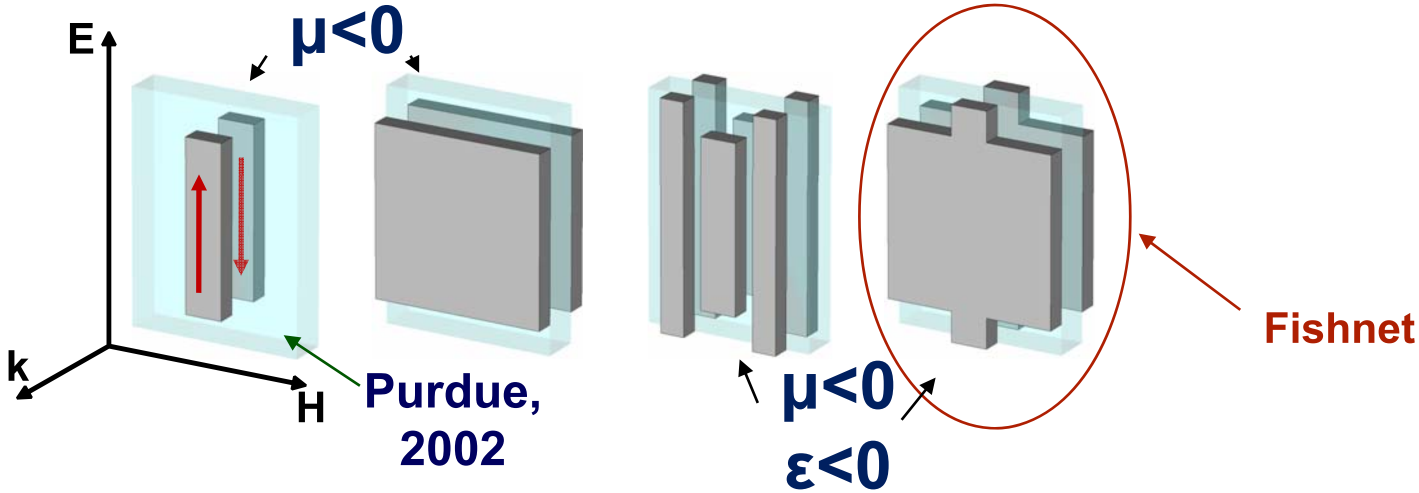


How to scale MM's to optical frequencies



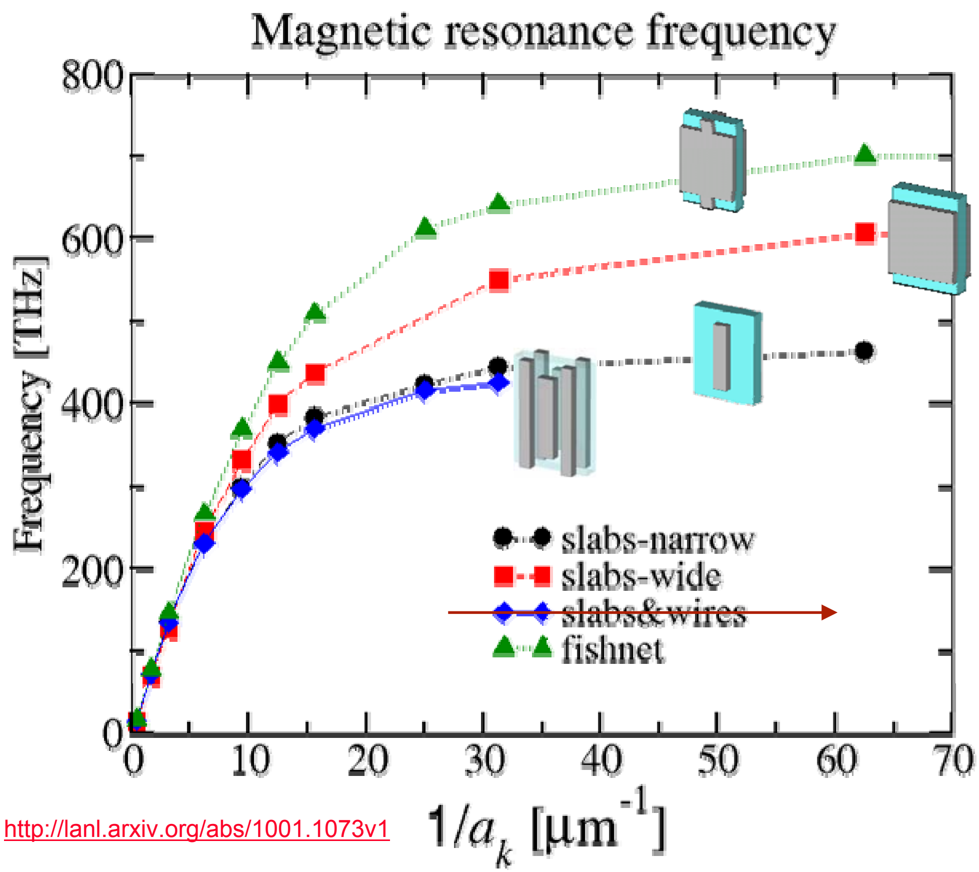
Shrink resonators to the nanoscale

For magnetic behavior:

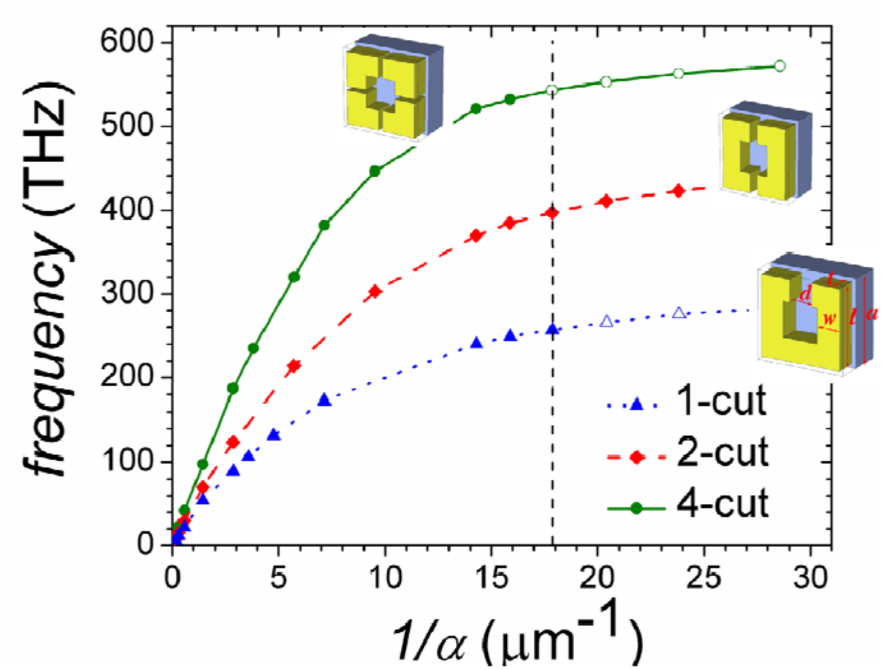


Scaling: saturation of magnetic behavior

Al metal
Glass substrate



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



J. Zhou, Th. Koschny, M. Kafesaki, E. N. Economou, J. B. Pendry and C. M. Soukoulis, *Saturation of the magnetic response of split-ring resonators at optical frequencies*, Phys. Rev. Lett. 95, 223902 (2005).

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

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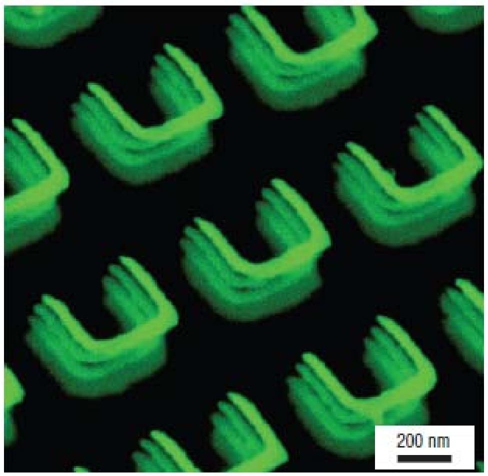
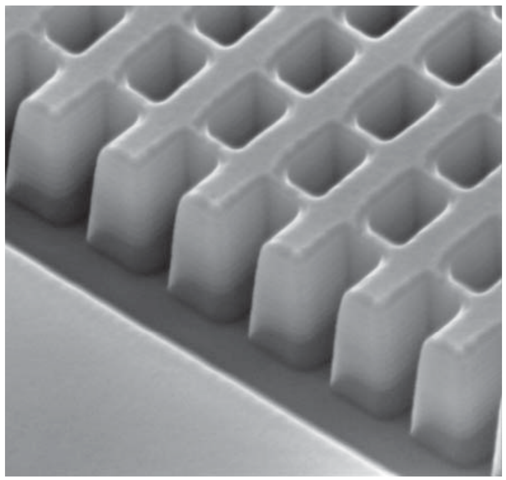
Scaling: Fabrication challenges

"stacked" designs

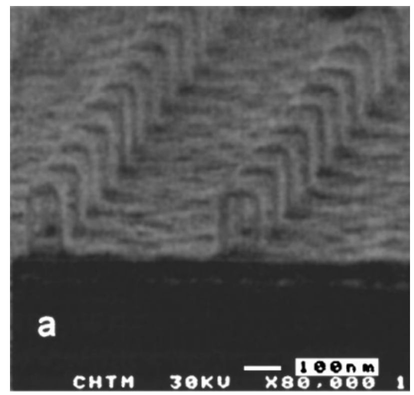


Giessen- Nature Mat **7**, 31, (2008)

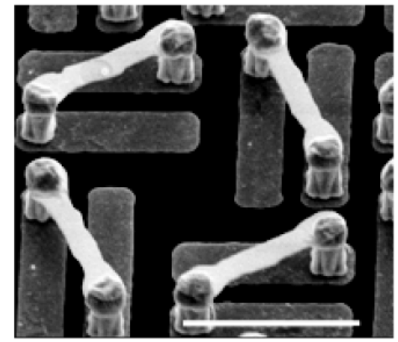


Zhang, Nature **455**, 376 (2008)

Out-of-Plane Current

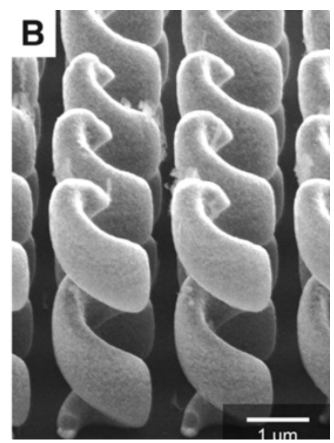


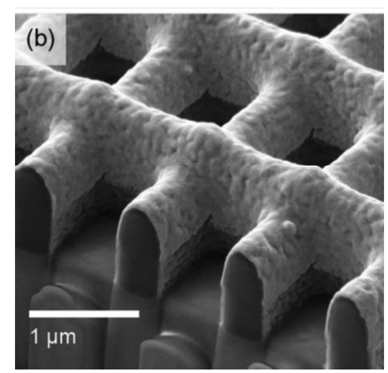
Brueck - JOSA B **23**, #3, 434, (2004)



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

Direct Write





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

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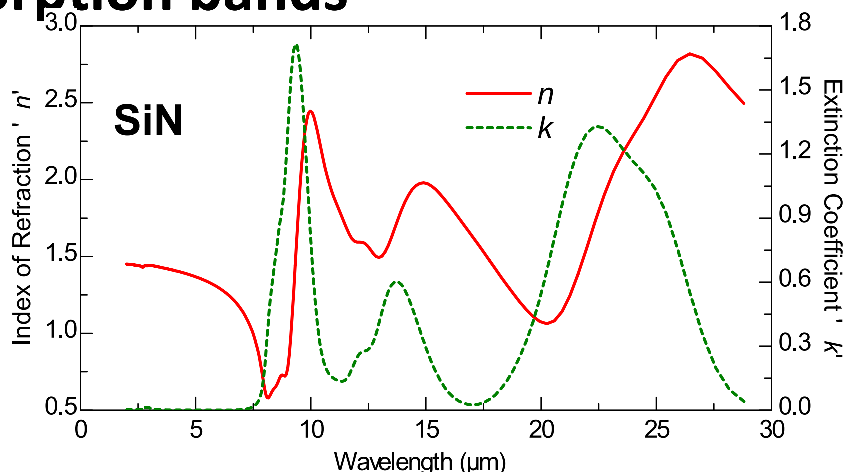
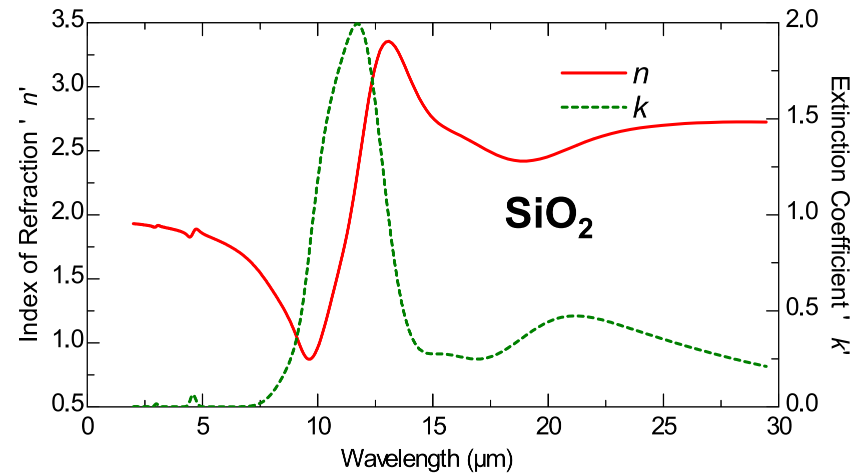
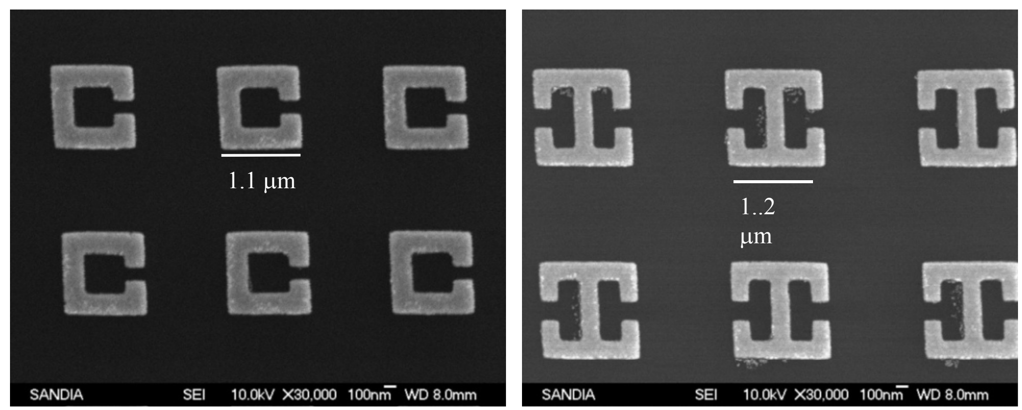
Issues for Metamaterials in the Infrared

- **Many dielectrics have IR absorption bands**





- **Fabrication is challenging but doable**



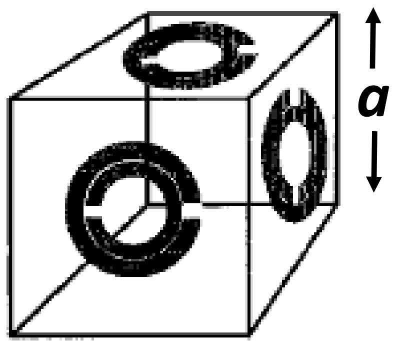
- **For active metamaterials, need to achieve large background ε changes somehow**

Outline

- Introduction, metamaterials, scaling, etc
- Fabrication of IR 3D Metamaterials
- Optical modulators based on single layer metamaterials
- Hybridization between metamaterial resonances and material dielectric resonances

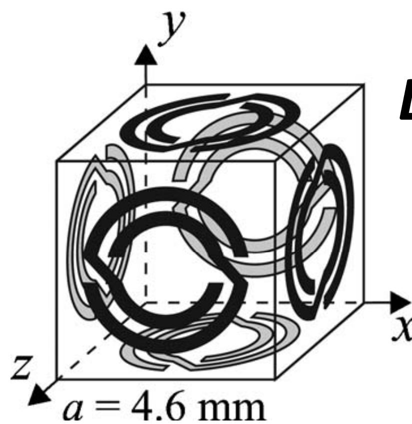
Path to true 3D IR Metamaterials

- 3D is easy in the RF ($1<\varepsilon_r<300$, $1<\mu_r<30$)
- Would like to make the same structures in the IR



a ~ mms

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



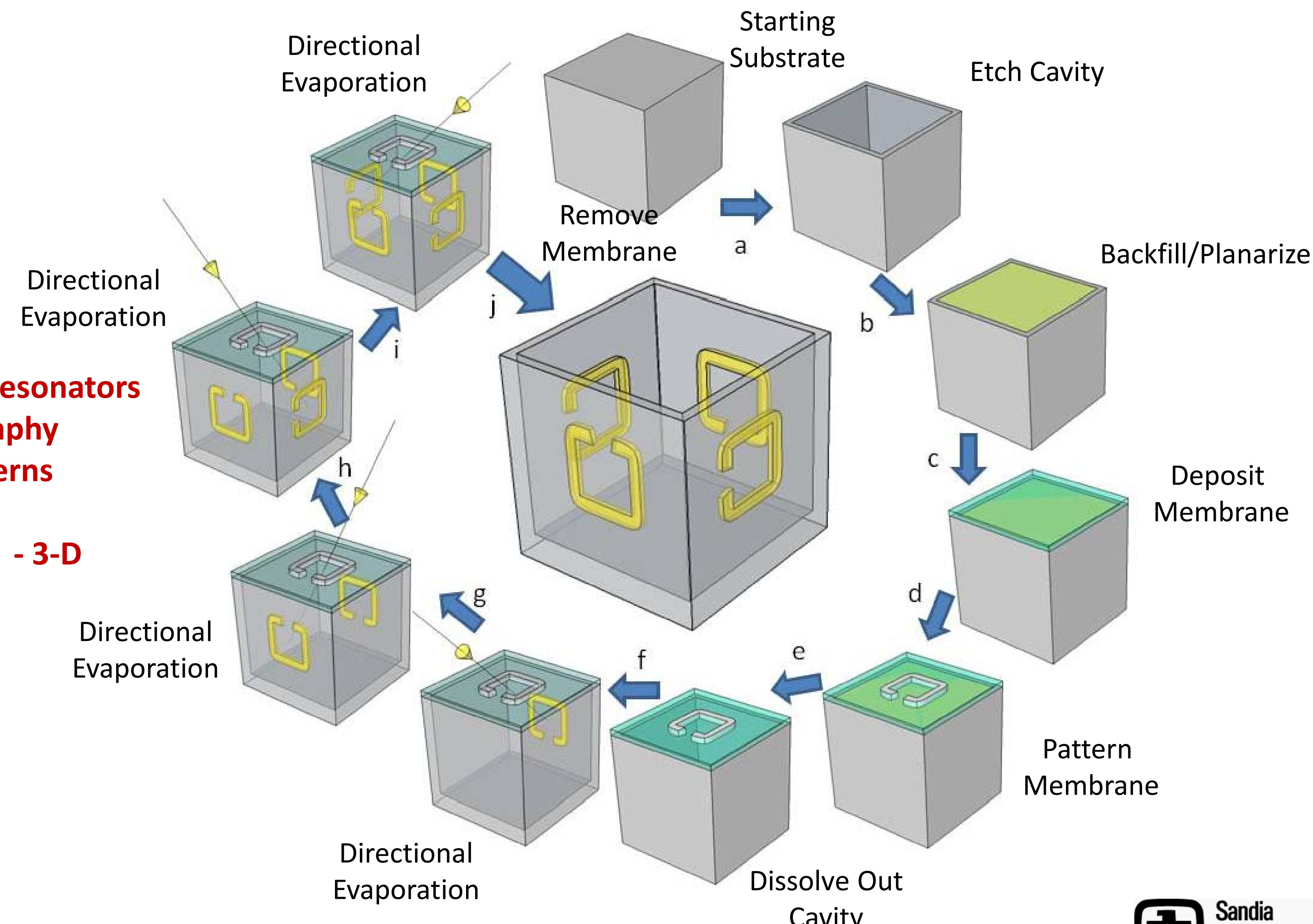
Linewidth ~ mms

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

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

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

New Approach:
Membrane Projection Lithography



- **Out-of-plane resonators**
- **Planar lithography**
- **Arbitrary patterns**
- **Scalable**
- **Layer-by-layer - 3-D**

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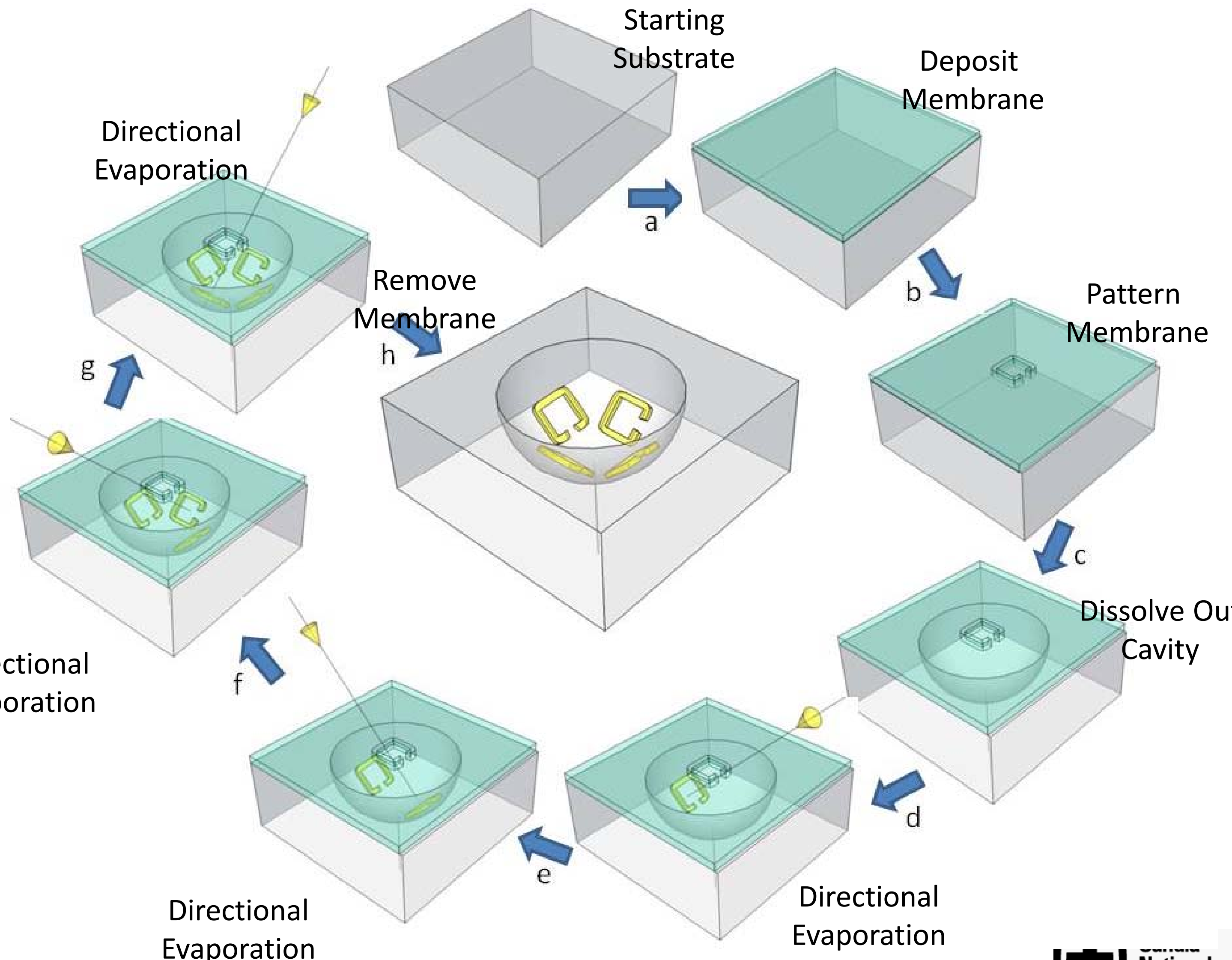
Self-Aligned MPL (SAMPL)

Advantages

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



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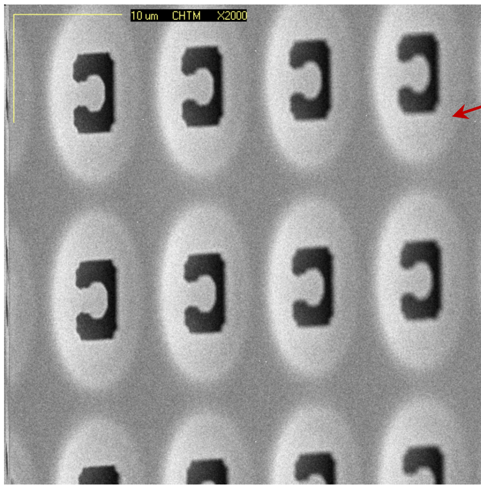
SAMPL – Examples

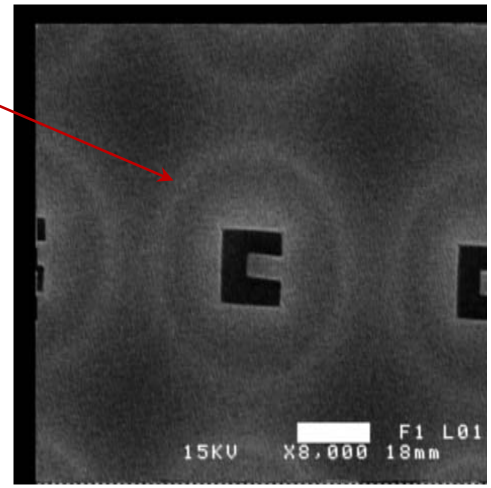
Contact Lithography

E-Beam Lithography

THz
Freqs.

