SAND2015-5365C

Optical magnetic mirrors using all dielectric metasurfaces
&
III-V semiconductors based dielectric metamaterials

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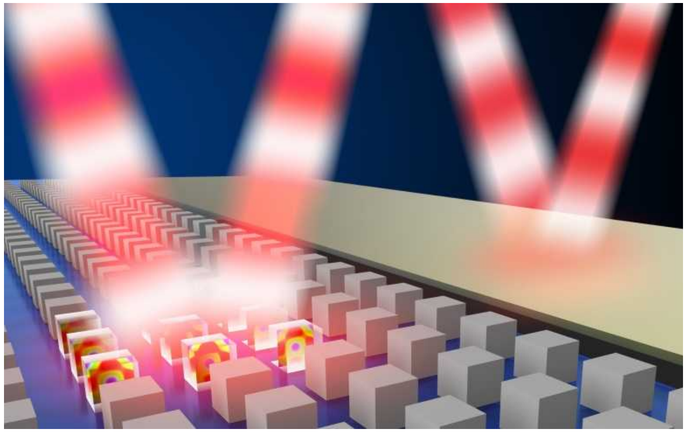
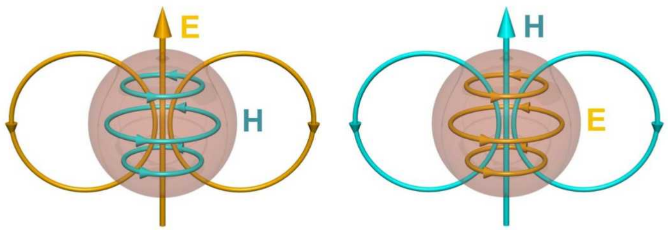
Optical magnetic mirrors without metals, Optica, 1, 250 (2014)



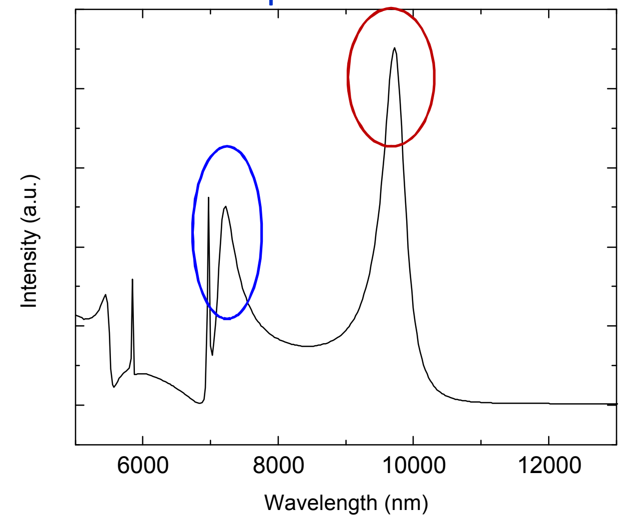
This work was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. Department of Energy, Office of Basic Energy Sciences user facility. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Dielectric Resonators

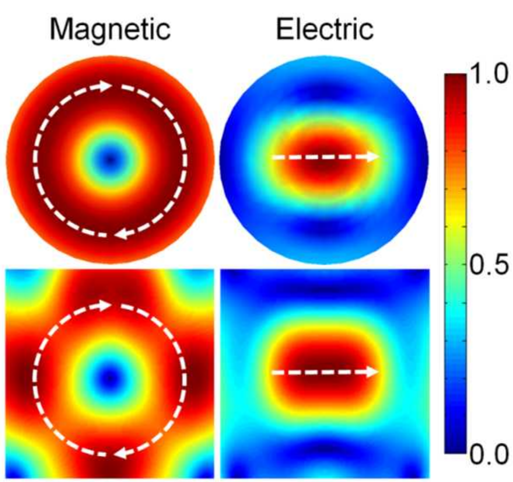


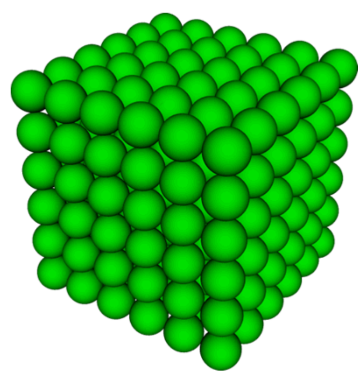
Images: A. Miroshnichenko

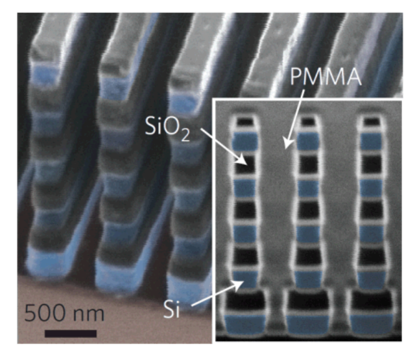
Magnetic dipole resonance: tailor μ
Electric dipole resonance: tailor ε



- Cubes/cylinder work fine too







Jason Valentine

3D structure is possible
Isotropic response can be achieved

Dielectric Resonators for E&M Manipulation-- Historical Interlude…

- Mie's paper: 1908
- Gans & Happel, Annalen der Physik, 1909, same equation as in Lewin!
- Schaefer & Stallwitz Annalen der Physik, 1916, 2D (rods)
- Lewin's paper: 1946
- Sakurai 1949, "Artificial Matter for electromagnetic wave".
- …….
- Bell Labs, etc. (artificial dielectrics): 40's-60's
- Early 2000's: Kuester & Holloway (RF), Hasman (near IR), Connie J. Chang-Hasnain (high contrast gratings)
- Last ~10 years:
  - *Visible&Near IR: Kuznetsov, Luk'yanchuk, Evlyukhin, Polman, Kivshar, Brener, Brongersma, Valentine, etc, etc.* **III-V semiconductors**
  - *IR: Brongersma, Sandia, …* **Magnetic mirrors @~9um**
  - *RF: Cummer, Gopinath, Lippens, Kuester&Holloway, etc.*

Please let us know if we miss any important work!

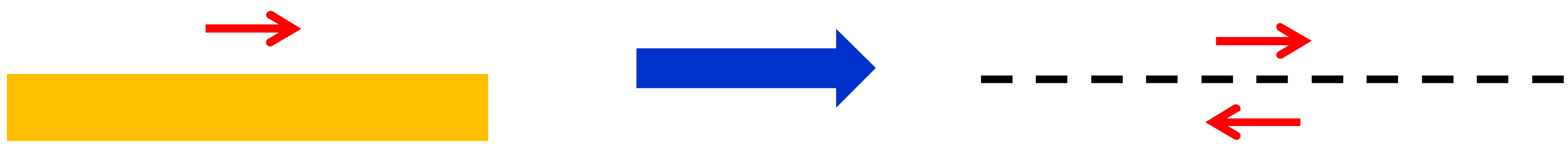
Many thanks to Ed Kuester, CU Boulder

For a complete reference list, see Kuester& Holloway, Antennas and Propagation, IEEE Transactions on 51, no. 10 (2003): 2596,PIER B, vol. 33, p. 175 (2011).

Dipoles emitter close to surfaces

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

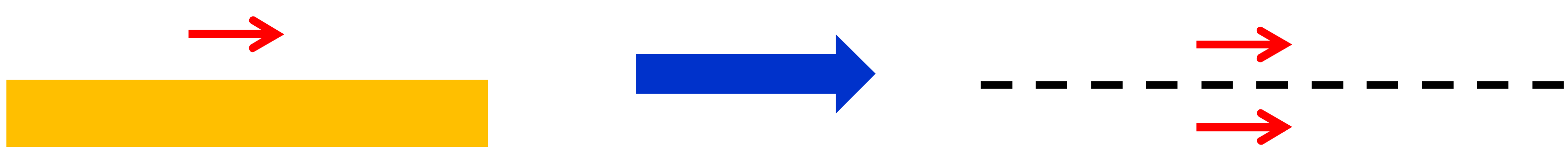
IMAGE THEORY



- 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

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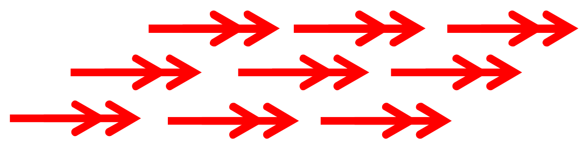
Magnetic Dipoles

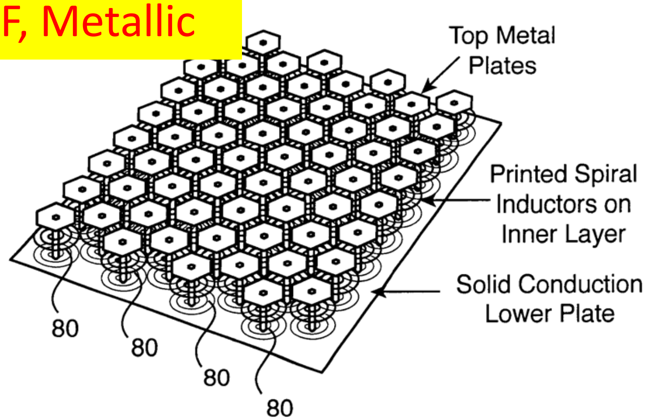
However, a perfect magnetic conductor does not exist in nature

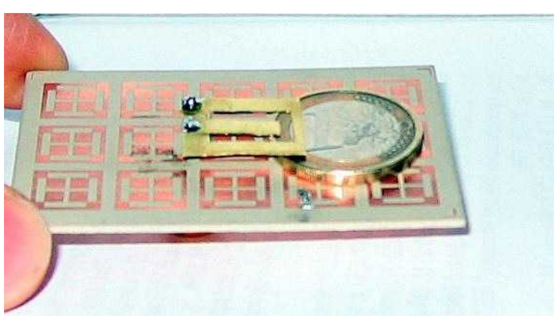
Array of magnetic dipoles



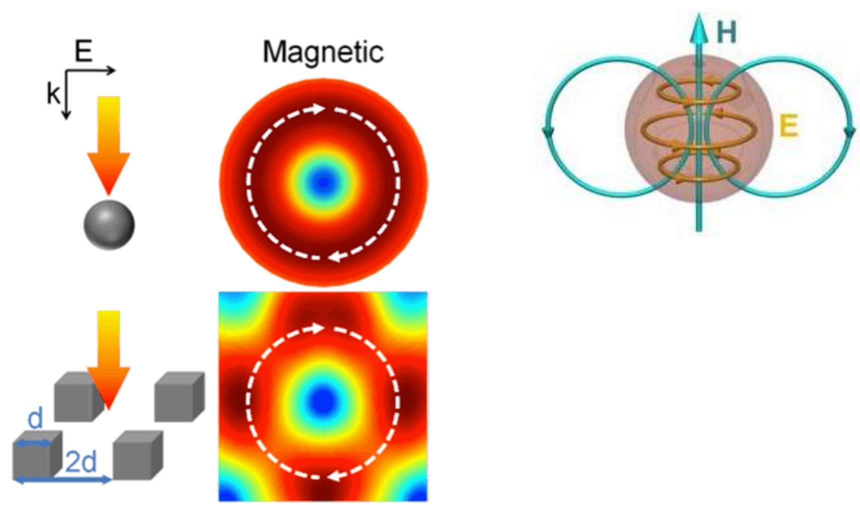
Because the magnetic dipole responds in phase with the electric field, this represents an **artificial magnetic conductor**

RF, Metallic



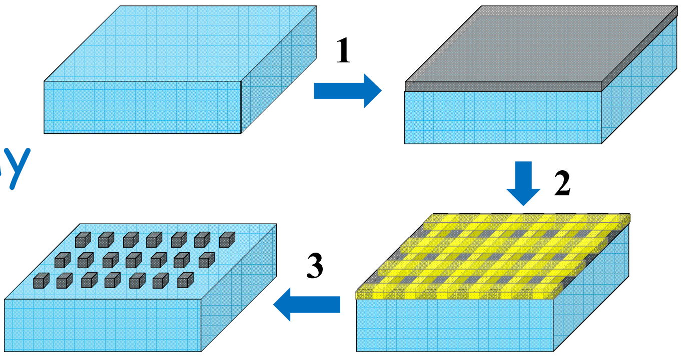


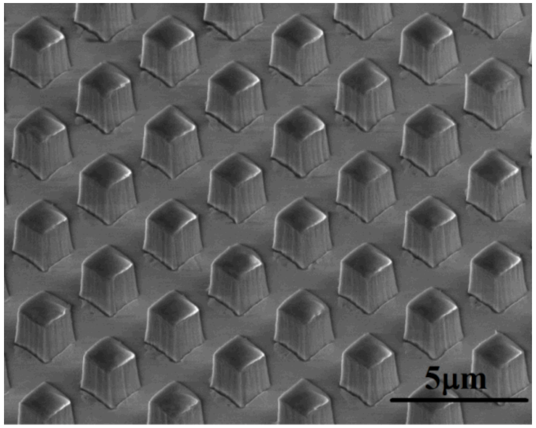
We can create magnetic dipoles with dielectric resonators in optical frequencies

