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Dielectric Resonator Metamasurfaces: Optical Magnetism, Emission and Optical Devices

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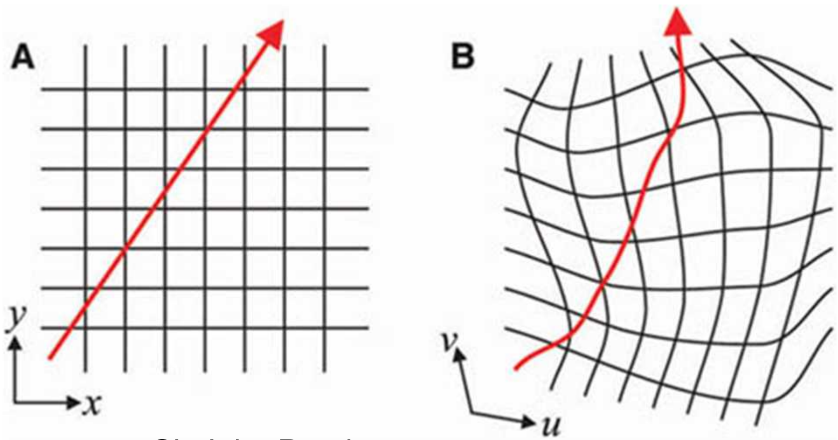
for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

Outline

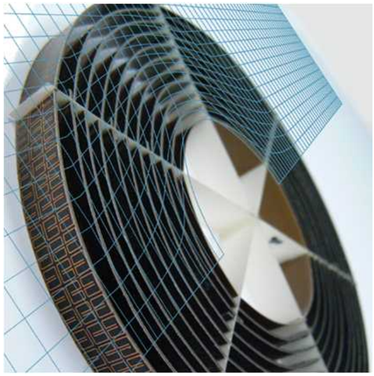
- Dielectric Resonators as Metamaterials
- Optical Magnetism
- Directional Emission, Fano Resonances, and Third-Harmonic Generation

The Promise of 3D Metamaterials

- **Engineer ε and μ everywhere in space using deep subwavelength structures (usually resonators)**
- **Then light will do wonderful things**



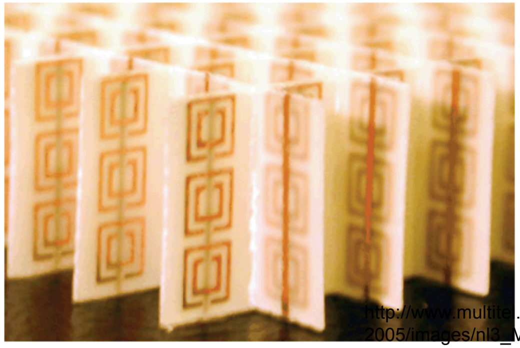
Sir John Pendry



David Smith, Duke

- For RF (~3GHz), λ~cm
- We need to create sub-wavelength "inductors" and "capacitors"

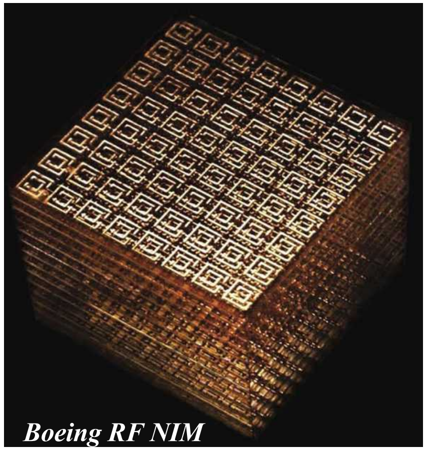
~XXmm



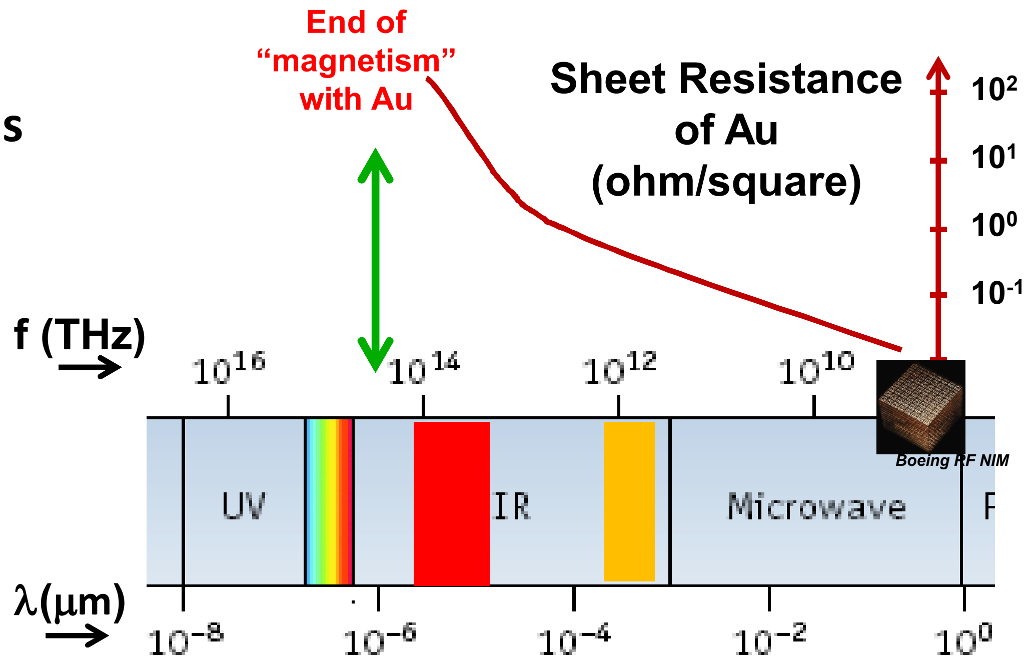
http://www.multitel.be/newsletter/mn7 2005/images/nl3_Metamaterials_type 1.jpg

Metamaterials at Optical Frequencies?

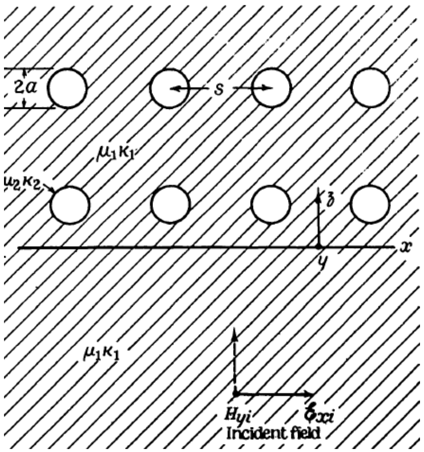
Issue 1: Fabrication



Issue 2: Loss of metals



Dielectric Resonators for Metamaterials



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.)

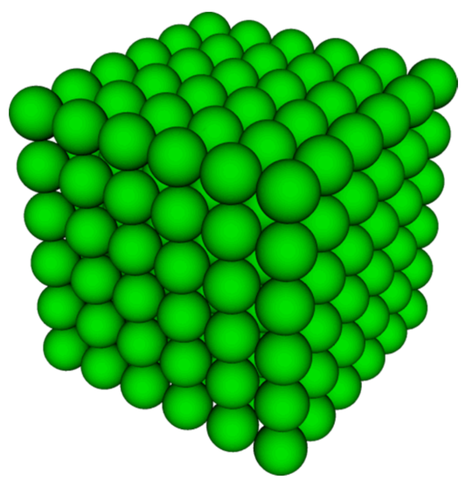
$$\mu'_{\rm re} = \mu_{r1}\left(1 + \frac{3v_f}{\frac{F(\theta)+2b_m}{F(\theta)-b_m} - v_f}\right)$$

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

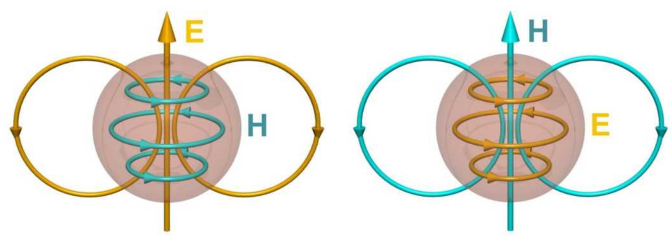
$$F(\theta) = \frac{2(\sin\theta - \theta\cos\theta)}{(\theta^2-1)\sin\theta + \theta\cos\theta}$$

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

$$b_{\rm e} = \frac{\epsilon_1}{\epsilon_2}, \qquad b_m = \frac{\mu_1}{\mu_2}$$

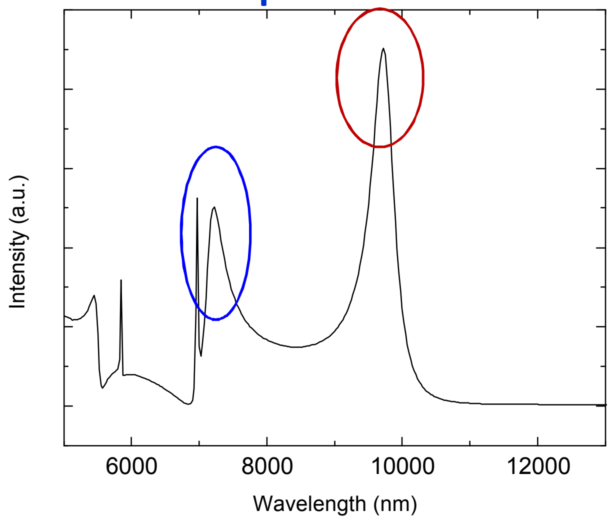


Dielectric Resonators



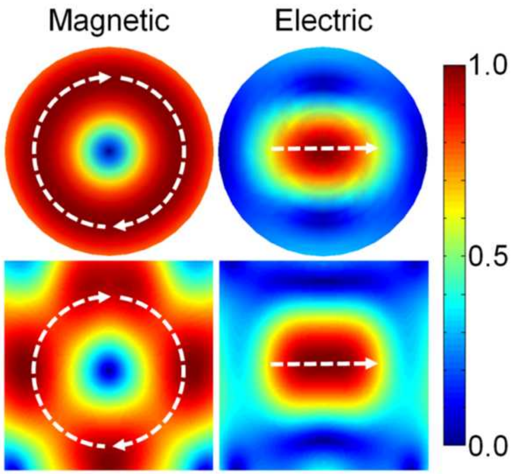
Images: A. Miroshnichenko

magnetic dipole resonance
electric dipole resonance



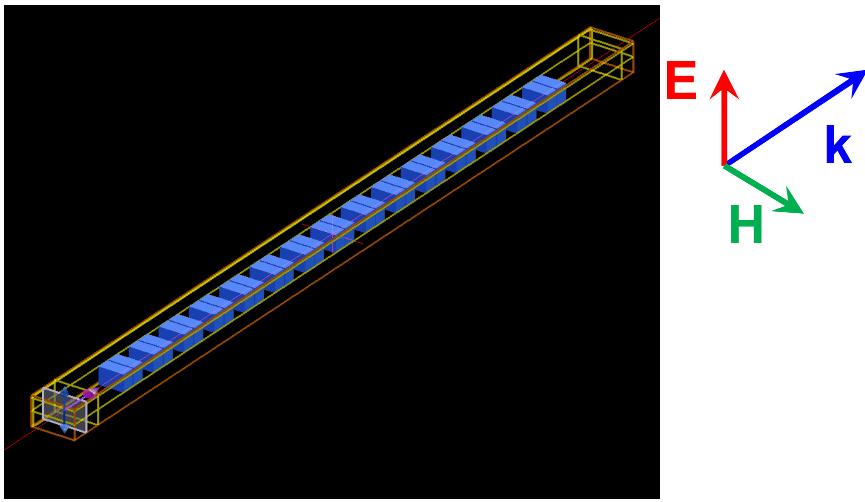
Magnetic dipole resonance: tailor μ
Electric dipole resonance: tailor ε

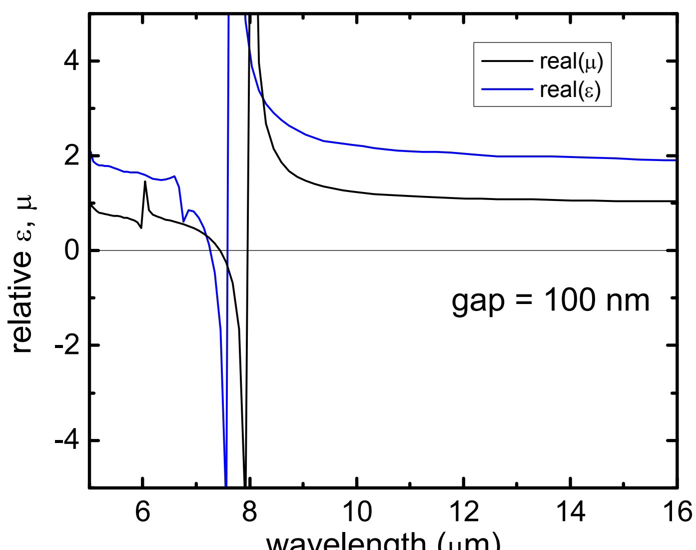
- **Cubes work fine too**
- **Introducing "cuts" in cube can move relative positions of resonances**



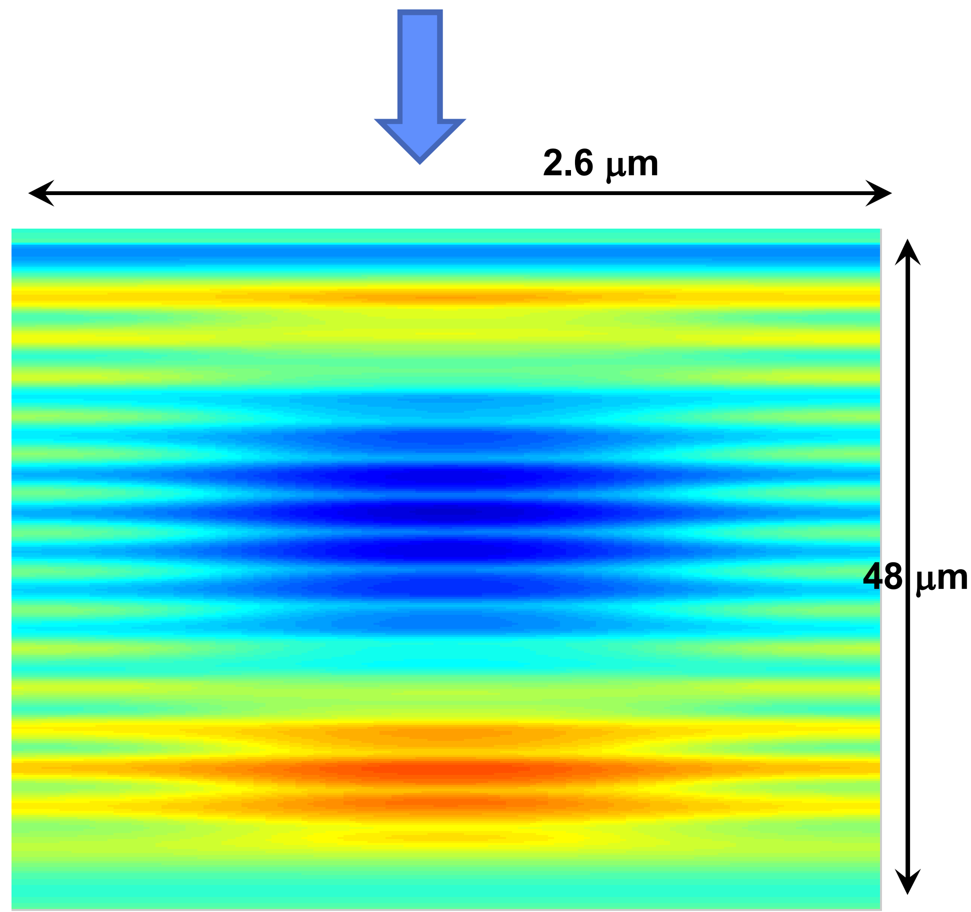
Full Wave Simulation of Propagation Through Split Cube Array

ε=32, edge = 1.53 μm, gap = 100 nm





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



λ = 7.5 μm

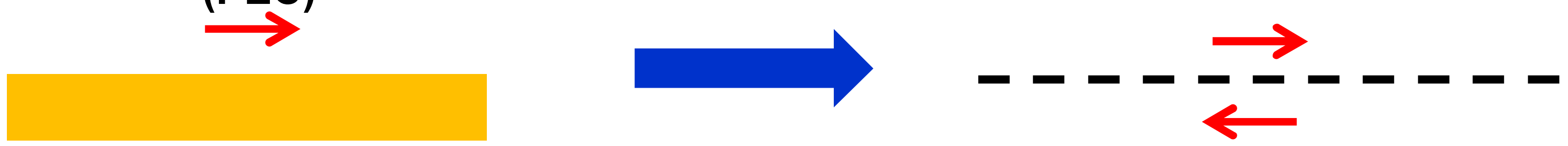
What is a mirror?