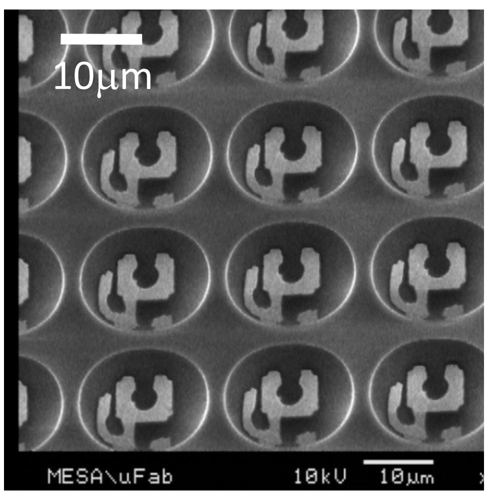


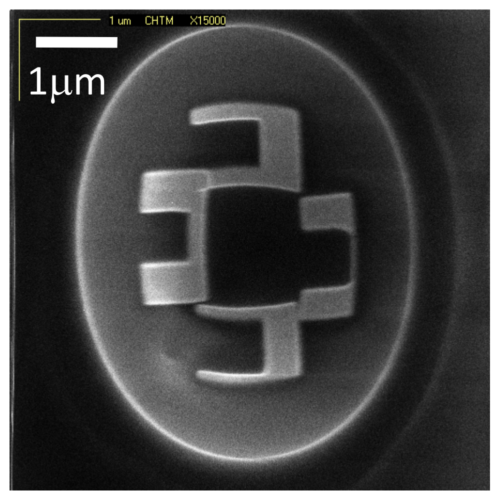
Halos show extent of cavity



IR
Freqs.

Suspended Patterned Membrane





Au-SRRs After Liftoff

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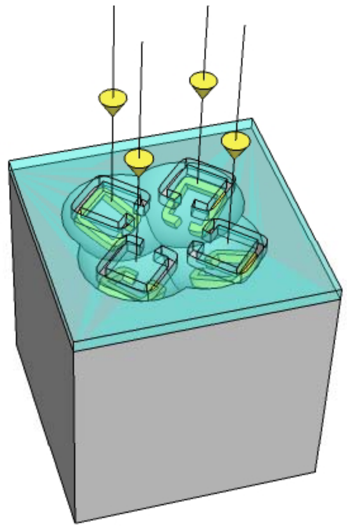
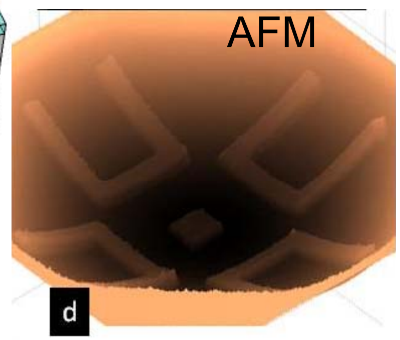
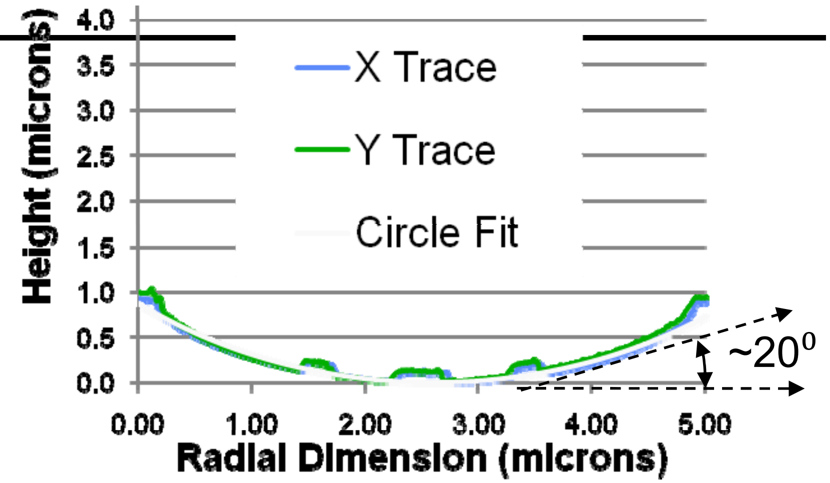
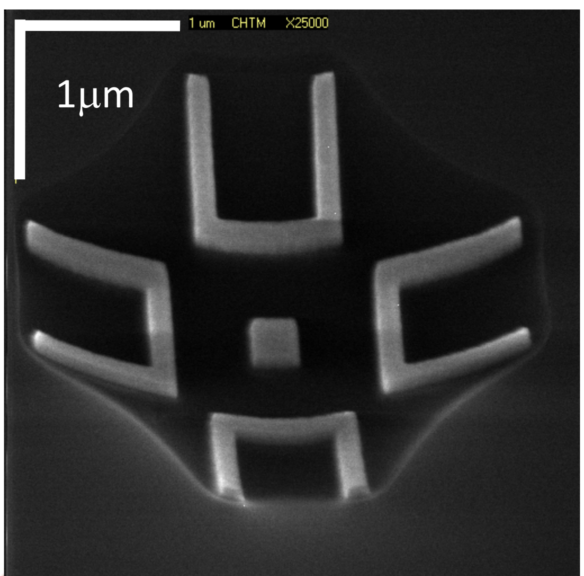
Fabrication of Out-of-Plane MM Resonators

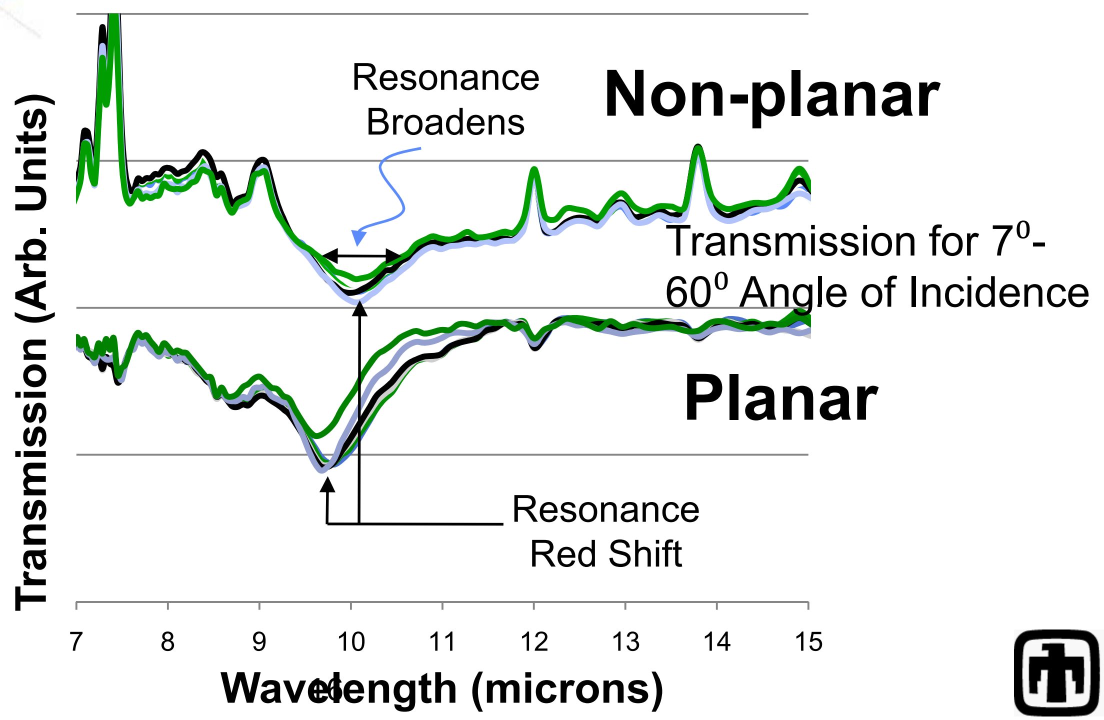


Single Evaporation Self-Aligned Membrane Projection Lithography

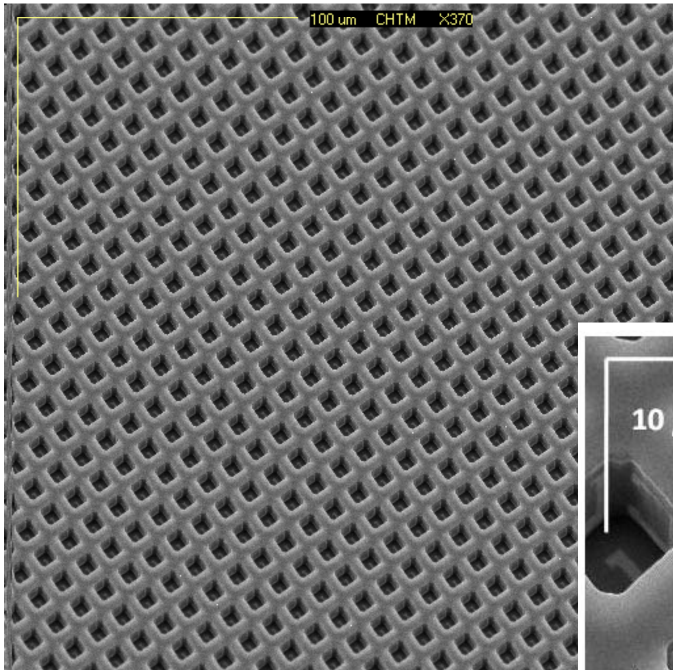




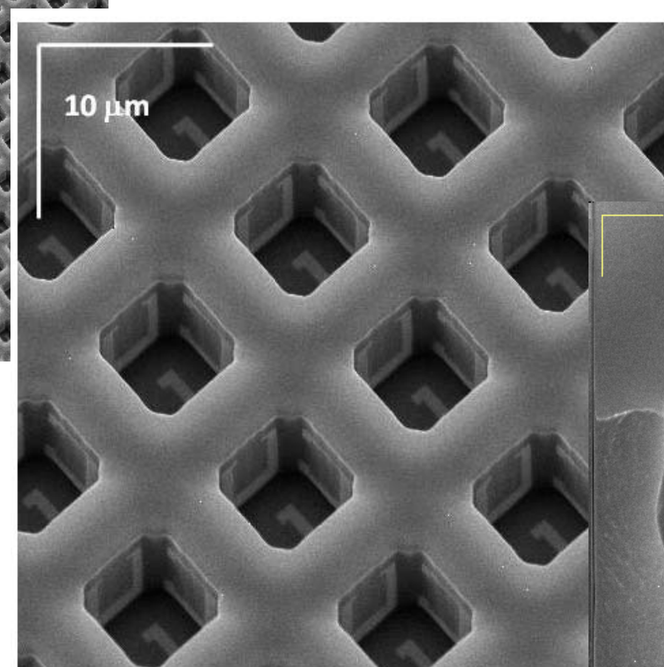


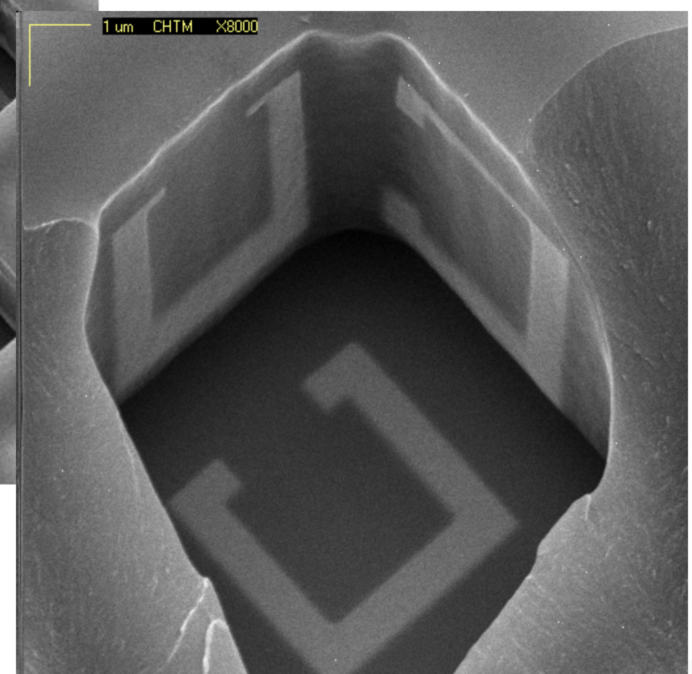


3D Metamaterials via MPL



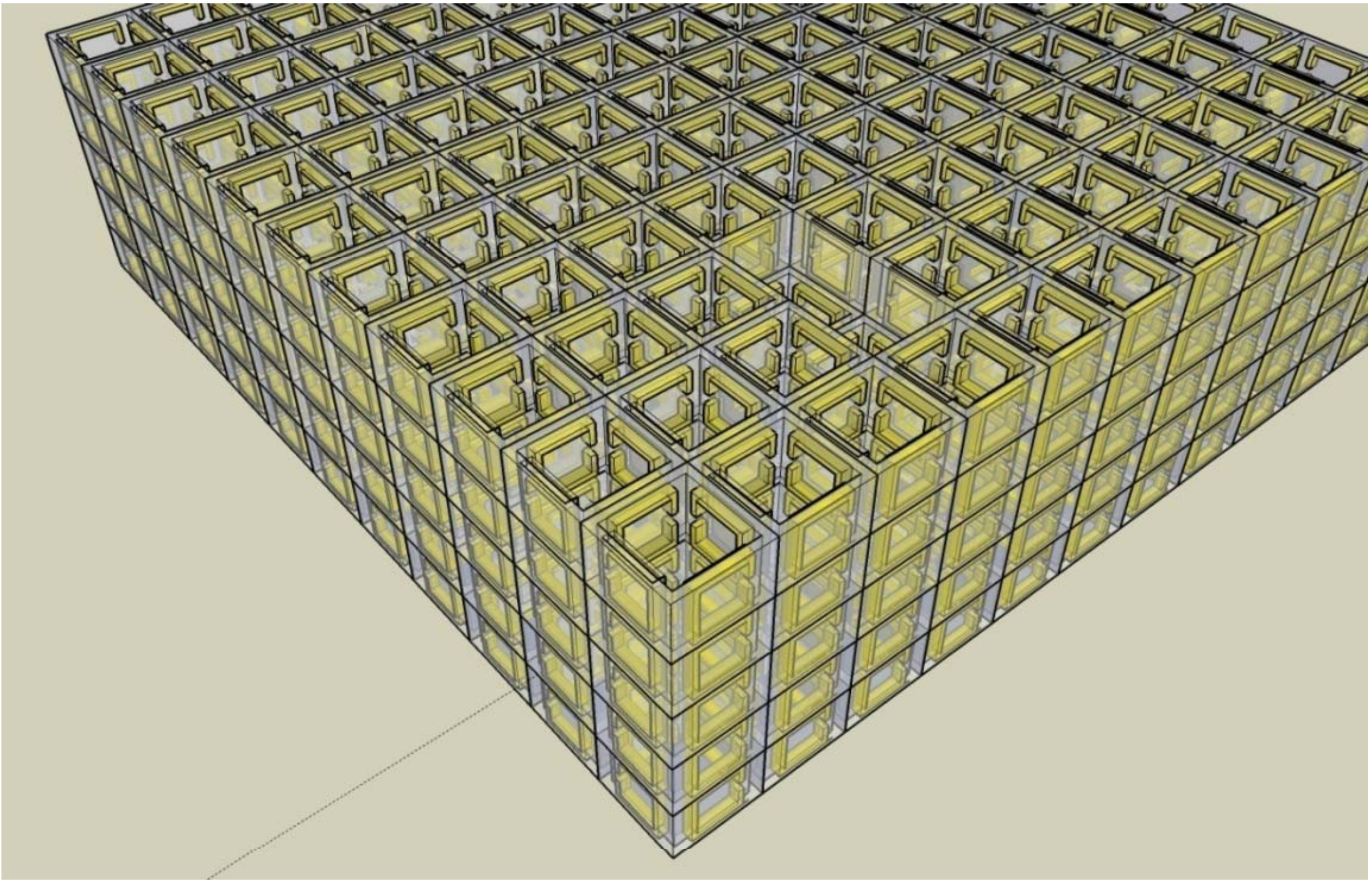
- Ti/Au SRRs on 4 sides and bottom
- Operating wavelength ~ 40 μm
- Characterization in progress





Pushing to smaller unit cell dimensions to move into thermal IR

Layer-by-layer Route To 3D Material



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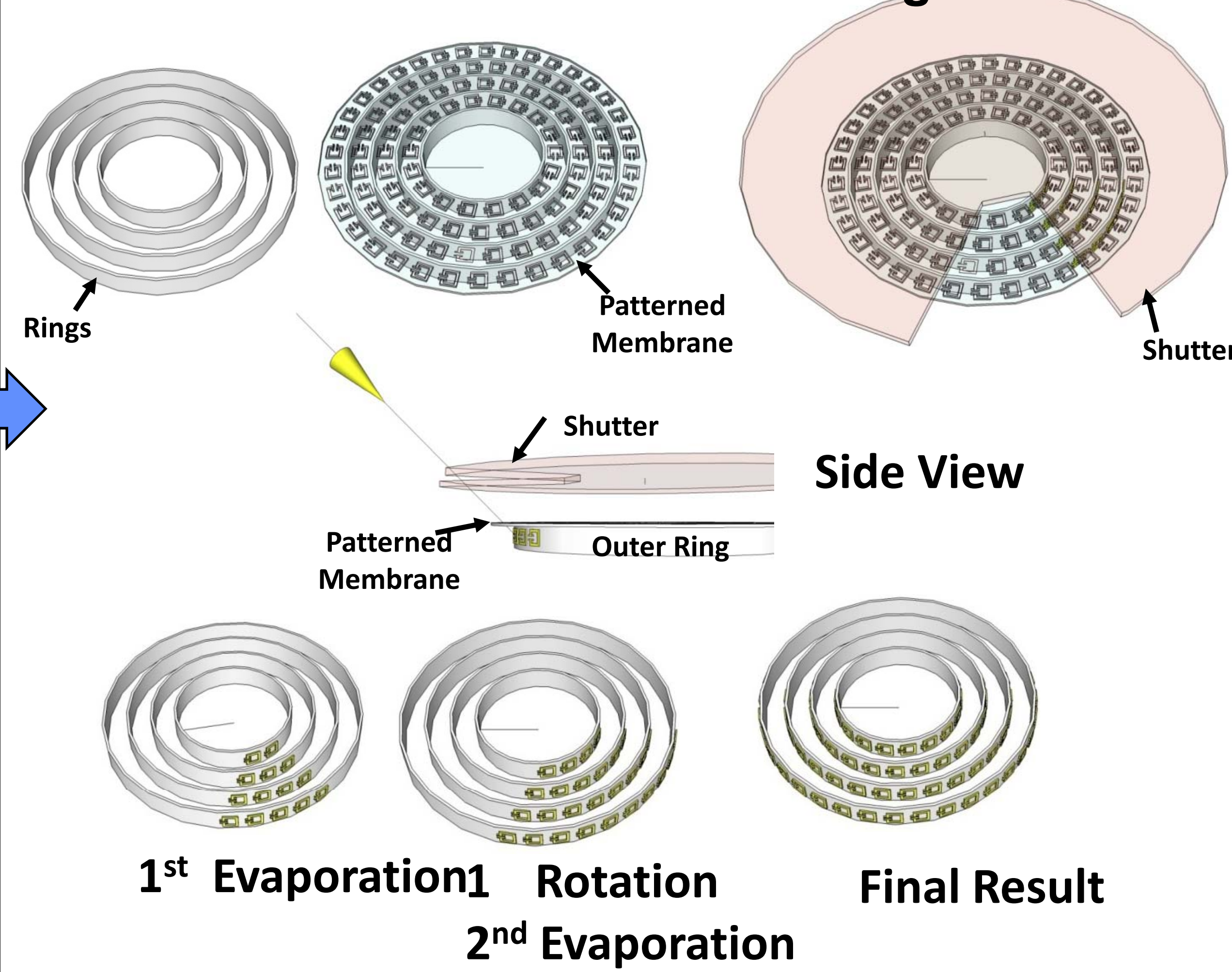
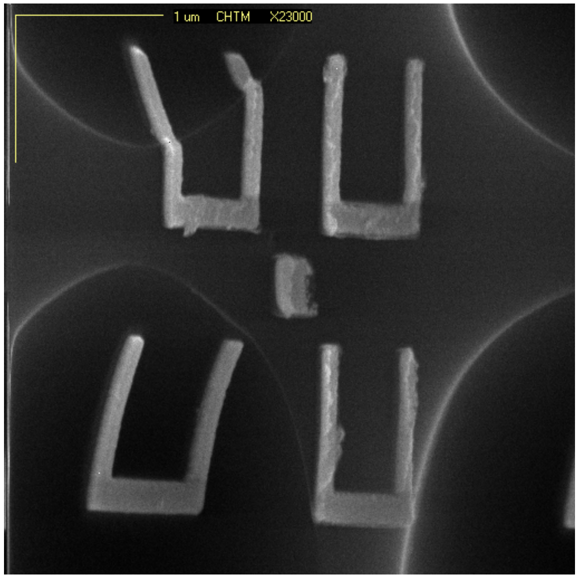
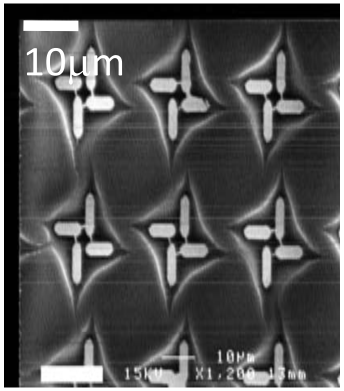
Beyond Homogeneous Metamaterials: Direct Fabrication of IR Metamaterial Devices

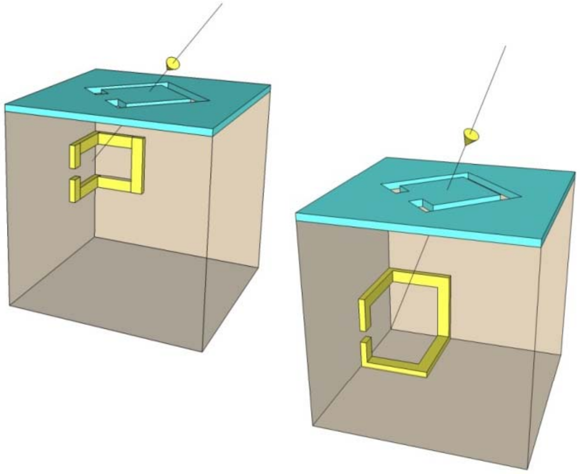
- MPL is not restricted to rectangular geometries
- Multilayer devices possible

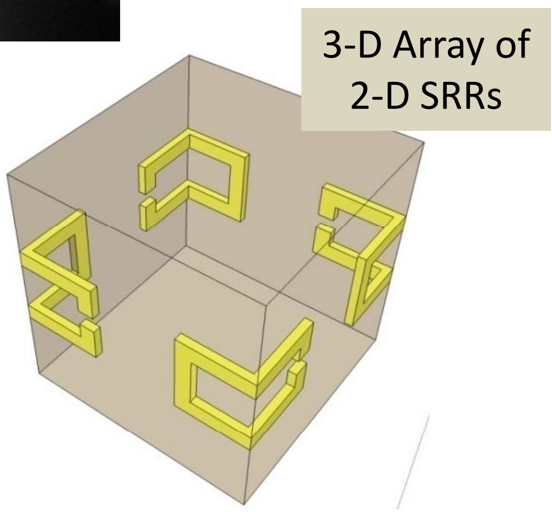
MPL Fab Route for Schurig’s cloak

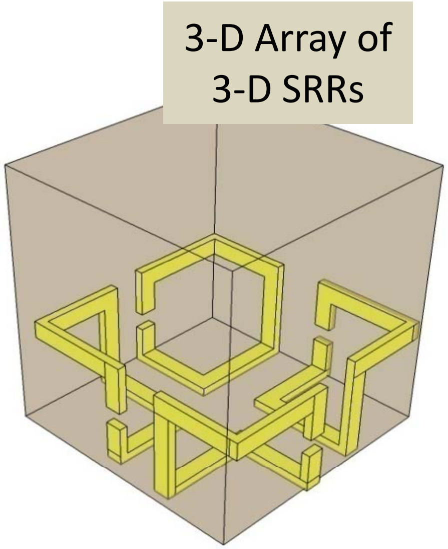












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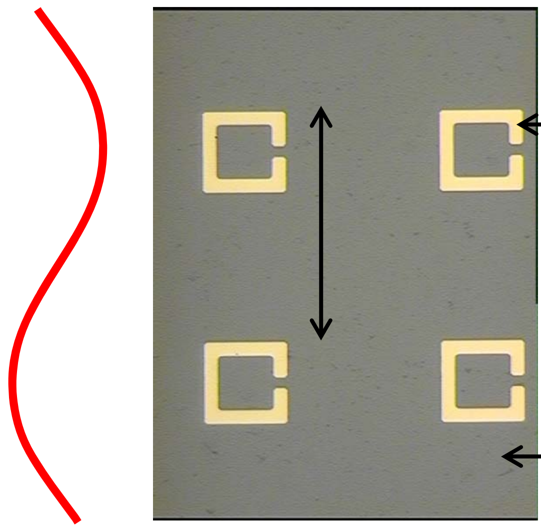
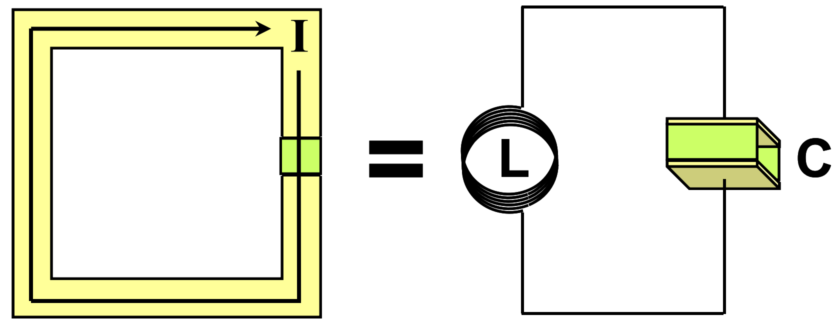
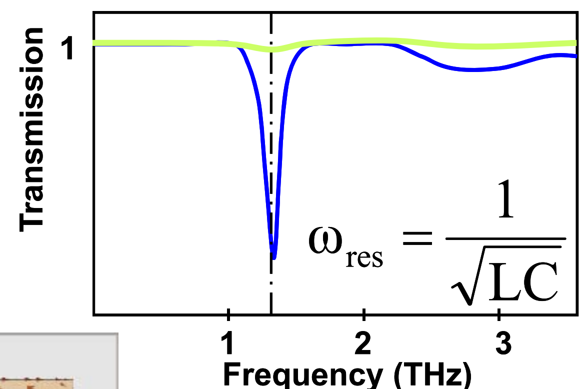
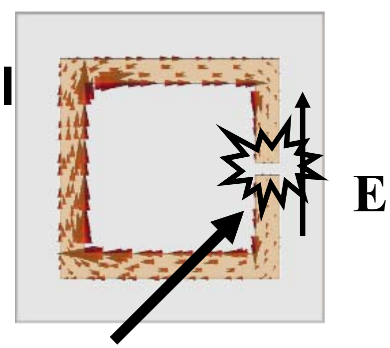
Active metamaterials can be used as optical modulators







