SAND2016-5452C

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

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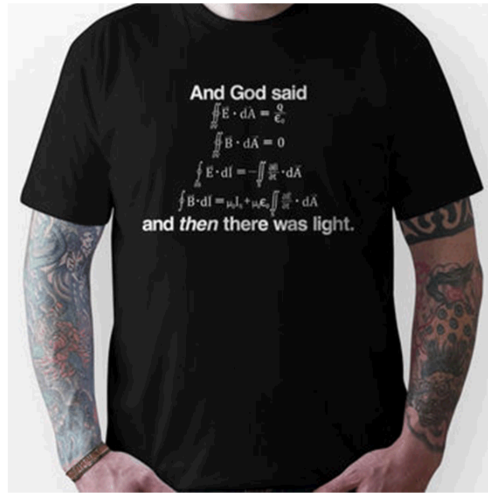
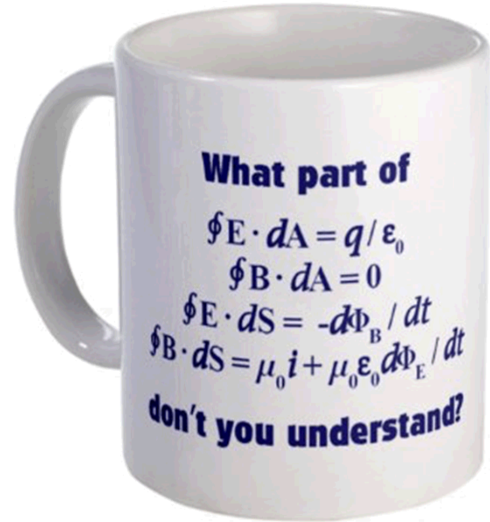
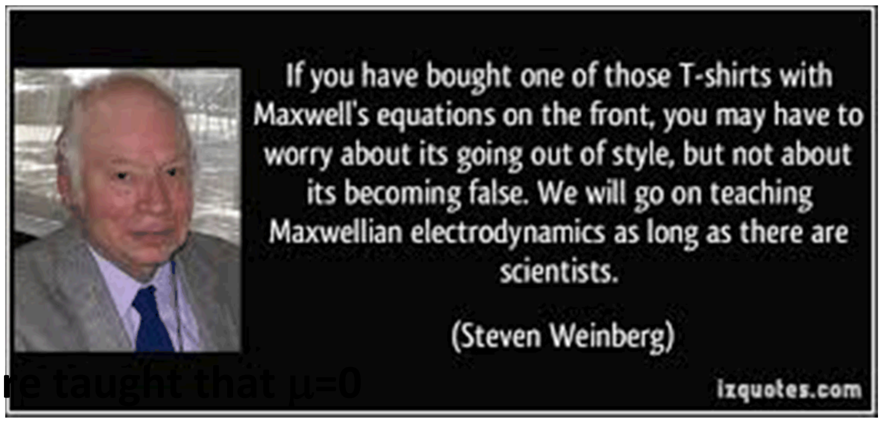




$$\nabla \cdot \mathbf{D} = \rho$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

$D = \varepsilon E$

$B = \mu H$



We were taught that μ=0

What if ε and μ can take any value and/or depend on the local coordinates?

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

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

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:

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

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

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

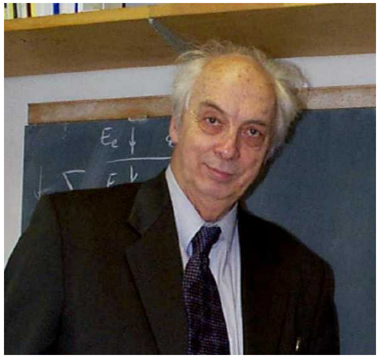
If we do not take losses into account and regard n, ϵ, and μ as real numbers, it can be seen from (2) and

