SAND2014-0847C

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

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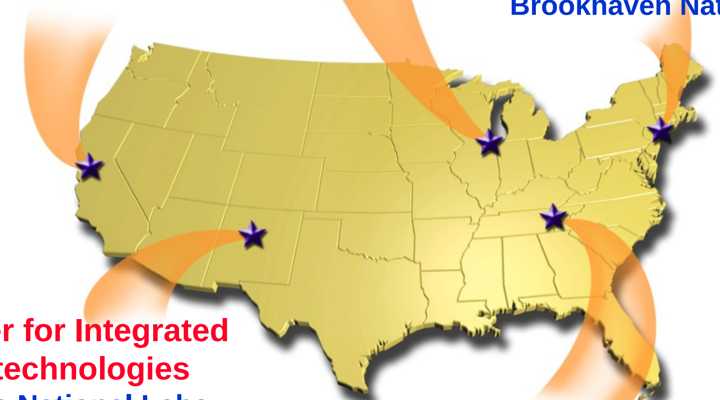
Center for Integrated Nanotechnologies: CINT



- one of five U.S. Dept. of Energy Nanoscience Centers
- Between 150 and 300 active user projects

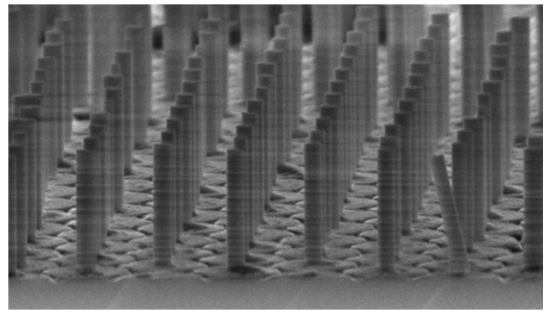
User facility: free to use

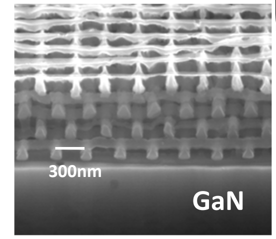
http://cint.sandia.gov

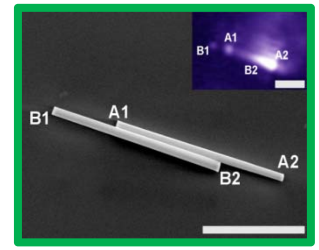
Other Activities in Nanophotonics

Solid State Lighting "Energy Frontier Research Center"

- Enhanced Spontaneous Emission
- Nanowire Lasers (III-N) (new: electrical injection)

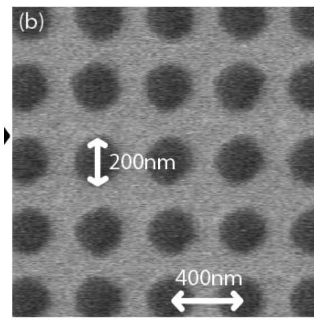


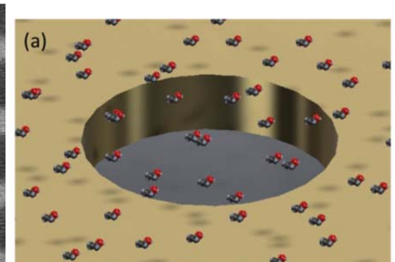


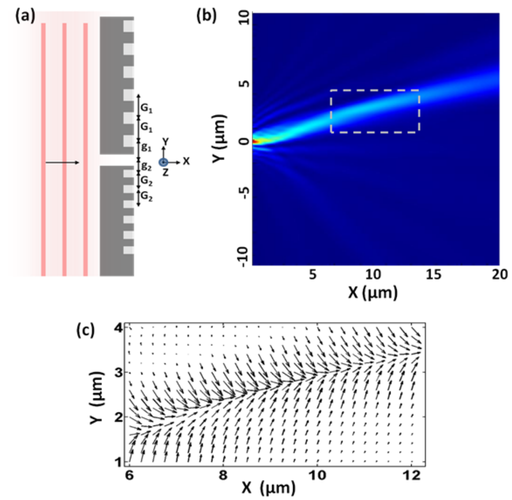


Plasmonics

- Sensors (gas)
- Optical trapping

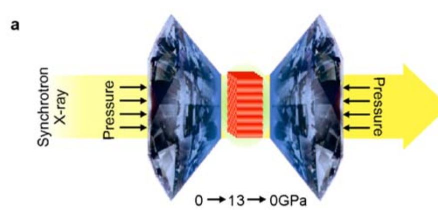


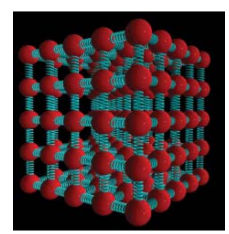


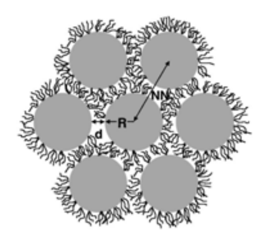


Nanophotonics, etc

- Energy transfer in QDs
- QD "solids" (new)

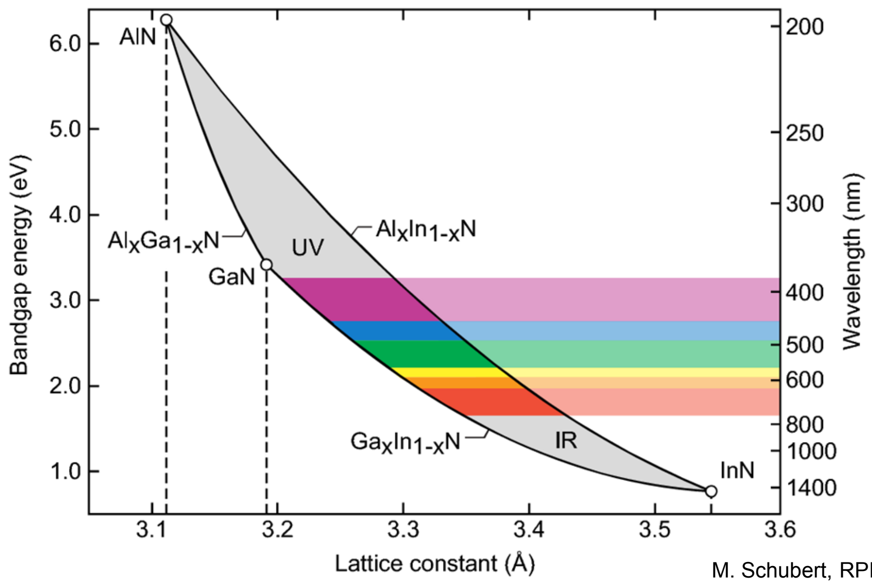






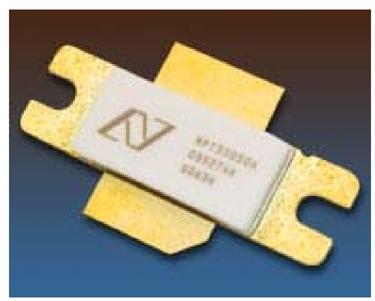
III-Nitride (AlGaInN) semiconductors – The Most Interesting Materials System?

- **Direct RT bandgaps: ~0.7-6.2 ev**
- Solid alloy system (tuneable bandgaps)
- High breakdown field, mobility, thermal conductivity, melting temperature
- Radiation resistant and chemically inert
- InGaN covers entire visible & bulk of solar spectrum (PV material?)



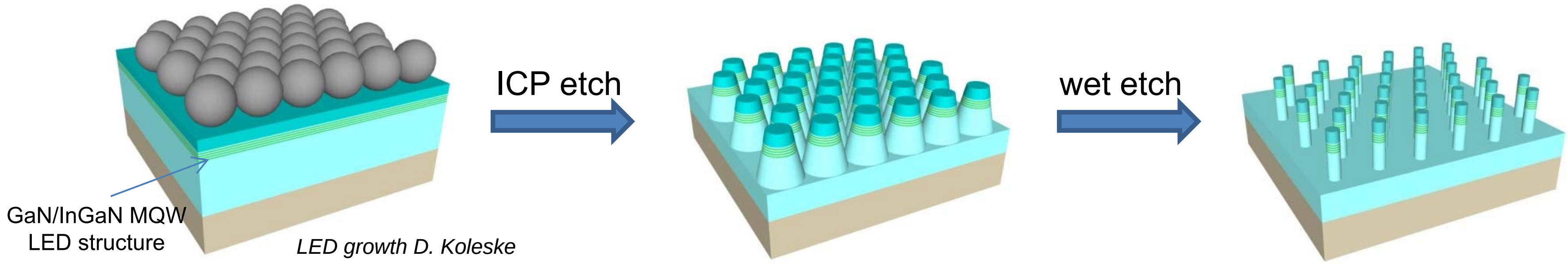
M. Schubert, RPI

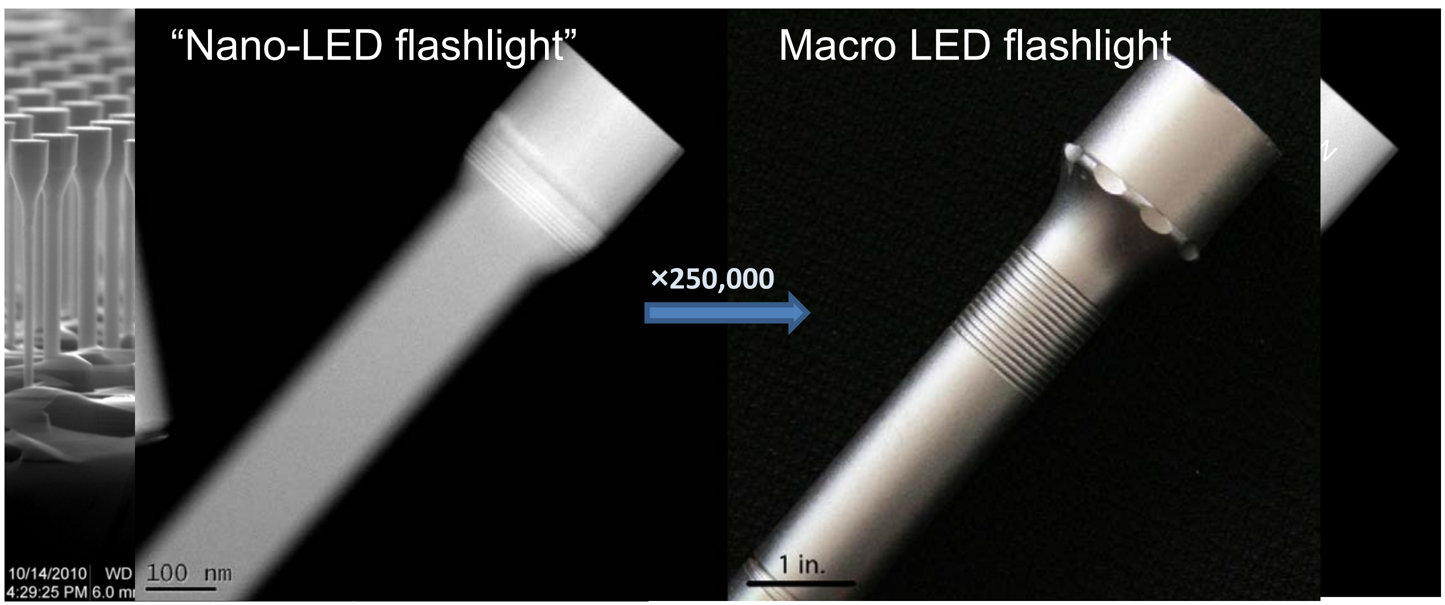
- *Commercially used in LEDs, blue laser diodes, high power electronics, HEMTs*



Nitronex GaN power transistor

Axial GaN/InGaN nanowire LEDs

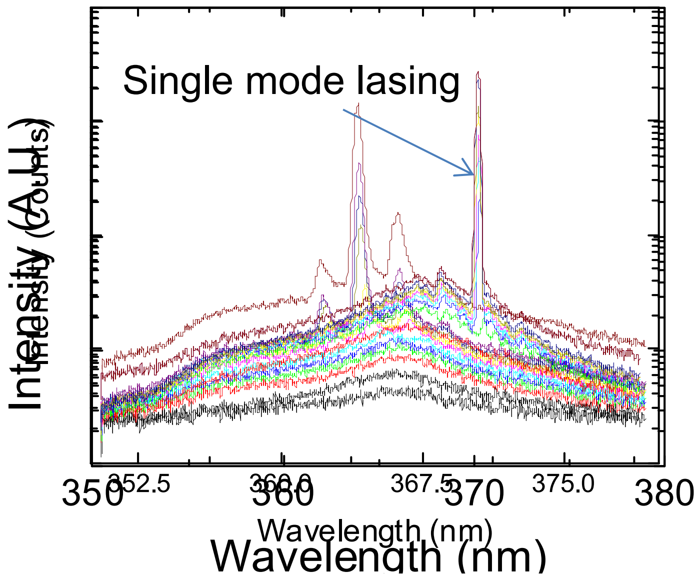


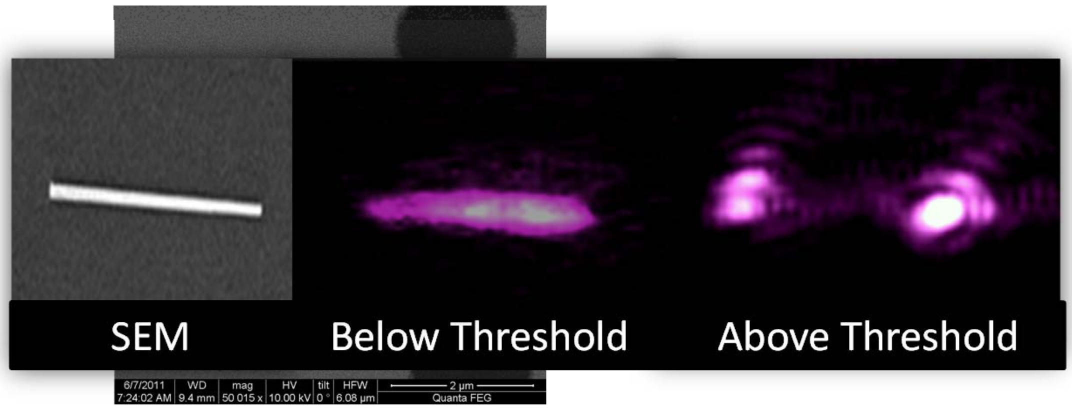


Q. Li et al., *Optics Express* **19**, 25528 (2011)

Method 1: Single-mode GaN nanowire laser via geometry control

- Nanowire lasers generally exhibit *multiple modes*
- *Single mode* behavior desired for highest resolution and beam quality





Nanowire dimensions: ~**130nm** x 4.7µm
Nanowire dimensions: ~**500 nm** x 4.7µm

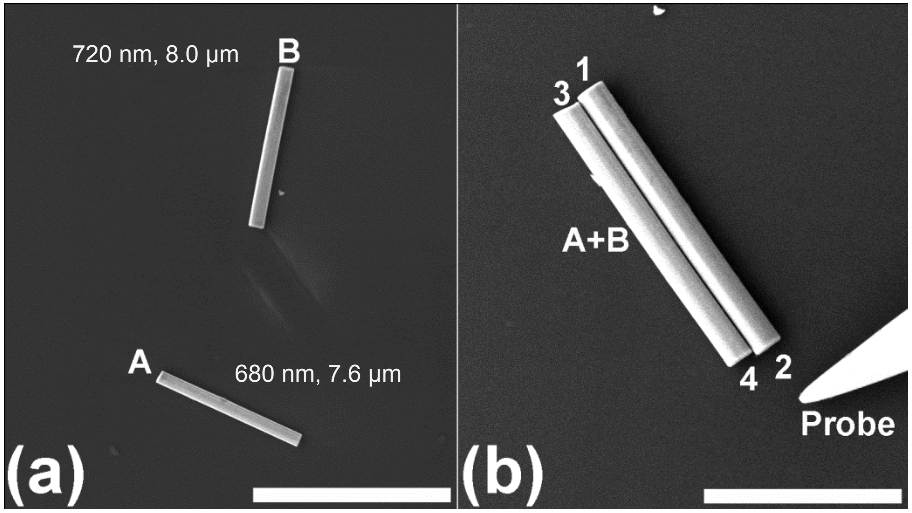
Q. Li et al., *Opt. Exp.* ***20*** *17873 (2012)*

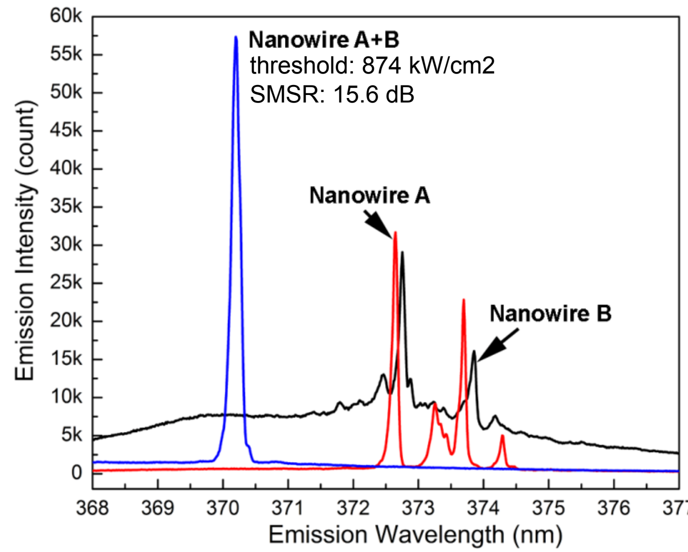
Single-mode: Narrow linewidth (<0.1 nm), ~15dB Side Mode Suppression Ratio, and **Low Threshold** (~250 kW/cm^2)

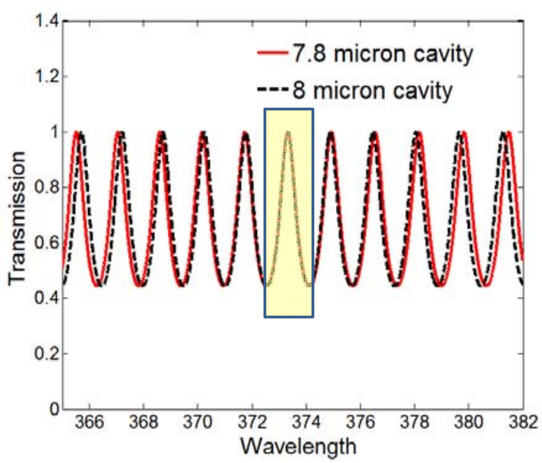
Multi-mode: Threshold ~500 kW/cm^2

Reducing the dimensionality of the wire (< ~130 nm diameter and < ~6 µm length) lowers the number of competing modes, leading to single-mode lasing.