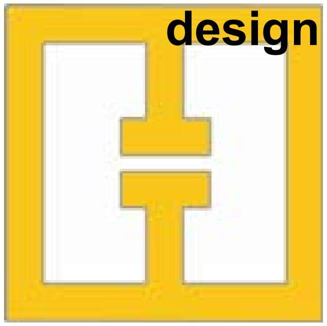
Modulation can be done optical or electrically:

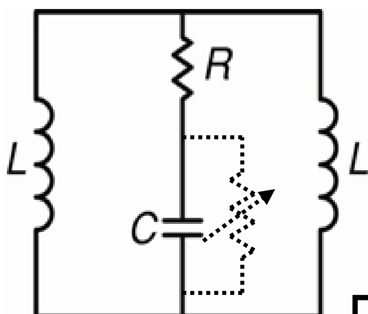


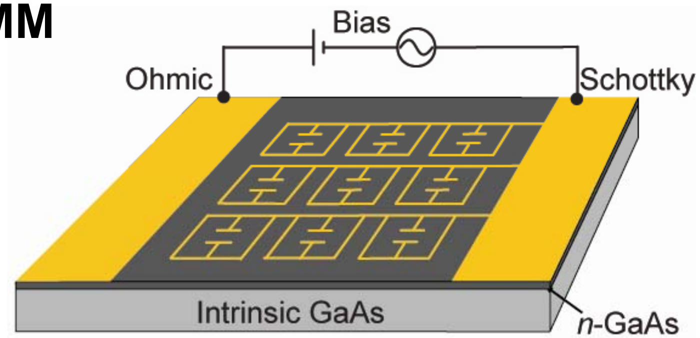
W.J. Padilla et al, Phys. Rev. Lett. 96, 107401 (2006)
And many papers at this conference

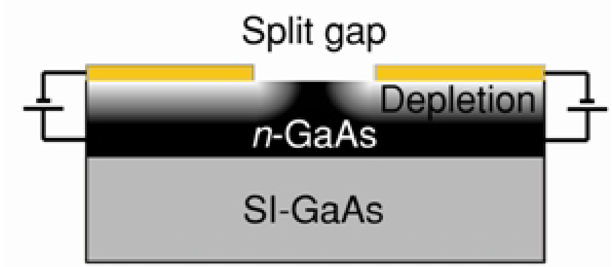
THz Electrical Switch/Modulator

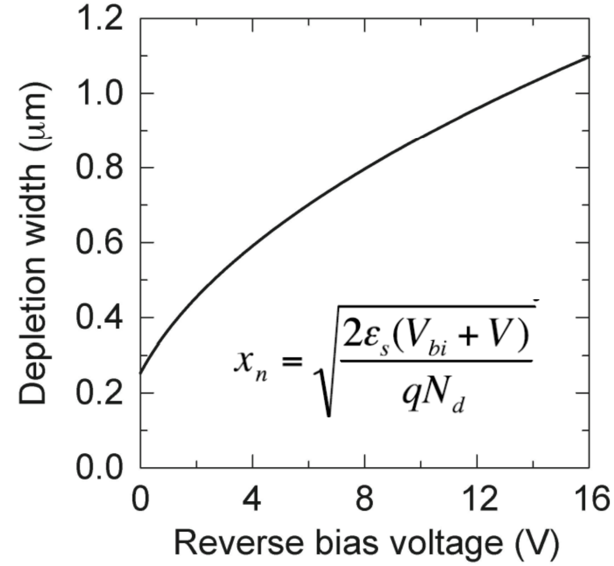
Use “electrical” MM design



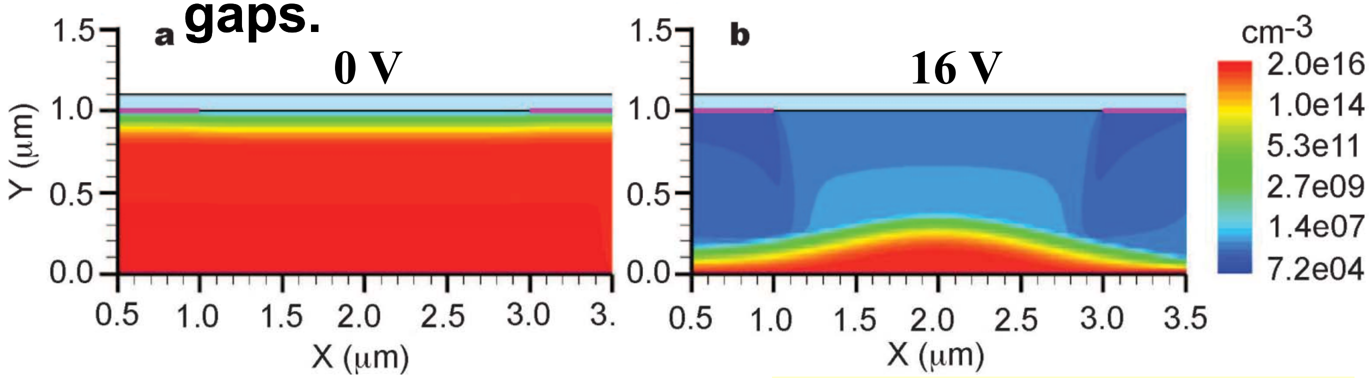








Principle: shunt on or off the capacitive split gaps.



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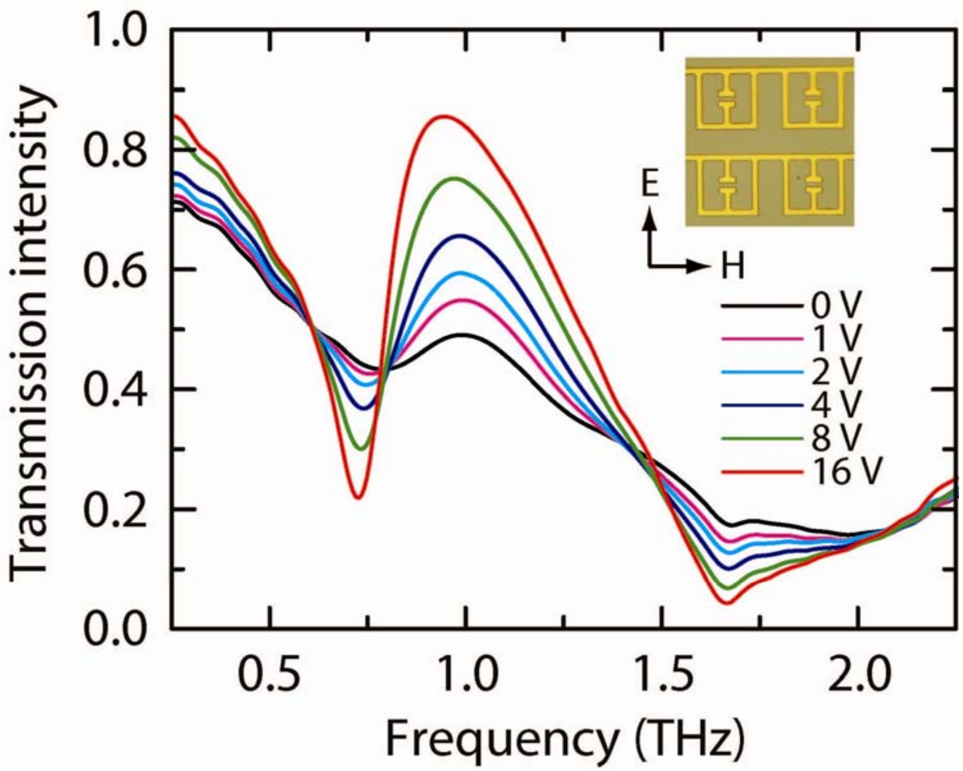
H.-T. Chen *et al.*, *Nature* 444, 597 (2006).

Electrically Switchable THz Metamaterials – Early results

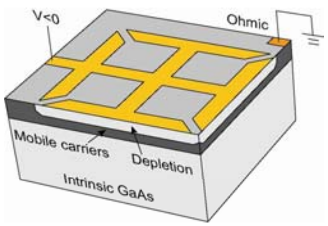


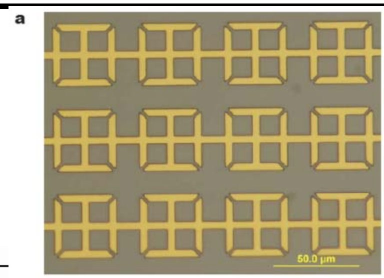
- Modulation depth: $M = (I_{0V} - I_{16V}) / I_{0V} = 50\%$
- Room temperature operation
- Modulation speed limited by total capacitance (10's MHz, can be higher)

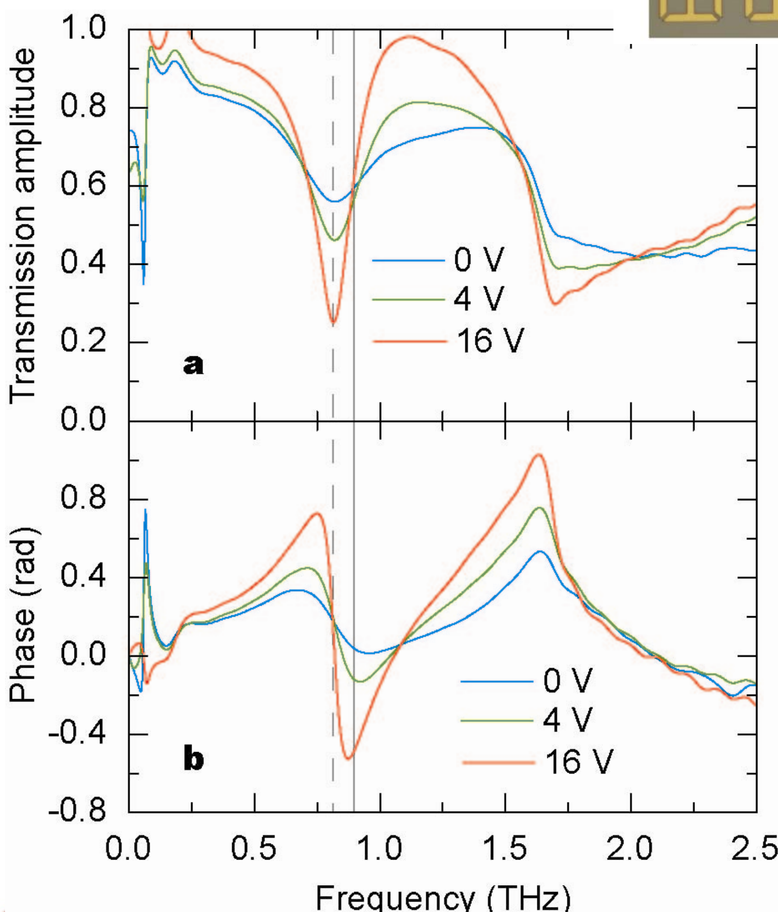
In order to shunt gap effectively, plasma frequency of doped layer needs to match the MM resonance frequency

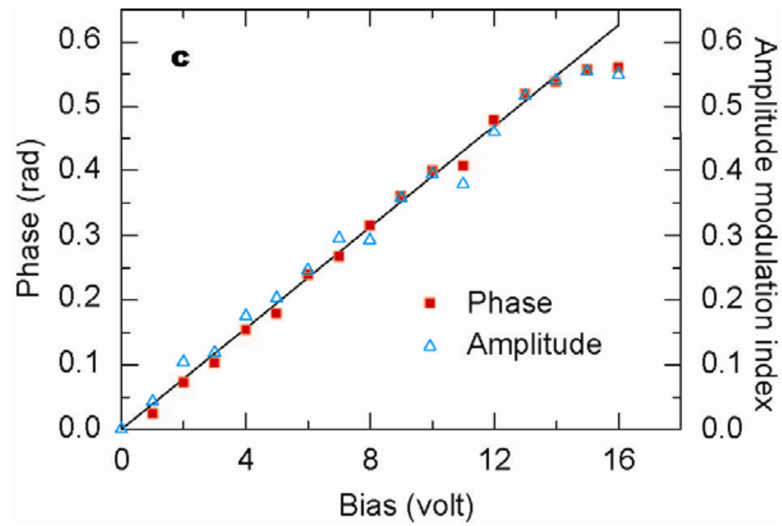
H.-T. Chen *et al.*, *Nature* 444, 597 (2006).

Amplitude Switching and Phase Shifting









- **Modulation depth better than previous design**
- **Transmission phase shifts by 0.56 rad for a single layer metamaterial.**
- **Amplitude switching and phase shifting are linked**
- **Linear dependence on voltage bias**

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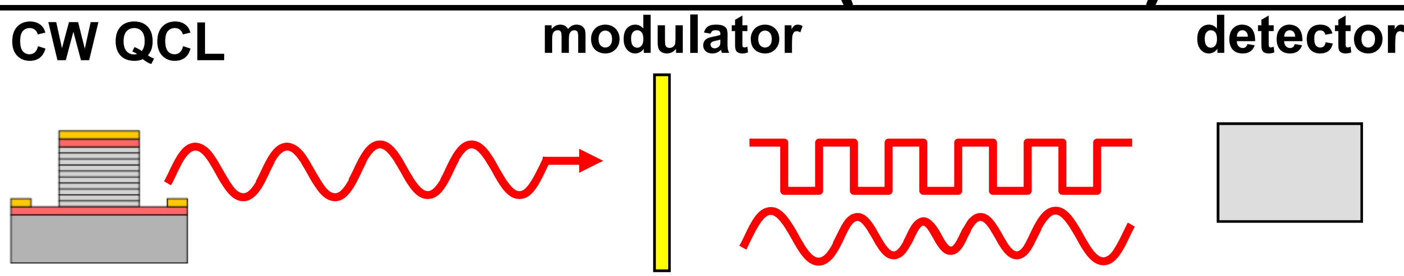
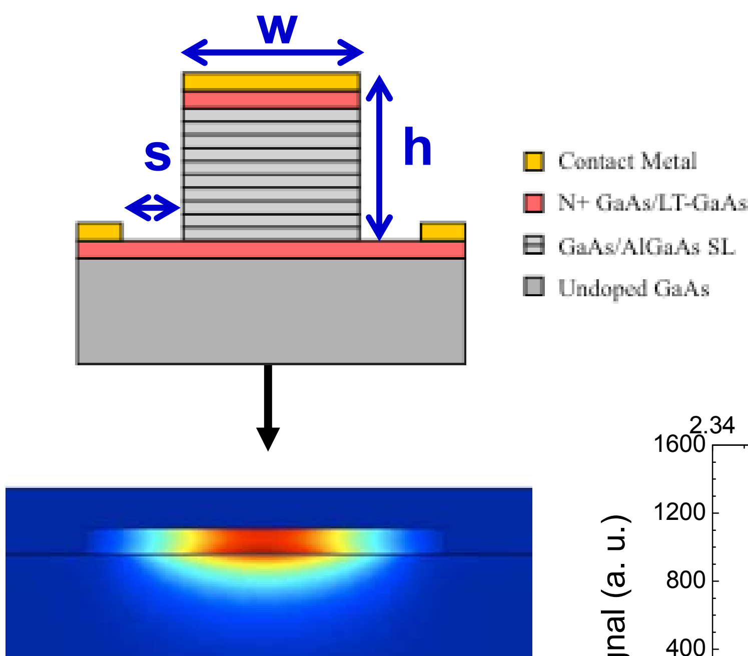
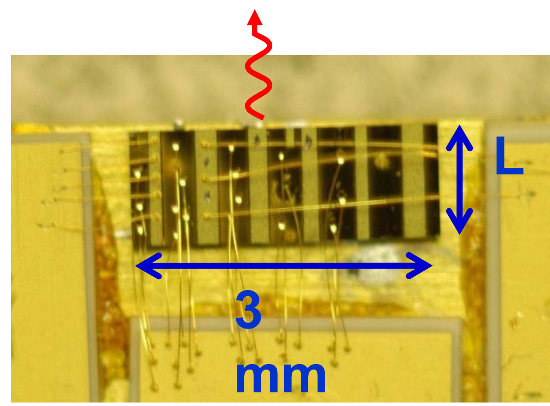
H.-T. Chen *et al.*, *Nature Photonics* 3, 148 (2009).

External modulators for THz Quantum Cascade Lasers (~2-3THz)



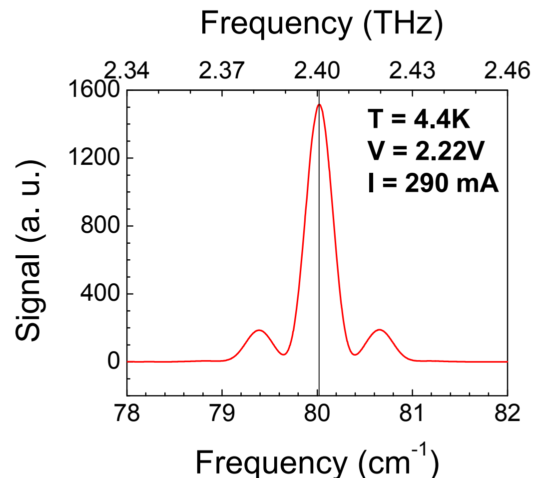


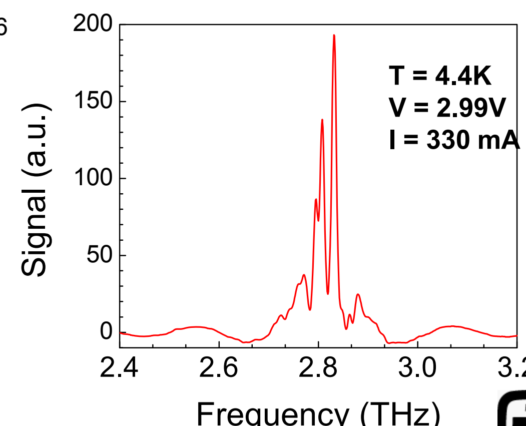
Demichel, *Opt. Exp.*, 14, 5335, 2006



w

6 QCLs integrated on a chip





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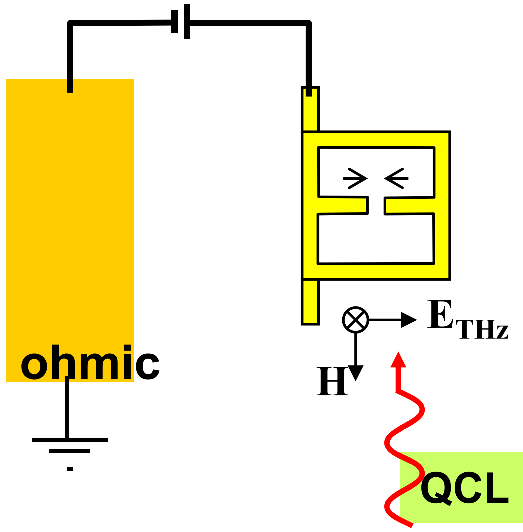
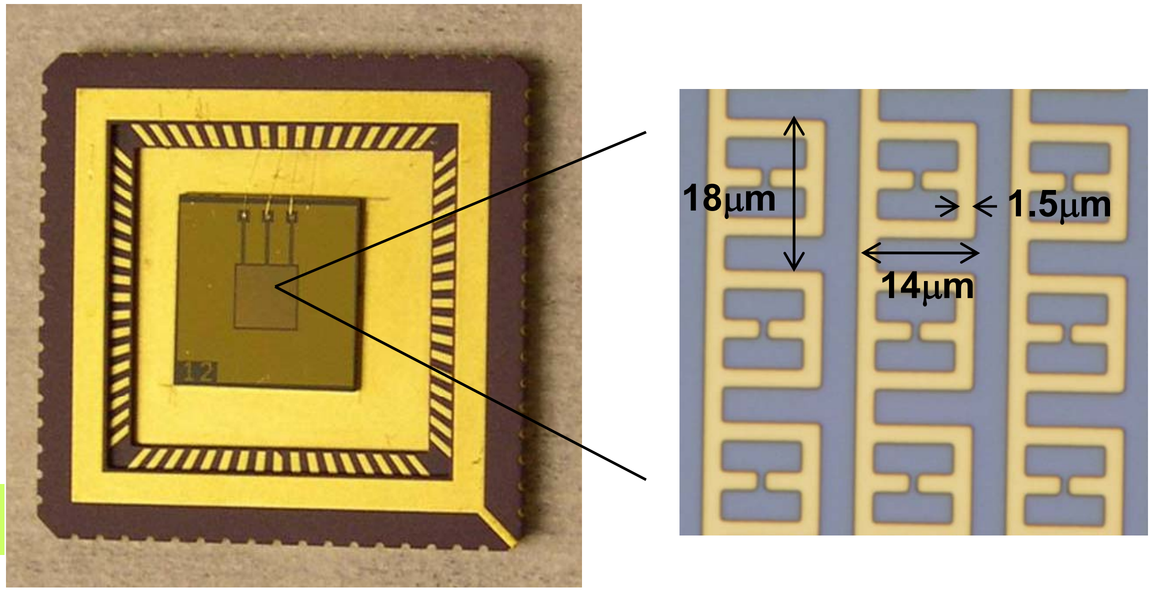
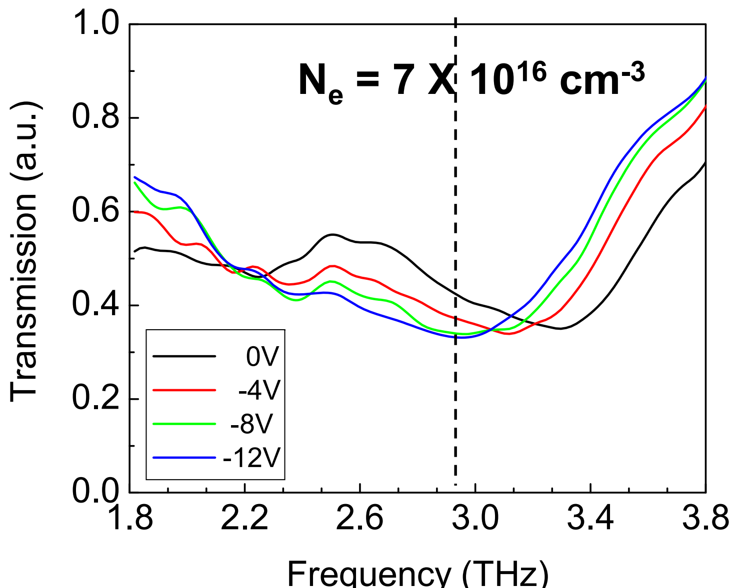
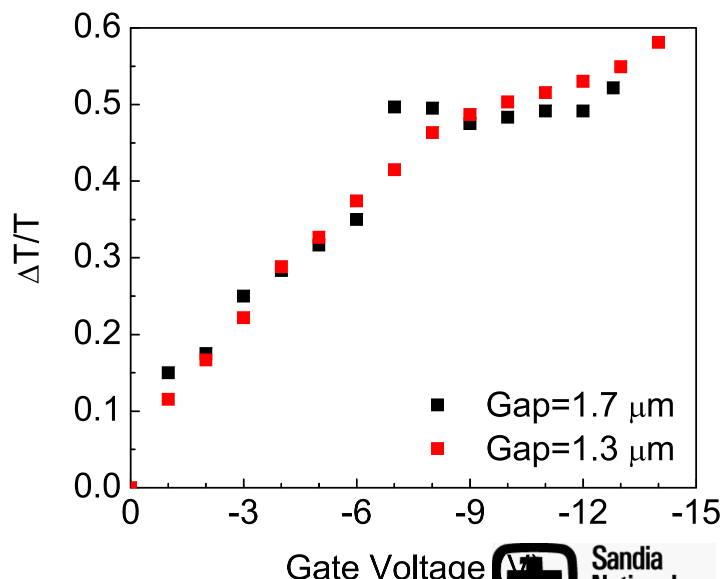
Metamaterials for electrical modulation of ~3THz Quantum Cascade Lasers





