



Active Metasurfaces: Metamaterials meet Optoelectronics

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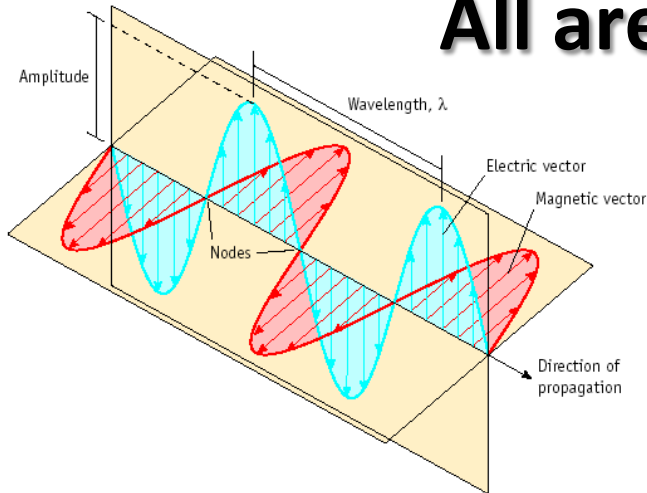


Outline

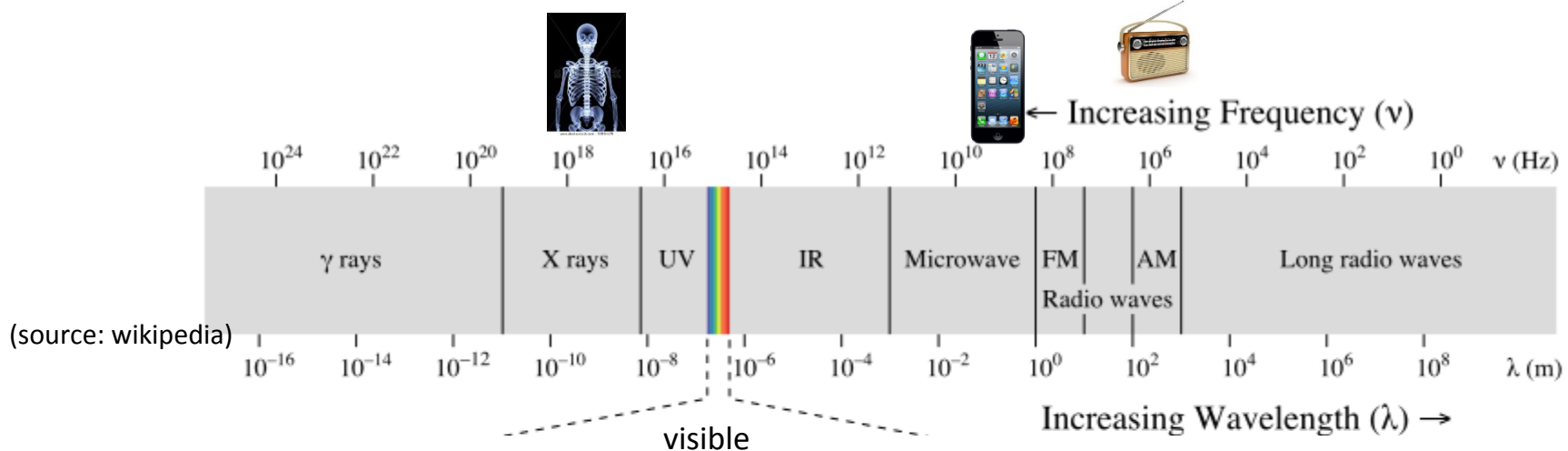
- **Introduction: metamaterials, 3D, 2D, etc.**
- **Metasurfaces I: some terahertz devices**
- **Metasurfaces II: enhanced IR detectors**
- **Metasurfaces III: a “magnetic mirror”**



X-rays, T-Rays, Light, Radio.... All are Electromagnetic Waves



$$\text{Frequency} = c/\lambda$$





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)

1. 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

$$\left| \frac{\omega^2}{c^2} \epsilon_{ij} - k^2 \delta_{ij} \right| = 0, \quad (1)$$

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

$$n^2 = \epsilon\mu, \quad (3)$$

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

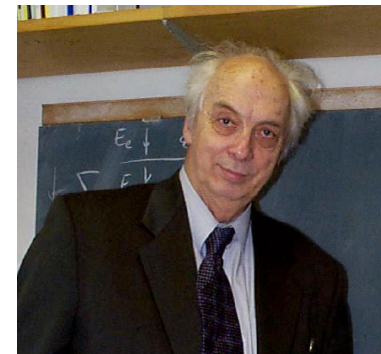
$$n^2 = \epsilon\mu$$

$$n = \sqrt{\epsilon\mu}$$

Permittivity (ϵ) is a measure of how an electric field affects and is affected by a dielectric medium.

Permeability (μ) is the degree of magnetization that a material obtains in response to an applied magnetic field

Viktor G. Veselago



<http://www.tkk.fi/Yksikot/Sahkomagnetiiikka/kuvia/Veselago2.jpg>

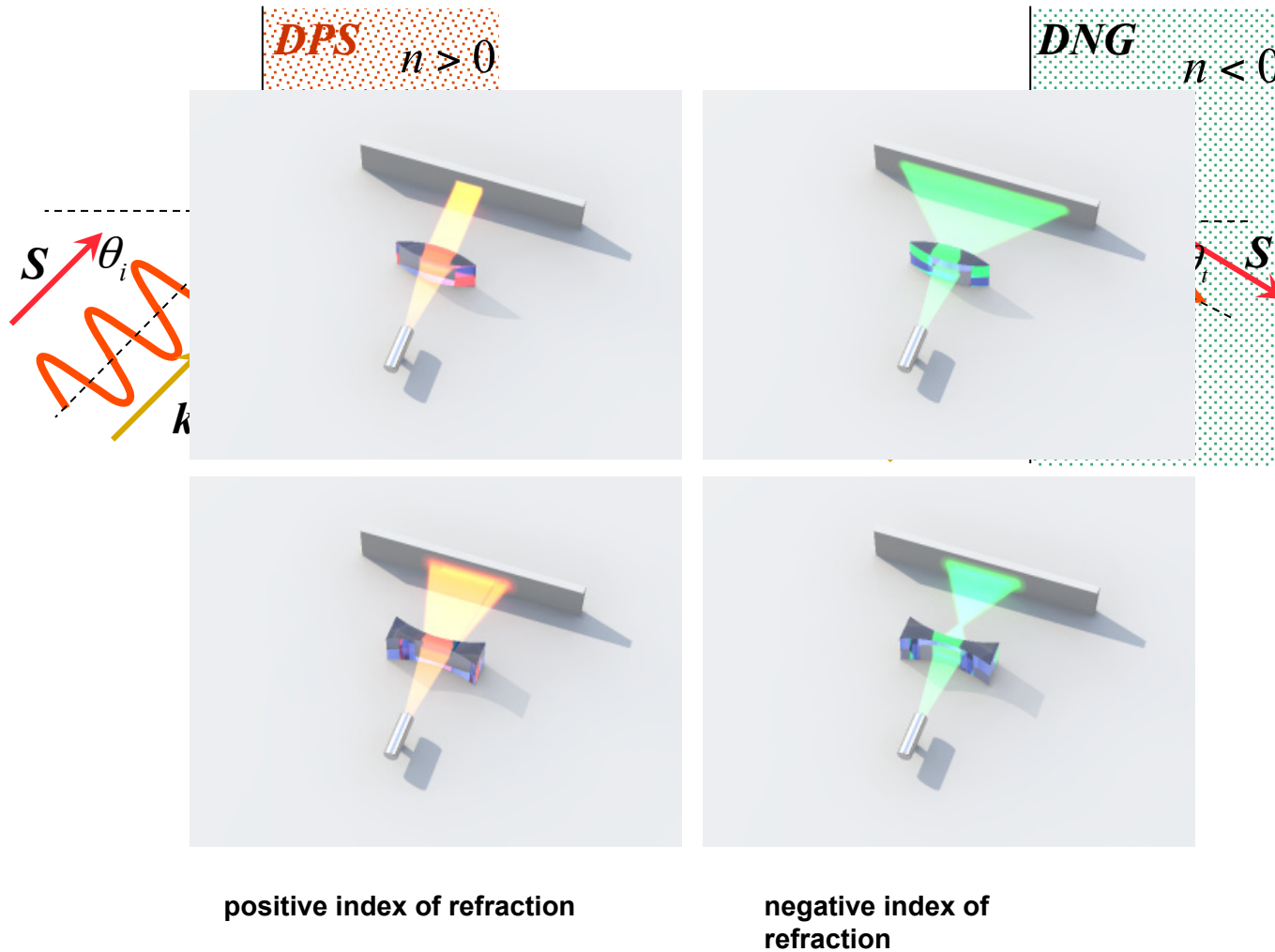
If $\epsilon < 0$ and $\mu < 0$ simultaneously, from considerations of wave propagation, n needs to be negative

Excellent Review: Science 305 (2004)



Negative Refraction

$$n_o \sin \theta_i = n_l \sin \theta_t$$

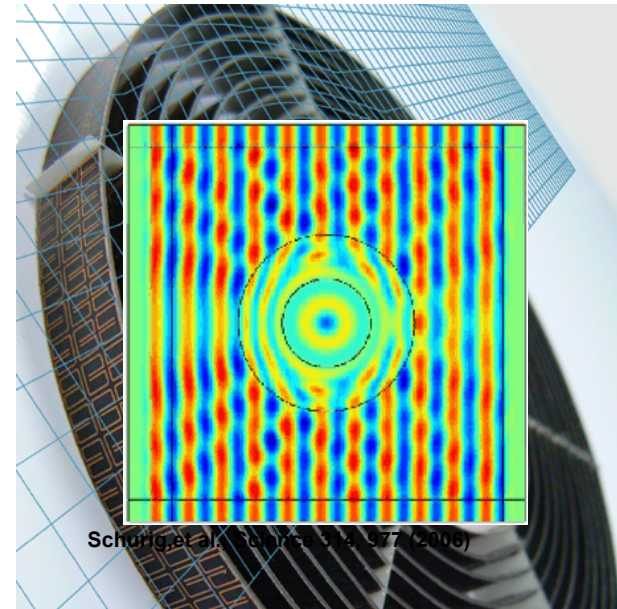
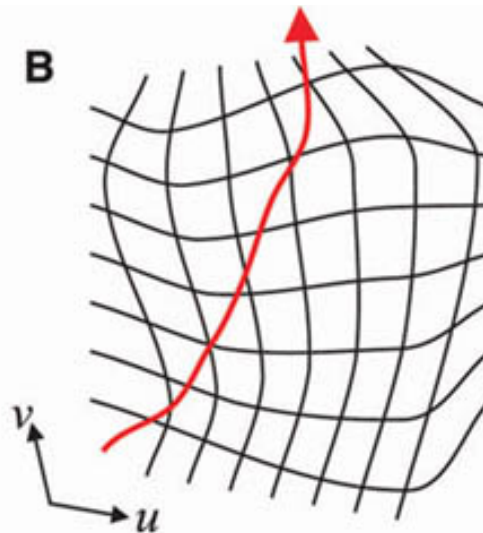
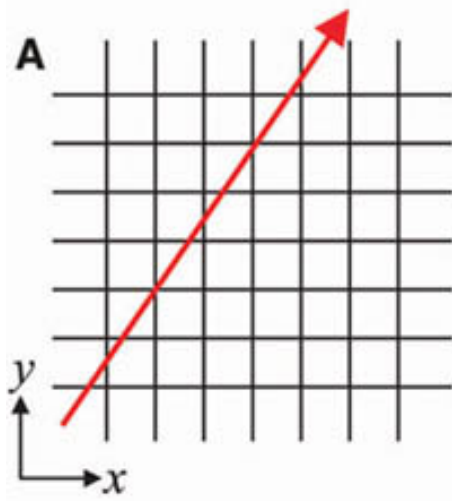