Method 2: Single-mode lasing via coupled nanowire cavities







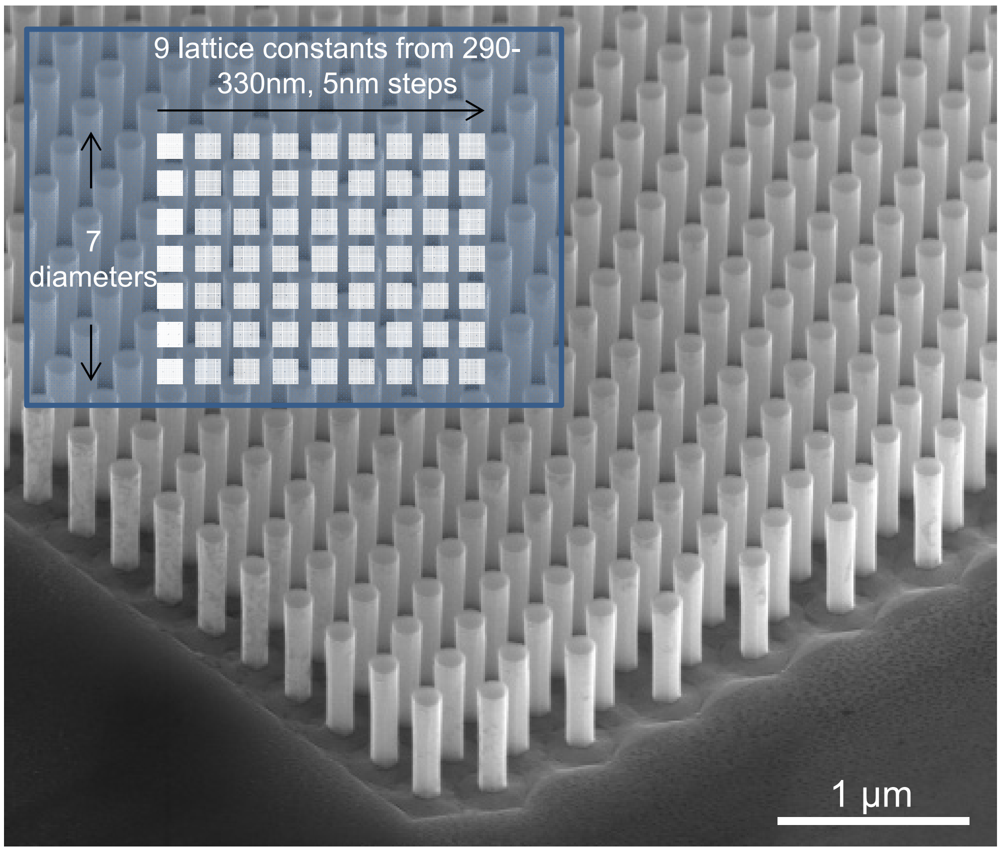
- GaN NWs need to be <~130 nm for single transverse mode behavior; larger single-mode NWs?
- Individual large NWs shows multiple modes.
- Coupled nanowires show single mode!
- Vernier effect – only resonant modes survive

modeling: Huiwen Xu (UNM)

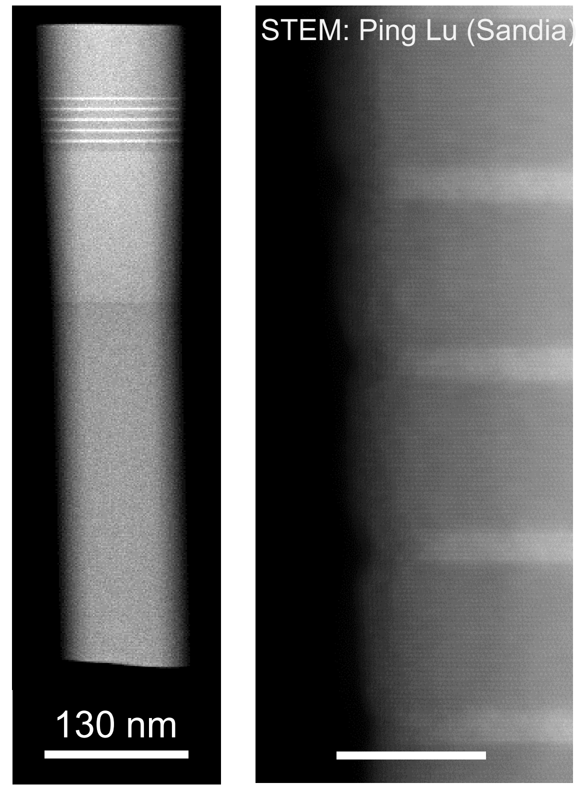
H. Xu et al., *Appl. Phys. Lett.* **101** 113106 (2012)

III-N Nanowire Photonic Crystal (PC) Lasers

Motivation: Achieve single-mode, tunable lasing on same chip. Applications in optical information processing, biology, solid state lighting, displays, etc.



Nanowire PCs fabricated by top-down method using e-beam lithographic mask



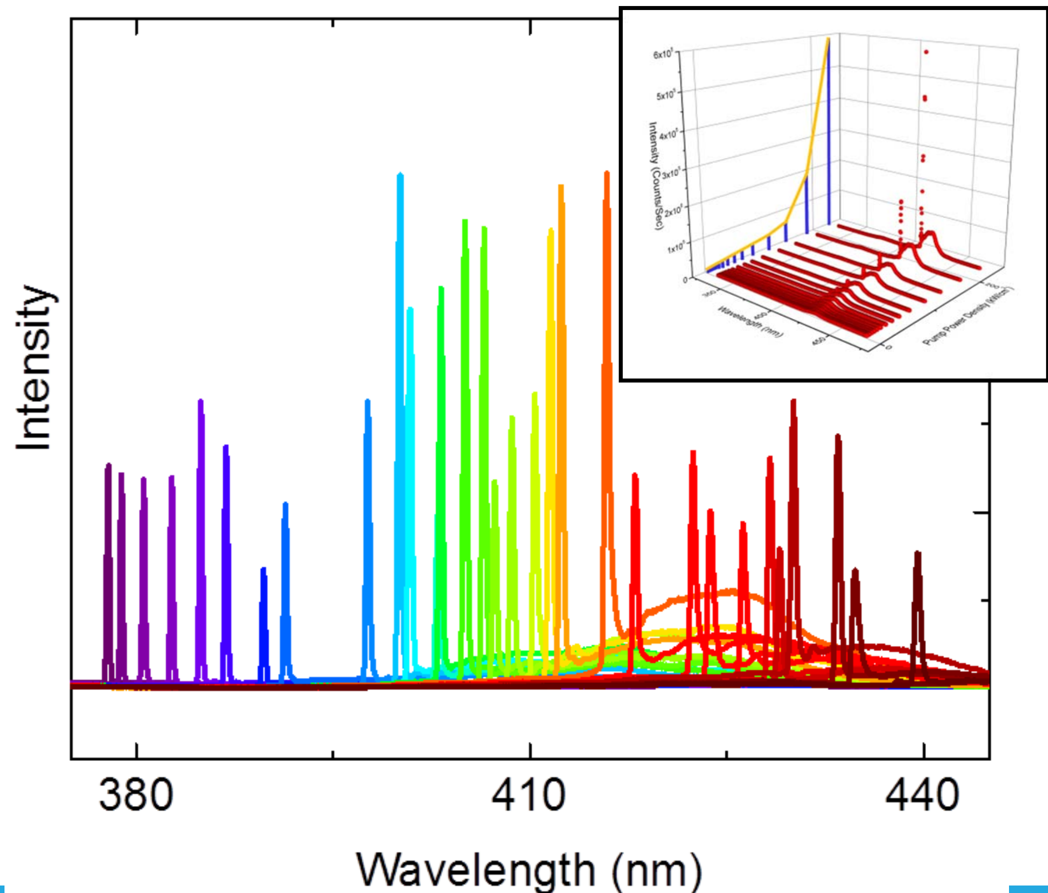
NW STEM images: 5x MQW InGaN emission centered at 420nm, $In_{0.02}GaN$ underlayer

SSLS EFRC

III-N Nanowire Photonic Crystal Lasers

Broad gain width of InGaN MQWs with PC design allows for tunable single mode lasing over large range on same chip

61 color nanowire laser array



- High-yield >95% (2 of the PCLs were accidentally removed during sample handling.)
- Spectral Coverage from 380-440nm.
- Emission wavelength increases with the diameter and the lattice constant
- Thresholds are reasonable compared to other optically pumped III-N nanowire devices. (<500kW/cm^2 for all devices)

J.B. Wright et al., Scientific Reports 3, Article number: 2982 (2013) doi:10.1038/srep02982

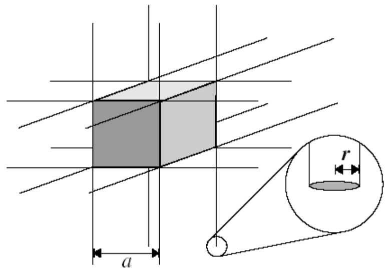
Outline

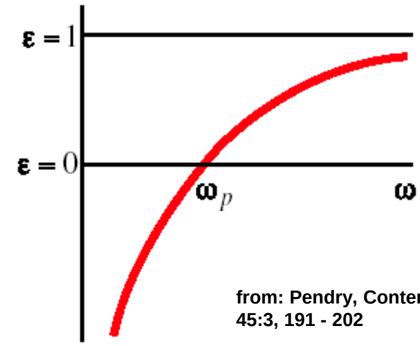
- 3D Passive Metamaterials
  - With Metals: Membrane Projection Lithography
  - Without Metals: Dielectric Resonators
- 2D Active Metamaterials

How to make a “Metamaterial”

“Dilute” a metal to control electric permittivity (ε)

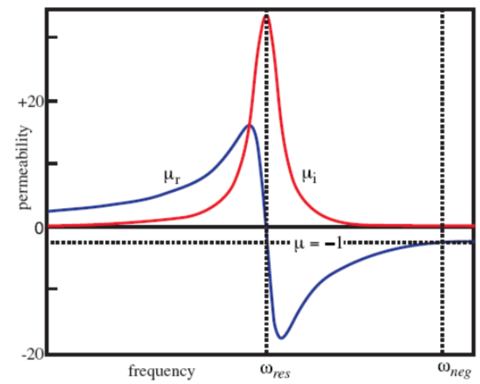
$$\omega_p = \sqrt{\frac{ne^2}{m^*\varepsilon_o}}$$

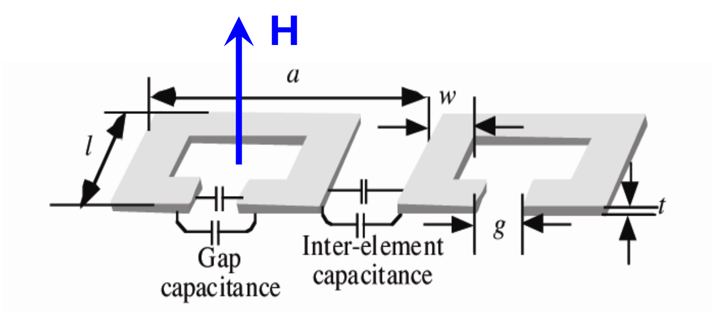




from: Pendry, Contemporary Physics, 45:3, 191 - 202

LC “Resonators” to control magnetic permeability (μ)

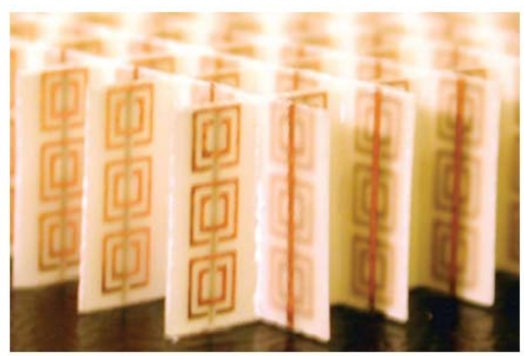


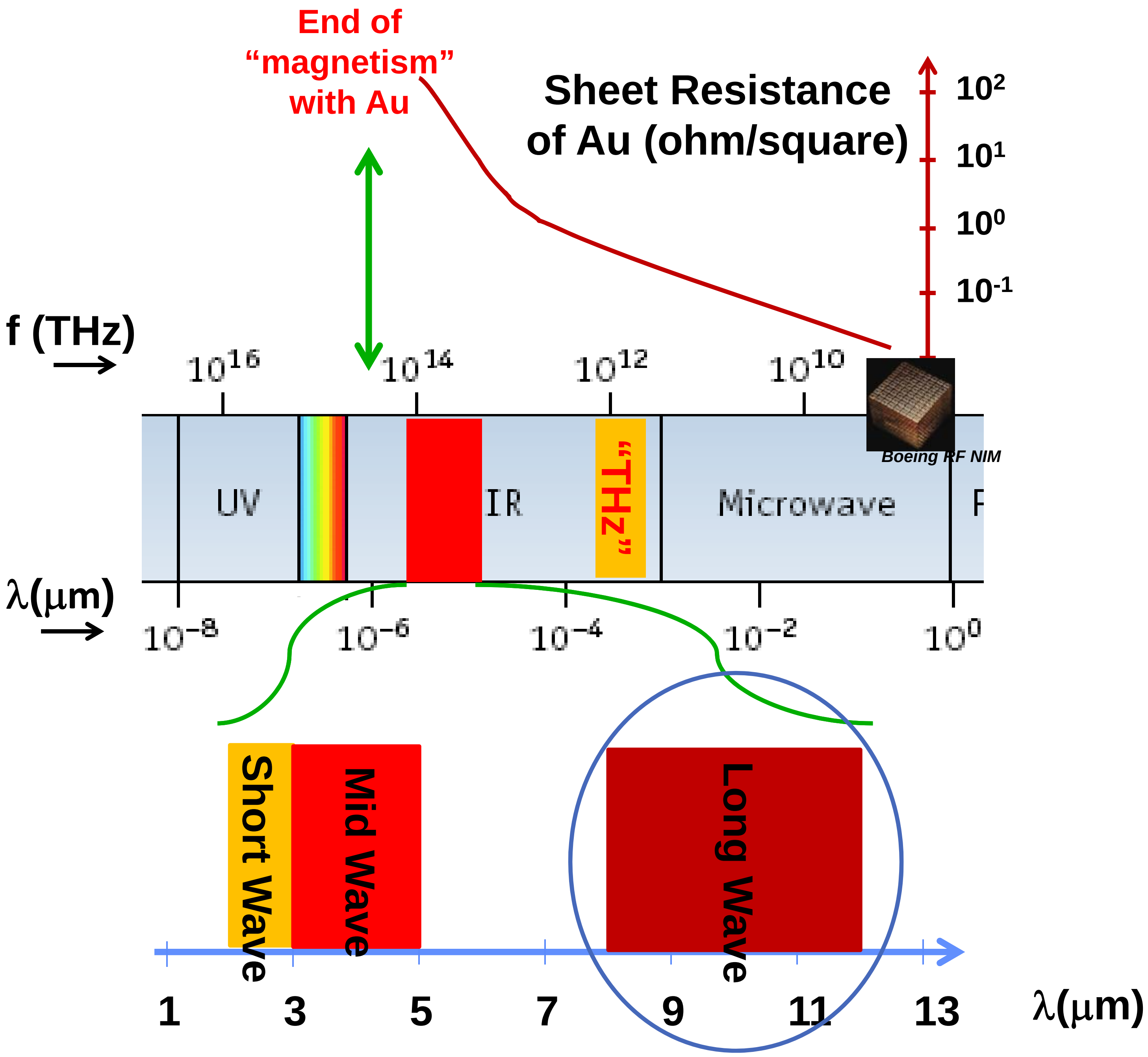


from; S. McMeekin, Proc. Of SPIE, Vol. 6581

Combine the two:

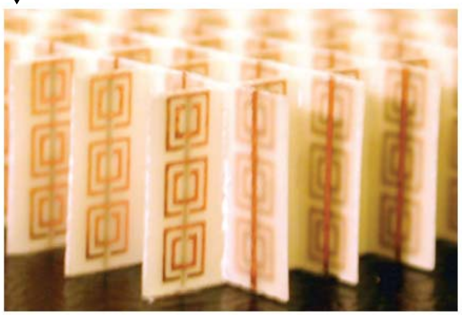
http://www.multitel.be/newsletter/mn7 2005/images/nl3_Metamaterials_type 1.jpg

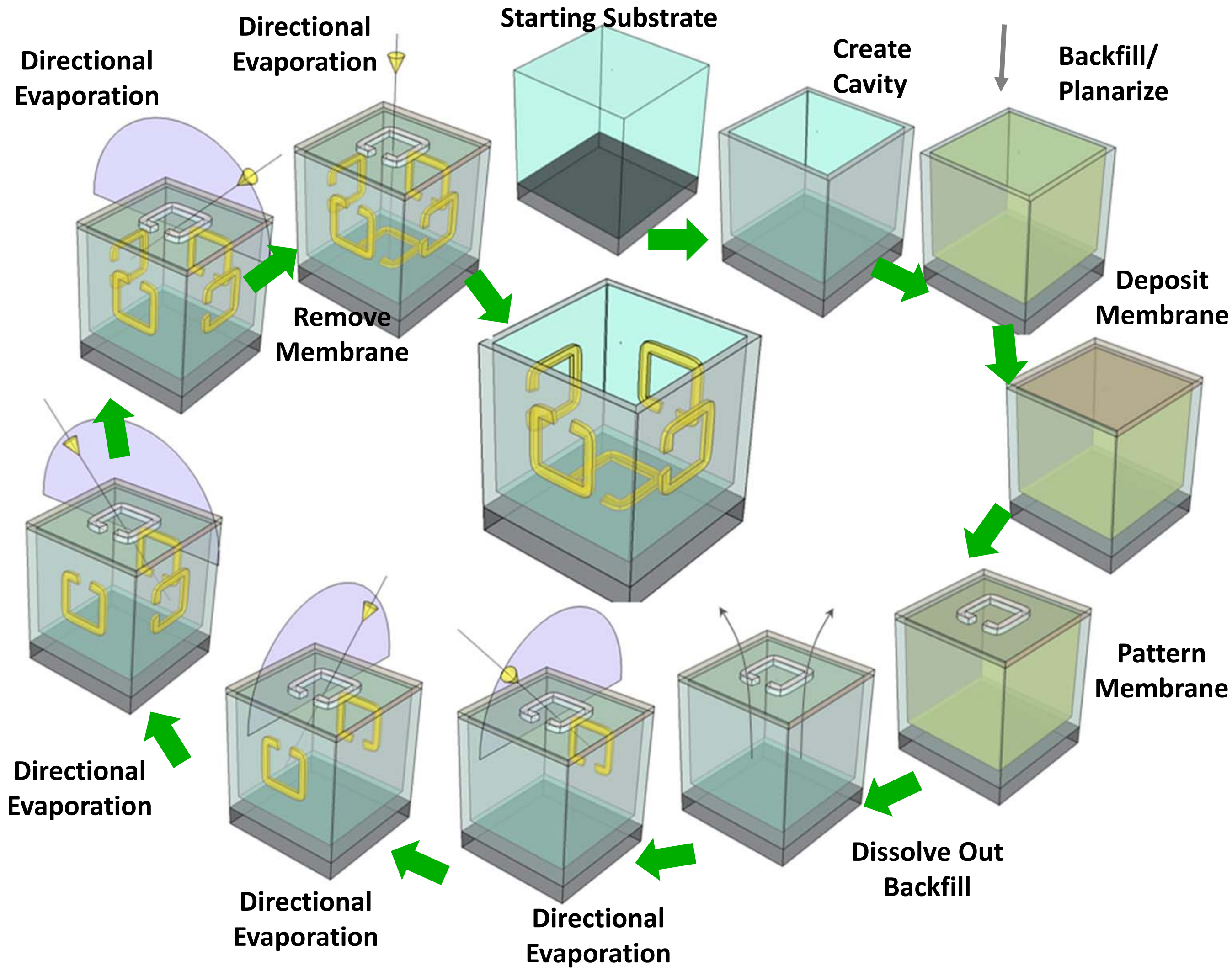



End of "magnetism" with Au
Sheet Resistance of Au (ohm/square)
10^2
10^1
10^0
10^-1
f (THz)
10^16
10^14
10^12
10^10
UV
IR
"THz"
Microwave
Boeing RF NIM
λ(μm)
10^-8
10^-6
10^-4
10^-2
10^0
Short Wave
Mid Wave
Long Wave
1
3
5
7
9
11
13
λ(μm)