N_e = 7 X 10^{16} cm^{-3} corresponds to ω_p ~ 2.5THz





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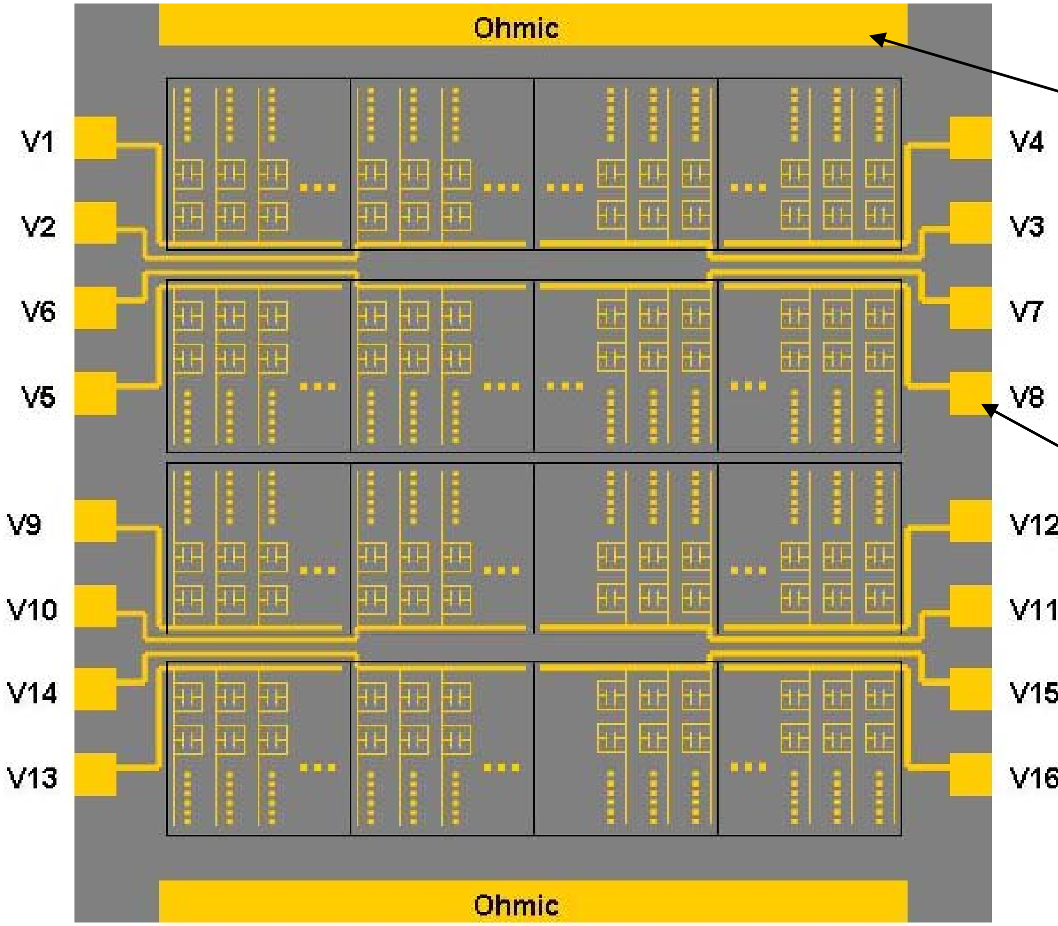
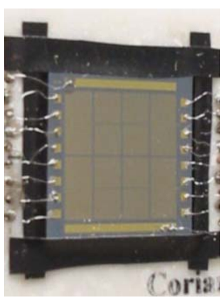
Multi-pixel metamaterial THz-SLM



Ohmic contact (connect to ground)

Schottky electric pad (voltage input)



(with Rice)

- **4 × 4 pixel array of split-ring resonator (SRR) elements**
- **Each pixel independently controlled by an external voltage**

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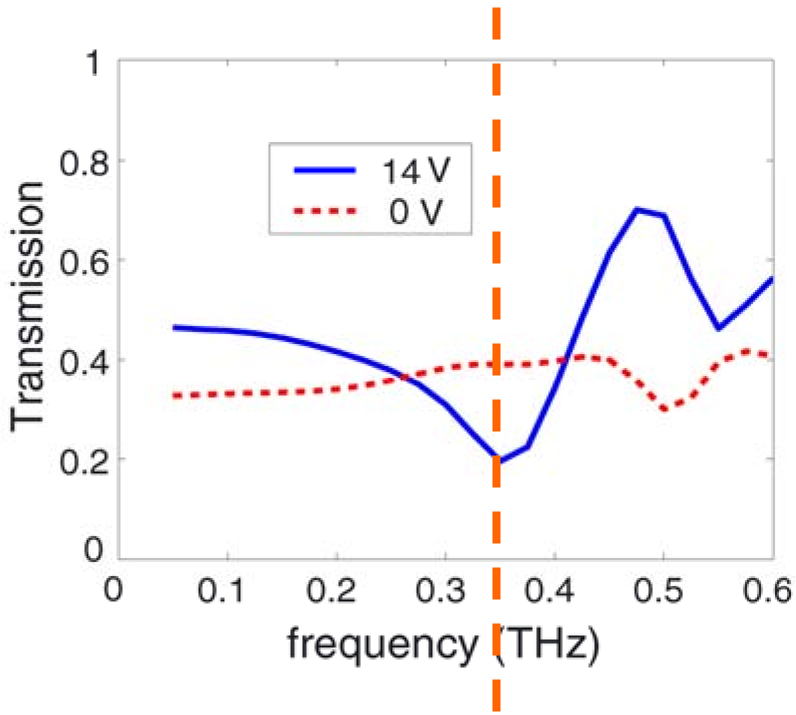
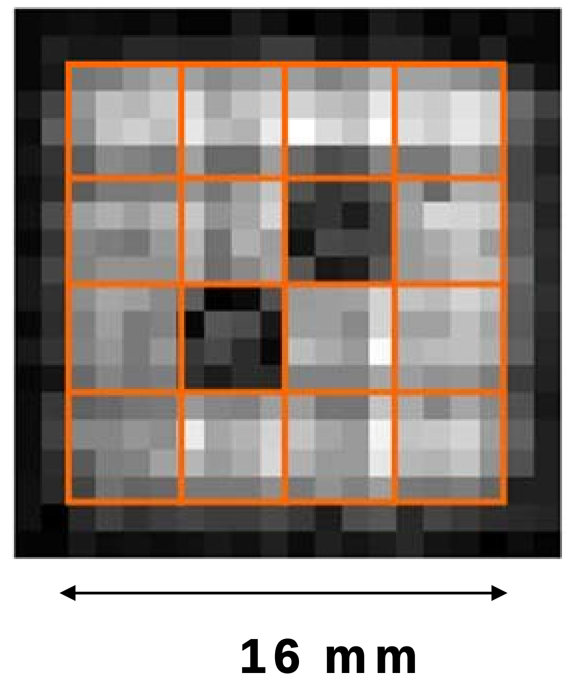
Uniform Spatial Modulation

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



Resonant frequency at 0.36 THz

Transmission image of THz-SLM at 0.36 THz

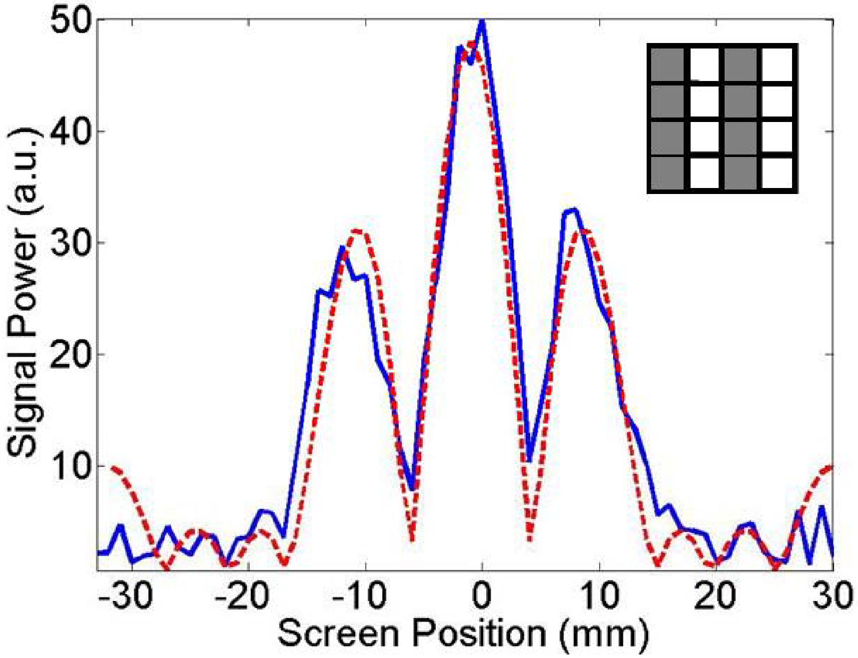


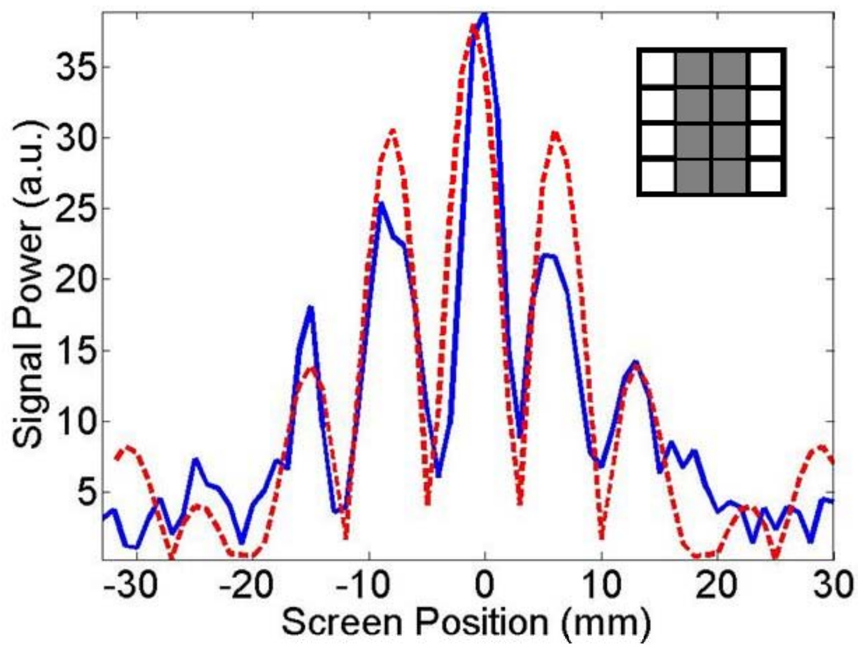
- **~40% modulation**
- **Uniform across 16 pixels**

W.L. Chan *et al,* APL 94, 213511 (2009)

THz-SLM Switching Performance

- Double-slit experiments with THz-SLM
- Demonstration of fast dynamical modulation of THz beams

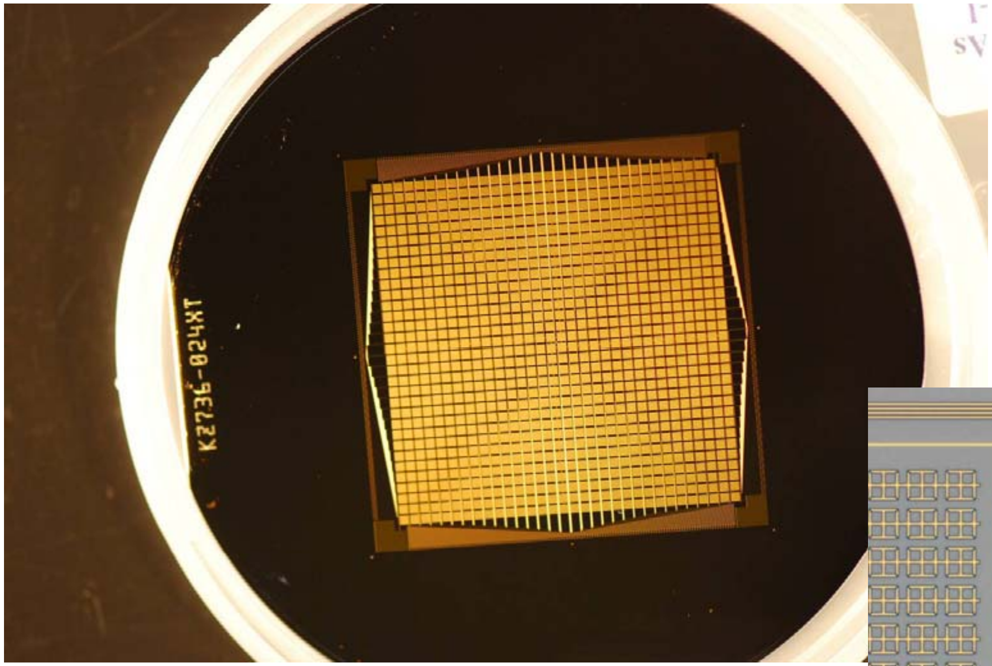




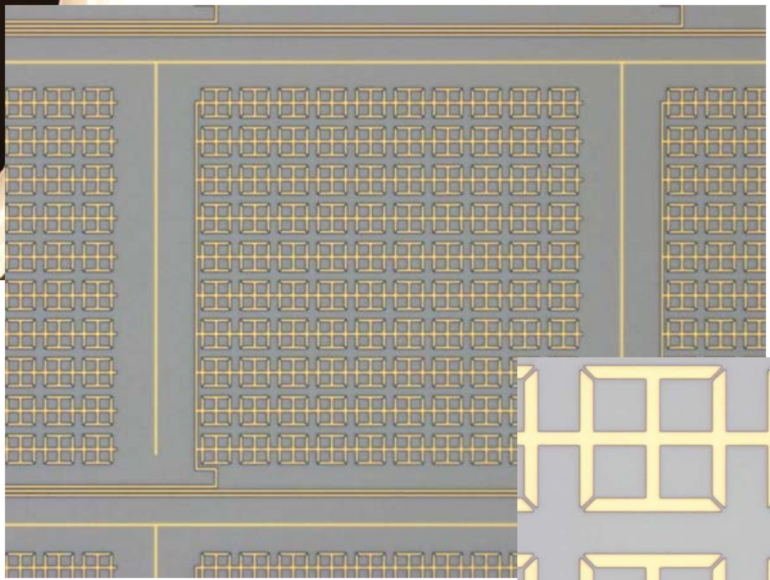
□ pixel modulated with 3kHz square wave

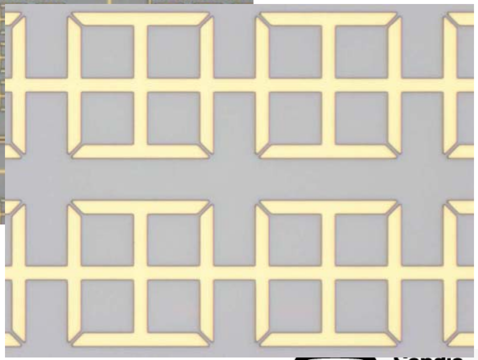
■ pixel without voltage bias

Towards bigger SLM's



32x32 pixel array



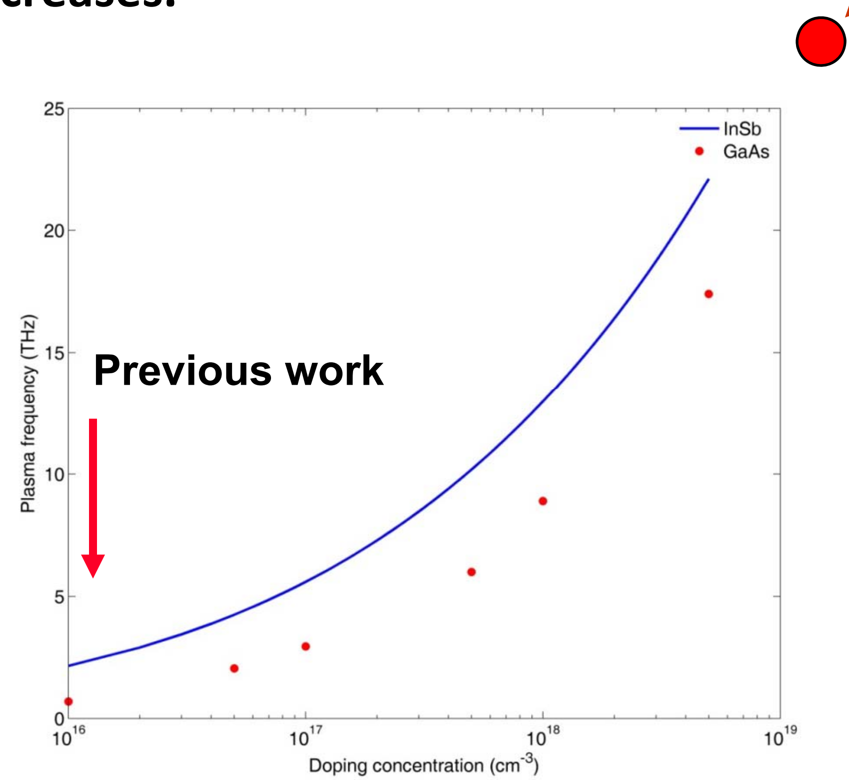


Scaling to higher frequencies (thermal IR, 30THz)

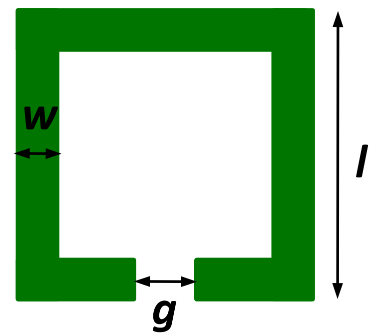
- **Issue 1:** need to raise plasma frequency increasing doping density or changing semiconductors
- **Issue 2:** requires nanolithography
- **Issue 3:** for high doping, depletion width decreases.

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

(1) We need to be here



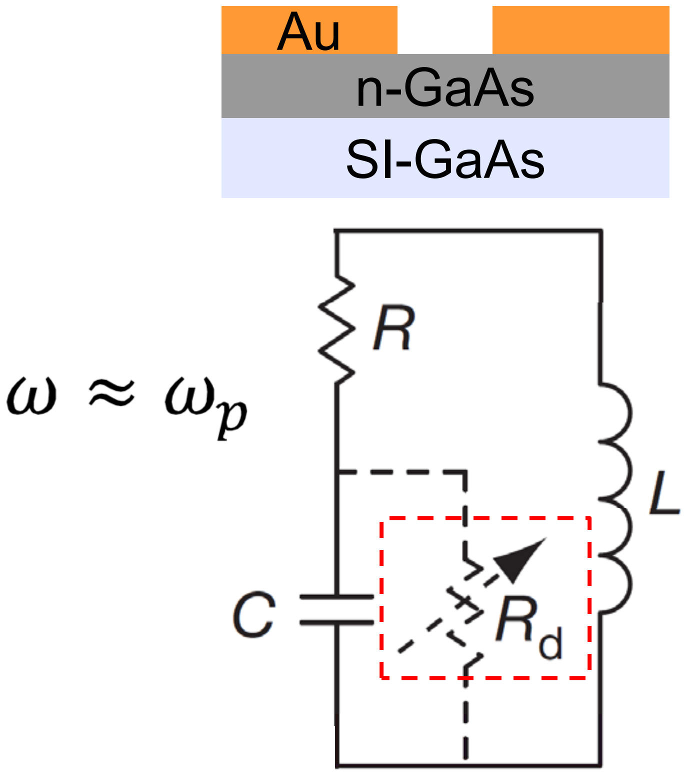
(2)



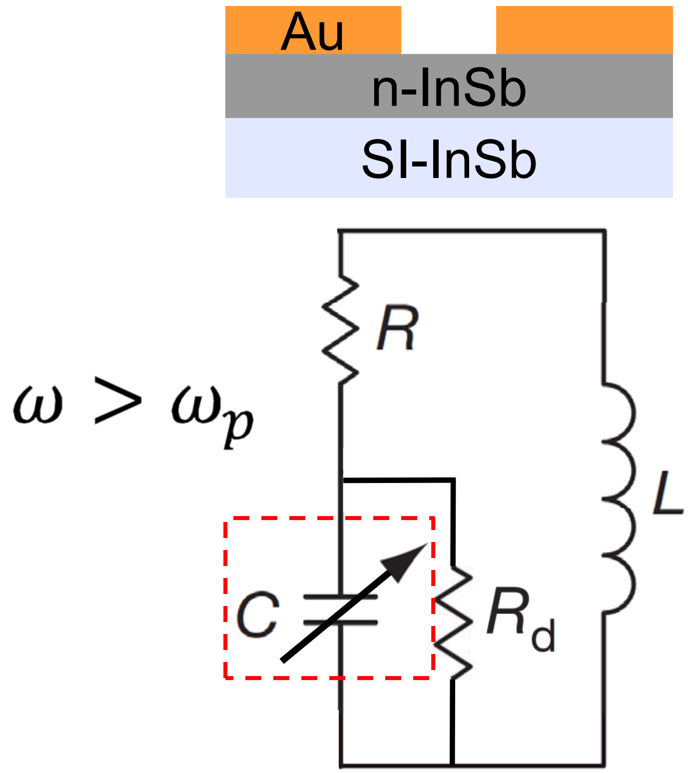
l = 660 nm
w = 130 nm
g = 100 nm

Scaling Tunable Metamaterials to the IR

Terahertz



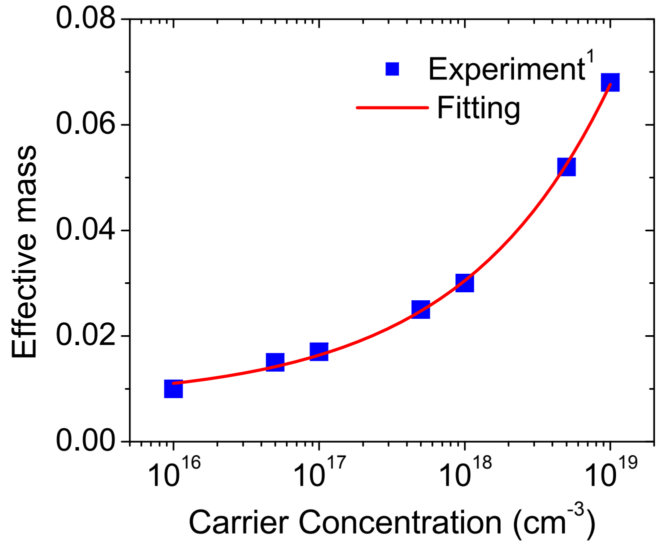
Mid-infrared

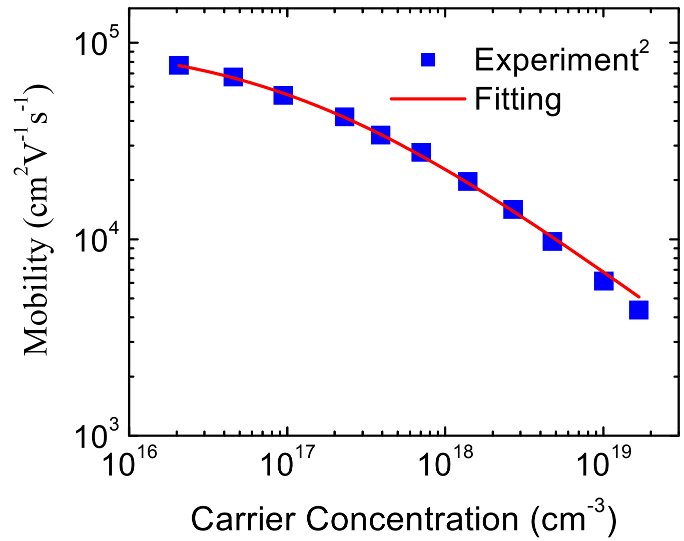


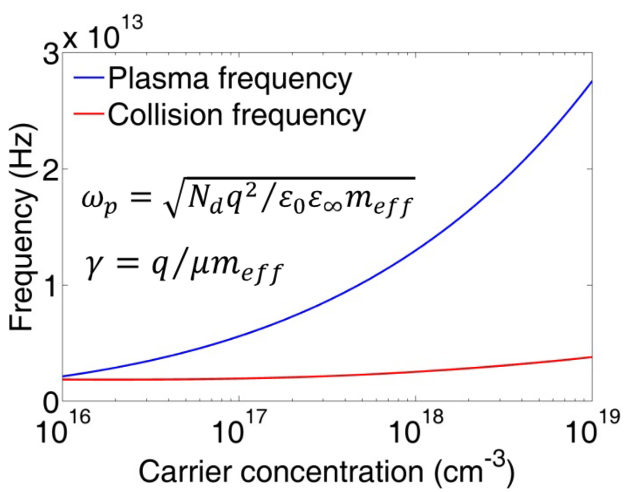
- Micron-sized features.
- Depletion layer resistance dependent on the carrier concentration.
- Amplitude modulation.

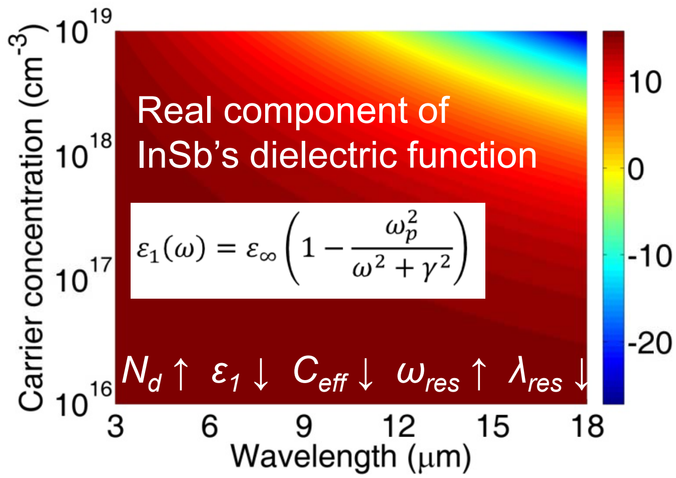
- Nano-sized features.
- Dielectric function of n-InSb dependent on the carrier concentration.
- Resonance shift.