“Regular” mirrors invert the phase of the reflected wave

Dipoles Close to Surfaces

Electric dipole on top of a perfect electric conductor (PEC)

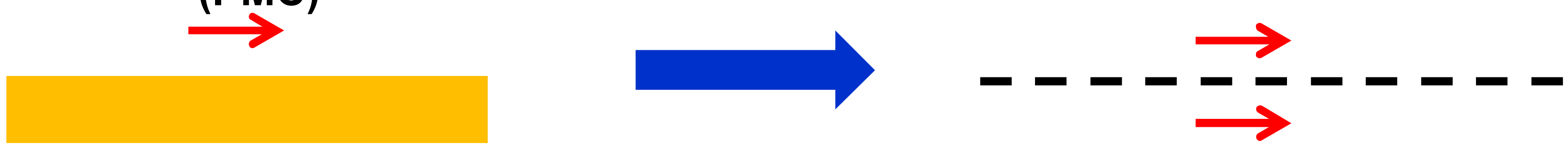
IMAGE THEORY



- Because of boundary condition of the PEC surface, the electric field at the dashed plane has to be zero
- This means that the radiation of an electric dipole close to PEC is quenched

Electric dipole on top of a perfect magnetic conductor (PMC)

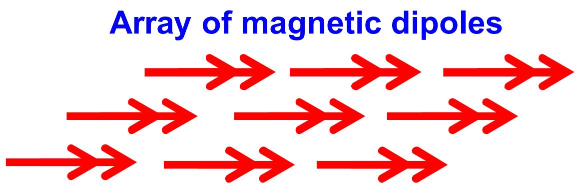
IMAGE THEORY



- This means that the radiation of an electric dipole on a PMC is enhanced

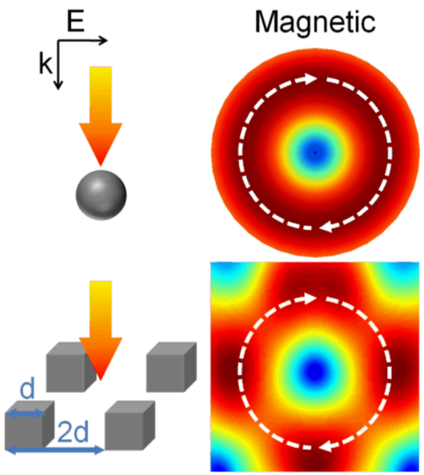
Magnetic Dipoles

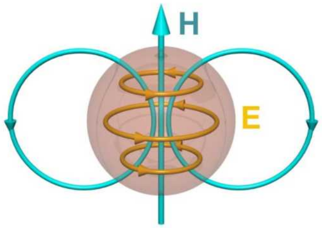
However, a perfect magnetic conductor does not exist in nature



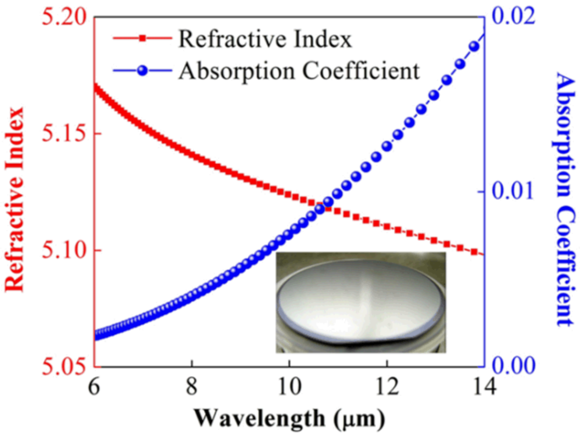
Because the magnetic dipole responds in phase with the electric field, this represents an artificial magnetic conductor

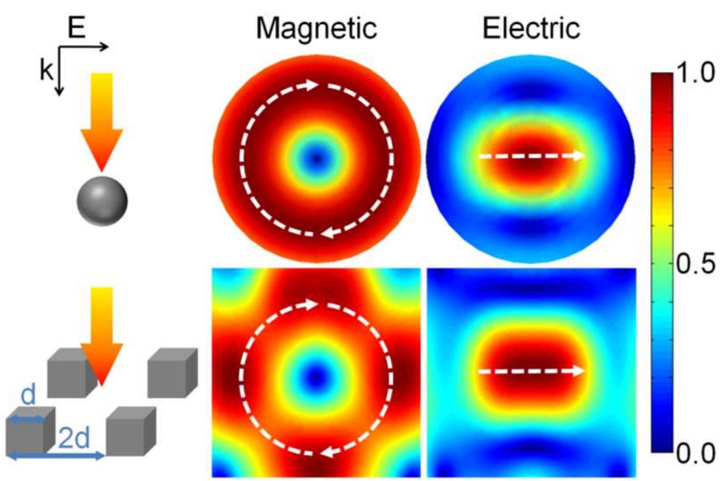
Dielectric Spheres



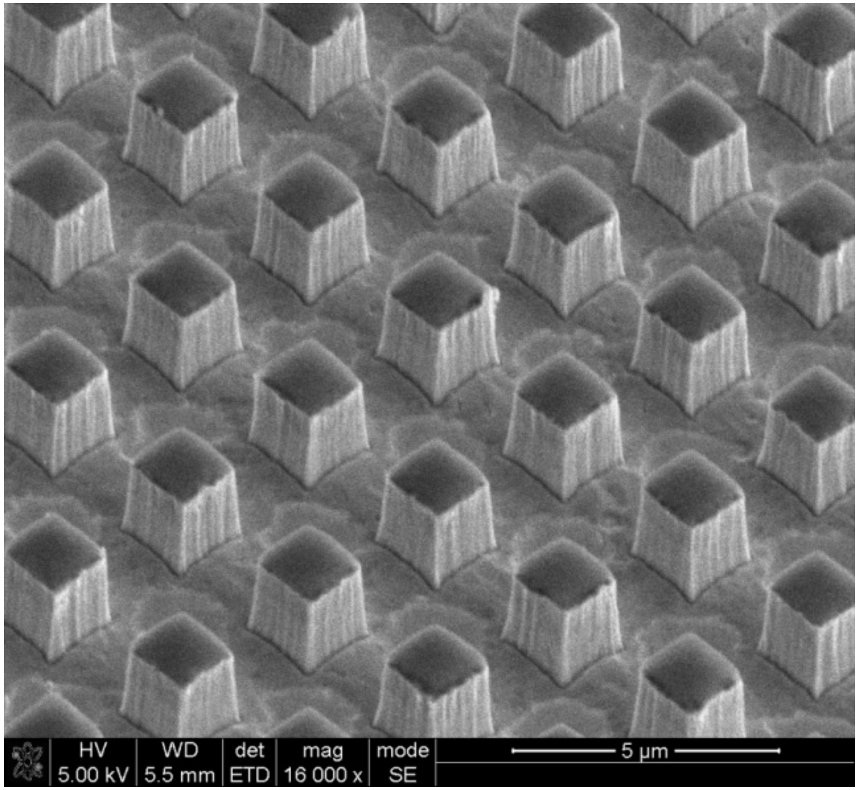


Dielectric Resonator IR Metamasurface: Te/BaF_2





Mask + RIE etch



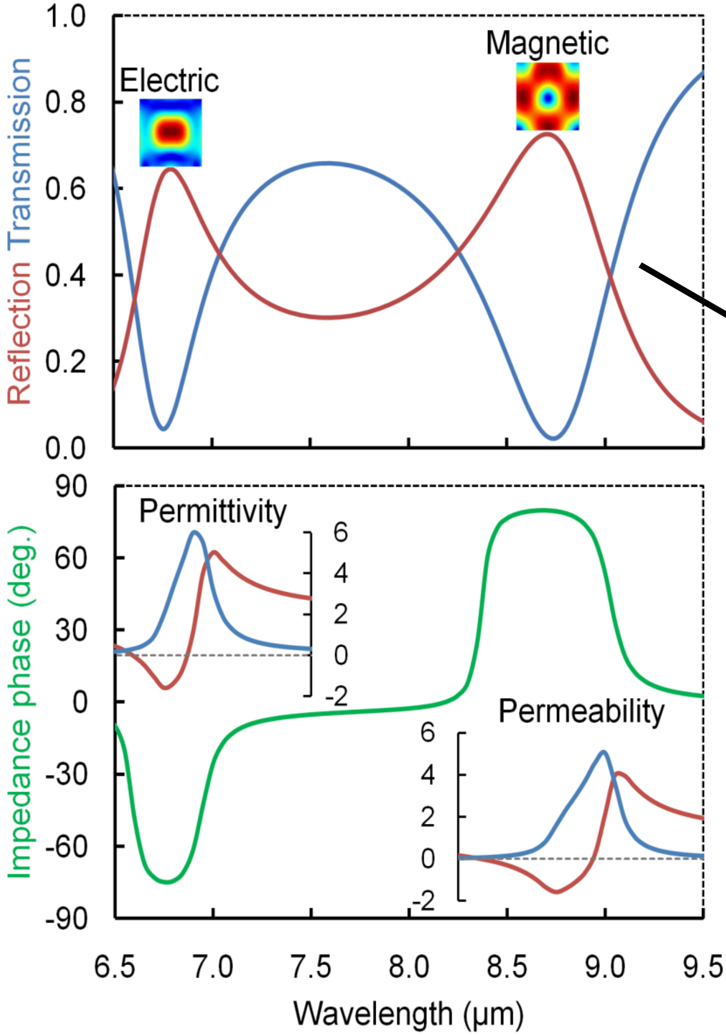
$1.53x1.53x1.7mm^3$

10 deg wall slope

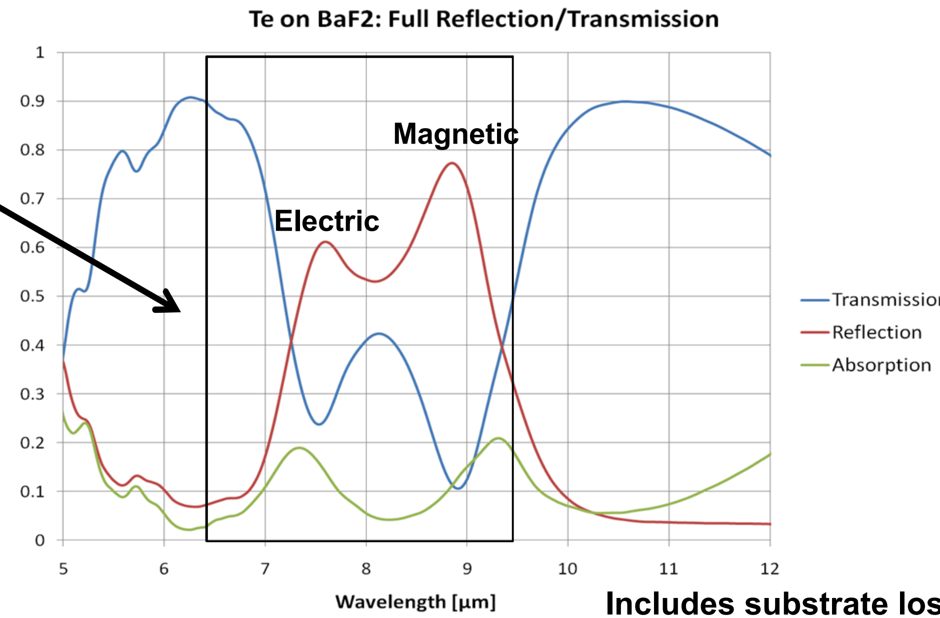
Phys. Rev. Lett. 108, 097402 (2012)

Dielectric Resonator IR Metasurface: Te/BaF_2

Theory



Experiments

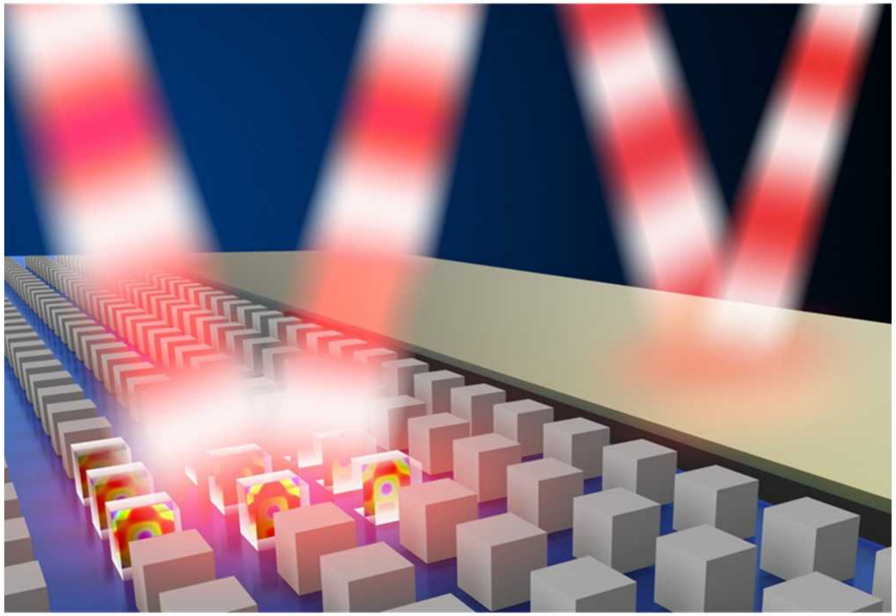


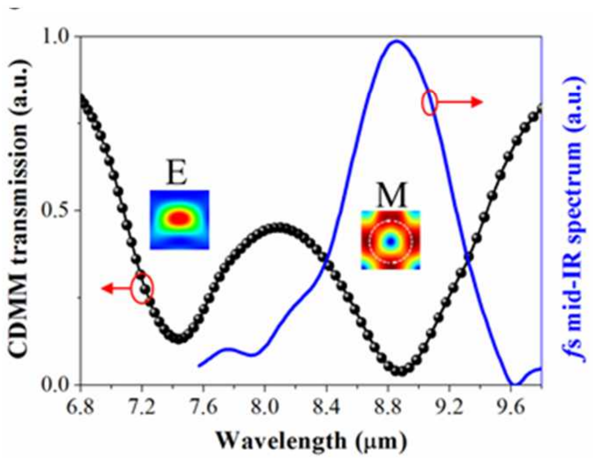
Includes substrate losses

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

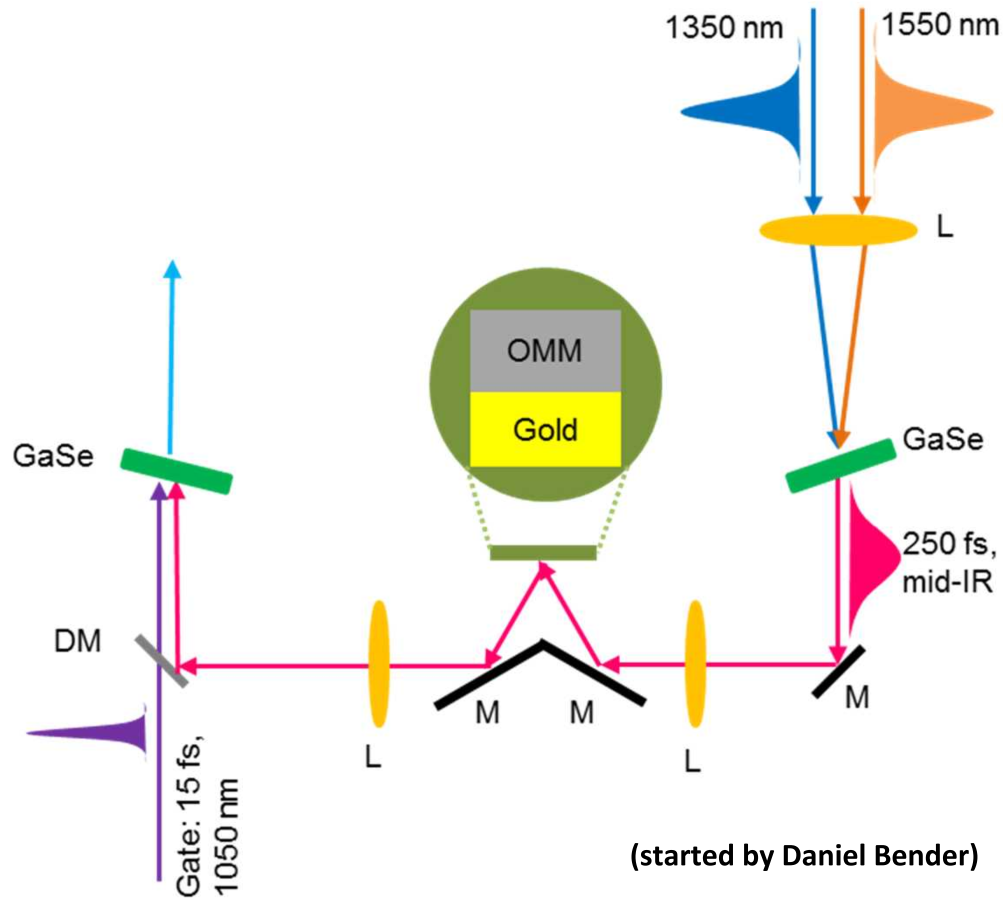
Proving Optical Magnetism:
Measure Absolute Phase of Reflected Wave