3D MMs: Membrane Projection Lithography (MPL)

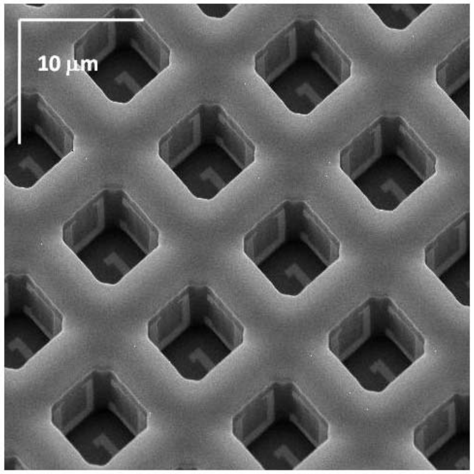
Goal: achieve this at optical frequencies

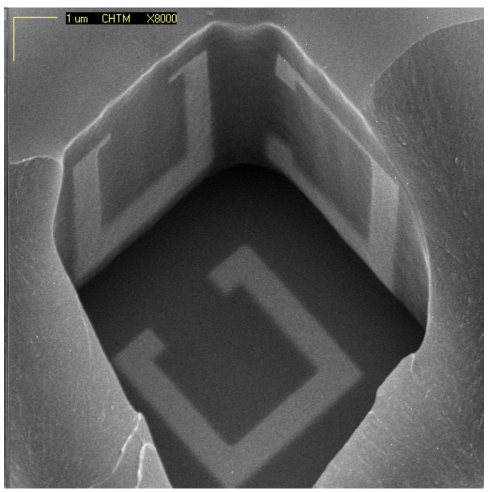




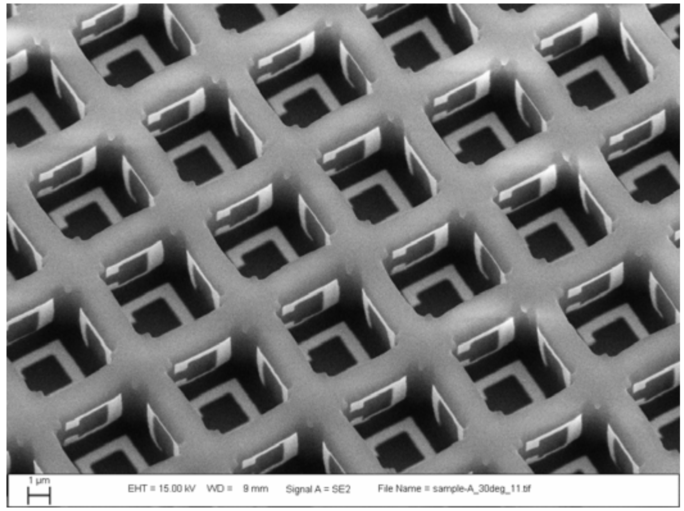
Advanced Materials, 22: 5053–5057 (2010)

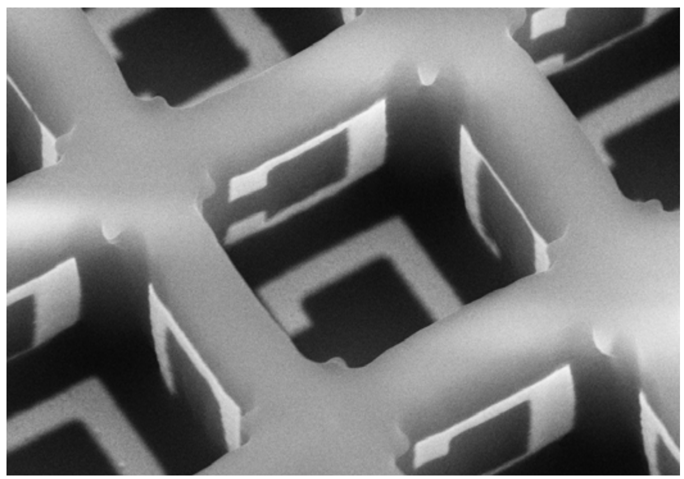
3D Metamaterials via MPL





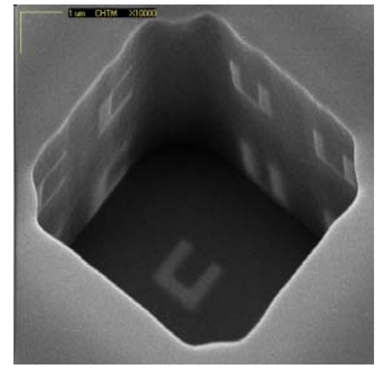
- ➢Unit Cell Dimension = 14 μm pitch
- ➢SRR Dimension = 8 μm
- ➢Resonance wavelength ~ 50 μm

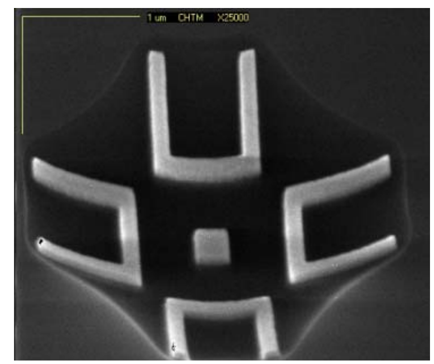




- ➢Unit Cell Dimension = 6 μm pitch
- ➢SRR Dimension = 3 μm
- ➢Resonance wavelength ~ 22 μm

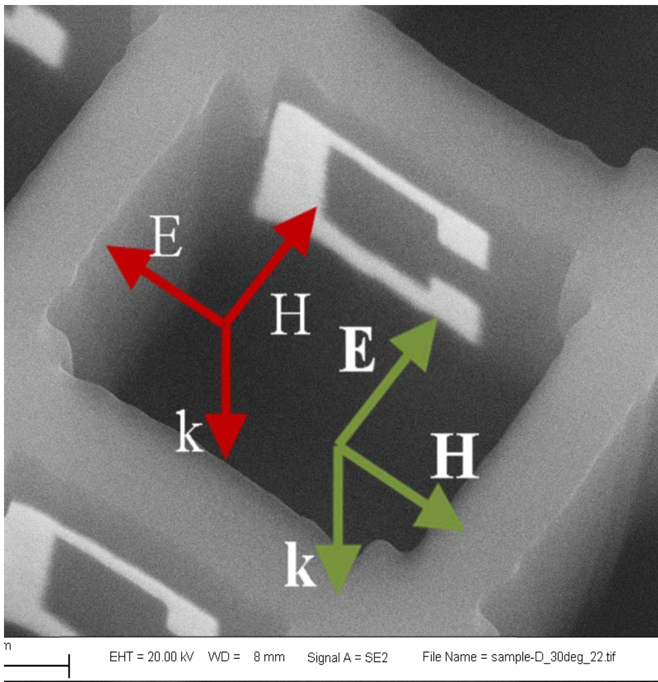
- ➢Multi-aligned MPL



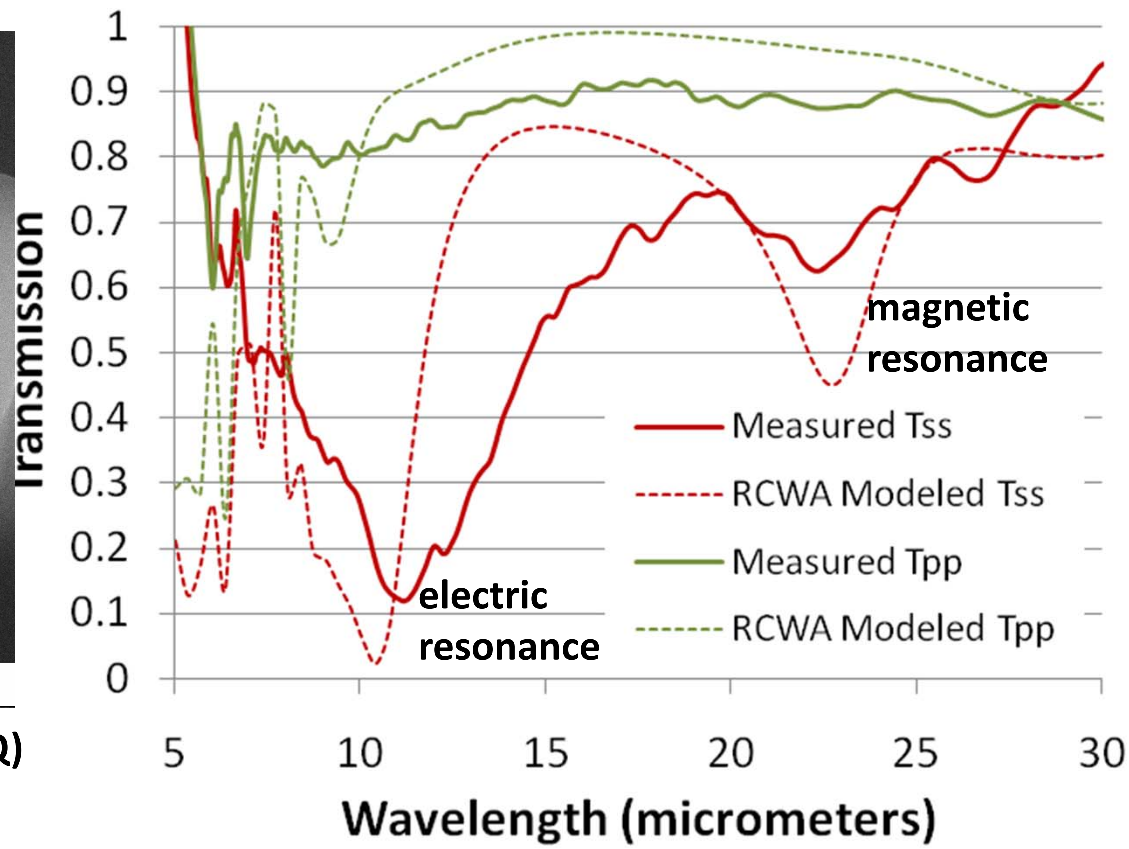


- ➢Self-aligned MPL: spherical cavities

Proof of “Magnetic Resonances”: Polarized Transmission



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

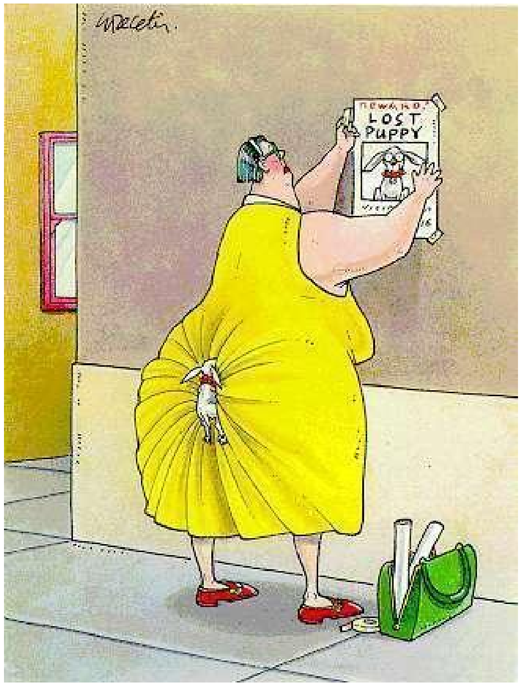
- **can’t couple to any SRR resonances**

Advanced Materials, 22: 5053–5057 (2010).

Outline

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

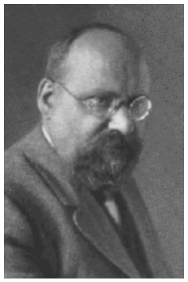
What's wrong with metals? LOSS!!

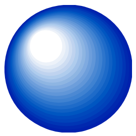


Ohmic Losses….

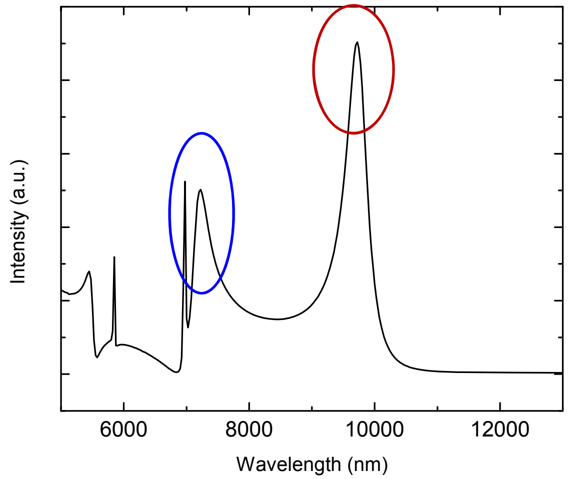
A Non-Metallic Path to Low Loss Metamaterials: Dielectric Resonators

Gustav Mie

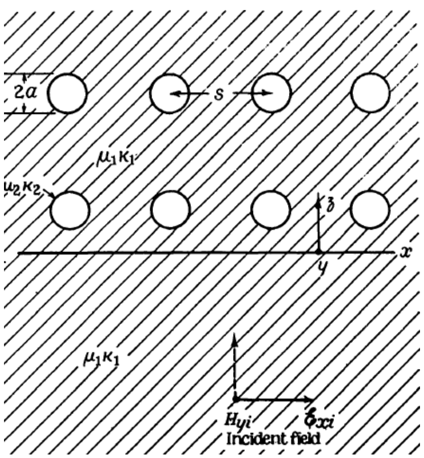




http://www.philiplaven.com/mieplot.htm



First (Primary) resonance is magnetic for most materials; Second 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.)

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

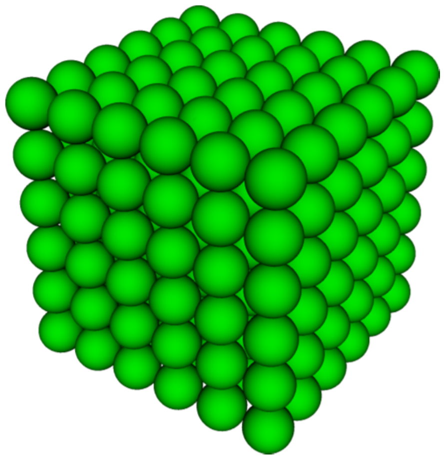
$$\epsilon'_{\rm re} = \epsilon_{r1}\left(1 + \frac{3v_f}{\frac{F(\theta)+2b_e}{F(\theta)-b_e} - v_f}\right)$$

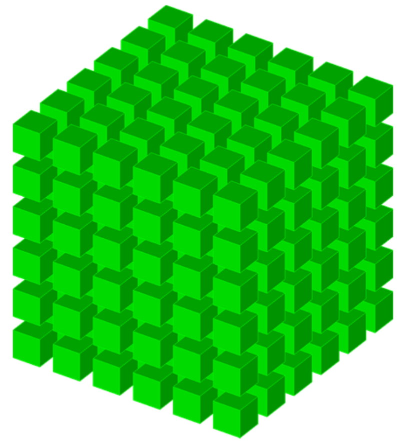
$$F(\theta) = \frac{2(\sin\theta - \theta\cos\theta)}{(\theta^2-1)\sin\theta + \theta\cos\theta}$$

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

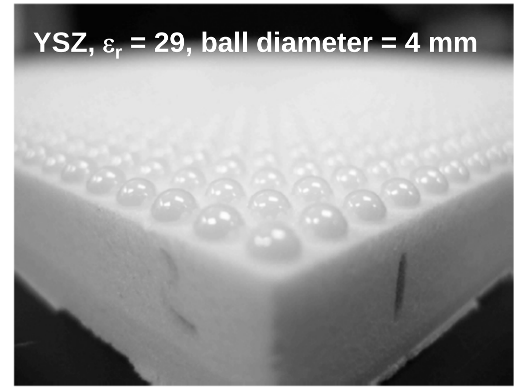
$$b_e = \frac{\epsilon_1}{\epsilon_2}, \quad b_m = \frac{\mu_1}{\mu_2}$$

Arrays of High ε Resonators: Low Loss Metamaterials





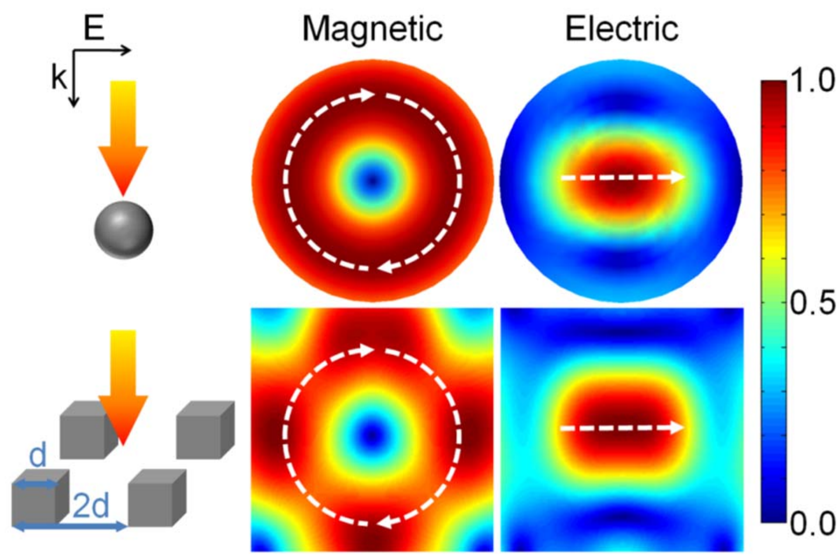
Works nice in the RF



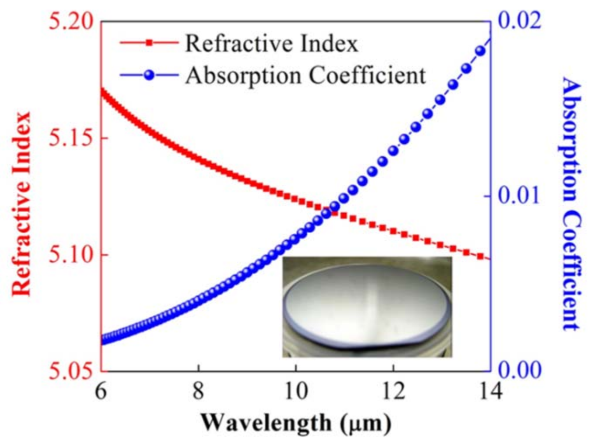
(negative ε, negative μ)

