SAND2015-1920PE

Active Dielectric and Metallic Metasurfaces: Strong Coupling, Tuning and Nonlinearities

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Materials with Negative Permittivity and Permeability

SOVIET PHYSICS USPEKHI VOLUME 10, NUMBER 4 JANUARY-FEBRUARY 1968

538.30

THE ELECTRODYNAMICS OF SUBSTANCES WITH SIMULTANEOUSLY NEGATIVE VALUES OF ϵ AND μ

V. G. VESELAGO

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Usp. Fiz. Nauk 92, 517–526 (July, 1964)

I. INTRODUCTION

THE dielectric constant ϵ and the magnetic permeability μ are the fundamental characteristic quantities which determine the propagation of electromagnetic waves in matter. This is due to the fact that they are the only parameters of the substance that appear in the dispersion equation

$$\left|\frac{\omega^2}{c^2}\varepsilon_{il}\mu_{lj} - k^2\delta_{ij} + k_i k_j\right| = 0, \quad (1)$$

which gives the connection between the frequency ω of a monochromatic wave and its wave vector k. In the case of an isotropic substance, Eq. (1) takes a simpler form:

$$k^2 = \frac{\omega^2}{c^2} n^2. \quad (2)$$

Here n^2 is the square of the index of refraction of the substance, and is given by

$$n^2 = \varepsilon\mu. \quad (3)$$

If we do not take losses into account and regard n, ϵ, and μ as real numbers, it can be seen from (2) and

II. THE PROPAGATION OF WAVES IN A SUBSTANCE WITH $\epsilon < 0$ AND $\mu < 0$. "RIGHT-HANDED" AND "LEFT-HANDED" SUBSTANCES

To ascertain the electromagnetic laws essentially connected with the sign of ϵ and μ, we must turn to those relations in which ϵ and μ appear separately, and not in the form of their product, as in (1)—(3). These relations are primarily the Maxwell equations and the constitutive relations

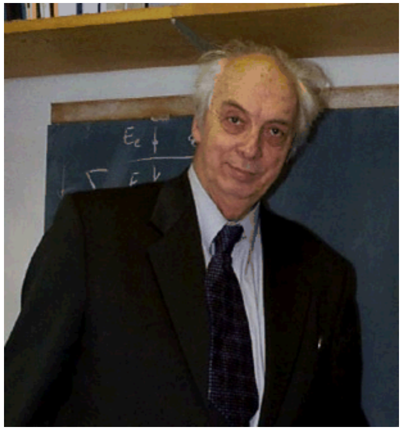
$$\mathrm{rot}\,\mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}, \quad \mathrm{rot}\,\mathbf{H} = \frac{1}{c}\frac{\partial \mathbf{D}}{\partial t}. \quad (4)^*$$

$$\mathbf{B} = \mu\mathbf{H}, \quad \mathbf{D} = \varepsilon\mathbf{E}. \quad (4')$$

For a plane monochromatic wave, in which all quantities are proportional to $e^{i(kz-\omega t)}$, the expressions (4) and (4′) reduce to

$$[\mathbf{kE}] = \frac{\omega}{c}\mu\mathbf{H}, \quad [\mathbf{kH}] = -\frac{\omega}{c}\varepsilon\mathbf{E}. \quad (5)^\dagger$$

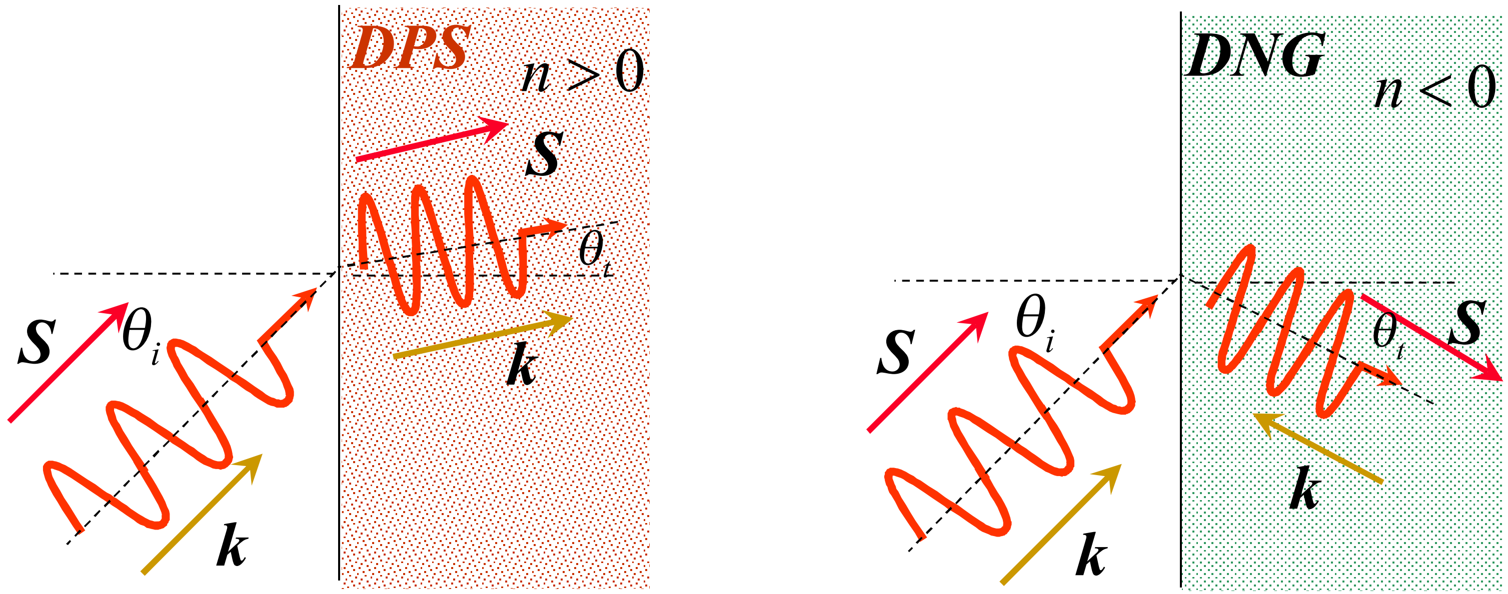
Viktor G. Veselago



http://www.tkk.fi/Yksikot/Sahkomagnetiikka/kuvia/Veselago2.jpg

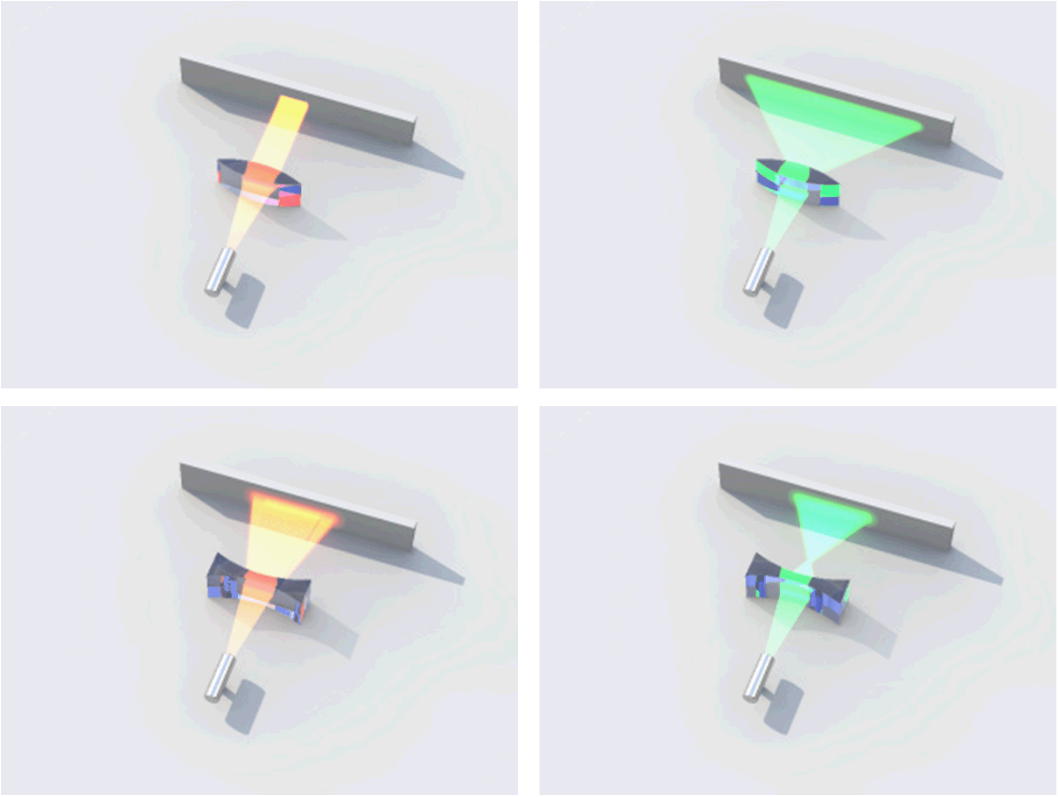
Negative Refraction

- *Viktor G. Veselago, Usp. Fiz. Nauk (1967)*



$$n_o \sin\theta_i = n_1 \sin\theta_t$$

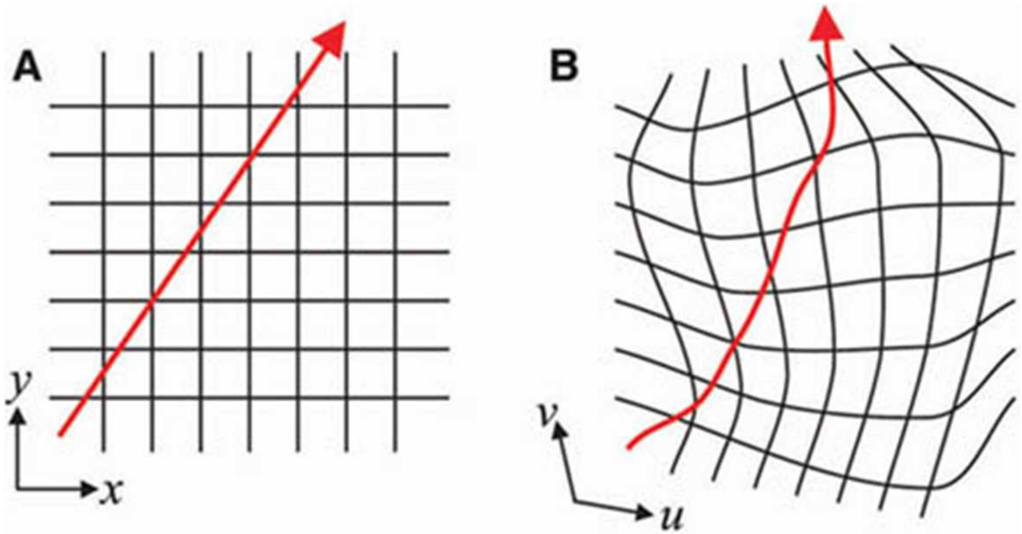
Negative Refraction



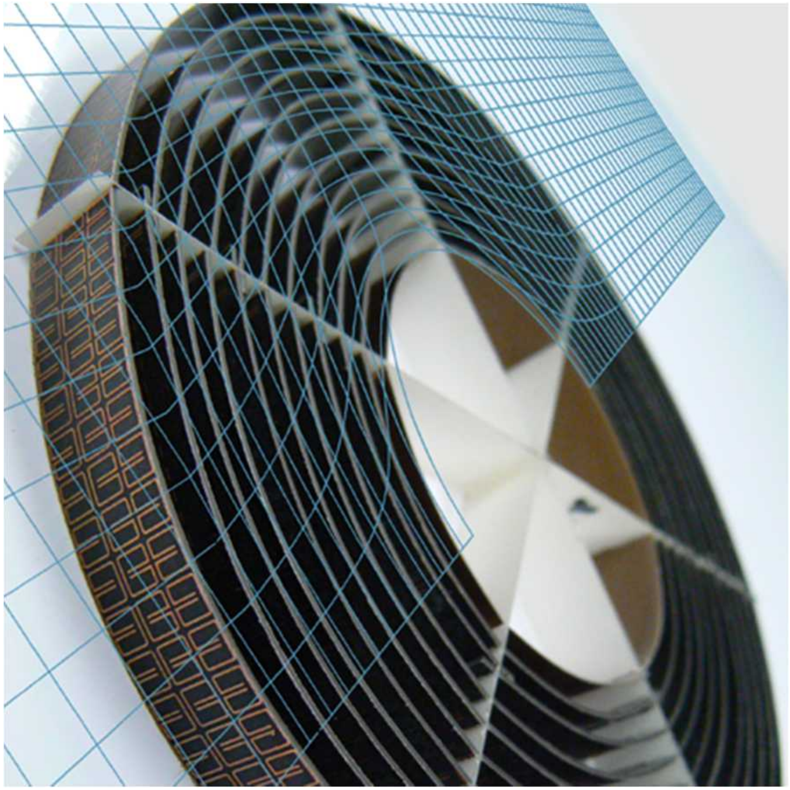
positive index of refraction   negative index of refraction

http://www.imagico.de/pov/metamaterials.php

“Transformation Optics”



J. Pendry

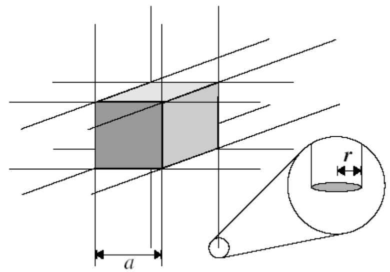


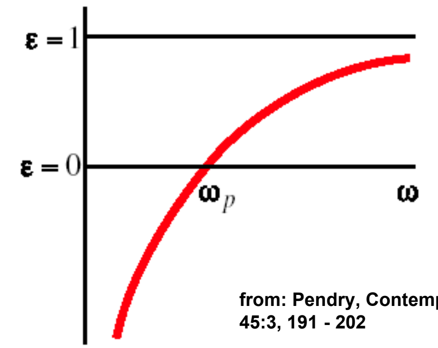
D. Smith, Duke

How to make a “Metamaterial”

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

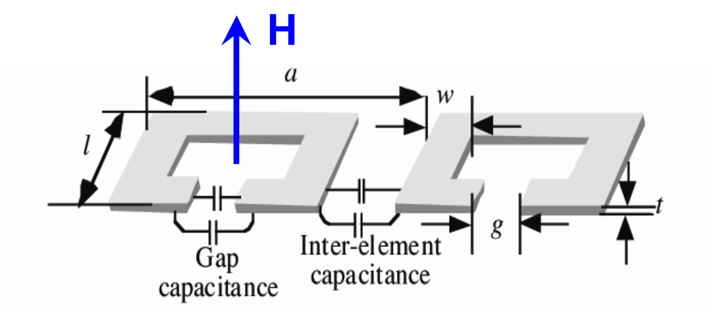
$$\omega_p = \sqrt{\frac{ne^2}{m^* \varepsilon_o}}$$



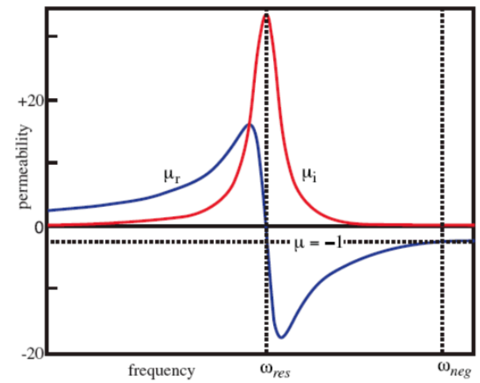


from: Pendry, Contemporary Physics, 45:3, 191 - 202

LC “Resonators” to control magnetic permeability (μ)

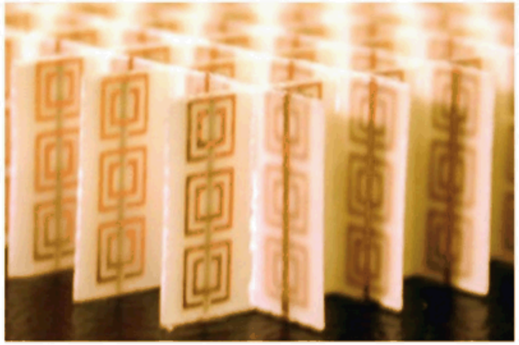


from; S. McMeekin, Proc. Of SPIE, Vol. 6581



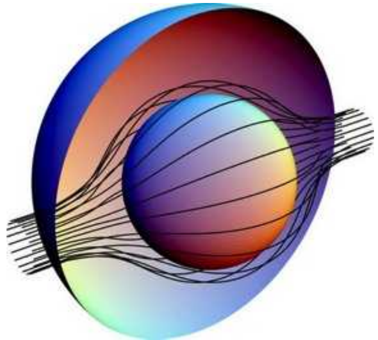
Combine the two:

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



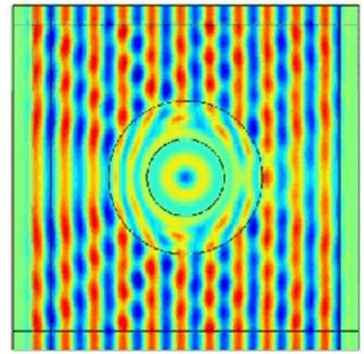
"New" Optics Enabled by Metamaterials

Cloaks



Pendry,et al., Science (2006)

cloak design



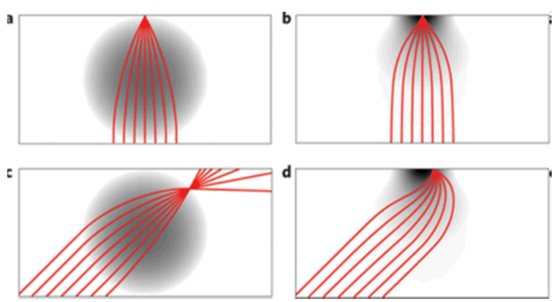
Schurig,et al., Science 314, 977 (2006)

RF experimental validation (2D)

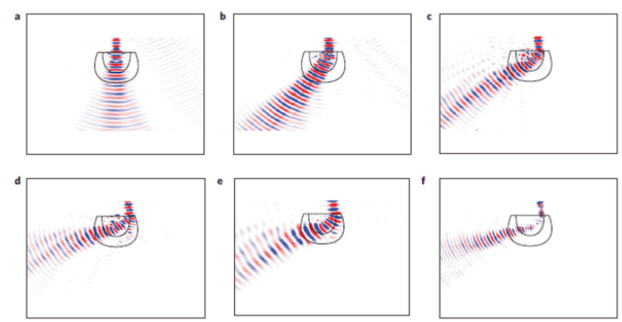
Other devices:

- Perfectly matched absorber
- Beam splitters
- Negative index lens
- Sub-wavelength imaging
- .....

Optics



flattened Luneberg lens design



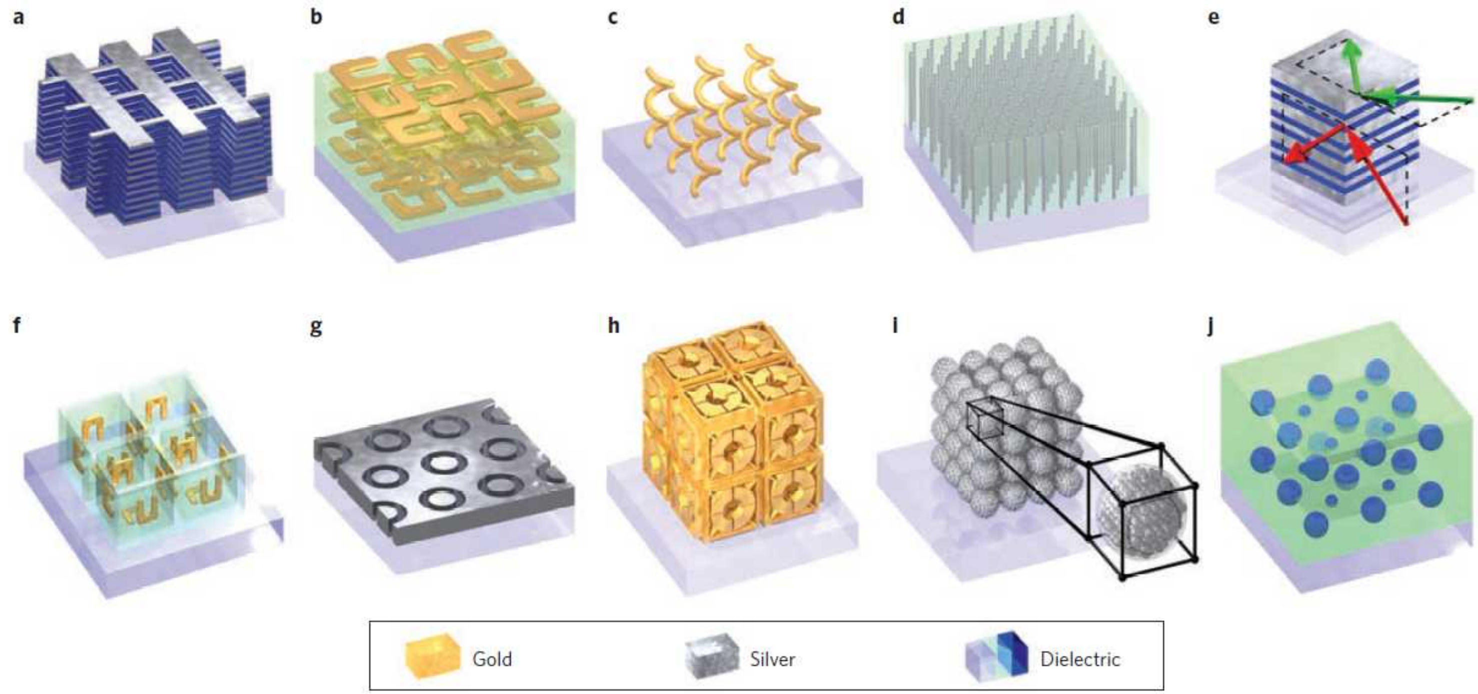
Kundtz and Smith, Nature Materials (2009)

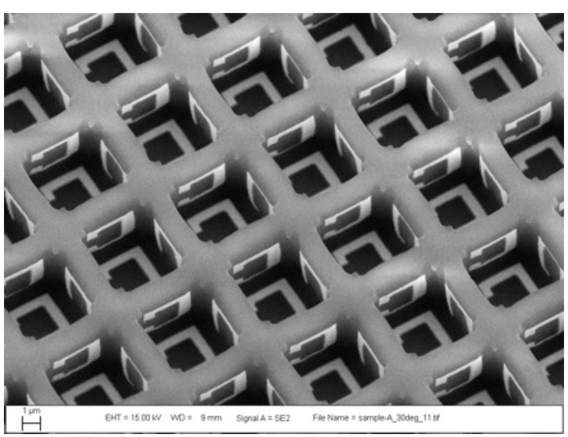
RF experimental validation (2D)

Optical transparency is a key requirement for many devices

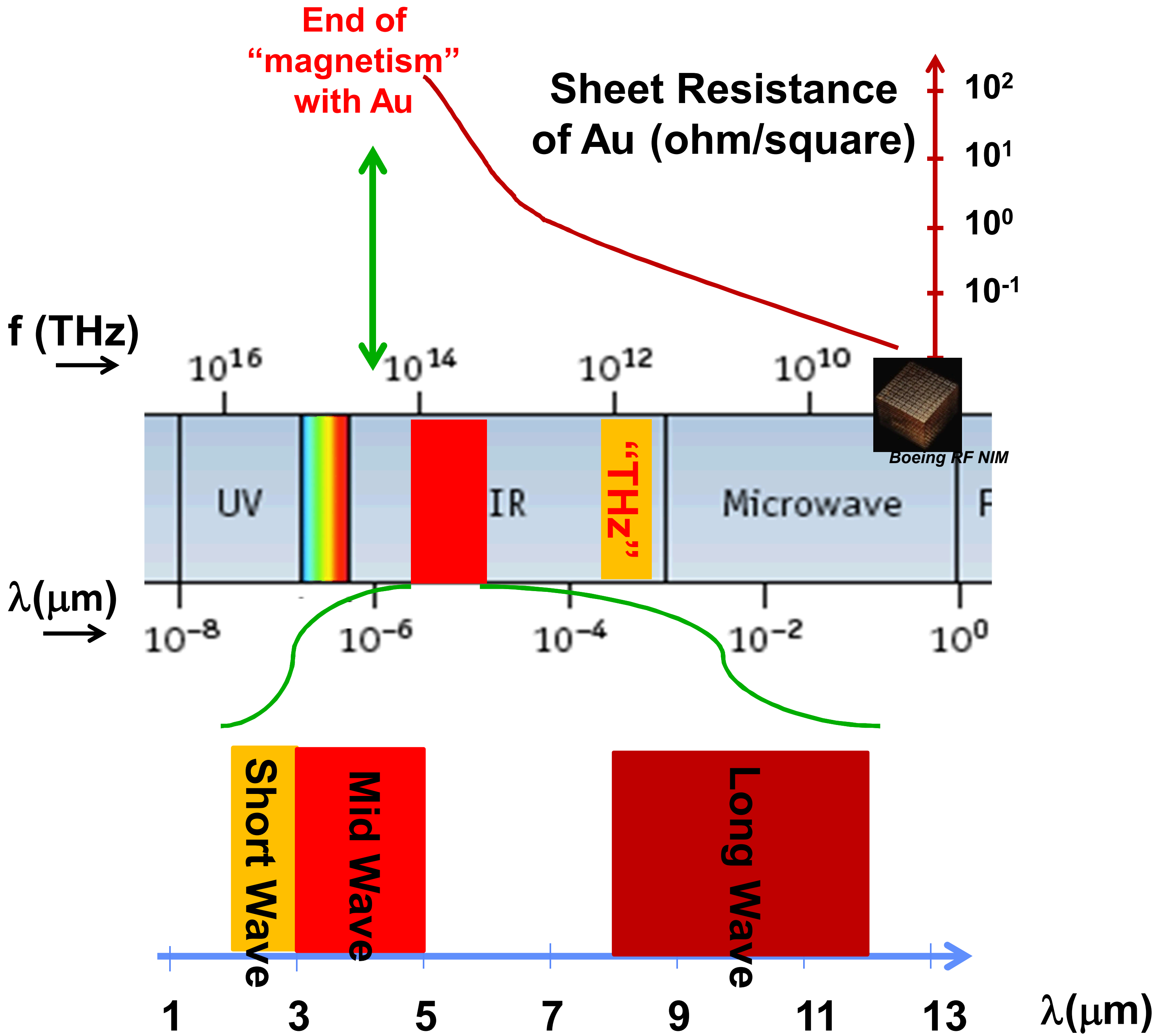
Optical Metamaterials

C. M. Soukoulis, M. Wegener, Nature Photonics (2011)



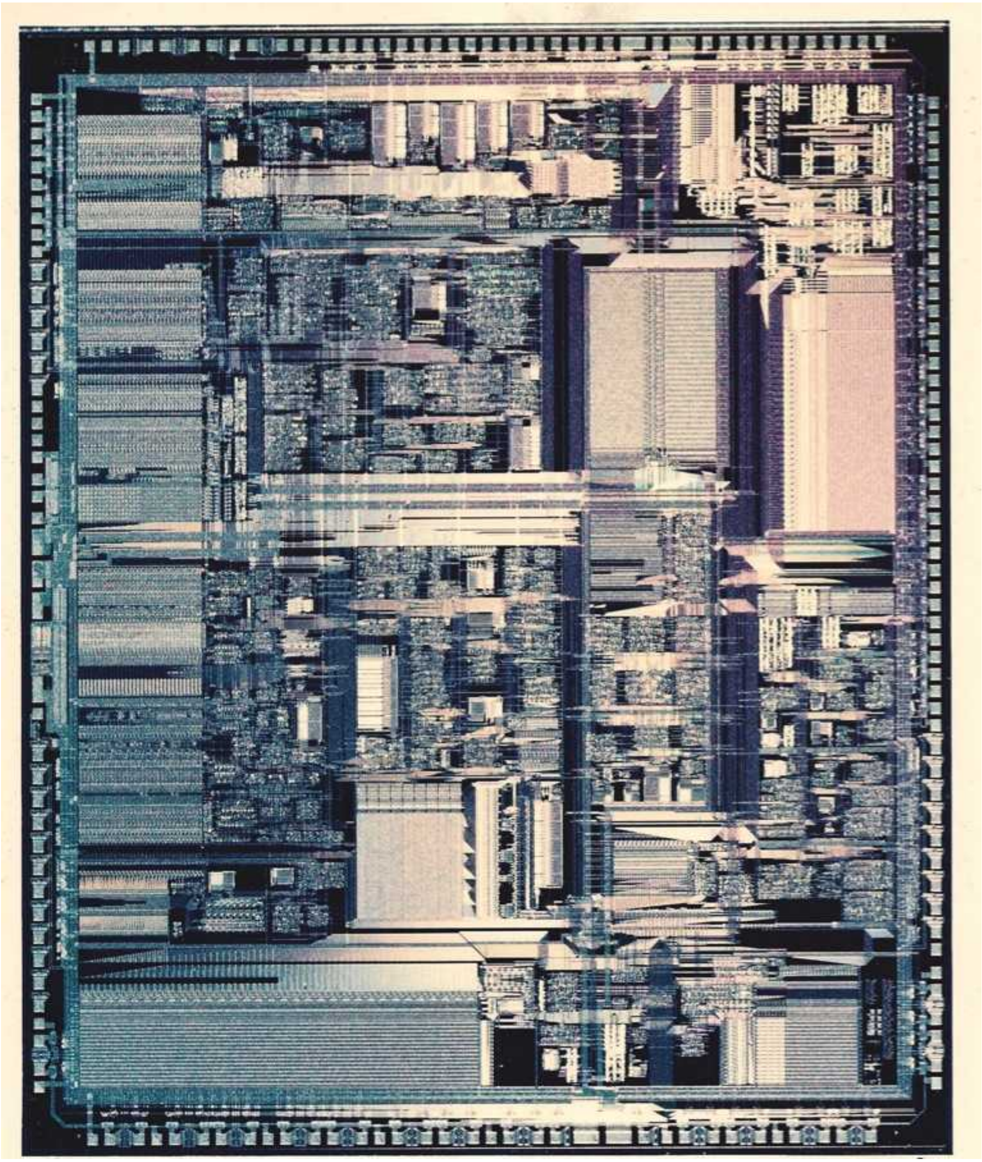


Burckel *et al,* Advanced Materials 2010

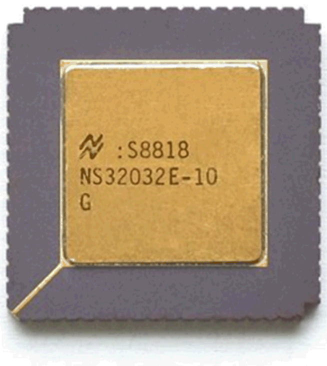


End of "magnetism" with Au
Sheet Resistance of Au (ohm/square)
10^2
10^1
10^0
10^-1
f (THz)
10^16
10^14
10^12
10^10
UV
IR
"THz"
Microwave
Boeing RF NIM
λ(μm)
10^-8
10^-6
10^-4
10^-2
10^0
Short Wave
Mid Wave
Long Wave
1
3
5
7
9
11
13
λ(μm)