<http://www.imagico.de/pov/metamaterials.php>



Sir John Pendry

“Transformation Optics”



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

David Smith, Duke

- For RF ($\sim 3\text{GHz}$), $\lambda \sim \text{cm}$
- We need to create sub-wavelength “inductors” and “capacitors” $\sim \text{XXmm}$

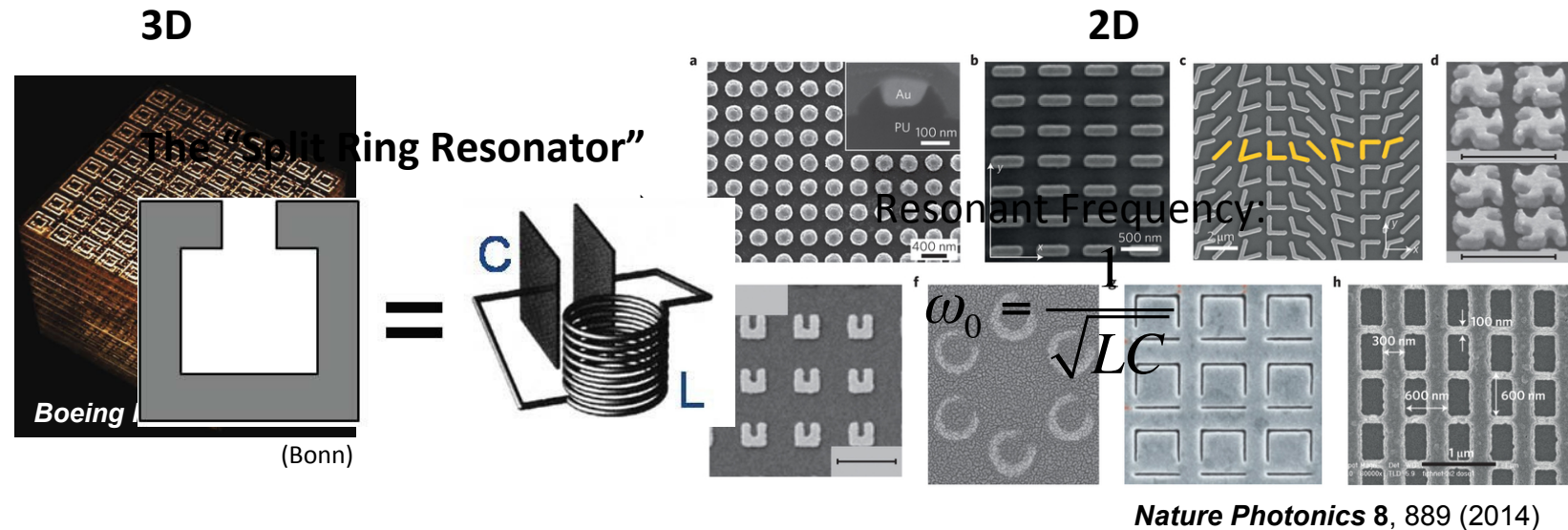


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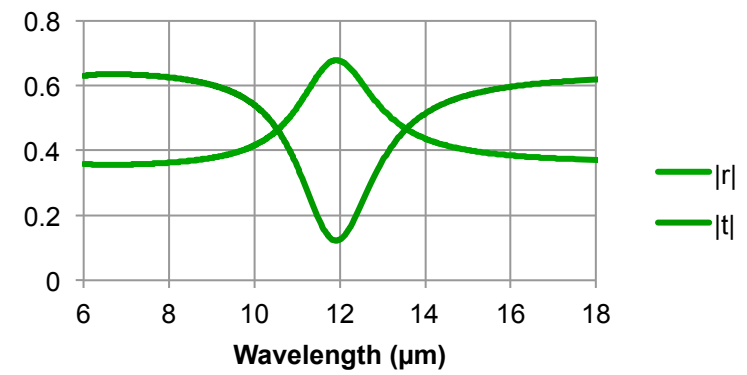
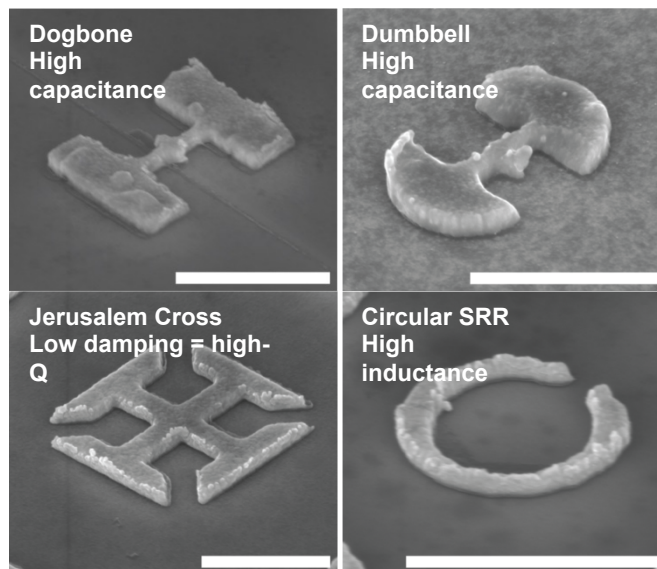
http://www.multimedia.be/newsletter/mn72005/images/nl3_Metamaterials_type1.jpg



“Metasurfaces”



Even for different shapes, many metallic resonators behave like LCR circuits (or “antennas”)





Optical Modulators, Tunable Filters

Optical Modulators, Thorlabs

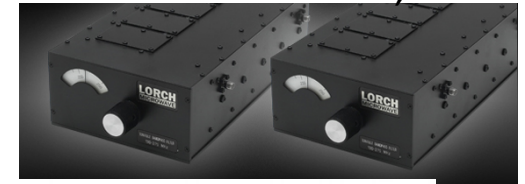


Spatial Light Modulator
Holoeye

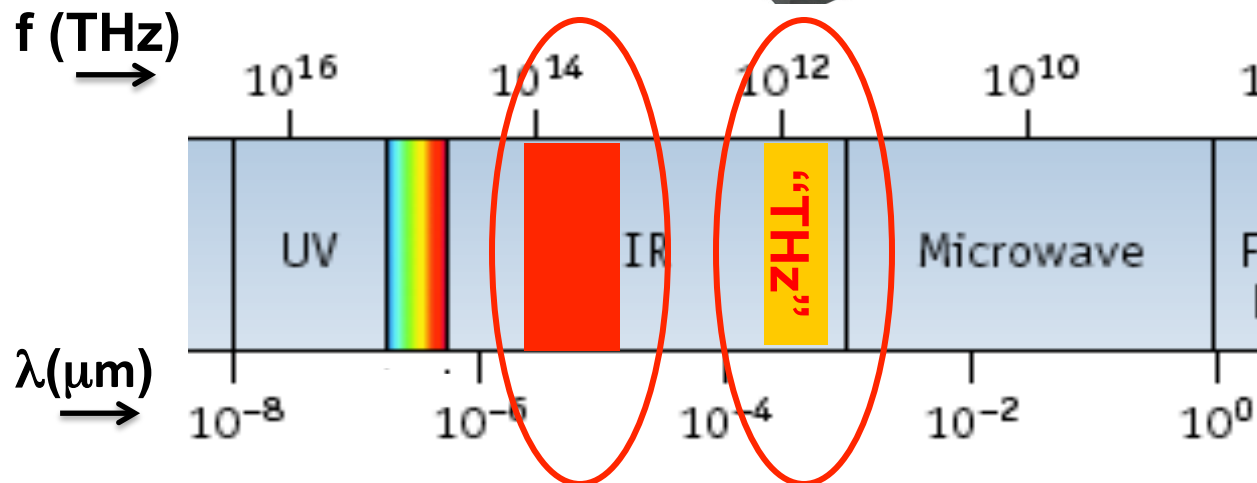


Tunable Filters

Microwave, Lorch

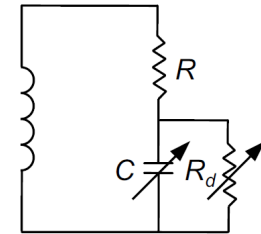
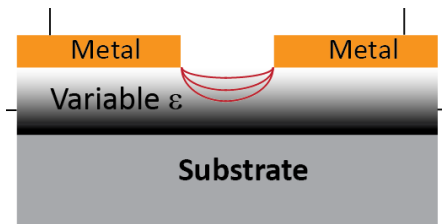
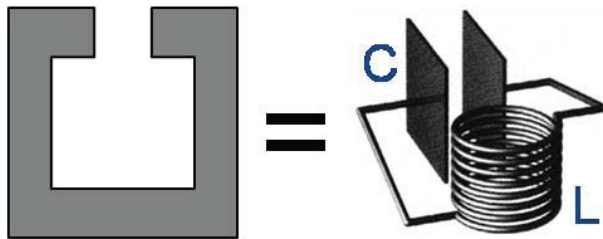
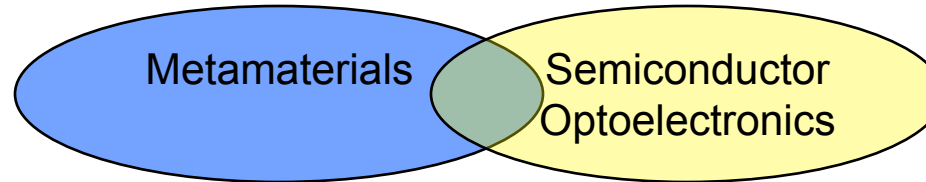