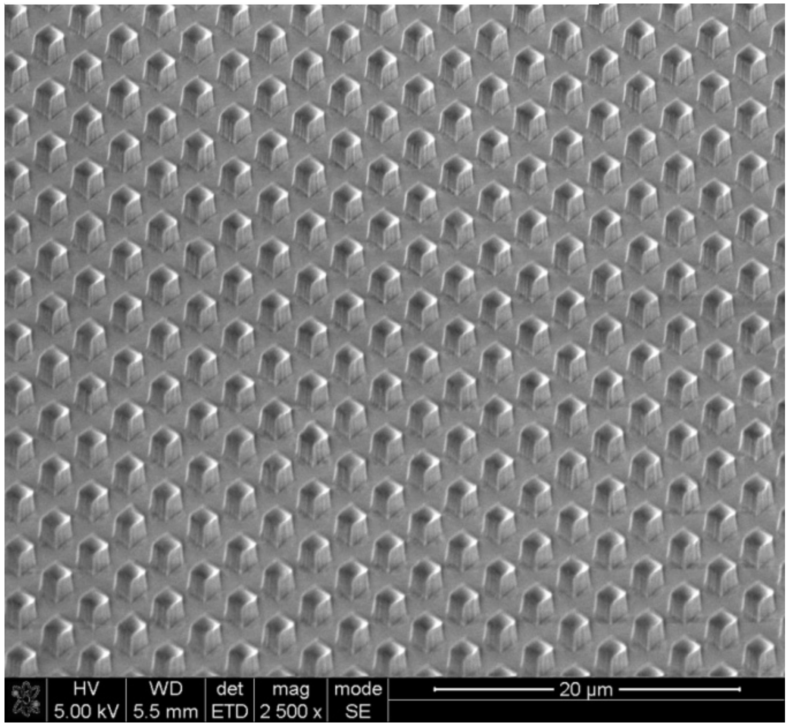
Spherical

Cubic

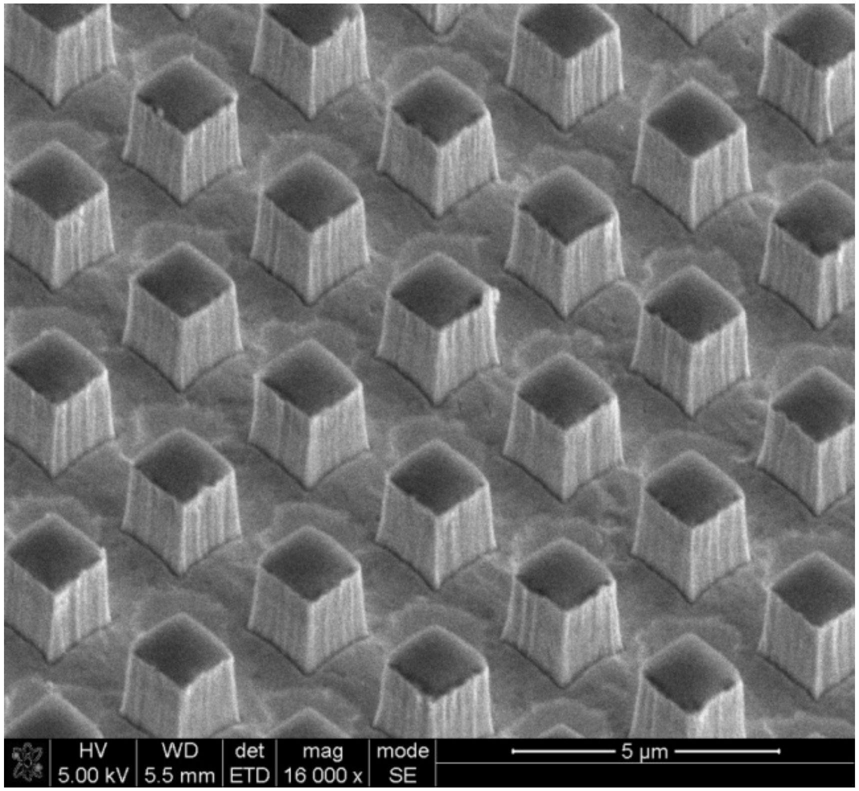


Dielectric Resonator IR Metamaterial: Te/BaF_2





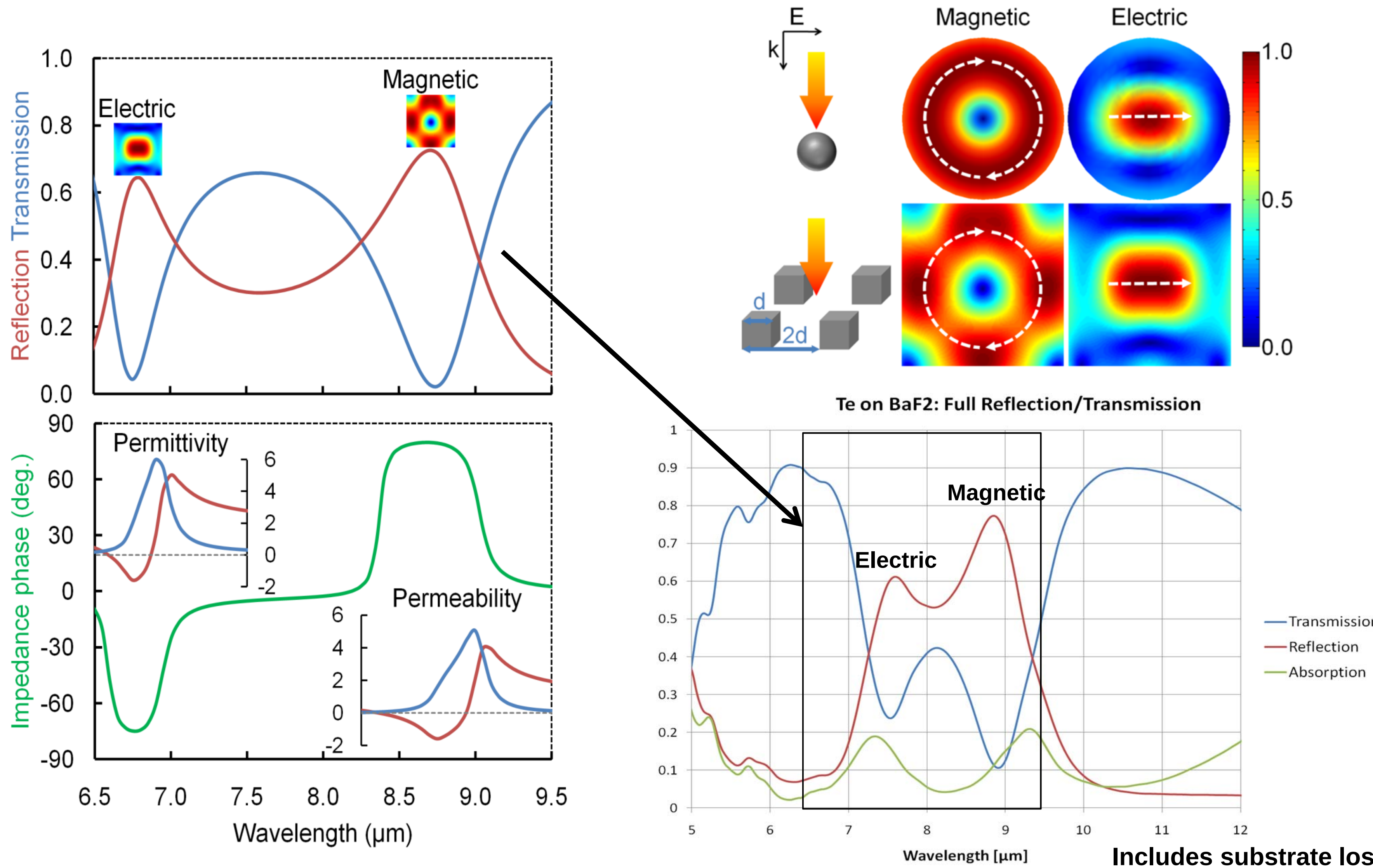
Mask + RIE etch



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

Phys. Rev. Lett. 108, 097402 (2012)

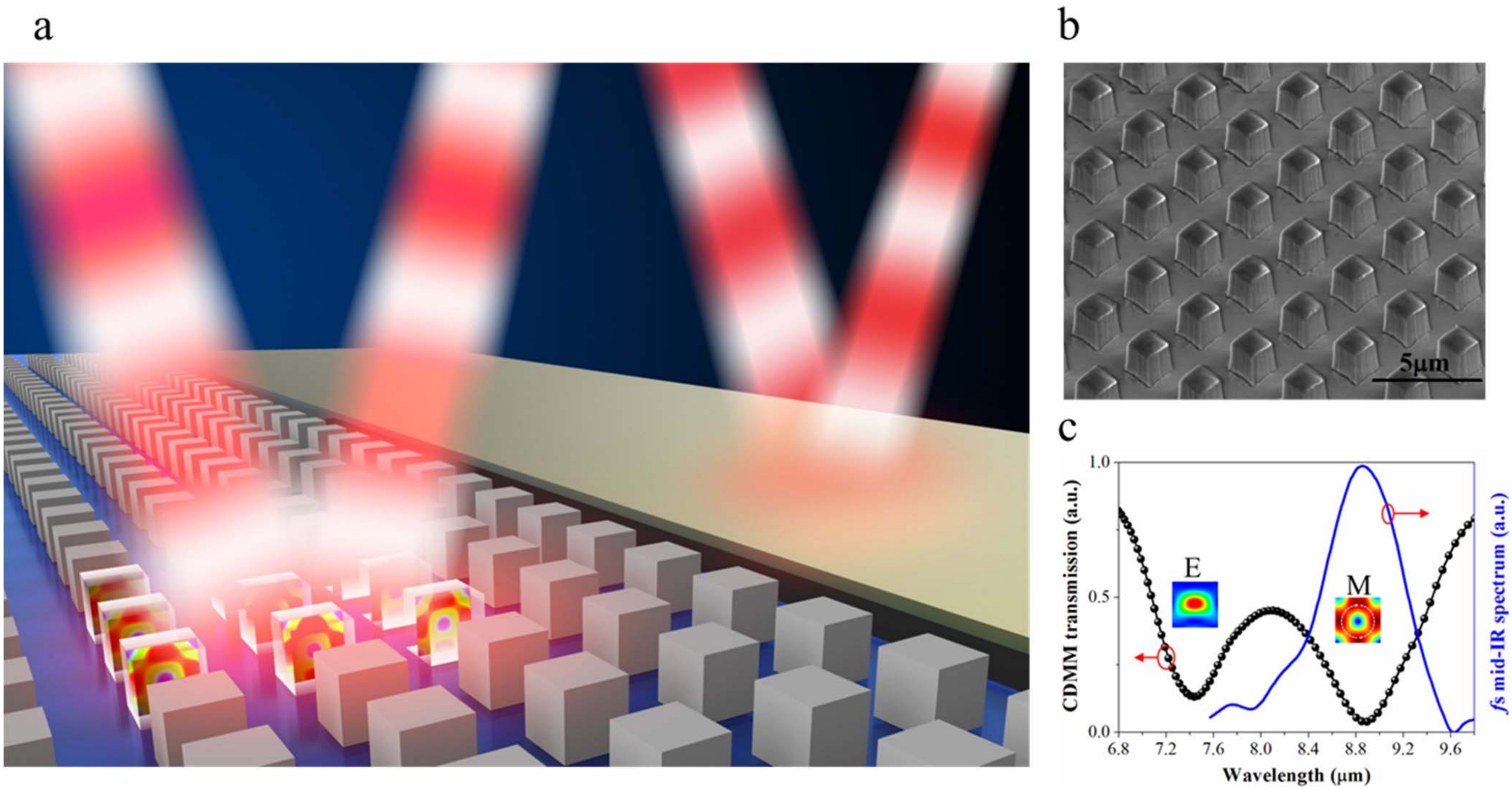
Dielectric Resonator IR Metamaterial: Te/BaF_2



Includes substrate losses

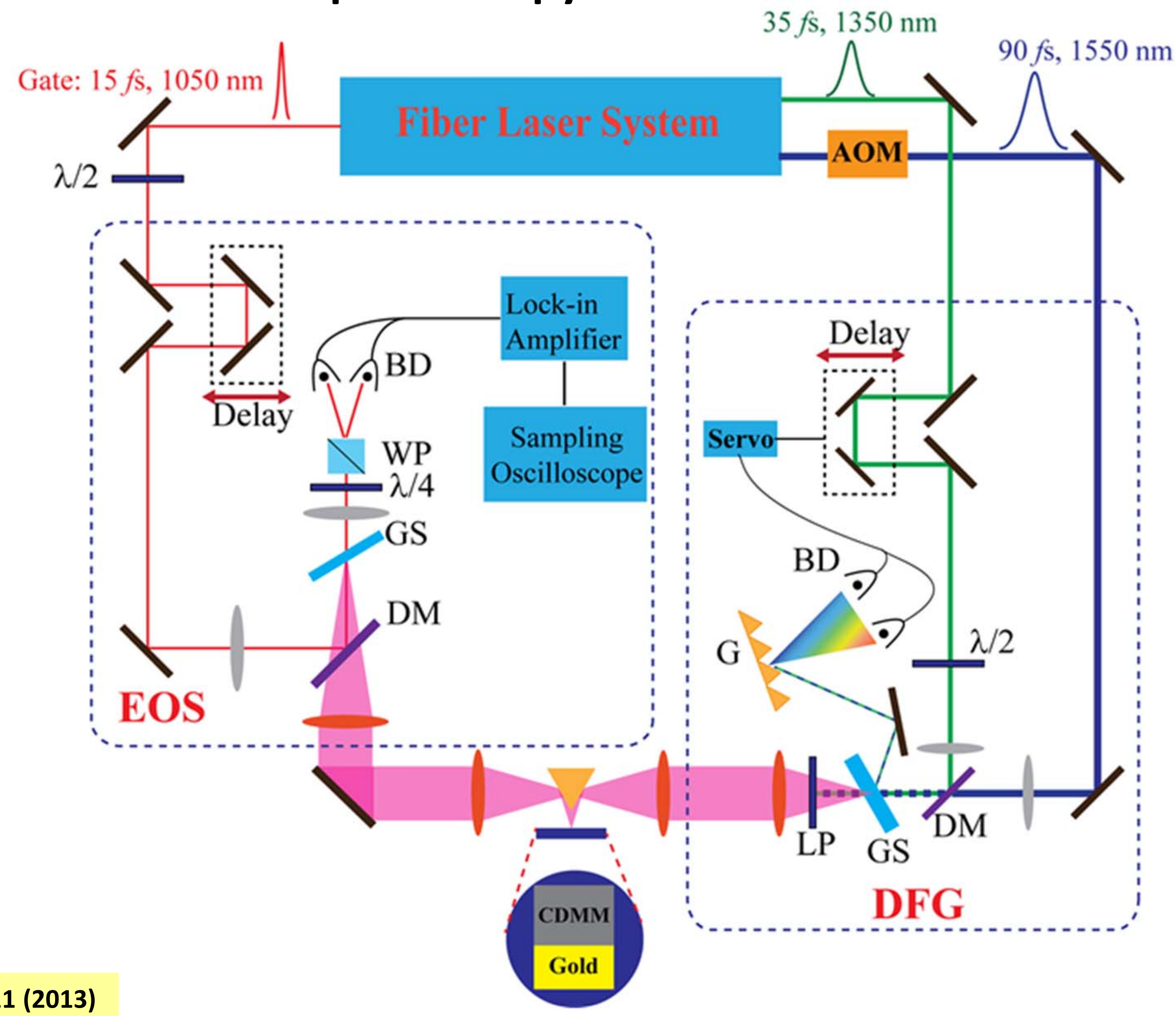
Phys. Rev. Lett. 108, 097402 (2012)

Proving Optical Magnetism:
Reflection Does Not Invert the Phase



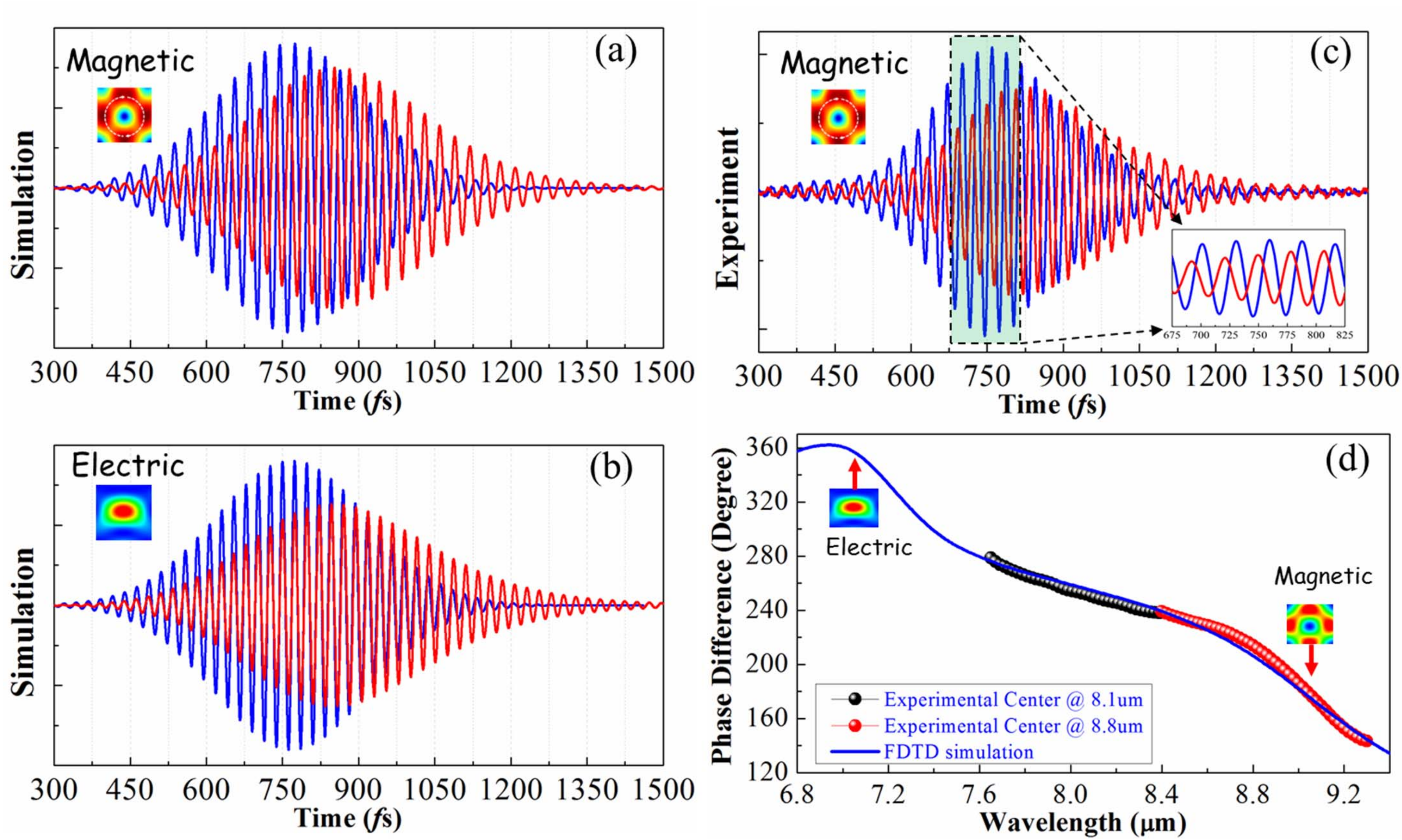
Proving Optical Magnetism:
Measure Phase of Reflected Wave