a





Phase-locked Time Domain Spectroscopy

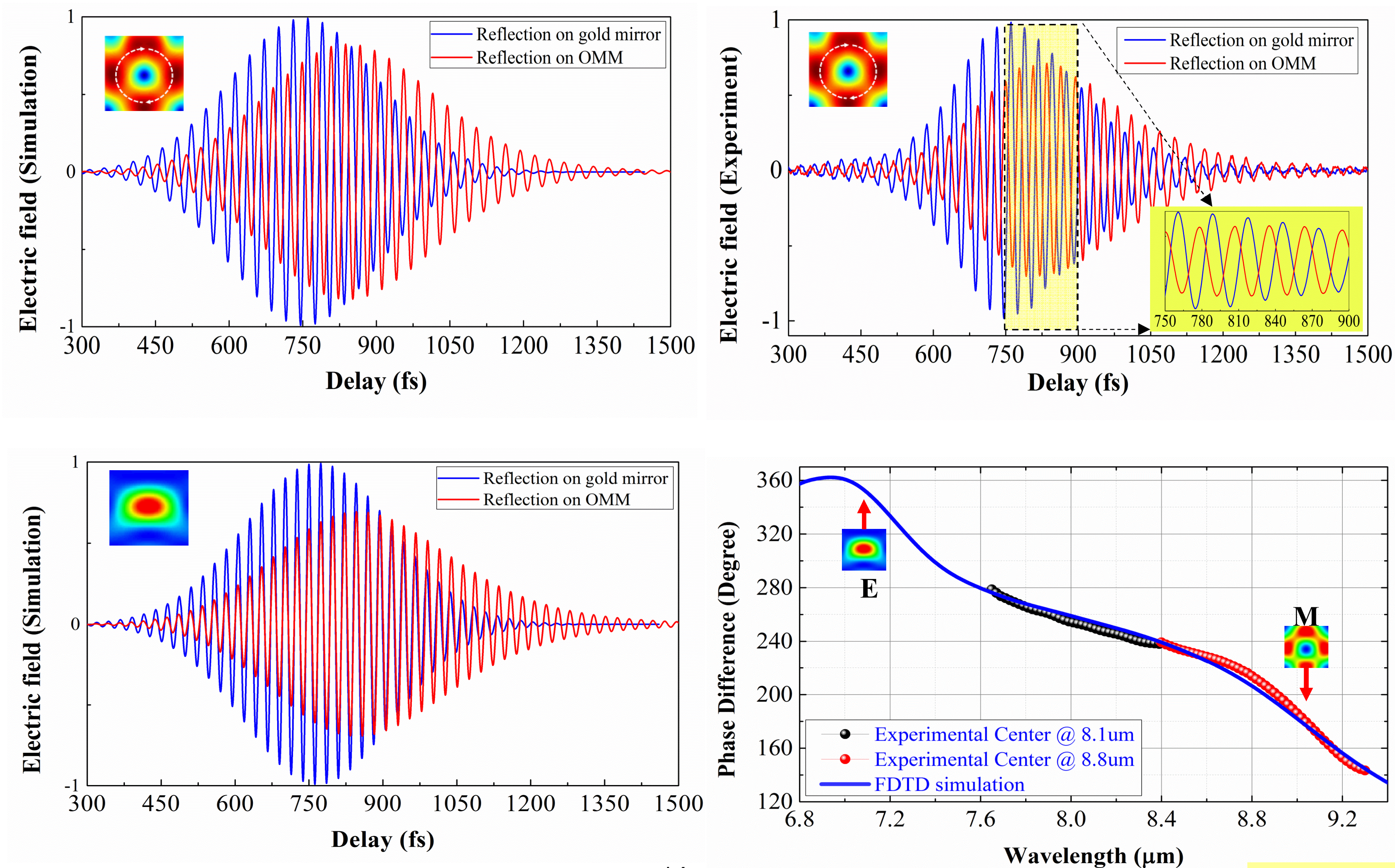


(started by Daniel Bender)

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

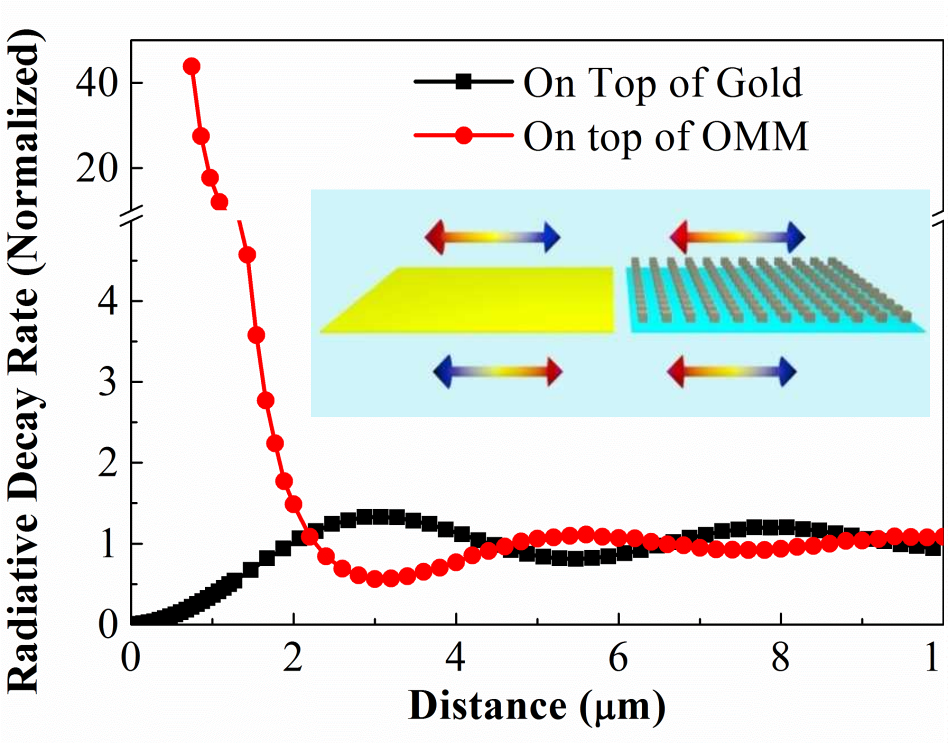
Optica (2014)

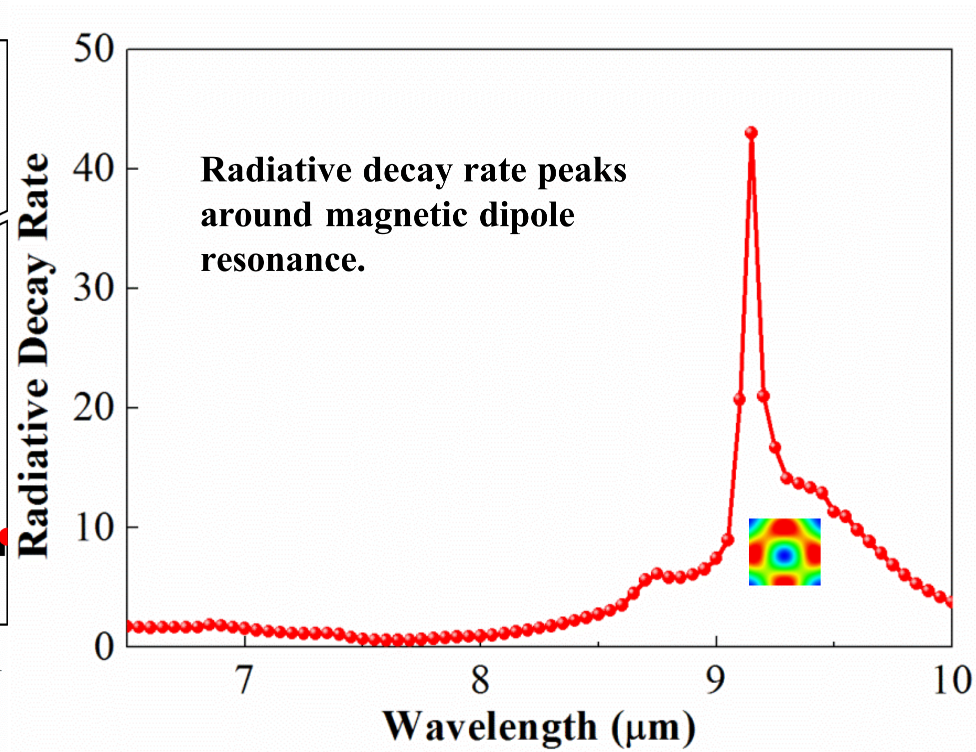
Experimental Demonstration of "Optical Magnetism"



Optica (2014)

Radiative Decay Rate of a Transverse Electric Dipole Near Au and OMM Surfaces

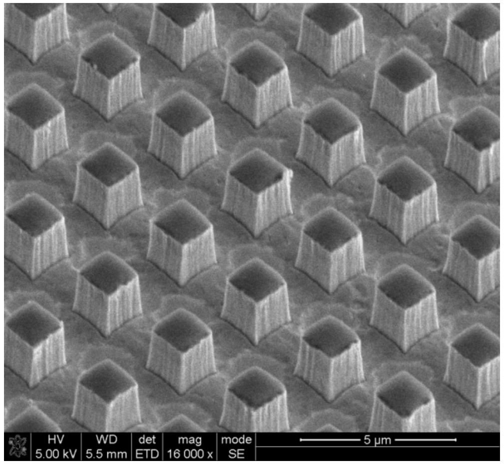


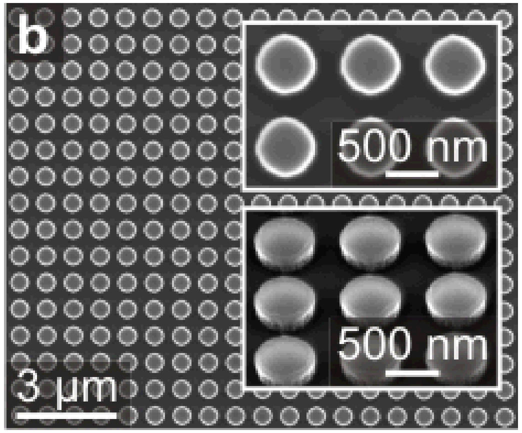


- Oscillatory dependence on distance is shifted by about half a period
- Dipole emission near the magnetic mirror is enhanced even for very small distances

Optica (2014)

Scaling Dielectric Resonators to the Near IR: Silicon Nanostructures

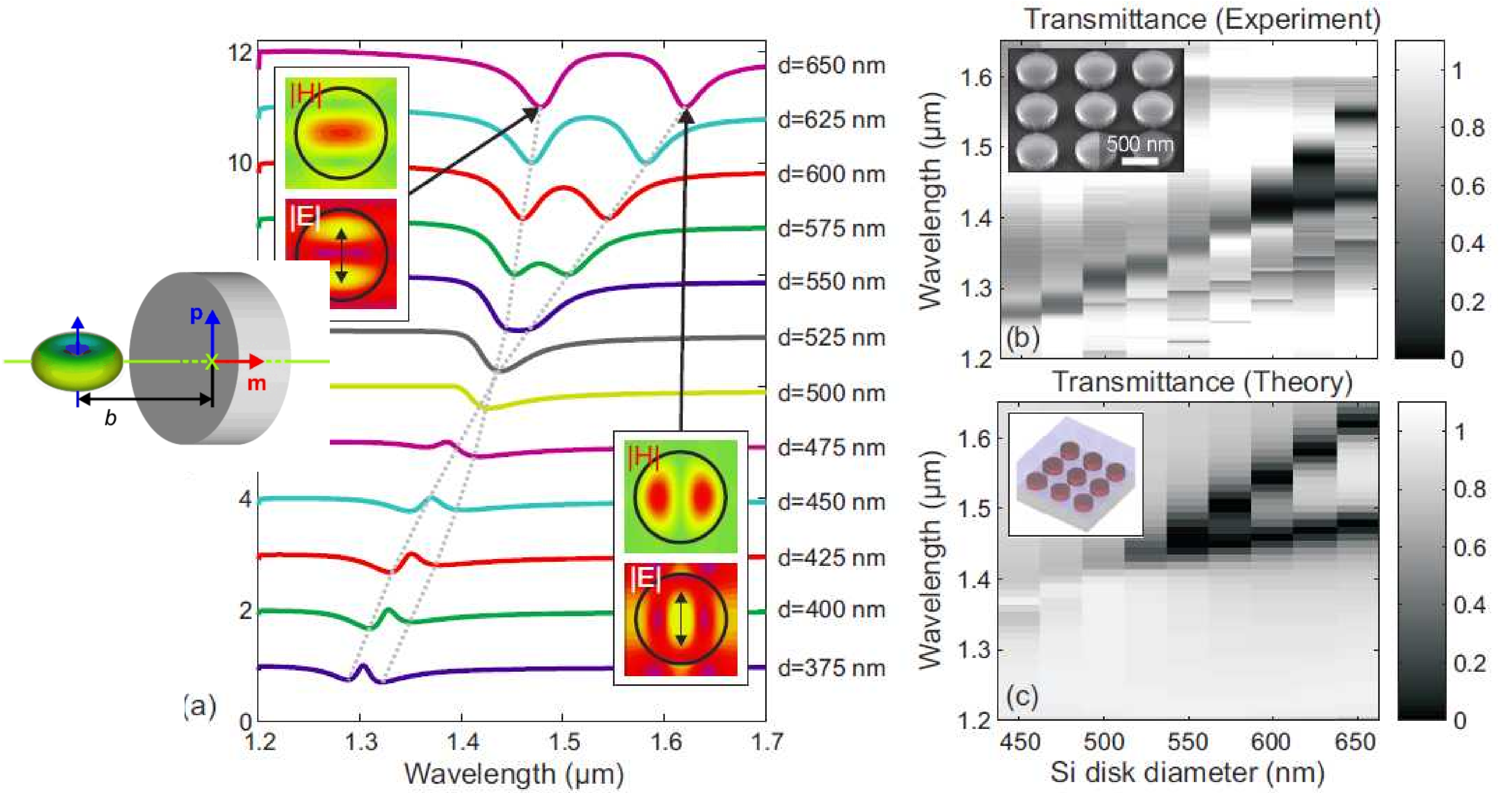




Tellurium: n~5, Size~1.5μm
λ>5μm

Silicon: n~3.5, Size<200-500nm
λ>1μm

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

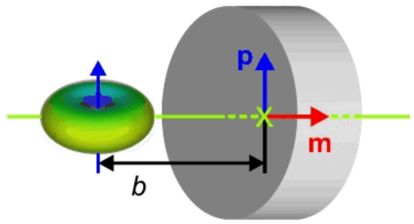


Changing the aspect ratio of the nanocylinder, changes relative position of E & H resonances