VLSI, National Semiconductors



NS32032: 1st 32 bit microprocessor



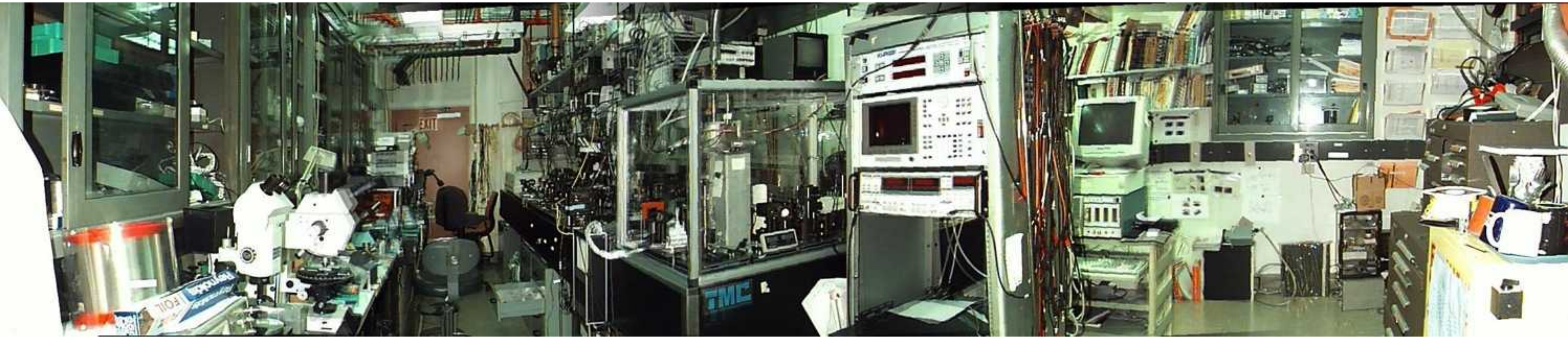
6 Engineers, a few 10K transistors

Intel's 15-core Xeon IvyBridge-EX, <u>4.3 billion transistors</u>!

Bell Labs

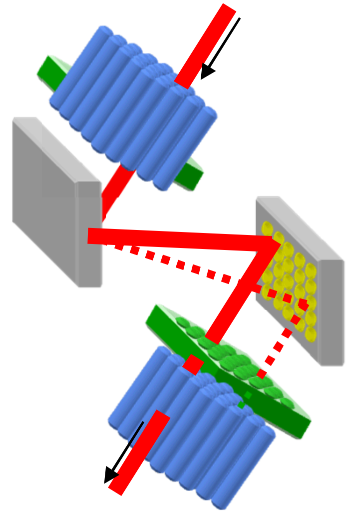

(B. Juang, G. Tech)

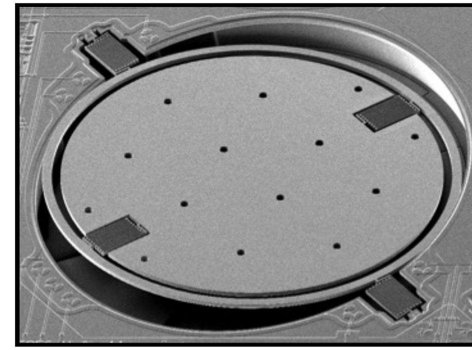
- Ultrafast
- THz
- Fiber Telecom



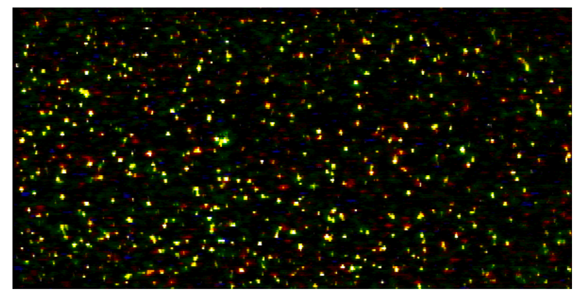
Tellium (2000-2002)

-All-Optical MEMS cross-connect





Praelux/Amersham/GE (2002-2004)

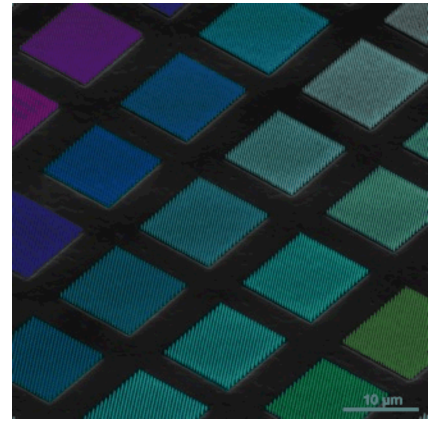


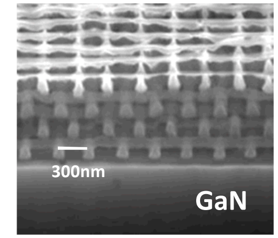
-Single molecule DNA sequencing
-High throughput microscopy

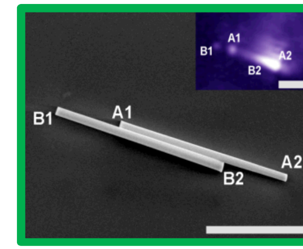
At Sandia: Other Activities in Nanophotonics

Solid State Lighting "Energy Frontier Research Center" (<2014)

- Enhanced Spontaneous Emission
- Nanowire Lasers (III-N)

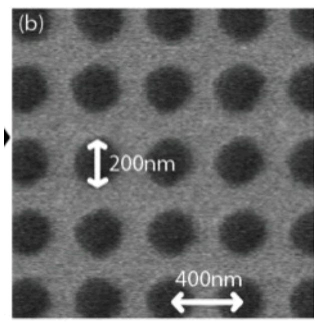


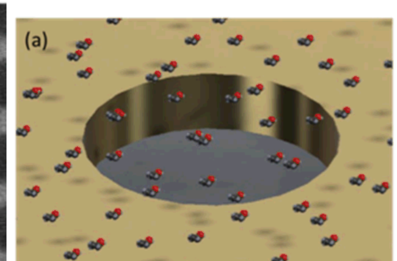


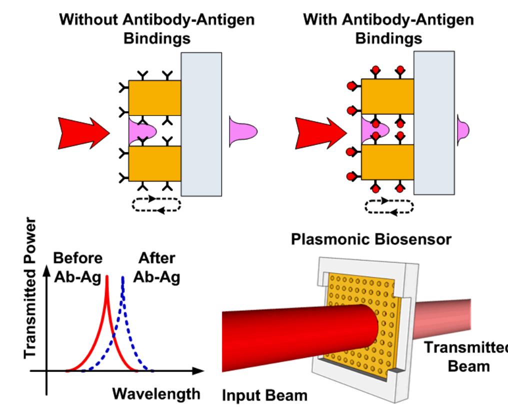


Plasmonics

- Sensors (gas)
- Biosensing



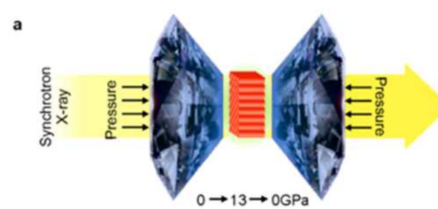


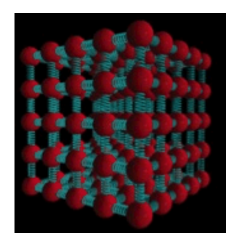


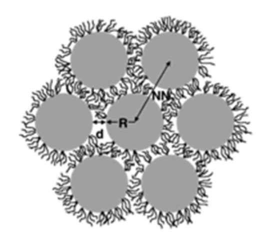
w/NMSU

Nanophotonics, etc

- Energy transfer in QDs
- QD "solids"





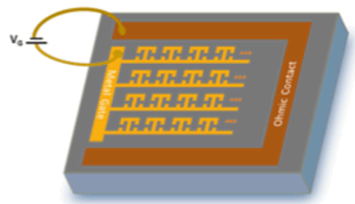


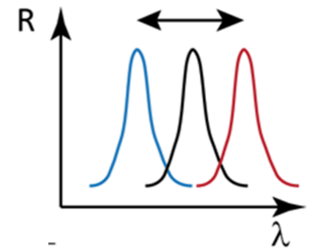
Outline

- **Metallic Metasurfaces**
  - Tuning
  - Strong Coupling
  - Nonlinearities
- **All Dielectric Metasurfaces**
  - Fundamentals
  - Optical Magnetism
  - Directional Emission, Fano Resonances, and third-harmonic Generation

Why Tunable Metasurfaces?

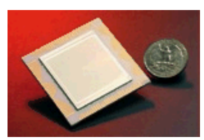
Potential for planar optical devices: modulators, tunable filters, etc.



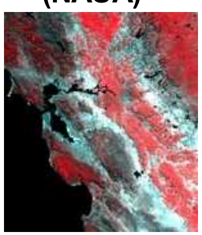


Examples: hyperspectral imaging

(NASA)

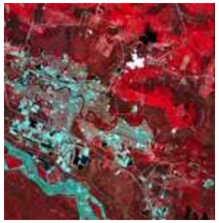


(JPL)



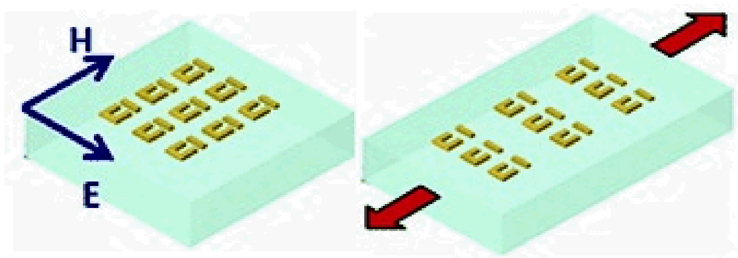
(Cedip)

Mechanical filters!



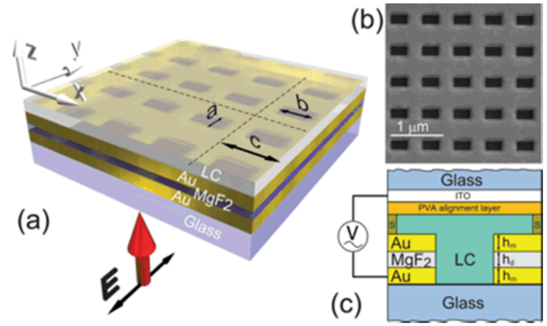
Examples of Tunable Metamaterials (Metasurfaces)

Mechanical movement or stretching



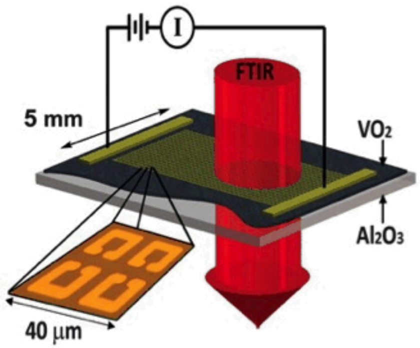
I. M. Pryce, Nano Lett (2010)

Re-orientation of liquid crystals



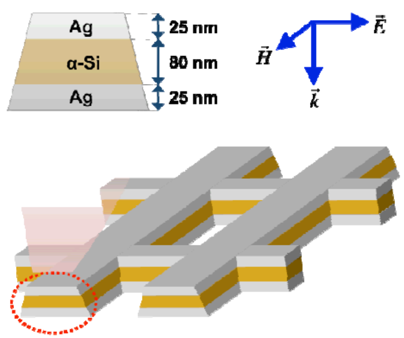
A. Minovich, APL (2012)

Phase transitions in VO_2



T. Driscoll, Science (2009)

Optical free carrier generation

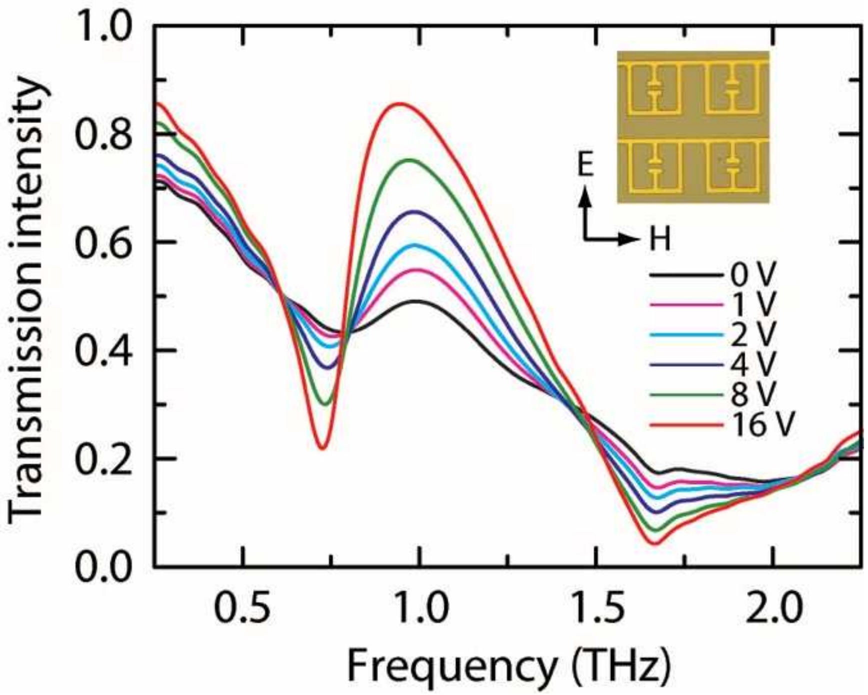


D.J. Cho, Opt. Express (2009)

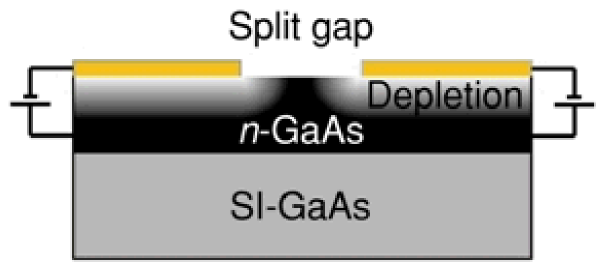
- **Electrical tuning based on semiconductor device structures is more technologically appealing for practical, chip-scale applications**

Electrically Switchable THz Metamaterials:

Controlling Interaction With Electrons



Chen, Nature 444, 597 (2006).



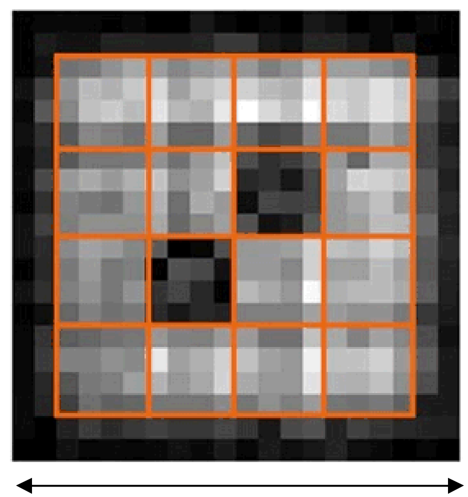
This works by increasing the damping (ε_2). Plasma frequency of doped layer needs to match the MM resonance frequency

However: it doesn't scale well to shorter wavelengths

0.36 THz,4x4 SLM

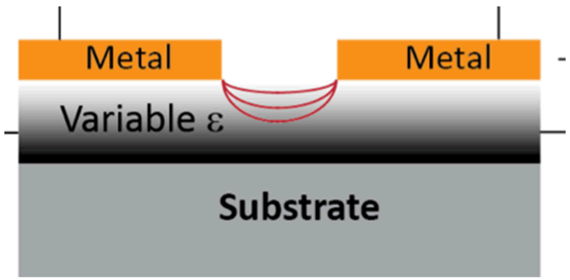
(With Rice Univ.)

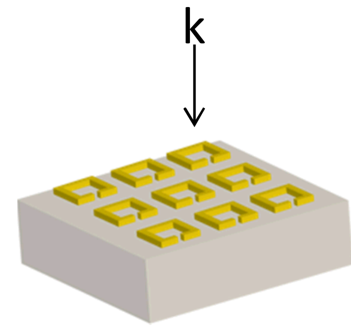
Appl. Phys. Lett. 94, 213511 (2009)

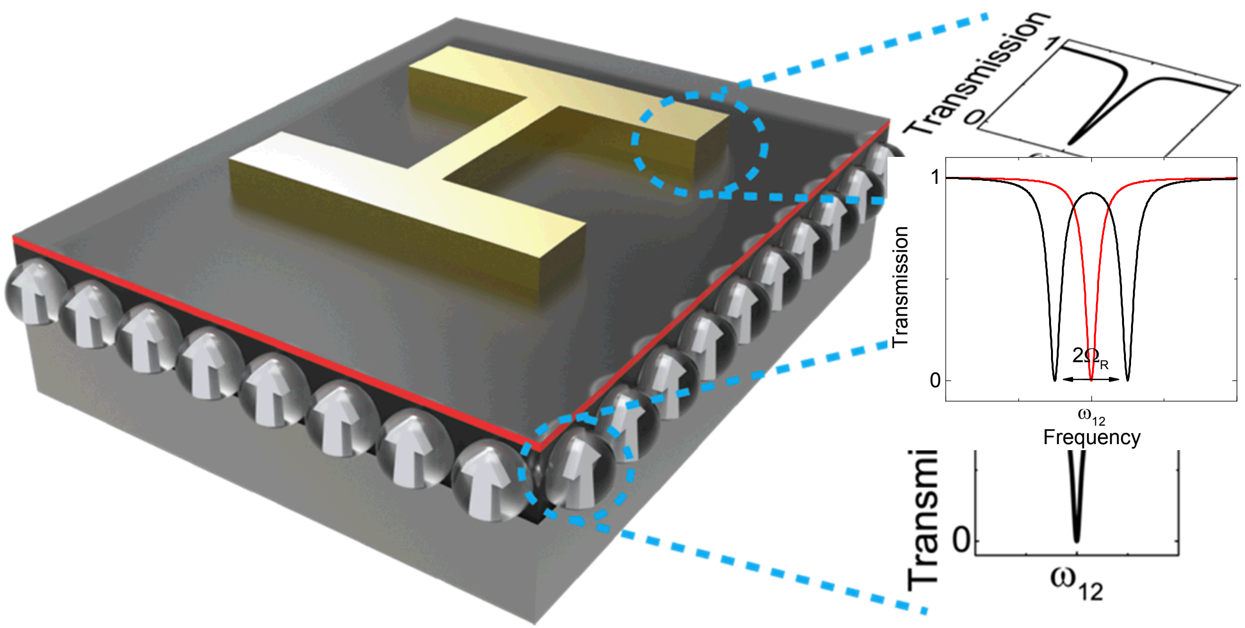


16 mm

Planar Metamaterials Resonators: Strong Coupling





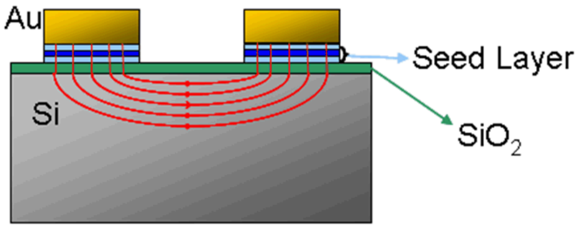


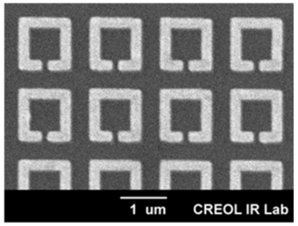
<u>2D resonators (or metasurfaces):</u>

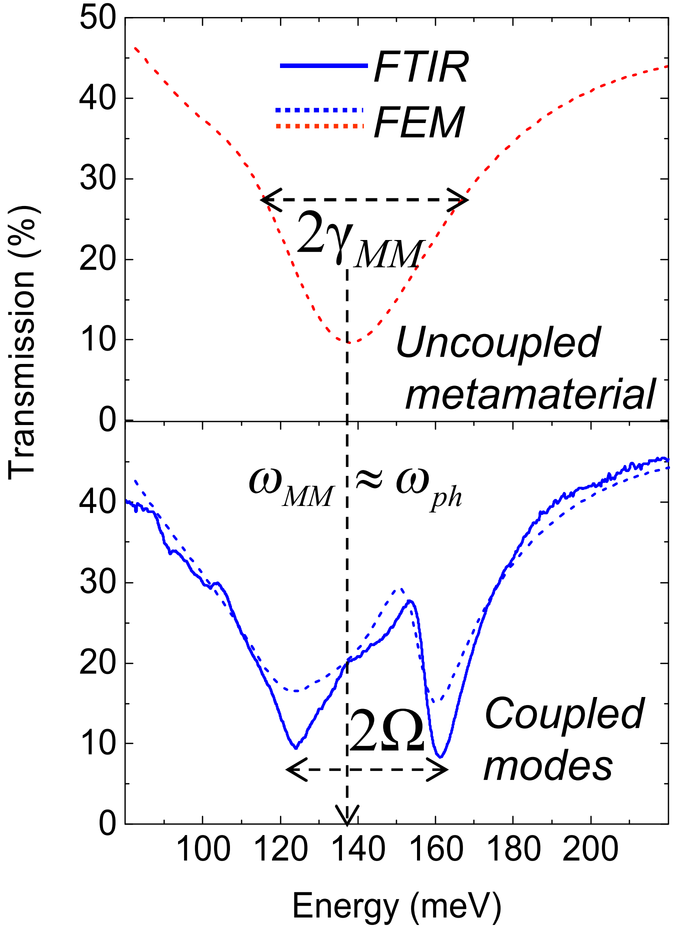
- **subwavelength**
- **large cross section**
- **Spectral response is extremely sensitive to local changes in ε**
- **Field decays from the metal surface exponentially into the substrate**

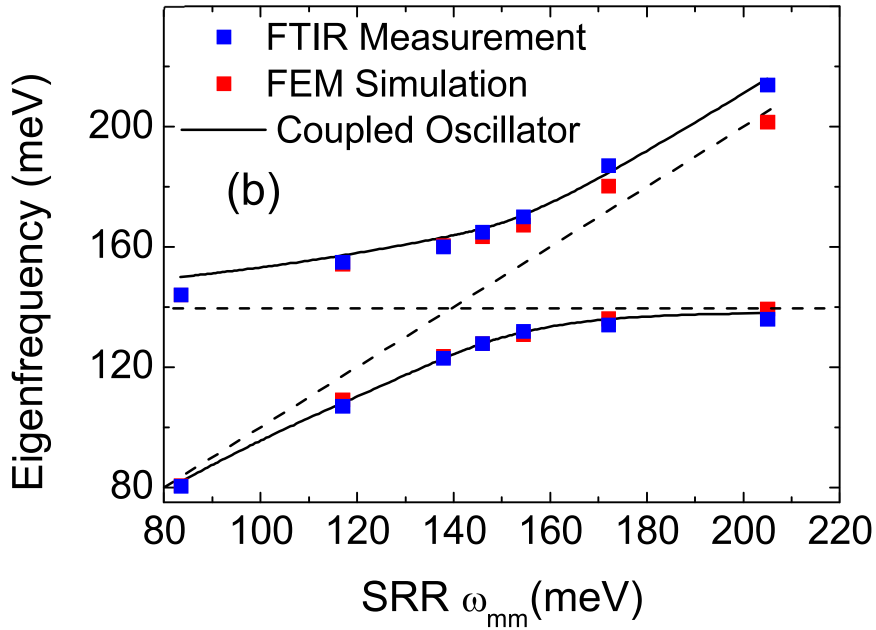
Strong Coupling: MM & Phonons

Oxide is only 10nm!