near-IR, Santec

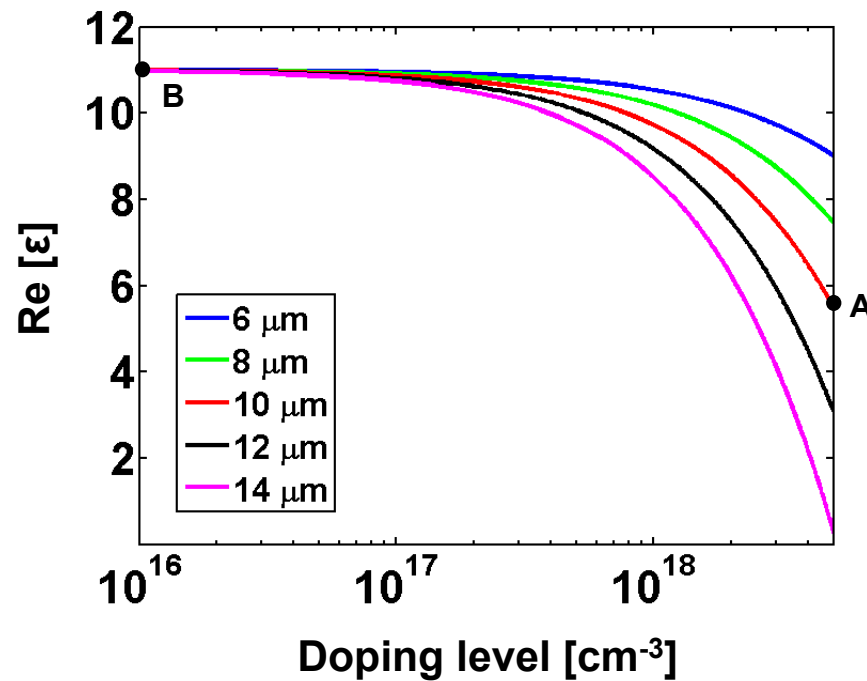




Metamaterials <> Semiconductors

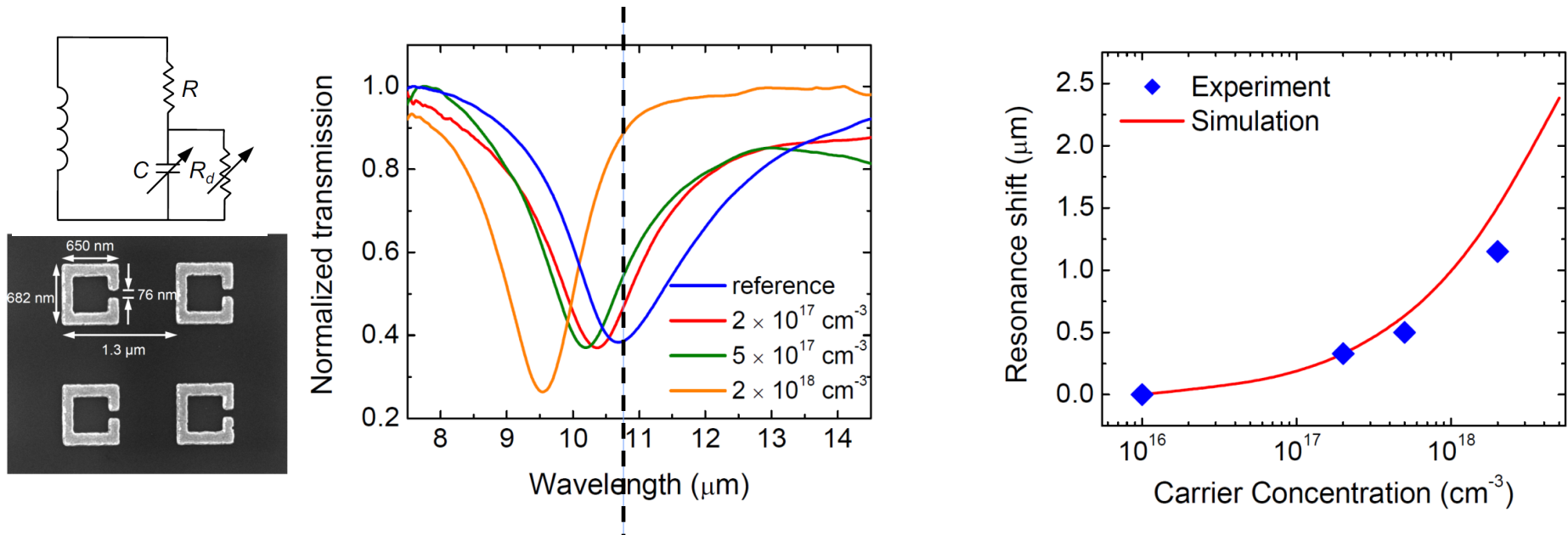


$$n = \sqrt{\epsilon}$$





Tuning Metasurfaces Using Semiconductors



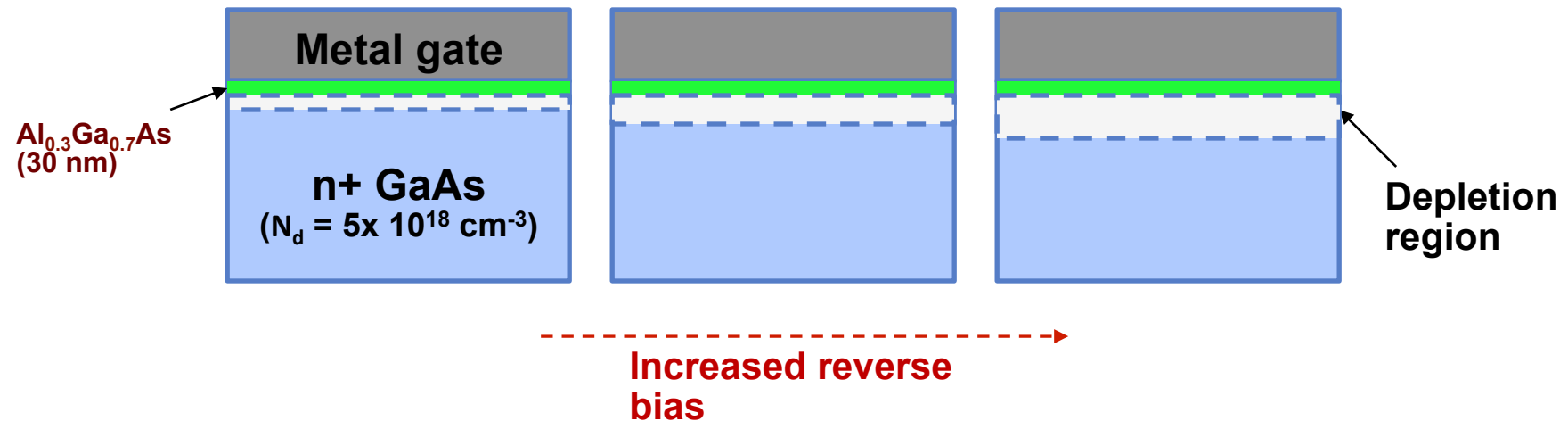
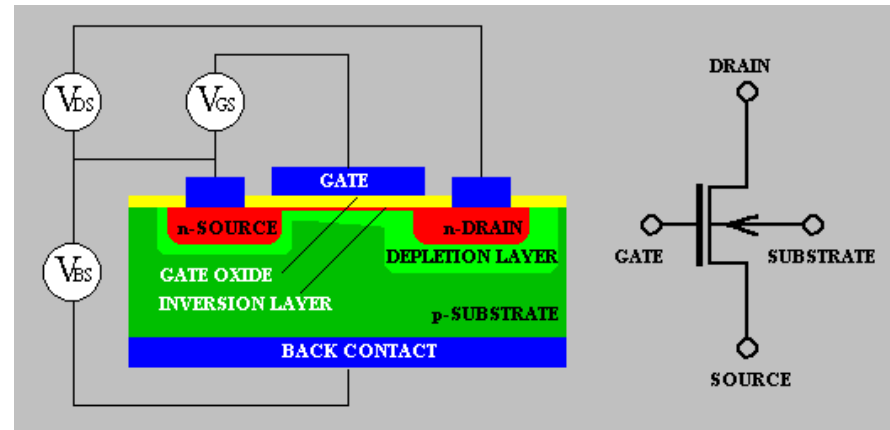
- SRRs made on InSb substrates with different doping
- Experimentally observed doping dependent resonance
 - A resonance shift of 1.15 μm ($1 \times 10^{16} \text{ cm}^{-3} \rightarrow 2 \times 10^{18} \text{ cm}^{-3}$)

$$\Delta\lambda/\lambda \approx 10.8\%$$



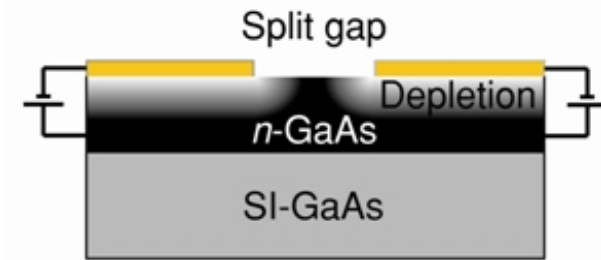
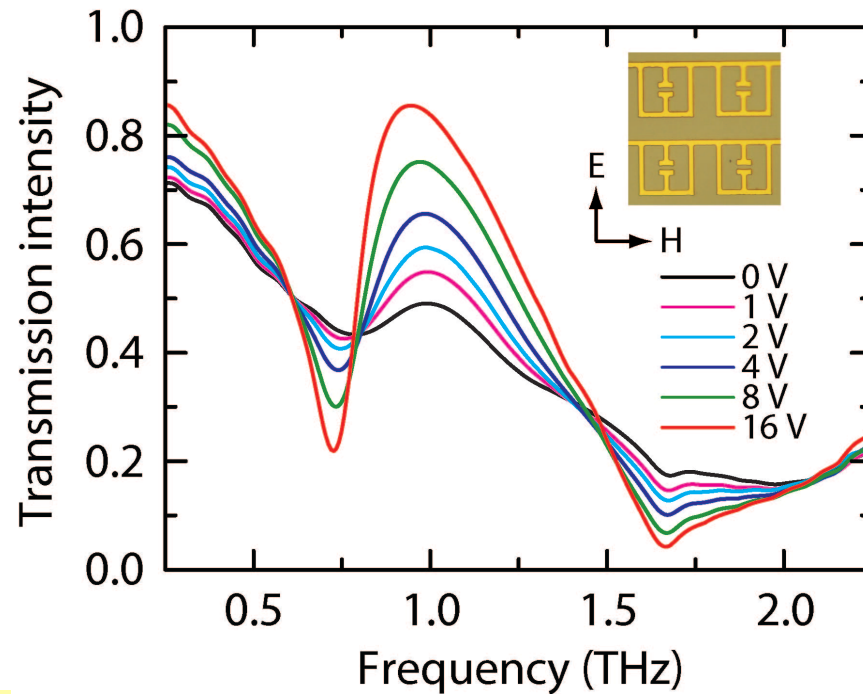
Remember the MOSFET?