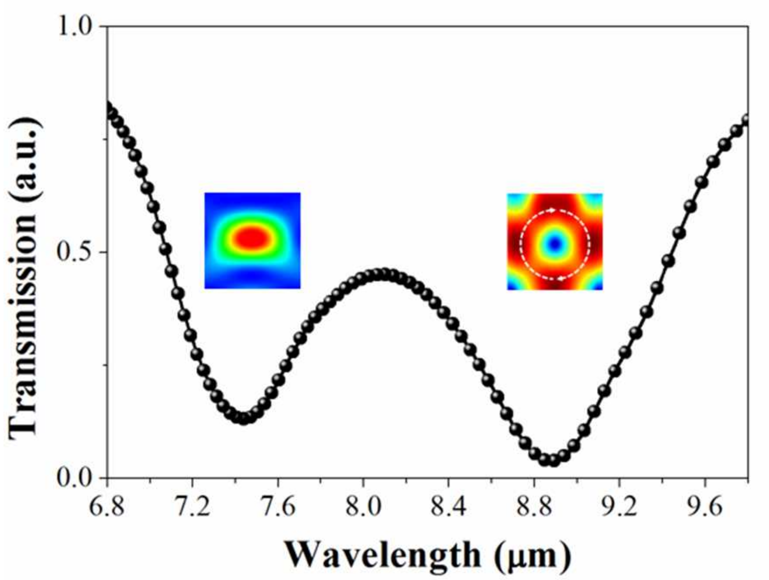


Fabrication of Cubic Dielectric Metamaterial

1. Deposition of Te (n~5) on BaF_2
2. Patterned using E-beam lithography
3. Etching (Reactive Ion Etching)







- ➢Good uniformity over large areas (cm^2)
- ➢Slight over-etching

Works in mid-infrared

J. Ginn, PRL **108**, 097402 (2012)
S. Liu, APL **102**, 161905 (2013)

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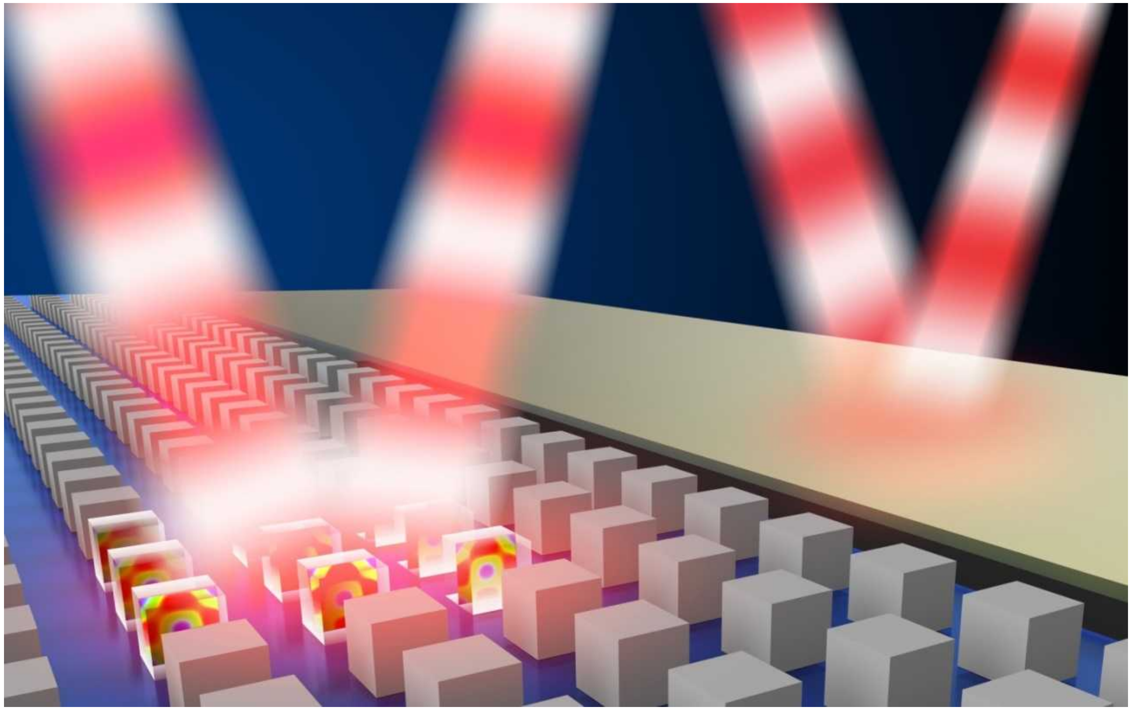
How to experimentally demonstrate magnetic mirror behavior?



Height of Gold mirror is placed at the center of the cubes

The red and white sections of the beams represent positive and negative phase fronts of the optical field.

- **Time Domain Spectroscopy (TDS)**
  - Typical spectroscopy is frequency domain based spectroscopy.
  - Time domain spectroscopy technique provides both amplitude and phase information—full information of EM wave.

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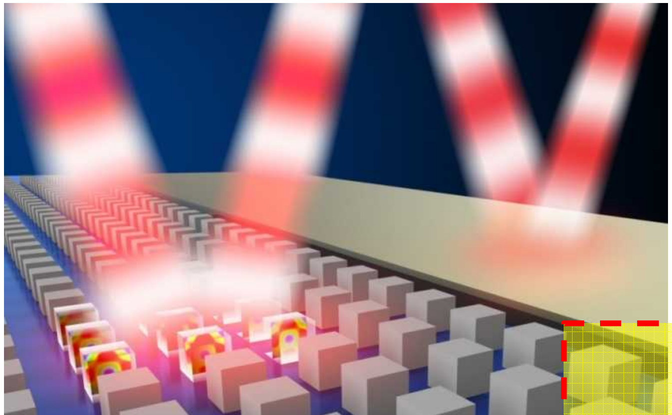
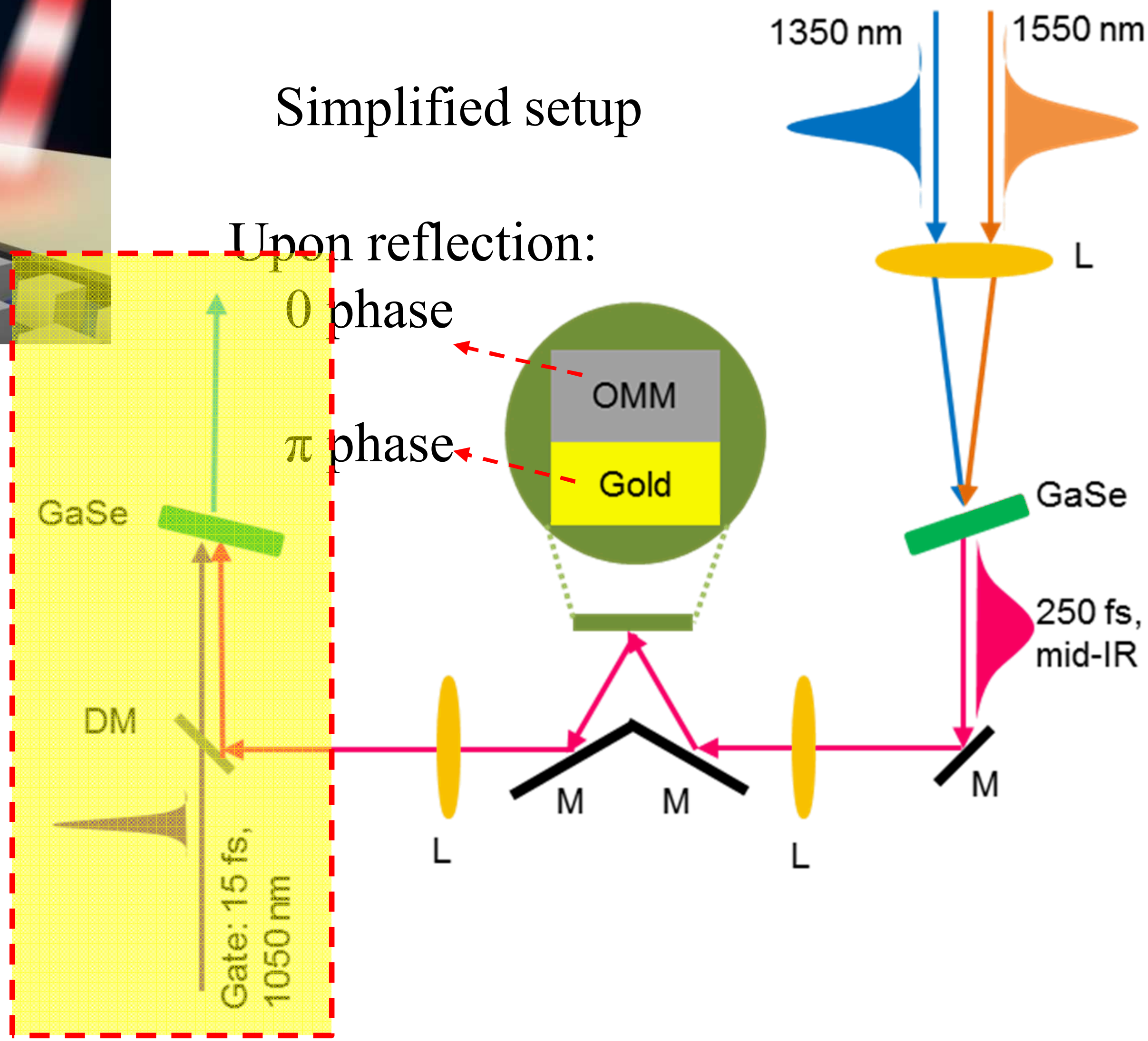
Mid-IR time domain spectroscopy setup



Simplified setup

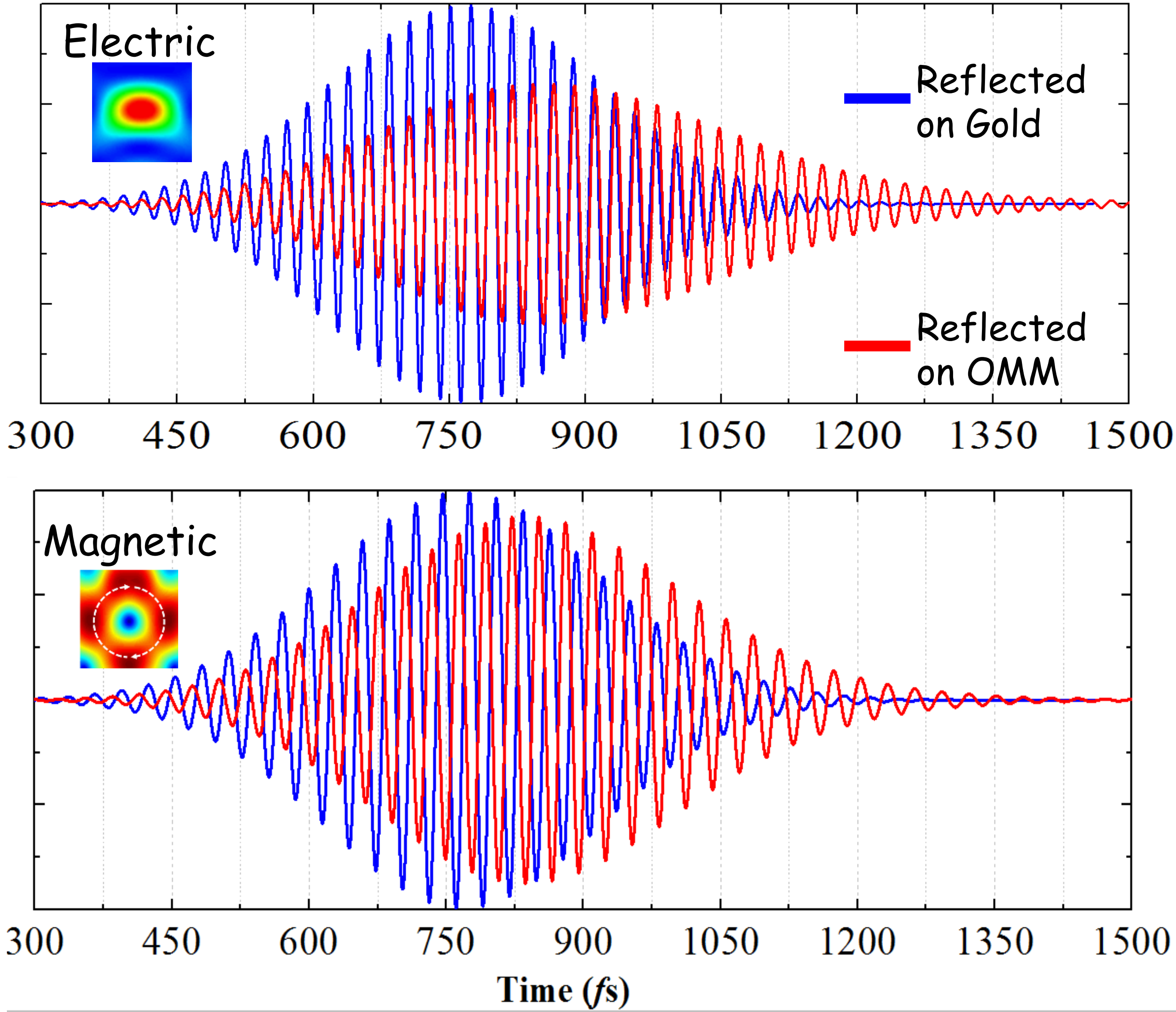


Electro-optic sampling

FDTD Simulation of Reflected Electric Field

- Higher amplitude for reflection on gold.
- Reflected electric field envelope delay.
- @ Electric resonance: fringes match.
- @ Magnetic resonance: fringes mismatch.