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

Linewidth of phonon is comparable to MM

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

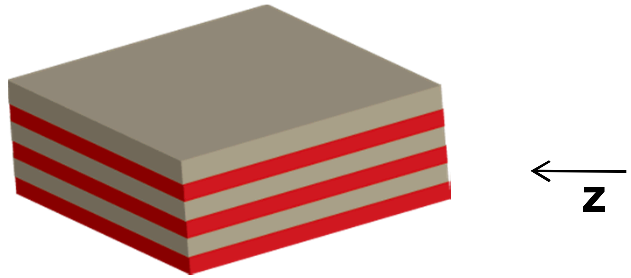
Nano Letters 11, 2104 (2011)

Strong Coupling to Inter-subband Transitions in Quantum Wells

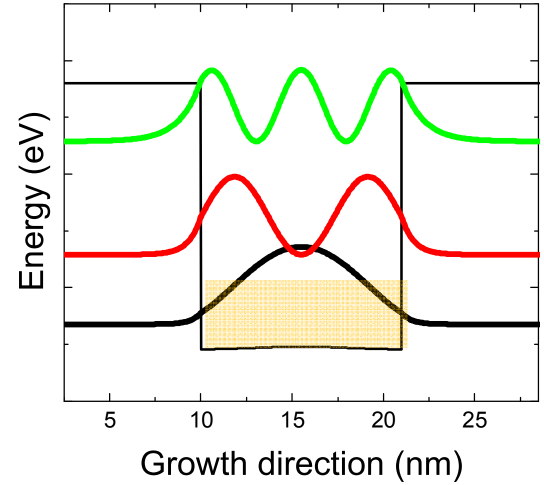
Alex Benz

•<u>Scalable</u> (far IR to near IR), <u>Mature, Versatile</u>

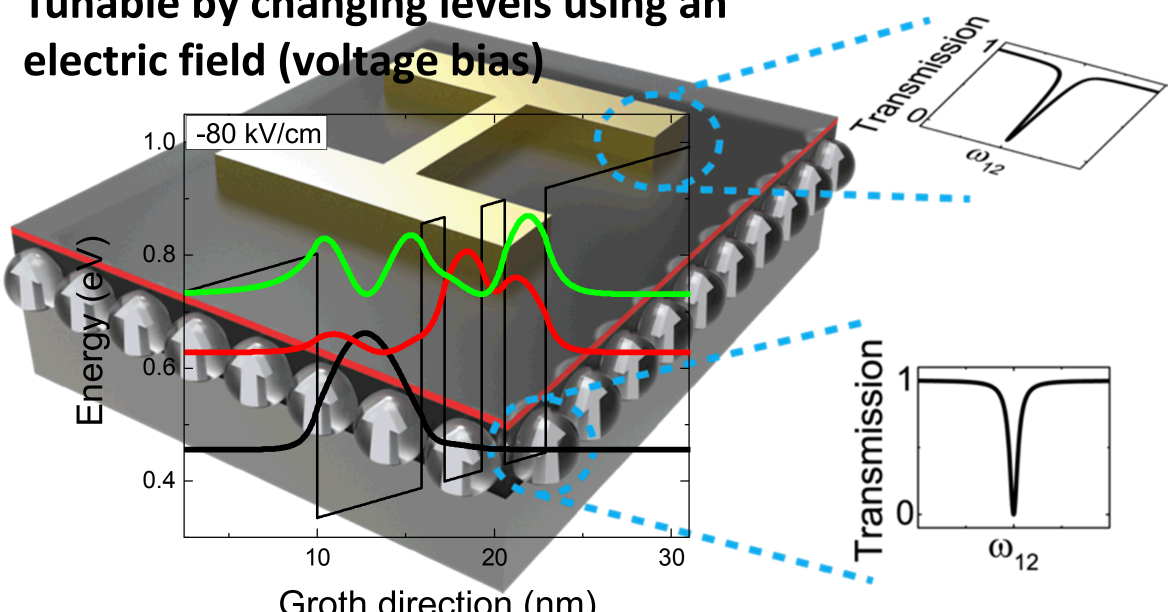
Opt. Express 20, 6584 (2012),
APL 98, 203103 (2011)



$\varepsilon_{xx}=\varepsilon_{yy}\neq\varepsilon_{zz}$

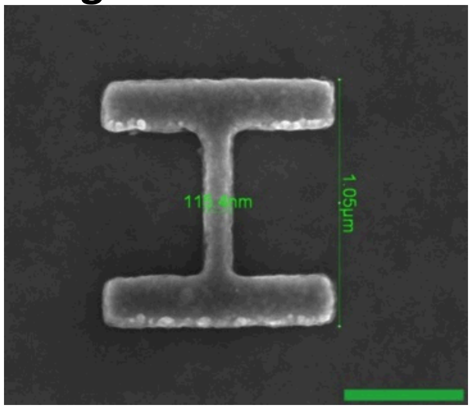


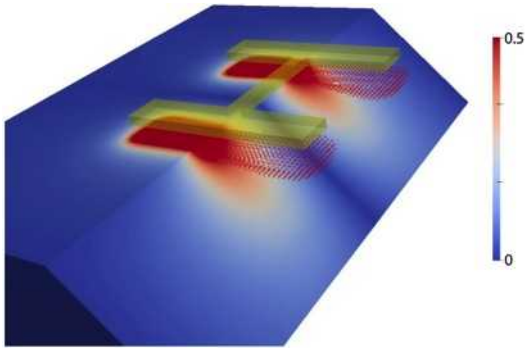
Tunable by changing levels using an electric field (voltage bias)

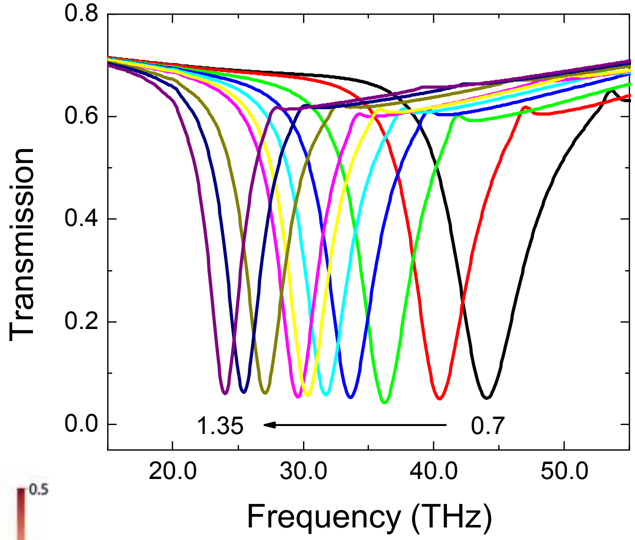


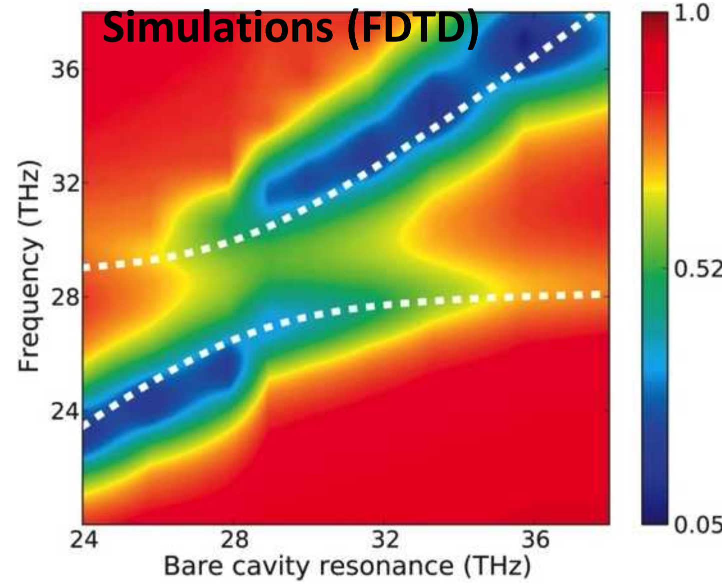
Strong Coupling Theory vs. Experiment

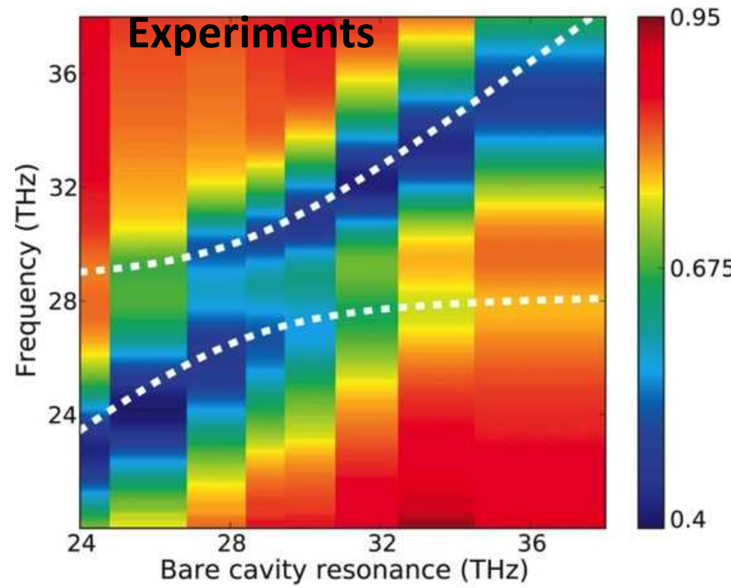
"Dogbone" resonators











Plasma frequency

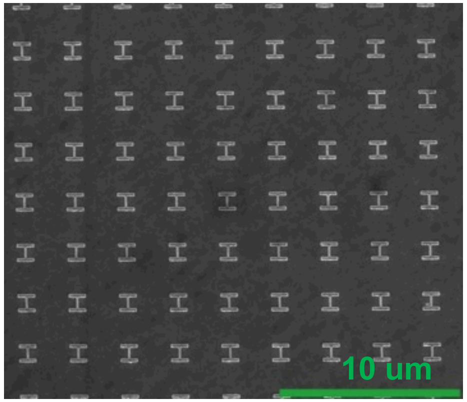
$$\Omega_R = \sqrt{f_W}\,\omega_p/2$$

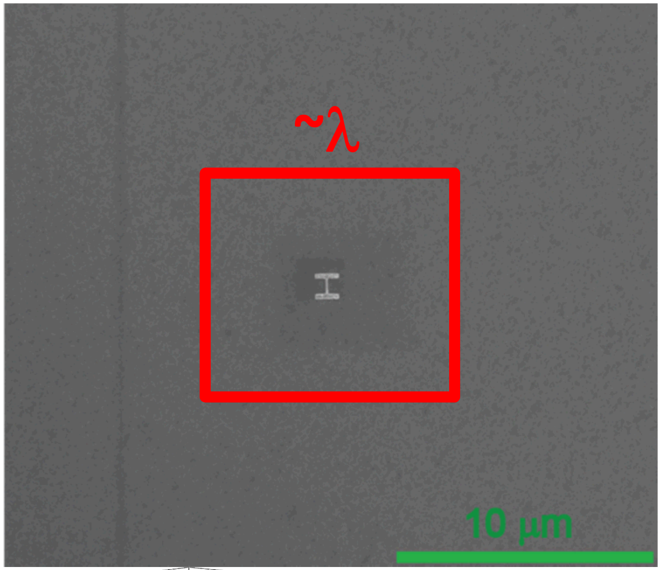
Geometry factor

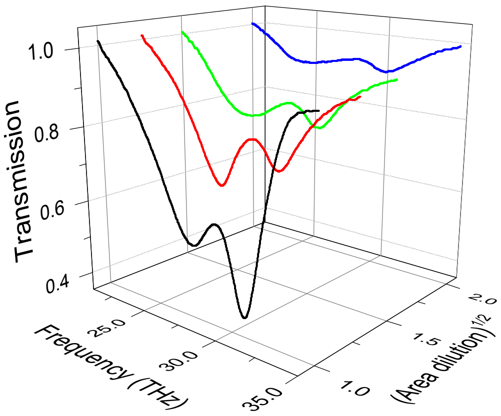
Rabi frequency depends on simple parameters

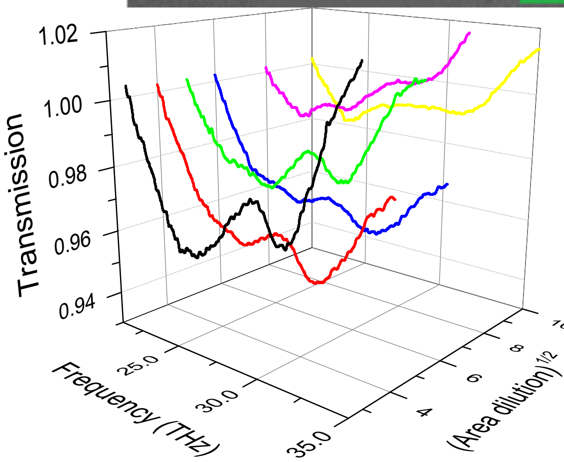
Nature Communications 4, (2013)
Phys. Rev. B 89, 165133

This is a "Single Resonator" Behavior









Same Rabi splitting remains down to a single resonator!

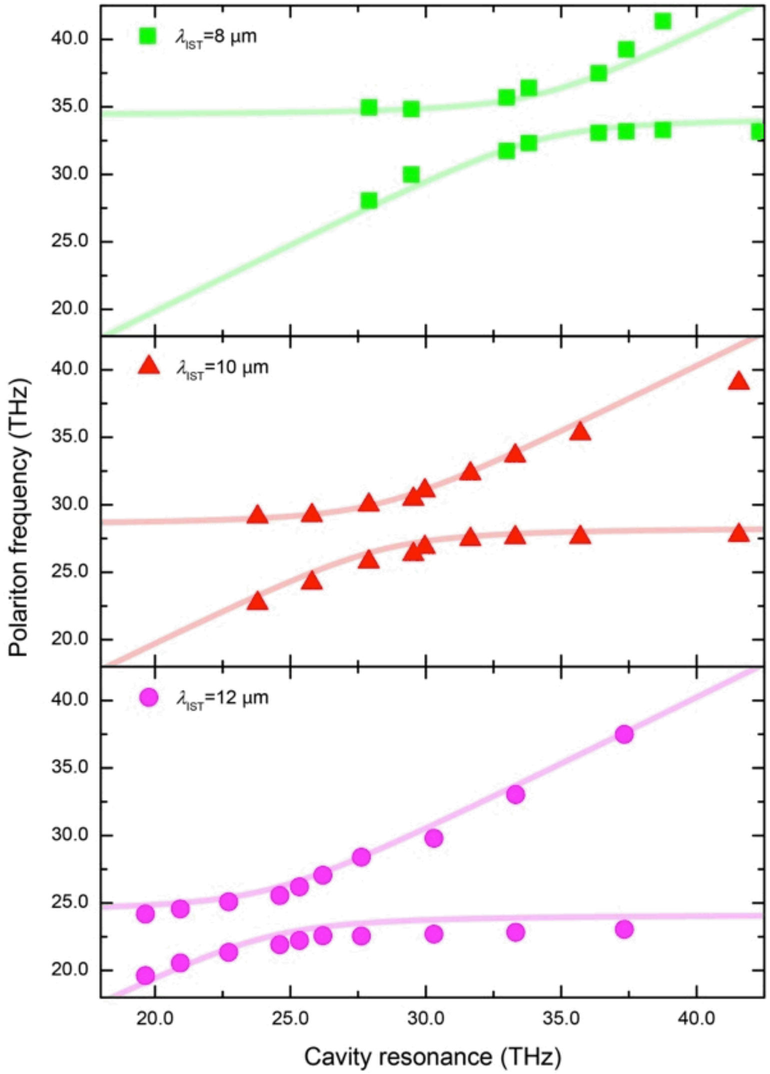
Nature communications **4**, (2013)

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

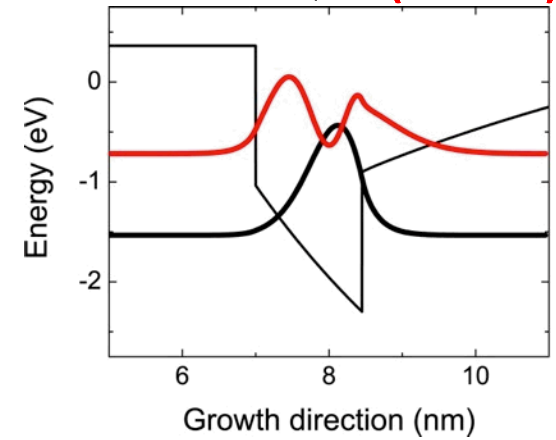
From Mid-IR to Near IR

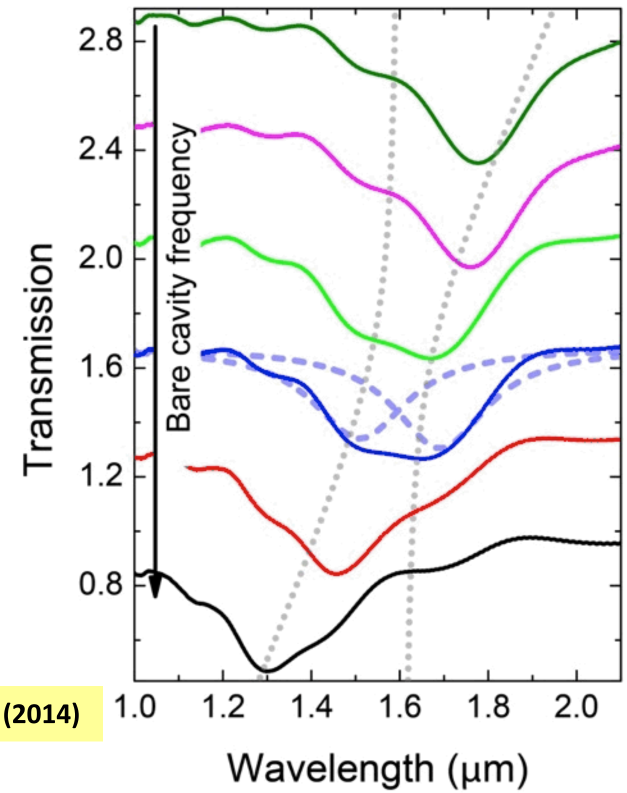
Alex Benz

InGaAs QWs (mid IR)



GaN QWs (near IR)

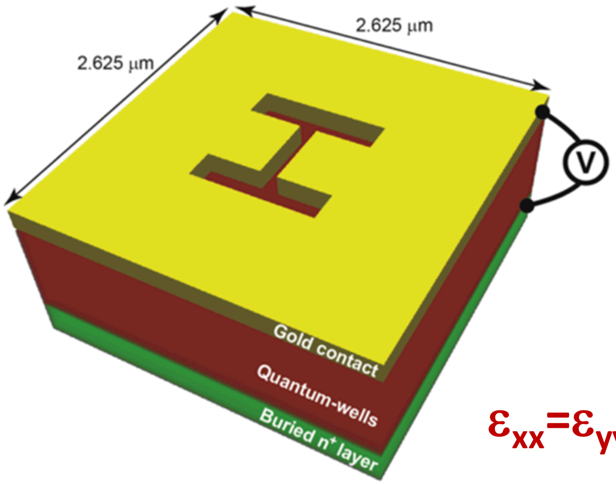




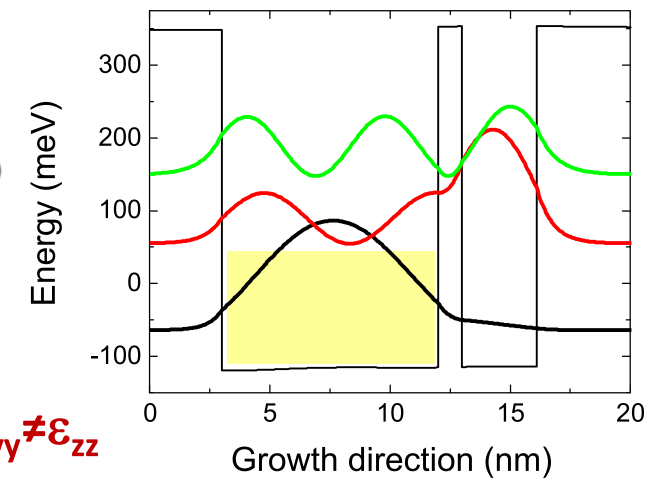
ACS Photonics (2014)

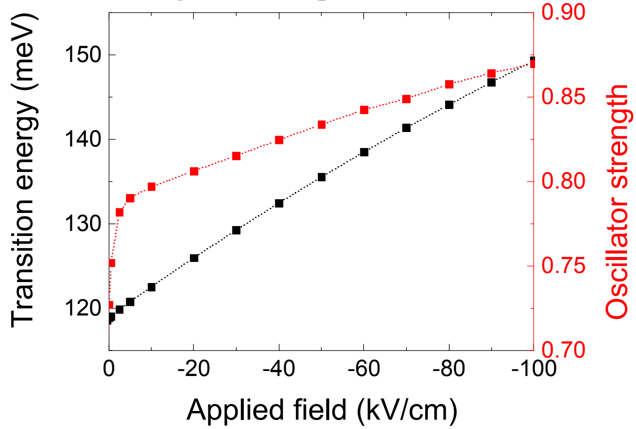
Nature Communications 4, (2013)

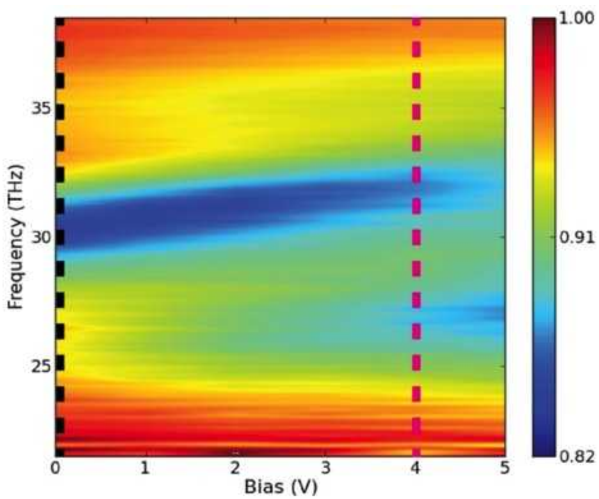
Electrically Tunable Strong Coupling

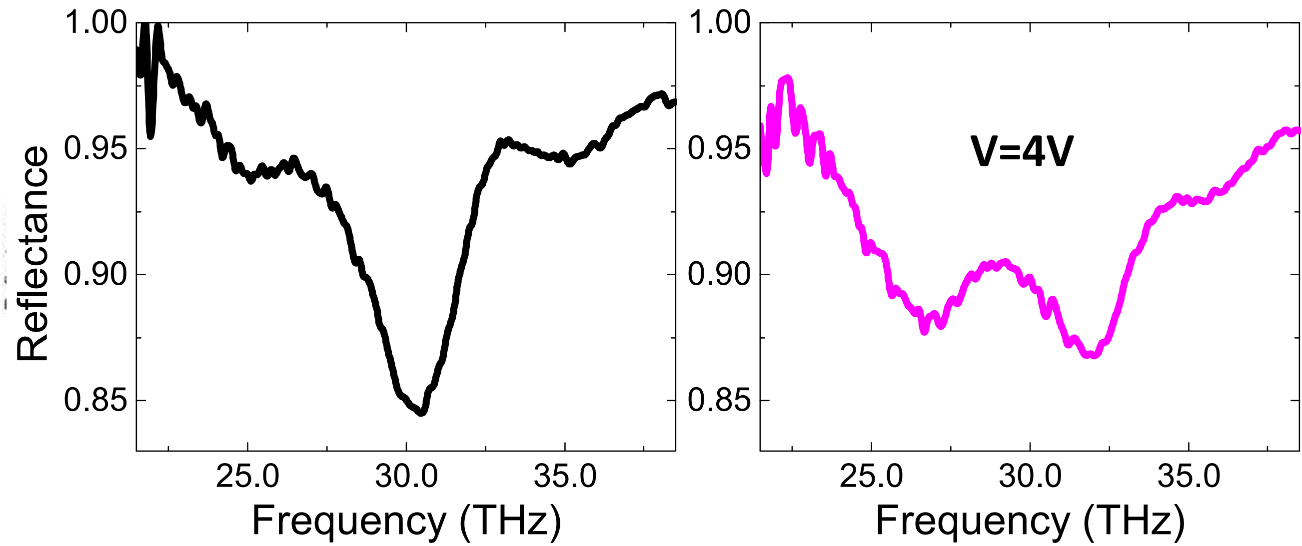


$\varepsilon_{xx}=\varepsilon_{yy}\neq\varepsilon_{zz}$









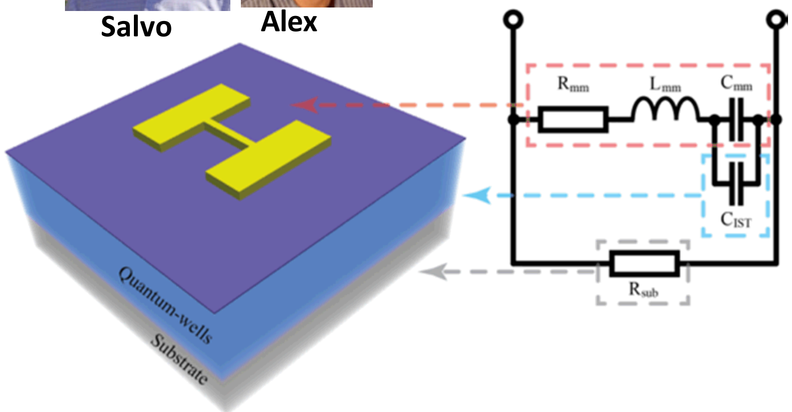
Upper polariton shifted by 2.5 THz (~8% of center frequency)

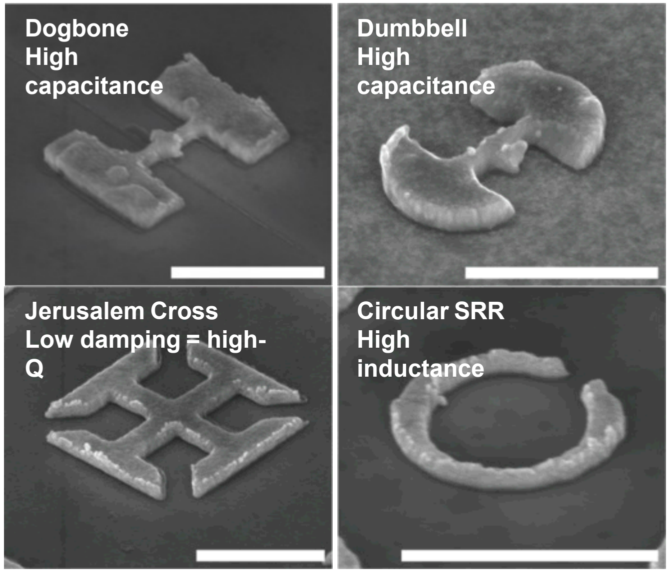
Appl. Phys. Lett. 103, 263116 (2013)

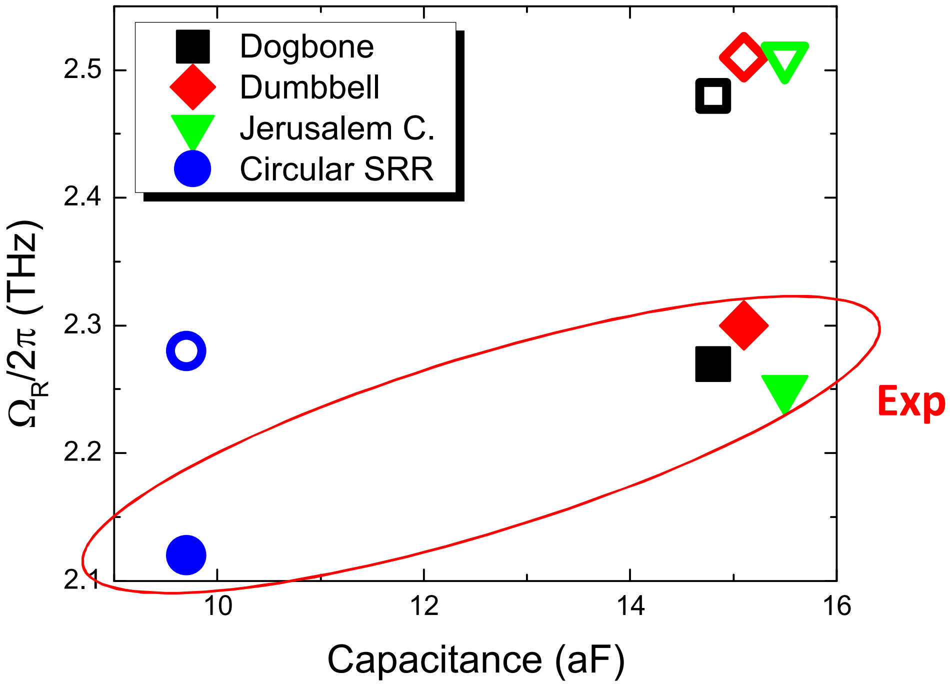
Salvo

Alex

Rabi Frequency vs. Geometry





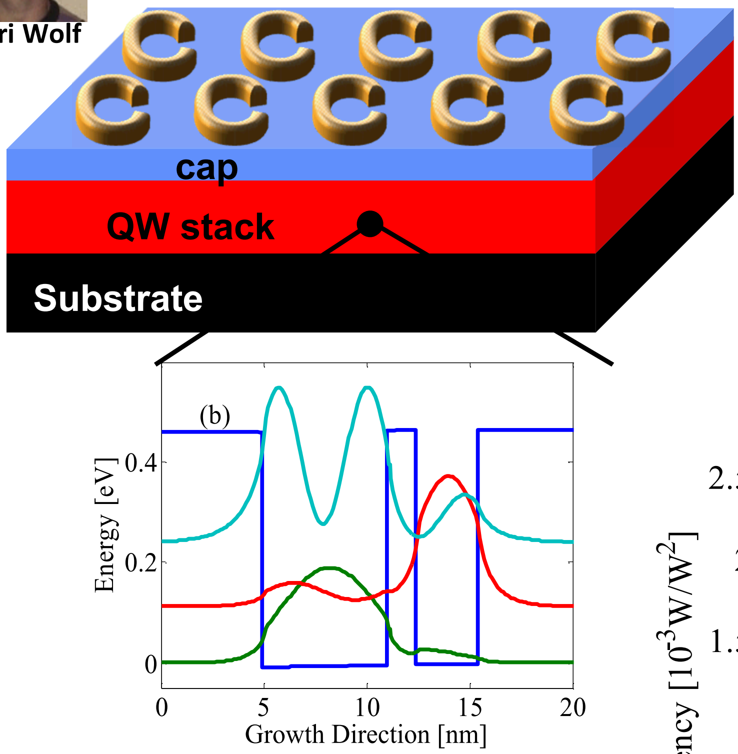


Physical Review B89, 165133 (2014)
NanoLetters (2015)

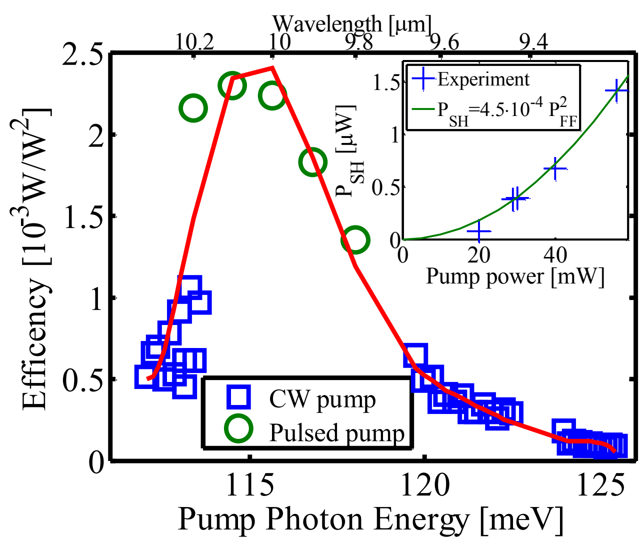
- **<u>Larger capacitance leads to larger Rabi splitting</u>**

SHG From Strongly Coupled MMs and Intersubband Transitions

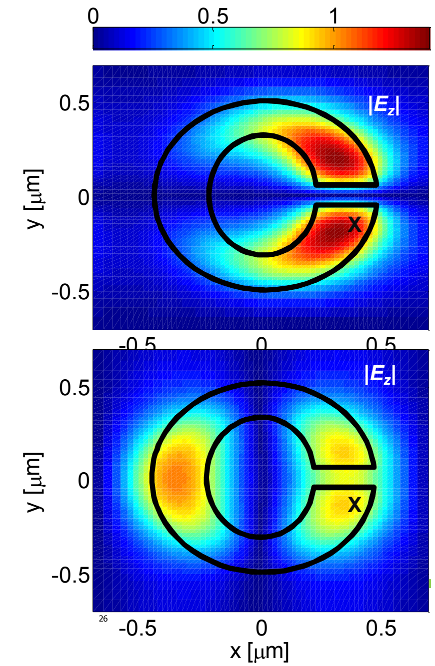
Omri Wolf



3 levels are designed to create a $\chi^{(2)}$



Resonators are designed to have resonances at 30 & 60 THz



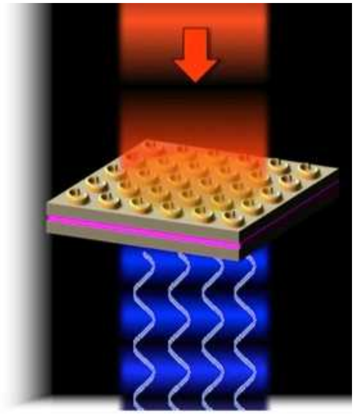
High Efficiency with ~700nm thickness!