Phase-locked Time Domain Spectroscopy



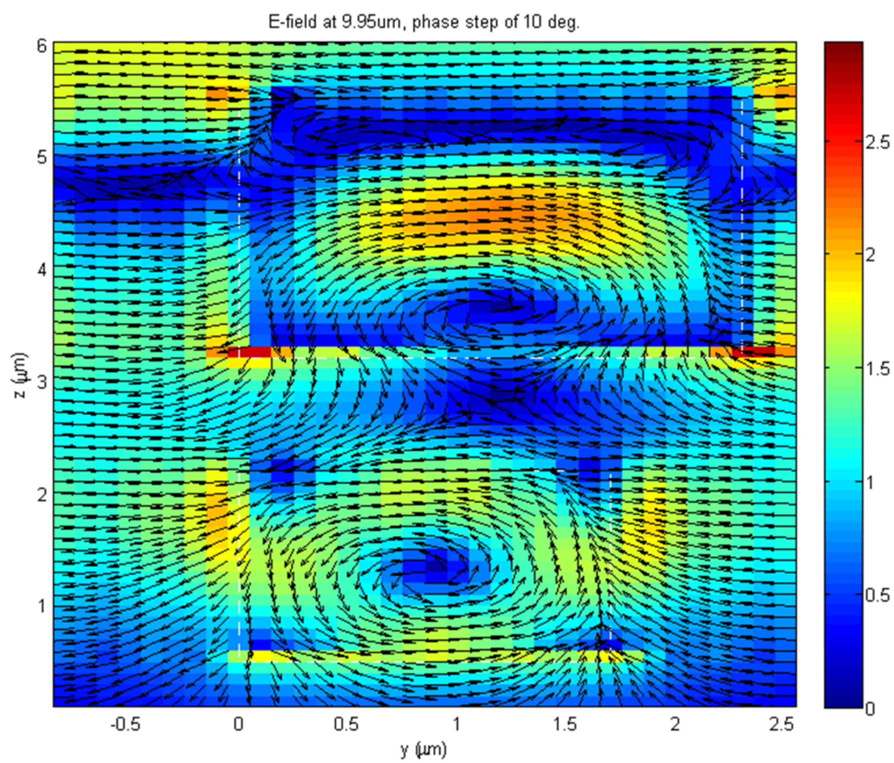
Appl. Phys. Lett. 103, 181111 (2013)

Experimental Demonstration of "Optical Magnetism"



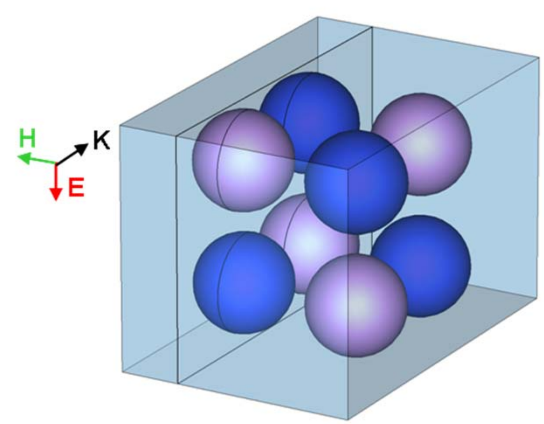
Tailoring both ε and μ: Dual Species Unit Cell Designs

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

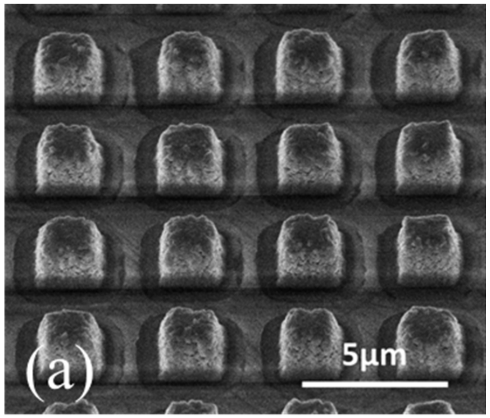


Primary Drawbacks:

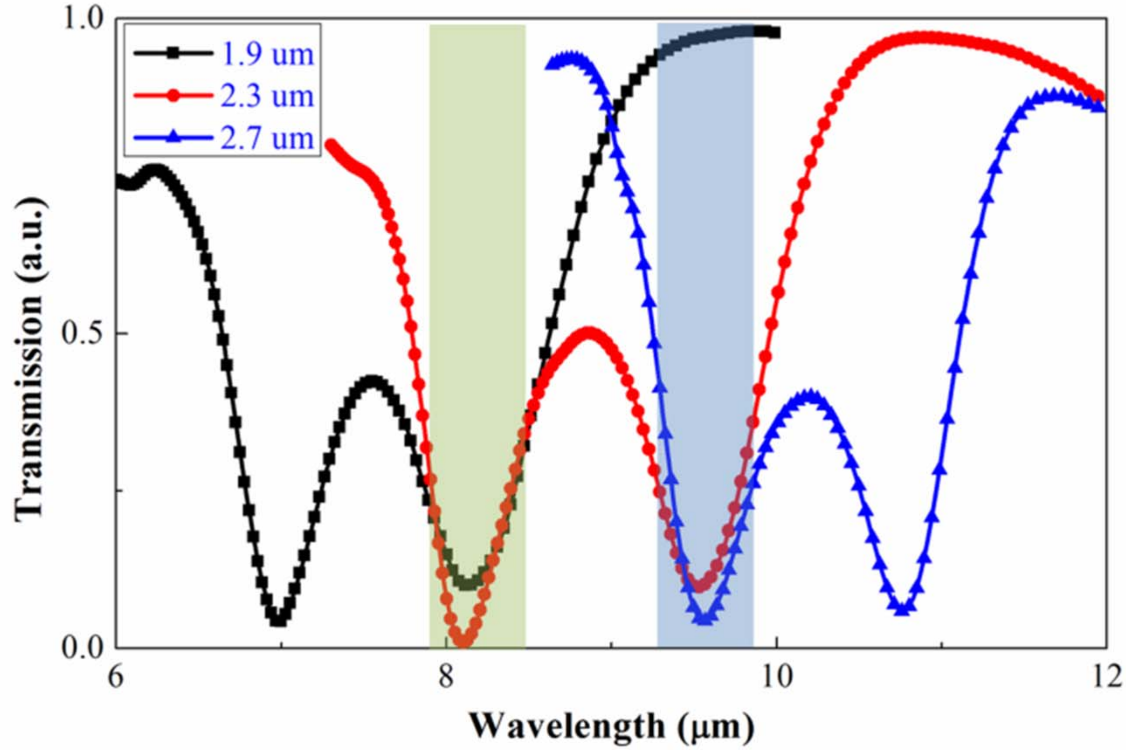
- **Doubling of the unit cell size**
- **Difficult to stay within the effective medium regime**
- **Can't achieve high index metamaterials due to cut-off**



Te Resonators: Overlapping Electric and Magnetic Resonances



Te resonators using a single multiple deposition & liftoff process.



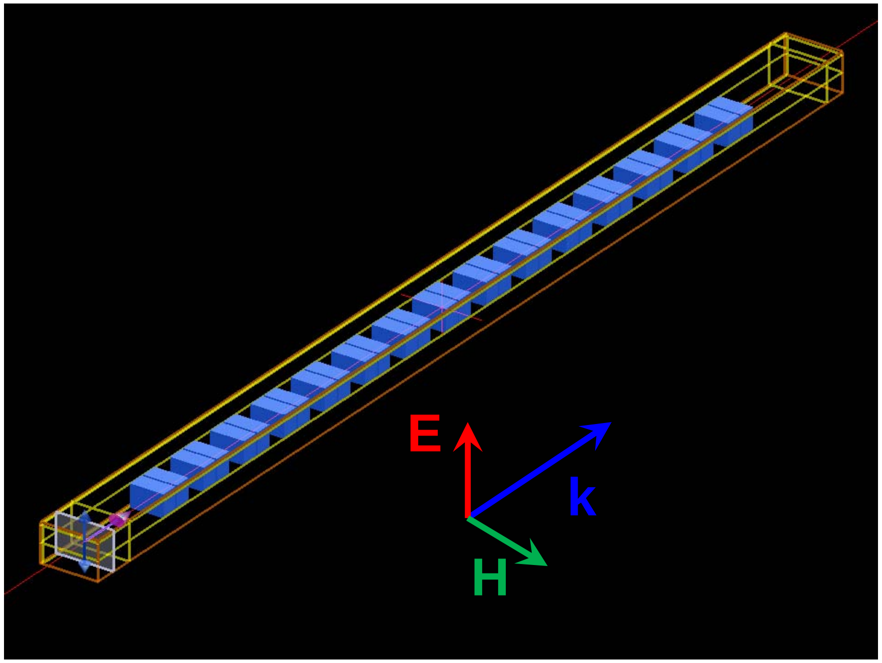
- Side: 1.7 µm, 2.3 µm and 2.7 µm with 50% duty cycle (height constant at ~1.8 µm).
- Shaded areas are the spectral regions where magnetic and electric resonances overlap.

Appl. Phys. Lett. 102, 161905 (2013)

Full Wave Simulation of Propagation Through Split Cube Array

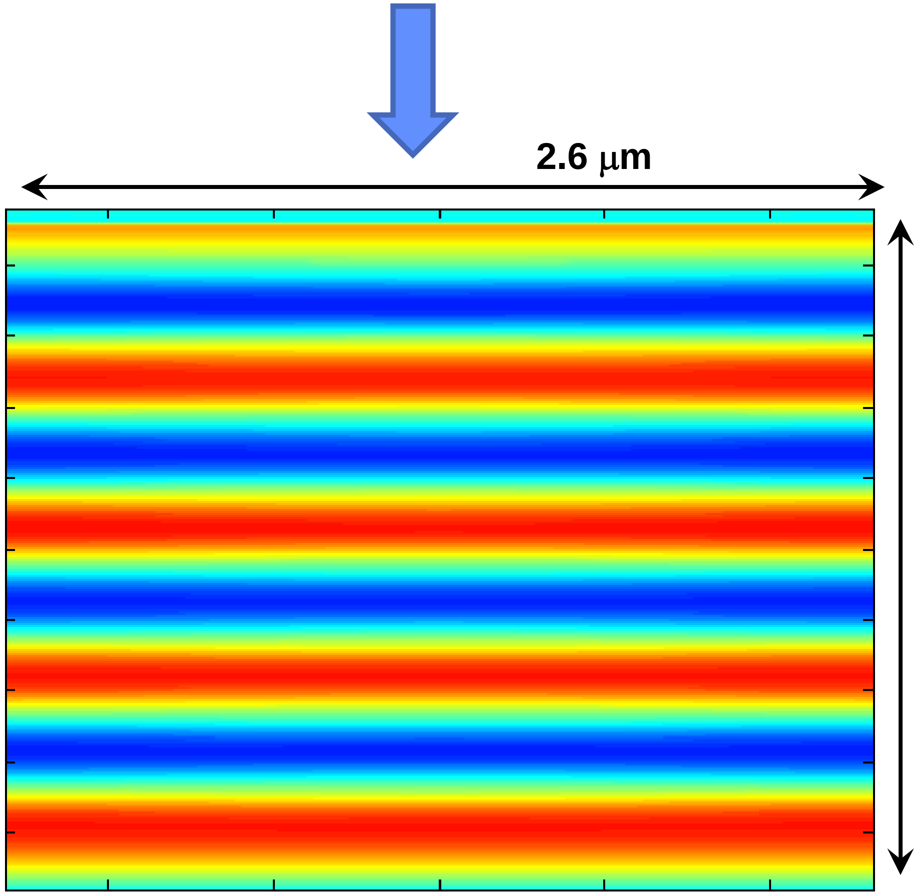
ε=32, edge = 1.53 μm, gap = 100 nm

Lumerical FDTD



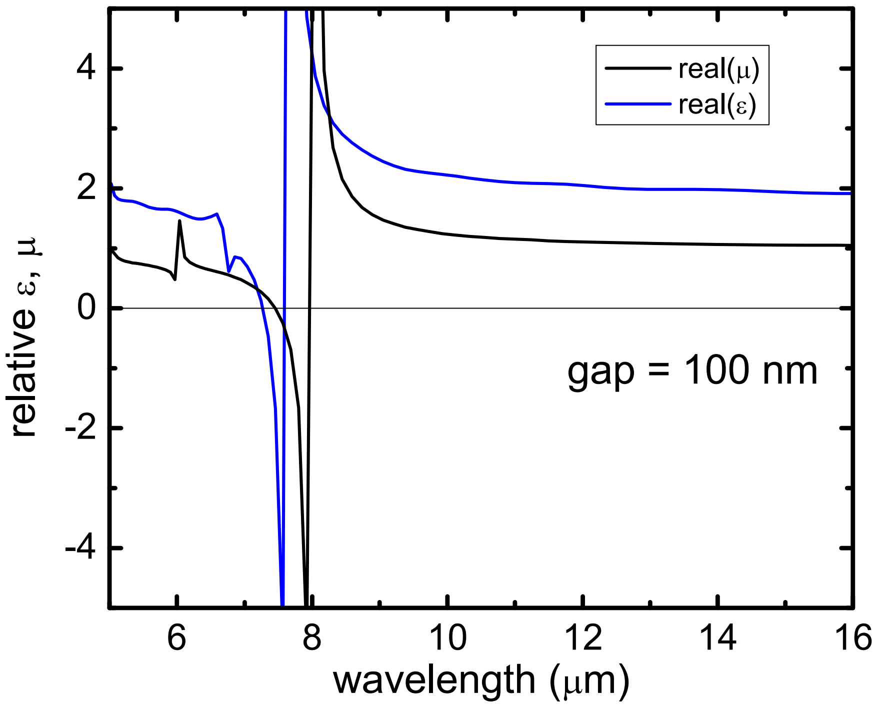
Periodic BC in x & z, 15 cubes thick in y

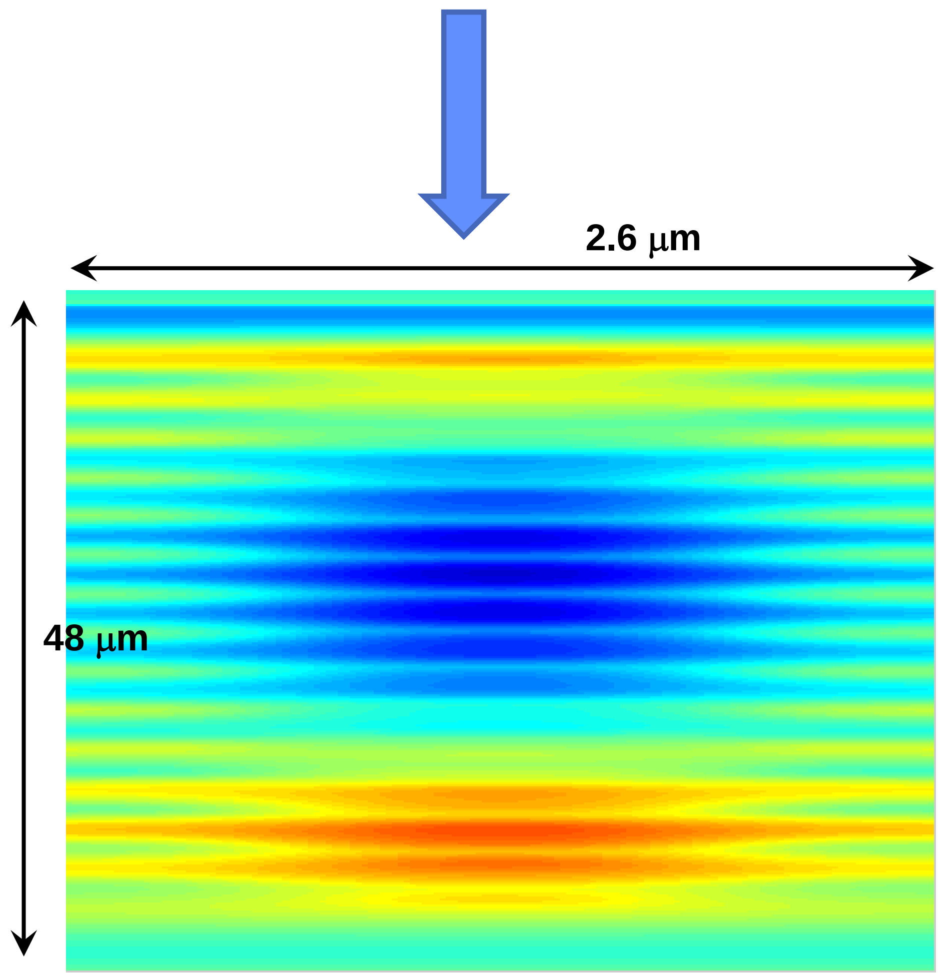
H_x at top of unit cell (z=1.3 μm)
Incident waves