"magnetic" mirror



"Optical magnetic mirrors without metals", Optica, 1, 250 (2014)

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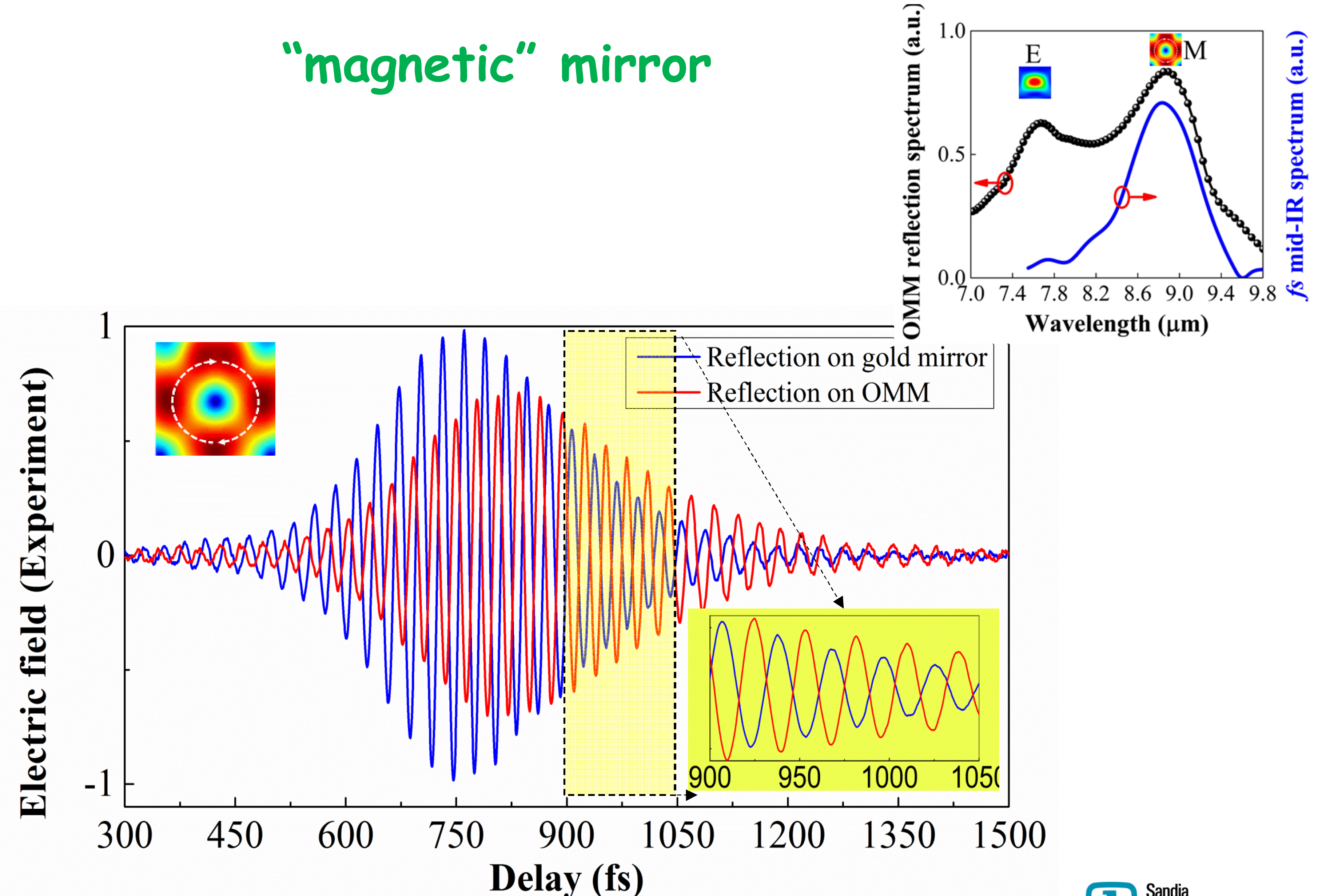
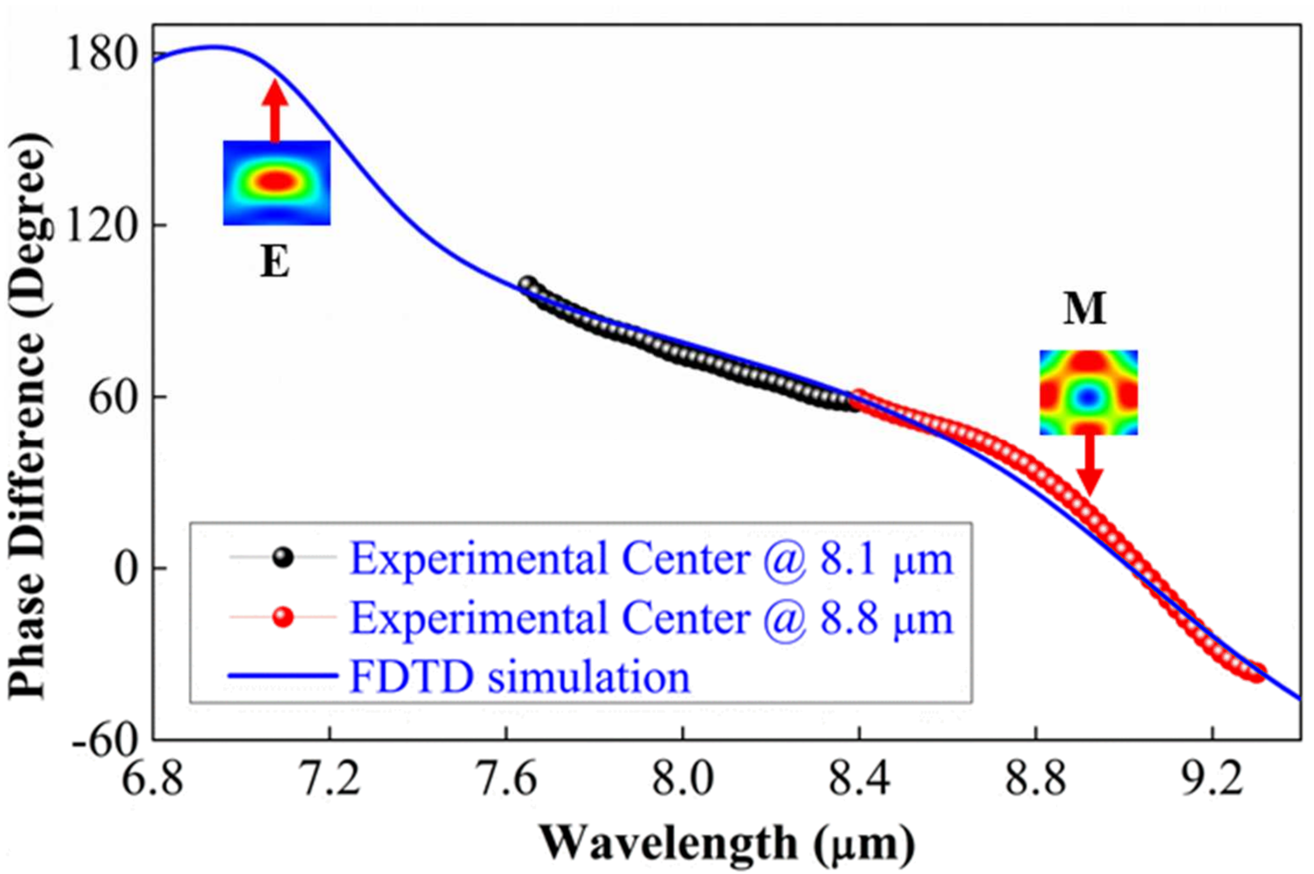
Experimental Results of Reflected Electric Field

"magnetic" mirror



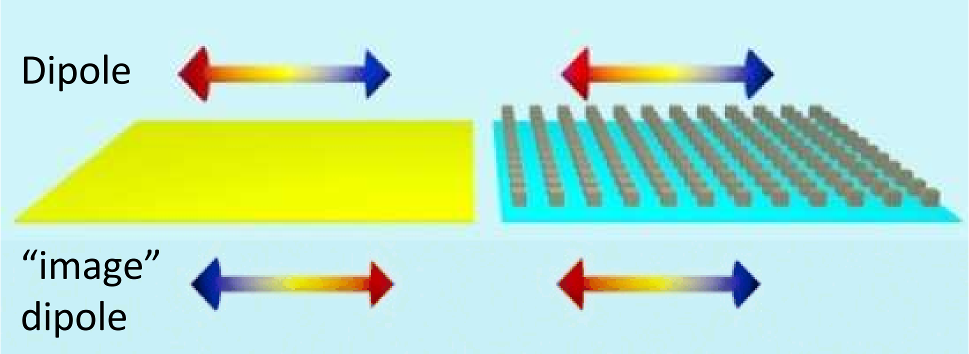
Fourier Transform of Experimental Results (Phase)



- Phase difference between magnetic (~170 degree) and electric (10 degree) resonance is ~160 degree (close to π)

Optical magnetic mirrors without metals, Optica, 1, 250 (2014)

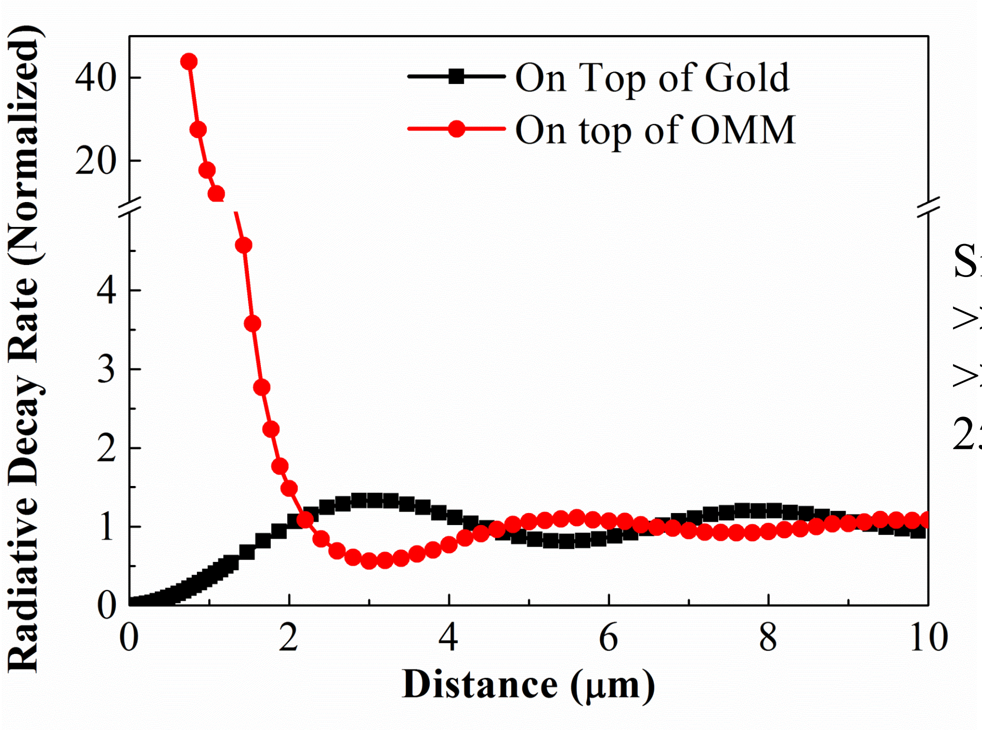
Potential applications—enhancing emission and absorption



Optical magnetic mirror: OMM

radiation of a transverse electric dipole close to PEC is **quenched**

radiation of a transverse electric dipole on a PMC is **enhanced**



Simulation >>>>>>>>>>>>>>>>>>Optica, 1, 250 (2014)

III-V semiconductor based dielectric metamaterials

- ***Single layer***
- ***Multi-layer—why do we need it?***

Limitations of Si (indirect bandgap materials)

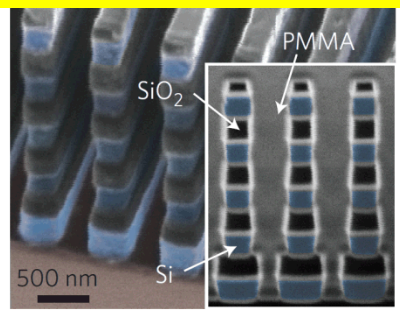
- Inefficient light emission (hard to incorporate active media)
- Free carrier absorption of Silicon due to long electron lifetime
- Centrosymmetry of Silicon ➔ NO second order nonlinearity
- Challenging to realize real 3D metamaterials (multi-layers)

Direct bandgap semiconductor: III-V (AlGaAs, InGaAs, GaAs)

nature photonics | LETTERS
PUBLISHED ONLINE: 25 AUGUST 2013 | DOI: 10.1038/NPHOTON.2013.214

Realization of an all-dielectric zero-index optical metamaterial

Parikshit Moitra[1†], Yuanmu Yang[1†], Zachary Anderson[2], Ivan I. Kravchenko[3], Dayrl P. Briggs[3] and Jason Valentine[4*]



GaAs based disk resonators

Demonstration ... Nanoparticles

3D & No flip chip bonding?