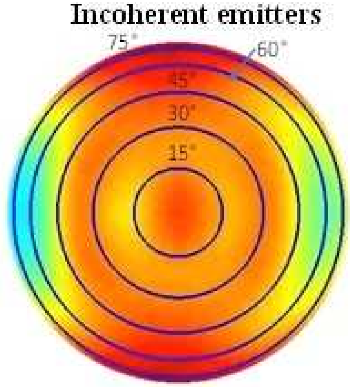
APL 104, 131104 (2014)
Also, see work by Belkin&Alu

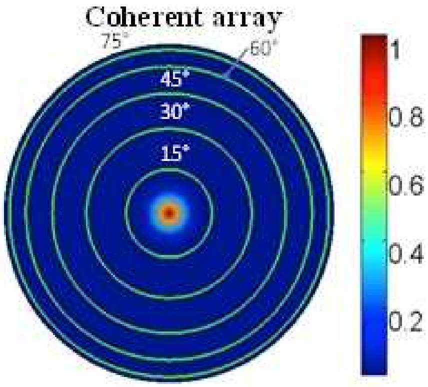
Spatial Coherence: each resonator acts as a point source of SHG

Omri Wolf

- We simulate the radiation pattern of two cases:
  - the nanocavities emit incoherently
  - the nanocavities are coherent and the relative phase of the emitted radiation is determined by the FF pump

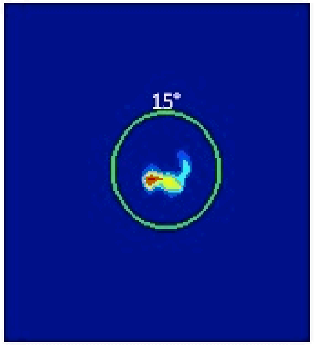






Simulation

- The spatial coherence of the resonators is then proven experimentally:

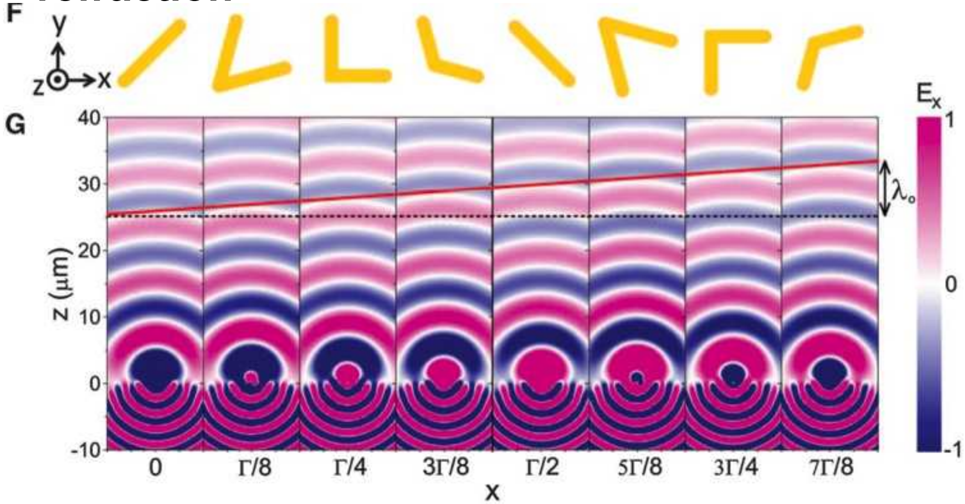


Experiment

All the resonators act as a collection of phase coherent sources of SH radiation

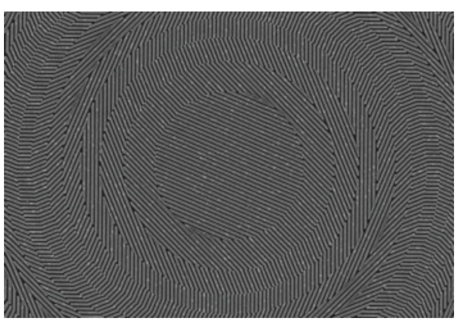
Beam Manipulation With Metasurfaces

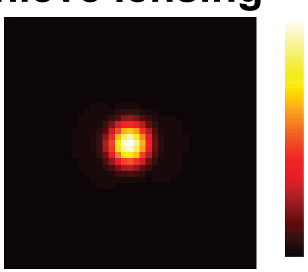
Phase gradient to achieve anomalous refraction



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

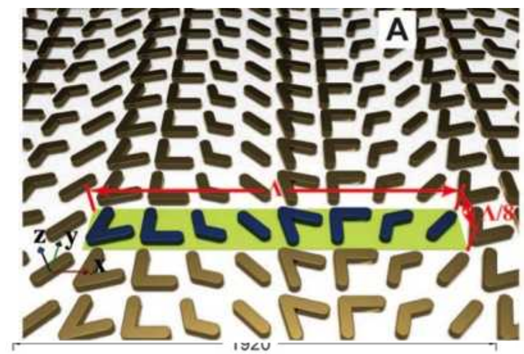
Phase gradient to achieve lensing

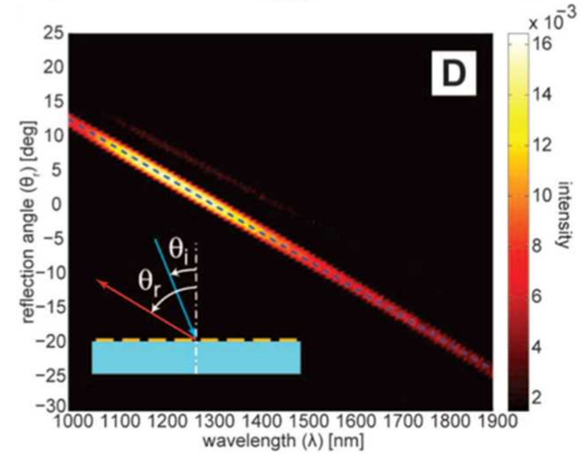




Lin et al. *Science* 345, 298 (2014)

Phase gradient to achieve anomalous reflection





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

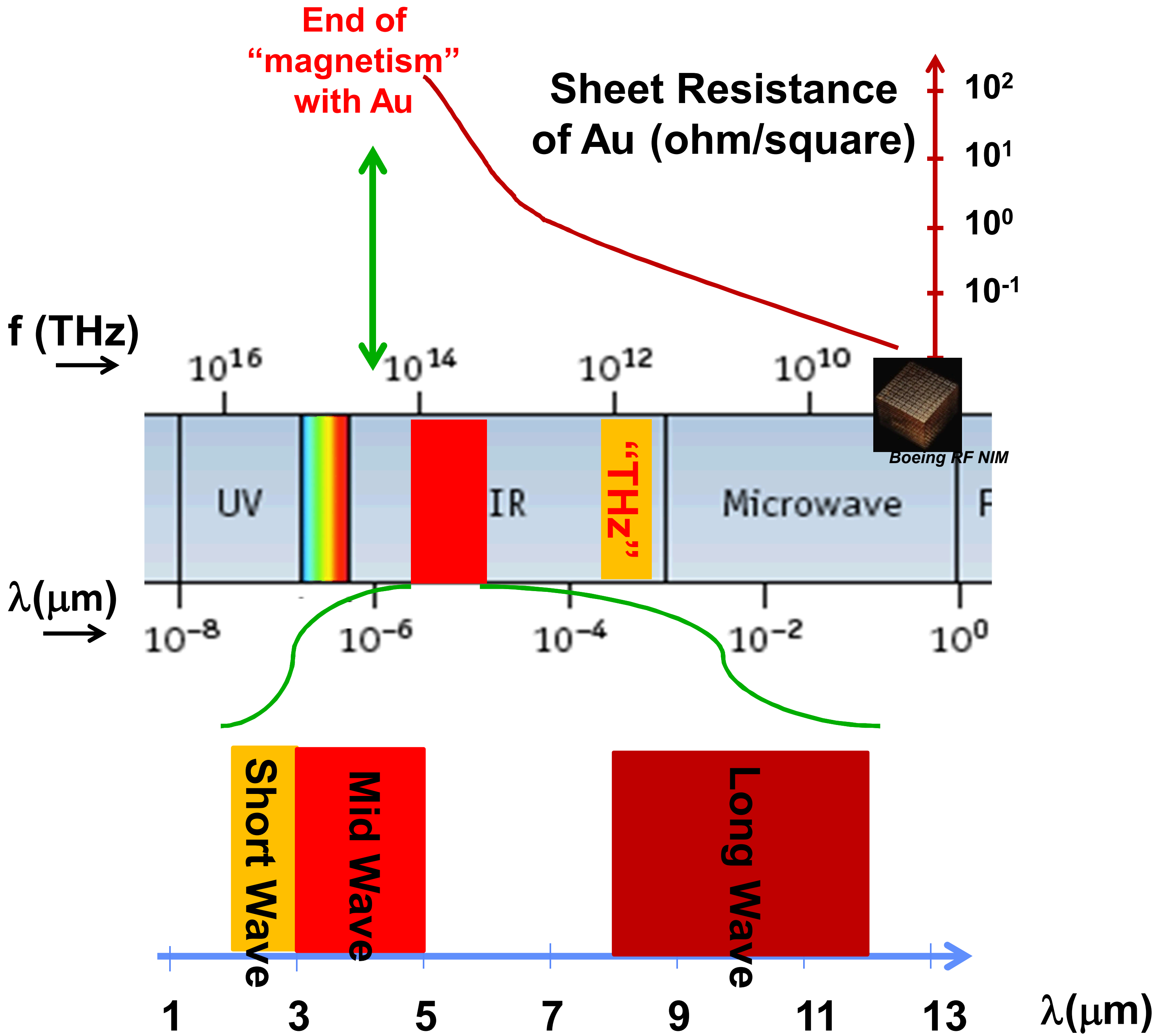
We can do this at the SH wavelength: non-degenerate

Outline

- Metallic Metasurfaces
  - Tuning
  - Strong Coupling
  - Nonlinearities
- All Dielectric Metasurfaces
  - Fundamentals
  - Optical Magnetism
  - Directional Emission, Fano Resonances, and third-harmonic Generation

What's wrong with metals? LOSS!!

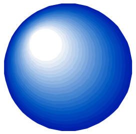
(at higher frequencies (shorter wavelengths)



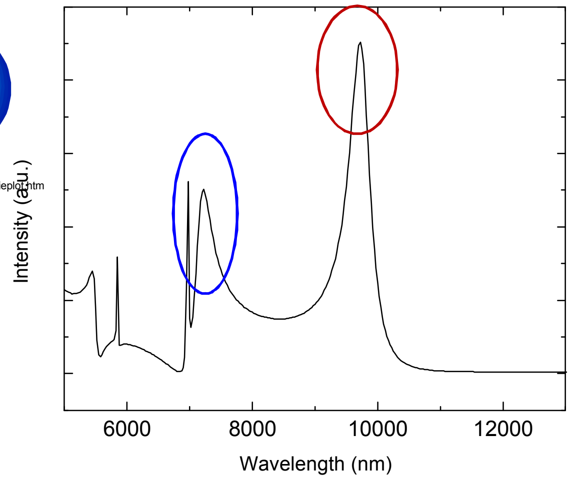
End of “magnetism” with Au
Sheet Resistance of Au (ohm/square)
10^2
10^1
10^0
10^{-1}
f (THz)
10^{16}
10^{14}
10^{12}
10^{10}
Boeing RF NIM
UV
IR
“THz”
Microwave
λ(μm)
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^0
Short Wave
Mid Wave
Long Wave
1
3
5
7
9
11
13
λ(μm)

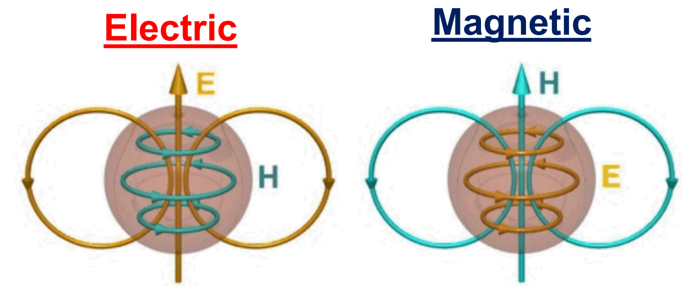
A Non-Metallic Path to Low Loss Metamaterials: Dielectric Resonators

Gustav Mie



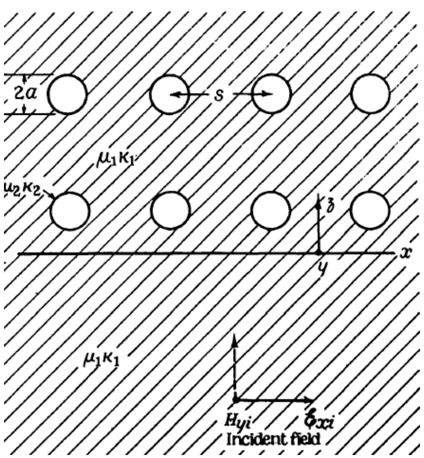
http://www.philiplaven.com/mieplot.htm

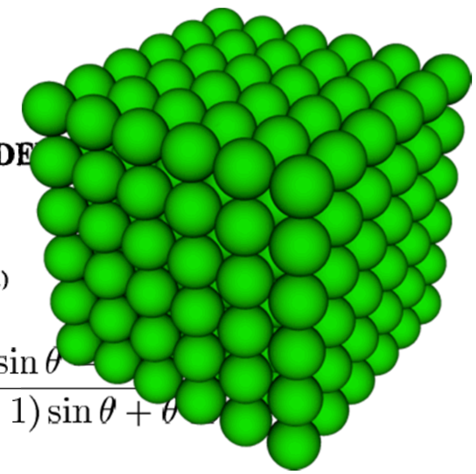




Images: A. Miroshnichenko

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





THE ELECTRICAL CONSTANTS OF A MATERIAL LOADE[D WITH] SPHERICAL PARTICLES*

By L. LEWIN.†

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

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

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

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

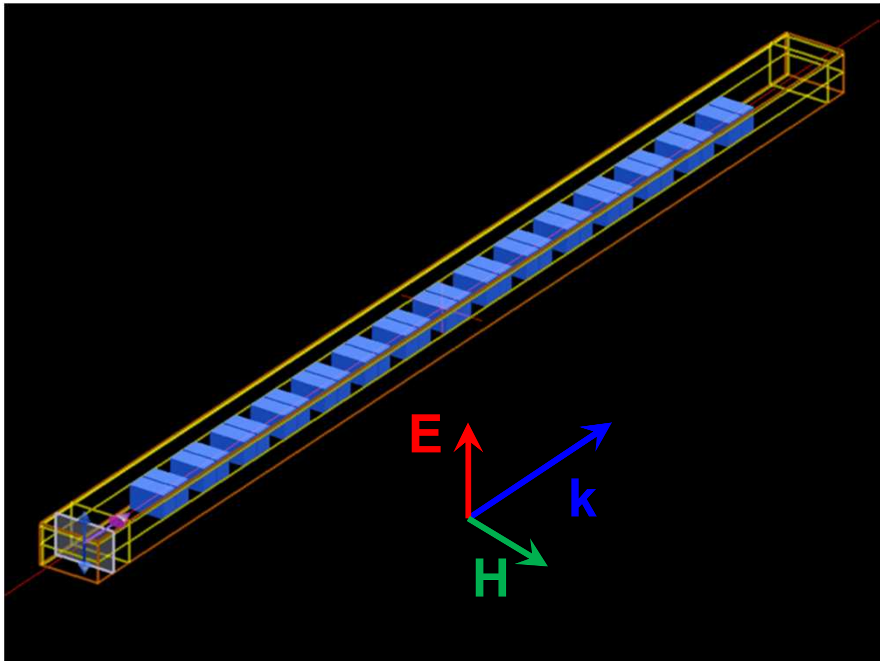
$$\theta = k_0 a\sqrt{\epsilon'_{r2}\mu'_{r2}}$$

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

Full Wave Simulation of Propagation Through Split Cube Array

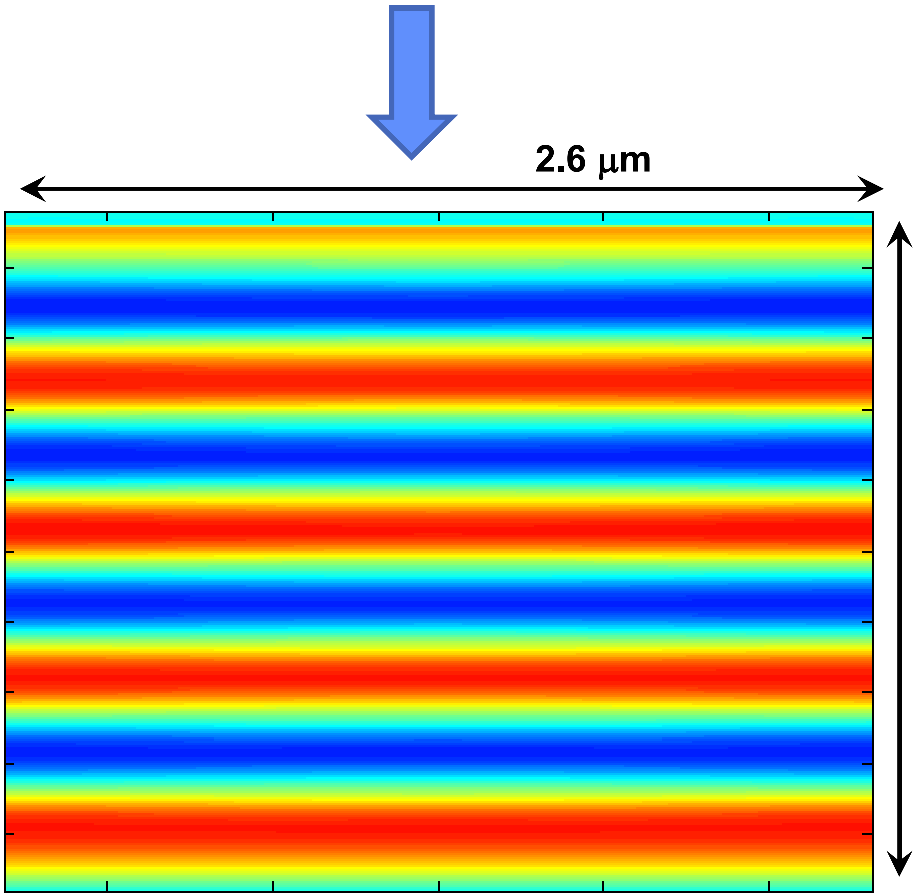
ε=32, edge = 1.53 μm, gap = 100 nm

Lumerical FDTD



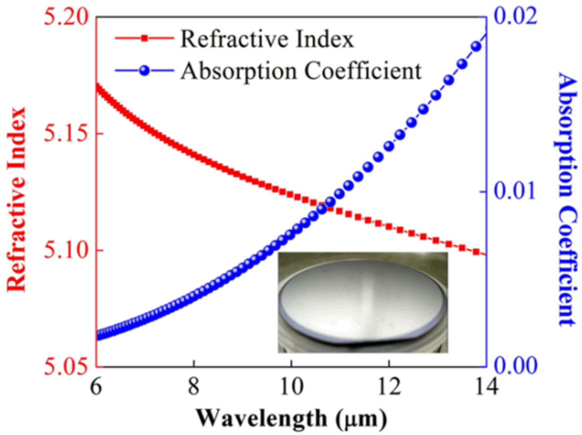
Periodic BC in x & z, 15 cubes thick in y

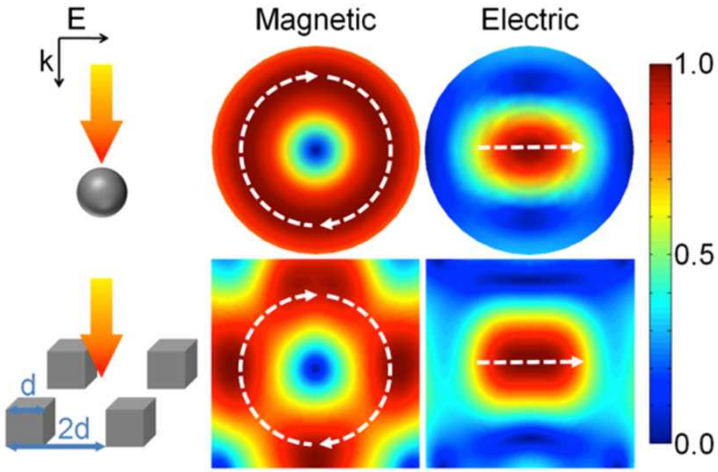
H_x at top of unit cell (z=1.3 μm)
Incident waves



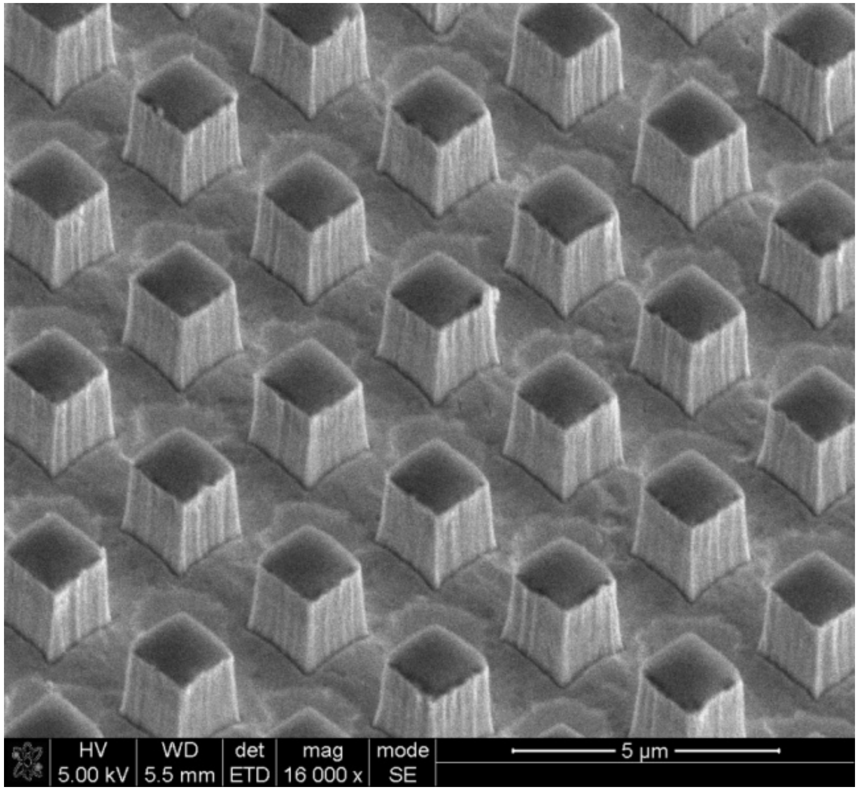
λ = 15 μm

Dielectric Resonator IR Metamasurface: Te/BaF_2





Mask + RIE etch

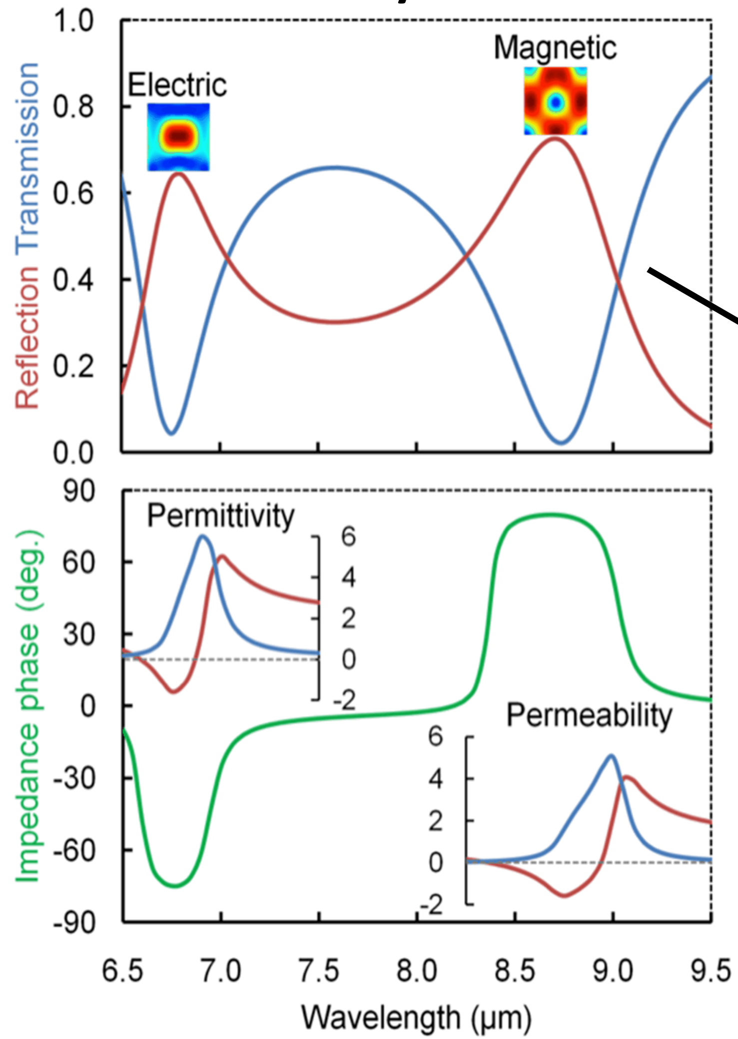


1.53x1.53x1.7mm^3
10 deg wall slope

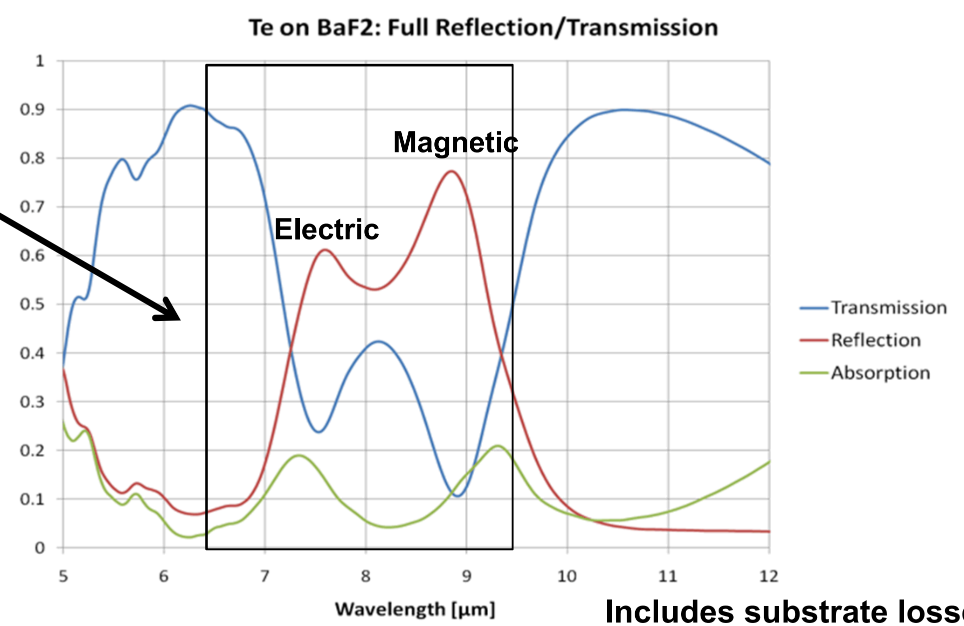
Phys. Rev. Lett. 108, 097402 (2012)