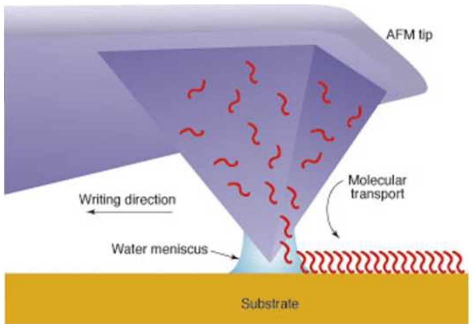
ACS Nano 2013 7 (9), 7824-7832

Integration with Quantum Dots

With J. Hollingsworth and F. Darwood, LANL

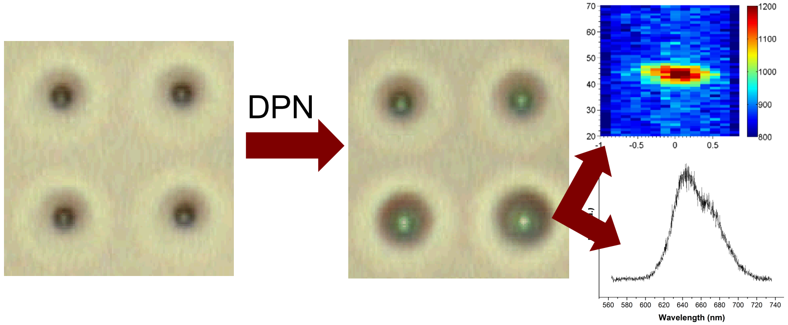


Dip-pen nanolithography



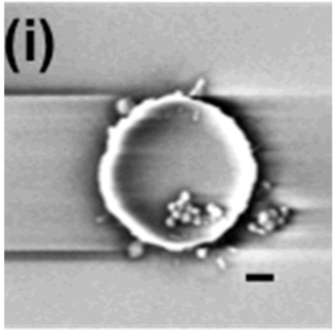
http://str.llnl.gov

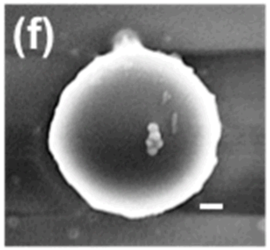
Many QDs



QDs in protective polymer coating selectively deposited onto the tops of Si nanoresonators

Towards Single QDs



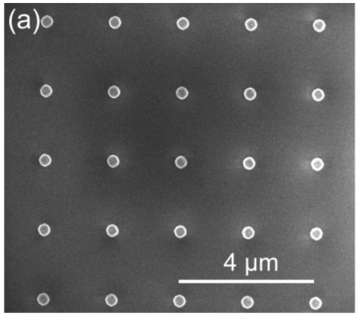


35°

(near-IR g-NQDs)
SEM: C. Sheehan, LANL

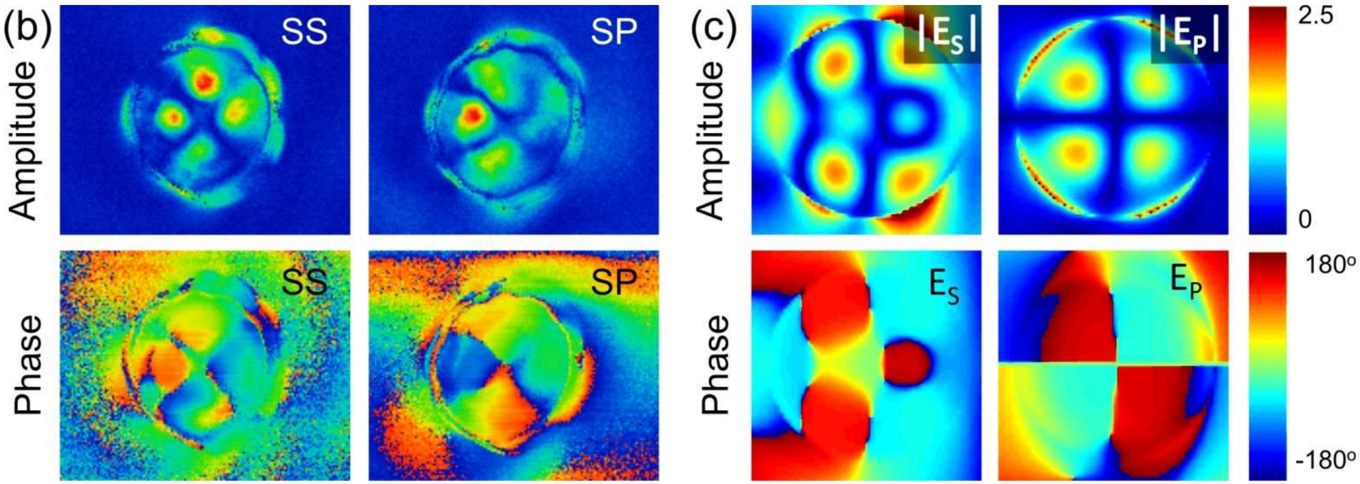
Near Field Imaging of Localized Modes

With Prof. Habteyes, UNM



nanodisk diameter 412 nm,
nanodisk height 140 nm
λ=633nm

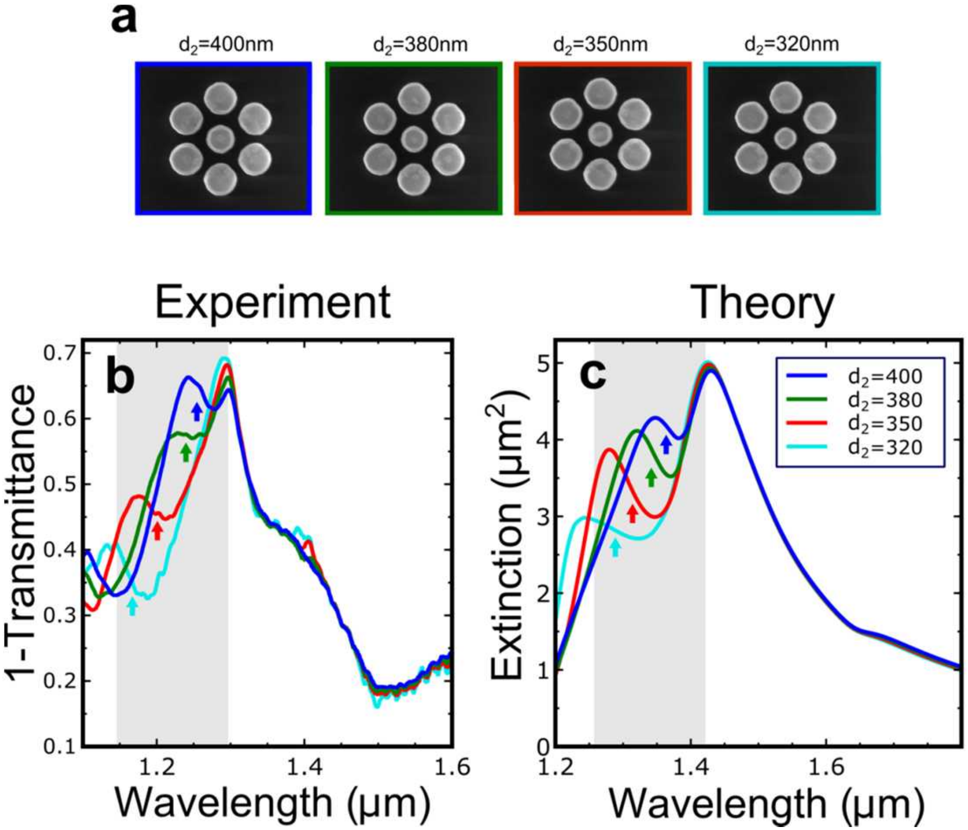
Measurements **Calculated near-field amplitudes**



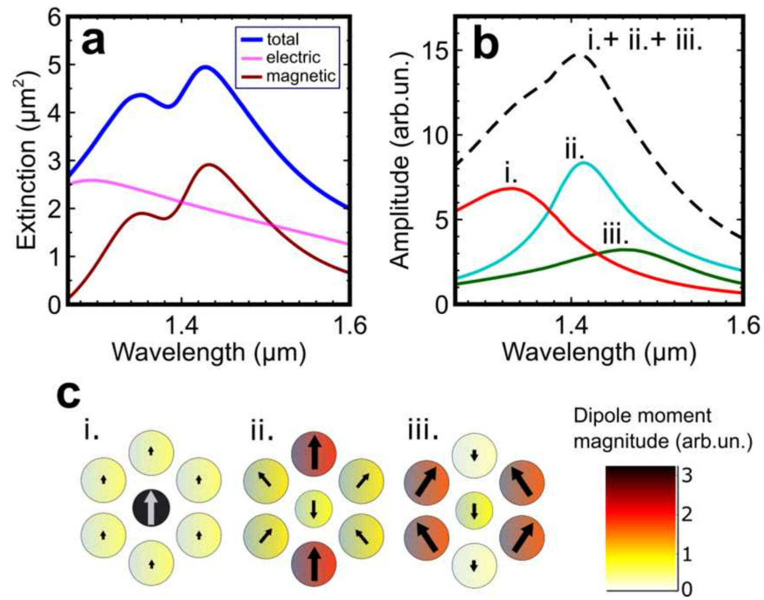
Mostly electric quadrupole

ACS Photonics (2014)

Fano Resonances in All-Dielectric Nanoparticle Oligomers



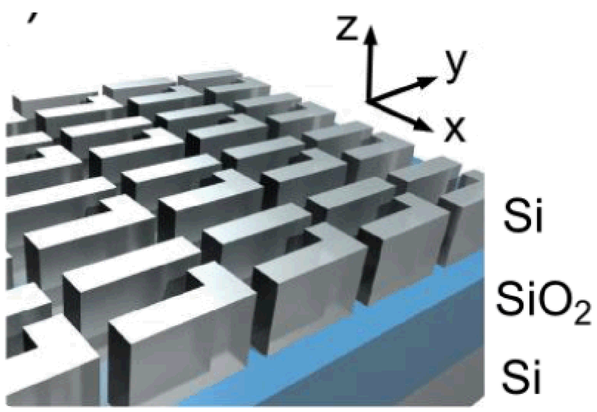
(with I. Staude & Y. Kivshar, ANU)

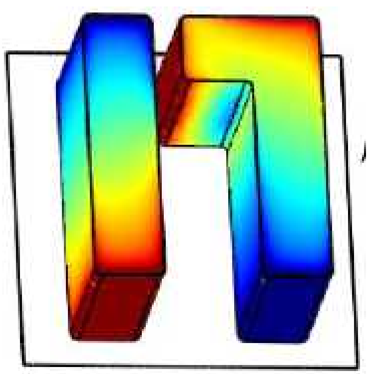


Small (2013)

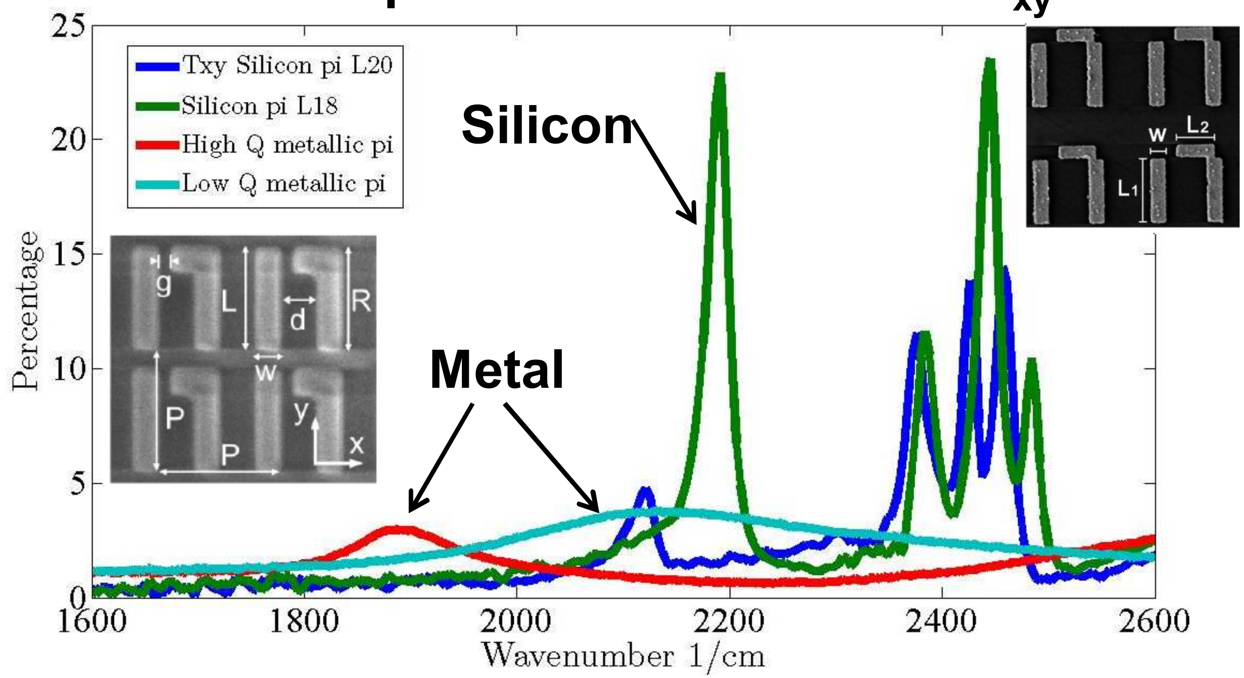
All-Dielectric Fano-Resonant 2D Chiral Metasurfaces:

Order of Magnitude Higher Q Than Similar Metallic Metasurfaces (with G. Shvets, UT Austin)



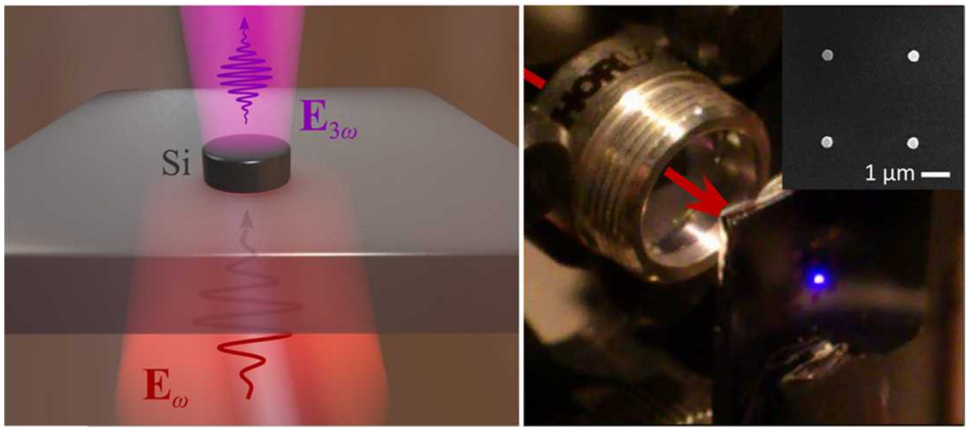


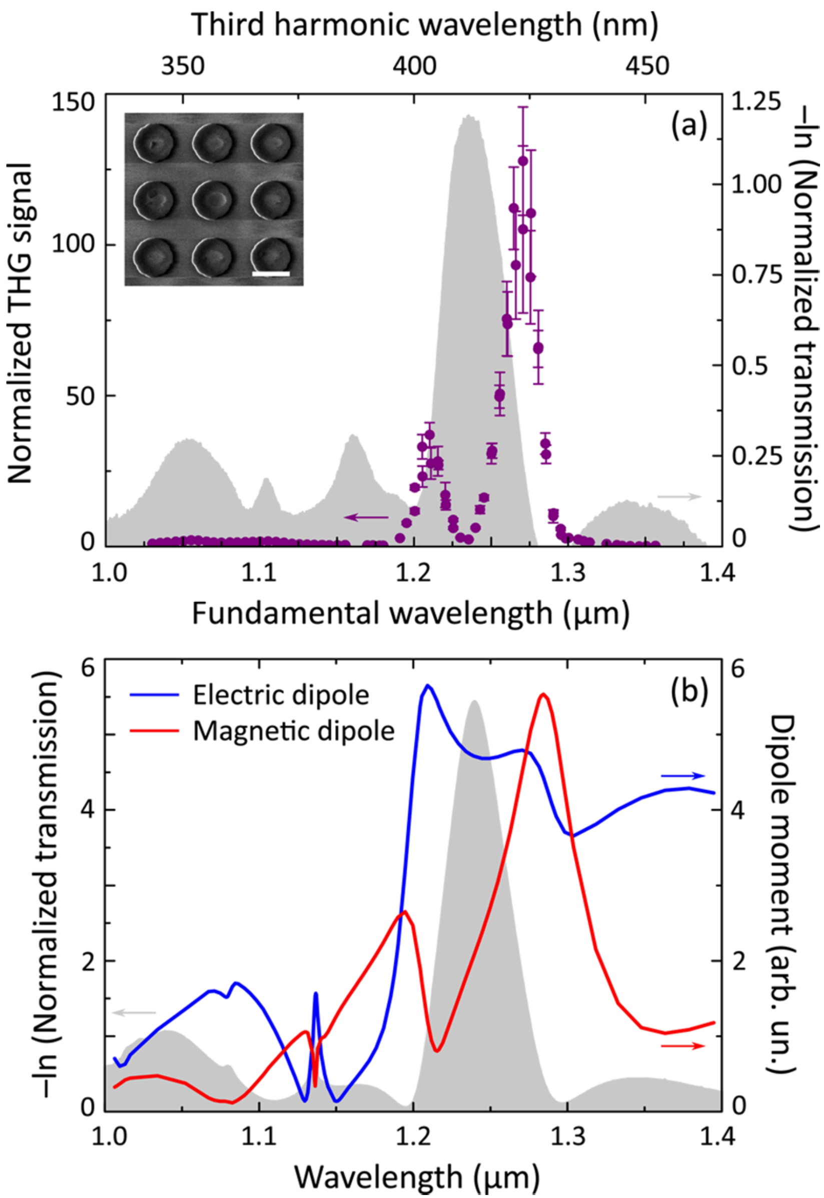
Cross-polarized transmission T_{xy}



Nature Communications (2014)