(<http://ecee.colorado.edu/~bart/book/mosintro.htm>)





A Single Pixel THz Optical Modulator

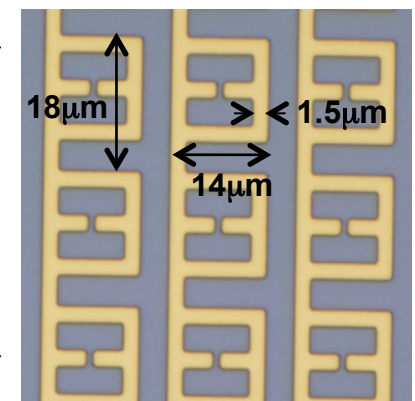
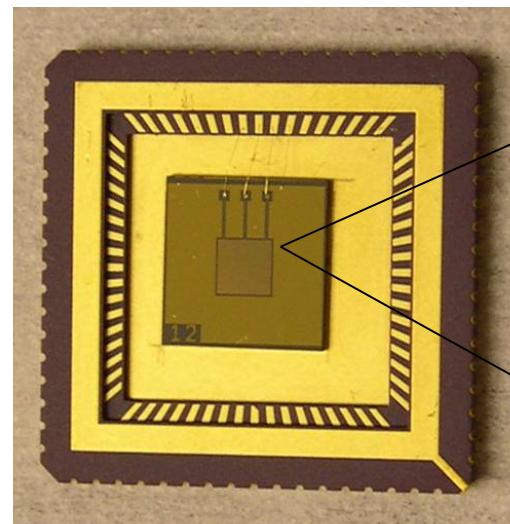


This works by increasing the damping (ϵ_2 , loss).

Chen, Nature 444, 597 (2006).

A 3THz Modulator

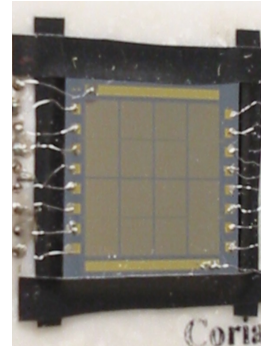
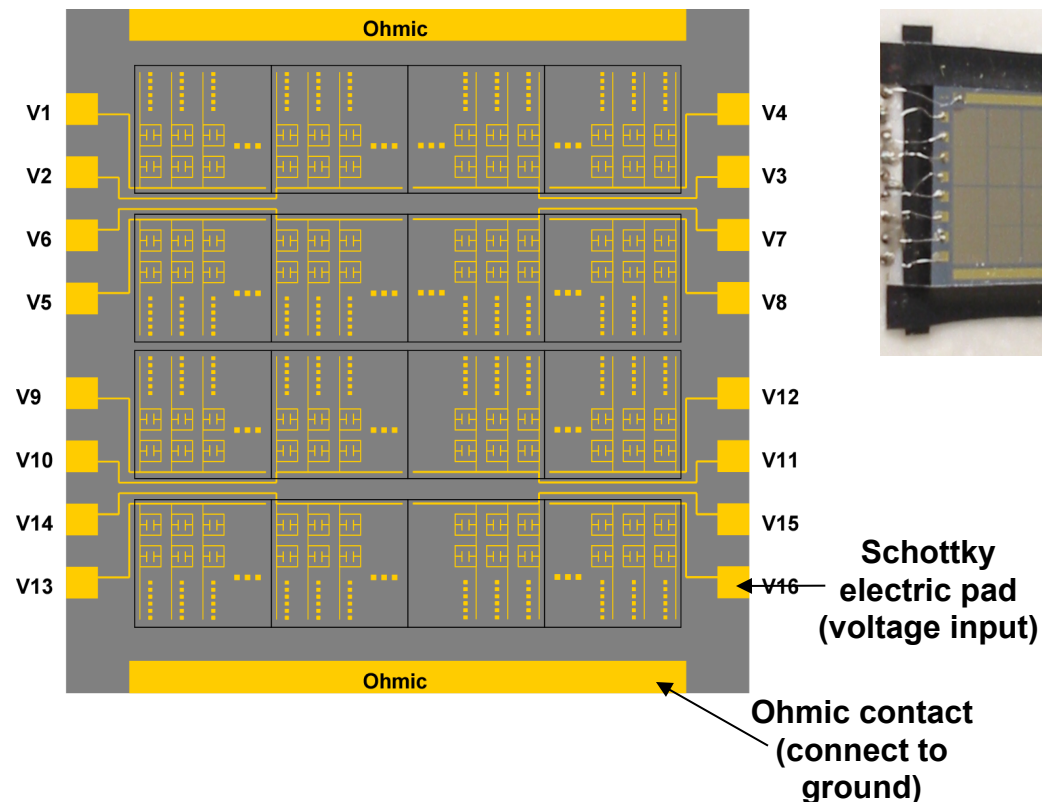
Metamaterials, 2010



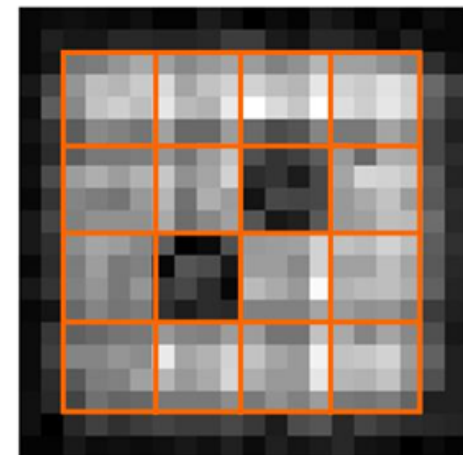


A First Generation THz Spatial Light Modulator

Rice, Sandia, Los Alamos



Transmission image of
THz-SLM at 0.36 THz



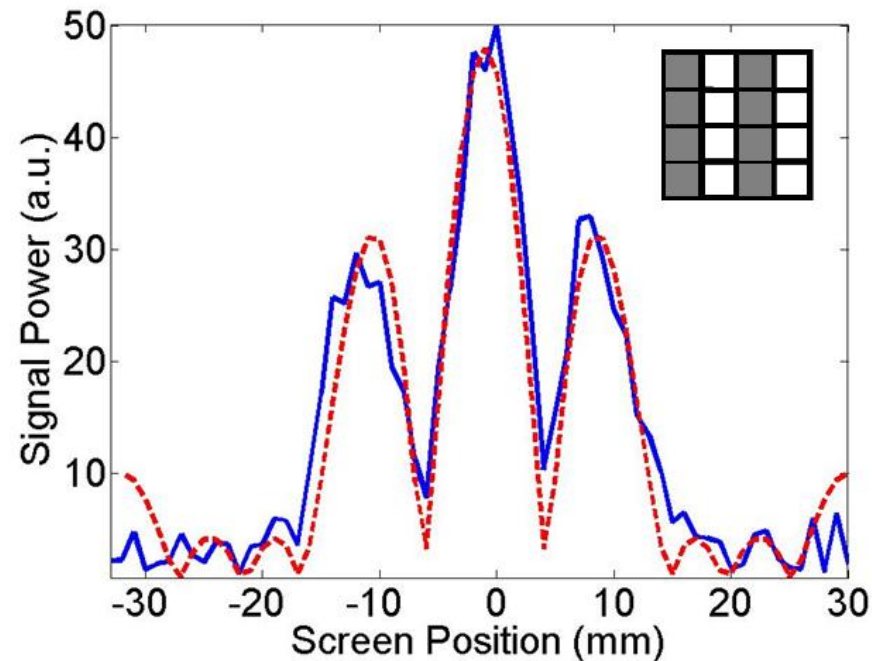
16 mm

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

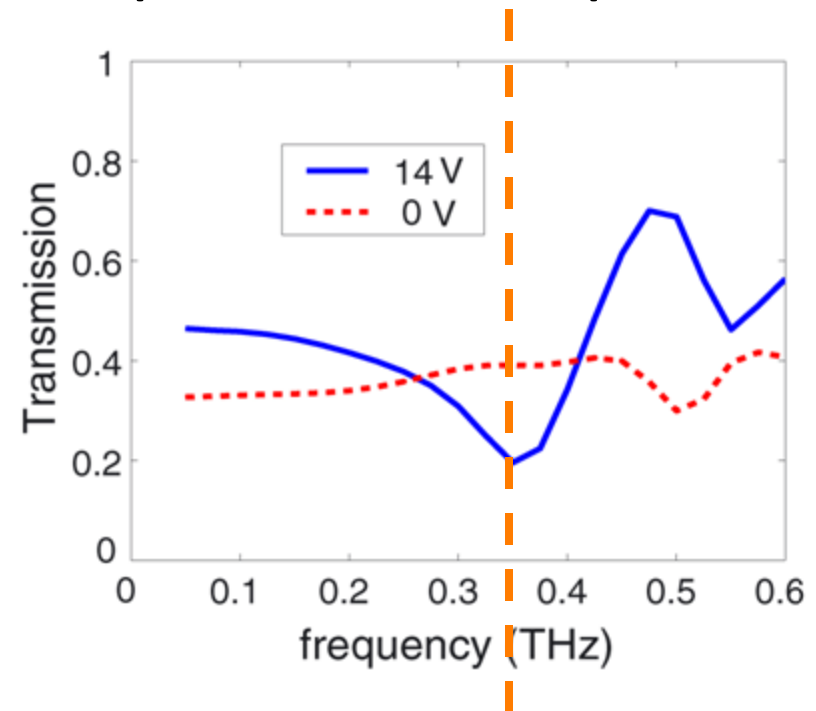


A First Generation THz Spatial Light Modulator

A demonstration based on double-slit diffraction



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



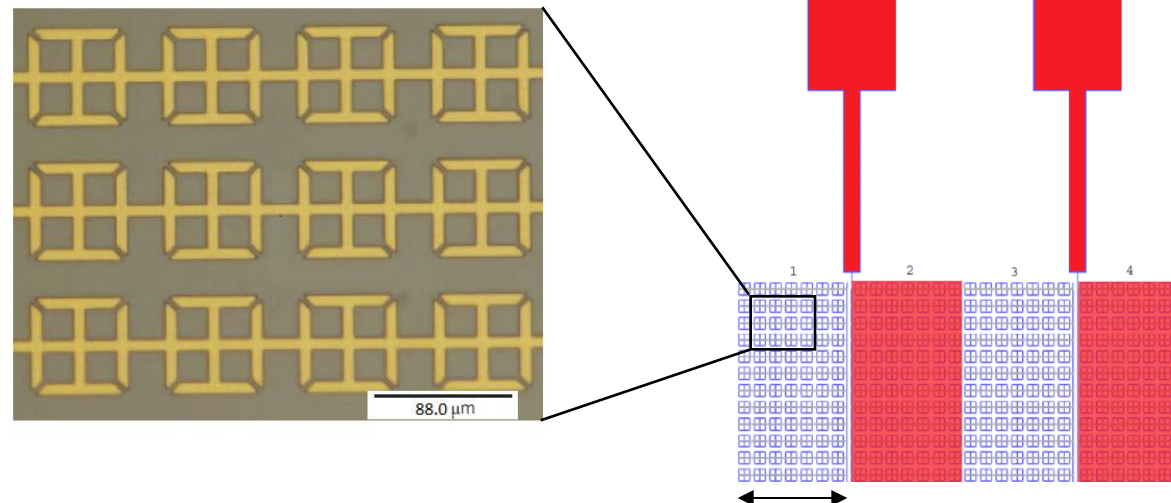
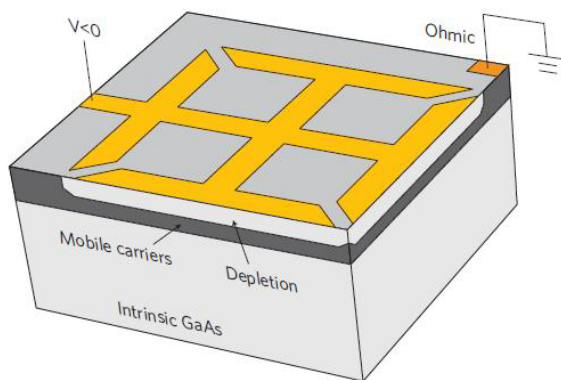
~40% modulation at the
resonant frequency: 0.36 THz