Dielectric Function of Doped InSb









[1]Zawaski et al, Advances in Physics, 1974 [2] Litwin- Staszewska et al, Physica Status Solidi (b), 1981

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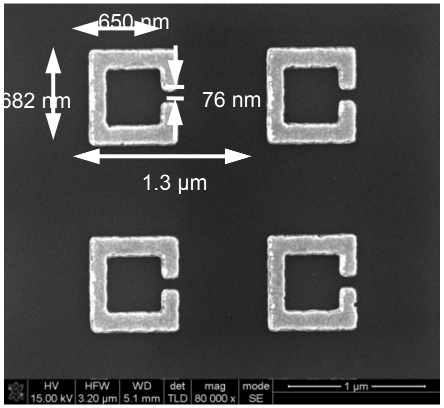
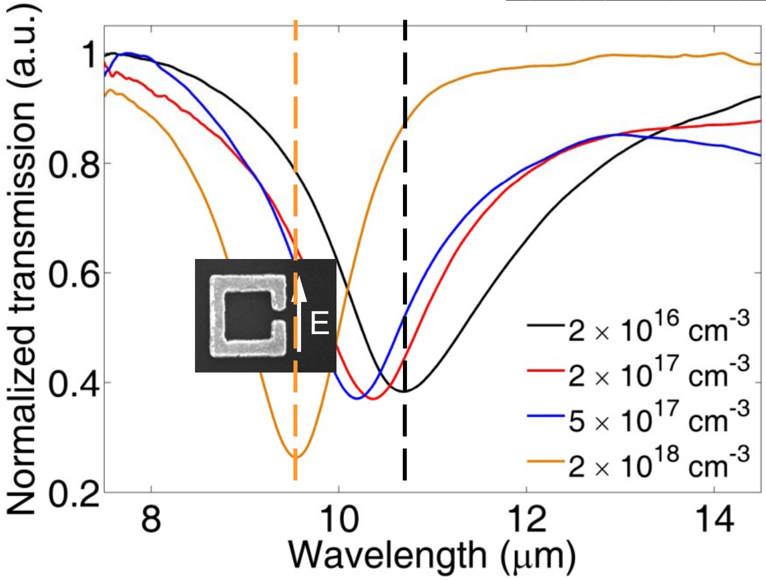
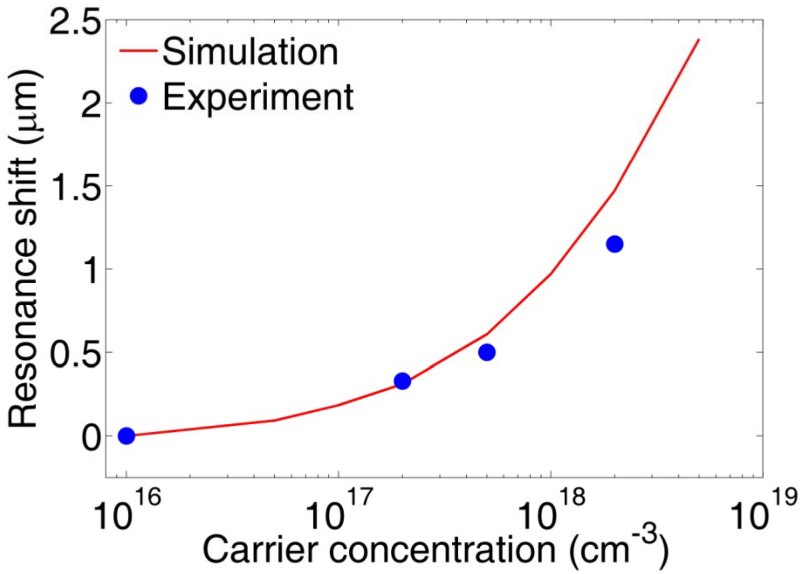
Fabrication and results: Doping Dependent Resonance



- •A thin n-type doped layer grown on semi-insulating InSb wafer.
- •Spin coated with PMMA and exposed using EBL.
- •Electron beam evaporation of Ti/Au.
- •Lift-off in an acetone bath

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



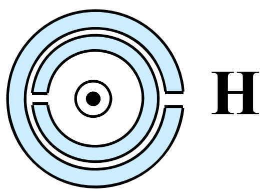


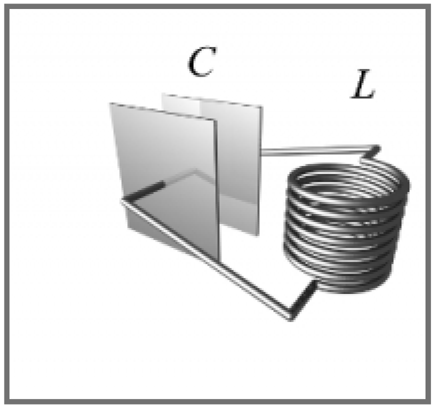
- Resonance shift of 1.15 μm is achieved by varying the carrier concentration of InSb epilayer from $1\times 10^{16}\ cm^{-3}$ to $2 \times 10^{18}\ cm^{-3}$.

Outline

- Introduction, metamaterials, scaling, etc
- Fabrication of IR 3D Metamaterials
- Optical modulators based on single layer metamaterials
- Hybridization between metamaterial resonances and material dielectric resonances

Metamaterial-Dielectric Resonant Coupling

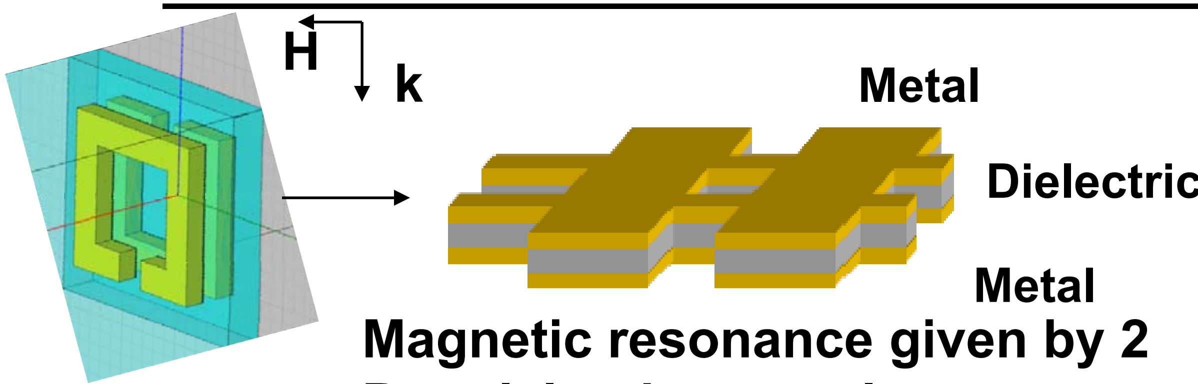




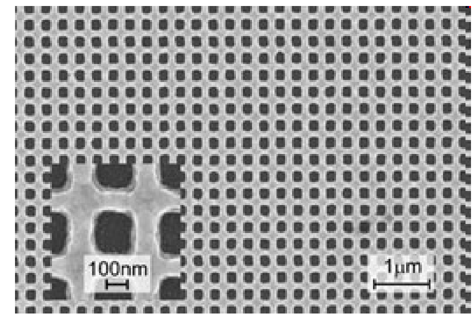
$$\omega_{res} = \frac{1}{\sqrt{LC}}$$

- We design some inductive loop to create a μ resonance
- This loop sits on top or is embedded in some dielectric
- What happens when there are resonances in these dielectrics? (i.e., phonons)

Example 1: IR Fishnets



Magnetic resonance given by 2 Parralel stripes or planes

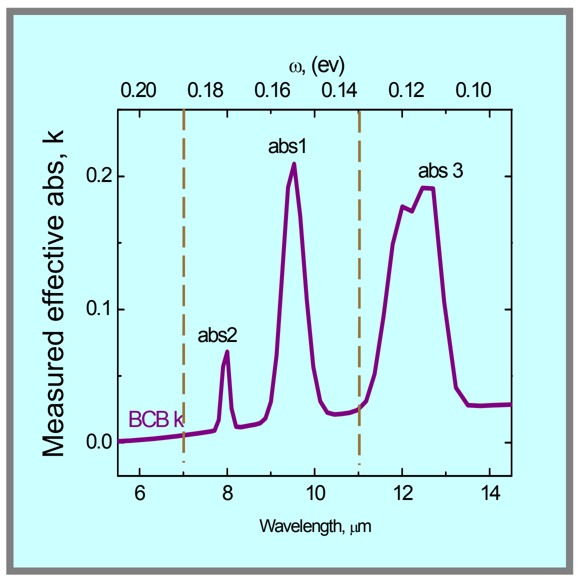


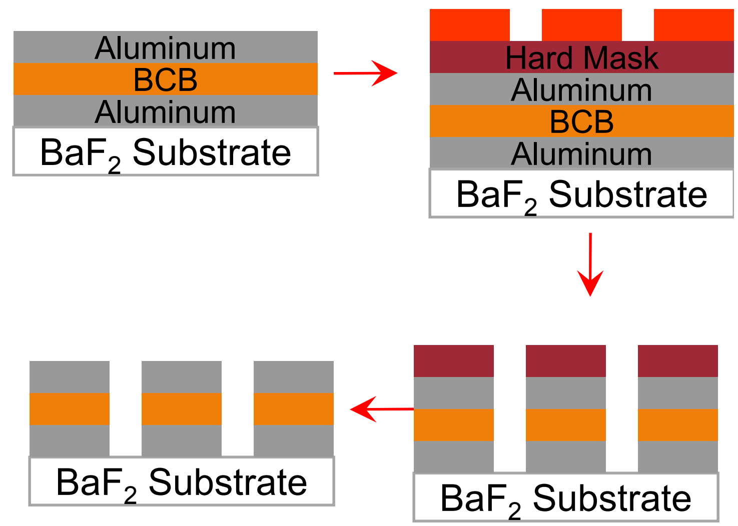
(Ames Lab)

(see work by Shalaev, Brueck, etc)

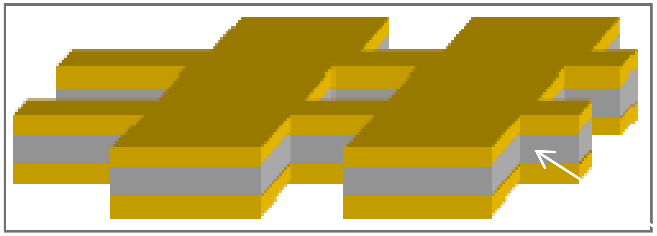
- **Fabrication constrains dictates use Aluminum and a polymer (BCB)**

(BCB absorption)



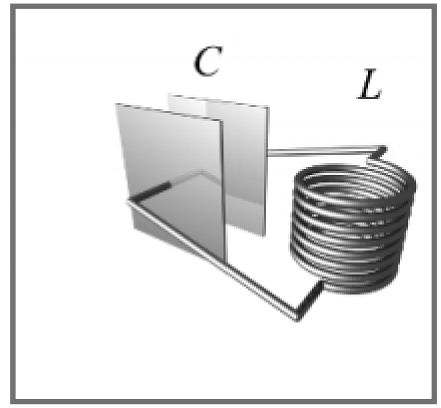


Modeling the dielectric-fishnet coupling



Can be modeled as

Dipole absorber



The effective permeability can be described by a Lorentzian-like response

$$\mu_{eff} = 1 - \frac{F\omega^2}{\omega^2 - \omega_0^2 + i\omega\gamma_0}$$

- ω_0 - resonance frequency;
- γ_0 – linewidth;
- *F* is a fill factor.

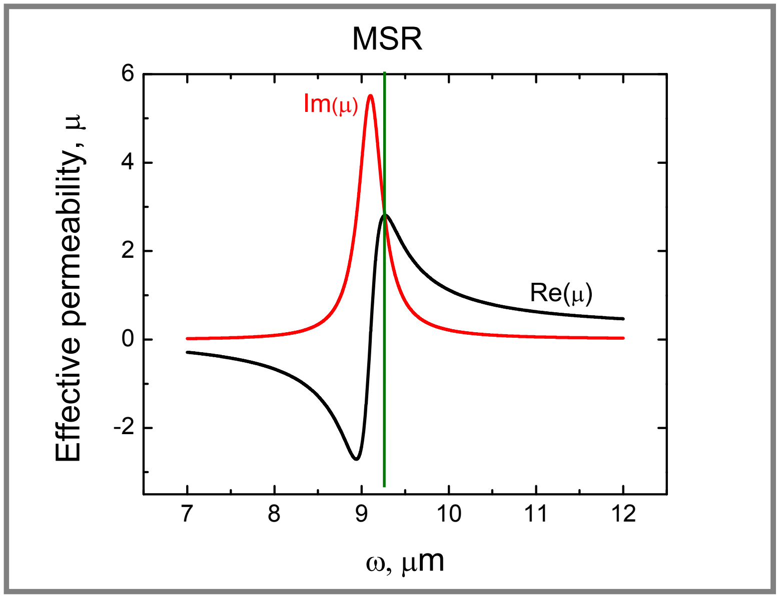
$$\omega_0^2 = \frac{1}{LC} = \frac{1}{LC_0\varepsilon_{abs}}$$

$$\frac{1}{\varepsilon_{abs}} = 1 - A\gamma_1 \left\{ \frac{1}{\omega + \omega_1 + i\gamma_1} + \frac{1}{-\omega + \omega_1 - i\gamma_1} \right\}$$

- *A* - related to the oscillator strength;
- γ_1 - the inverse linewidth;
- ω_1 - the resonance frequency of the electric dipole transition.

Simple Physical Model

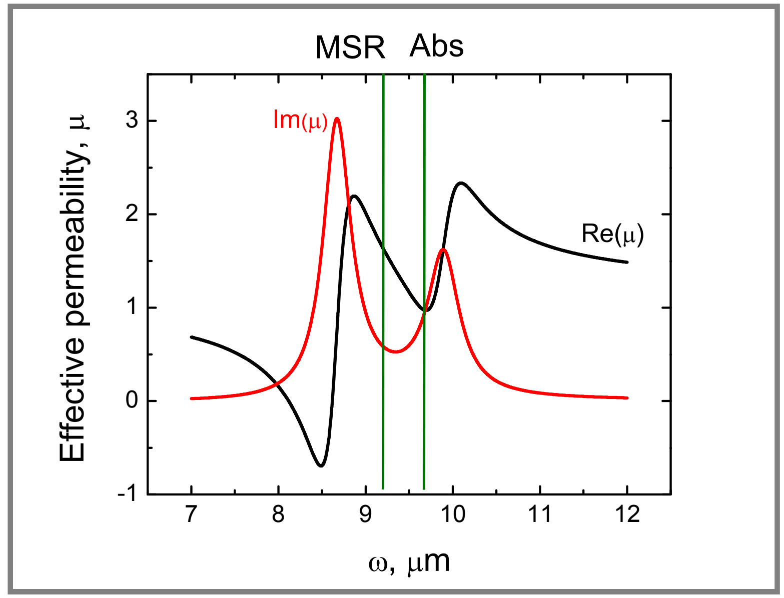
Without absorbing dielectric media



$F = 0.2; \gamma_0 = 0.33$

✓ *Metamaterial structural resonance (MSR) at 9.1 μm*

With absorbing dielectric media



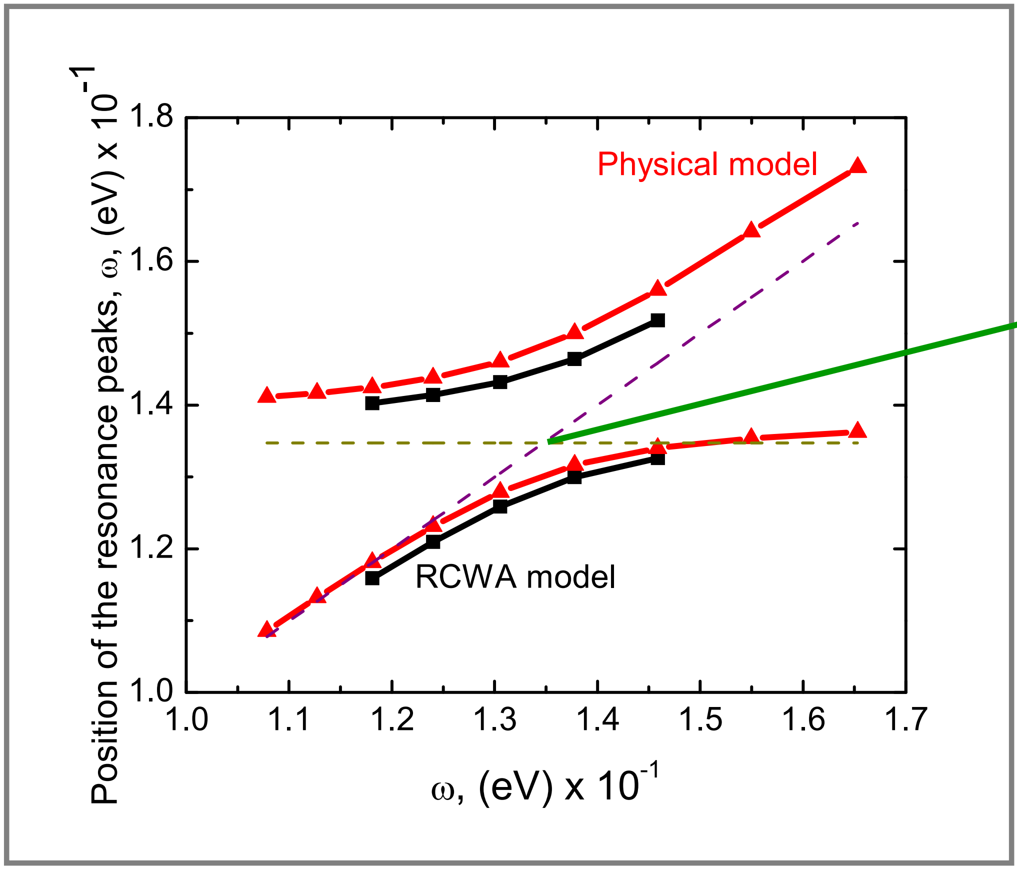
$F = 0.2; \gamma_0 = 0.33; A = 8x10^{-4} ; \gamma_1 = 3.5\ x10^{-3}$

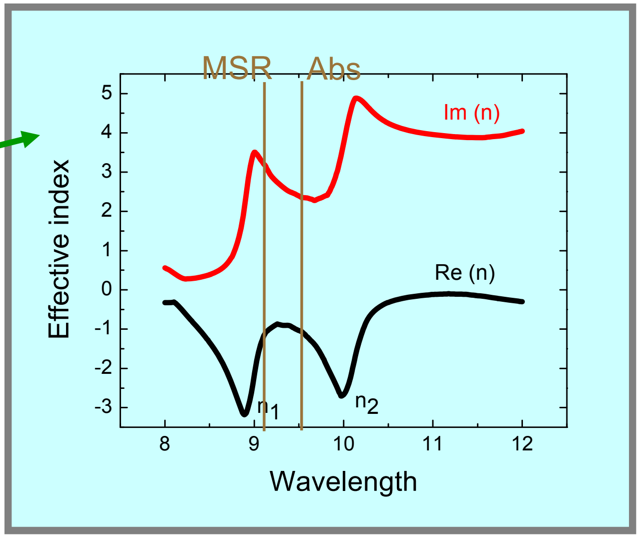
✓ *(MSR) at 9.1 μm;*

✓*Absorption peal at 9.5 μm.*

Theory and Modeling

➢ As the structural metamaterial resonance is tuned through the absorber resonance

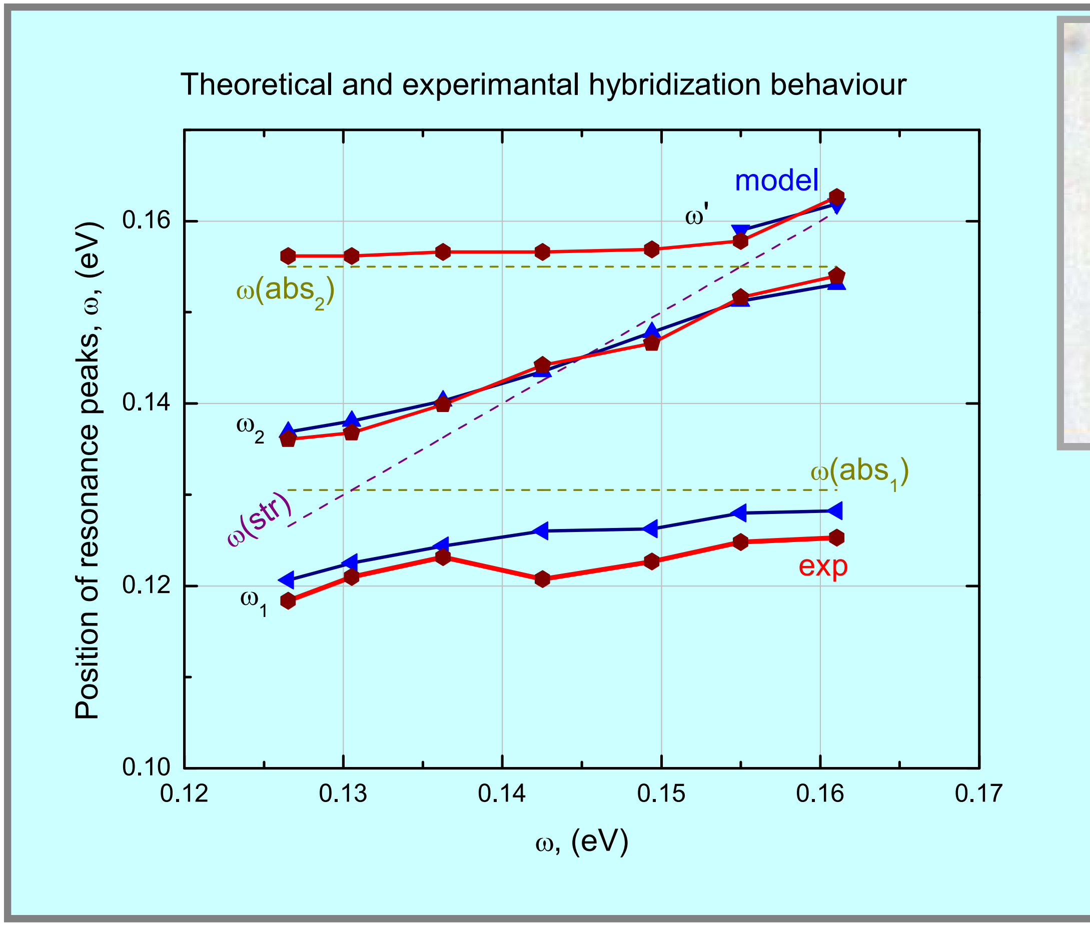


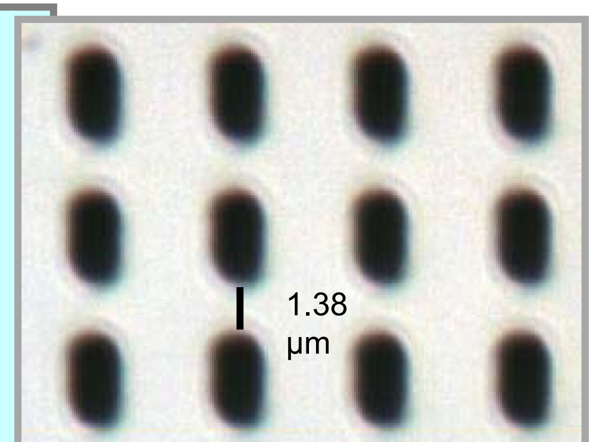


✓ **We obtain hybridization of resonances with an anti-crossing behavior and sharing of oscillator strength (and 2 negative index peaks)**

Experimental Data

Verified expected hybridization behavior of the resonances obtained by scanning structural NIM resonance through absorption resonance.

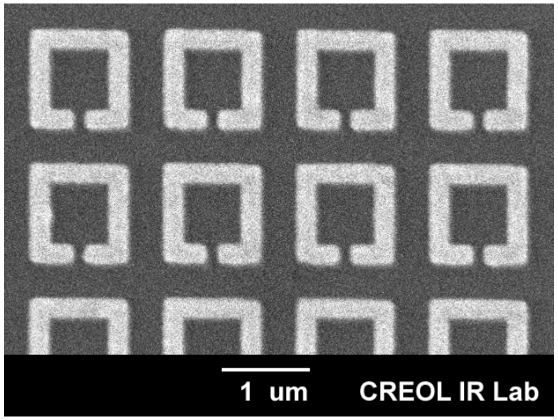


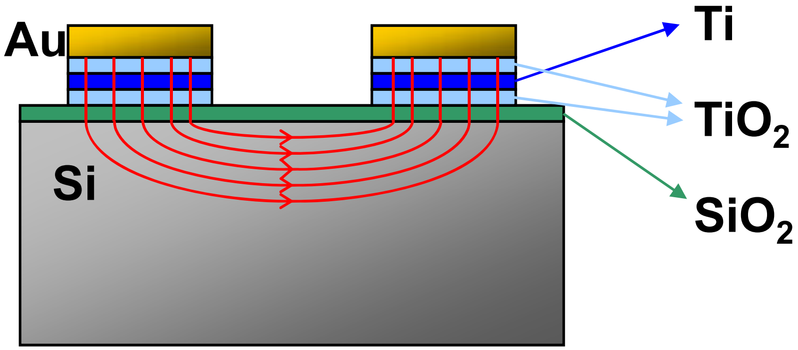


Example 2: SRRs and oxide layers

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

•Strong coupling will occur between phonon modes and surface-plasmon modes on the metamaterial elements.





Metallic split-ring resonator (SRR) elements on thin SiO_2 layer

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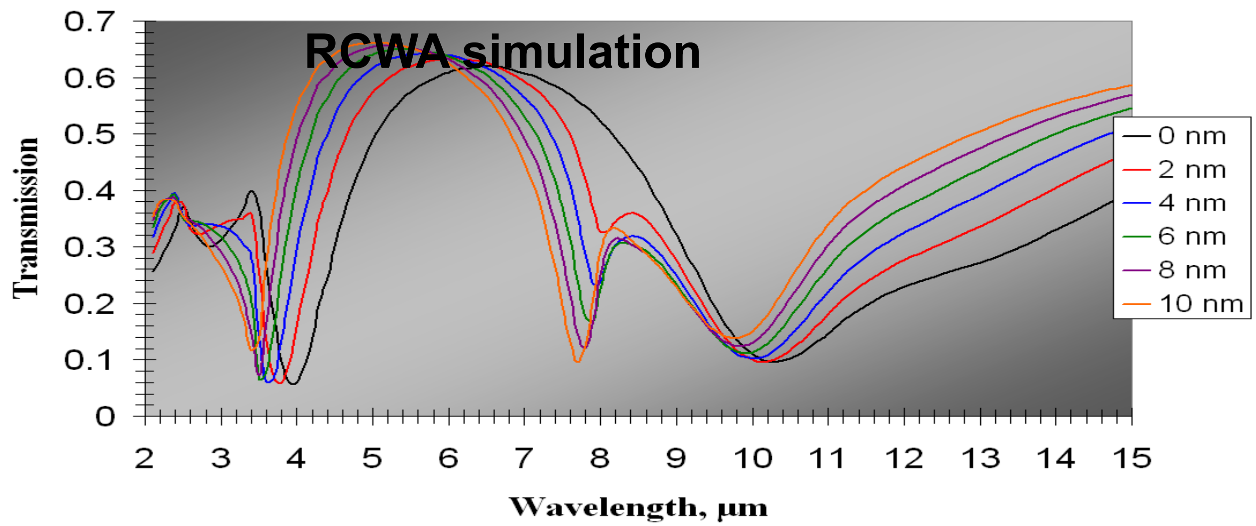
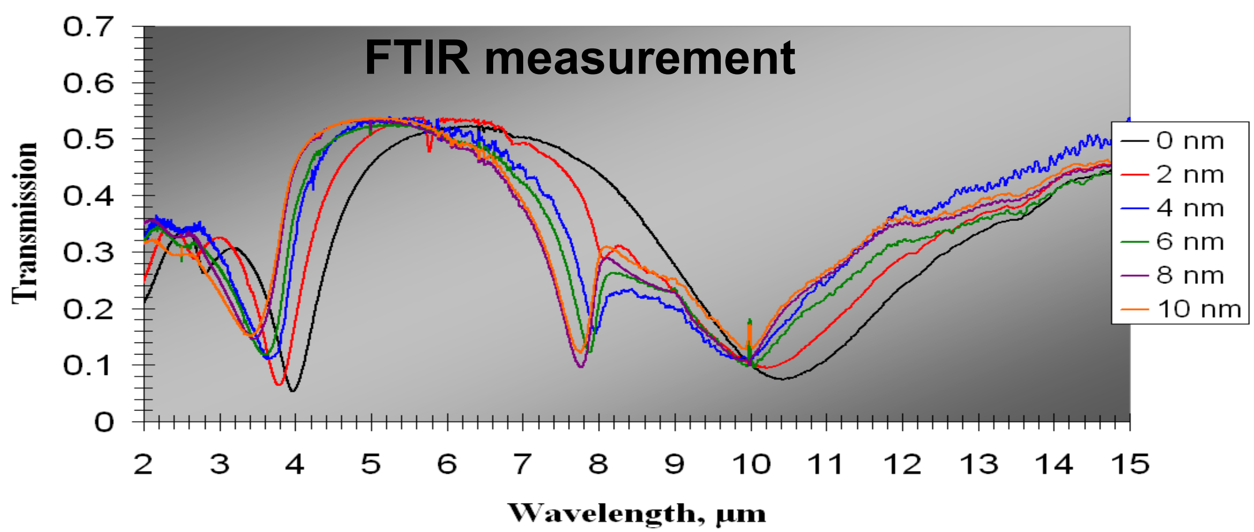
Effect of Thin Film Thickness

Both resonances shift to shorter wavelength with increasing oxide thickness.