Dielectric Resonator IR Metasurface: Te/BaF_2

Theory



Experiments

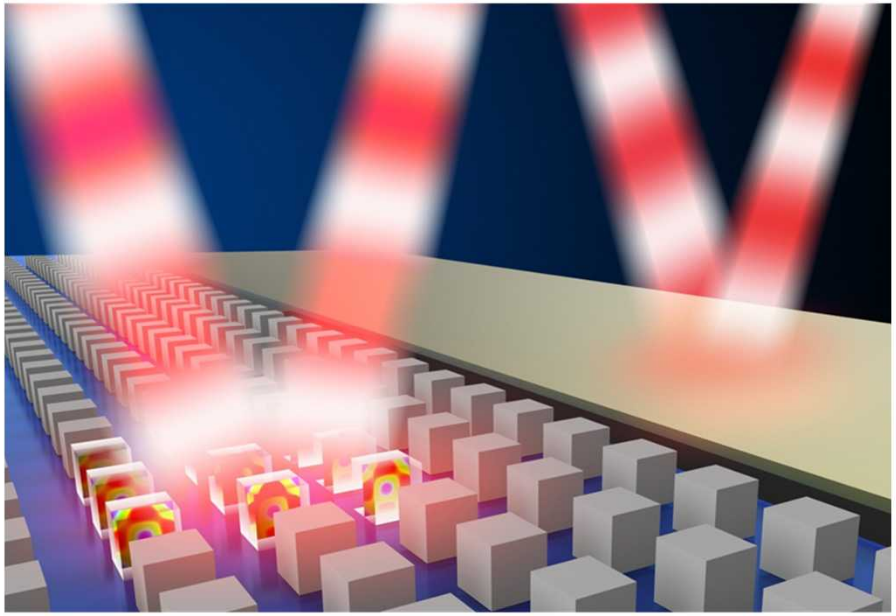


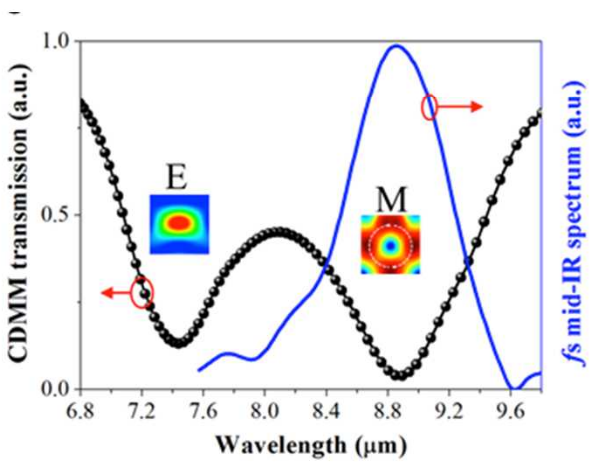
Includes substrate losses

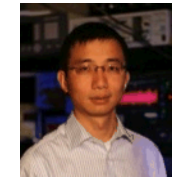
Phys. Rev. Lett. 108, 097402 (2012)

Proving Optical Magnetism:
Measure Absolute Phase of Reflected Wave

a

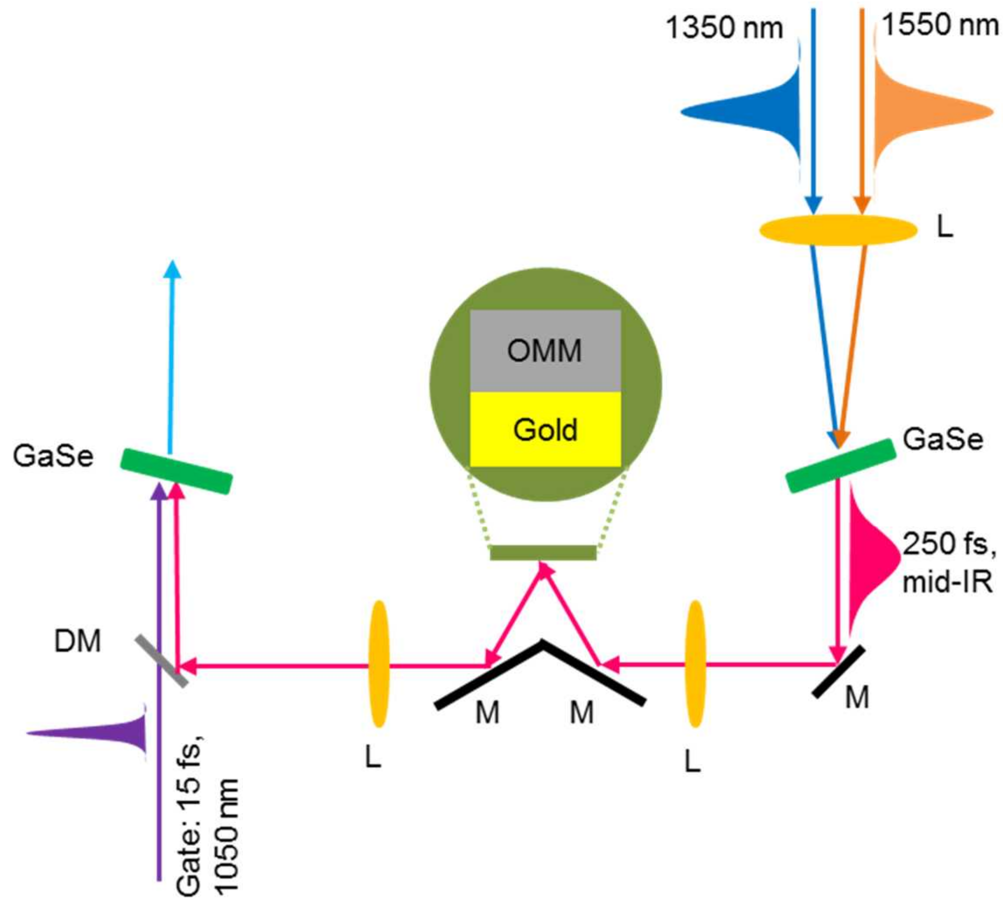






Sheng Liu

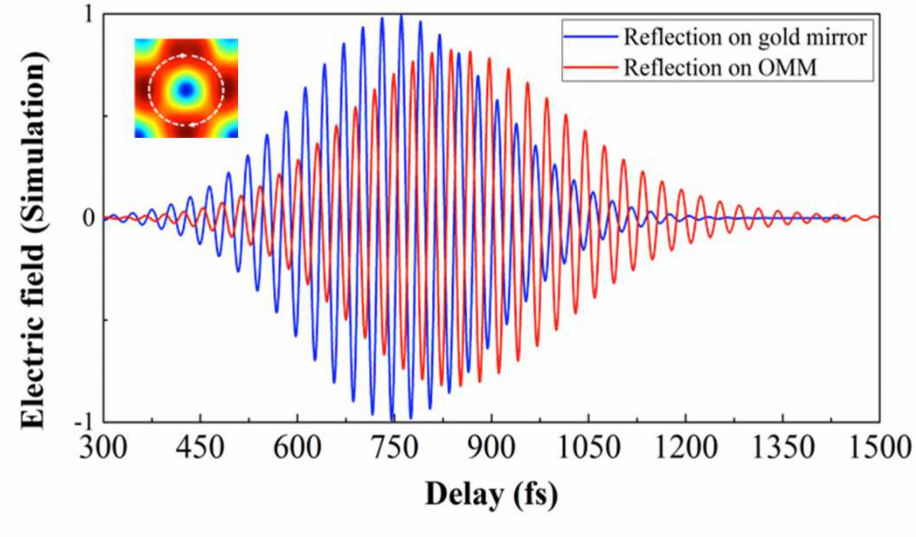
Phase-locked Time Domain Spectroscopy

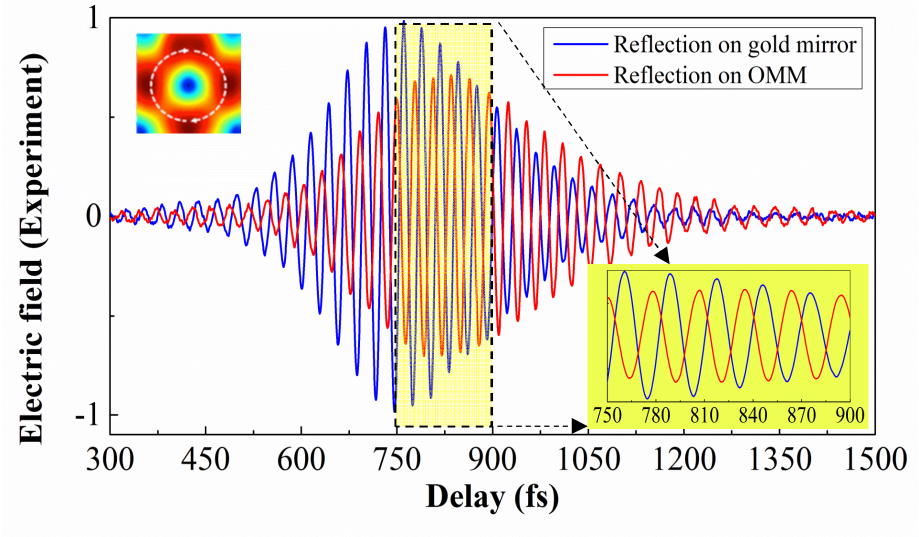


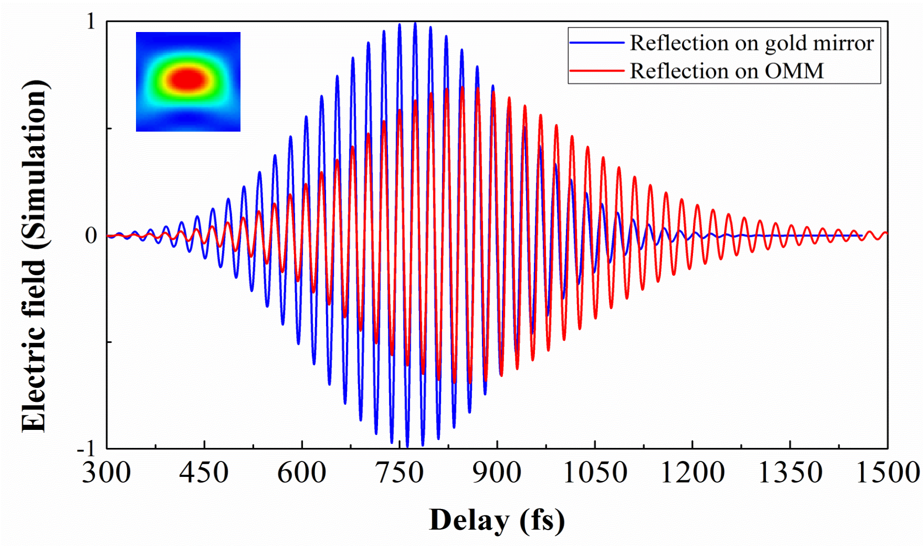
Appl. Phys. Lett. 103, 181111 (2013)

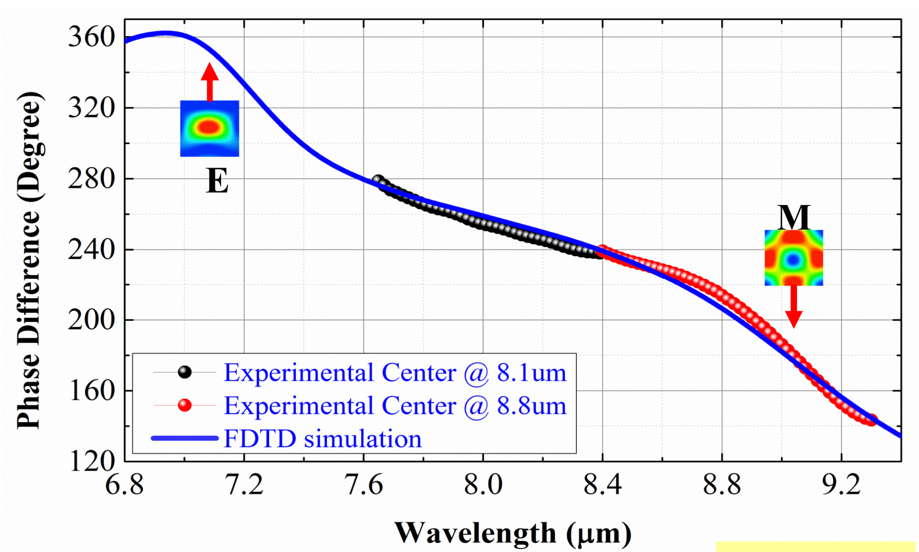
Optica 2014

Experimental Demonstration of "Optical Magnetism"



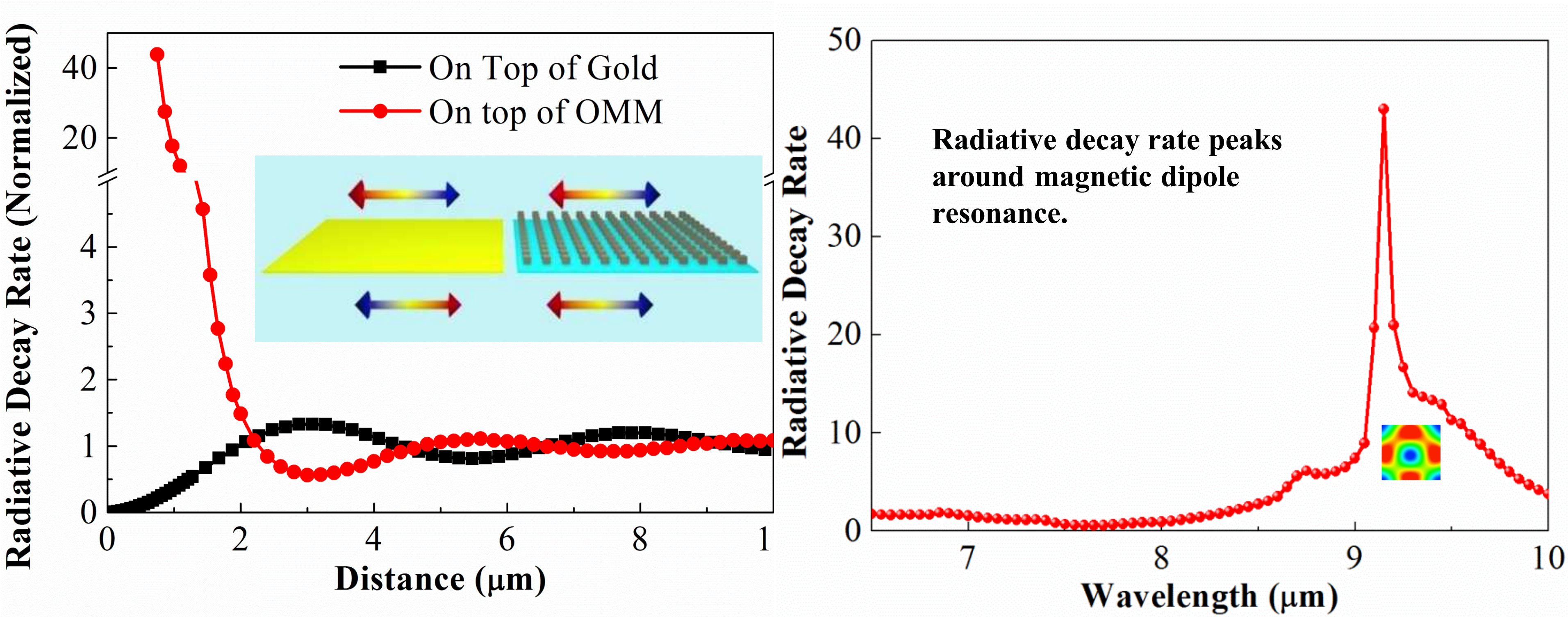






Optica 2014

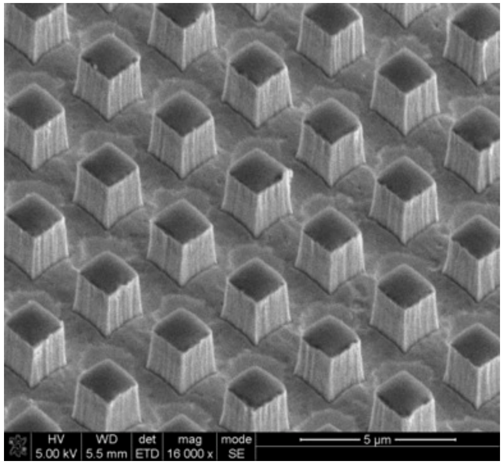
Radiative Decay Rate of a Transverse Electric Dipole Near Au and OMM Surfaces

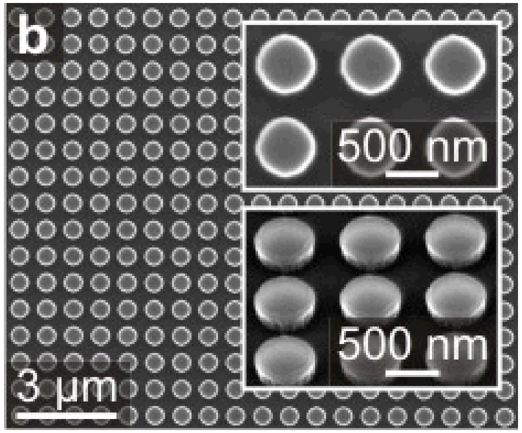


- Oscillatory dependence on distance is shifted by about half a period
- Dipole emission near the magnetic mirror is enhanced even for very small distances

Optica 2014

Scaling Dielectric Resonators to the Near IR: Silicon Nanostructures

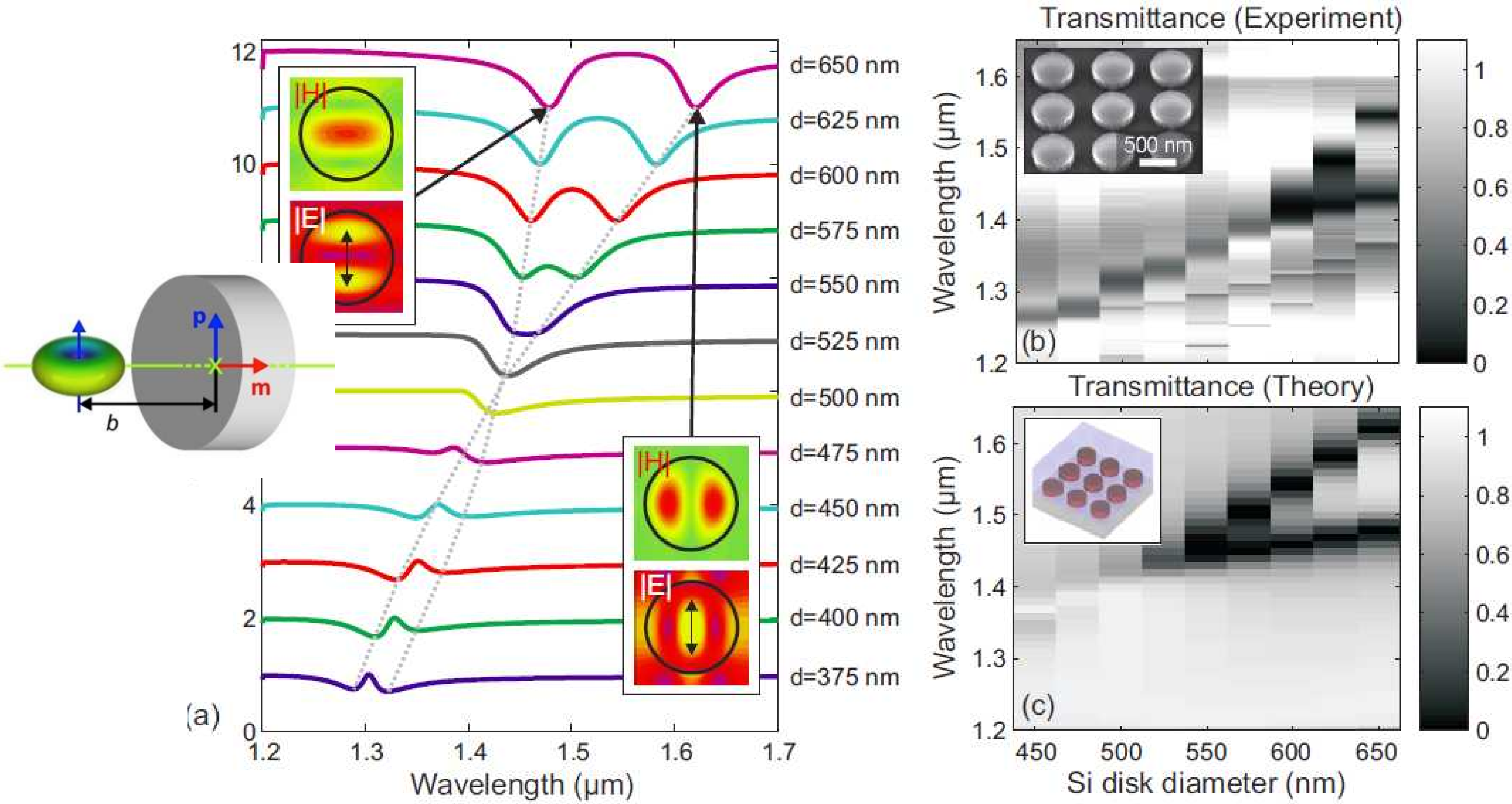




Tellurium: n~5, Size~1.5μm
λ>5μm

Silicon: n~3.5, Size<200-500nm
λ>1μm

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

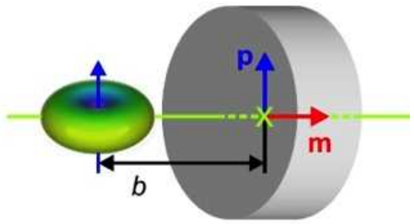


Changing the aspect ratio of the nanocylinder, changes relative position of E & H resonances