Third Harmonic Generation

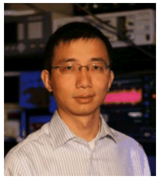




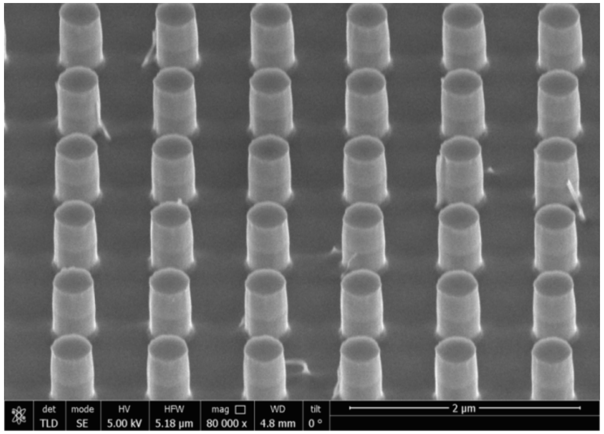
(With ANU & Moscow State)

Nano Letters (2015)

Dielectric Metamaterials with III-V's?

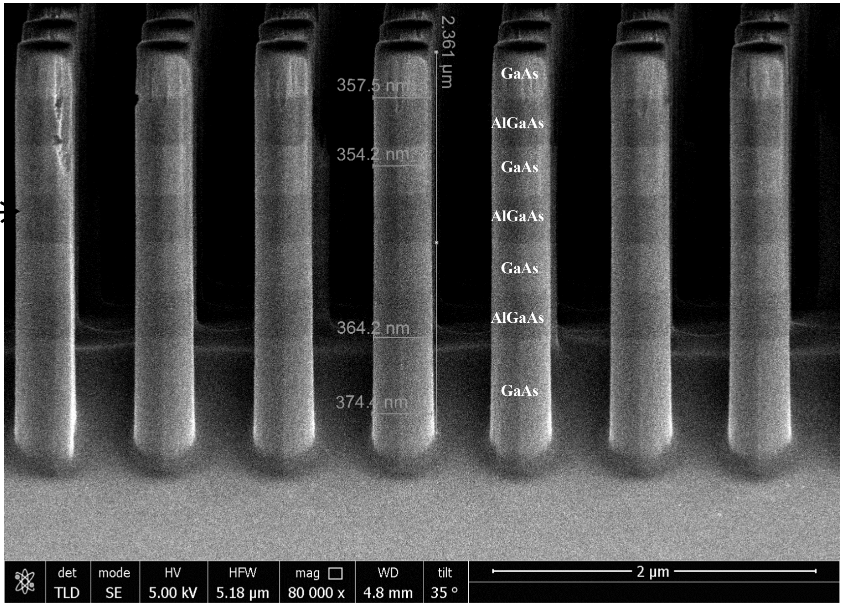


Sheng Liu

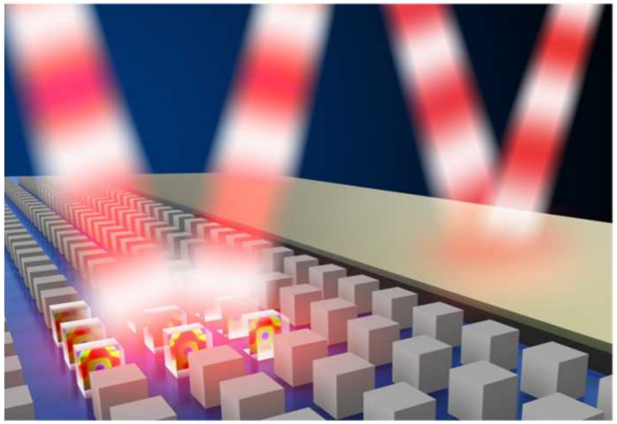


GaAs nanocylinders

Oxidized

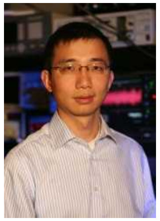


Summary



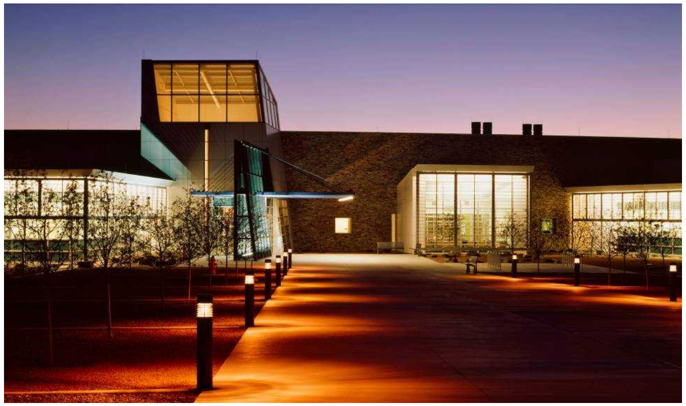
- Arrays of dielectric resonators were used to create an "optical magnetic mirror".
- Proved magnetic mirror behavior using absolute optical phase measurements

- Through geometry and mode control, high index dielectric resonators offer a platform to create optical devices and metamaterial functionality.

ACKNOWLEDGMENTS:
Postdocs: Sheng Liu (TDS),  Salvo Campione (Theory), 

- **CINT + Sandia**: Mike Sinclair, Jason Domingues, J. Ihlefeld, J. Ginn*, Lorena I. Basilio, Larry K. Warne, P. Clem, J. Wendt, D. Bender, T. Mahony, J. Wright
- **ANU**: Y. Kivshar, I. Staude, M. Decker, D. Neshev, …
- **Lomonosov Moscow State**: M. Shcherbakov,…
- **UNM**: T. Habteyes
- **UT Austin**: G. Shvets

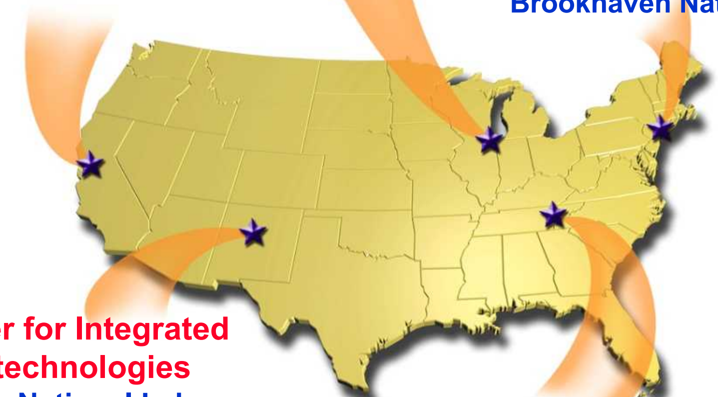
Center for Integrated Nanotechnologies: CINT



Center for Nanoscale Materials
Argonne National Lab.

Molecular Foundry
Lawrence Berkeley National Lab.

Center for Functional Nanomaterials
Brookhaven National Lab.



Center for Integrated Nanotechnologies
Sandia National Labs.
Los Alamos National Lab.

Center for Nanophase Materials Sciences
Oak Ridge National Lab.