Steven Person,[†] Manish Jain,[†] Zachary Lapin,[‡,†] Juan Jose Sáenz,[§] Gary Wicks,[†] and Lukas Novotny[*,‡,†]

flip-chip bonding to fused silica

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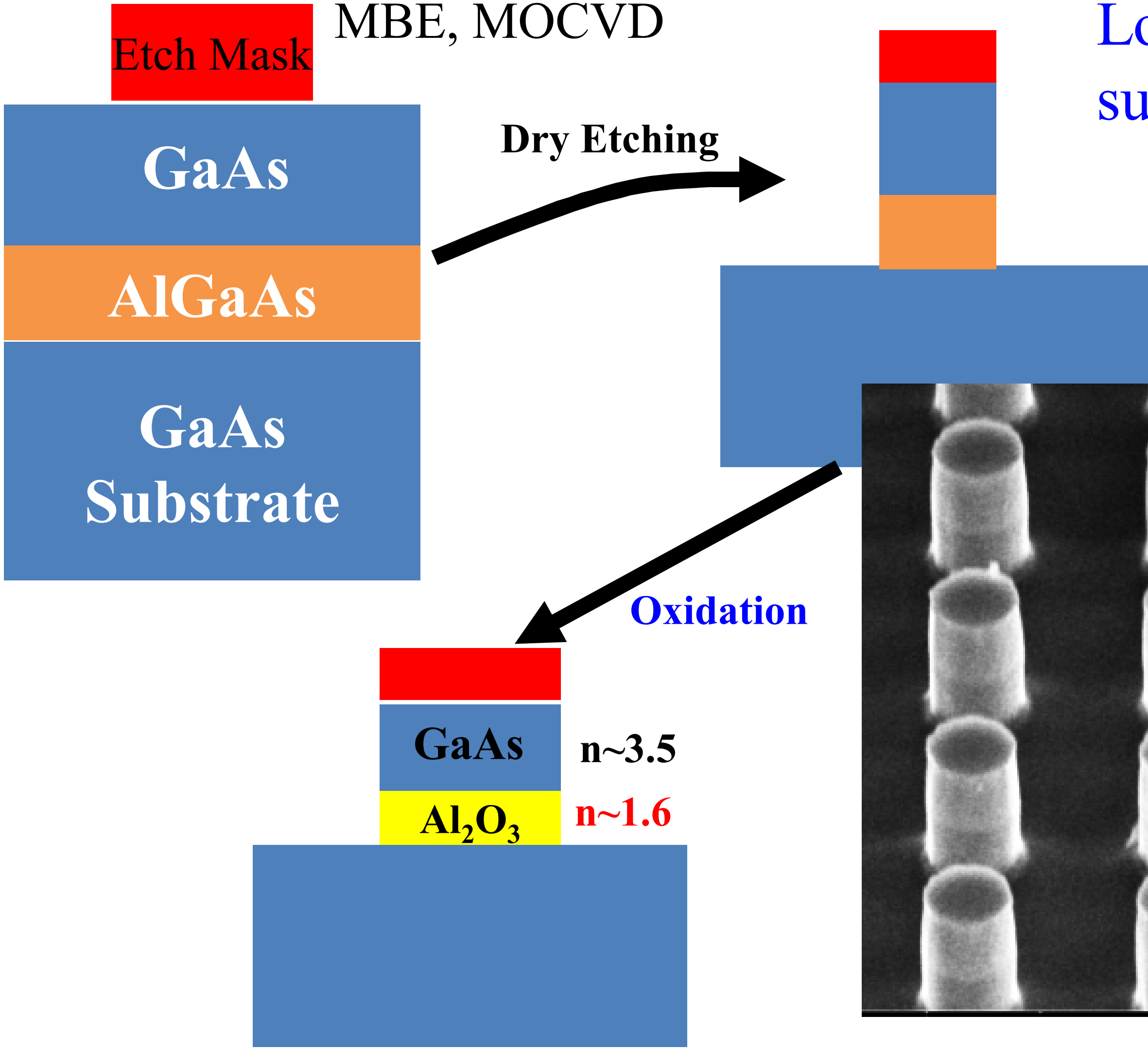
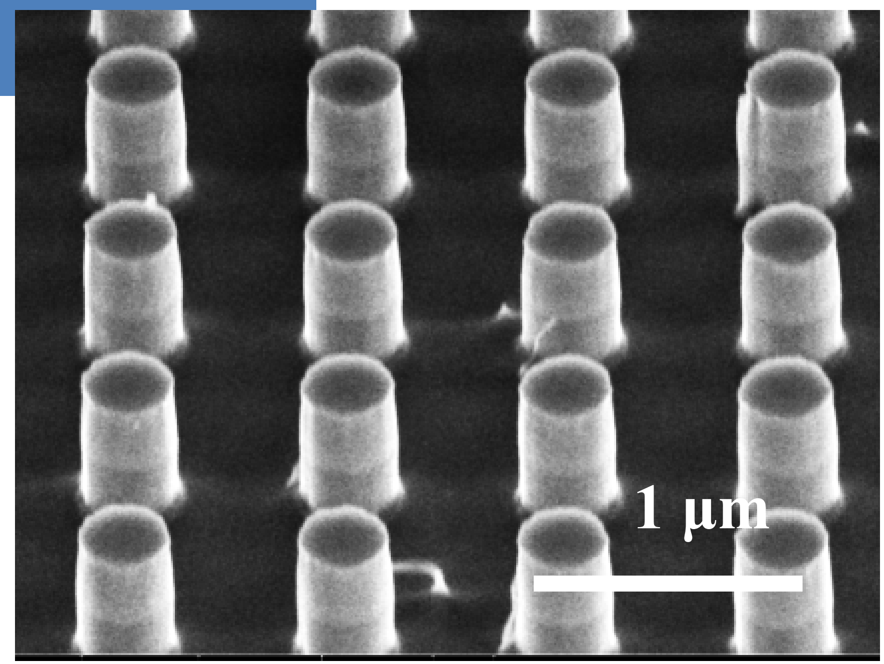
Fabrication of Al(In)GaAs based dielectric MM

Epitaxially grown:
MBE, MOCVD

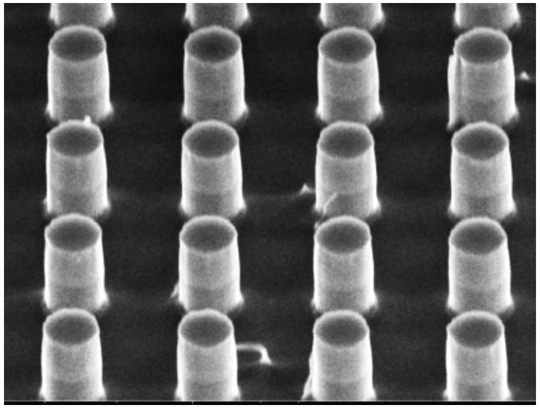
Low refractive index surrounding is needed!





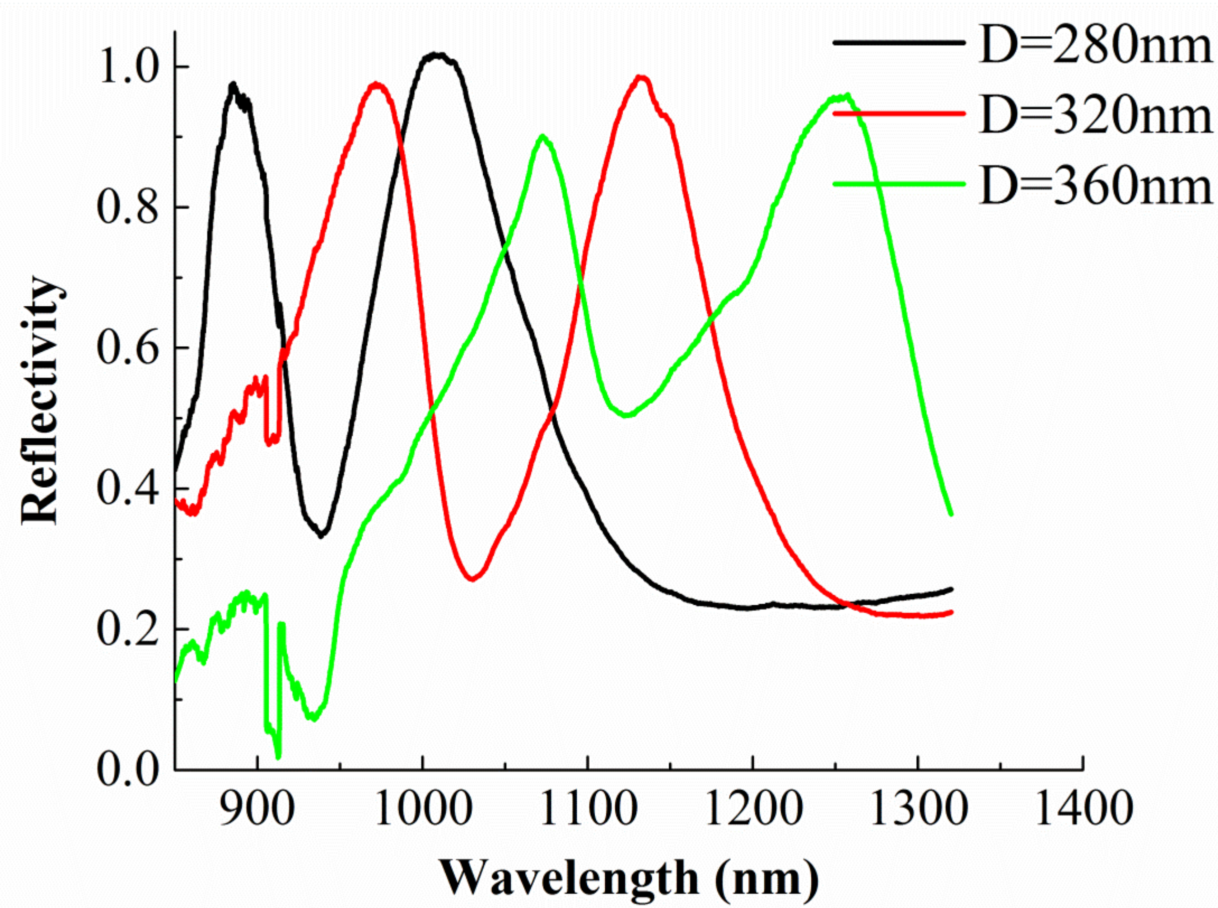
Sandia VCSEL: IEEE JSTQE, 3, 916 (1997)

GaAs disk resonators (1 layer)

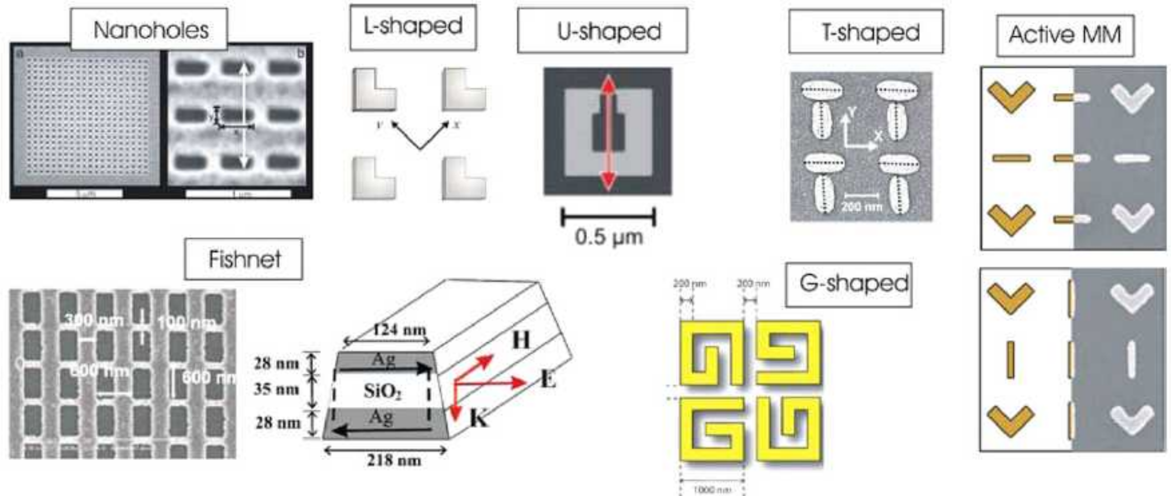


GaAs disk height ~300nm

Different diameters



Nonlinear optical generation in metasurfaces

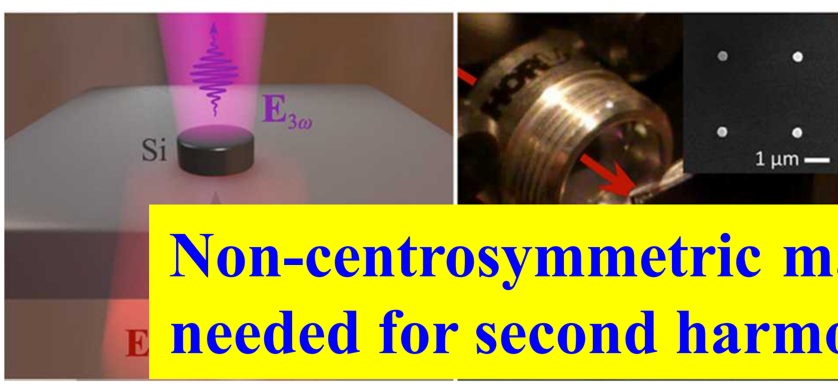


Metallic metasurfaces with different shapes.

Field localization within the nanostructures

Yuri et al, Laser Photonics Review, **9**, 195 (2015)

Dielectric metasurfaces—Silicon disk efficiently generate 3[rd] harmonic.