λ = 15 μm

Magnetic Field Movie – 7.5 μm

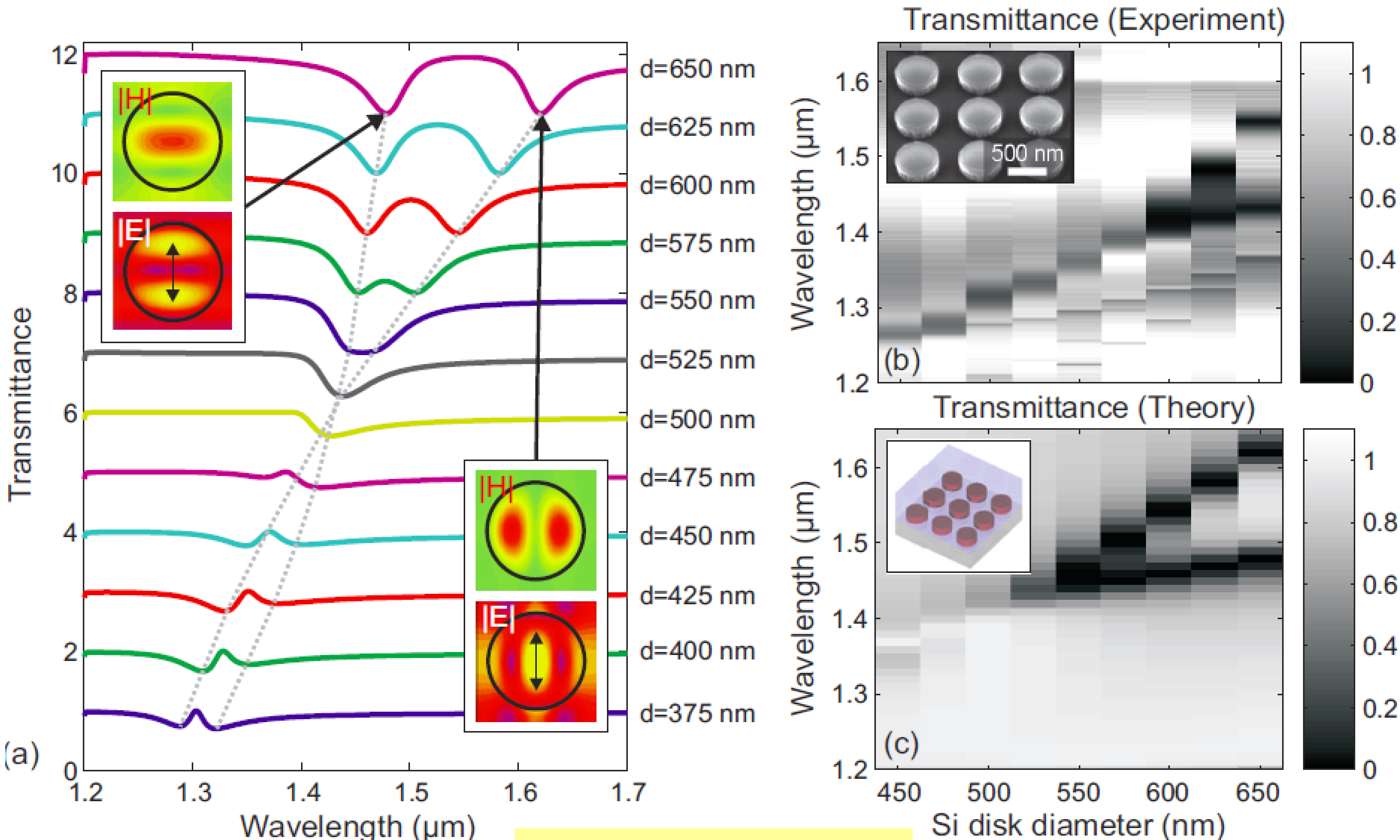




λ = 7.5 μm

H_x at top of unit cell (z=1.3 μm)

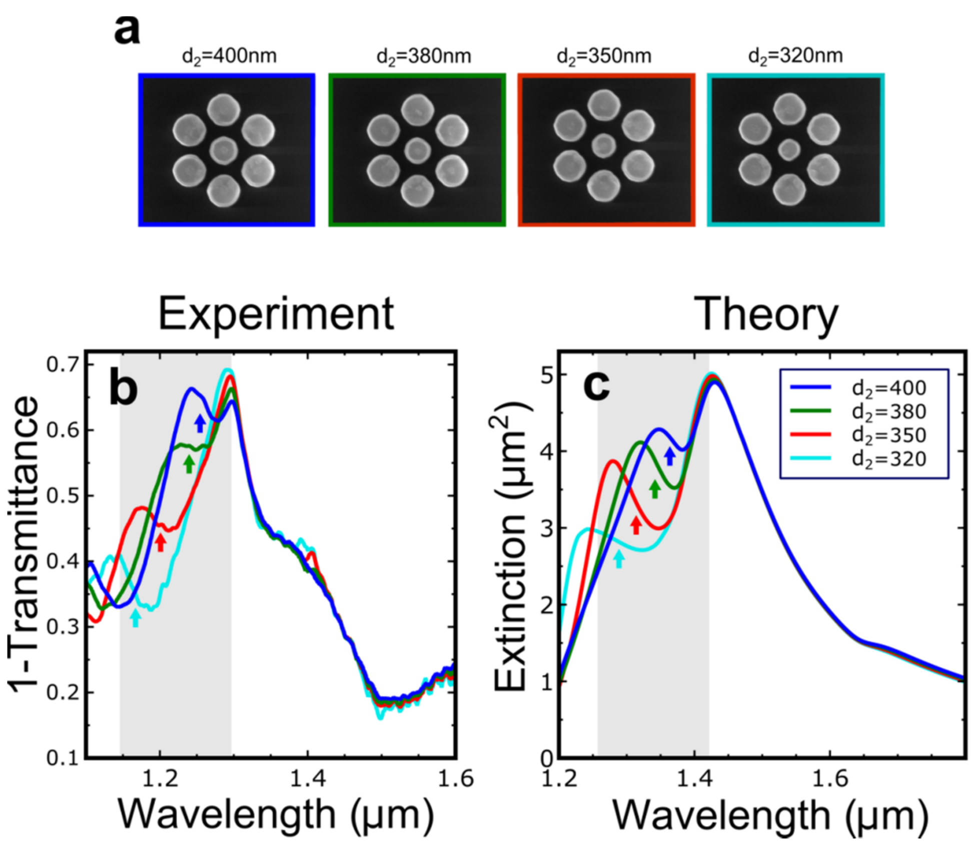
Scaling Dielectric Resonators to the Near IR: Silicon Cylinders (with I. Staude & Y. Kivshar, ANU)

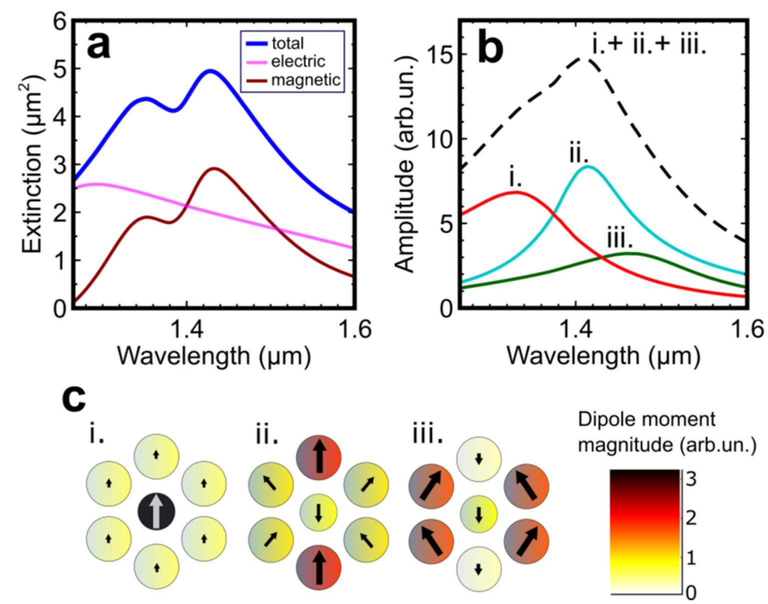


ACS Nano 2013 7 (9), 7824-7832

Fano Resonances in All-Dielectric Nanoparticle Oligomers

(with I. Staude & Y. Kivshar, ANU)

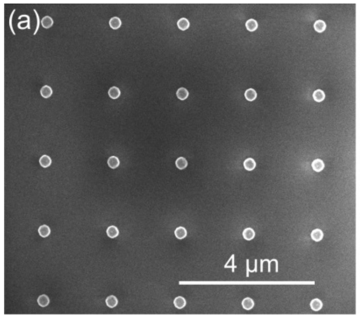




In press, Small, 2013

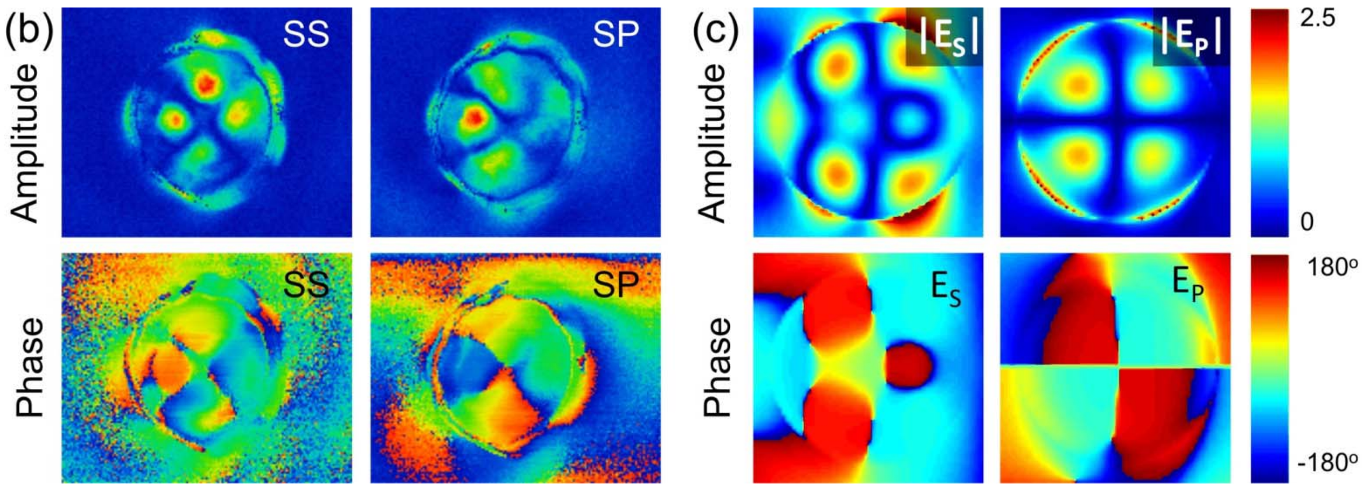
Near Field Imaging of Localized Modes

Terefe Habteyes, UNM



Measurements

Calculated near-field amplitudes

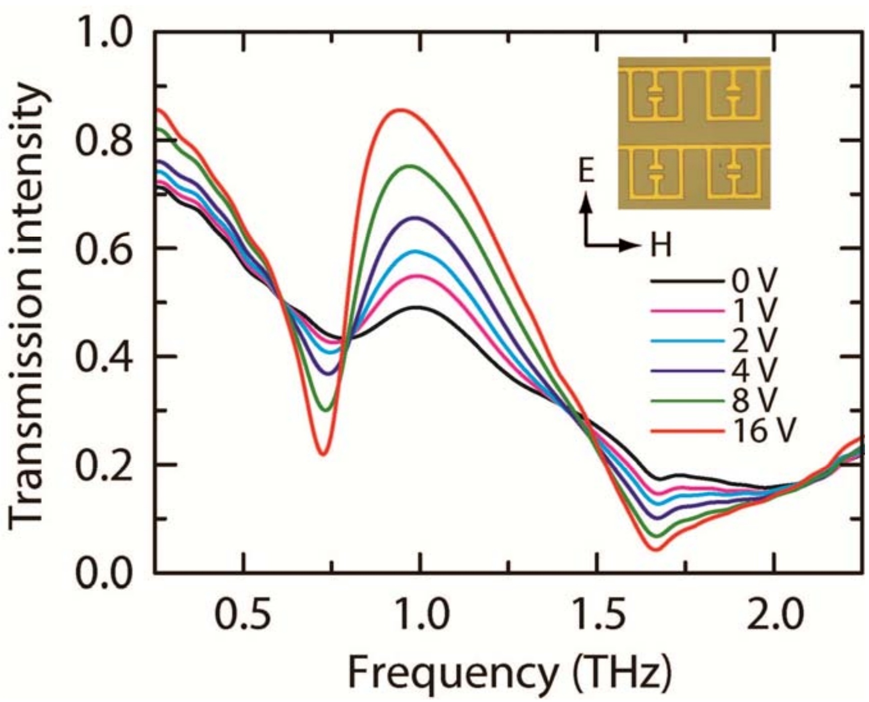


(submitted to CLEO 2014)

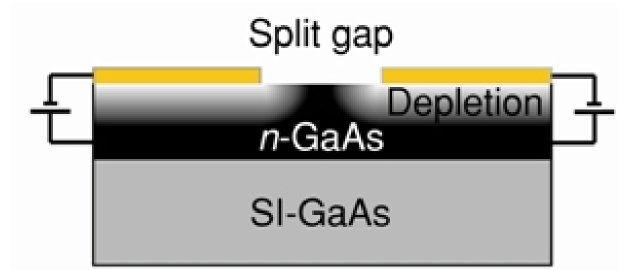
Outline

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

Electrically Switchable THz Metamaterials:
Controlling Interaction With Electrons

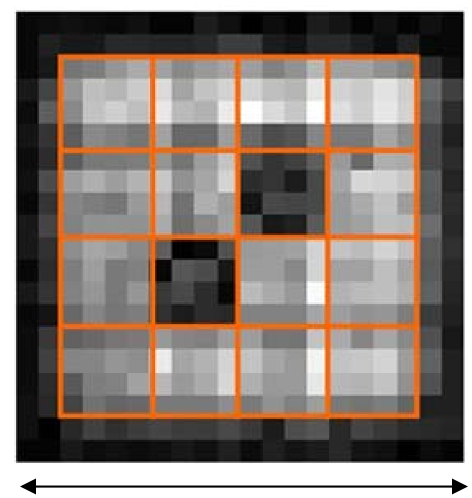


Nature 444, 597 (2006).



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

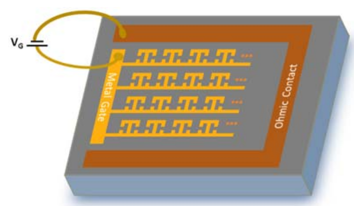


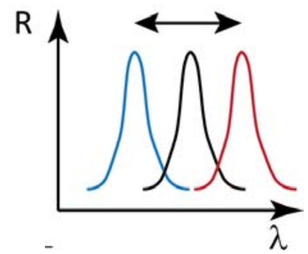
16 mm

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

Why Infrared Tunable Metamaterials?

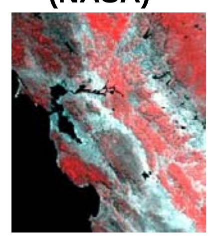
We would like to have semiconductor based, planar, electrically tunable IR filters that can be integrated with array detectors.



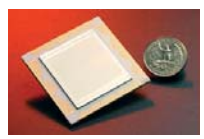


Examples: hyperspectral imaging

(NASA)

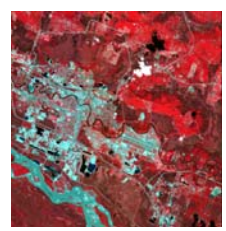


(JPL)



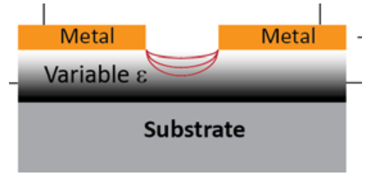
(Cedip)

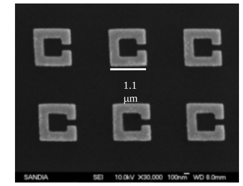
Mechanical filters!



Tunable Interactions with Planar Metamaterials are Needed

Example, SRRs interact strongly with thin layers underneath

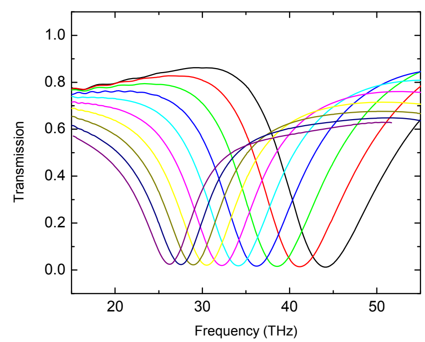


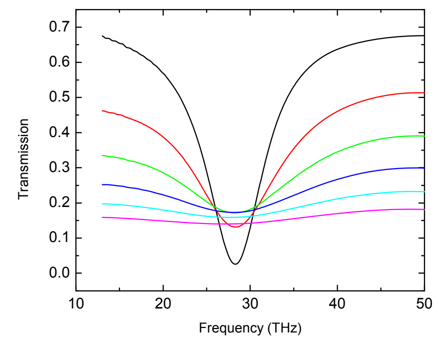


Change ε_1 (n)

Change ε_2 (n)

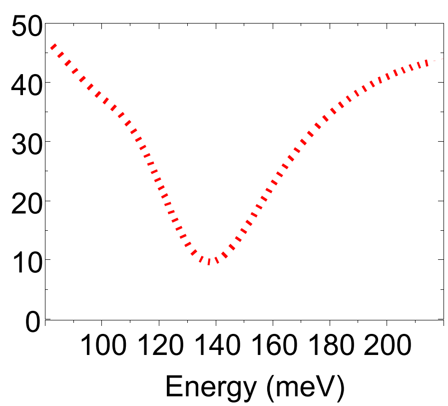
- **Nonresonant**

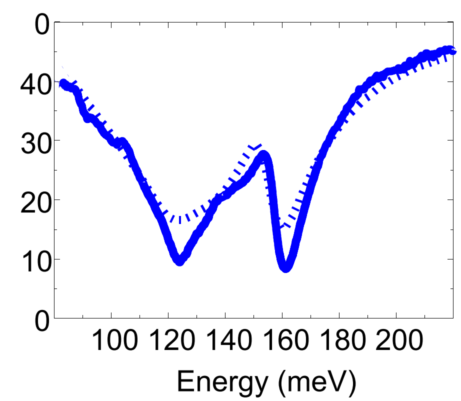




- **Resonant**

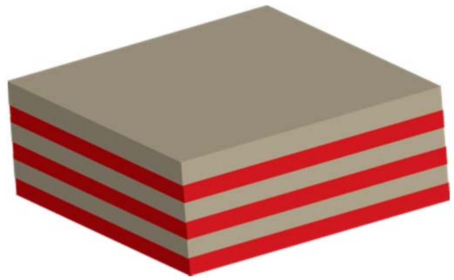
(Create a dipolar resonance, example: phonon)