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

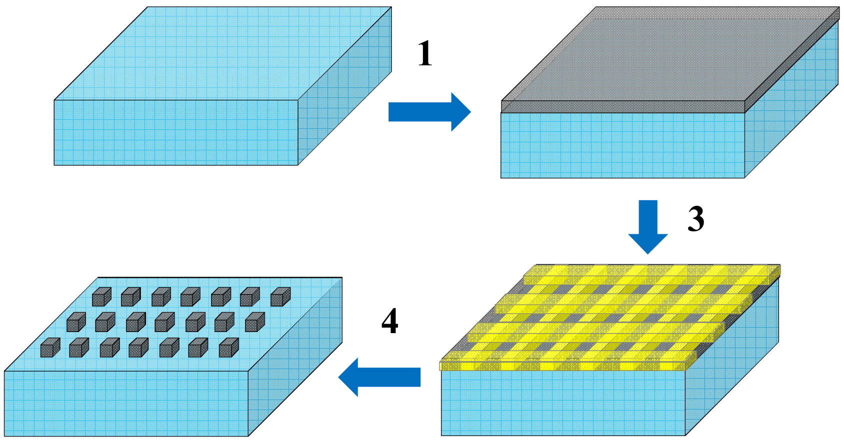
User facility: free to use

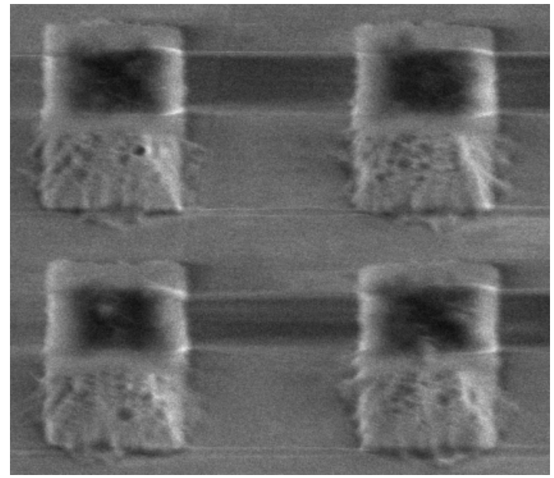
http://cint.sandia.gov

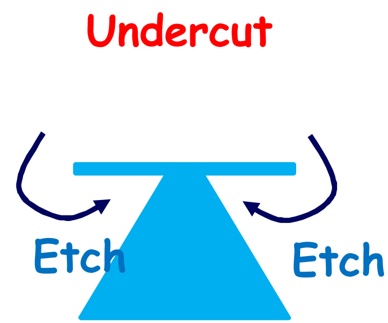
END

Prior (Difficult) Fabrication

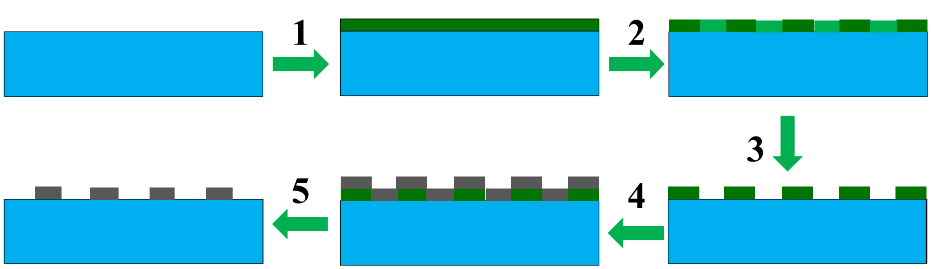
Deposition + Mask + Etching

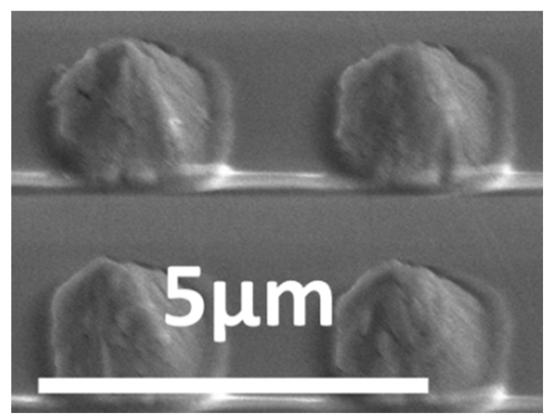


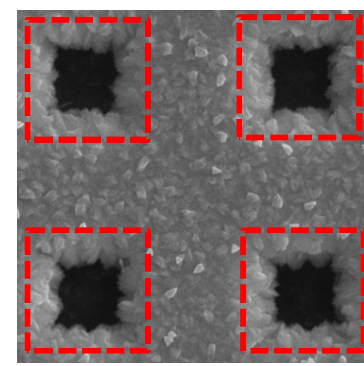




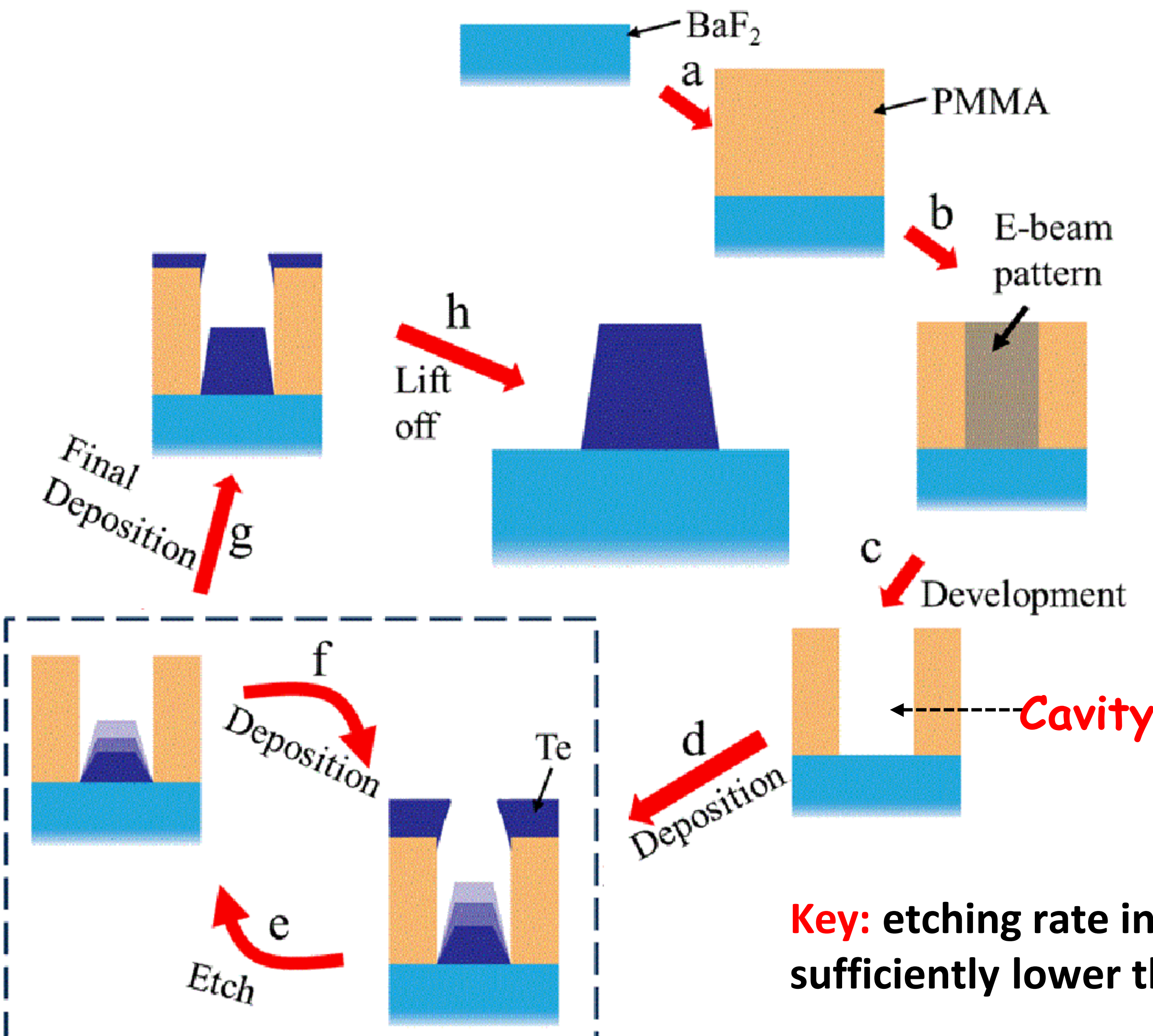
Deposition + Liftoff

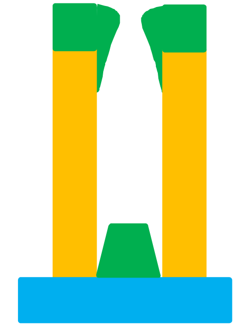






Multi-cycle Deposition-etch Process



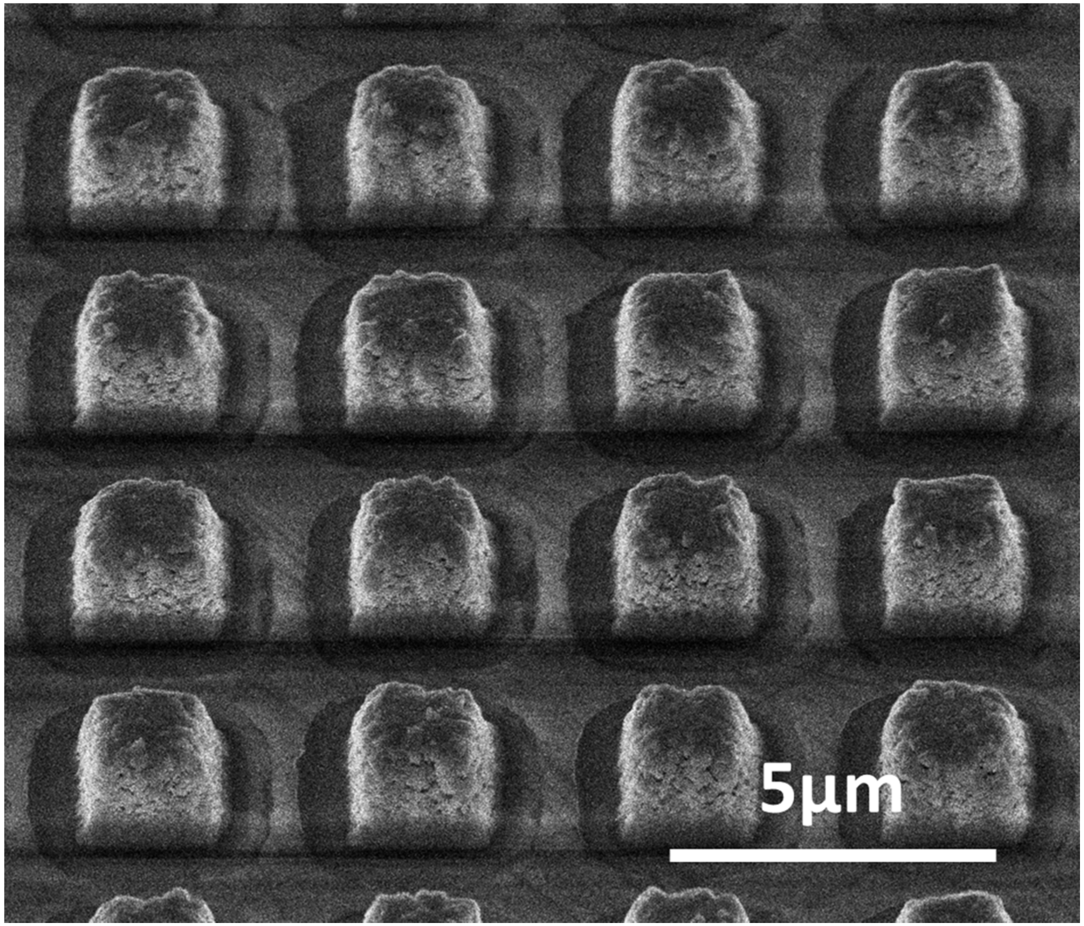


Pinch-off

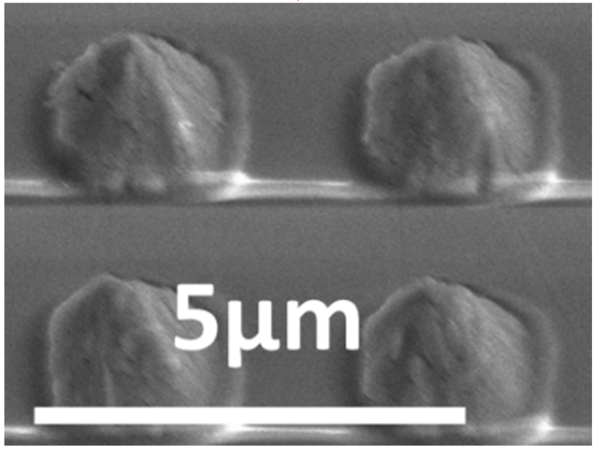
Key: **etching rate inside the cavity is sufficiently lower than that on surface**

Multi-cycle Deposition-etch Process

2 Dep-etch cycles

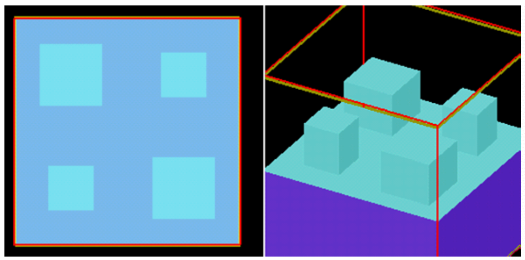


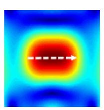
Single deposition



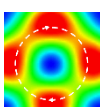
Transmission Spectra of Te metamaterial

- Tuning of electric and magnetic resonances
- Overlap of electric and magnetic resonances (potential for negative index material)

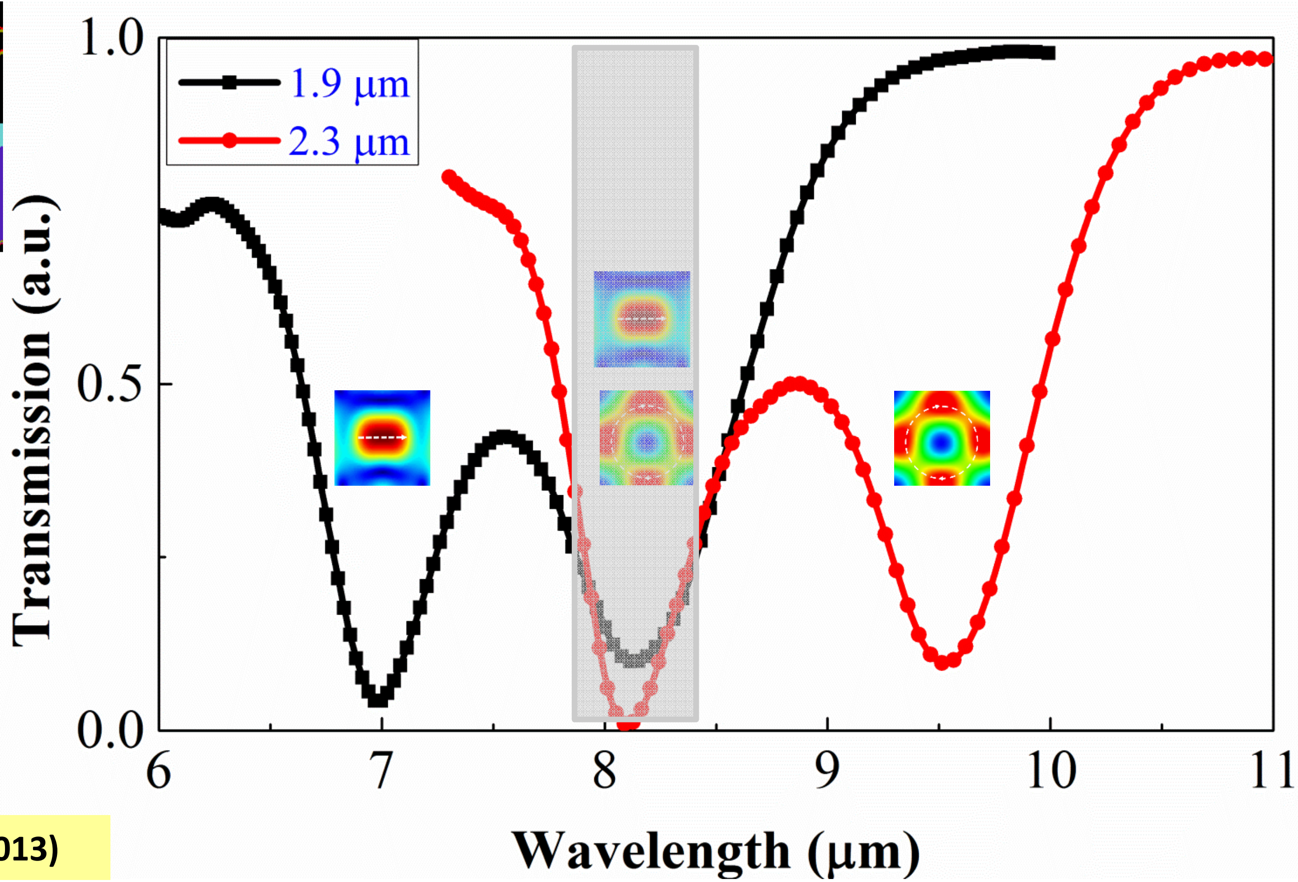




ε<0

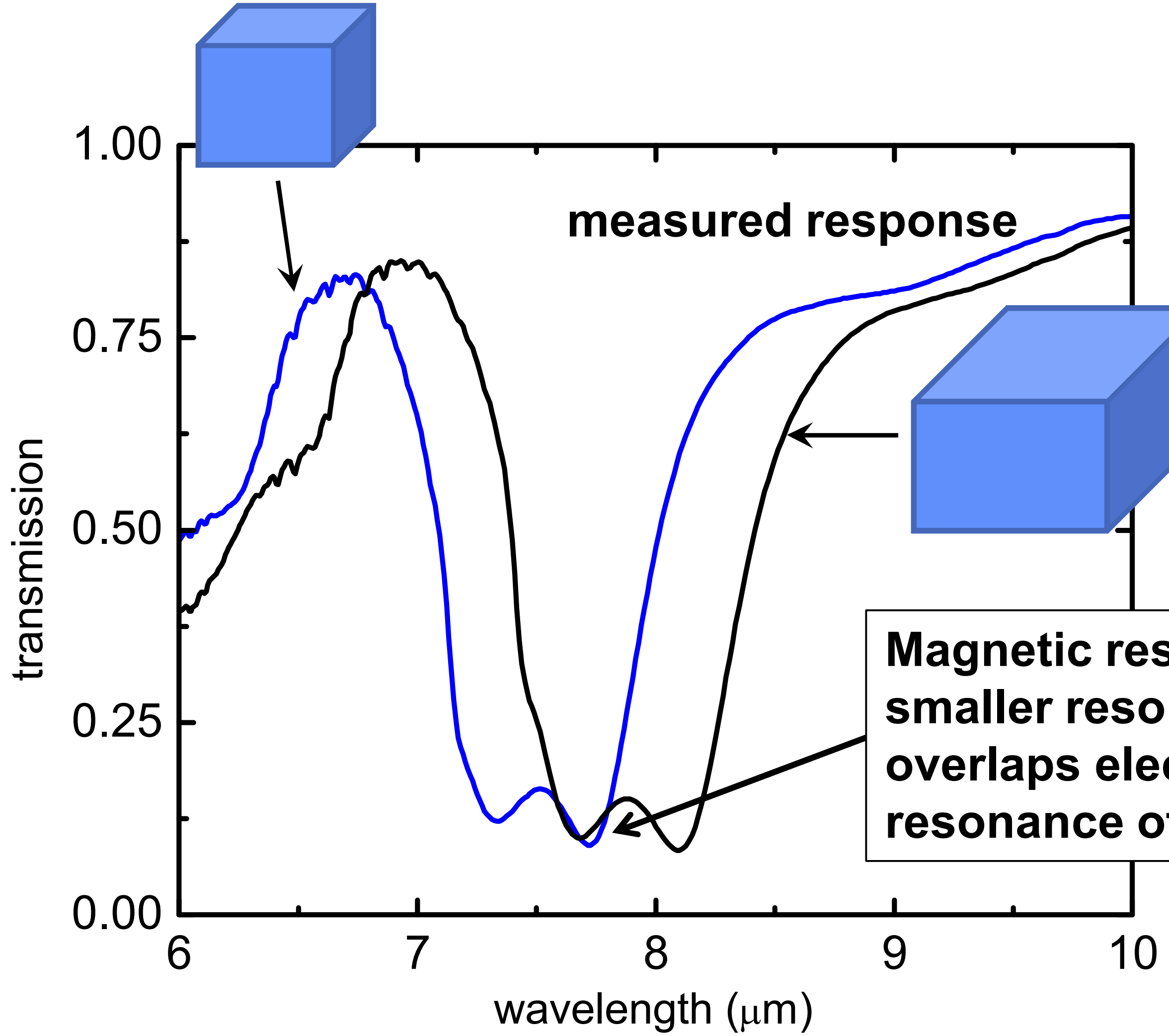


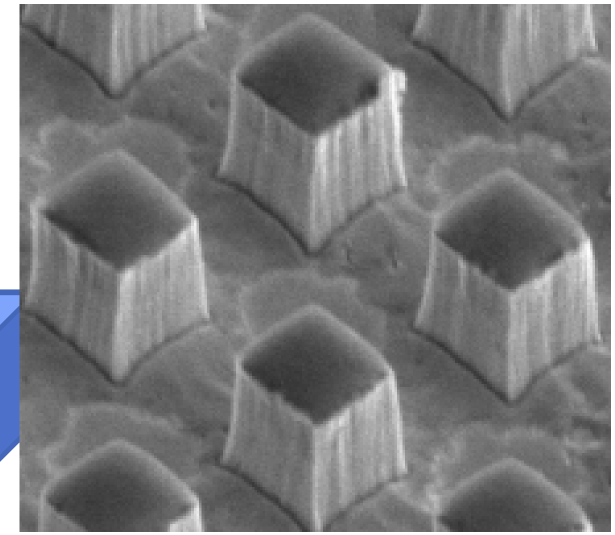
μ<0



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

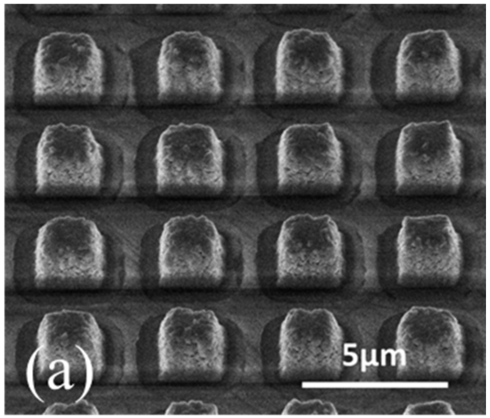
Te Resonators: Electric and Magnetic Mode Overlap