Nano Lett., **2014**, *14* (11), pp 6488–6492
DOI: 10.1021/nl503029j

Non-centrosymmetric materials are needed for second harmonic generation

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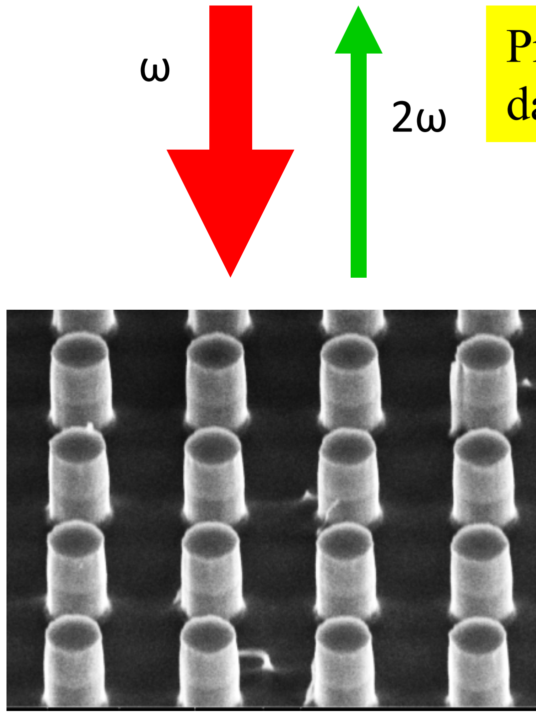
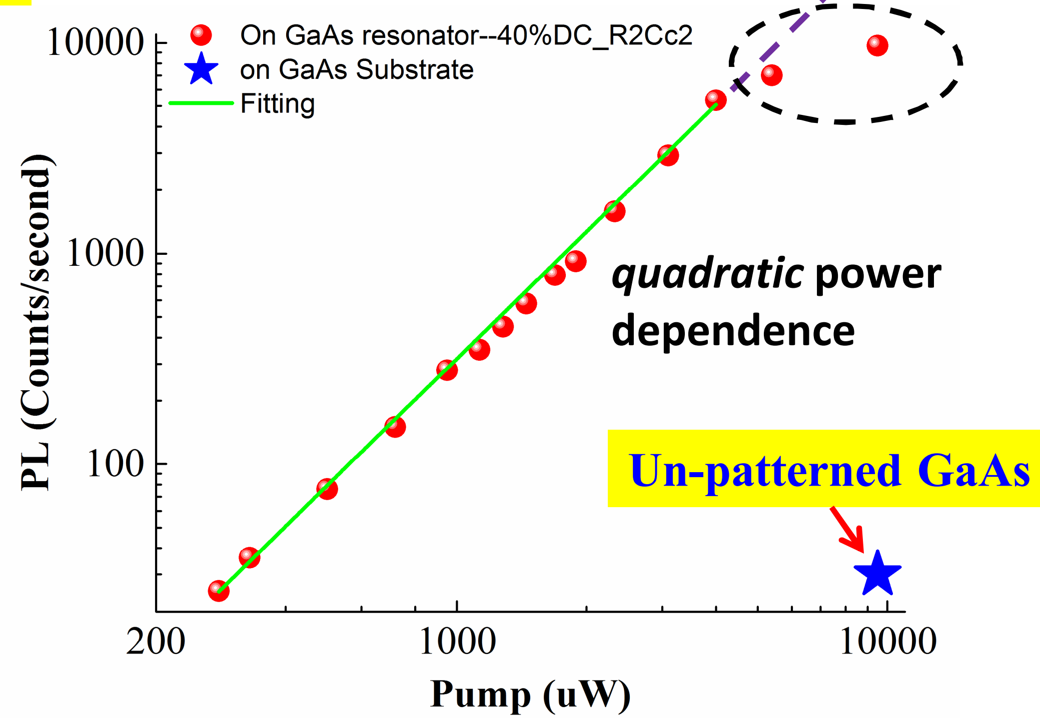
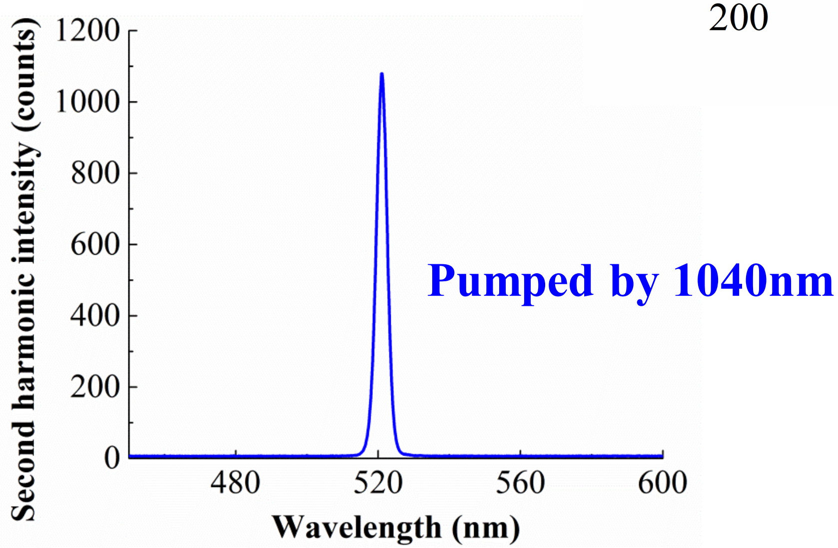
Nonlinear optical generation in metasurfaces

Preliminary data



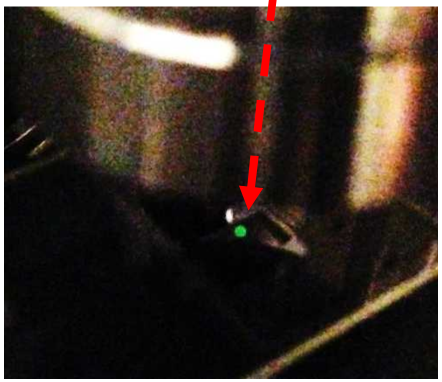
Pumped by 1040nm



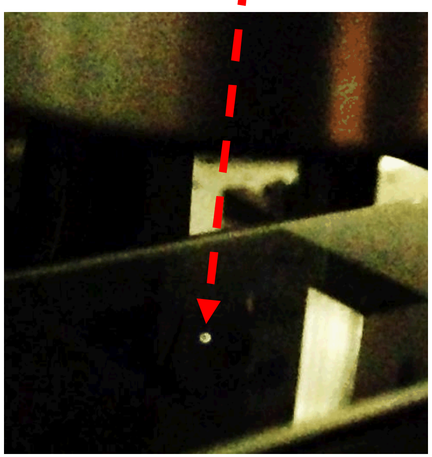


Second harmonic- pump wavelength dependence

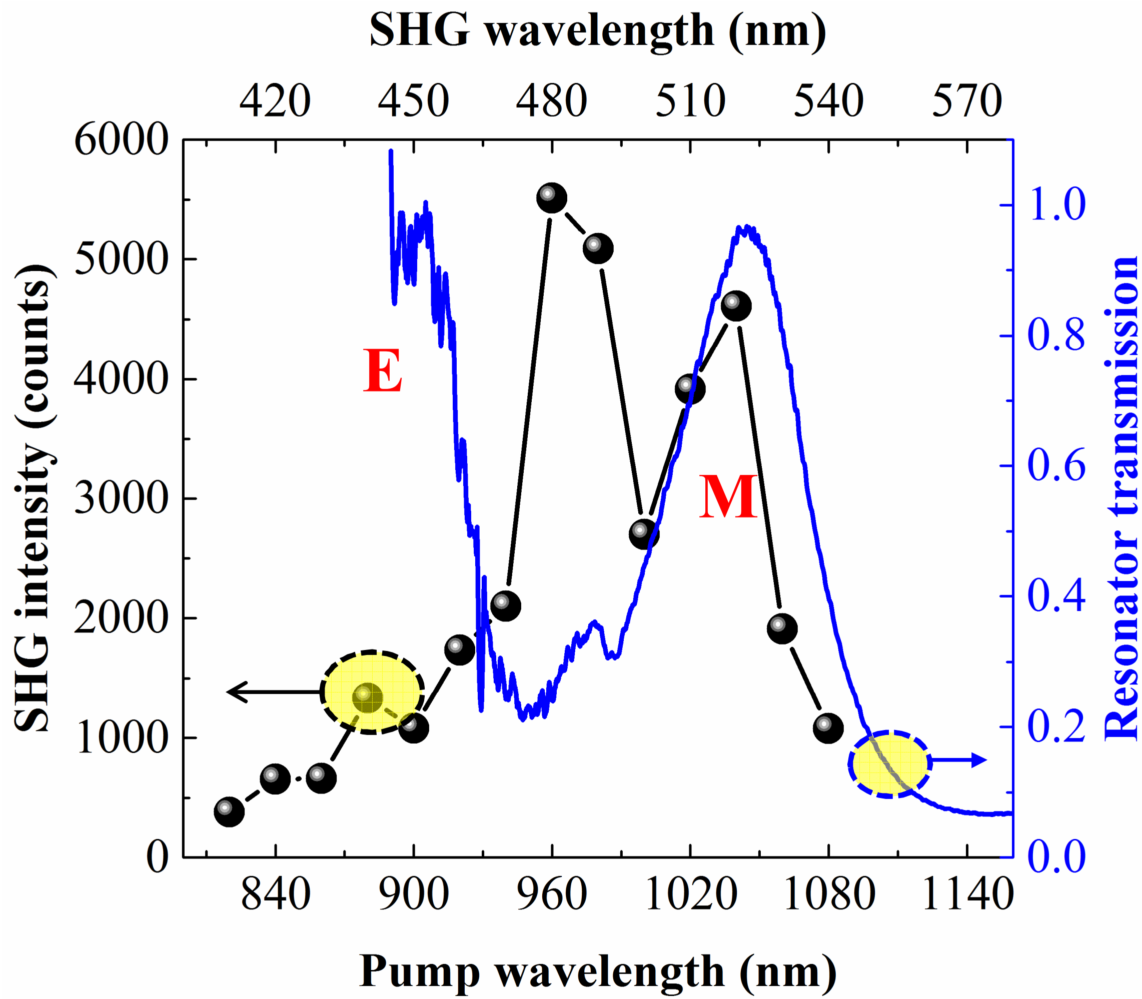
Pump @ 1040nm➔520nm



Pump @ 950nm➔475nm



Preliminary data



- Strong pump wavelengths dependence
- Different diameter resonators show different SHG efficiency
- More experiments are needed

III-V semiconductor based dielectric metamaterials

- *Single layer*
- ***Multi layer—why we need?***

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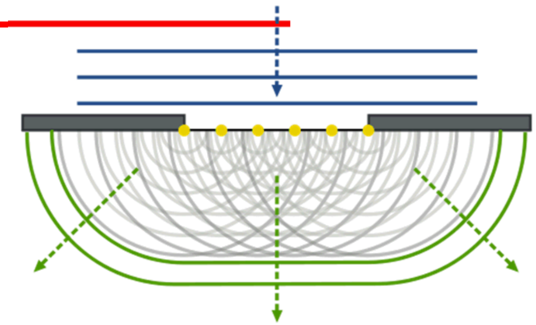
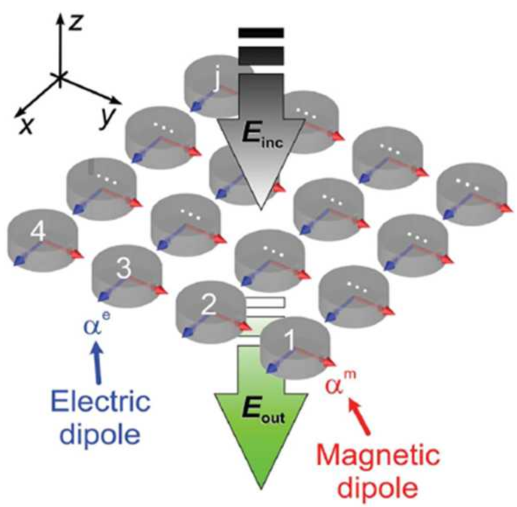
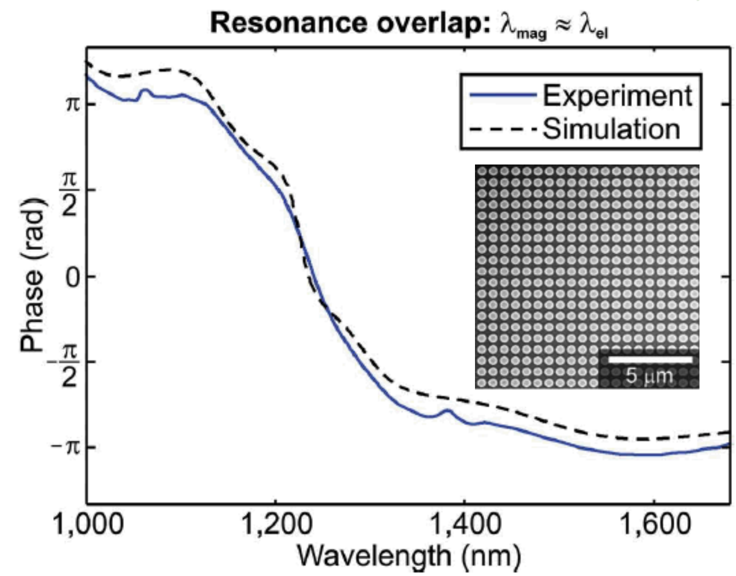
Huygens Metasurface

Huygens Principle (Love formalism) Huygens sources radiate unidirectional as superposition of electric and magnetic dipoles.