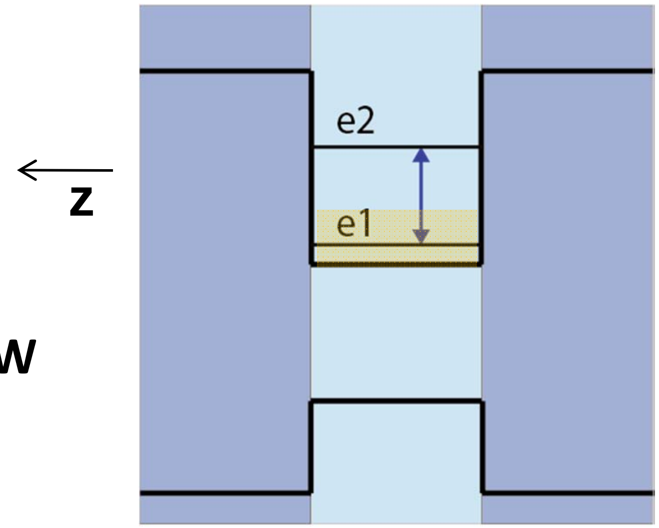




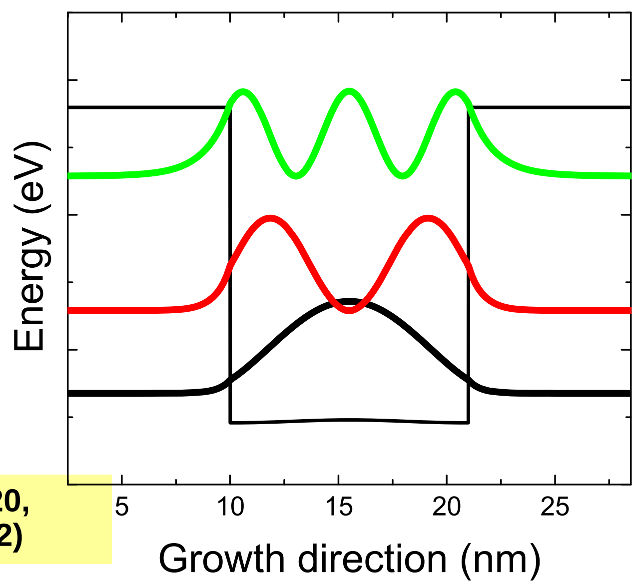
Nano Letters 11, 2104 (2011)

(Ultra) Strong Coupling to Inter-subband Transitions in Quantum Wells

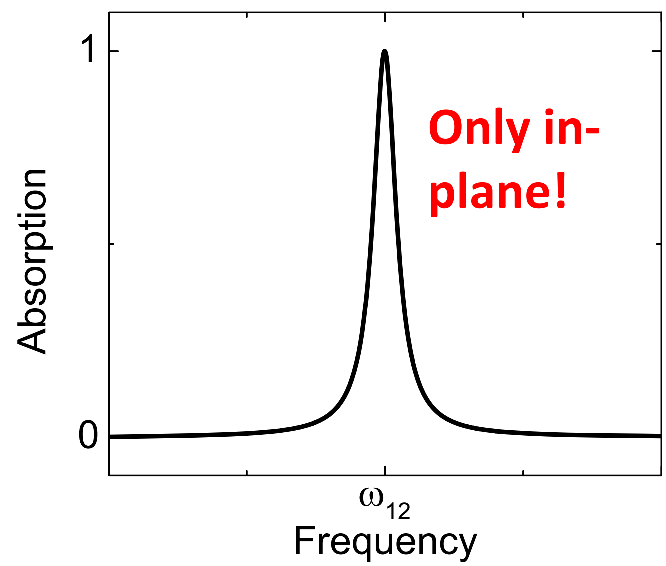




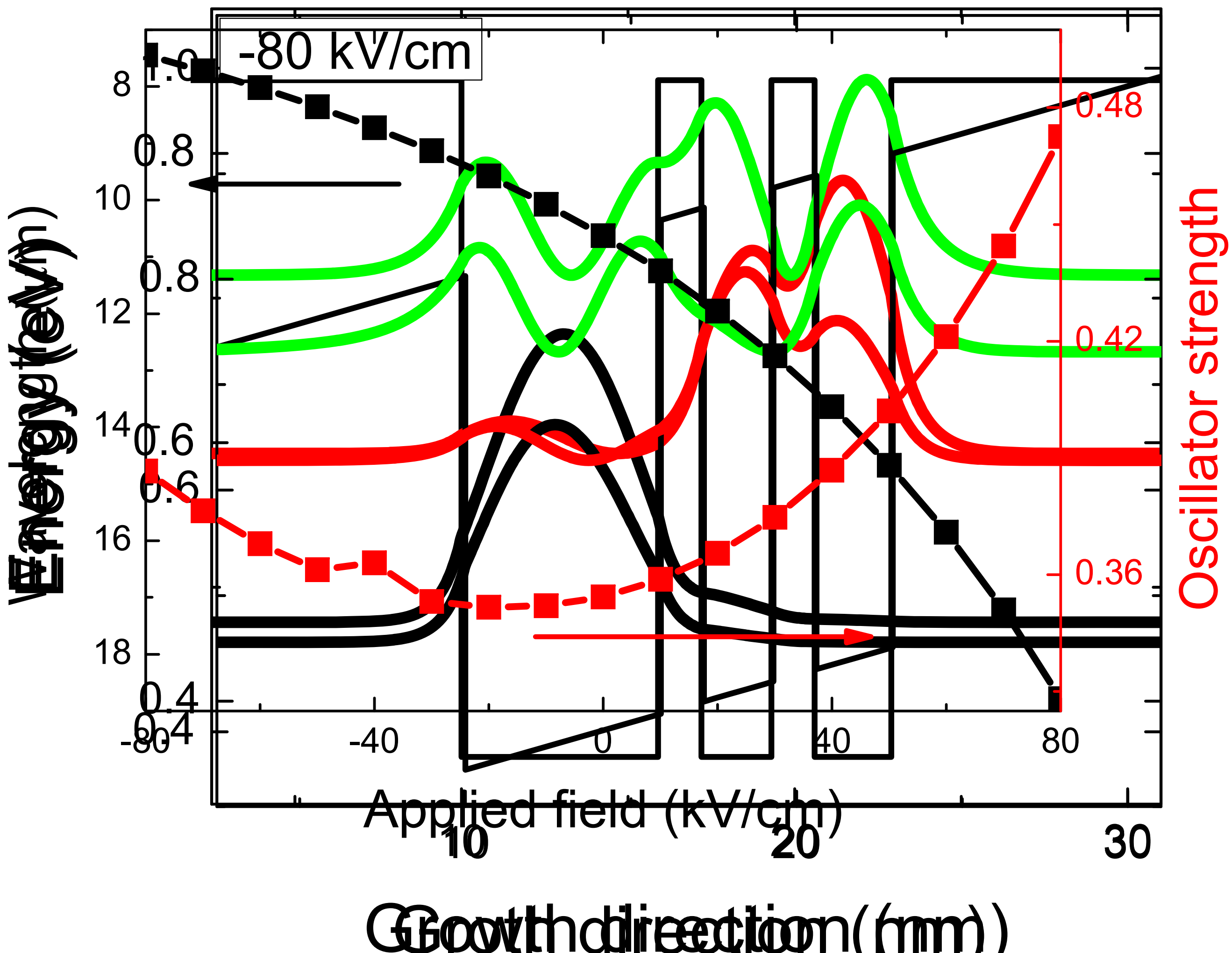
- **Scalabe** from far IR to near IR
- **Huge** parameter space: Coupled QW systems, parabolic wells, superlattices, etc.
- **Mature** Technology (MBE Growth)
- Material **Versatility** (GaAs, GaN, InGaAs)



Opt. Express 20, 6584 (2012)



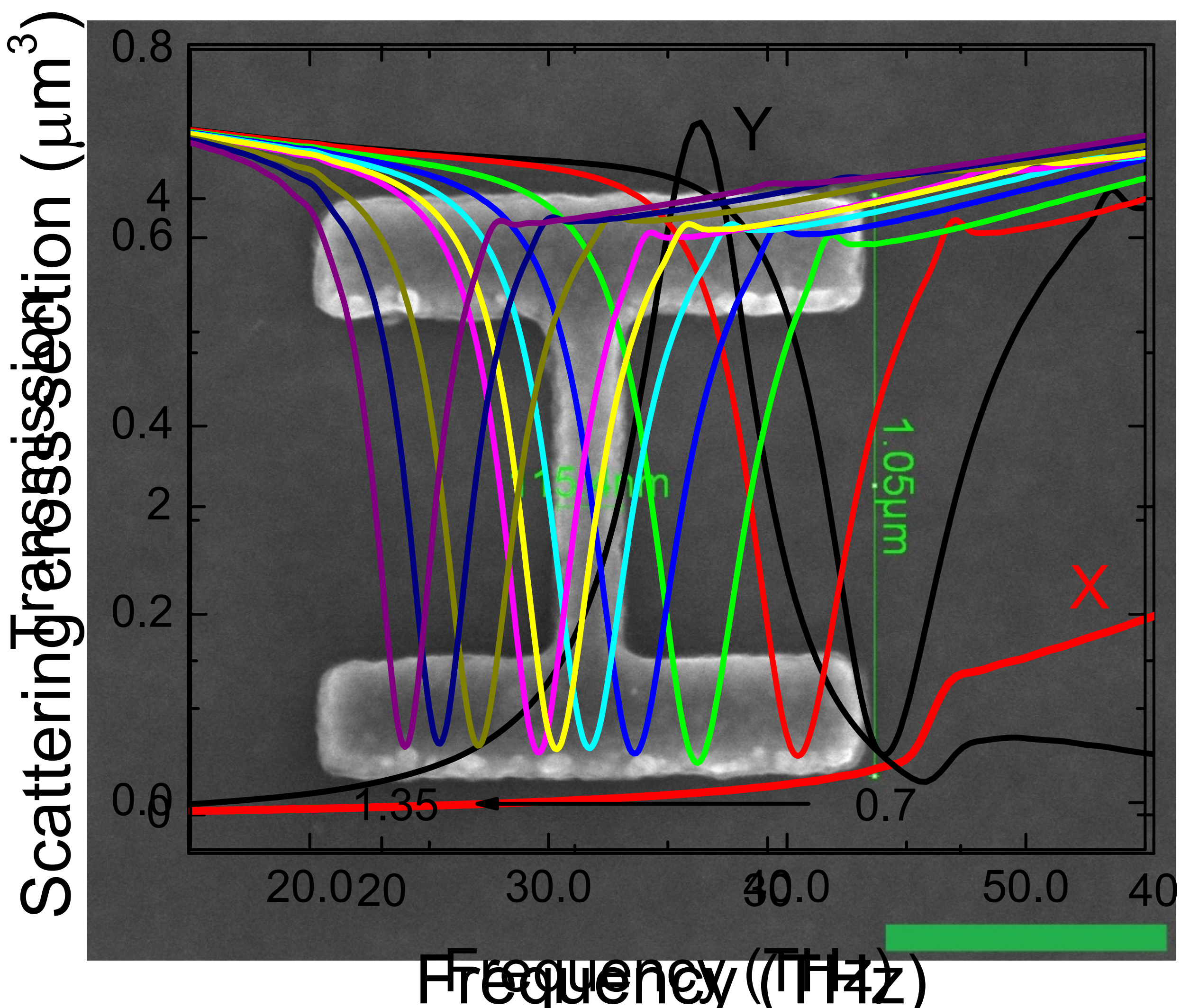
We can tune Intersubband transitions:
we can tune MMs



- Intersubband resonance tuned
  - Stark effect
  - Scales linearly
- Oscillator strength constant

Metamaterial Fabrication: “Dogbones”

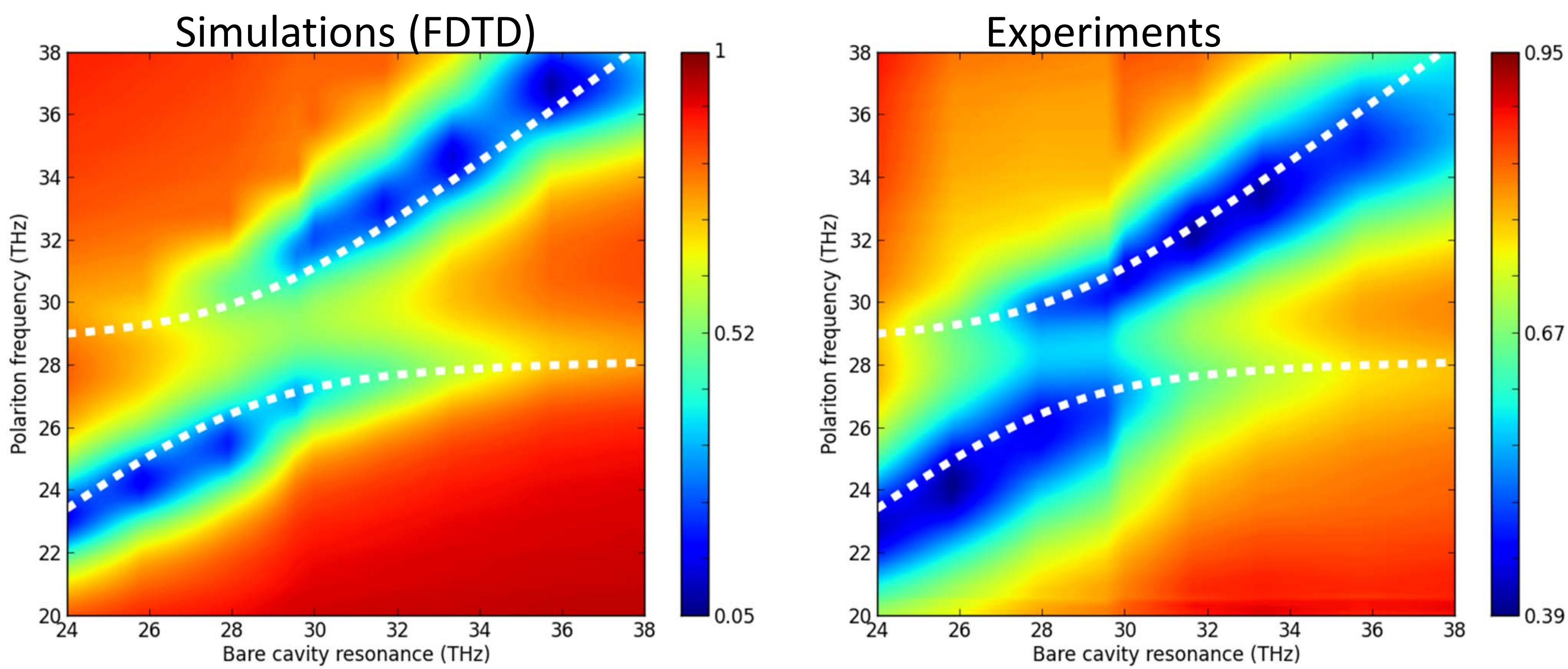
λ~10μm



- **Processing**
  - **Ebeam litho**
  - **100 nm gold**
- **Resonance adjustable by geometric scaling**

Nature communications **4**, (2013)

Strong Coupling Theory vs. Experiment



- **Anti-crossing**
- **Polariton picture[1,2]**

Plasma frequency

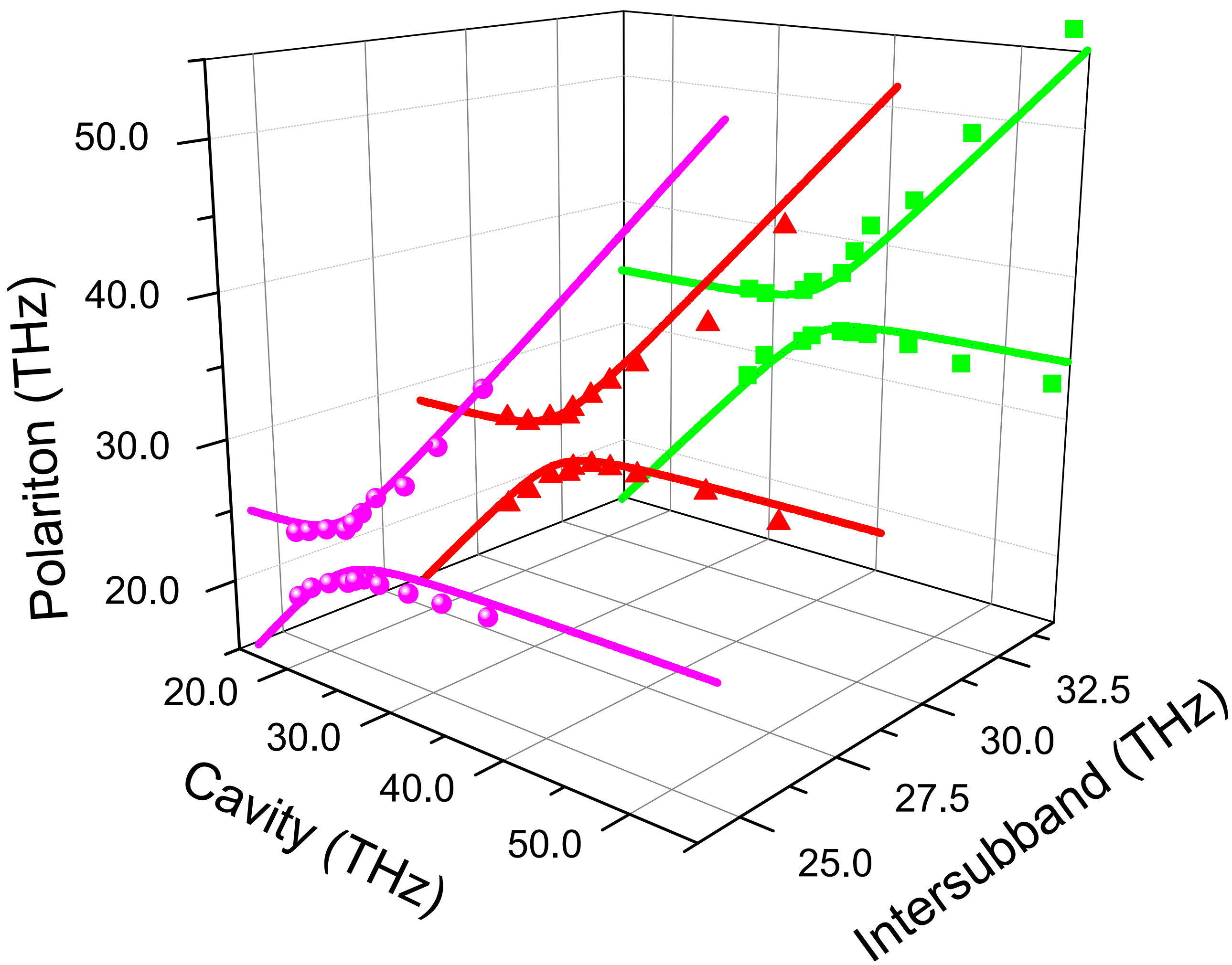
$$\Omega_R = \sqrt{f_W}\,\omega_p/2$$

Geometry factor

[1] A. Gabbay et al., APL 98, 203103 (2011)
[2] A. Gabbay et al., Opt. Exp. 20, 6584 (2012)