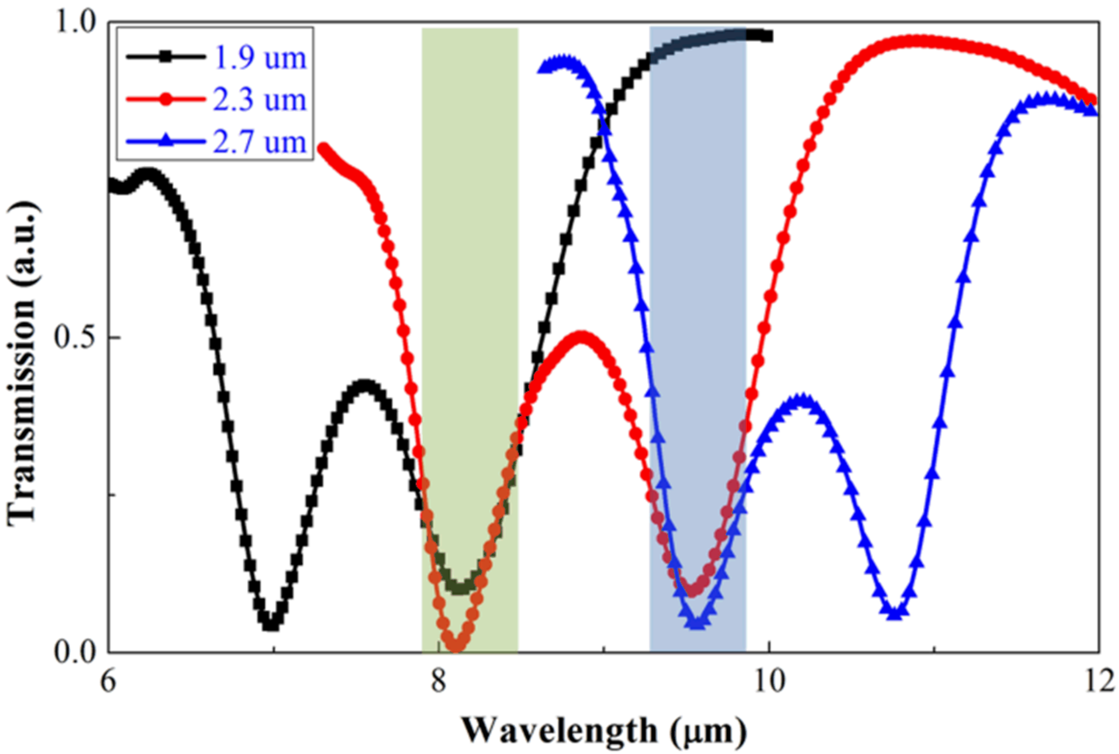




Magnetic and Electric resonances can overlap: different size cubes, or cubes with "cuts"

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.**

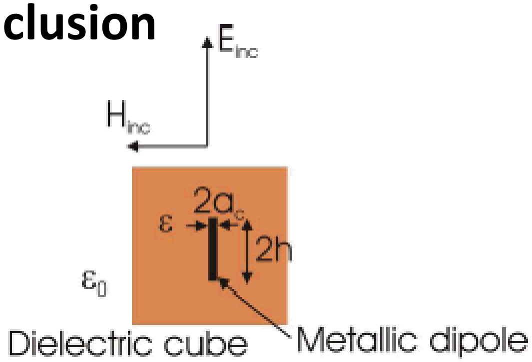
Appl. Phys. Lett. 102, 161905 (2013)

Sandia National Laboratories

Adjusting the Resonance Frequencies:
Perturbation Approach

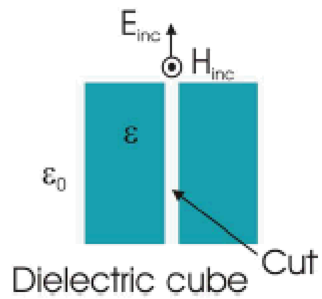
- **One approach to alignment of resonances is to place perturbations within the resonator volume**

High-permittivity inclusion



Frequency downshift of electric resonance

Low-permittivity inclusion



Frequency upshift of magnetic resonance

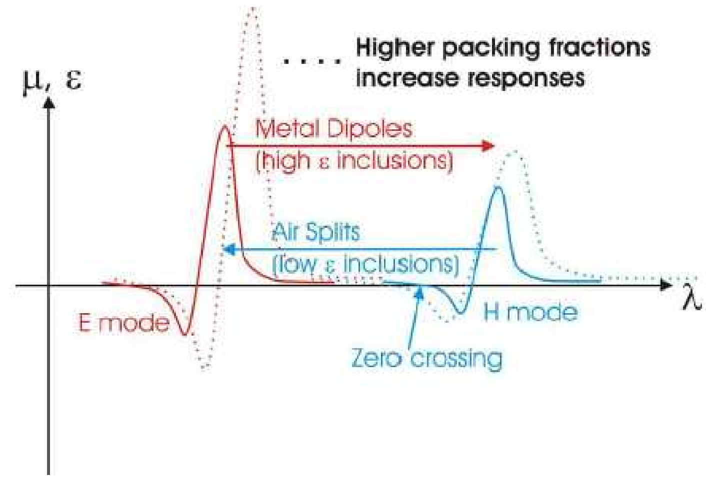


Illustration of resonance shifting using these methods

Warne et al. *PIER B* 44, 1 (2012); *IEEE Trans. Antennas Propagat.* 61, 2130 (2013)

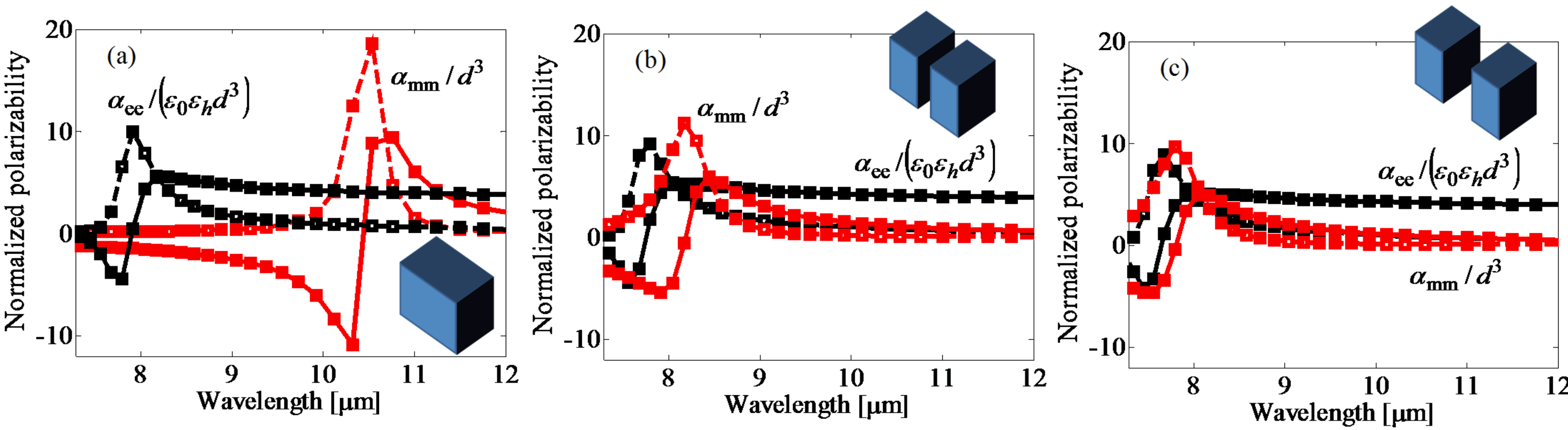
Perturbation theory to control relative location of electric and magnetic resonances

- **Apply perturbation theory to a dielectric cube e.g. by introducing a split**

  Warne et al. *PIER B* 44, 1-29 (2012); *IEEE Trans. Antennas Propagat.* 61, 2130-2141 (2013)

- **Retrieve electric and magnetic polarizabilities of single scatterers using full-wave simulations**

  Basilio et al. *IEEE Antennas Wireless Propag. Lett.* 10, 1567 (2011); Rockstuhl et al. *Phys. Rev. B* 83, 245119 (2011)

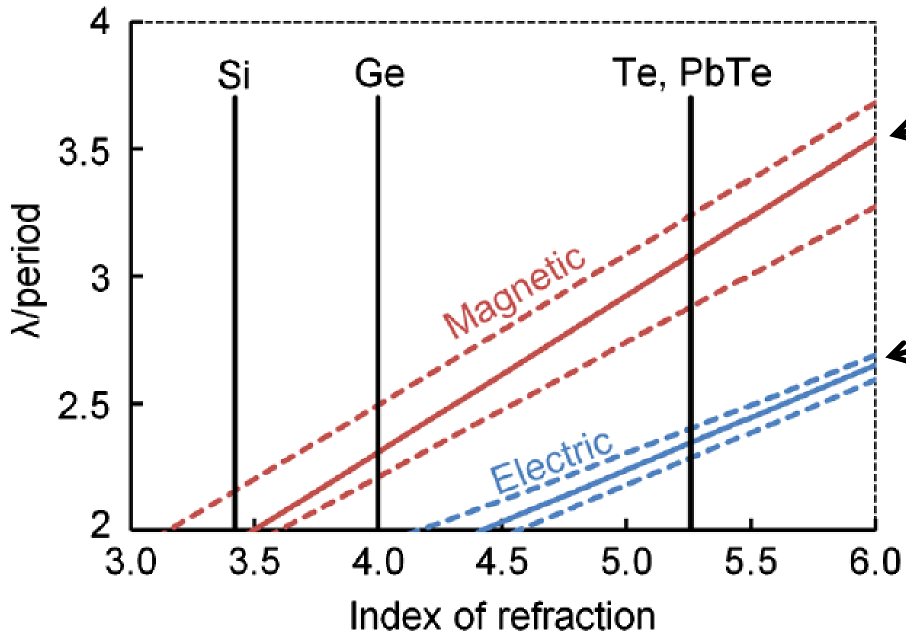


- **Electric and magnetic polarizabilities can be easily engineered to overlap at a given frequency**

Scaling Dielectric Resonators to the Near IR

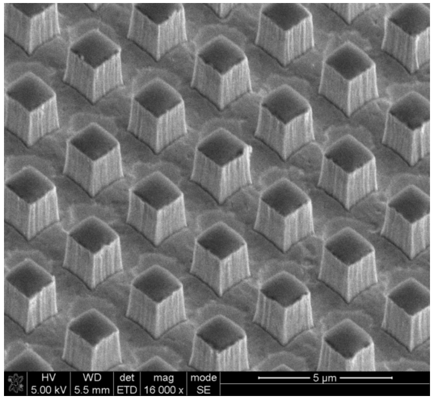
Design metric for 1:1 CDR metamaterials

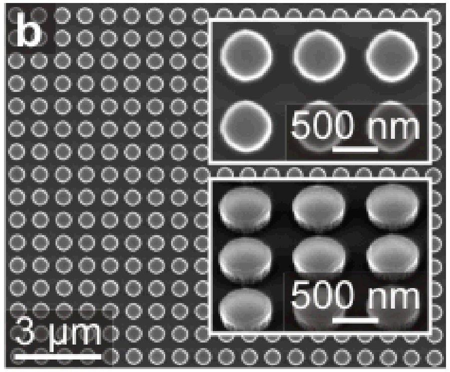
PRL 108, 097402 (2012)



Peak of M-resonance

Peak of E-resonance



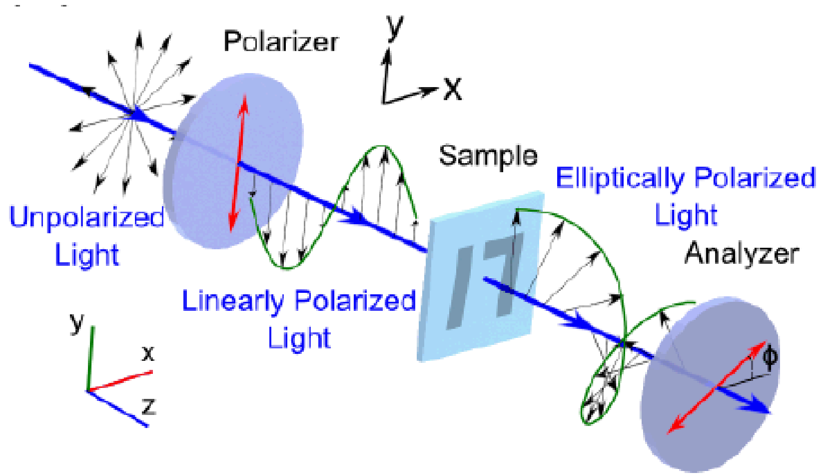


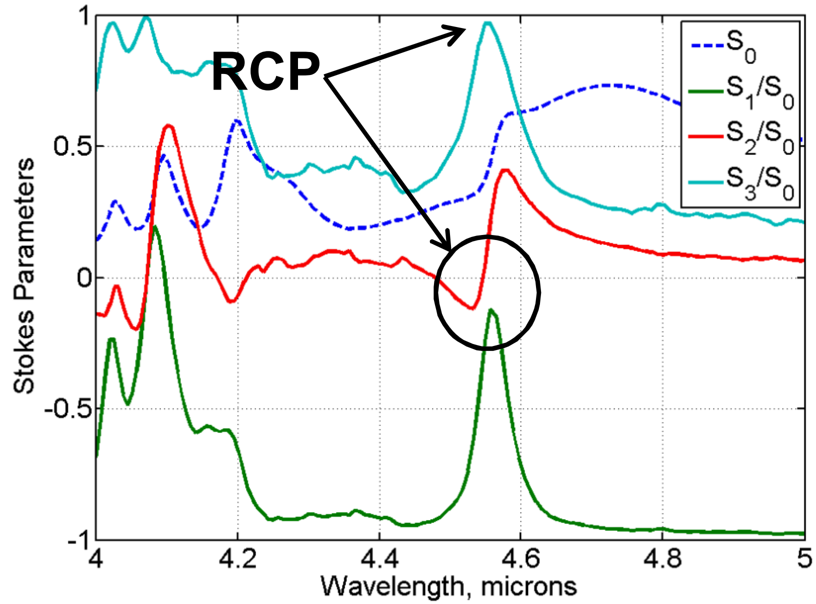
Tellurium: n~5, Size~1.5μm
λ>5μm

Silicon: n~3.5, Size<200-500nm
λ>1μm

LP-CP Metasurface Conversion

Rotating analyzer Stokes polarimetry



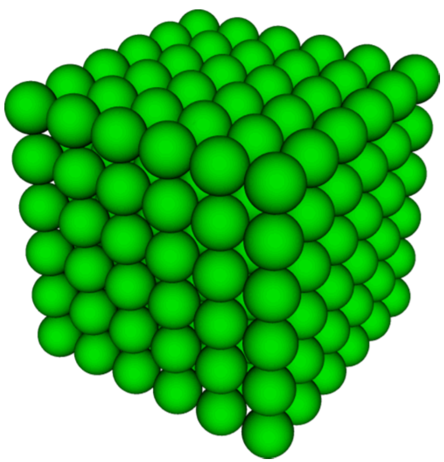


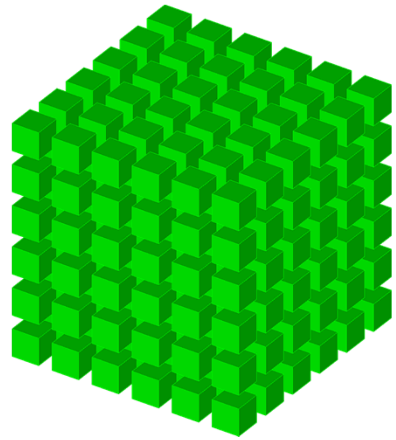
- LP→CP conversion by 1 micron thick MS with high efficiency (50%) at normal incidence
- Experimentally measured quality factor
- Close to 100% Degree of Circular Polarization