Using dielectric resonators, we can achieve this

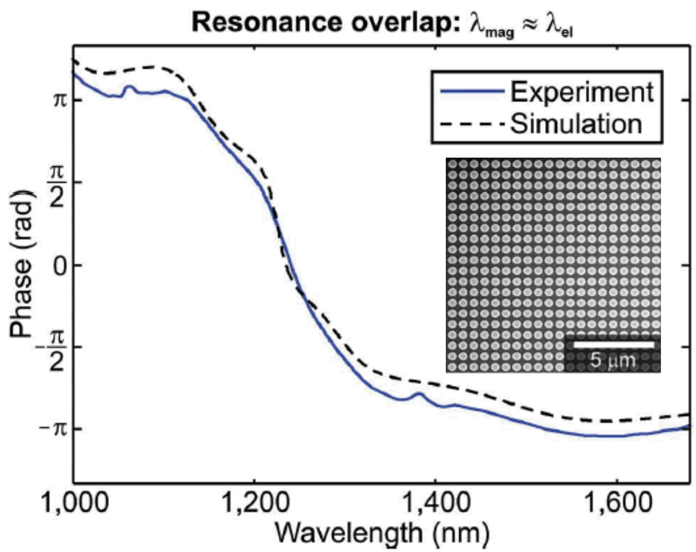




(I. Staude, I. Brener & Y. Kivshar, Adv. Opt. Mat. 2015

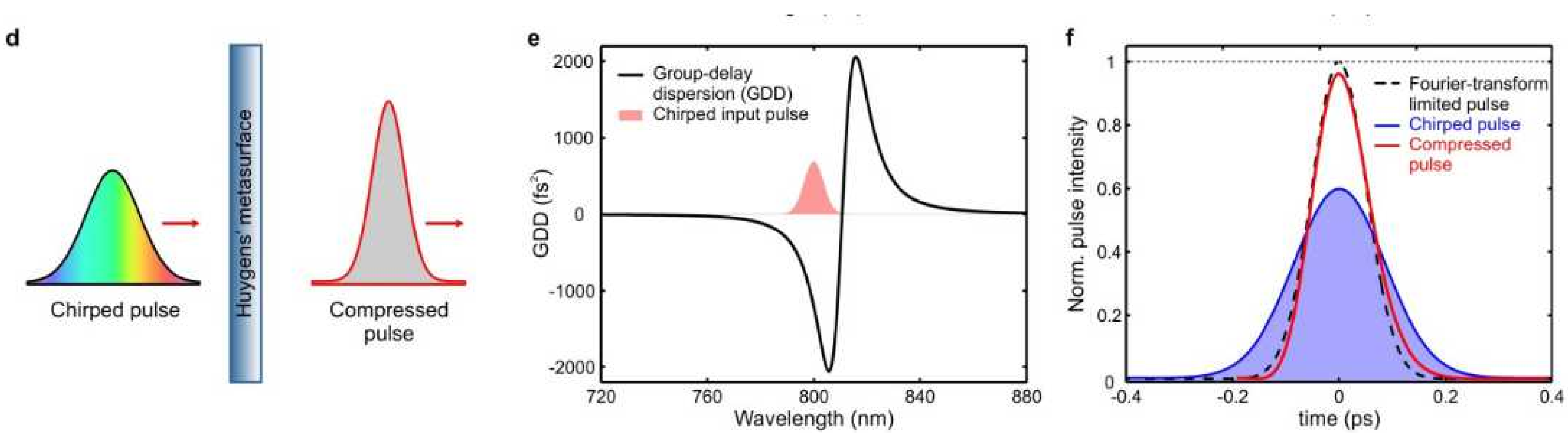
- **Complete 2π phase range in transmission**
- Near-unity transmittance
- No reflection losses, no absorption losses (NIR)
- No polarization conversion losses
- Single step lithography fabrication

Femtosecond pulse dispersion compensation by multi-layer Huygens metasurface



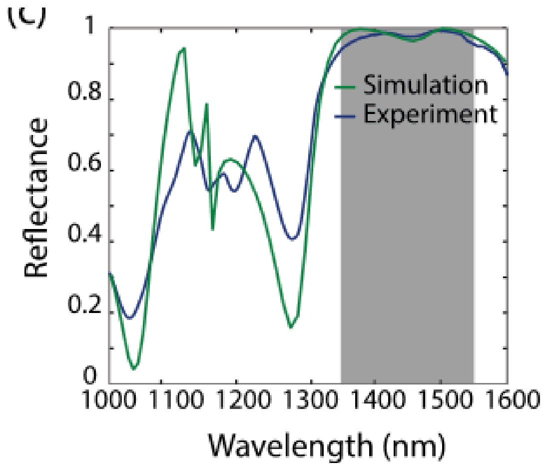
Single layer is not enough to generate sufficient phase difference within the spectrum of femtosecond pulses.

We need multi-layer!

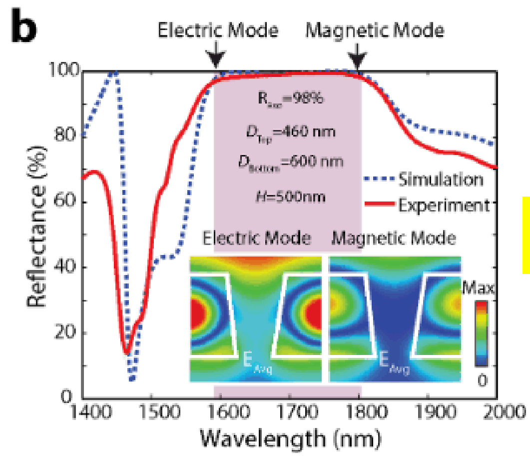


Yuri et al, "High-Efficiency Dielectric Huygens' Surfaces", Advanced optical materials, 3, 813 (2015)

Another example: Perfect reflector—3 layers of GaAs disks



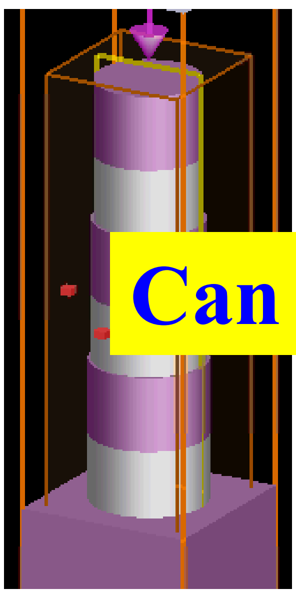
Appl. Phys. Lett. **104**, 171102 (2014)

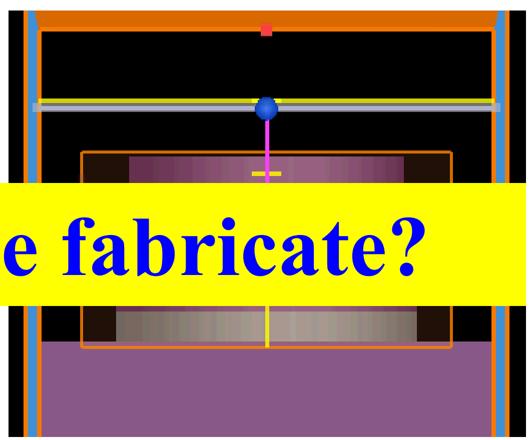


DOI: 10.1021/acsphotonics.5b00148

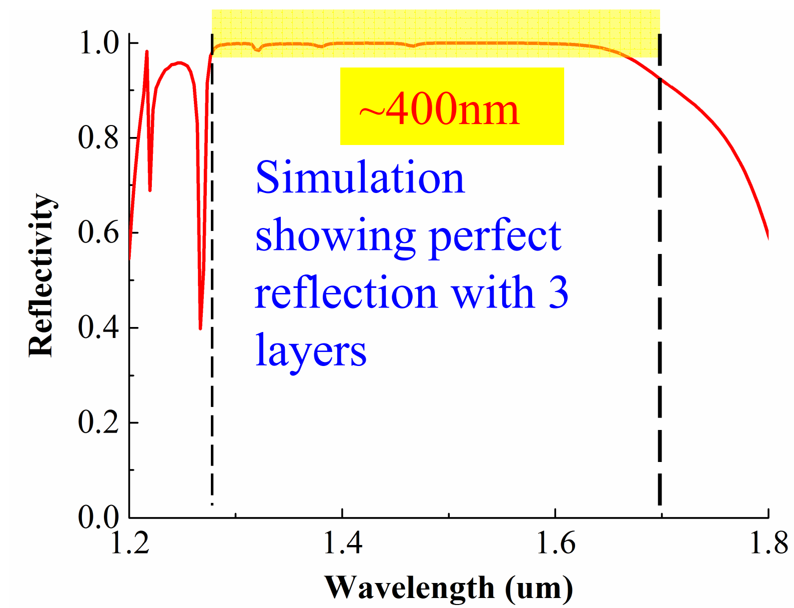
~200nm

Perfect reflector—1 layer silicon disk resonators





Can we fabricate?



~400nm

Simulation showing perfect reflection with 3 layers

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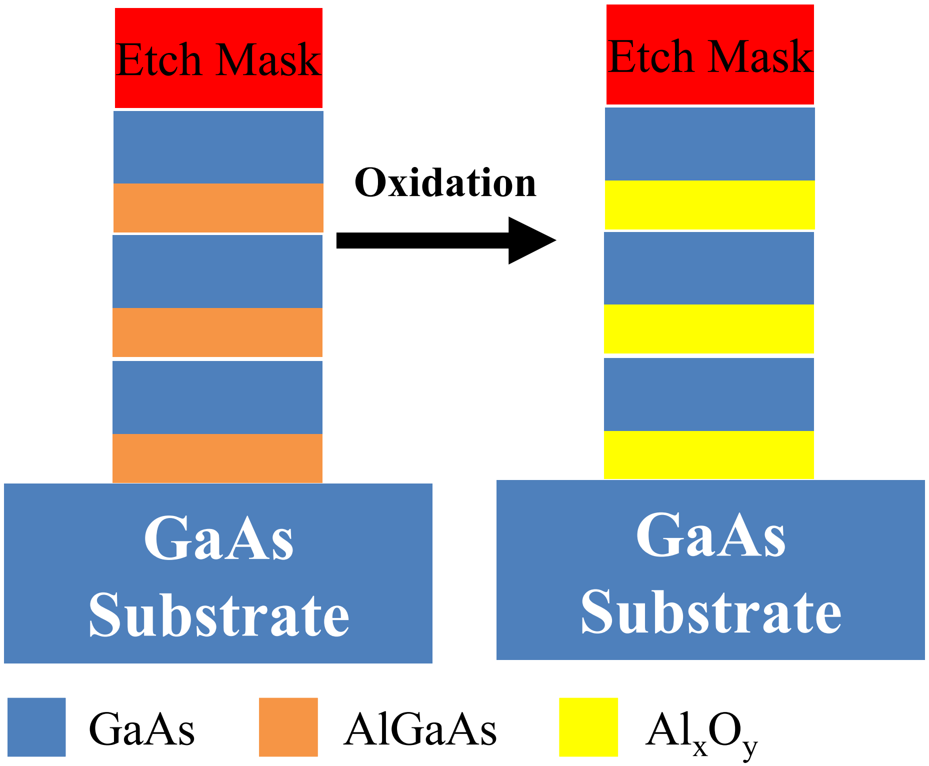
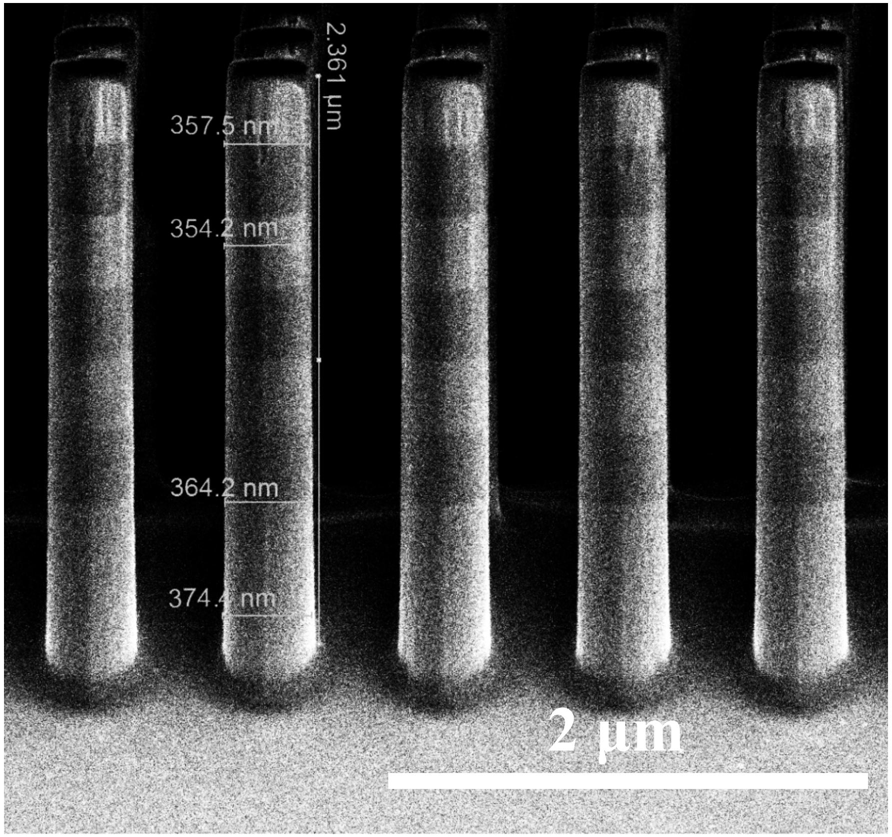
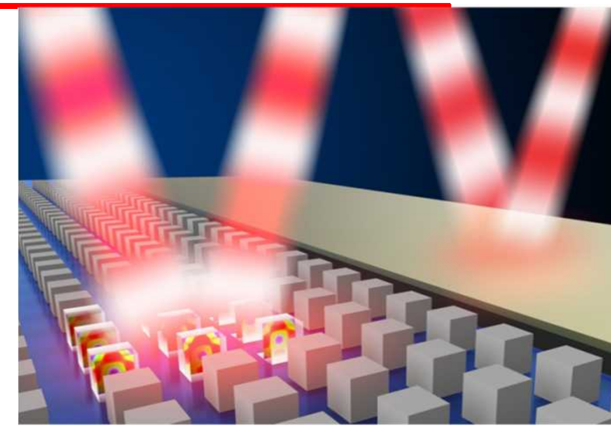
3D dielectric metamaterials

Epitaxially grown **multi-layer GaAs/AlGaAs**

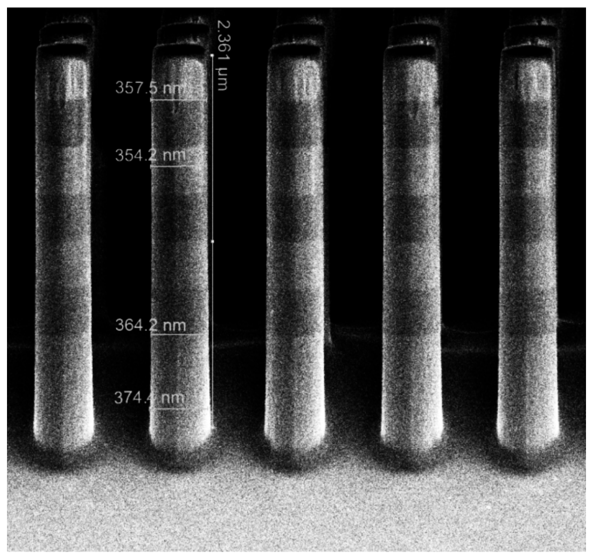


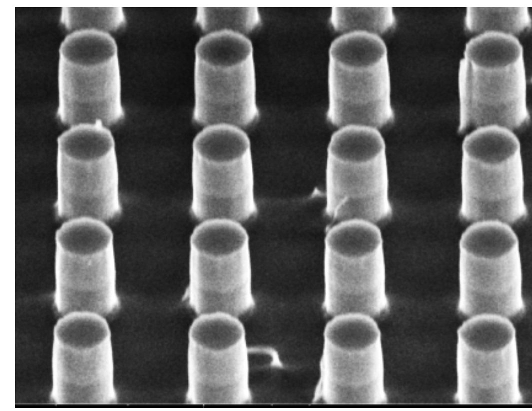


Summary



- Optical magnetic mirrors without metals
- III-V (AlGaAs/GaAs/InGaAs) based dielectric metamaterials open new possibilities for nonlinear optical generation, realizing 3D and active devices…???