Rice, Sandia & Los Alamos



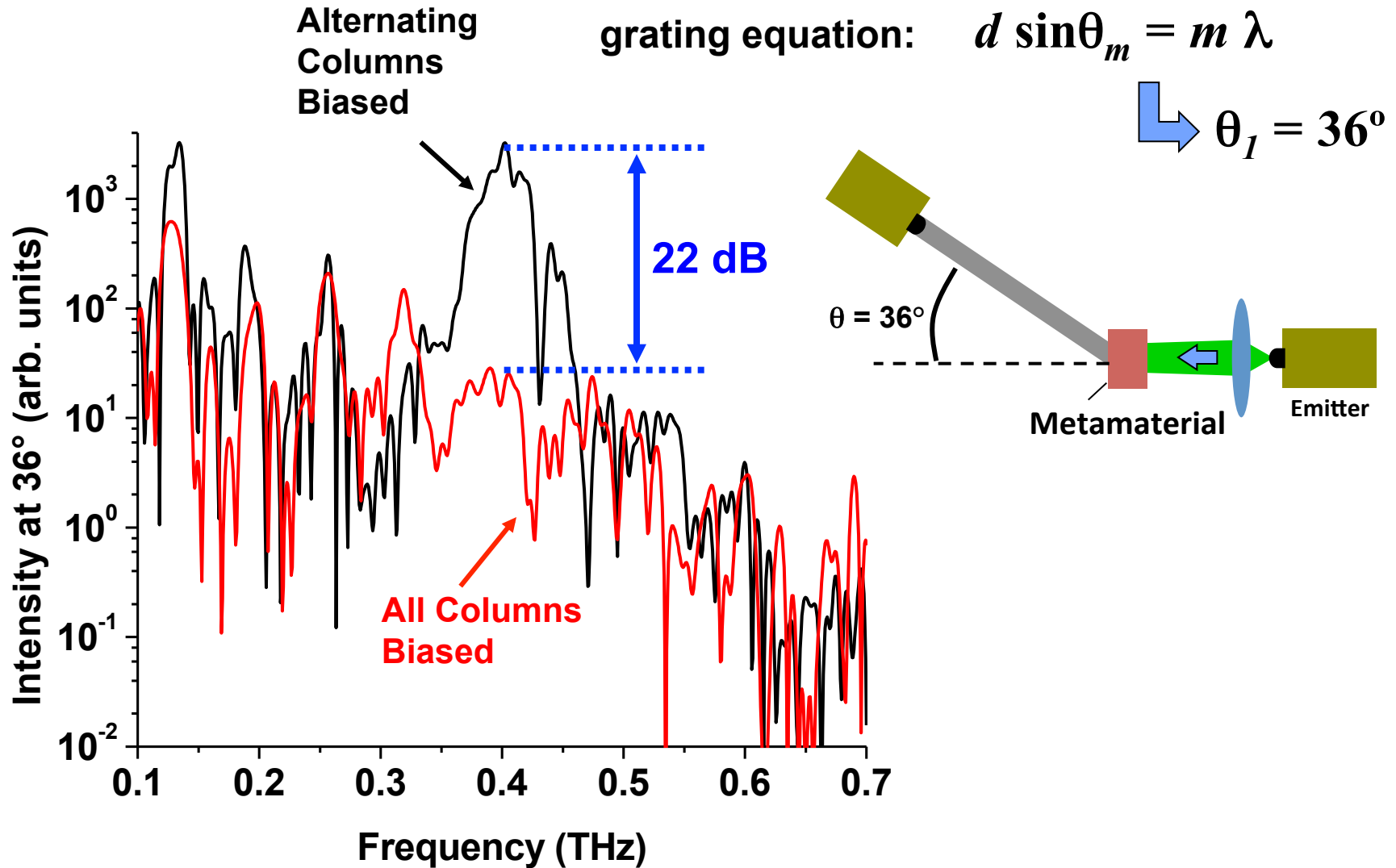
A Metamaterial Grating

- SRR resonance design frequency near 0.4 THz
- Array consists of 32 columns: column width = 596 nm ($\sim 0.85 \lambda$)
- All SRRs within a column are electrically connected to each other; isolated from other columns.





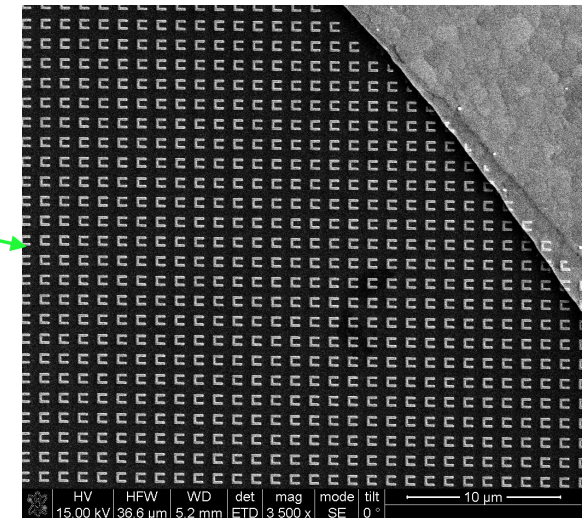
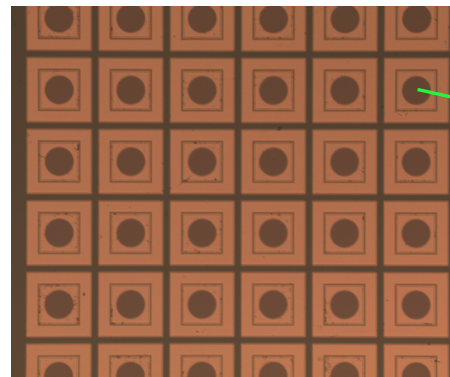
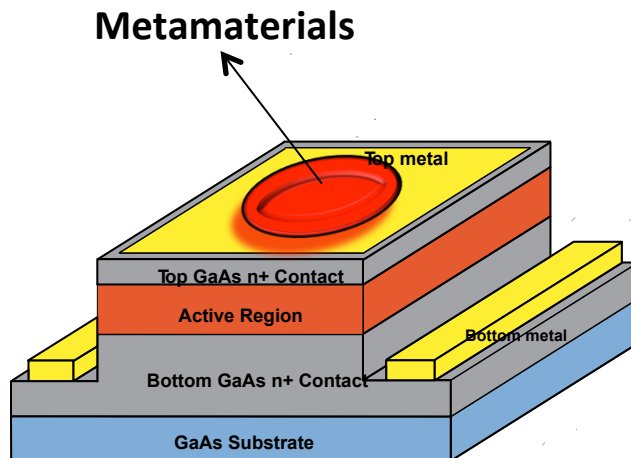
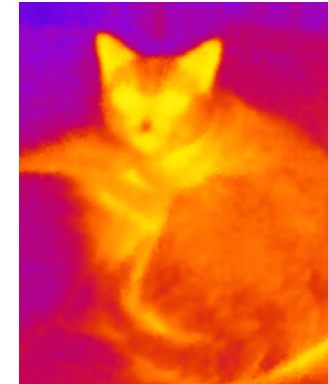
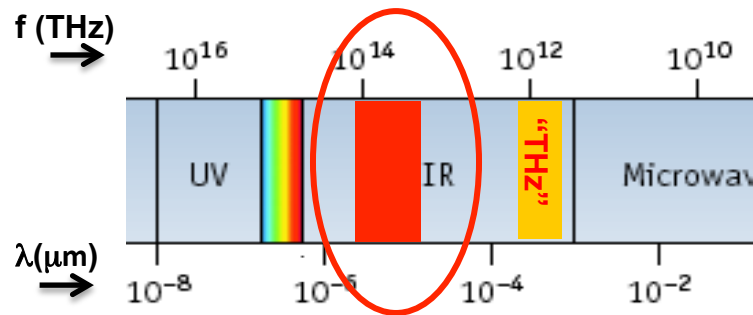
Diffraction: off axis ($\theta > 0$)