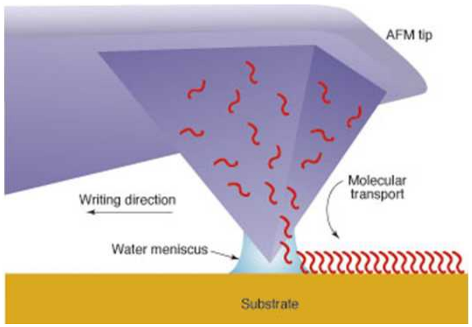
ACS Nano 2013 7 (9), 7824-7832

Integration with Quantum Dots

With J. Hollingsworth
and F. Darwood, LANL

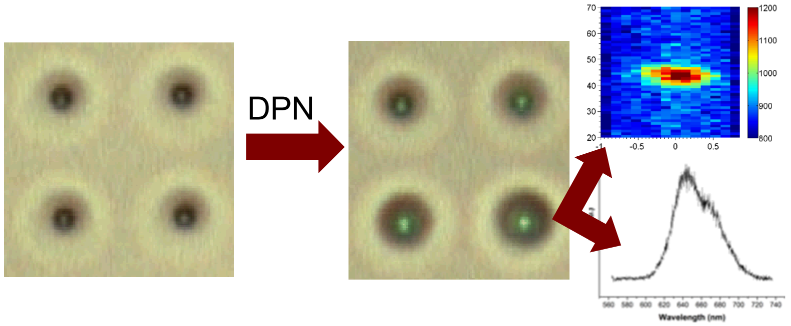


Dip-pen nanolithography



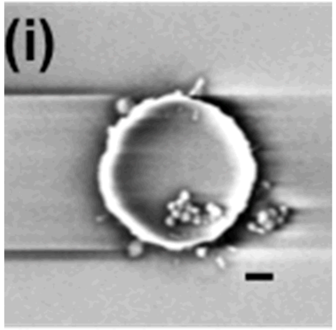
http://str.llnl.gov

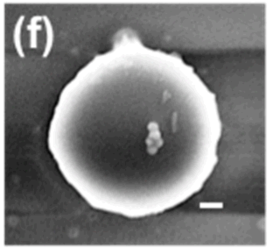
Many QDs



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

Towards Single QDs



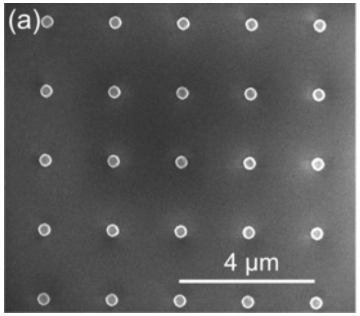


35°

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

Near Field Imaging of Localized Modes

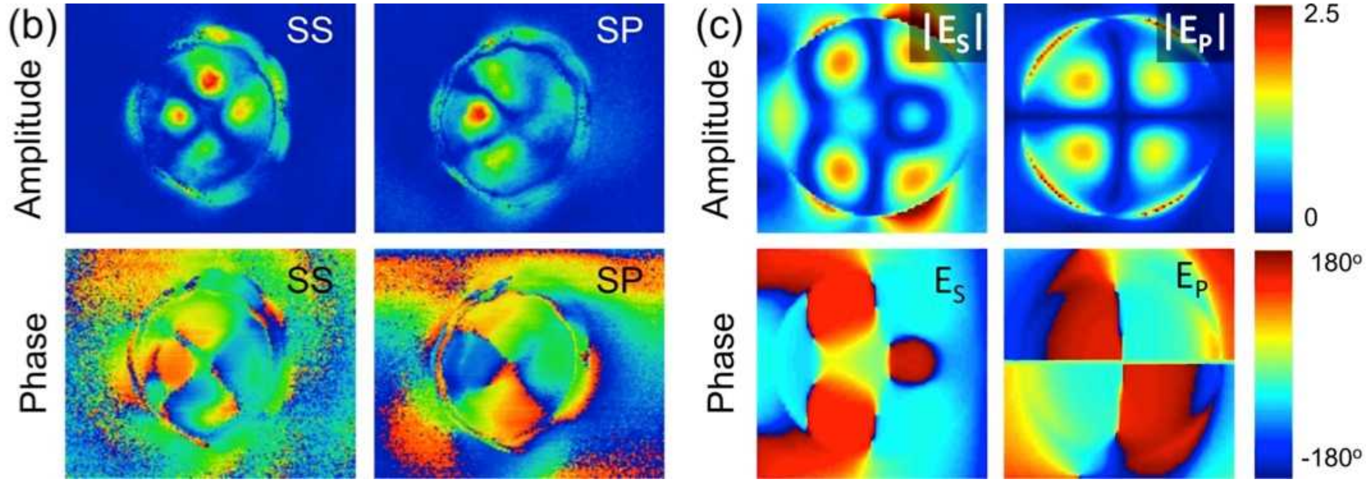
With Prof. Habteyes, UNM



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

Measurements

Calculated near-field amplitudes

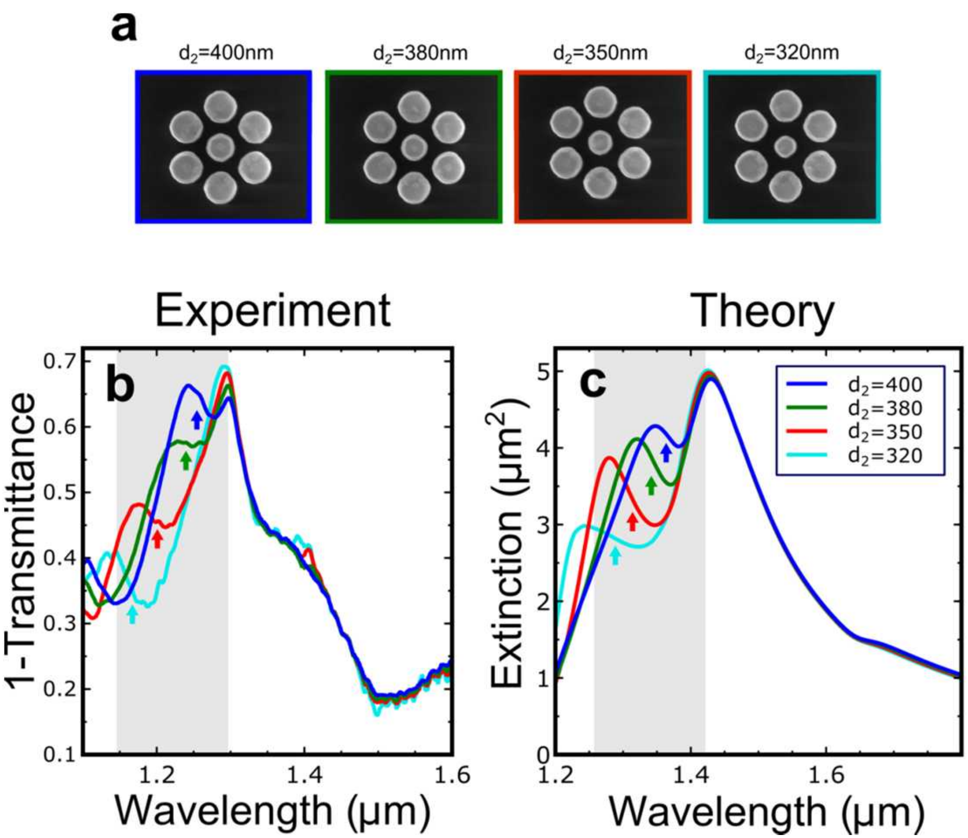


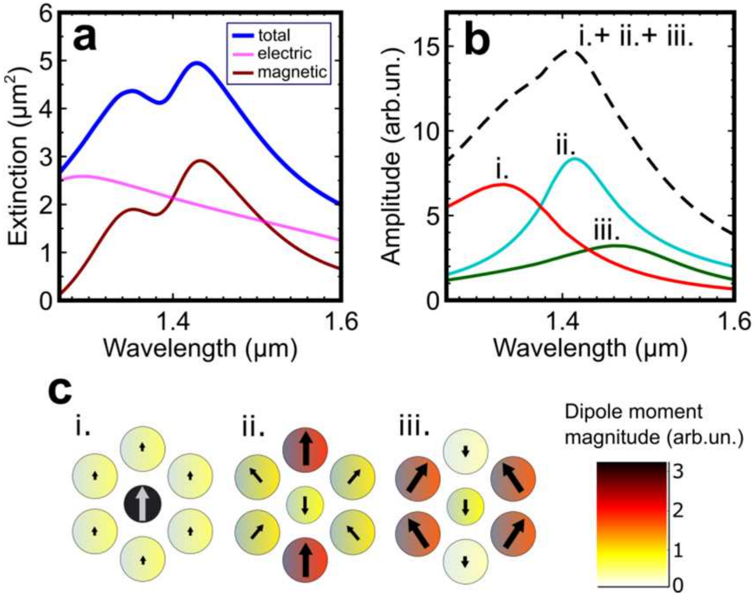
Mostly electric quadrupole

ACS Photonics 2014

Fano Resonances in All-Dielectric Nanoparticle Oligomers

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

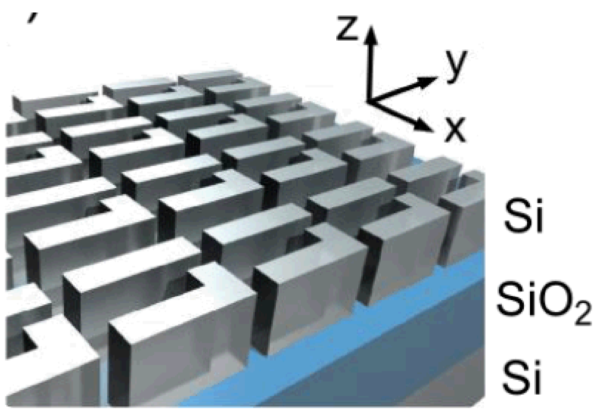


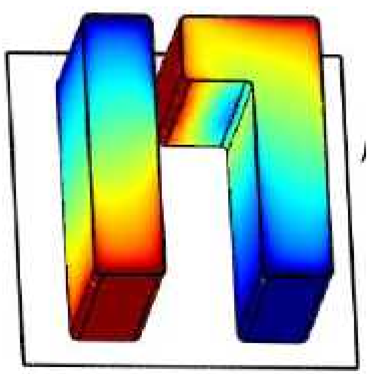


Small, 2013

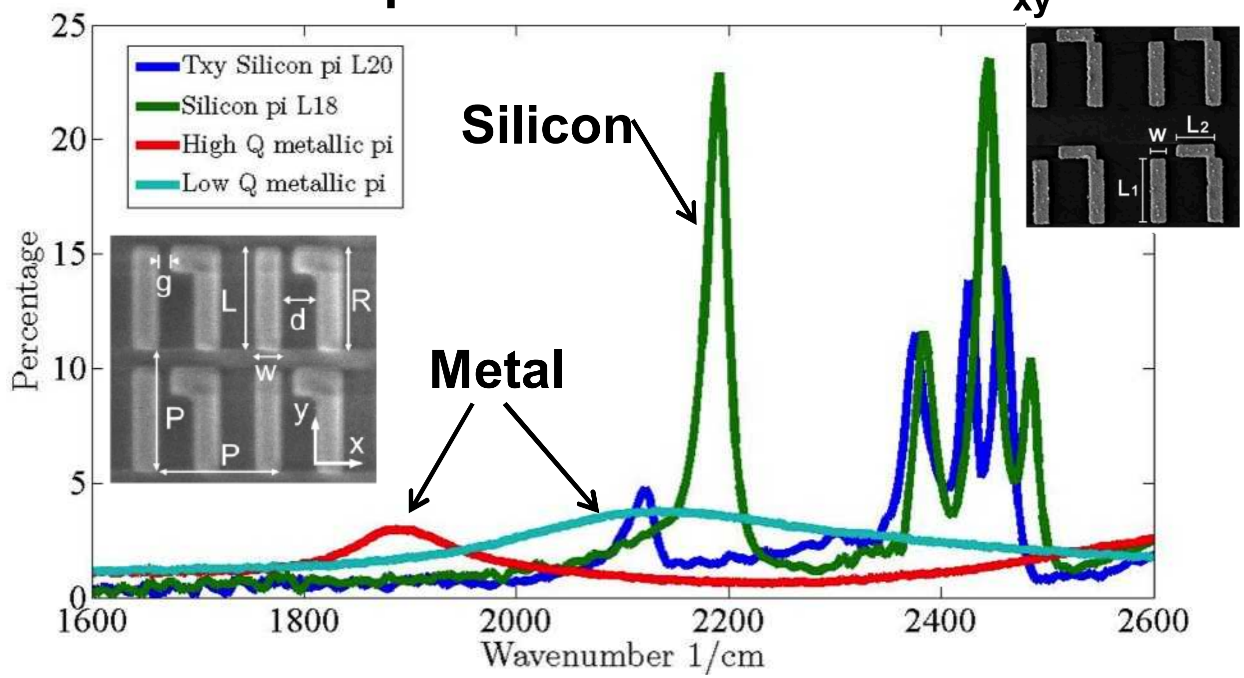
All-Dielectric Fano-Resonant 2D Chiral Metasurfaces:

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



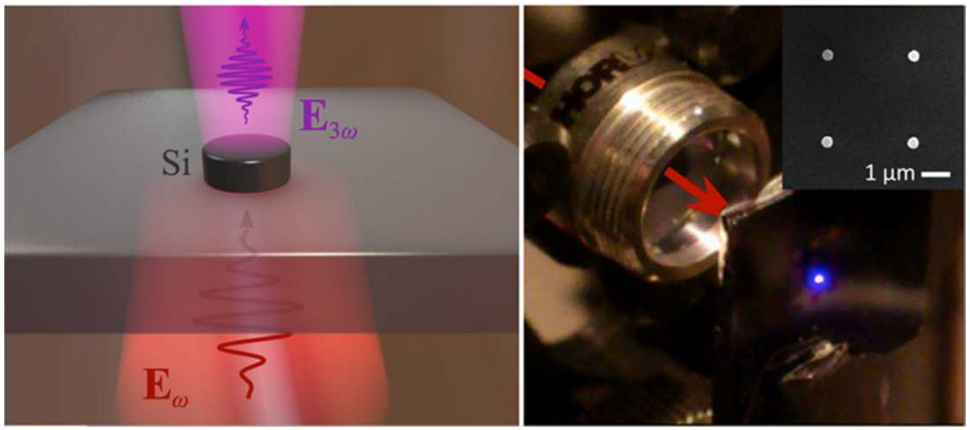


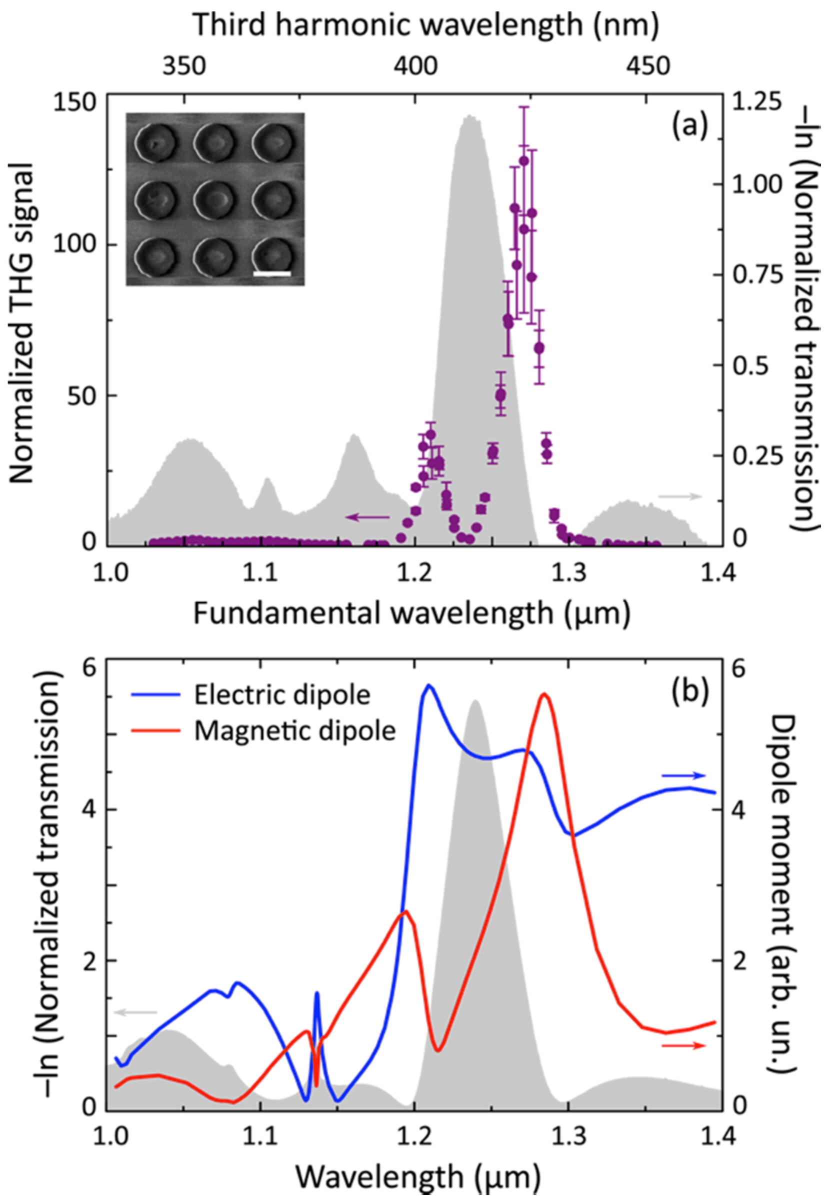
Cross-polarized transmission T_{xy}



Nature Communications (2014)

Third Harmonic Generation

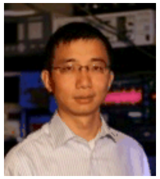




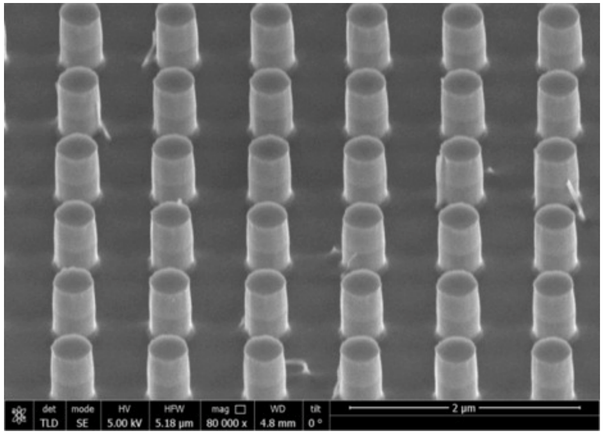
(With ANU & Moscow State)

Nano Letters 2015.

Dielectric Metamaterials with III-V's?

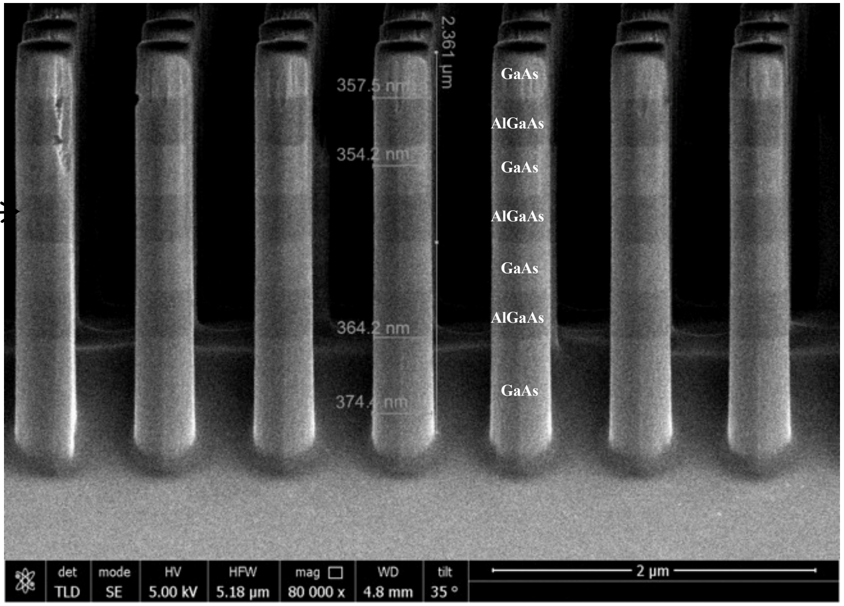


Sheng Liu



GaAs nanocylinders

Oxidized



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

Lomonosov Moscow State: M. Shcherbakov,…

UNM: T. Habteyes, S. Krishna

UT Austin: G. Shvets

U.S. DEPARTMENT OF ENERGY | Office of Science

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

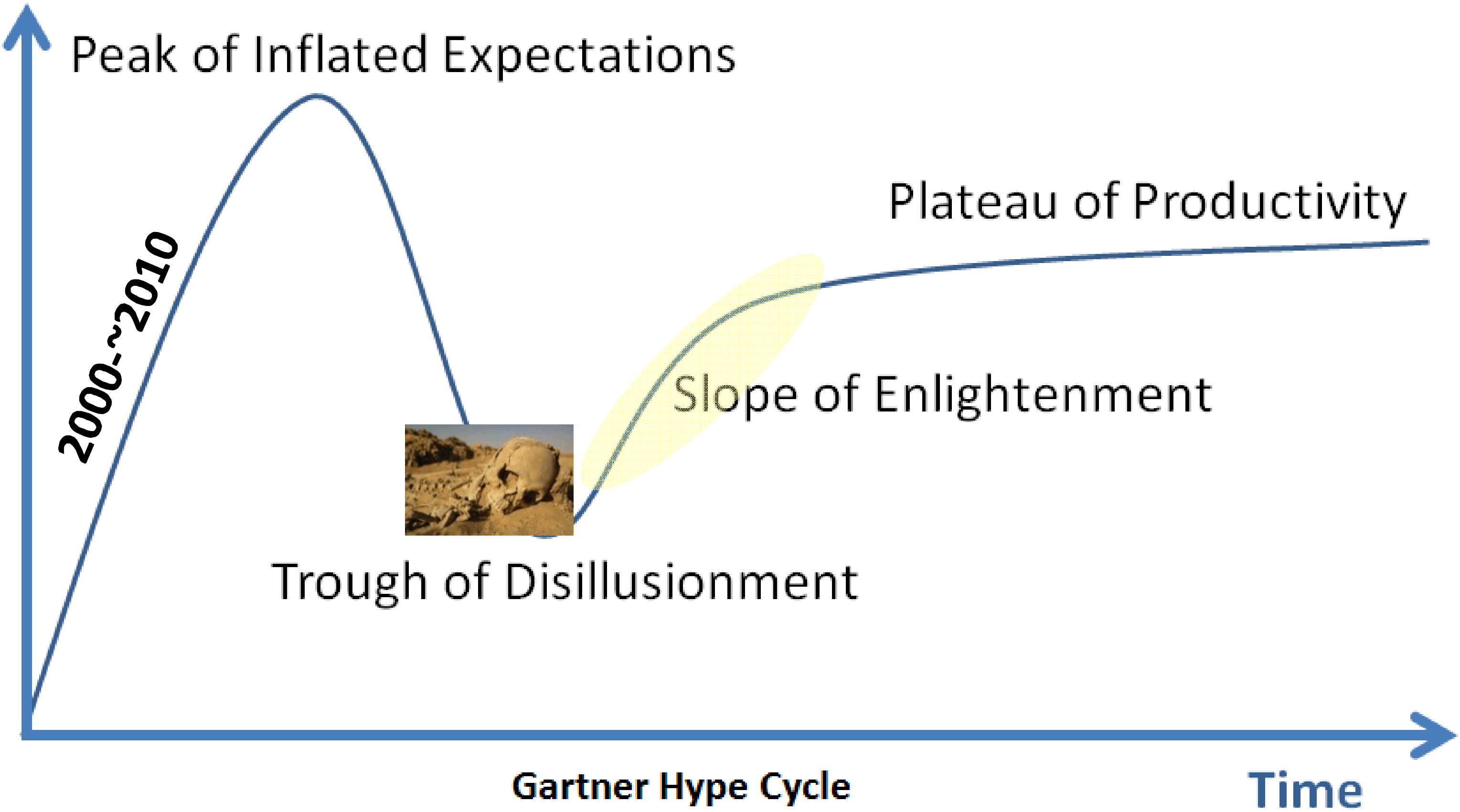
User facility: free to use

http://cint.sandia.gov

END

BACKUP

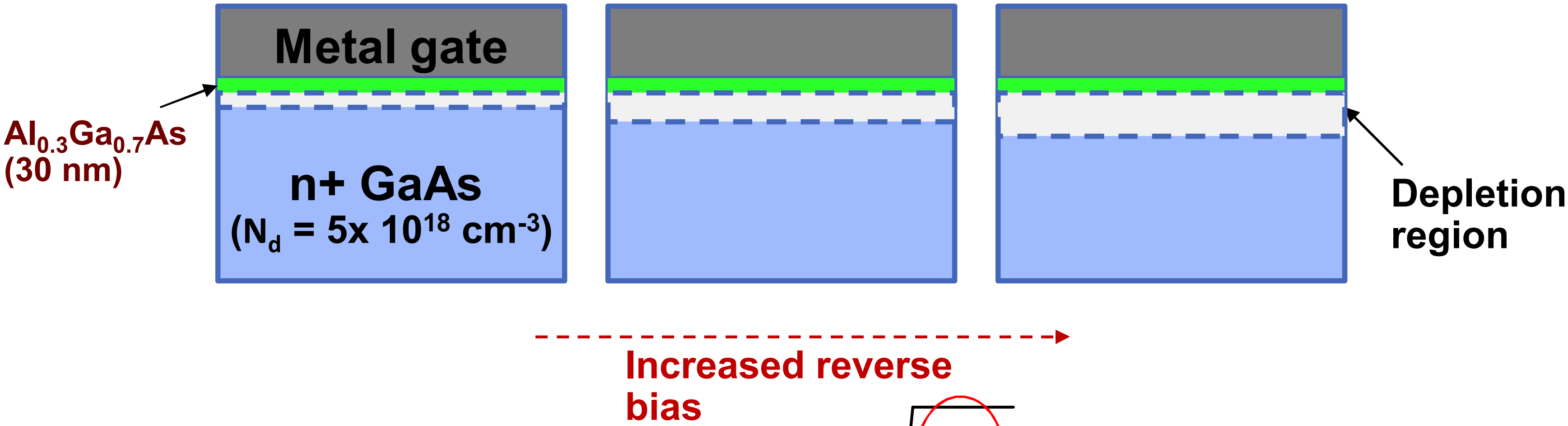
So What's the Future of Metamaterials?



Metamaterials "inspired" new directions. My own example:

3D Metamaterials >> Voltage tuning >> Planar MM resonators >> Strong coupling

Tuning MMs by Depletion of Carriers



Large changes in ε happen near the plasma frequency. Therefore increase *N*

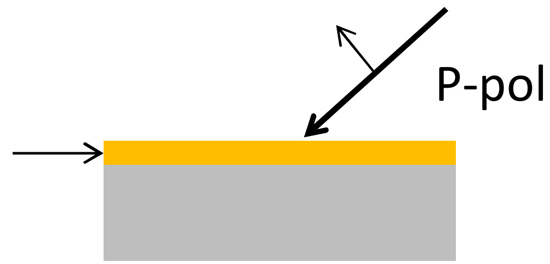
$$\omega_P \propto \sqrt{\frac{N_e}{m^*}}$$

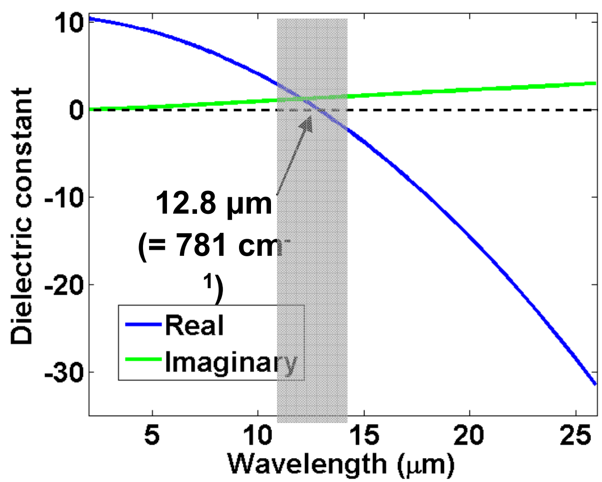
Depletion width

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

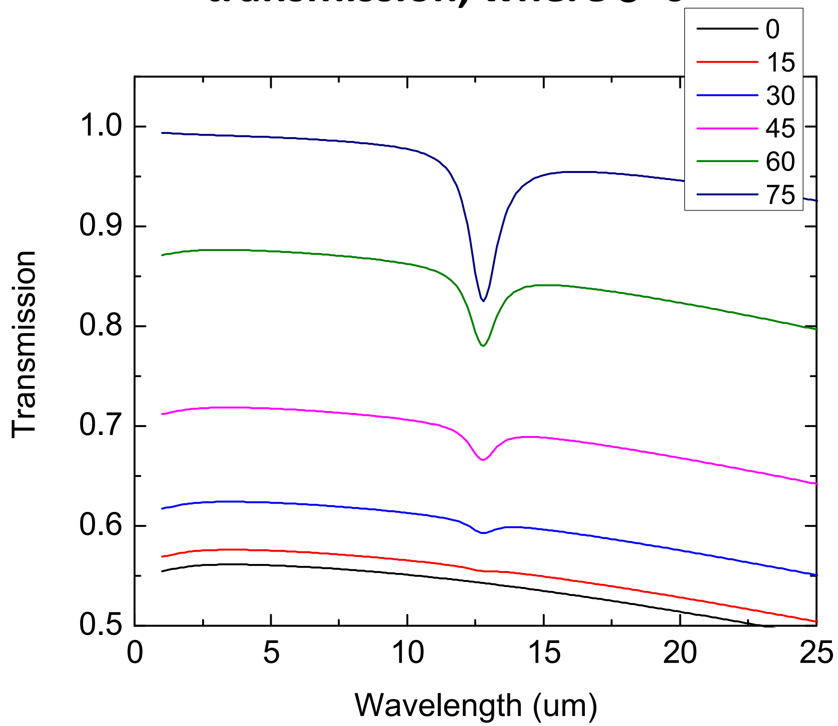
•Large N implies thin $W_{depletion}$ ->> *Interaction* ↓

Coupling Between Metamaterial Resonators and "Epsilon Near Zero" Waves





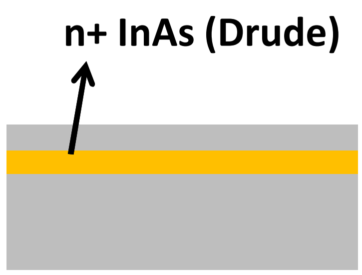
Transmission vs angle (p-pol): A sharp dip is observed in transmission, where ε~0

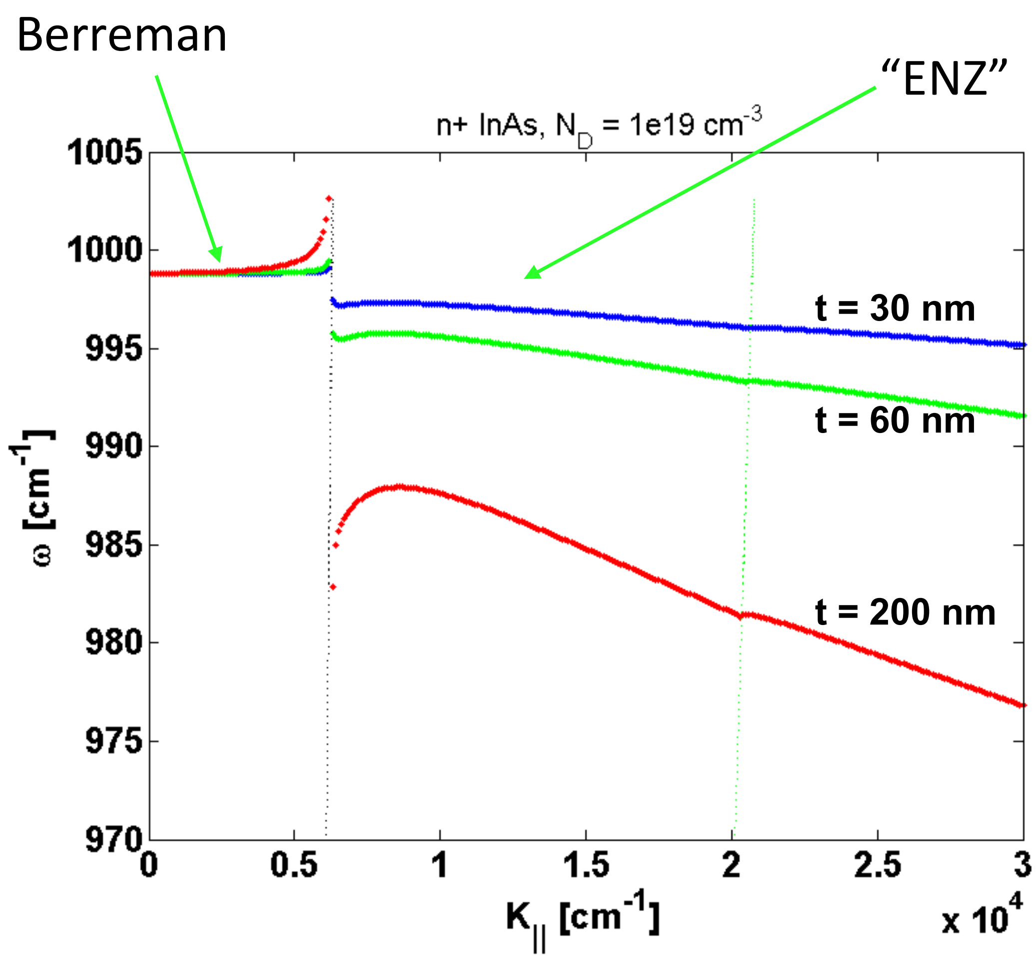


("Berreman" dip)

Berreman, Physical Review **130** (6), 2193 (1963).
McAlister and Stern, Physical Review **132**, 1599 (1963).