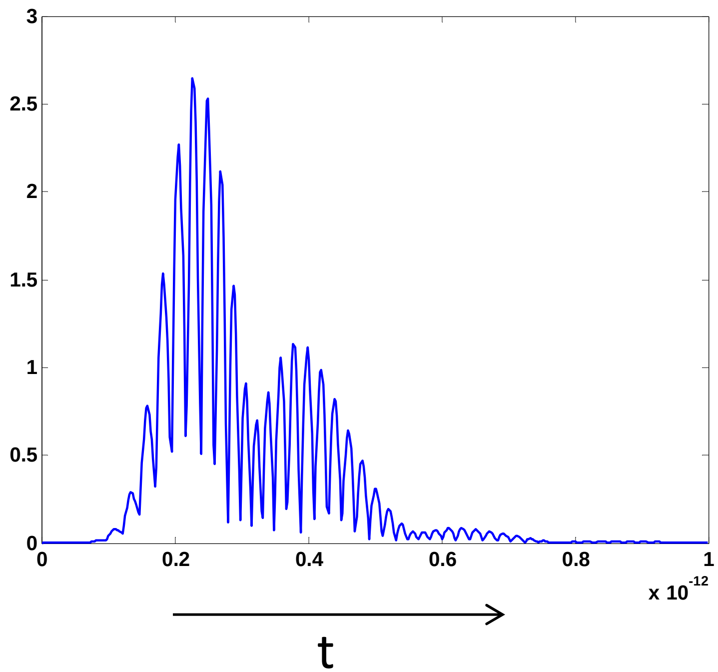
Nature communications **4**, (2013)

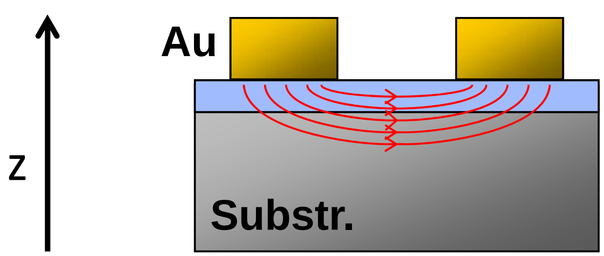
Intersubband Flexibility

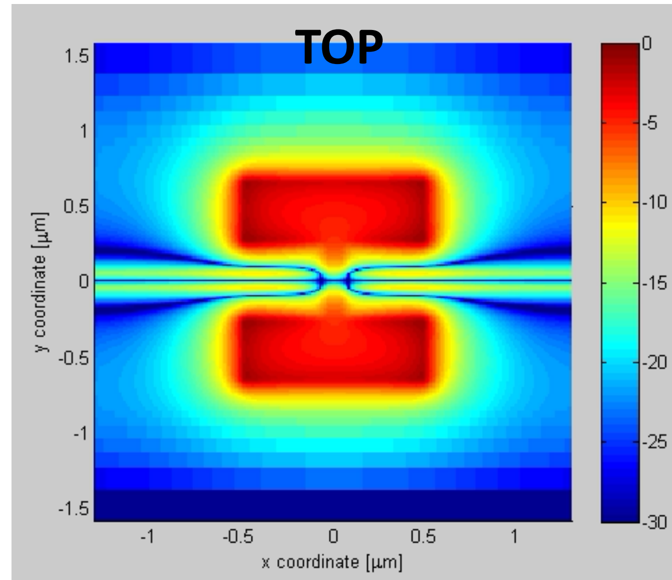


- Cover entire thermal IR
- Quantum-well transitions
  - 8, 10, 12 μm
- Model explains experiment
  - No free fitting parameters

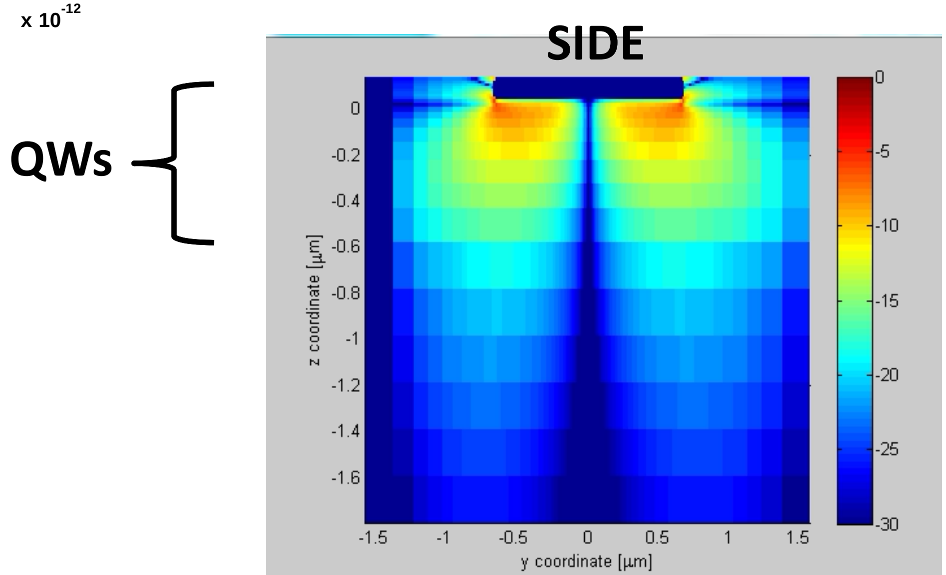
Rabi Oscillation Movies





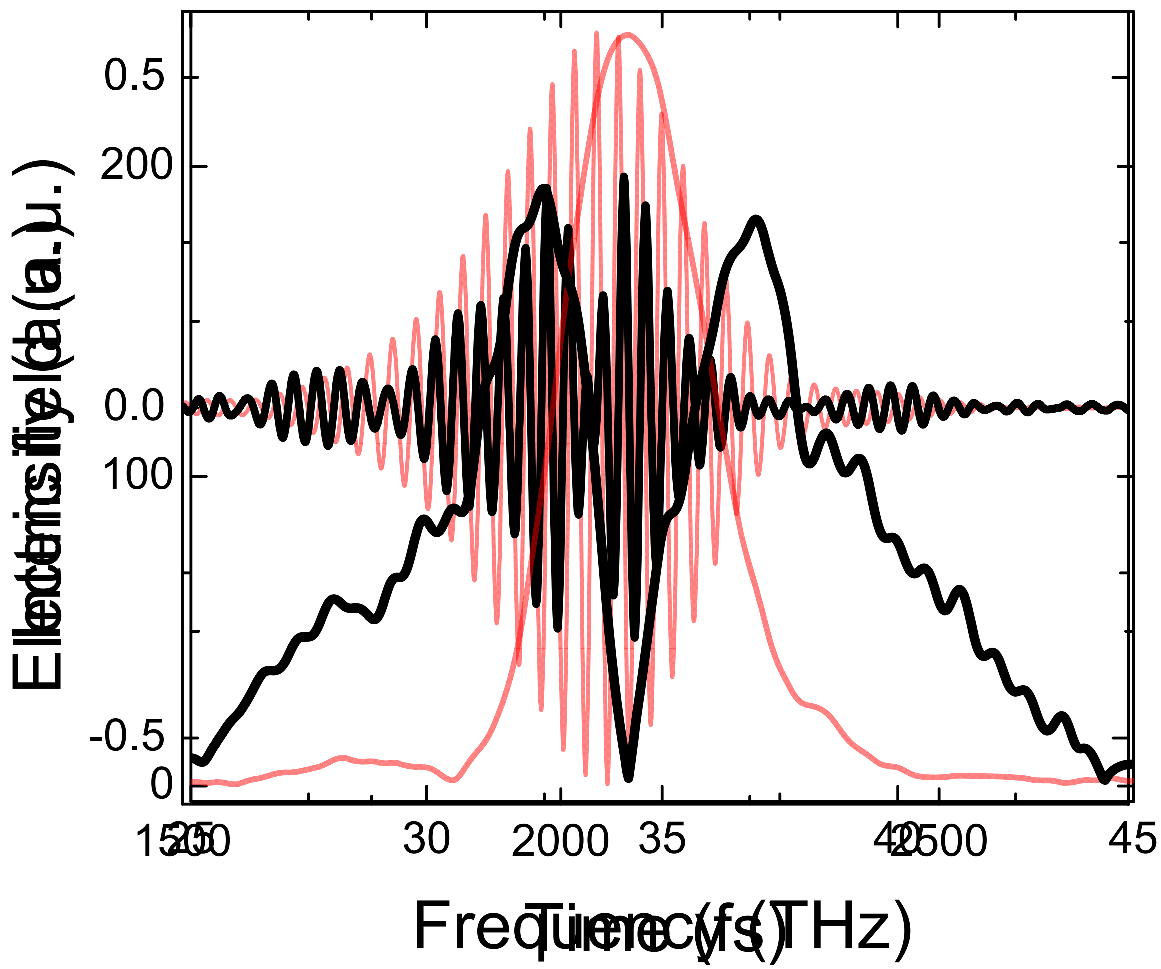


Ez



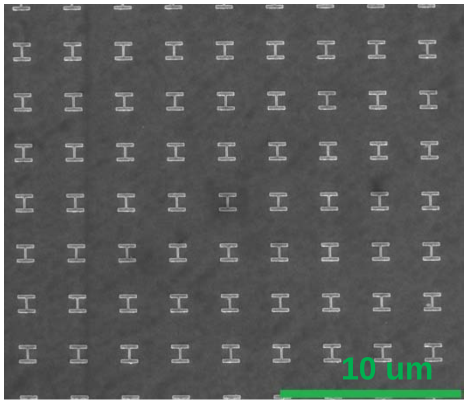
Experimental Rabi Oscillations

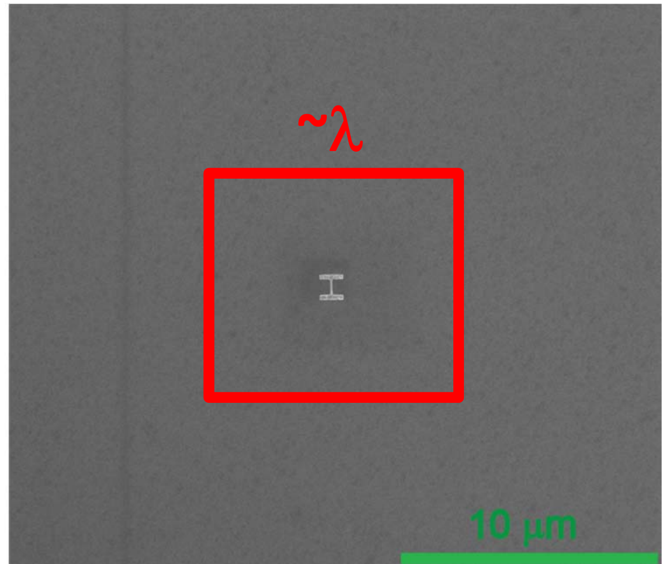
(using a mid-IR Time-domain fsec system)

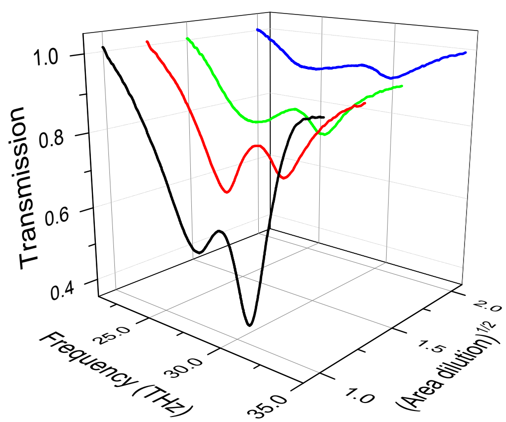


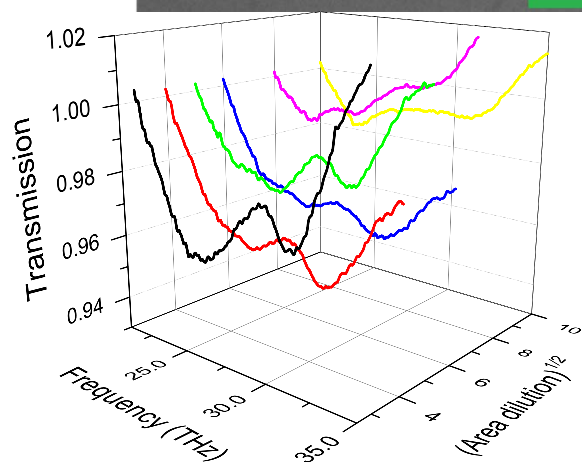
- **Energy exchange probed in time**
  - **33 fs oscillation**
  - **480 fs beating**
- **System strongly coupled**
- **Splitting of 4.2 THz measured**
  - **15 % of ω_{12}**

This is a “Single Resonator” Behavior







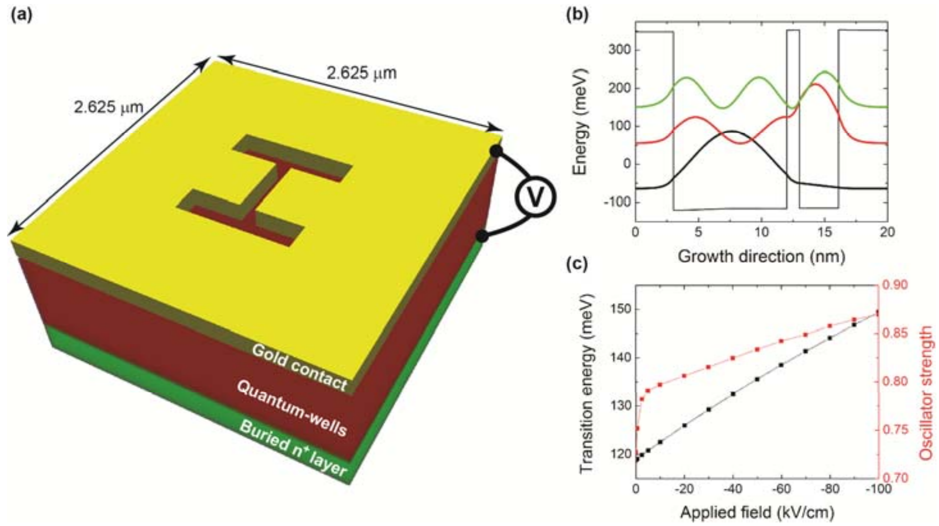


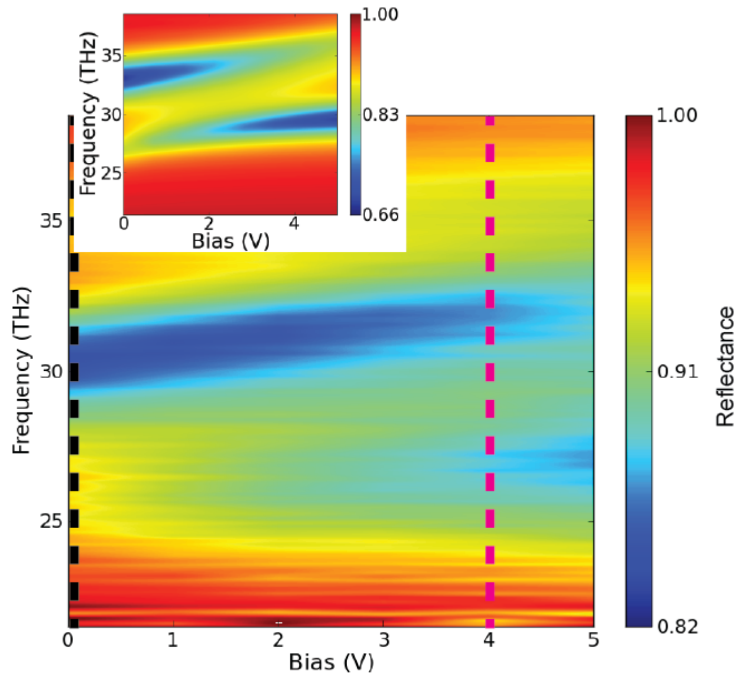
Same Rabi splitting remains down to a single resonator!

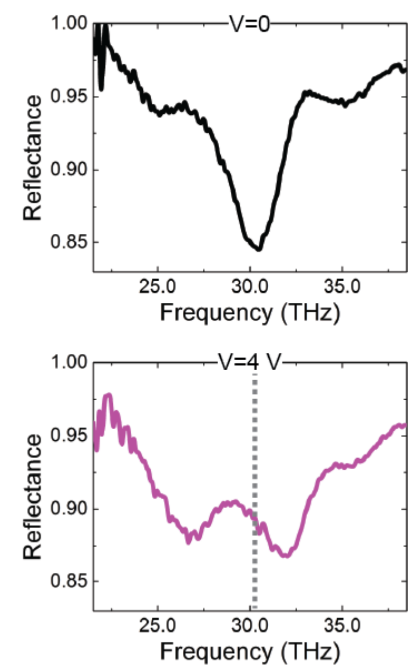
Nature communications **4**, (2013)

Area of a resonator * carrier density ~1000-3000 electrons!

Voltage Tuning of the Strong Coupling







APL **103**, 263116 (2013)

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Postdocs: Alex Benz ,  Sheng Liu (TDS), 

Departed: Young Chul Jun*, James Ginn*, Alon Gabbay*, Brandon Passmore*

CINT + Sandia: John Reno, Mike Sinclair, Ines Montano, John Klem, *, Eric Shaner, Mike Wanke, Joel Wendt, Paul Clem, Jon Ihlefeld, Bruce Burckel, ……

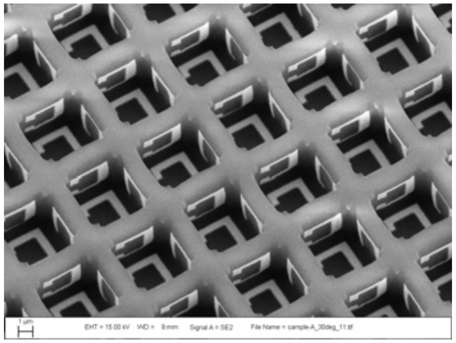
ANU: Y. Kivshar, I. Staude, D. Neshev, ….

UNM: T. Habteyes

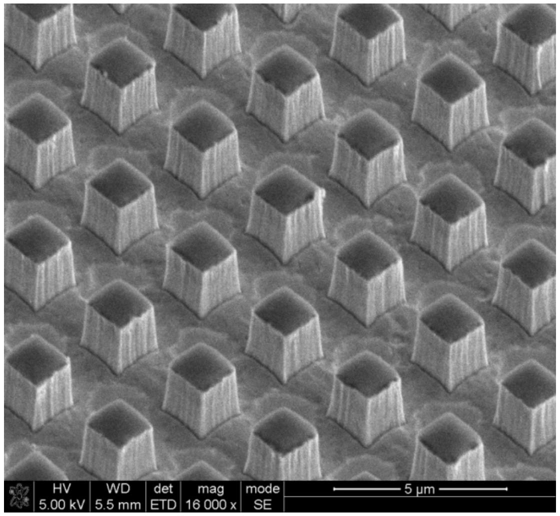
Summary

3D (Passive)

Metallic: Membrane Projection Lithography



Non-Metallic: Dielectric Resonators



2D (Active)