Rice, Sandia & Los Alamos



Metasurfaces for Improved Infrared Detectors

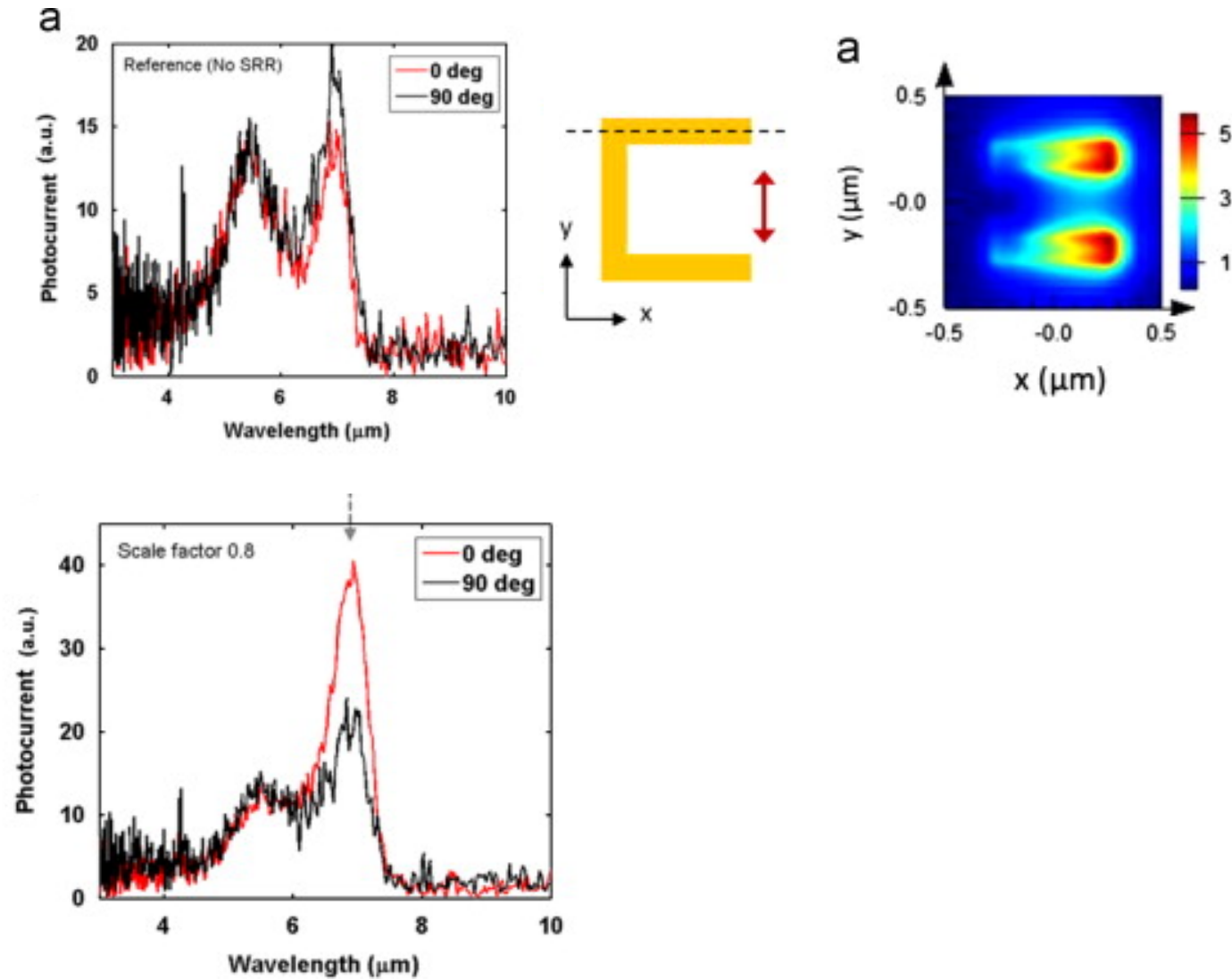


UNM & Sandia

Optics Communications 312 (2014) 31–34



Improved IR Responsivity





Interlude.....

What is a mirror?



“Regular” mirrors invert the phase of the reflected wave

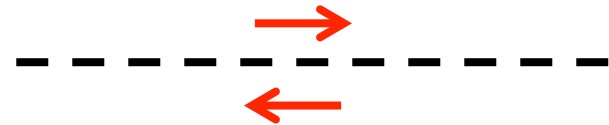


Dipoles Close to Surfaces

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)

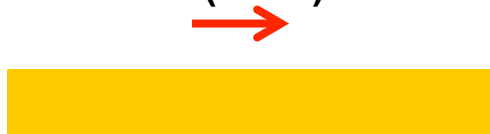
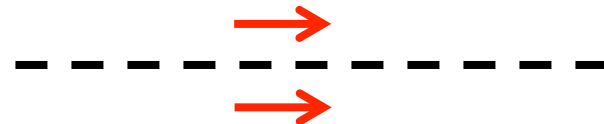


IMAGE THEORY



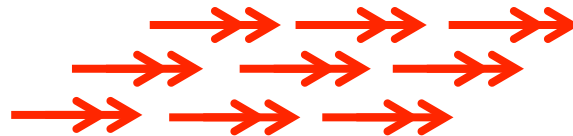
- This means that the radiation of an electric dipole on a PMC is enhanced



Magnetic Dipoles

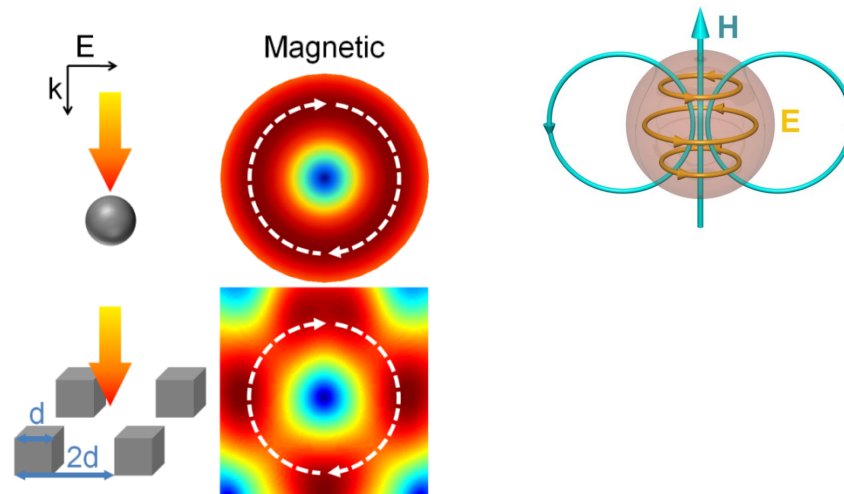
However, a perfect magnetic conductor does not exist in nature