Could use a chiral metasurface for developing a CP thermal emitter

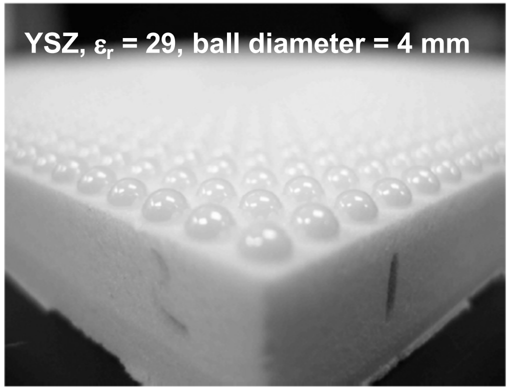
C. Wu et. al., Nature Communication (2014)

Arrays of High ε Resonators: Low Loss Metamaterials





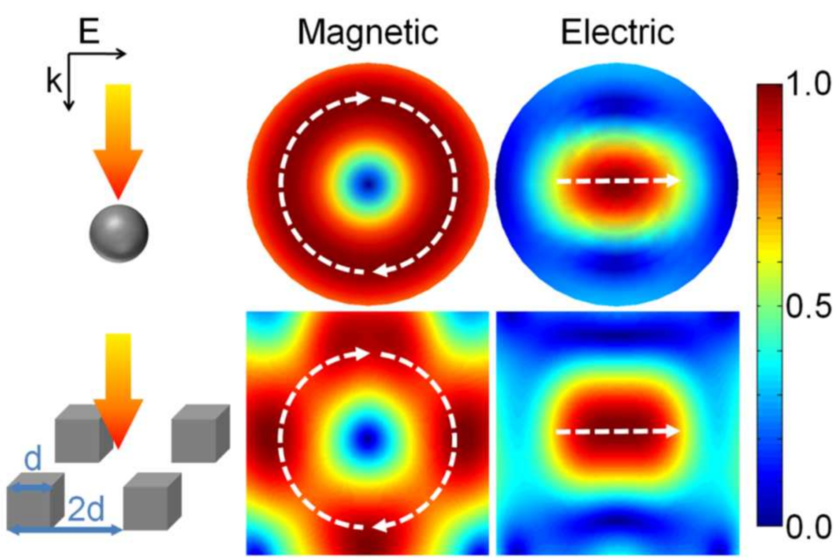
Works nice in the RF



(negative ε, negative μ)

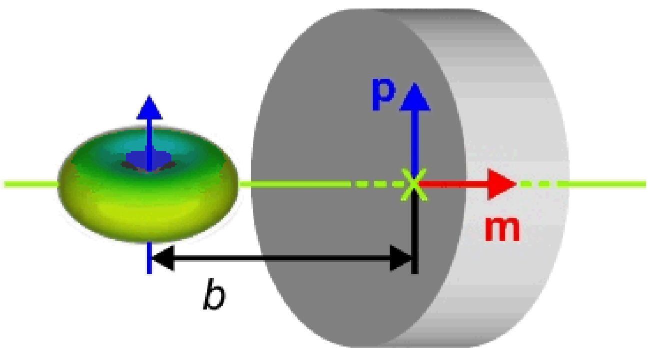
Spherical

Cubic



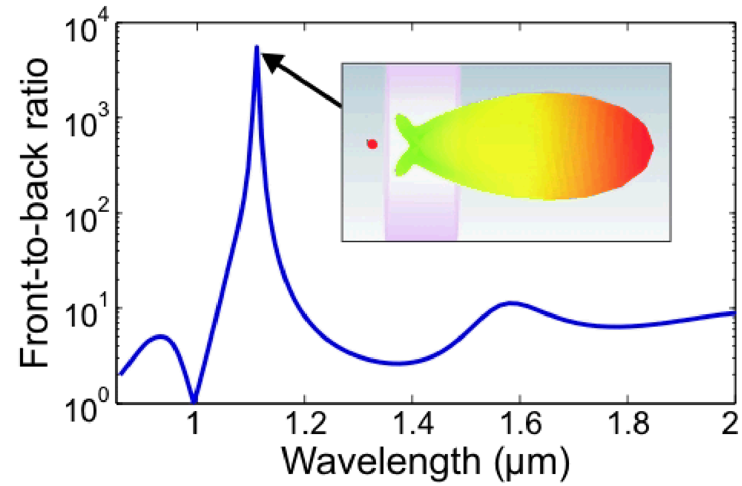
M. B. Sinclair, MRS Fall Meeting, Boston MA, December 2009.

Importance of the Quadrupole Mode

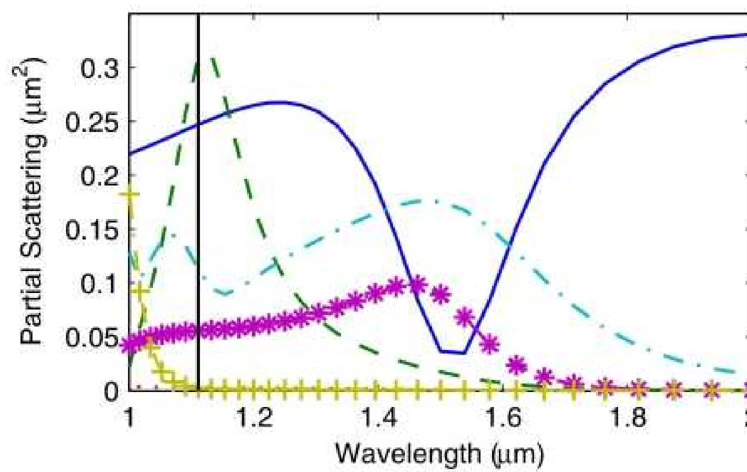


- **Silicon nanodisks: highly directional nanoantennas with giant front-to-back ratio**

- **Electric quadrupole mode essential to achieve high directivity**



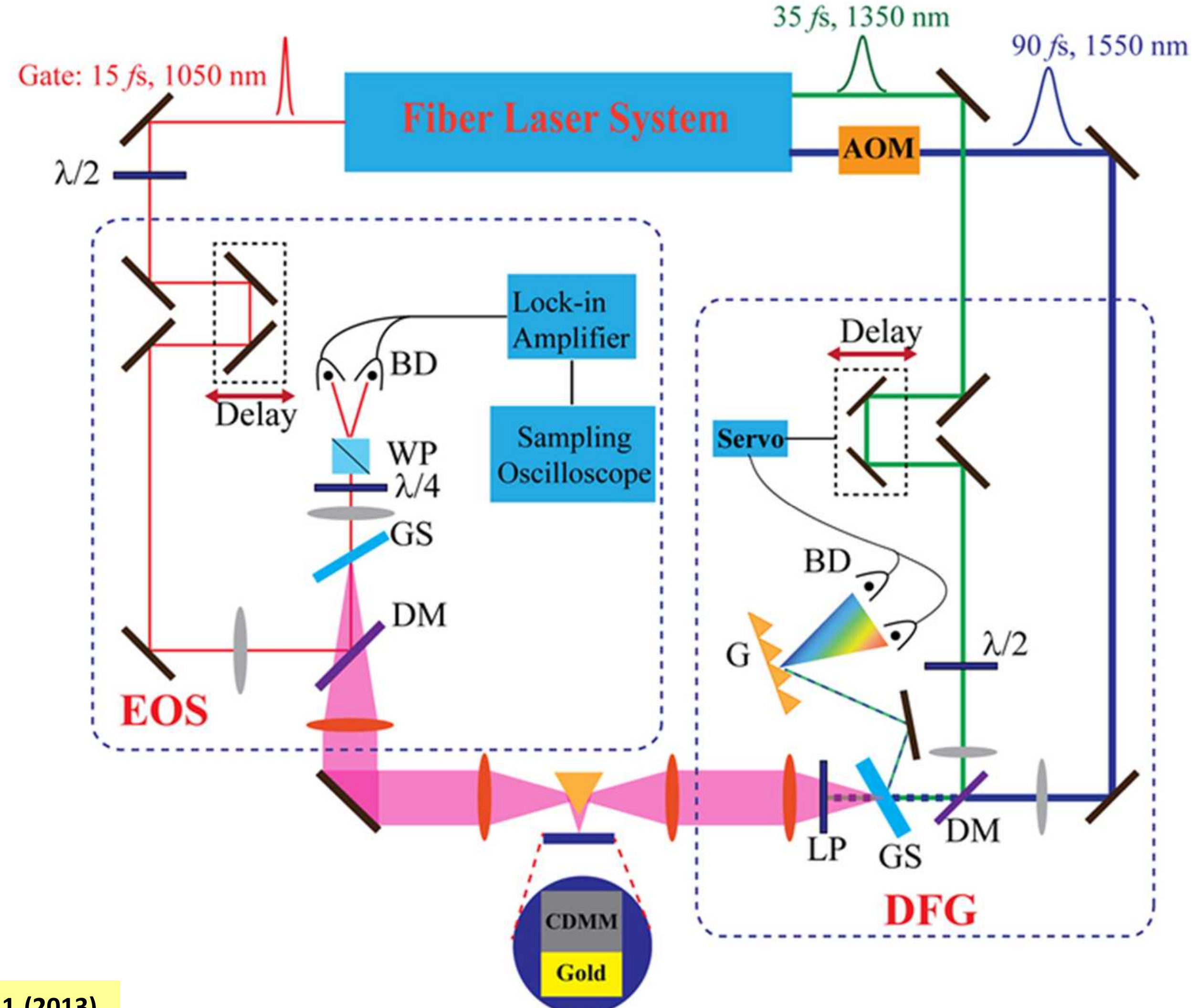
I. Staude *et al.*, *ACS Nano* 7, 7824, 2013.



E. Rusak *et al.*, *submitted* (2014).

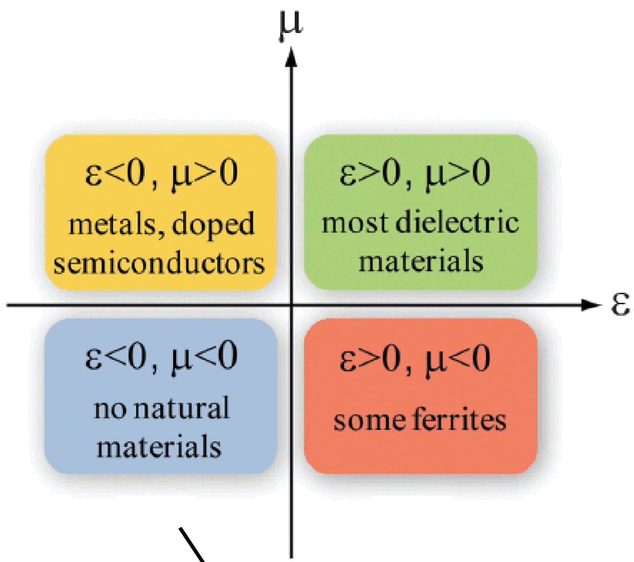
Proving Optical Magnetism:
Measure Phase of Reflected Wave

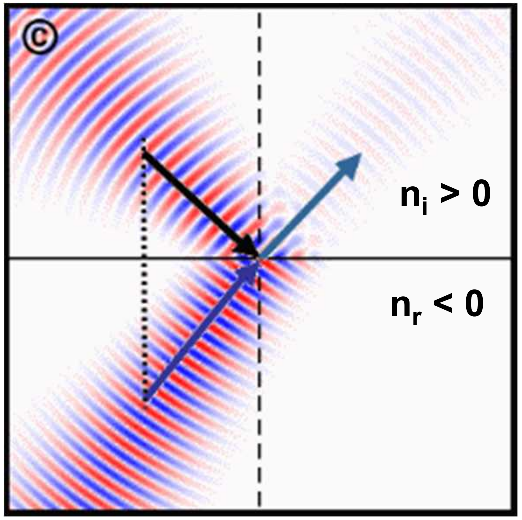
Phase-locked Time Domain Spectroscopy



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

Metamaterials: Exotic optical properties





Negative index, Negative refraction

$$n = -\sqrt{|\varepsilon_r||\mu_r|}$$

(Causality)

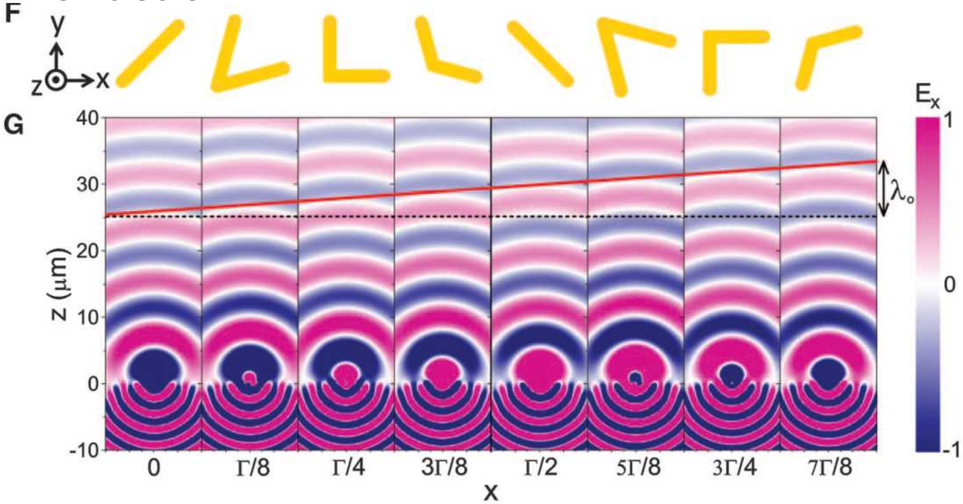
$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{n_r}{n_i}$$

(Snell's Law)

- **Superlensing, Cloaking, Chirality/Optical activity, Perfect absorption**
- **Enhanced nonlinear interaction, Optical force manipulation, Light emission control**

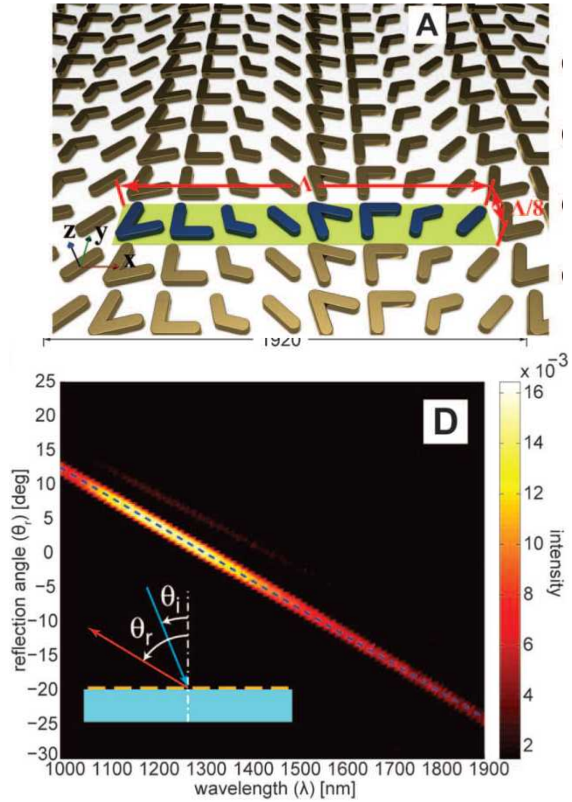
Beam Manipulation With Metasurfaces

Phase gradient to achieve anomalous refraction



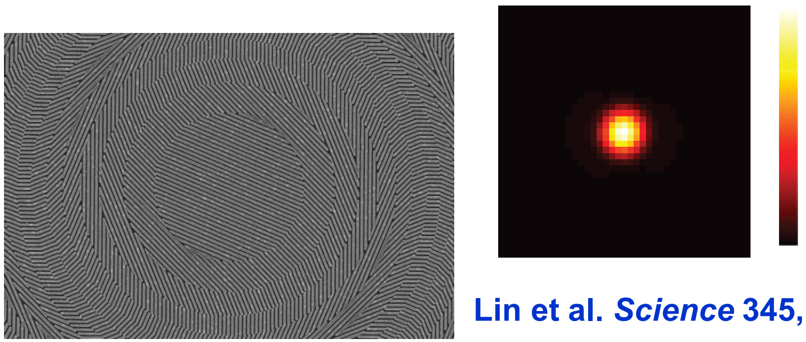
Yu et al. *Science* 334, 333 (2011)

Phase gradient to achieve anomalous reflection



Ni et al. *Science* 335, 427 (2012)

Phase gradient to achieve lensing



Lin et al. *Science* 345, 298 (2014)