Si-O absorption band couples to SRR resonance and additional absorption feature is observed near 8 µm.

For a 10 nm or less SiO_2 film the Si-O loss band is not normally observed by FTIR.





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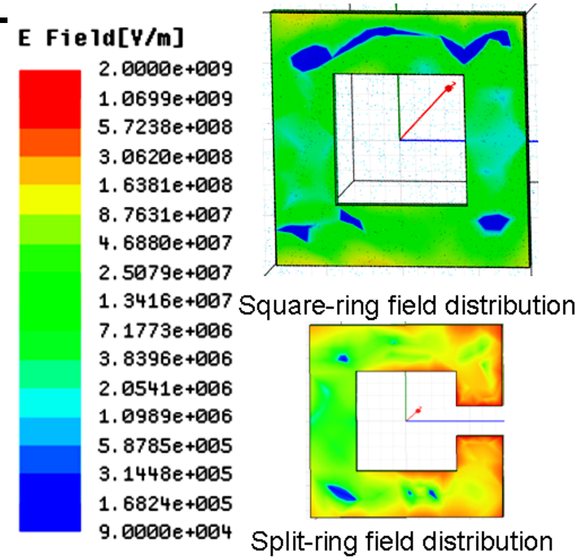
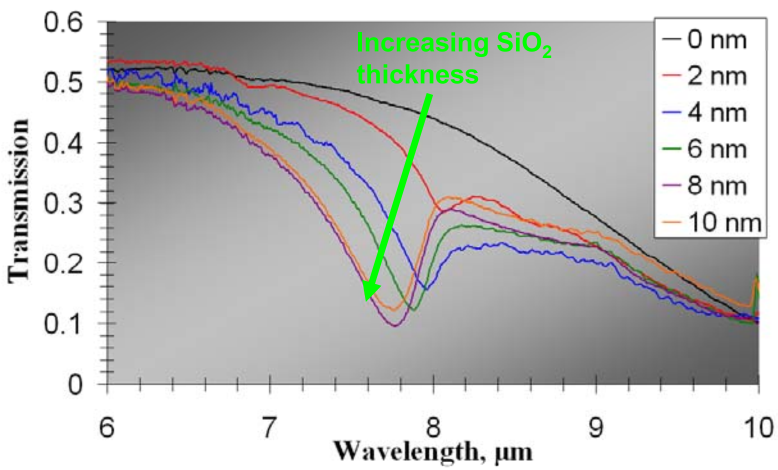
Coupling of Si-O Phonon Resonance with Structure Plasmon Resonance

Si-O bond resonance couples with the resonance of the structure.

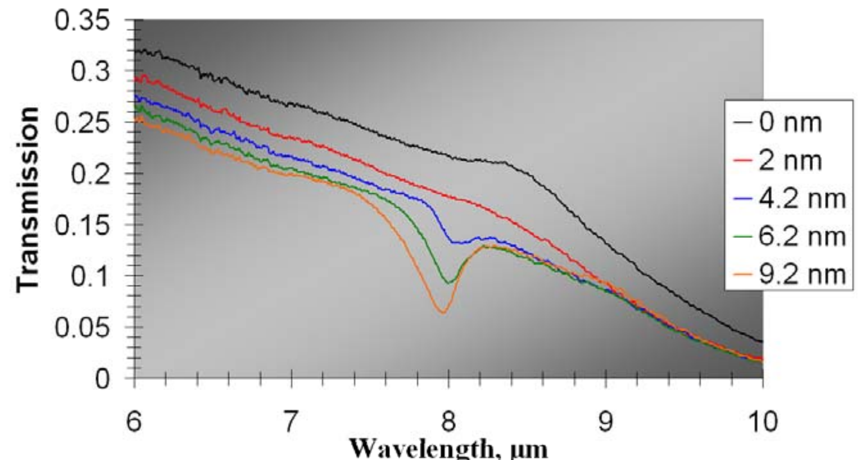
Coupling is seen more strongly in the SRR case.

SRR has a stronger field strength at the oxide layer.





SRR



Square loop

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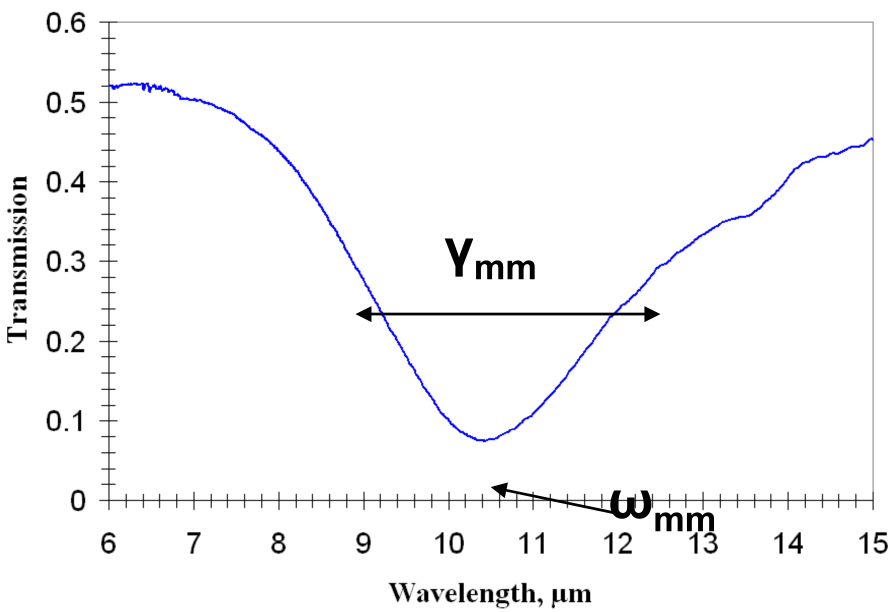
Strong coupling and polariton mode theory 1

All metamaterial elements may be described by a resonant frequency, ω_{mm}, and a damping frequency, γ_{mm}, that is defined as the full width half max of the spectral peak centered at ω_{mm}.



We can analytically determine ω_{mm} for SRR metamaterials using

$$\omega_{mm} = \sqrt{\frac{1}{LC}} = \sqrt{\frac{1}{L\left(C_g + C_f\right)}}$$

C_g = gap capacitance

C_f = fringing field capacitance

Shelton et. al. *Optics Express* 18: 1076-1084 (2010)

IB, *ibrener@sandia.gov*

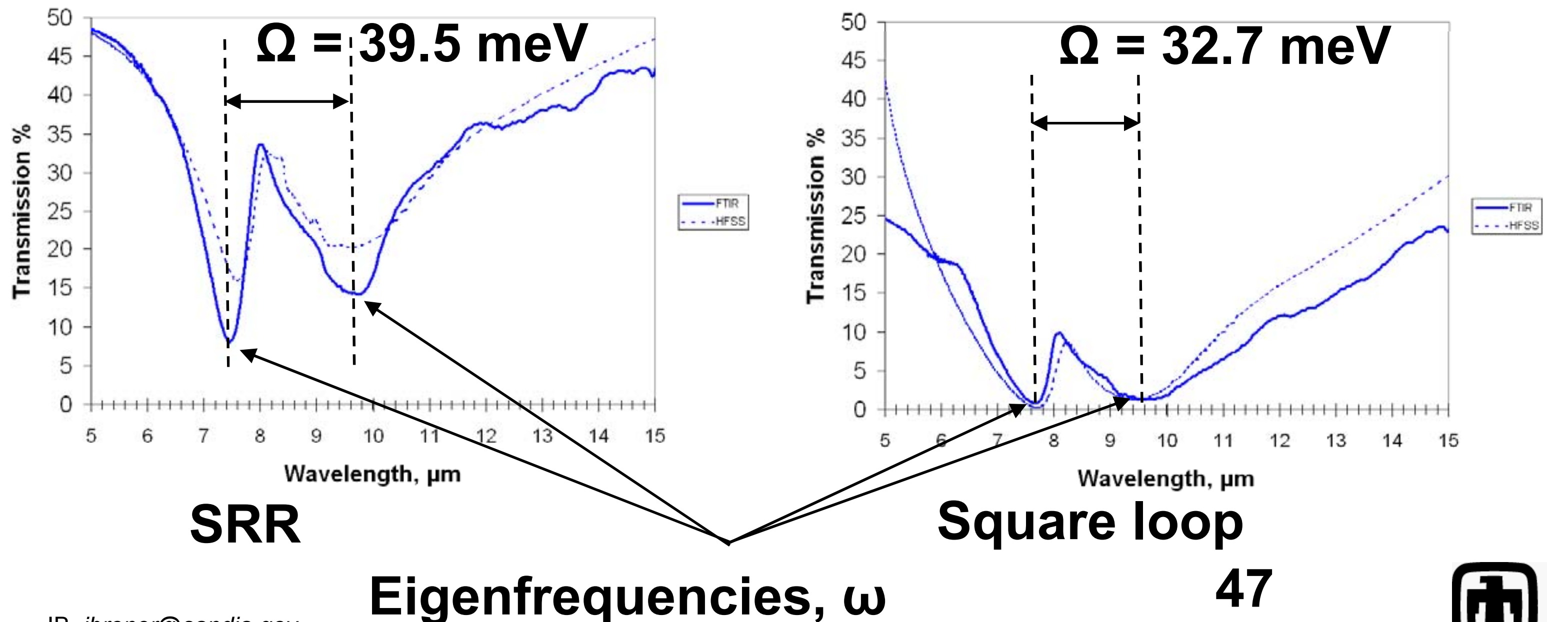
Polariton Modes

$$\frac{\partial^2 x_{mm}}{\partial t} + 2\gamma_{mm}\frac{\partial x_{mm}}{\partial t} + \omega_{mm}{}^2 x_{mm} = -Vx_n \qquad \frac{\partial^2 x_n}{\partial t} + 2\gamma_n\frac{\partial x_n}{\partial t} + \omega_{0n}{}^2 x_n = -Vx_{mm}$$

When $\omega_{mm} = \omega_{0n}$ the resonance splits into two modes.

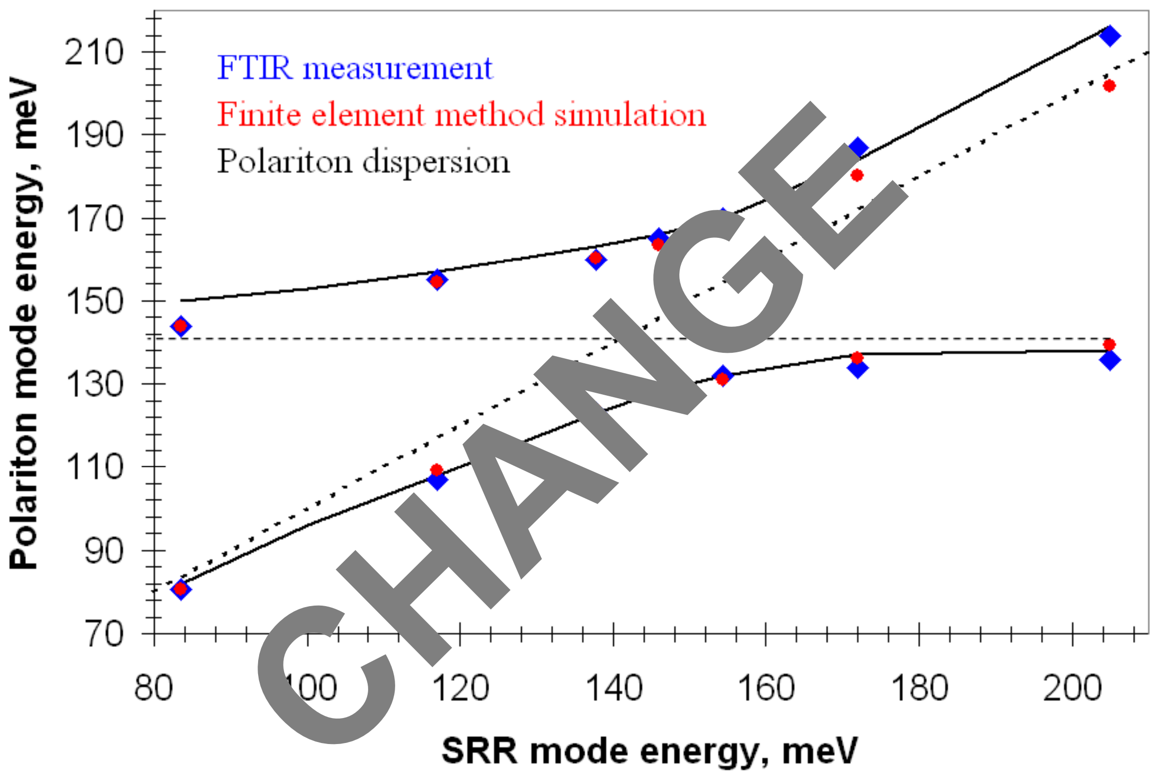
This is shown below in an experiment with an SRR and a square loop.

The energy gap, Ω, between the modes is larger for the SRR.



Polariton Dispersion Relationship

Plotting the eigenfrequencies of the polariton modes versus the resonant frequency of the uncoupled SRR we achieve agreement between the analytical model, FTIR measurements, and finite element method simulations.



SLIDE about plasmon-dielectric coupling?

Summary

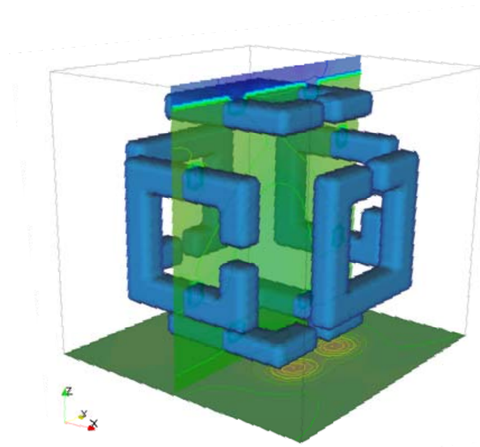
Acknowledgments

Design:
- Lori Basilio
- Larry Warne
- Dave Peters
- William Langston
- William Johnson

Active IR MMs:
- Xiaoyu Miao
- Brandon Passmore
- Eric Shaner
- Aaron Gin

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

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



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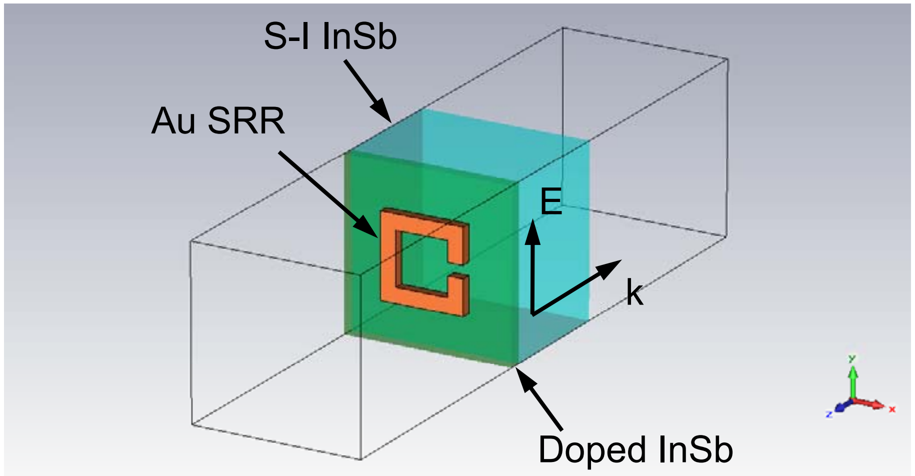
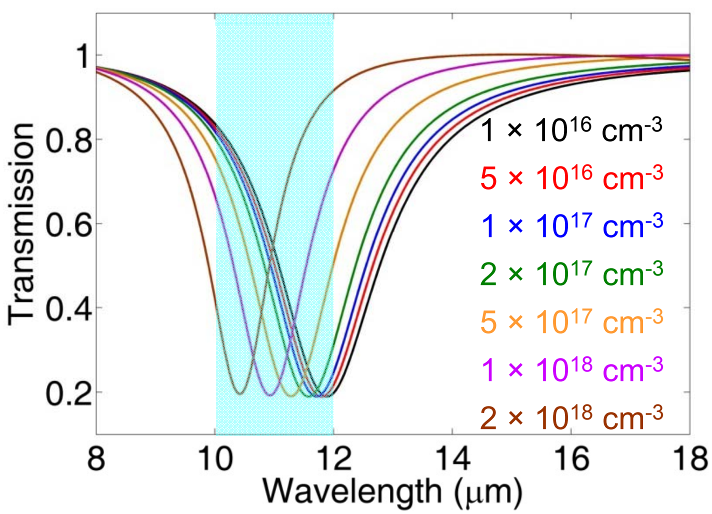
END

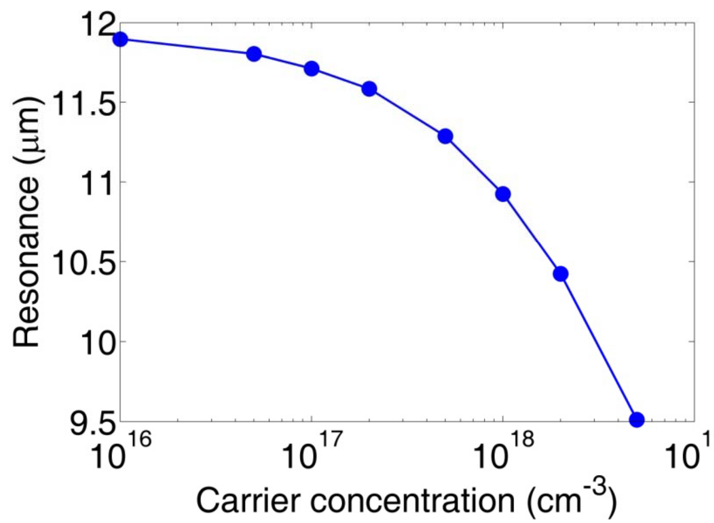
Finite Element Simulation of SRRs on InSb



Design parameters:

- Arm length: 660 nm
- Arm width: 130 nm
- Gap: 100 nm
- Thickness: 80 nm





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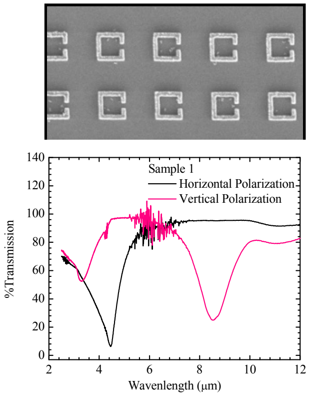
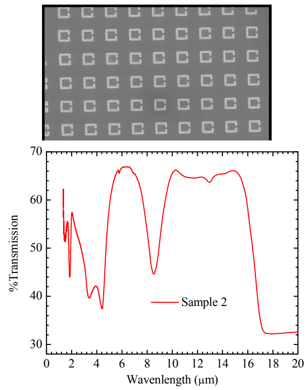
Jumpstart Metamaterial: Planar

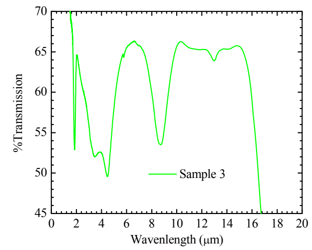
SRR 1



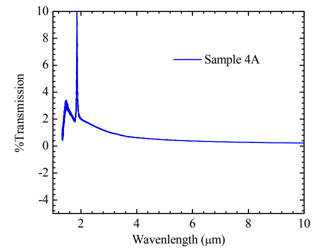
SRR 2



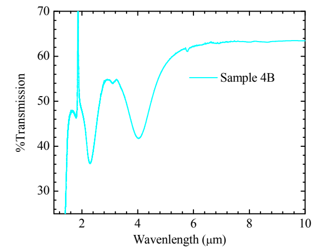
SRR 3



SRR 4A

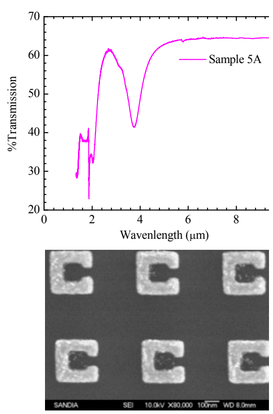


SRR 4B

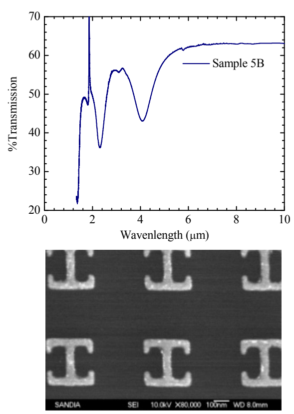


- Simulated with FEM, FITD, FDTD, RCWA, MOM
- Successfully compared with analytic models
- Used for first ever TDS characterization of IR MMs.
- Used with tandem interferometer system
- Fabricated on semiconducting and BaF2 substrates
- Fabricated a "graded" sample for UML: lenses

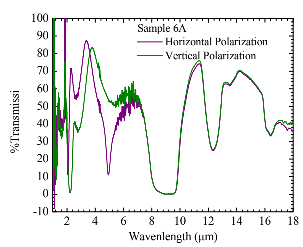
4 conference papers
2 publications (submitted)



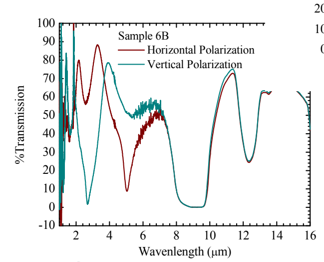
SRR 5A



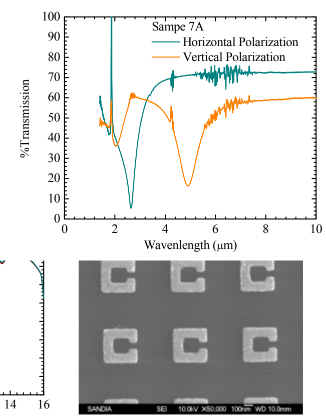
SRR 5B



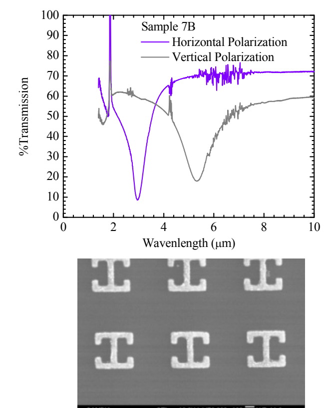
SRR 6A



Sample 6B



Sample 7A



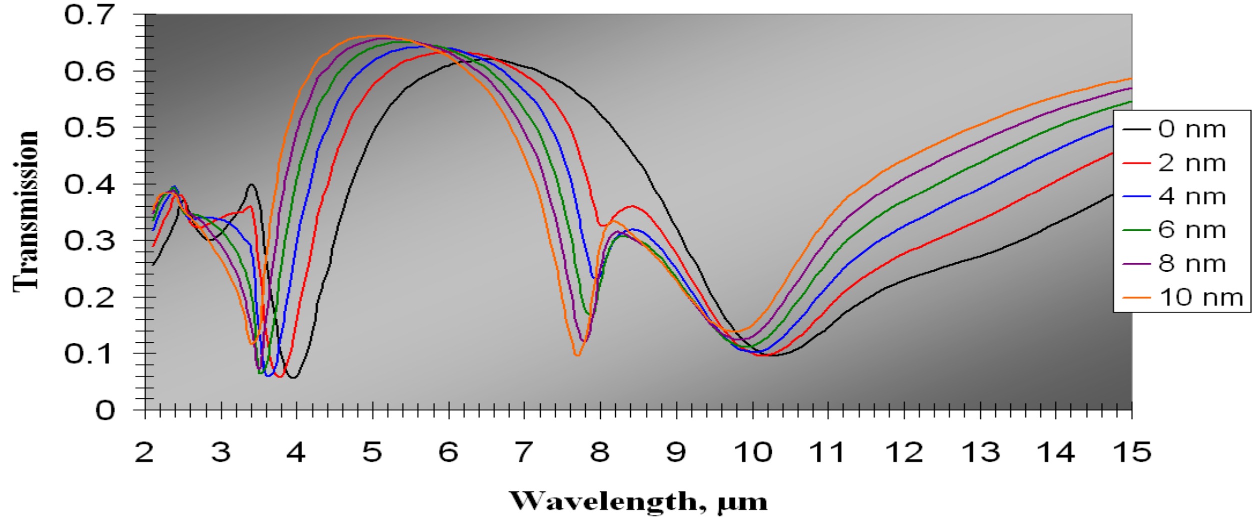
Sample 7B

Comparison of Simulation and Measured Results for the SRRs

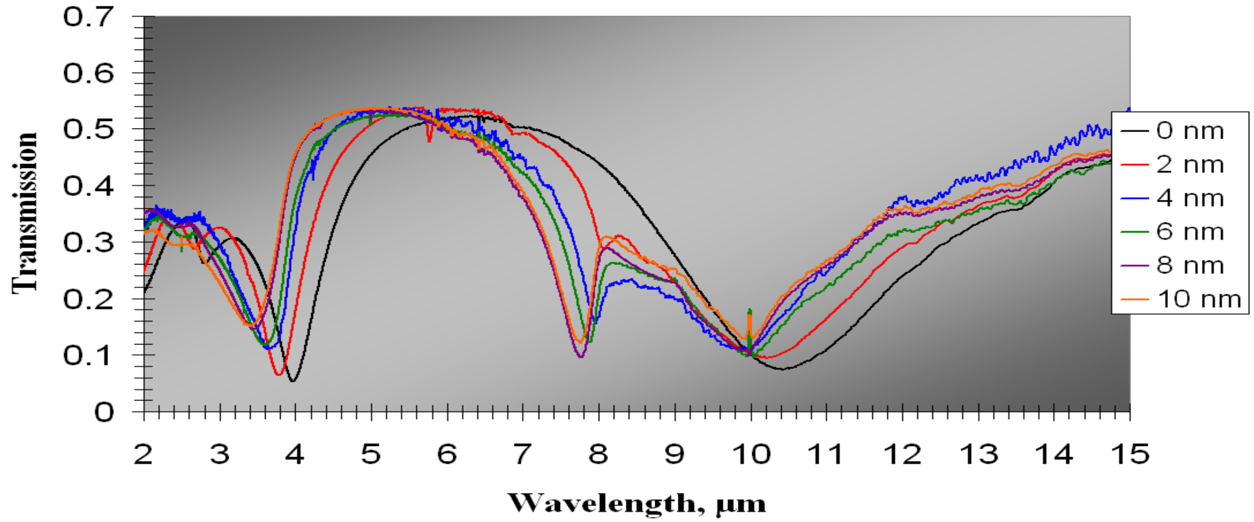
Both resonances shift to shorter wavelength with increasing oxide thickness