Array of magnetic dipoles



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

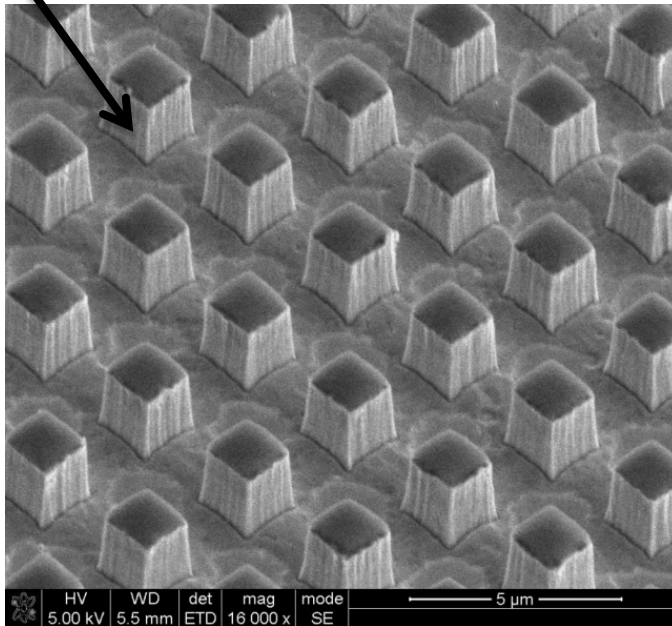
Dielectric Spheres



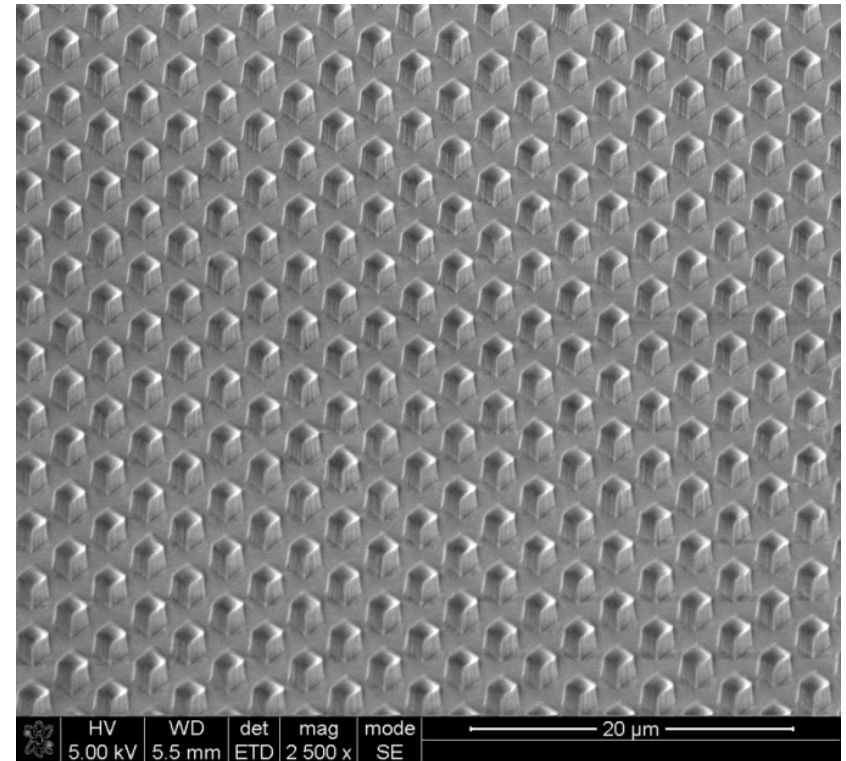


Optical Magnetic Mirror

Tellurium
 $n \sim 5$ in the IR



$1.53 \times 1.53 \times 1.7 \mu\text{m}^3$

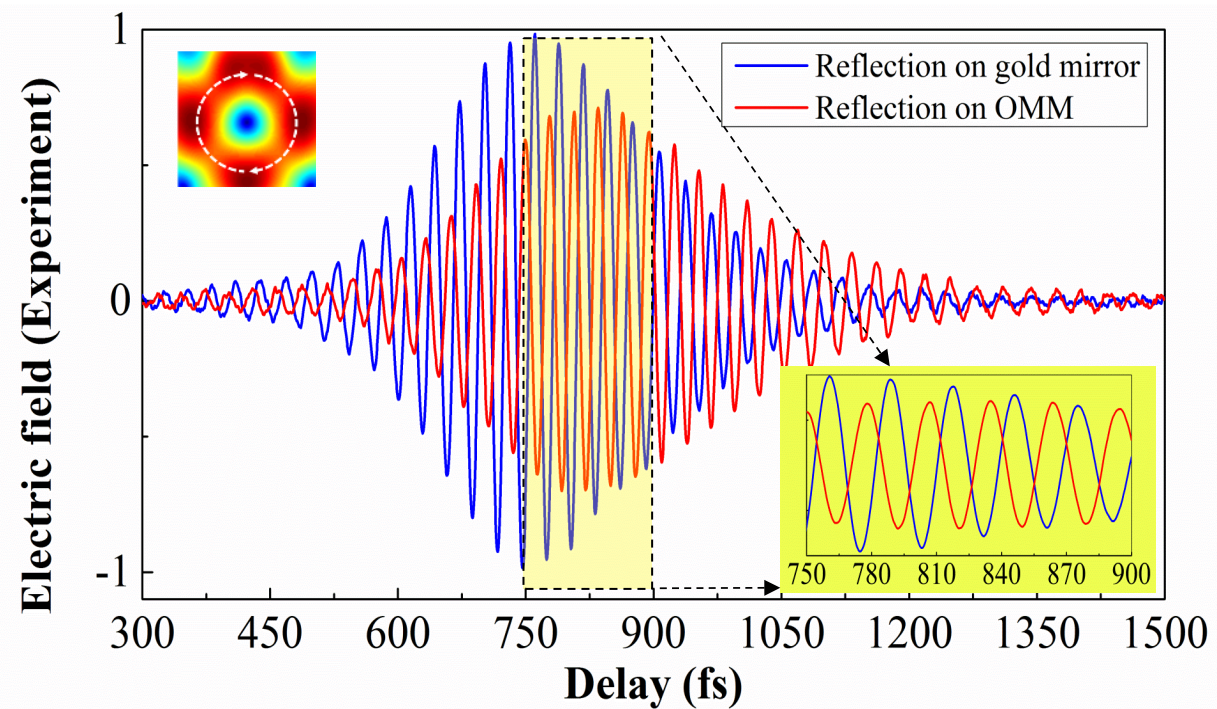
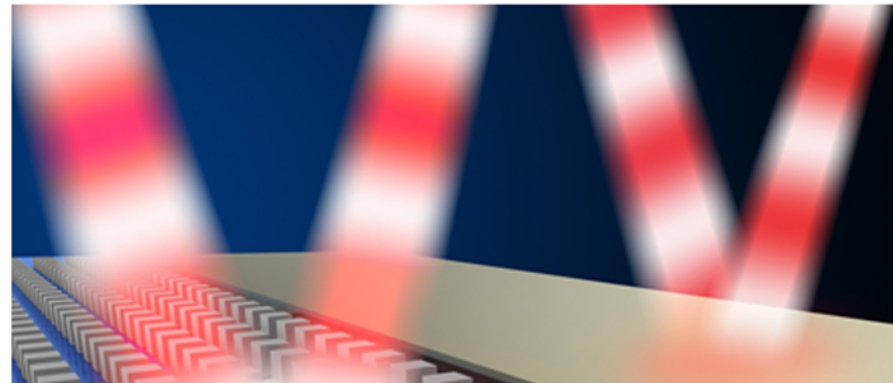


A Metasurface (dielectric)



Optical Magnetic Mirror

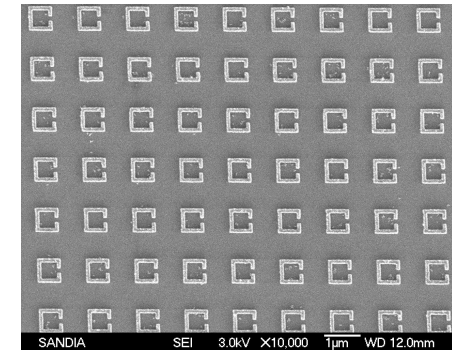
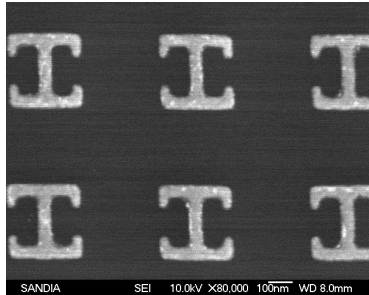
Measure Absolute Phase of Reflected Wave



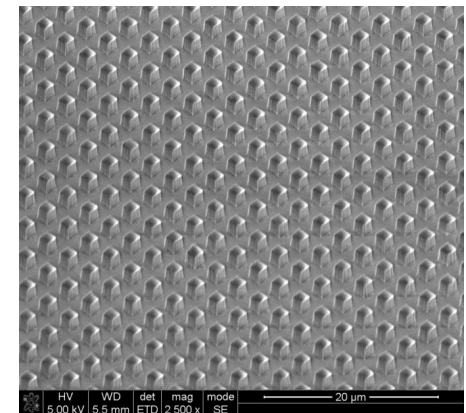
Measured at $\lambda \sim 9\mu\text{m}$



Summary



- Introduction: metamaterials, 3D, 2D, etc.
- Metasurfaces I: some terahertz devices
- Metasurfaces II: enhanced IR detectors
- Metasurfaces III: a “magnetic mirror”





Acknowledgments

Current Postdocs: Salvo Campione, Omri Wolf, Sheng Liu

Departed Postdocs: Alex Benz, Young-Chul Jun, James Ginn, Alon Gabbay, Brandon Passmore, Daniel Bender

CINT + Sandia: John Reno, Mike Sinclair, Ines Montano, John Klem, Eric Shaner, Mike Wanke, Joel Wendt, Paul Clem, Jon Ihlefeld, Bruce Burckel, Jason Domingues, Andy Allerman, Jon Wierer,

Rice: D. Mittleman, W. Chan, N. Karl,

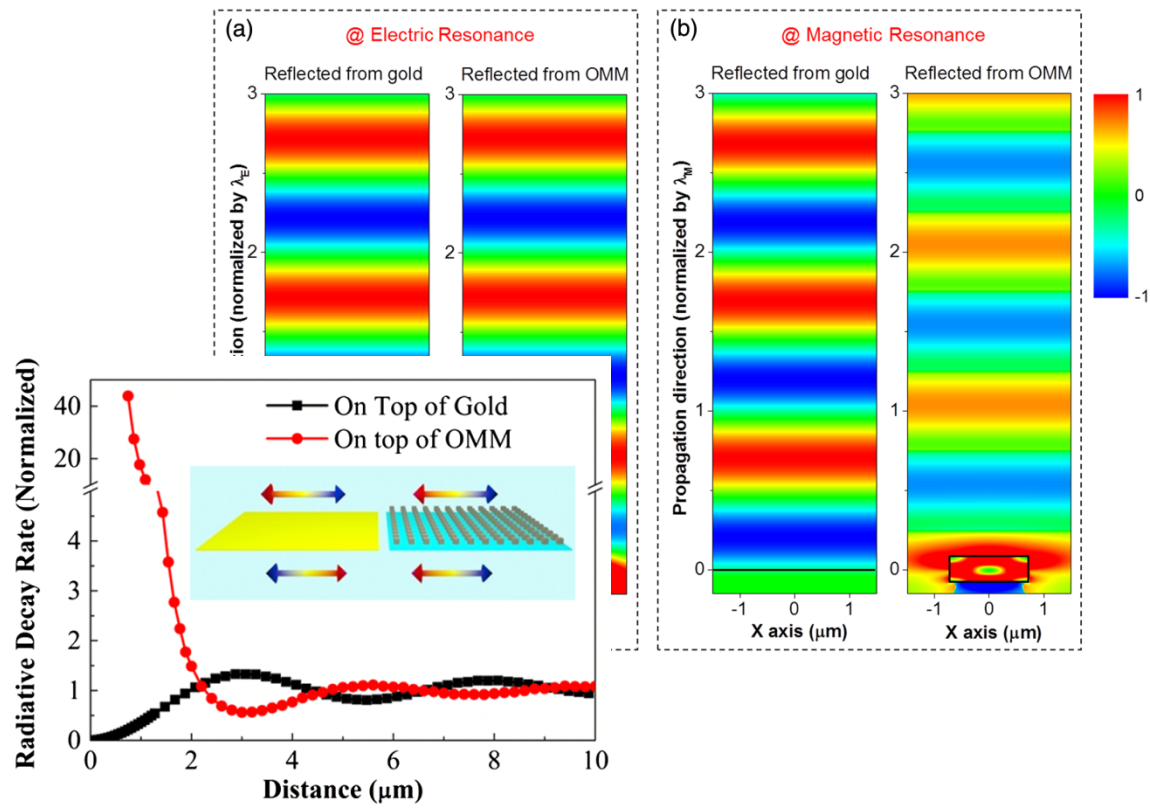
LANL: H. Chen, T. Taylor....

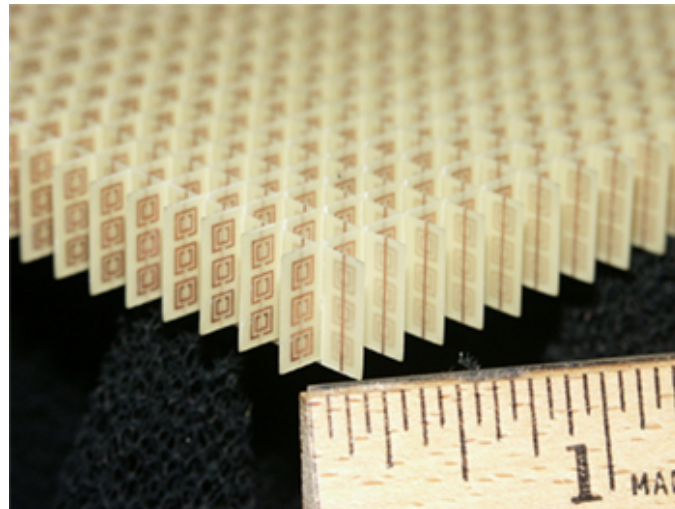
UNM: S. Krishna



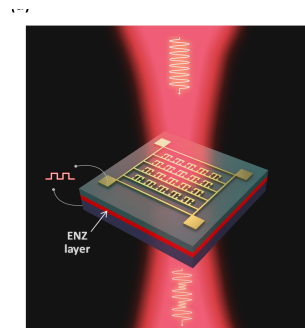
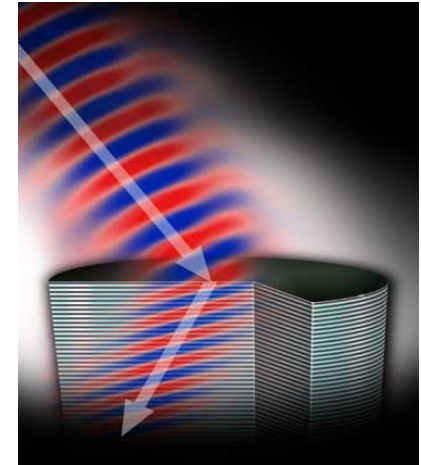
U.S. DEPARTMENT OF
ENERGY