Berreman mode vs ENZ mode in n+ InAs

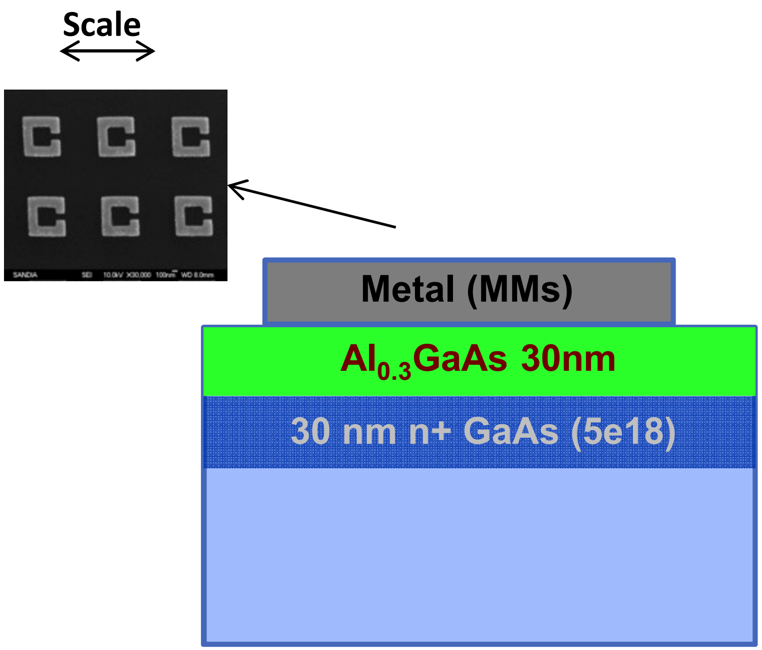


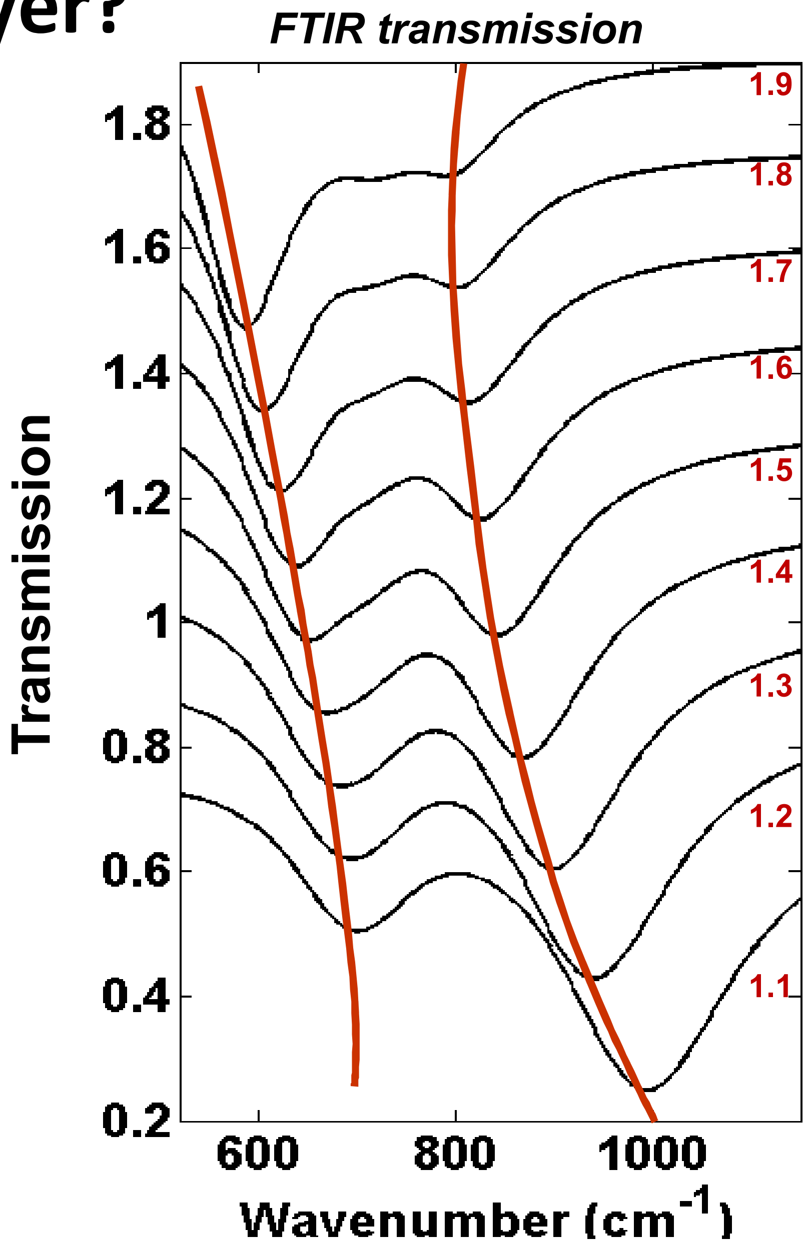


- Berreman mode is very flat for a thin doped layer and leaky into air
- ENZ mode does not couple to free space

Greffet et al, PRL 109, 237401 (2012)

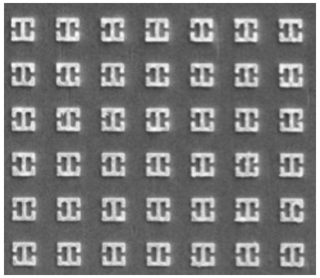
What Happens when MMs Resonate with ε~0 Layer?

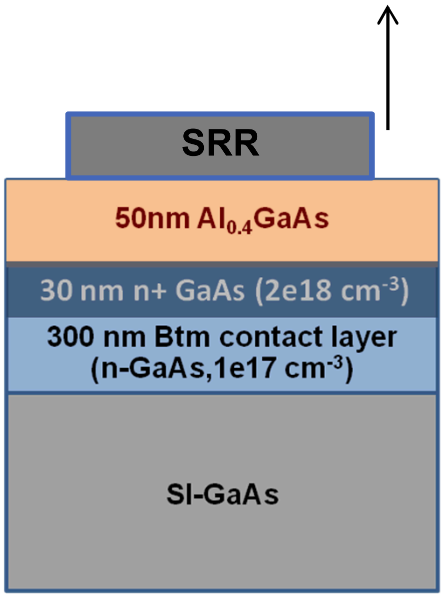




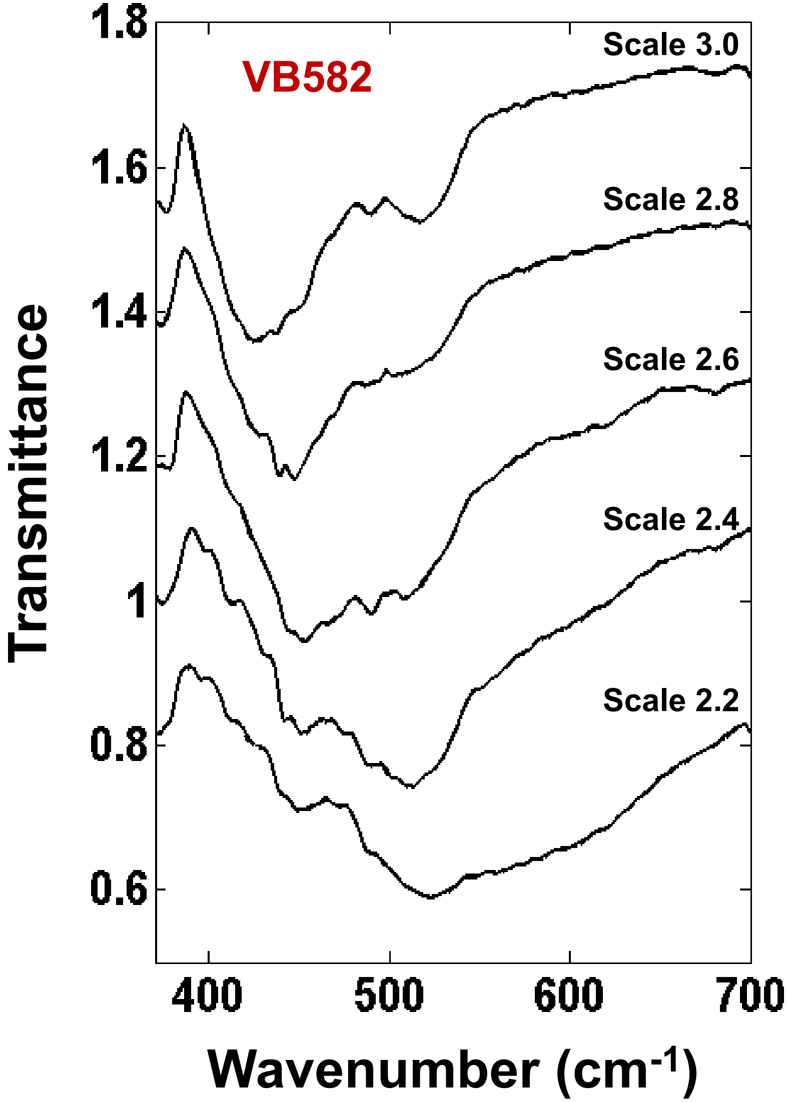
- **Strong coupling between the MM resonance and ENZ waves!**

ENZ Strong Coupling (N_D = 2e18 cm^{-3})

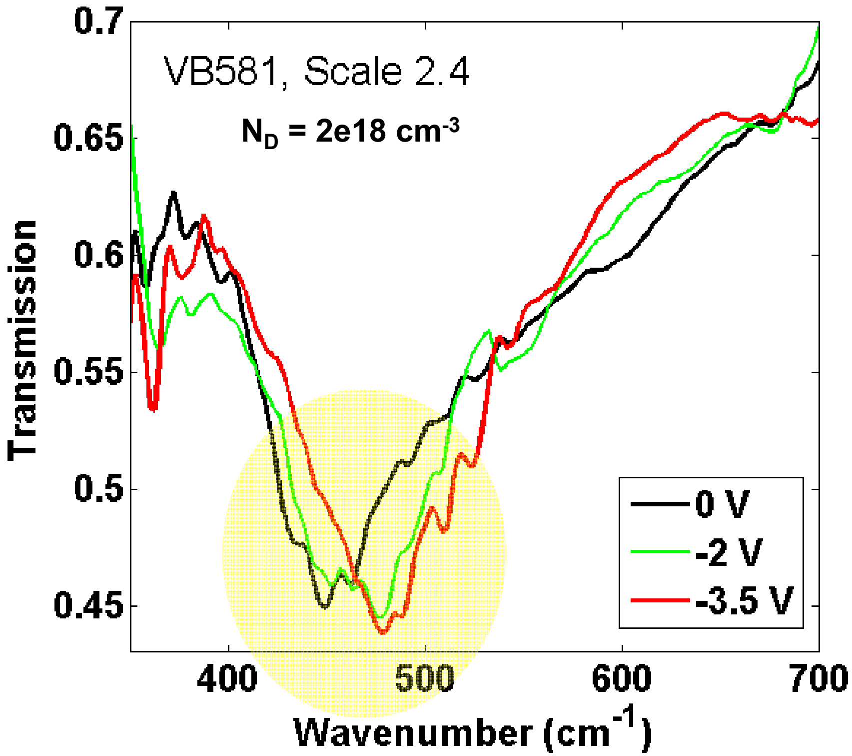


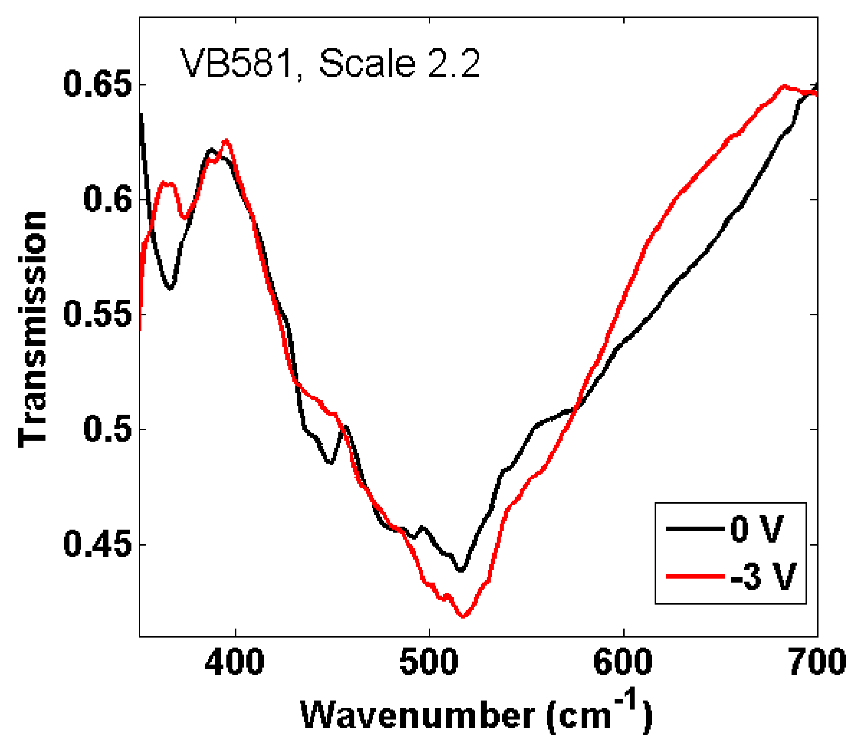


FTIR Transmission spectra



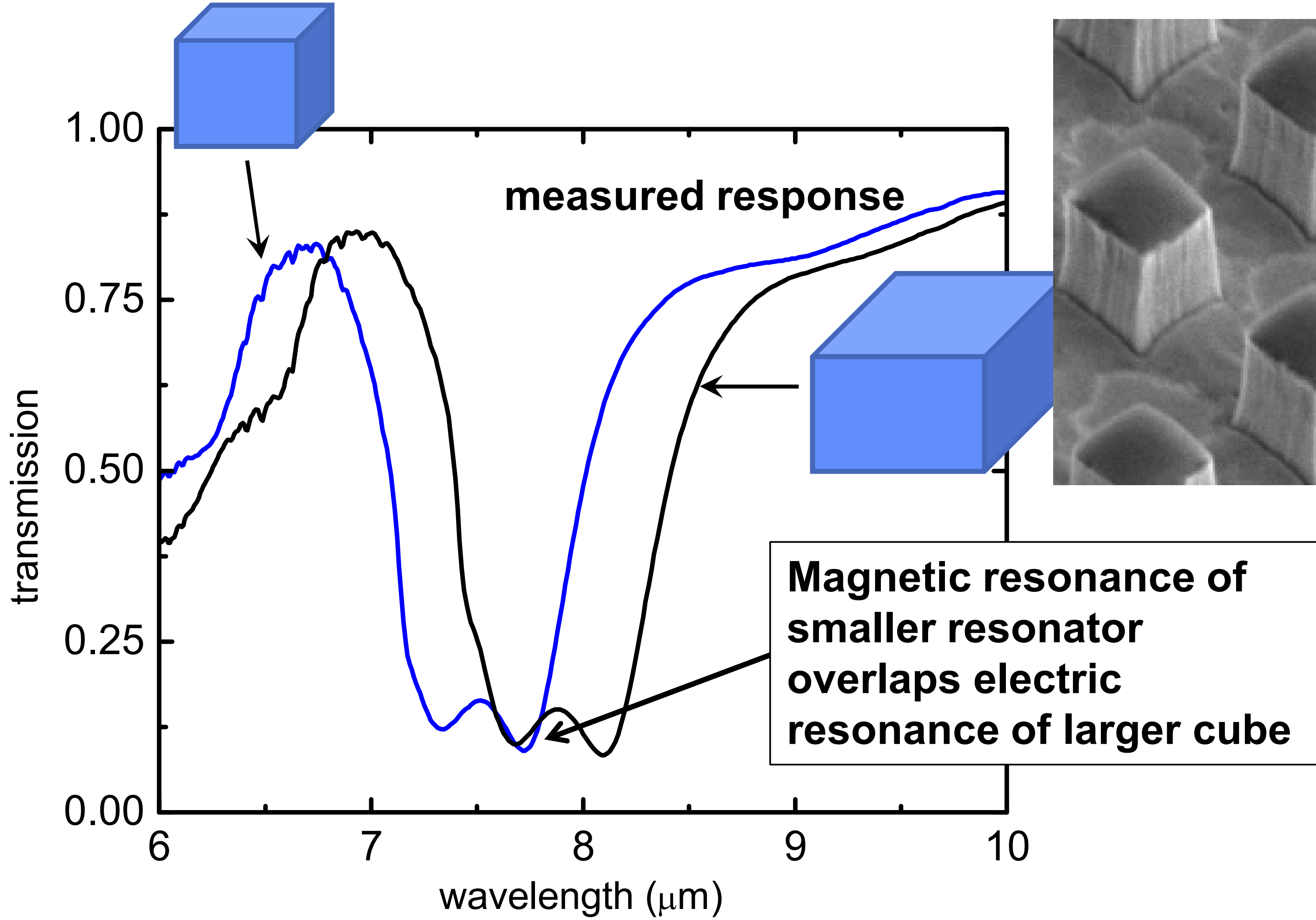
Electrical Tuning the Coupling to the ENZ Mode

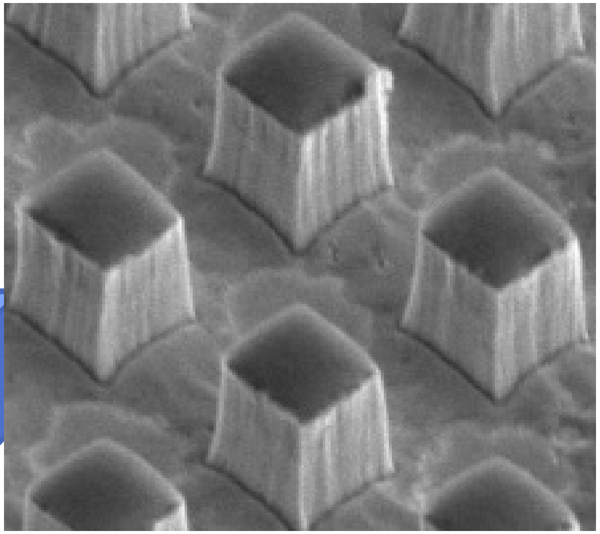




Fundamentally different than tuning just by changing a local permittivity!

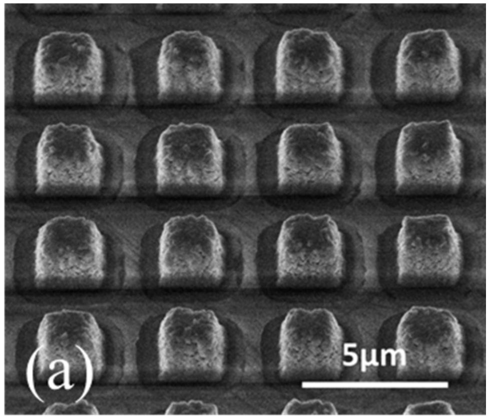
Te Resonators: Electric and Magnetic Mode Overlap



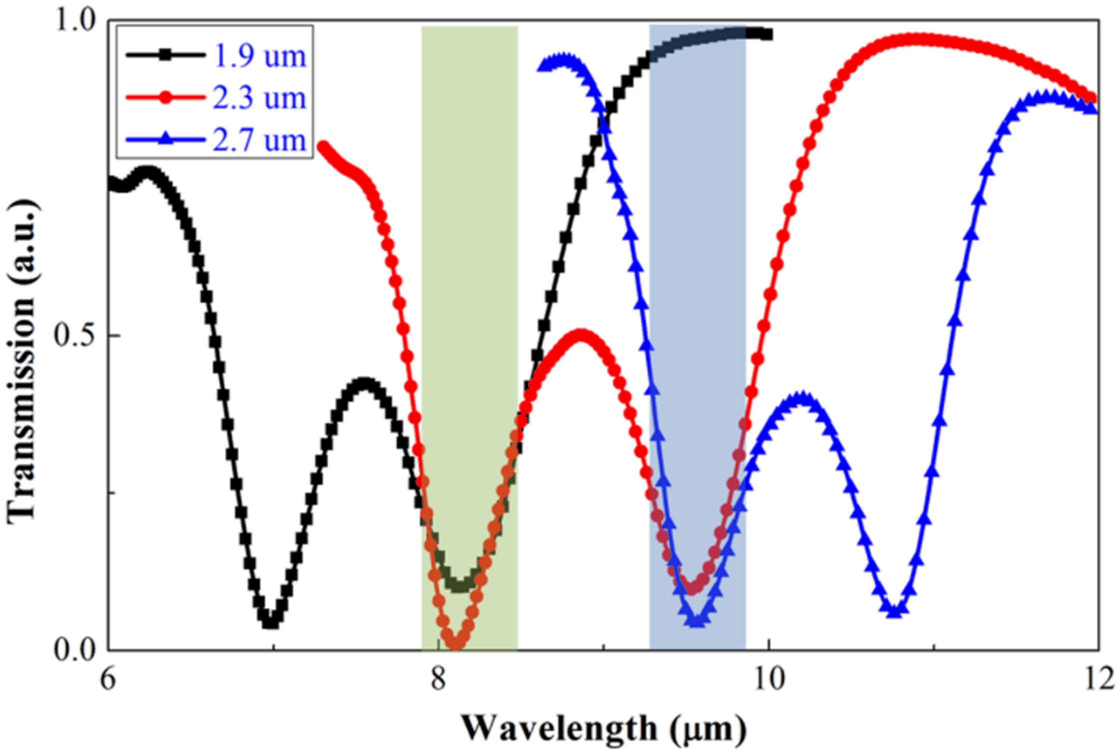


Magnetic and Electric resonances can overlap: different size cubes, or cubes with "cuts"

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.

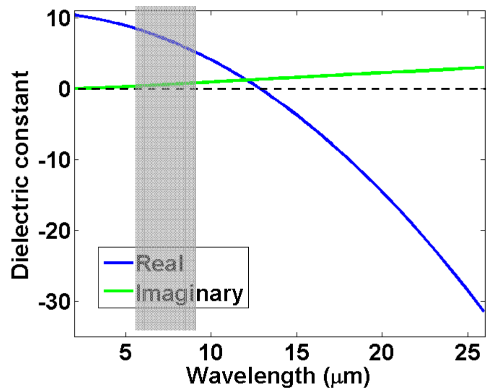
Appl. Phys. Lett. 102, 161905 (2013)

Interactions between MMs and Electrons in Doped Semiconductors

$$\varepsilon \approx \varepsilon_\infty \left(1 - \frac{\omega_p^2}{\omega^2 + i\omega\Gamma}\right) = \varepsilon_\infty \left(1 - \frac{\omega_p^2}{\omega^2 + \Gamma^2} + i\frac{\omega_p^2 \Gamma}{\omega(\omega^2 + \Gamma^2)}\right)$$

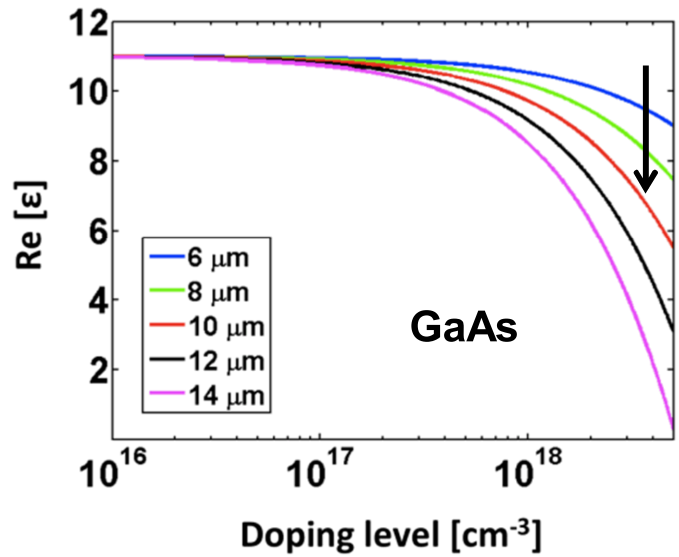
$$\Gamma = 1/\tau = \frac{q}{\mu m^*}$$

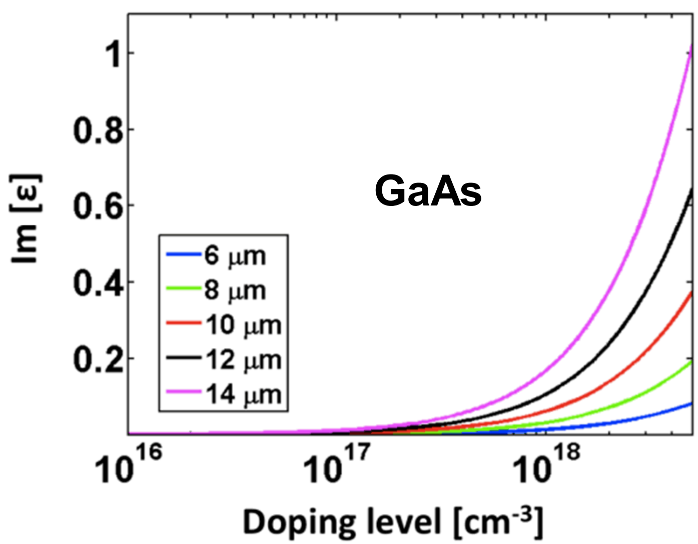
Drude (ex: n+GaAs, 5x10^{18}cm^{-3})



$$\omega_p^2 = \frac{Nq^2}{\varepsilon_0 \varepsilon_\infty m^*}$$

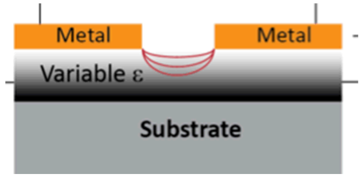
(a)

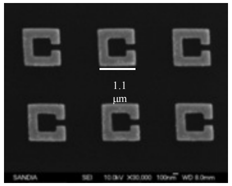




Examples of Tuning Mechanisms

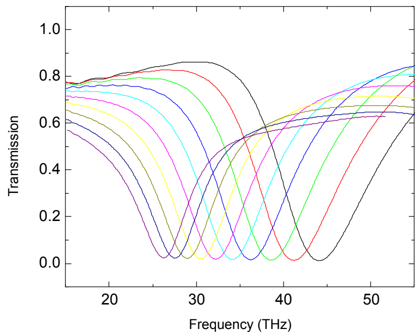
Example, SRRs interact strongly with thin layers underneath



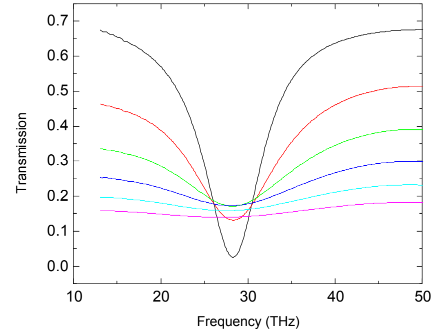


- **Nonresonant**

Change ε_1 (n)

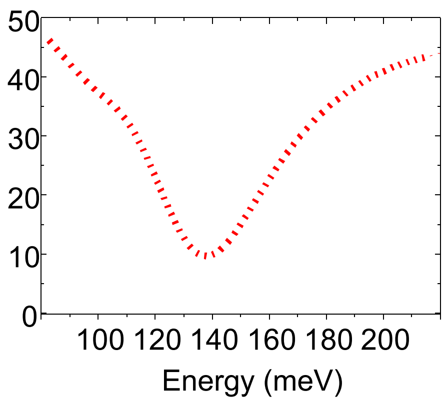


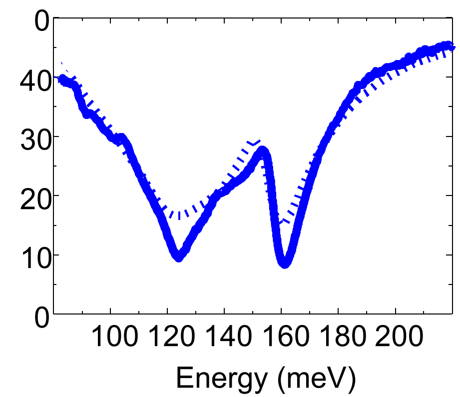
Change ε_2 (n)