S. Liu, et al, Optical magnetic mirrors without metals, Optica, **1**, 250 (2014)
S. Liu, et al, Appl. Phys. Lett., **102**, 161905 (2013)
S. Liu, et al, Appl. Phys. Lett., **103**, 181111 (2013)

High refractive index needed for dielectric magnetic mirror

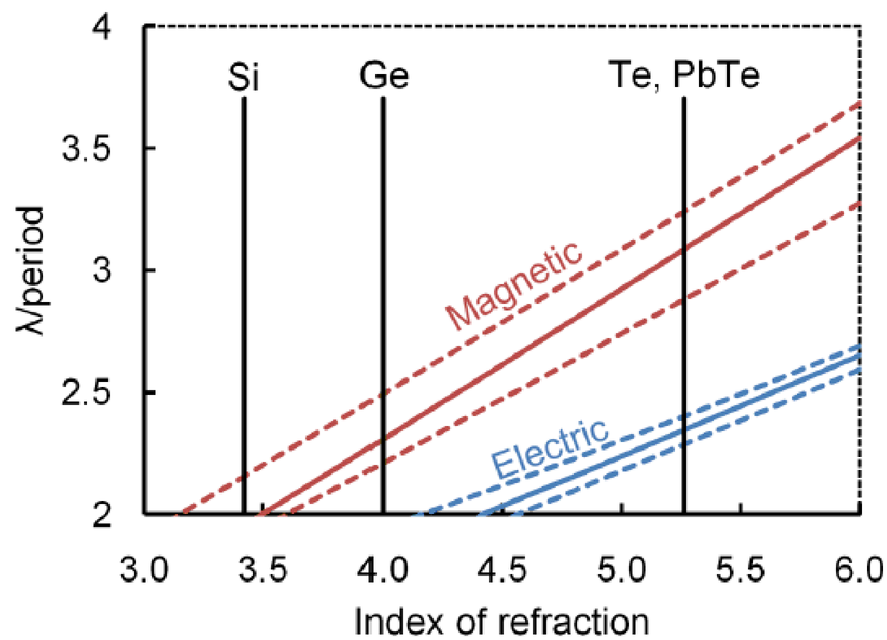
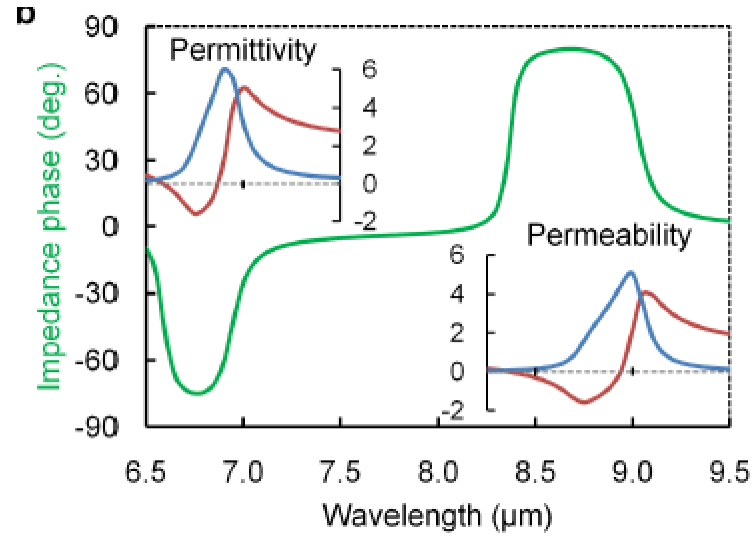


FIG. 4. (color online). Design metric for 1:1 CDR metamaterials. Solid lines correspond to the lowest-order magnetic (red) and electric (blue) resonances. The top dashed line defines the transition to a band-gap regime, and the bottom line defines where the effective parameter has its zero crossing. The indices of several materials at 10 μm are also labeled.

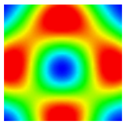
J. Ginn, et al., Phys. Rev. Lett. 108, 097402 (2012)



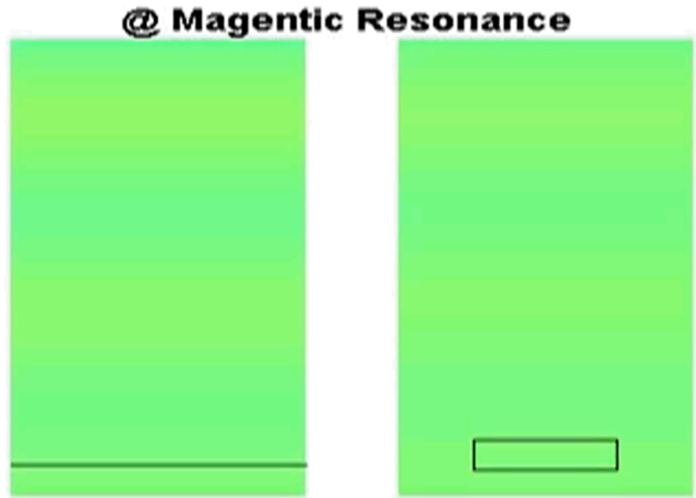
- When the effective wavelength in the OMM becomes equal to the array period, a photonic crystal band-gap regime is encountered for which field homogenization breaks down.
- In the immediate vicinity of the resonance, the phase advance of the wave across the unit cell becomes significant and spatial dispersion effects appear.

The significance of these band-gap and spatial dispersion effects increases as the permittivity of the resonator decreases since the size of the resonator and unit cell must grow relative to the operating wavelength. The lim-

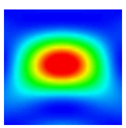
Light reflected upon normal mirror and magnetic mirror



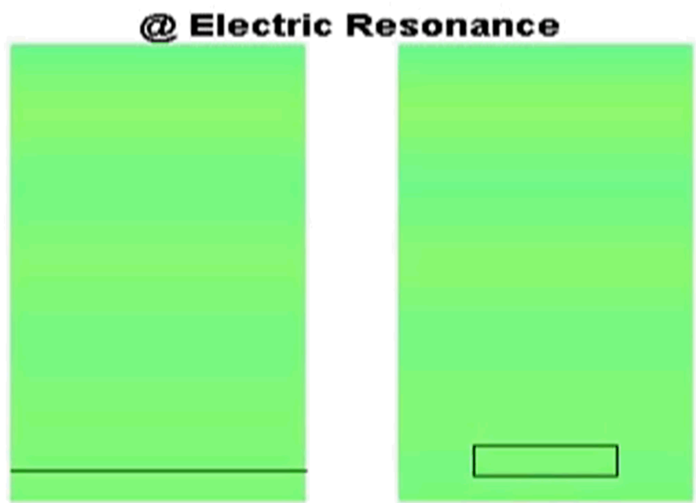
Magnetic
Resonance
λ~9μm



"magnetic" mirror



Electric
Resonance
λ~7.1μm



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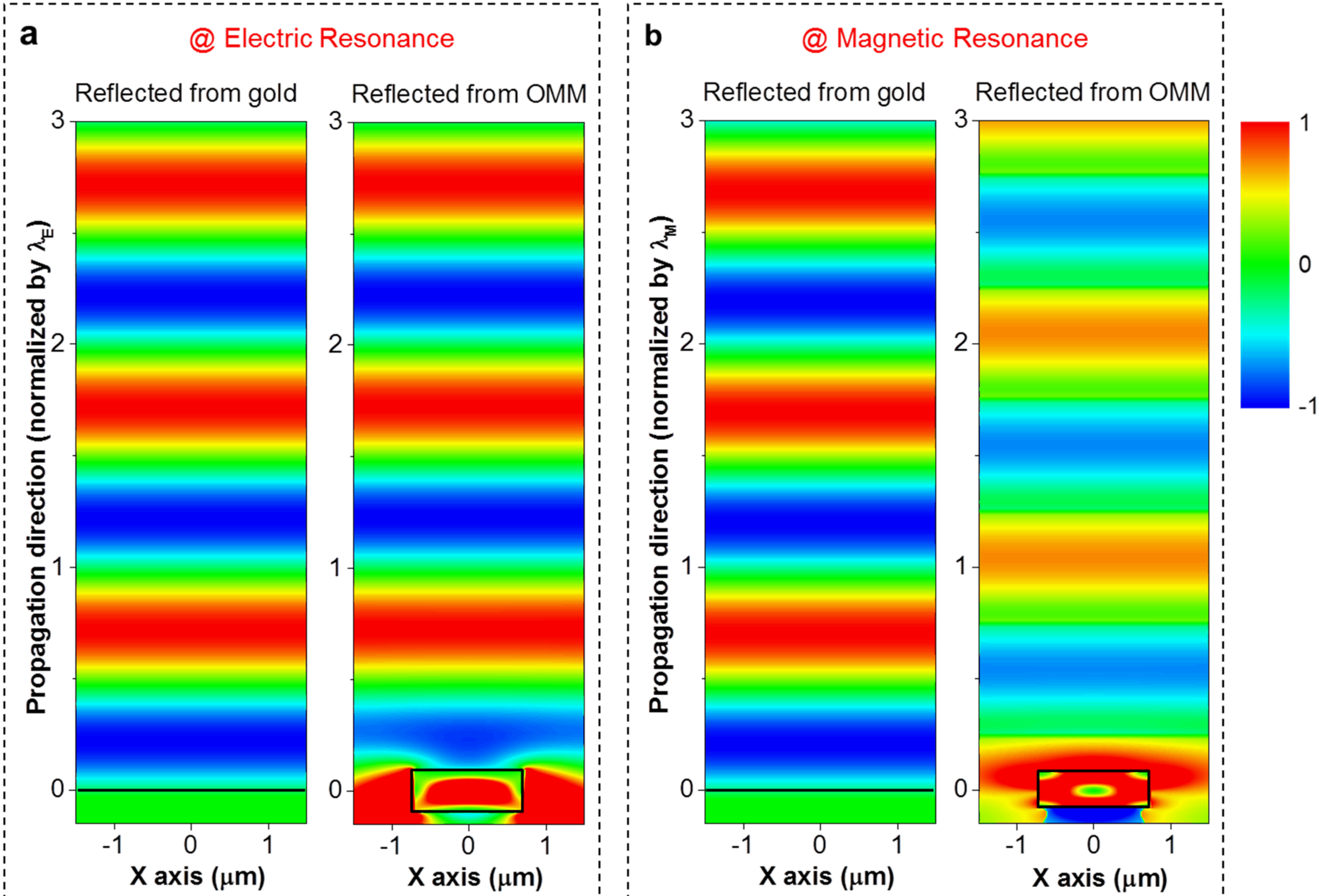
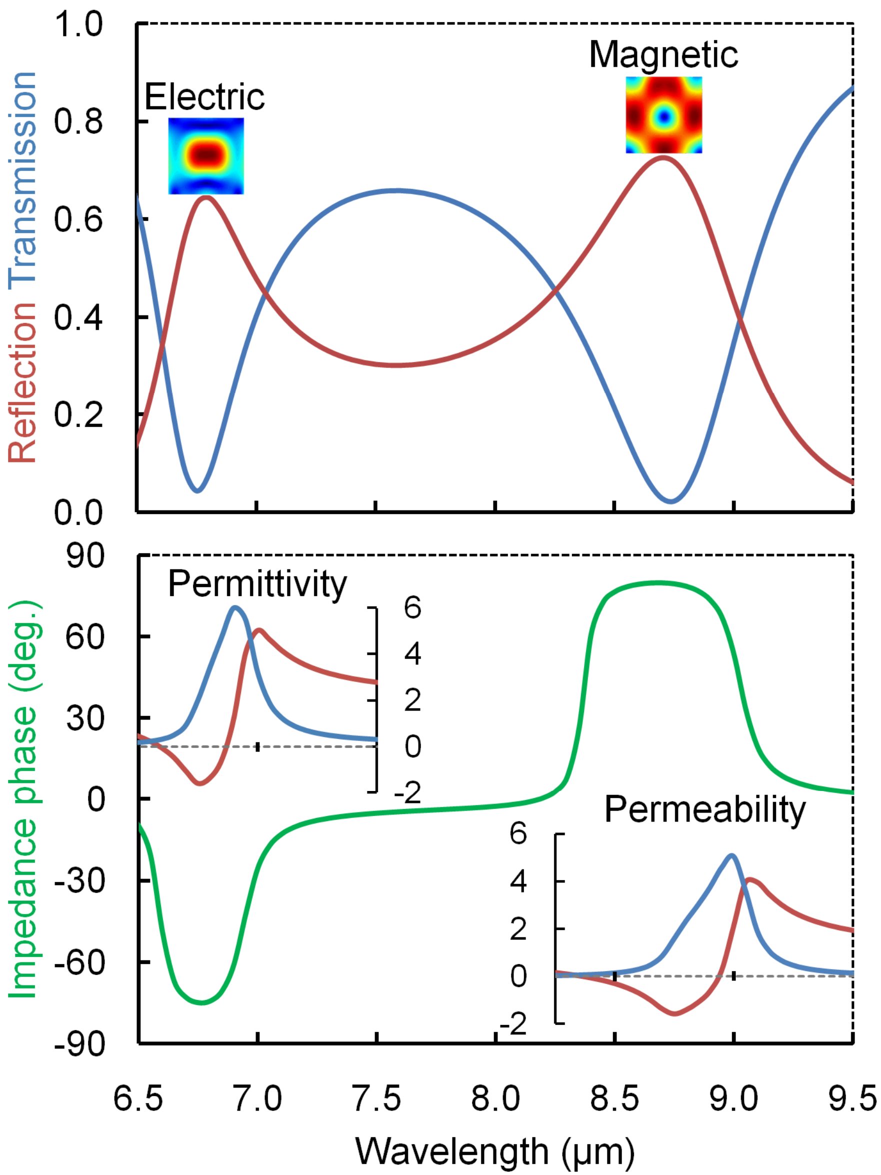


a
@ Electric Resonance
Reflected from gold
Reflected from OMM
Propagation direction (normalized by λE)
X axis (μm)
X axis (μm)
b
@ Magnetic Resonance
Reflected from gold
Reflected from OMM
Propagation direction (normalized by λM)
X axis (μm)
X axis (μm)
1
0
-1