Si-O absorption band couples to SRR resonance and additional absorption feature is observed near 8 μm

For a 10 nm or less SiO_2 film the Si-O loss band is not normally observed by FTIR



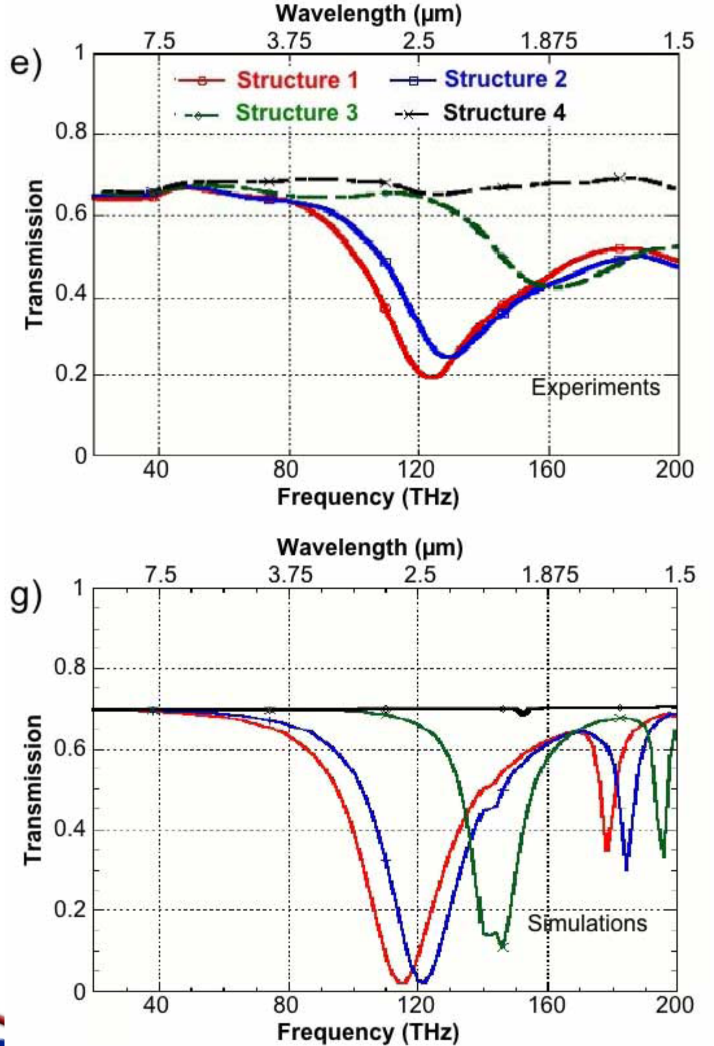
RCWA simulation



FTIR measurement

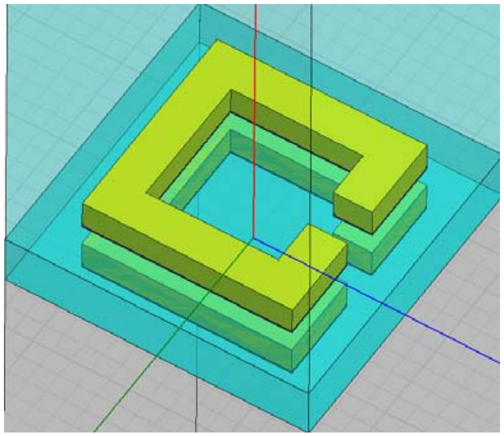
… not only for us, but also in the literature.

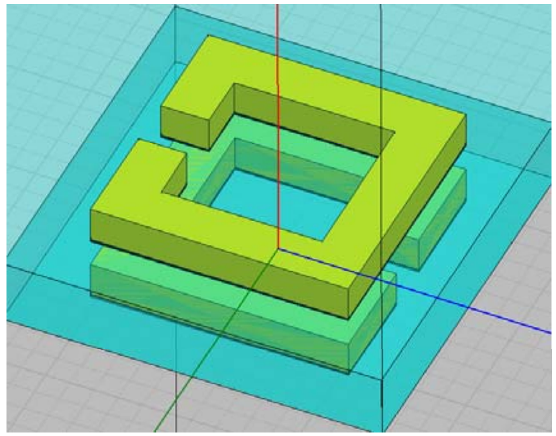
Kante, *et al., Opt. Express*, **16** p 6774, 2008; Ti/Gold SRRs on Si; Similar blue shift of measured resonance.

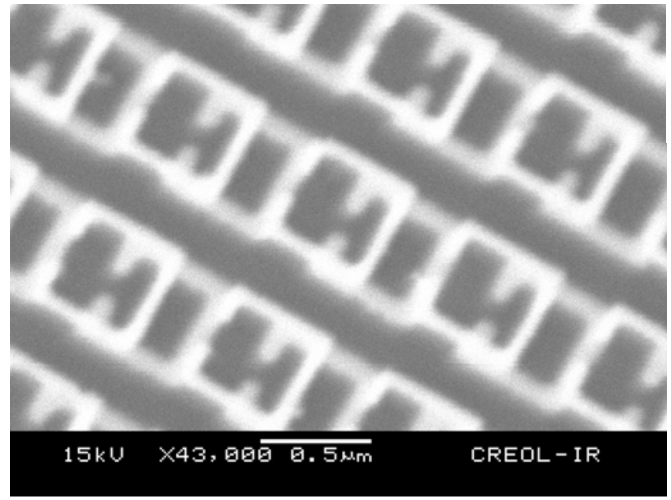


- ➢We systematically ruled out obvious causes (e.g. dimensional inaccuracies)
- ➢Question: Can thin oxides be causing these shifts?

Metamaterials on low dielectric, low loss substrates: SRR dimers on spin-coated PE







SRRd1 as fabricated

SRRd1

Element width = 100nm

Length = 540nm

gap = 100nm

Periodicity = 780nm

PE layer = 140nm

SRRd2

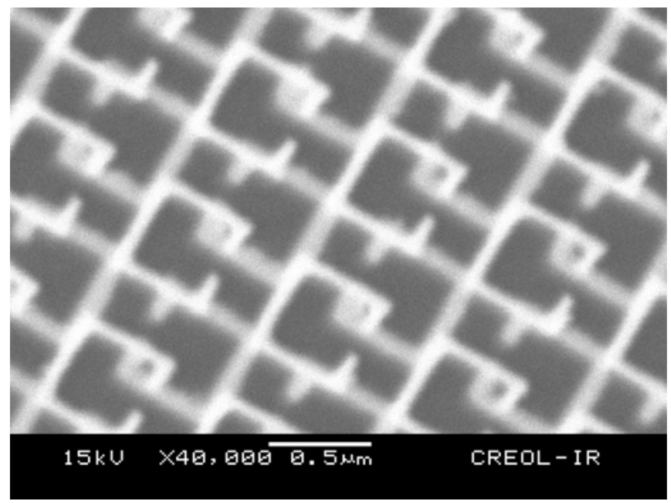
Element width = 100nm

Length = 540nm

gap = 100nm

Periodicity = 780nm

PE layer = 140nm

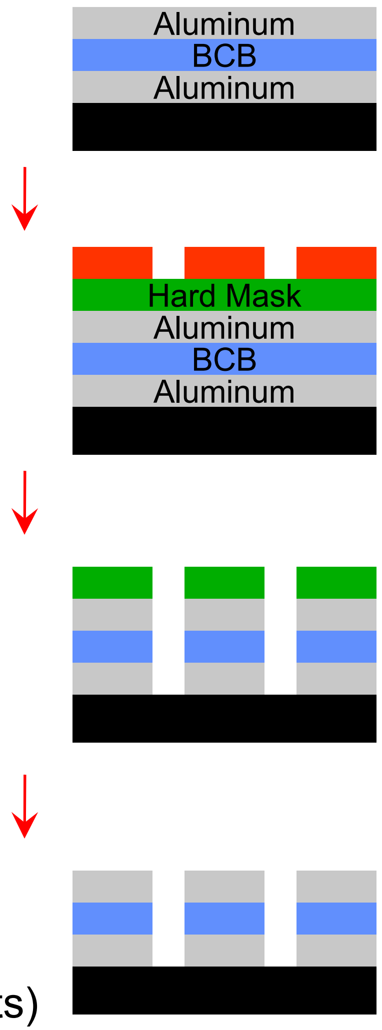


SRRd2 as fabricated

(with CREOL)

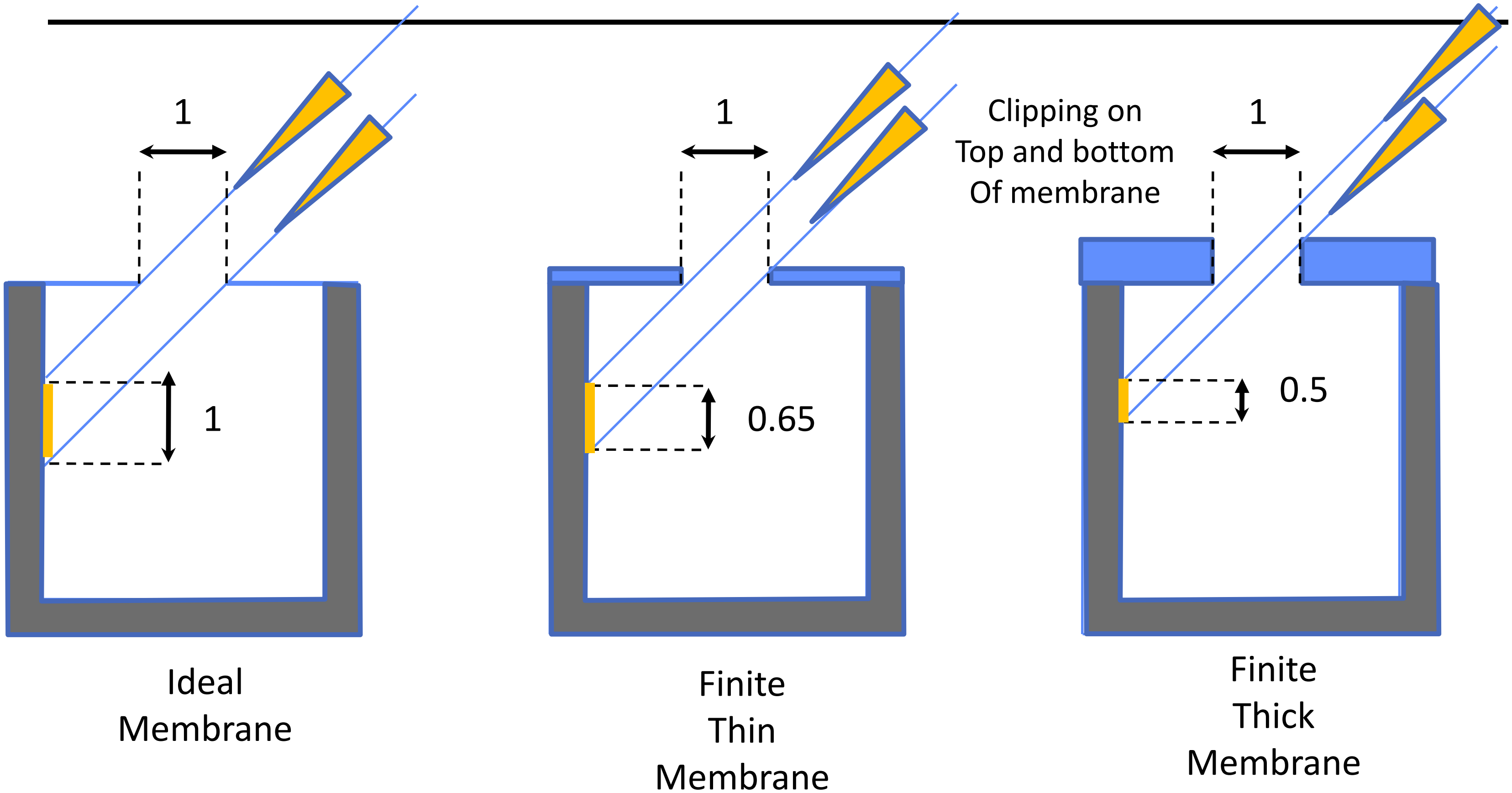
Fishnet Fabrication

- E-beam deposited Al films, spin-on BCB
- Hard mask PECVD deposited SiO_2
- Standard lithographic processing used
- Cl_2 based ICP-RIE Aluminum Etch
- CF_4/O_2 RIE BCB Etch
- Hard mask removal



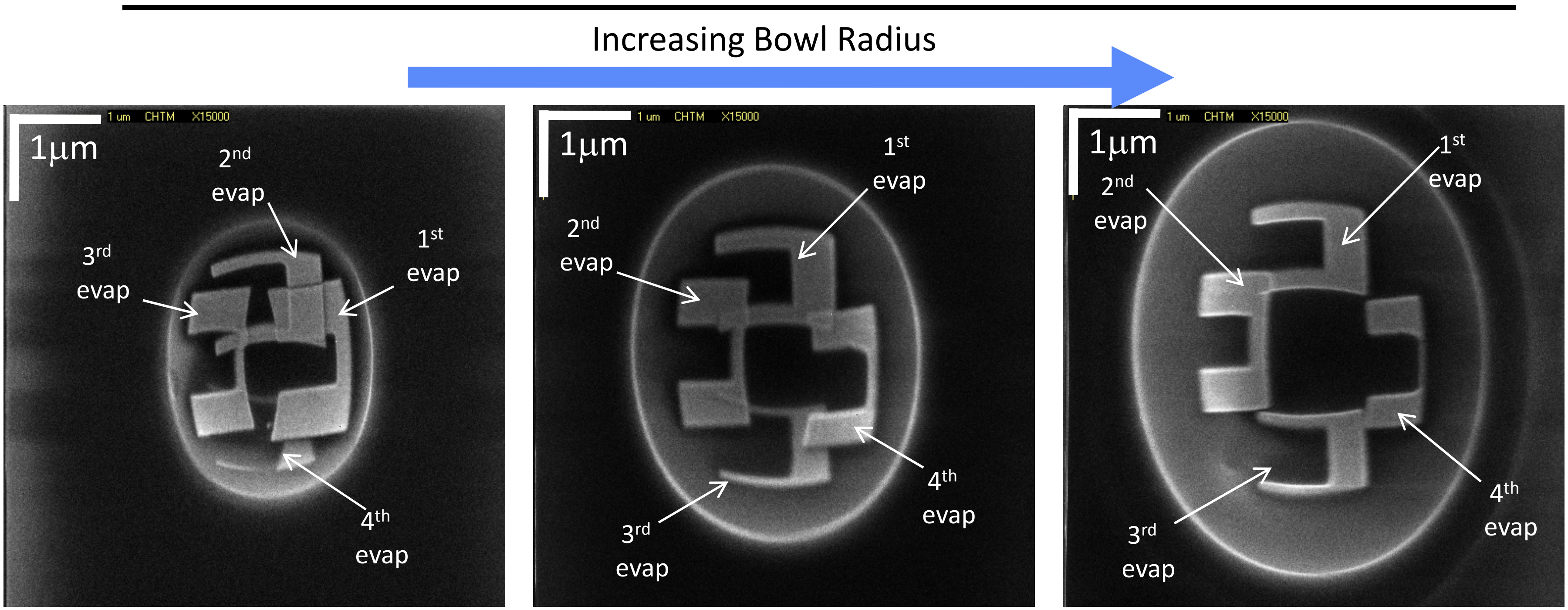
(very different process and materials from near IR/visible fishnets)

Impact of Membrane Thickness

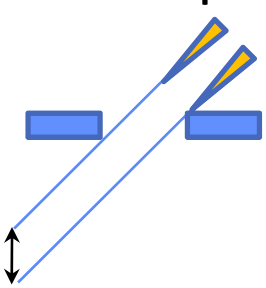


For evaporation at 45°, projected linewidth is decreased by the thickness of the membrane.

Curved SRRs via MPL

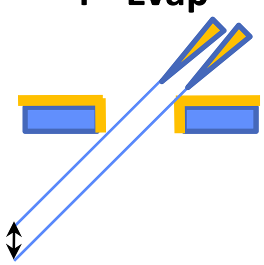


1st Evap



1st Evap linewidth inhomogeneity due to membrane thickness

4th Evap



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

240nm total deposition through ~340 nm clear aperture

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

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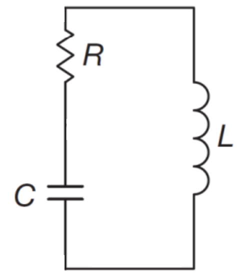
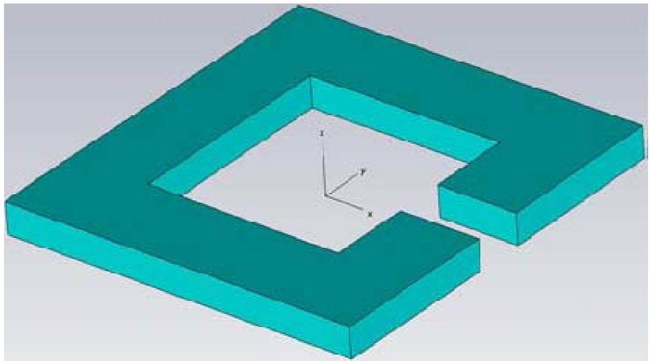
Most common paths to optical metamaterials

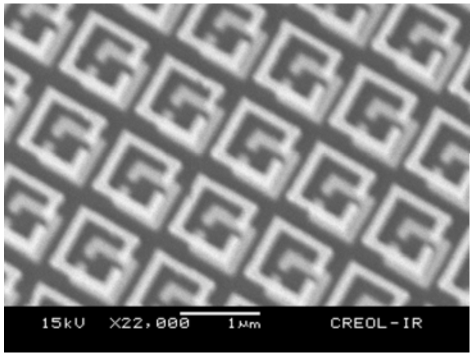
- Some metallic resonator on top of a dielectric



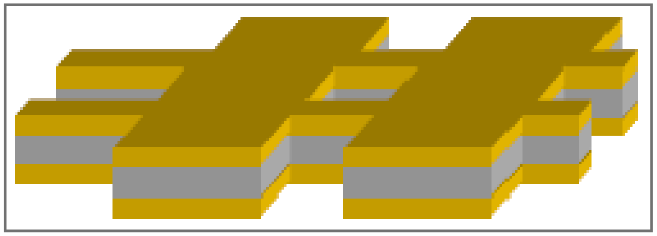


- Or “stacked’ resonators

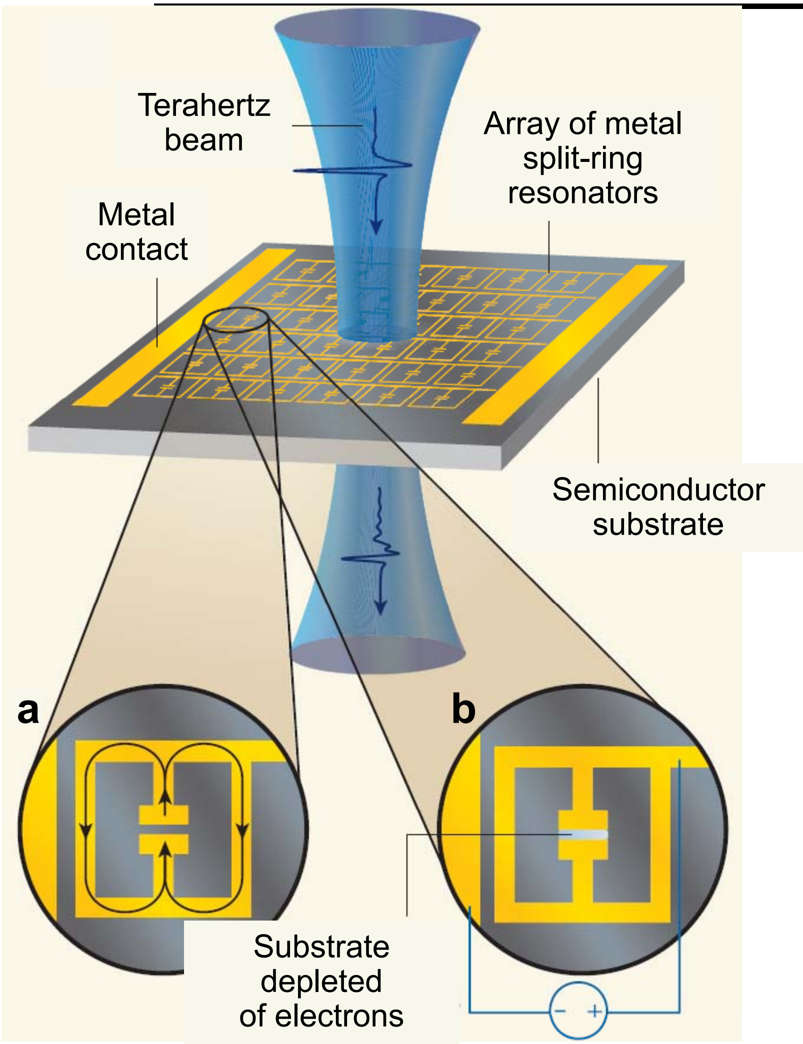
SRRs

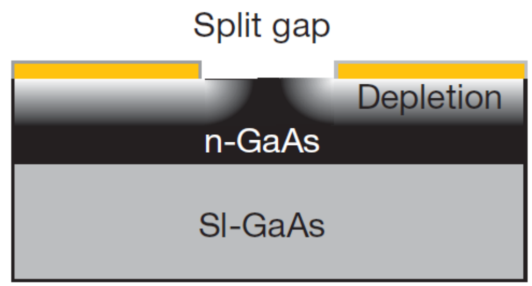


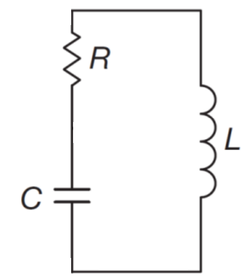
“Fishnets”



Tunable Metamaterials

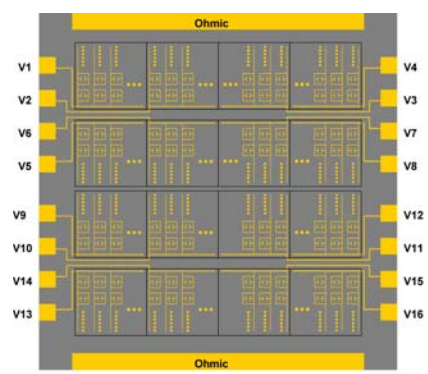


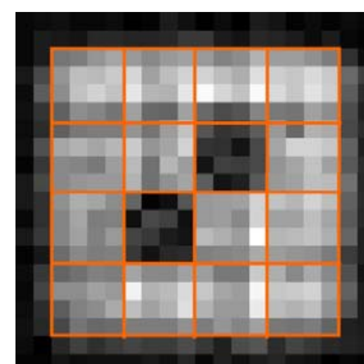




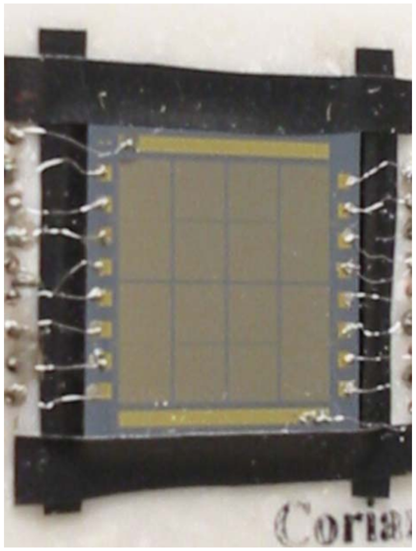
Modulate transmission by depleting carriers in GaAs (Chen et al, Nature, 2006)