- **Resonant**

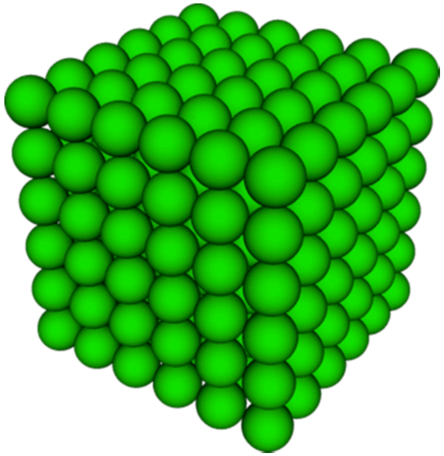
(Create a dipolar resonance, example: phonon)

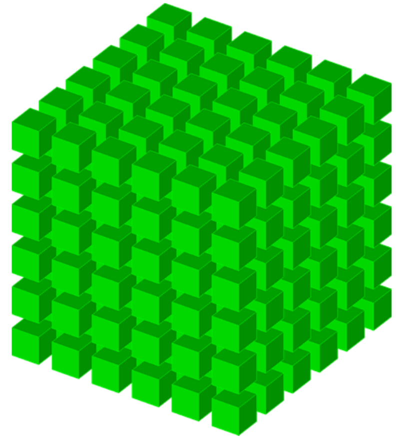




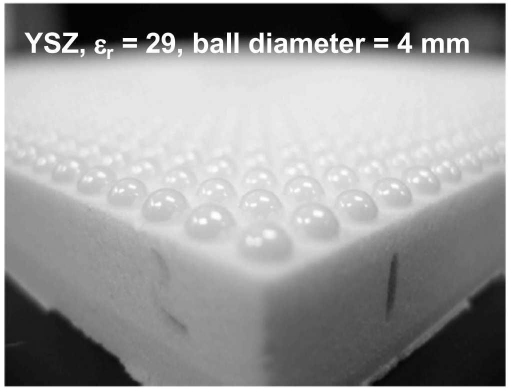
Nano Letters 11, 2104 (2011)

Arrays of High ε Resonators: Low Loss Metamaterials





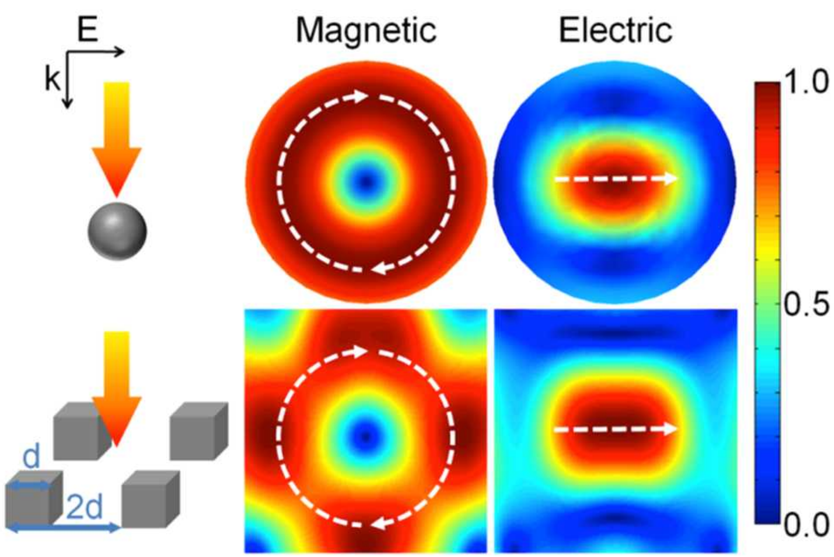
Works nice in the RF



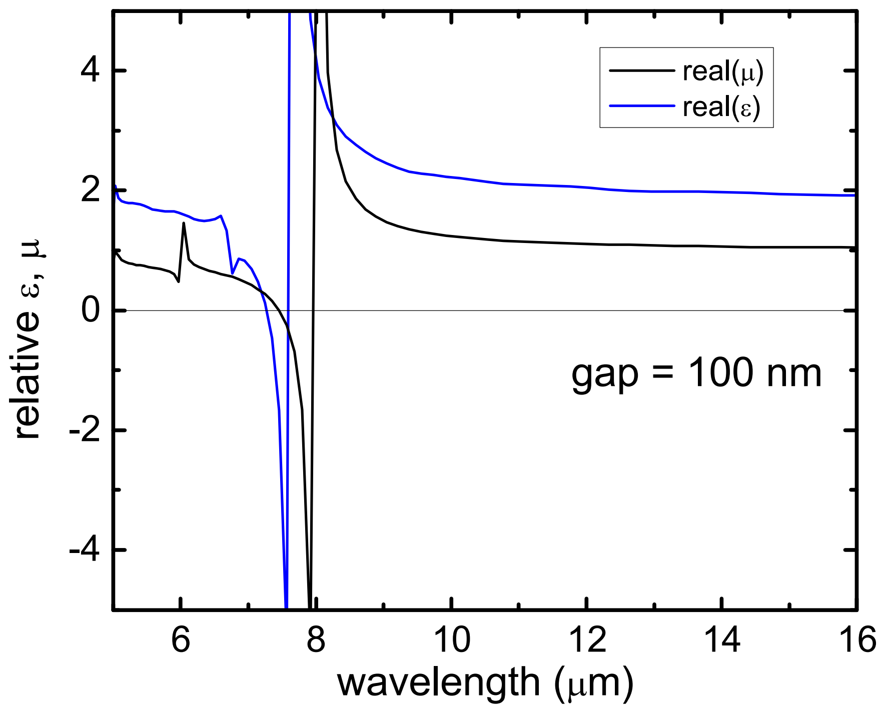
(negative ε, negative μ)

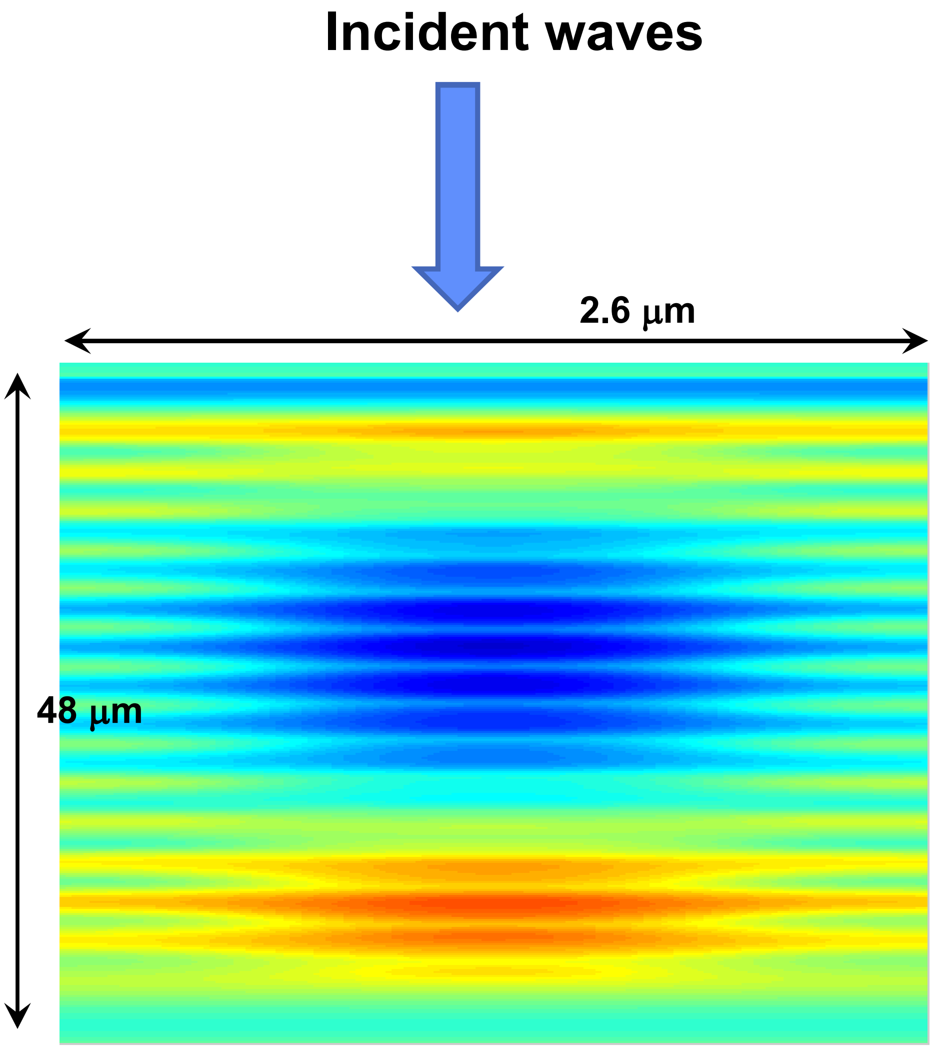
Spherical

Cubic



Magnetic Field Movie – 7.5 μm

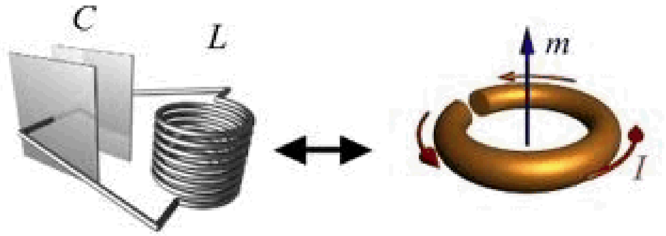




λ = 7.5 μm

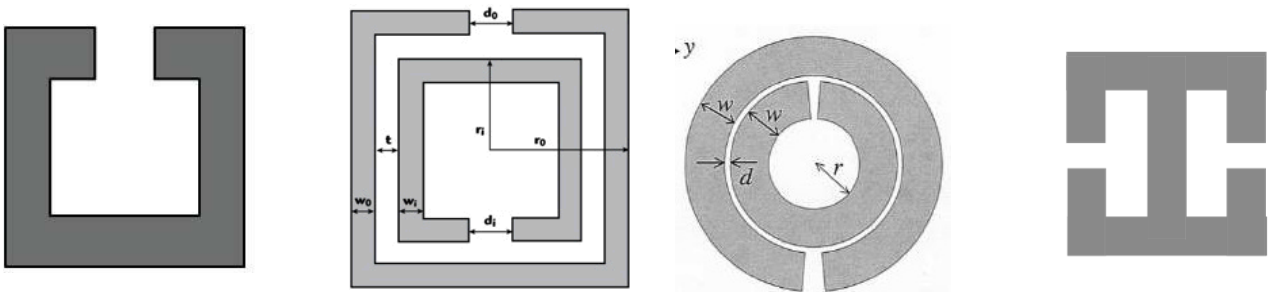
H_x at top of unit cell (z=1.3 μm)

Split-ring resonator



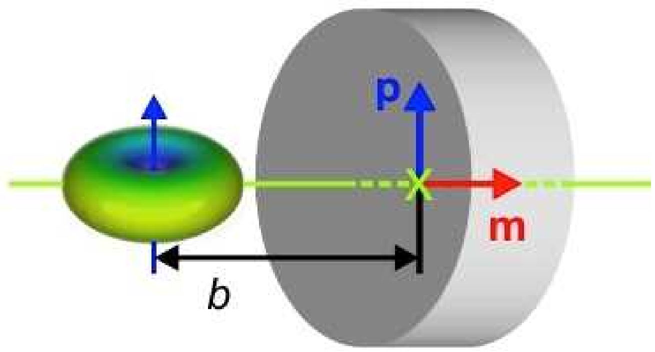
LC resonator: $\omega_R = \frac{1}{\sqrt{LC}}$

- **Variants:**



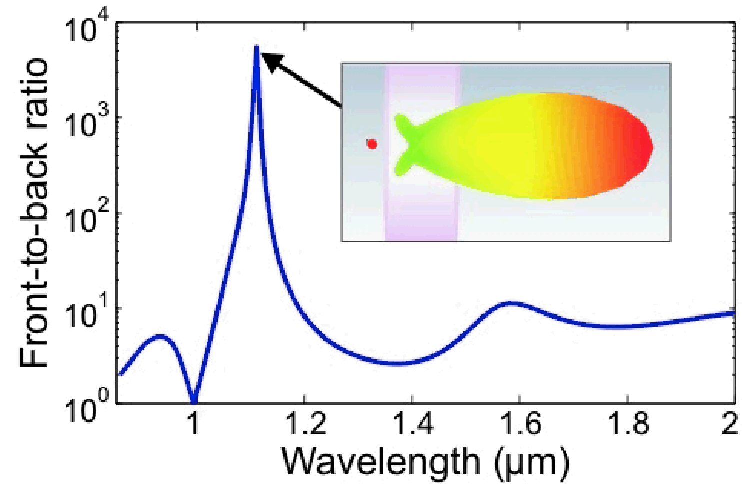
...

Importance of the Quadrupole Mode

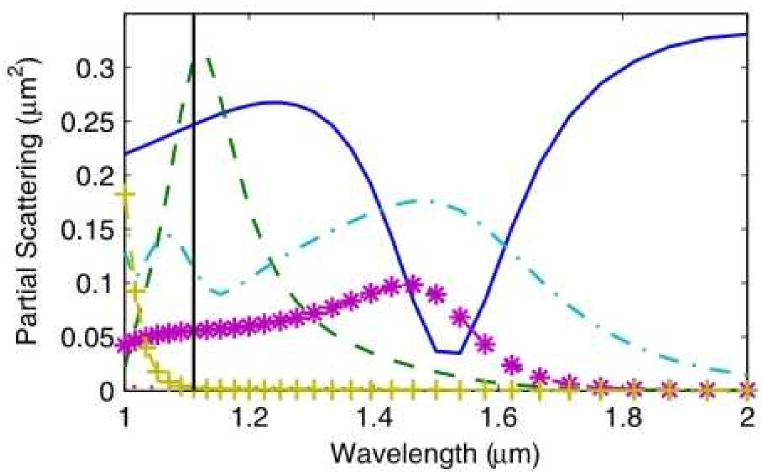


- **Silicon nanodisks: highly directional nanoantennas with giant front-to-back ratio**

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



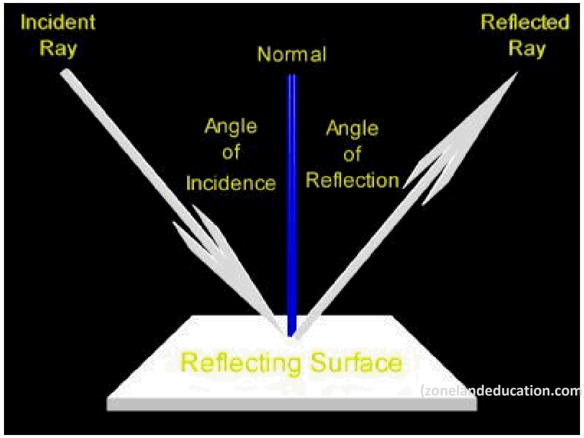
I. Staude *et al.*, *ACS Nano* 7, 7824, 2013.



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

What is a "Mirror"?

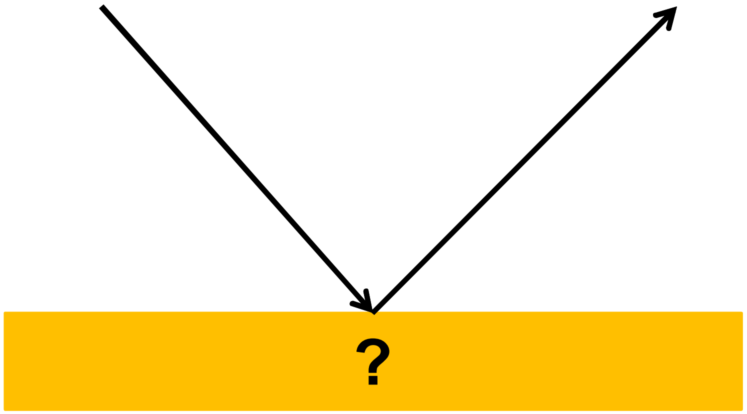
"Regular" mirrors invert the phase of the reflected wave

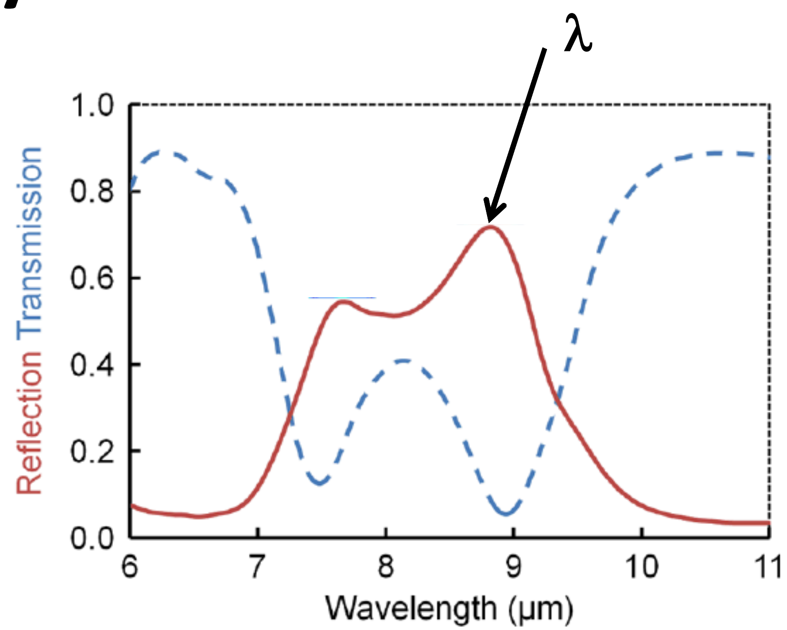


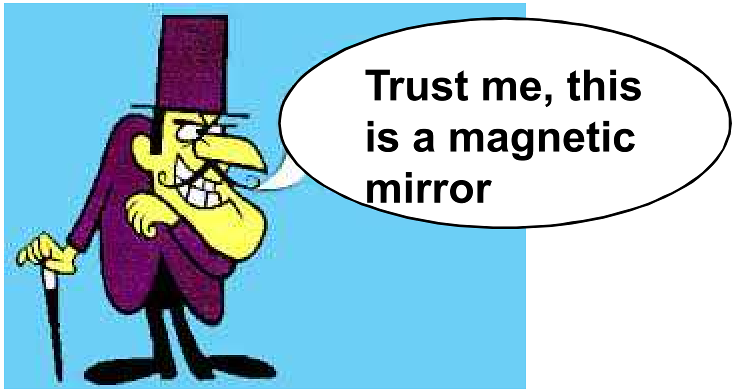
But…. we can make a "magnetic" mirror

How does it work, what does it do?

How much do you trust me?



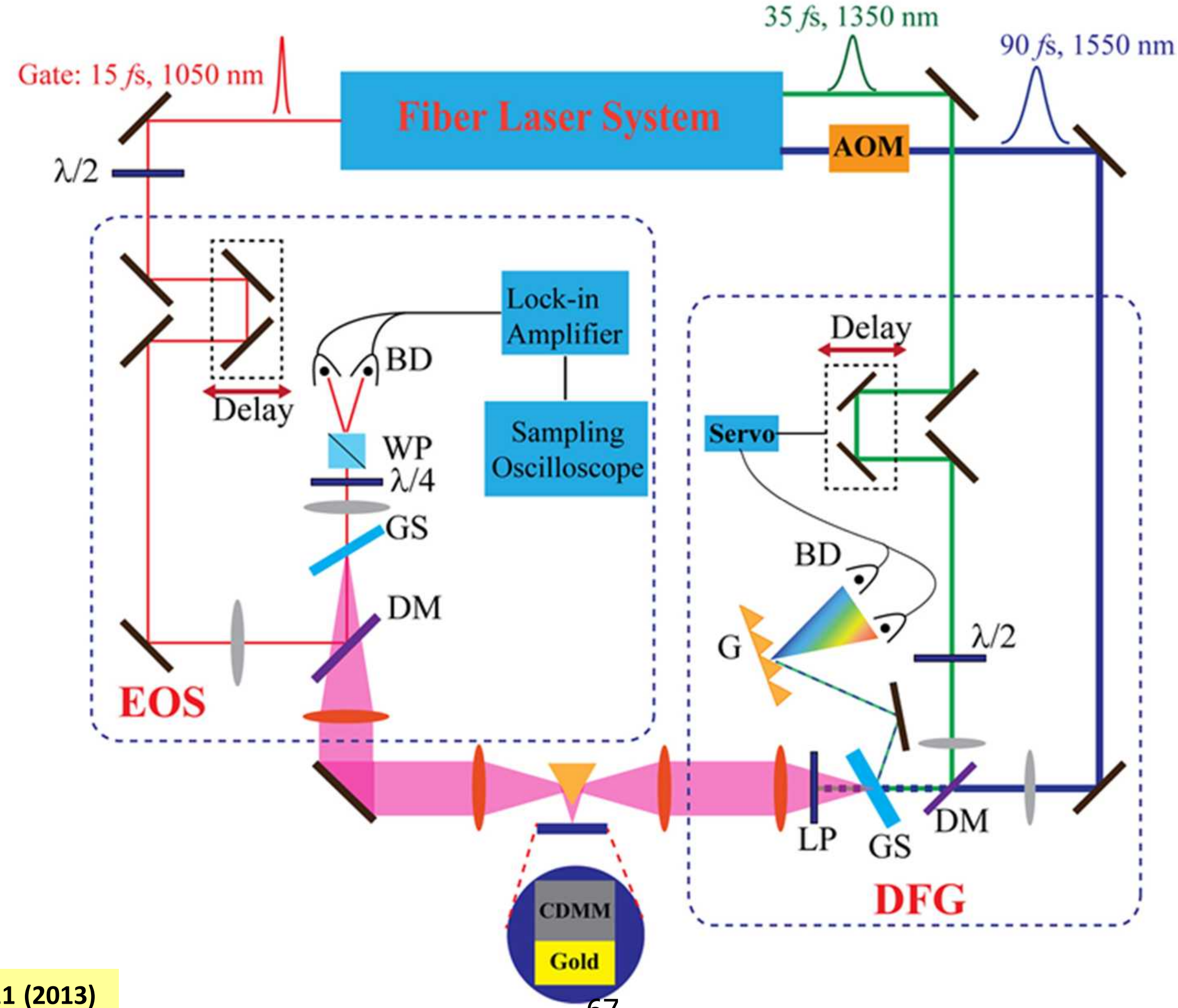




Show me the phase.....

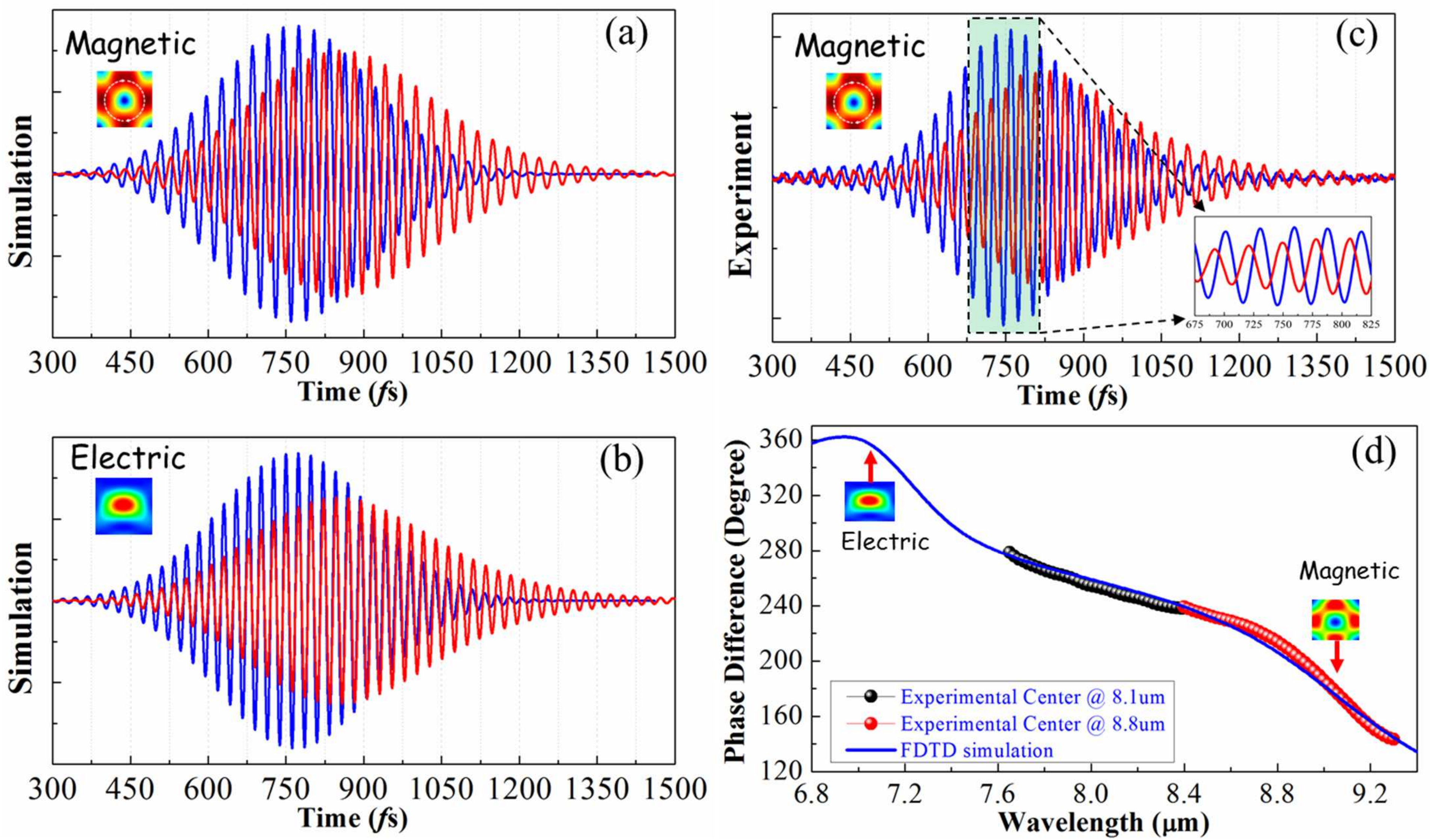
Proving Optical Magnetism:
Measure Phase of Reflected Wave

Phase-locked Time Domain Spectroscopy

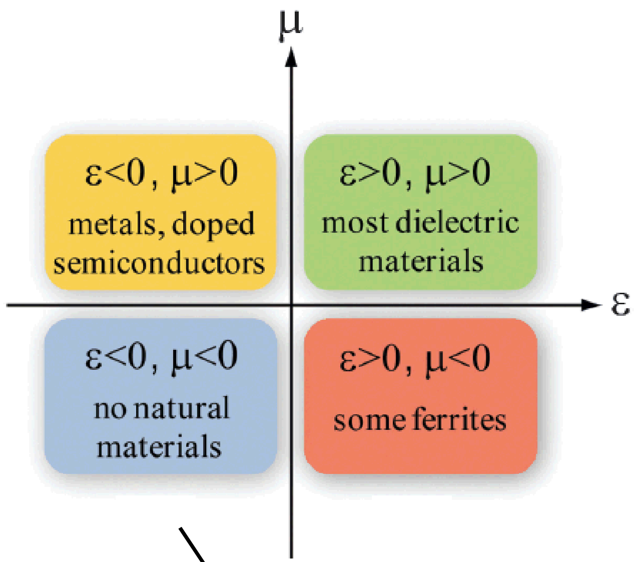


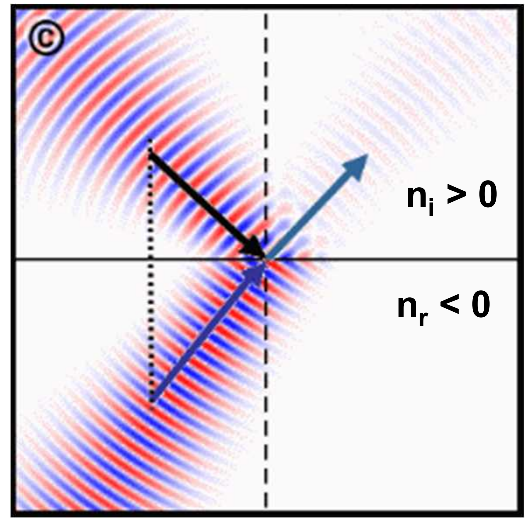
Appl. Phys. Lett. 103, 181111 (2013)

Experimental Demonstration of "Optical Magnetism"



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**