Simulated IR Transmission/Reflection and S-parameter retrieved effective parameters

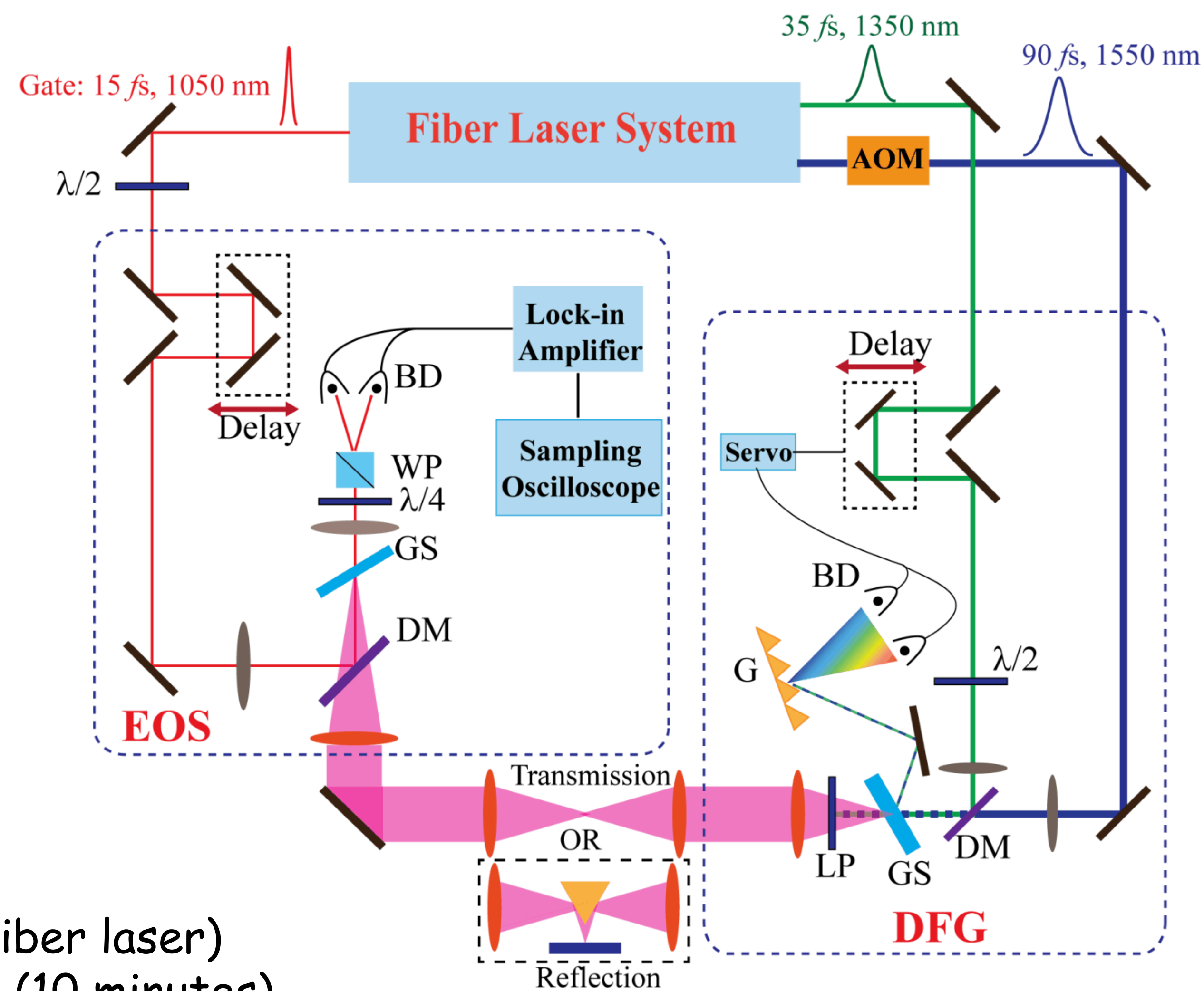


J. Ginn, et al., Phys. Rev. Lett. 108, 097402 (2012)

- Negative values of ε and μ are achieved near respective resonances
- Impedance phase shows hallmark of magnetic and electric behavior
- The optical magnetic mirror behavior occurs near the magnetic dipole resonance where the impedance is imaginary and the impedance phase is positive.
- Permittivity and permeability is retrieve using the standard algorithm following: D. R. Smith et al., PRB, 65, 195104 (2002)

Our mid-IR TDS experimental setup

AOM: acousto-optic modulator
DM: dichroic mirror
GS: GaSe nonlinear crystal
LP: long-wavelength pass filter
G: diffraction grating
BD: balanced detector
λ/2: half-wave plate
λ/4:quarter-wave plate
WP: Wollaston prism

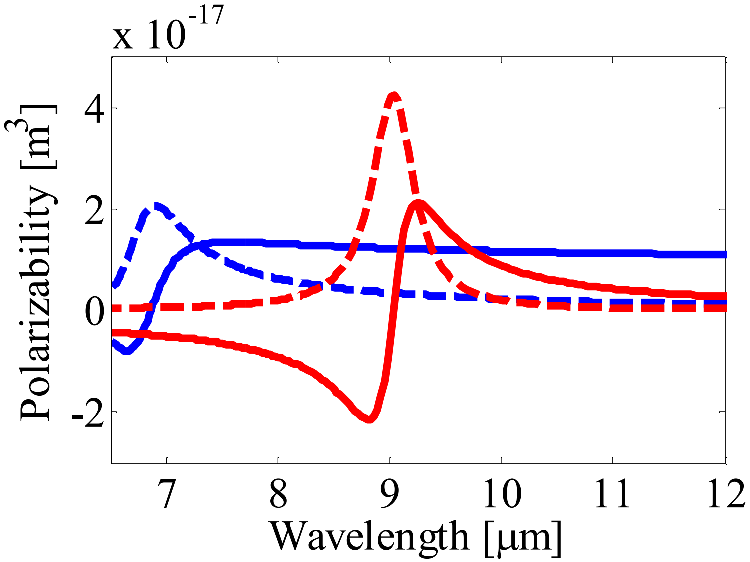


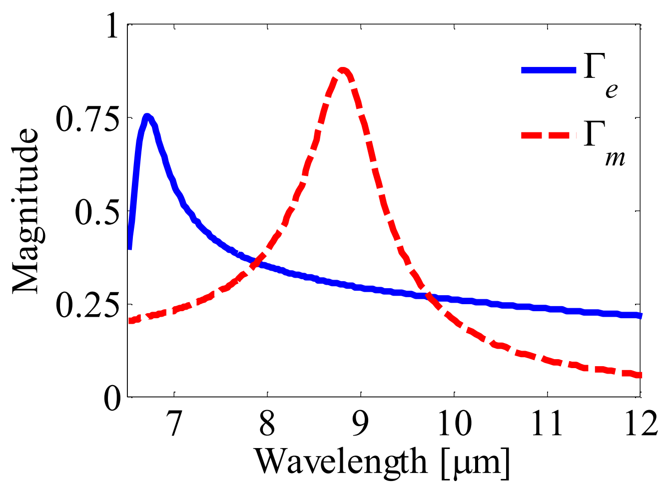
Advantages:

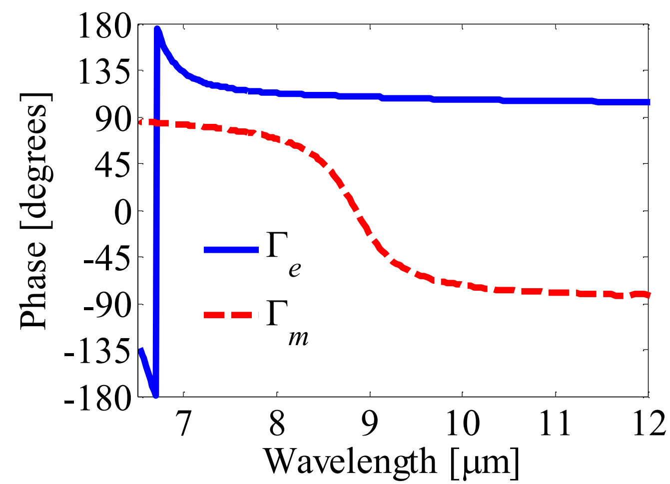
- Smaller footprint (fiber laser)
- Short warm-up time (10 minutes)
- Exchangeable transmission and reflection measurements

average power ~8 μW (~0.5 W peak)
Mid-IR ~200 fs

Theoretical explanation of the observed reflection phases employing two-dimensional periodic dyadic Green's functions

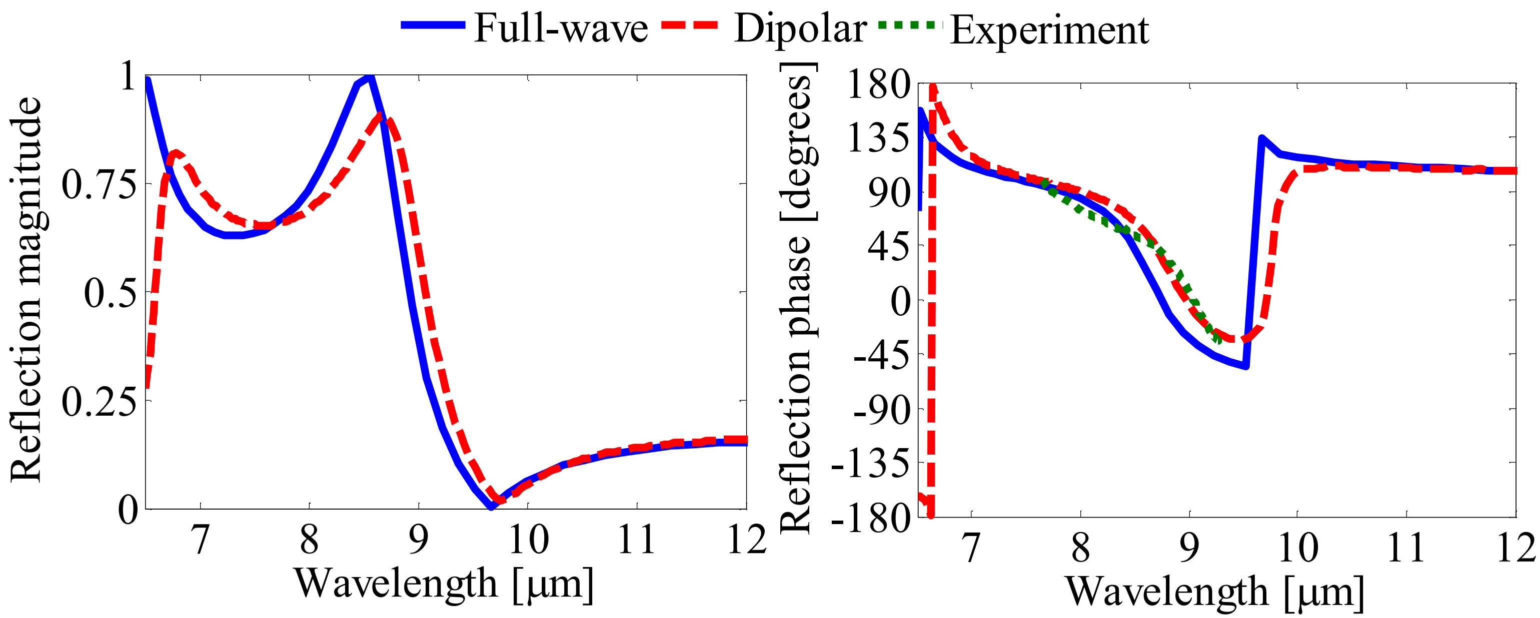






two reflection coefficients from the array of cubes modeled as an array of either electric (solid blue) or magnetic (dashed red) dipoles.

Theoretical explanation of the observed reflection phases employing two-dimensional periodic dyadic Green's functions



Magnitude and phase of the reflection coefficient at the array plane computed with full-wave simulations (blue solid) and dual (electric and magnetic) dipolar approximation (red dashed). The experimental result is reported for completeness as a green dotted curve.

http://arxiv.org/abs/1403.1308 (2014)