Office of
Science



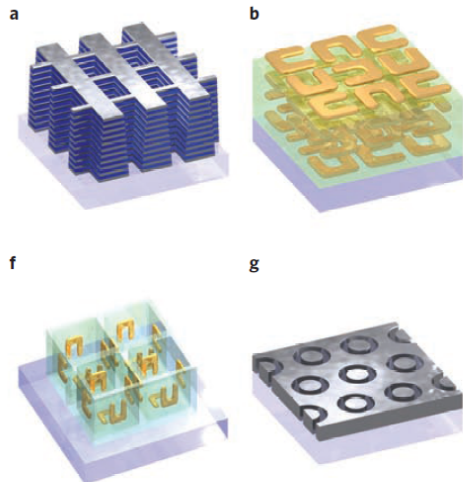


NASA Glenn Research

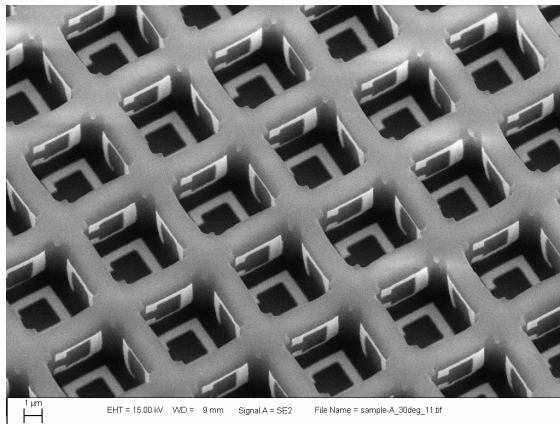




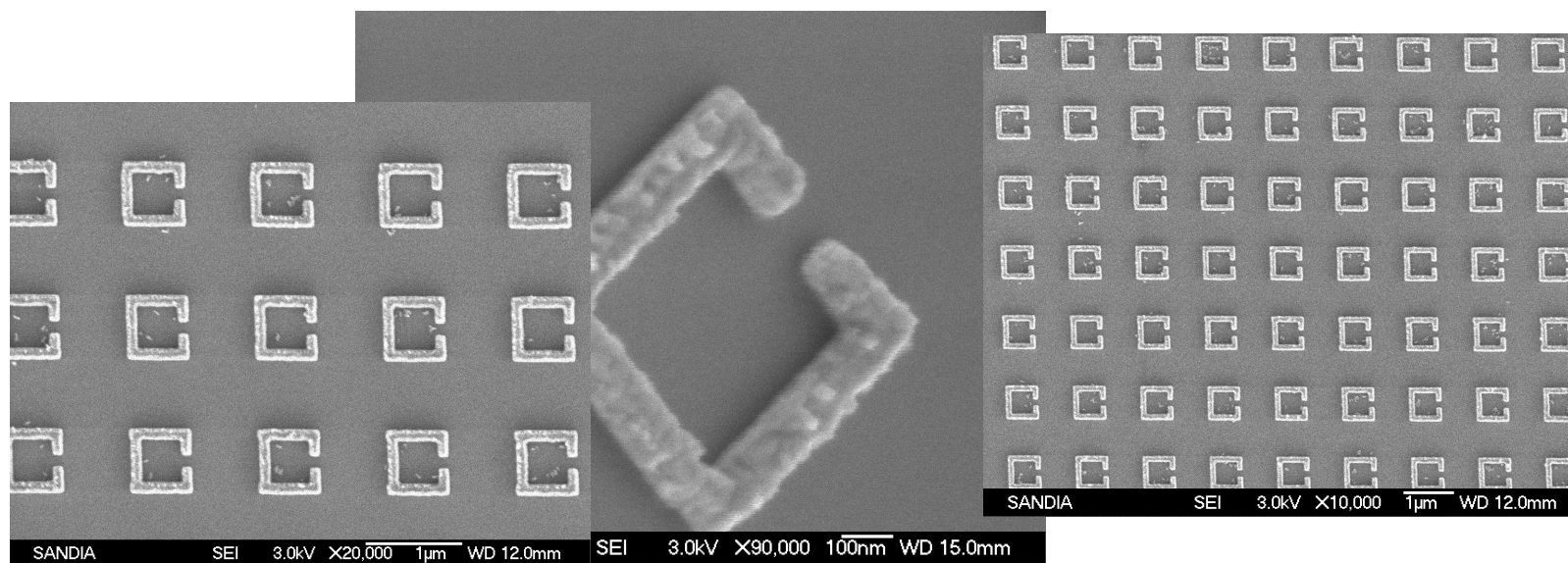
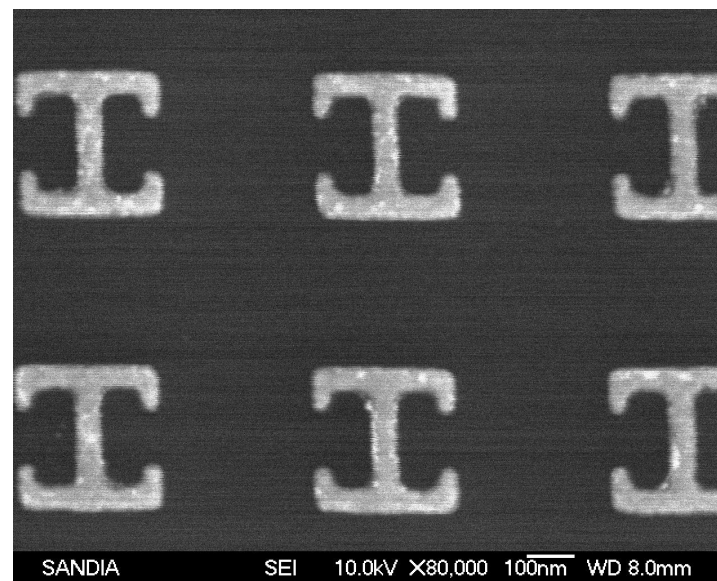
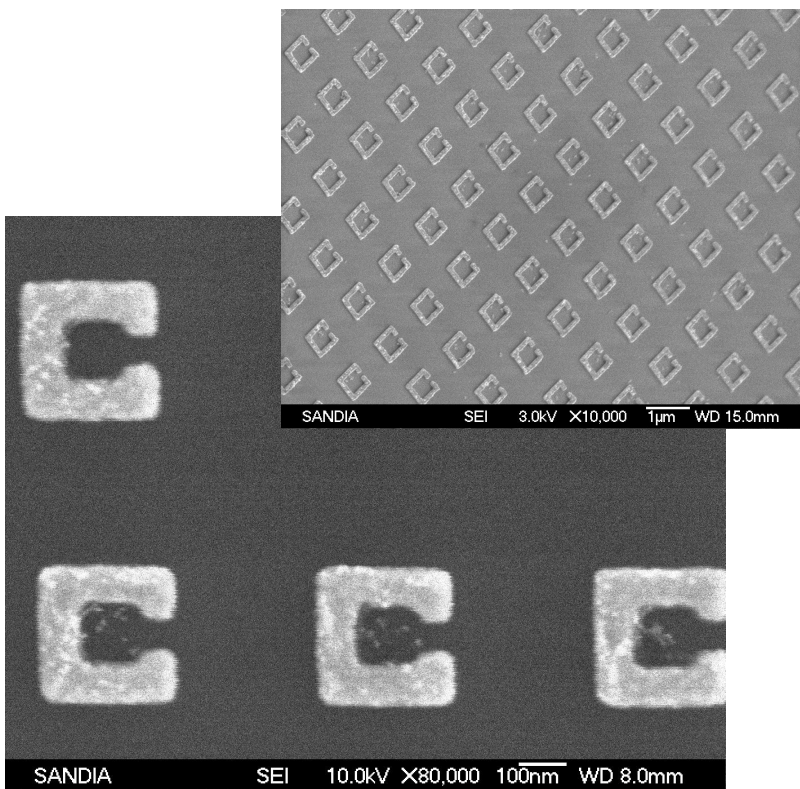
How to Scale This to Shorter Wavelengths?



Soukoulis & Wegener, Nature Photonics (2011)

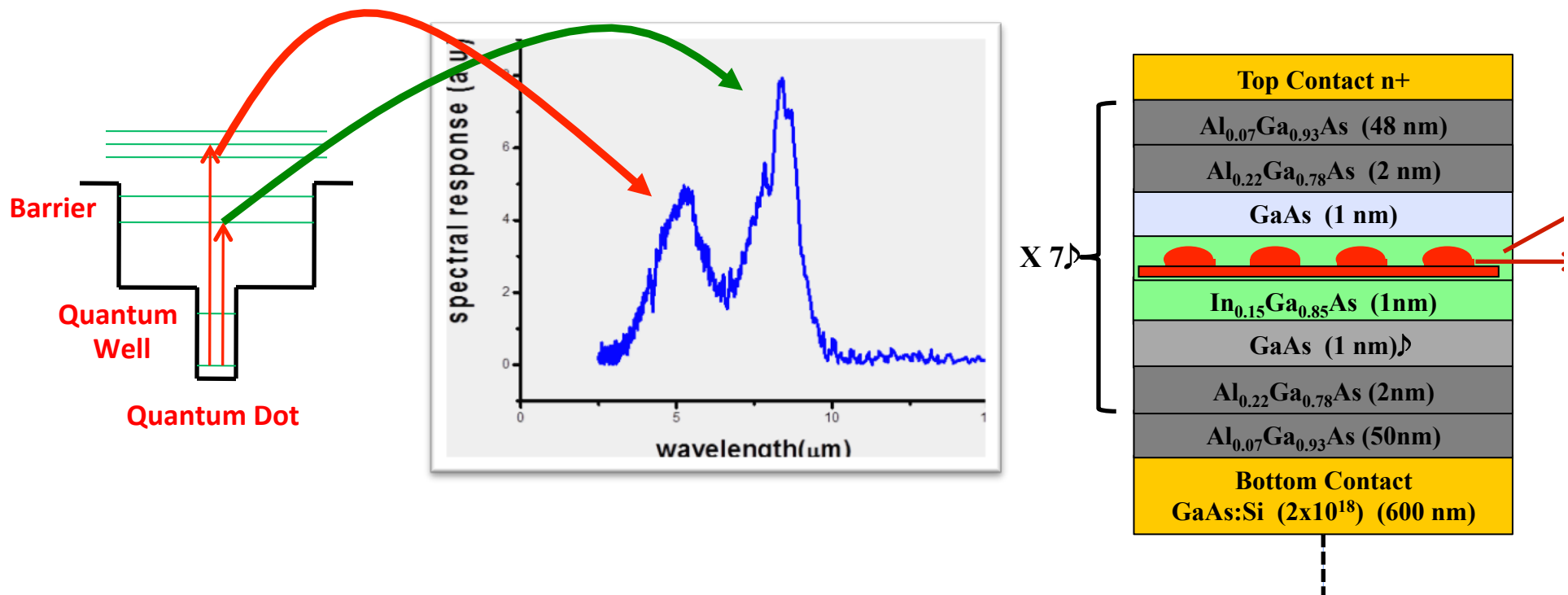


Burckel *et al*, Advanced Materials 2010



Using Epitaxial QDs for MM tuning

- Quantum dots (InAs) embedded in a quantum well (GaAs)
- In-plane selection rules for Intersubband Transitions are RELAXED



(with S. Krishna-UNM)



Diffraction: off axis ($\theta > 0$)

On-resonance signal vs. angle