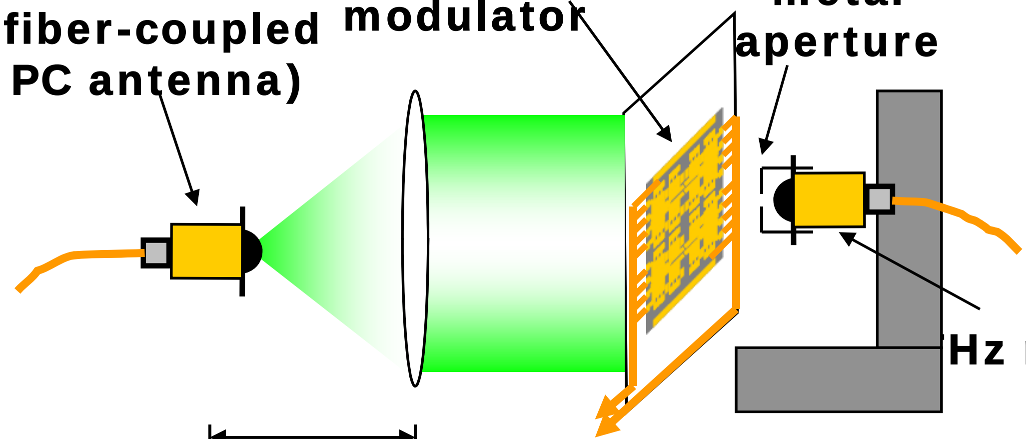
Example: multi-pixel array (ref)





THz-SLM performance characterization





We characterize:

- Modulation Depth
- Crosstalk
- Switching performance
- Amplitude and phase response (THz-TDS)

Metamaterial-Dielectric Resonant Coupling

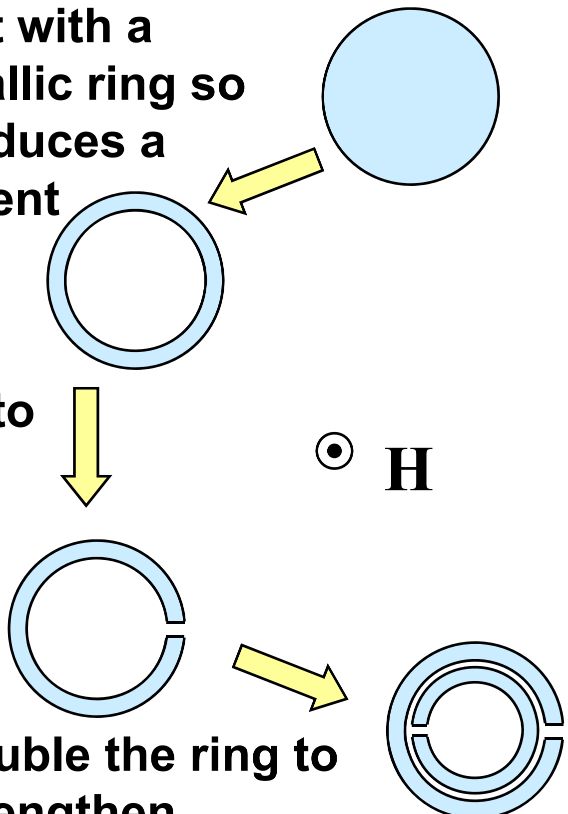
refractive index: $n = \sqrt{\mu\varepsilon}$ **wave impedance:** $\eta = \sqrt{\mu/\varepsilon}$

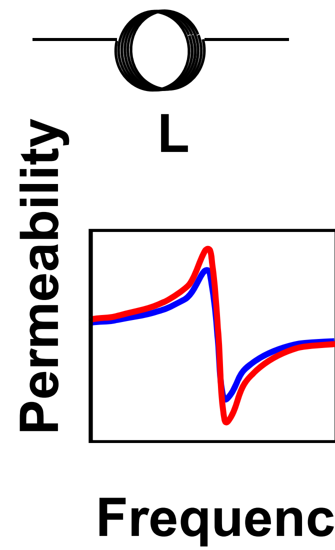
Example: how to achieve $\mu<0$

Start with a metallic ring so $\mathbf{H}$ induces a current

Cut the ring to introduce a capacitance

Double the ring to strengthen resonance



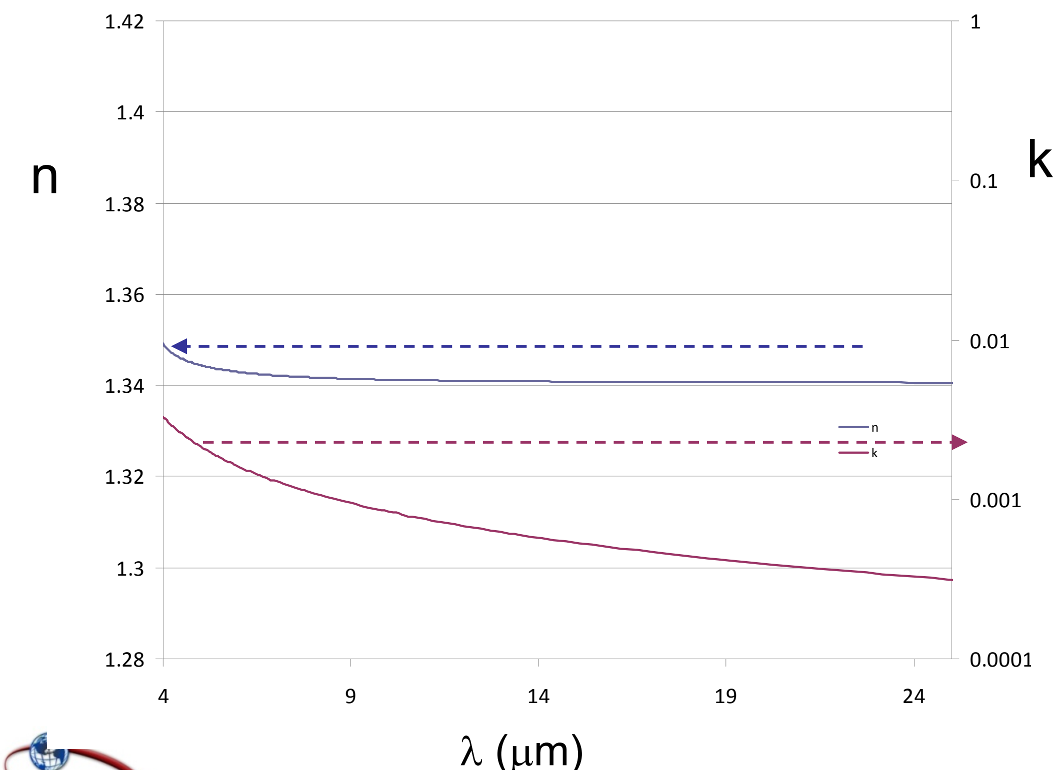


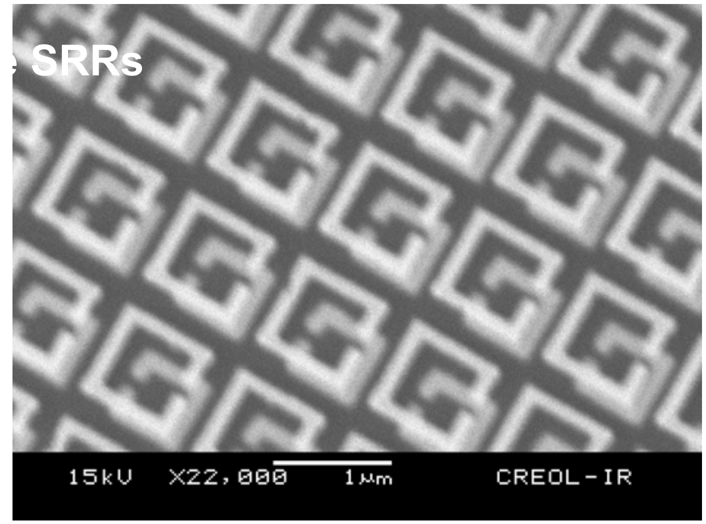
$$\omega_{res} = \frac{1}{\sqrt{LC}}$$

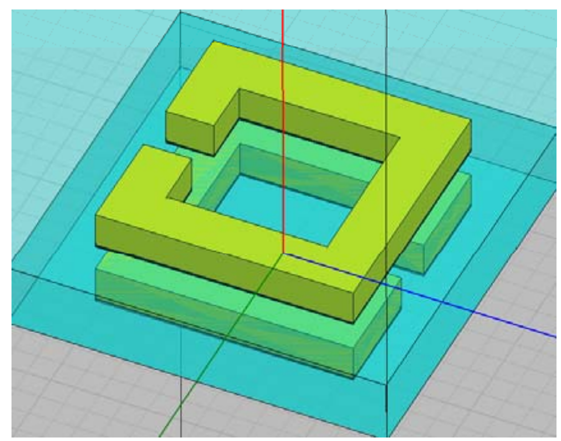
J.B. Pendry et al., IEEE Trans. Microwave Tech. 47, 2075 (1999).

Solution to the dielectric matrix problem

- **We developed spinnable polyethylene as a low loss dielectric matrix**
- **Example: a 2 layer metamaterial (SRRs) with a PE spacer.**







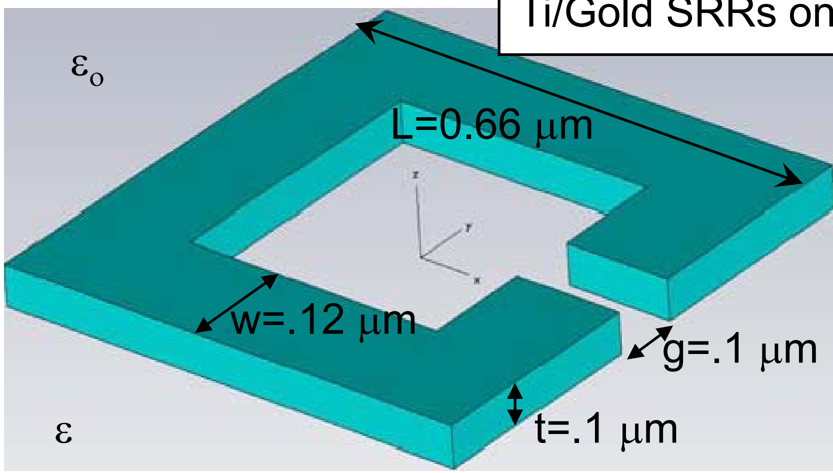
Element width = 100nm, Length = 540nm, gap = 100nm, Periodicity = 780nm, PE layer = 140nm

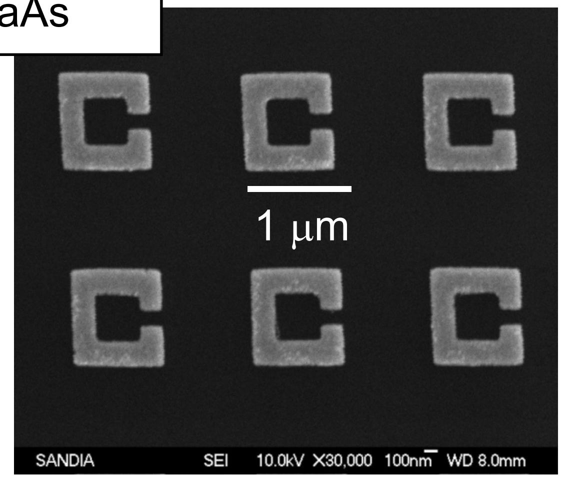
- **Metamaterials offer a scalable design environment for modifying the permittivity and permeability in ways not observed in nature. This allows the design of artificial materials with negative permeability and/or permittivity, and for example, negative refraction. In this talk I will present our progress towards 3D metamaterials for the infrared using state of the art nanofabrication. I will also show recent work on active metamaterials in the mid to far infrared. Finally, our group has recently observed the hybridization between metamaterial resonances and material dielectric resonances in the thermal IR, which will be presented in two different systems.**

IR transparent semiconductor substrates: the effect of oxides

In collaboration with D. Shelton & Glenn Boreman, UCF/CREOL

Ti/Gold SRRs on GaAs

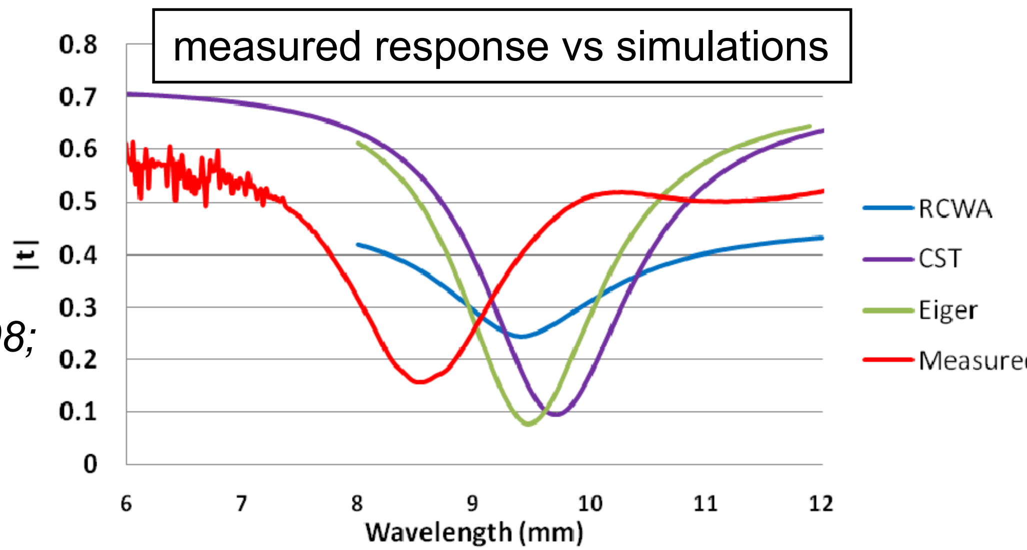




Problem: measured response did not match simulation.

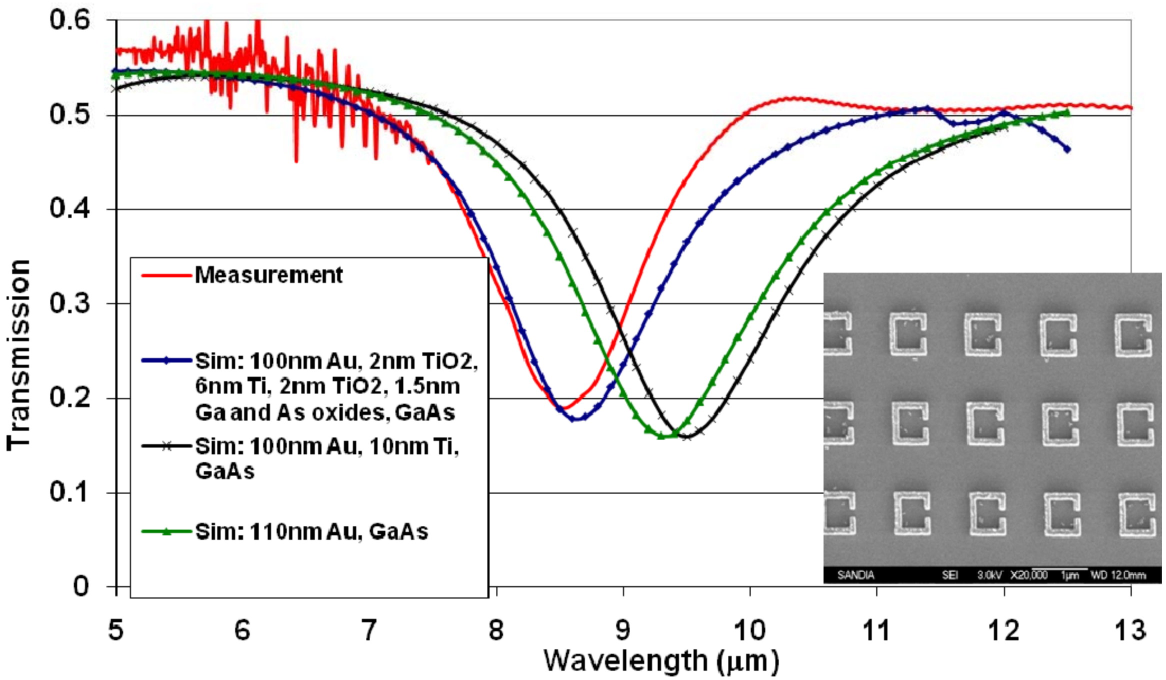
- experimental resonance at shorter wavelength
- simulated with 4 different codes

(Also reported before: Kante, et al., Opt. Express, ***16*** *p 6774, 2008; Ti/Gold SRRs on Si; Similar blue shift of measured resonance.*



Can thin oxides be causing these shifts?: modeling

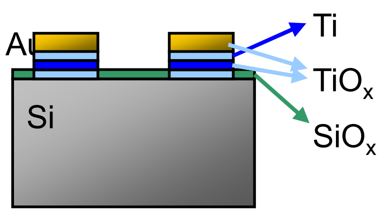
- Uses actual measured refractive index values, measured using IR ellipsometry.
- The Ti seed layer modeled as 1.5nm TiO_2, 2nm of Ti, and 1.5nm TiO_2.
- Ti/TiO_2 seed layer produces accurate prediction of measured results with accurate element dimensions.

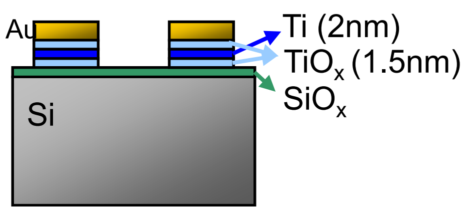


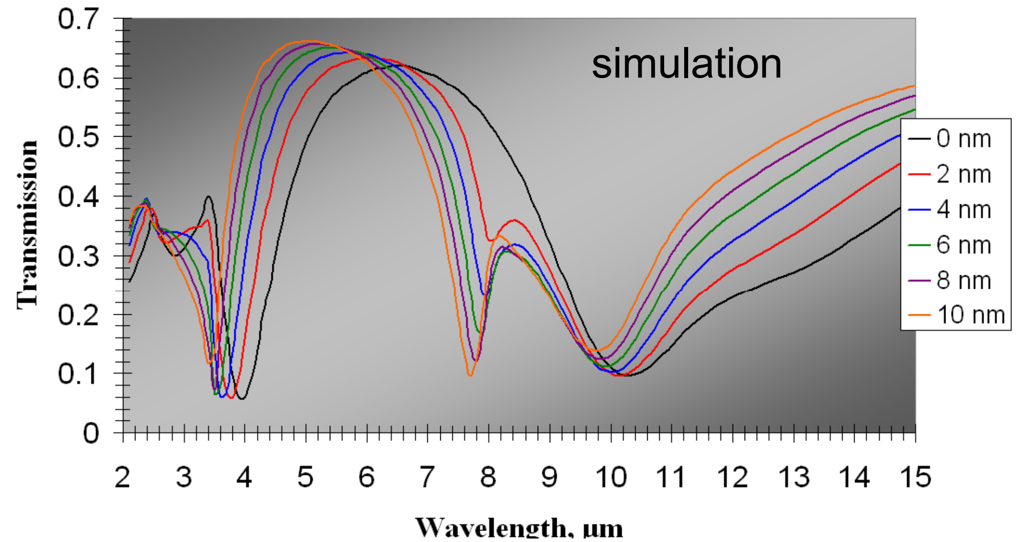
➢ Also constructed detailed circuit model that predicts blue-shift with increasing oxide thickness.

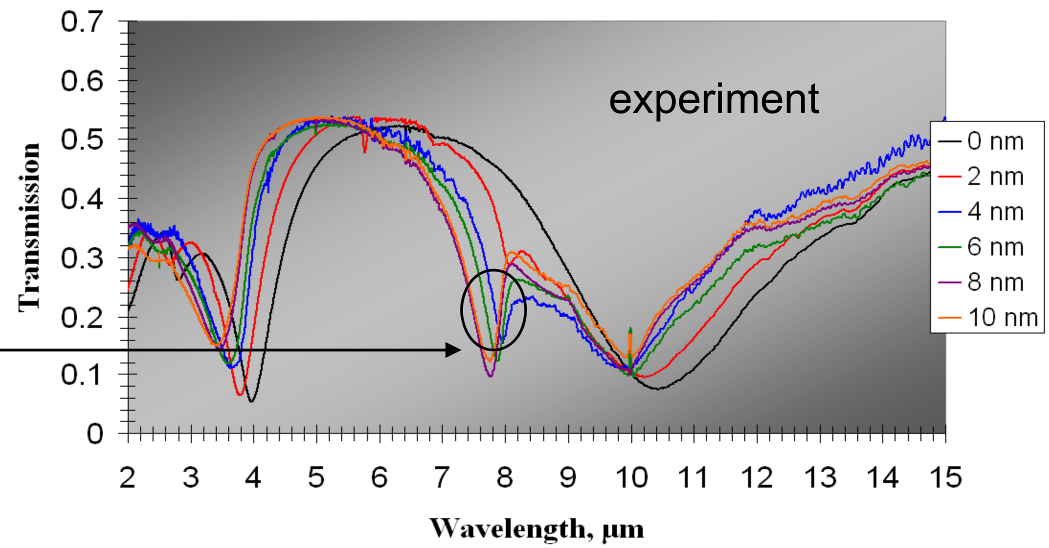
Experimental Verification: SRRs on Si with variable thickness oxides

Increasing blue shift observed with increasing oxide thickness









Low level SiO_2 absorption is resonantly enhanced (and hybridized)

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Strong Coupling and Polariton Mode Theory 3

If the coupling strength coefficient, *V*, is known then the eigenfrequencies may be determined using

$$V^2 = \left(\omega_{mm}{}^2 - \omega^2 - i\gamma_{mm}\omega\right)\left(\omega_{0i}{}^2 - \omega^2 - i\gamma_i\omega\right)$$

Coupling strength may be determined experimentally from the energy gap between polariton modes, Ω, using

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

We can experimentally test this theory by spectrally scanning ω_{mm} across ω_{0n}.

This can be done in multiple experiments by changing the unit-cell dimensions of an SRR, or with a tunable metamaterial.

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Strong Coupling and Polariton Mode Theory 2

Similarly a phonon mode in the ceramic thin film may be modeled as having resonant frequency ω_{on} and damping frequency γ_{0n}.

When ω_{on} is near ω_{mm}, and the ceramic thin film is within the near fields of the elements, strong coupling occurs resulting in polariton modes.

The eigenfrequencies of these new resonant modes may be calculated by modeling the system as damped harmonic oscillators.

$$\frac{\partial^2 x_{mm}}{\partial t} + 2\gamma_{mm}\frac{\partial x_{mm}}{\partial t} + \omega_{mm}{}^2 x_{mm} = -Vx_n$$

$$\frac{\partial^2 x_n}{\partial t} + 2\gamma_n\frac{\partial x_n}{\partial t} + \omega_{0n}{}^2 x_n = -Vx_{mm}$$

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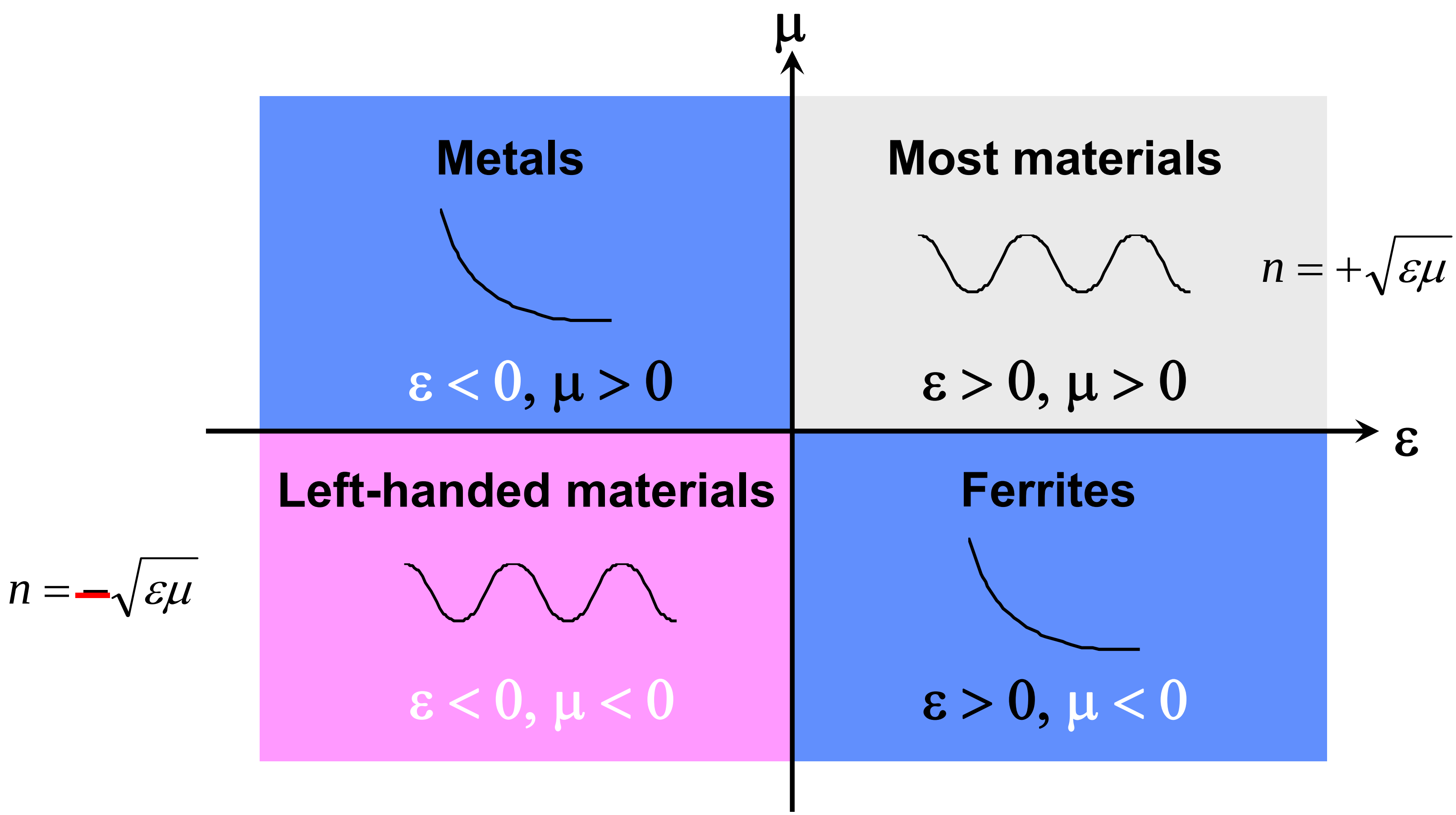
Electromagnetic waves propagation is given by solutions to the wave equation

Wave equation: $\nabla^2 E = \varepsilon\mu \frac{\partial^2 E}{\partial^2 t}$ **Solution:** $E = E_0 e^{-i\omega t}$



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