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

$$n^2 = \varepsilon\mu$$

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

Viktor G. Veselago



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

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

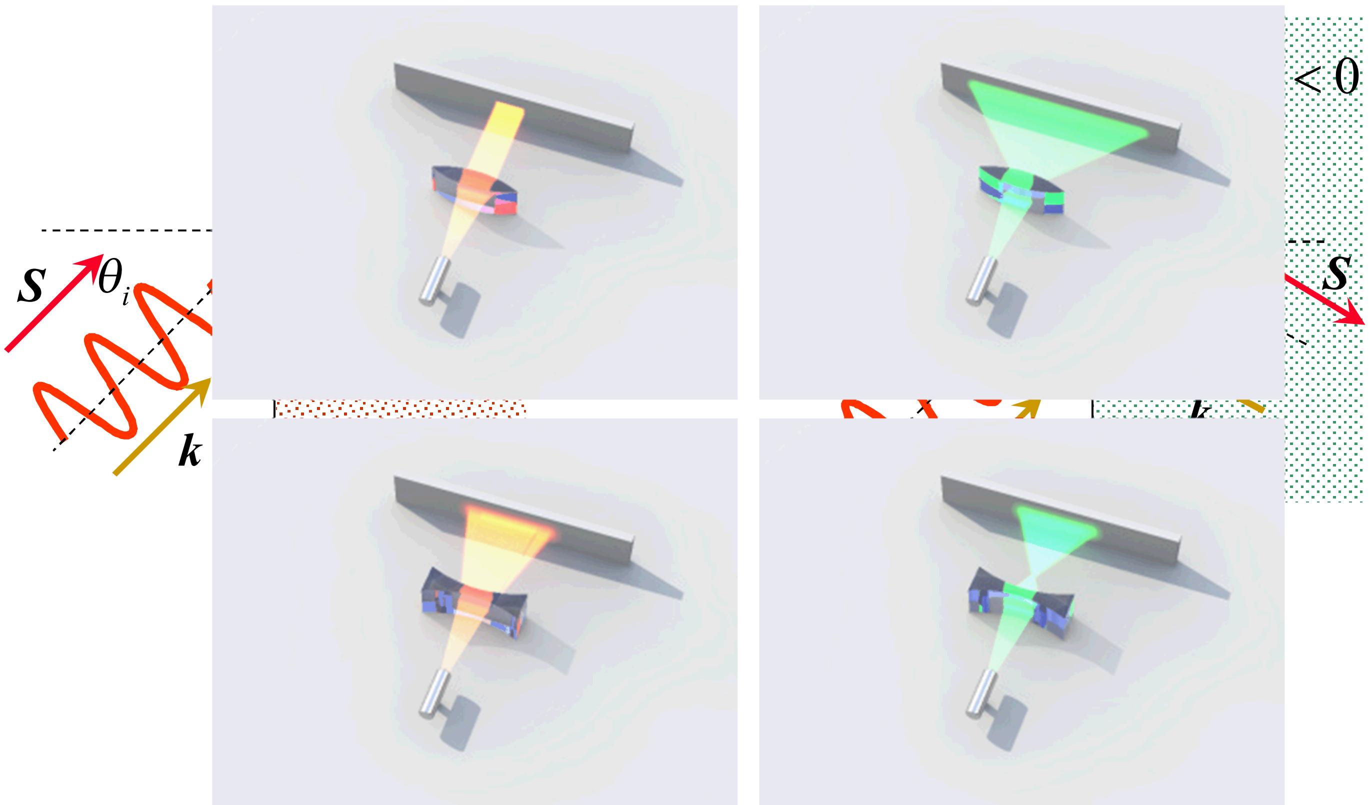
If $\varepsilon<0$ and $\mu<0$ *simultaneously,* from considerations of wave propagation, *n needs to be negative*

Excellent Review: Science 305 (2004)

Negative Refraction

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

(Courtesy, N. Enghetta)



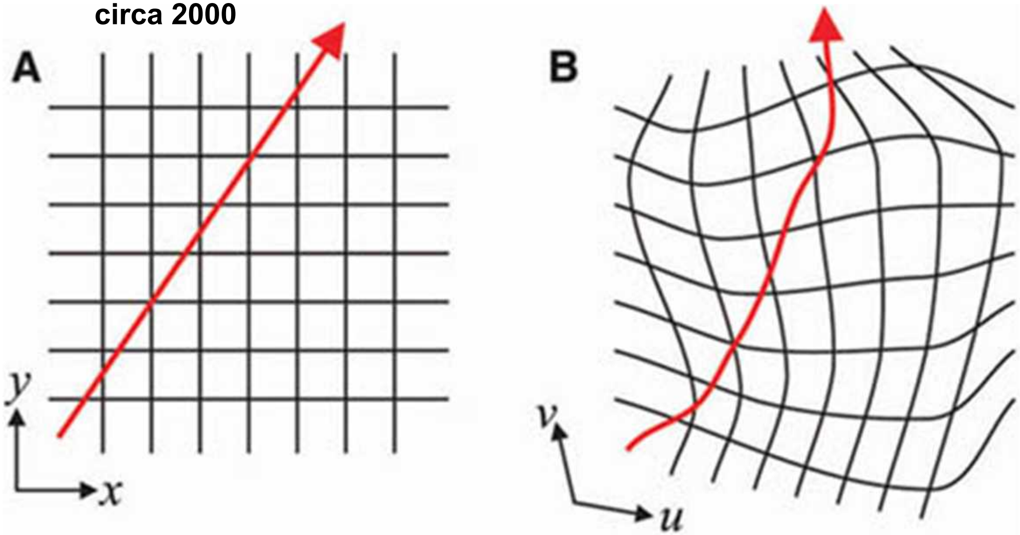
positive index of refraction

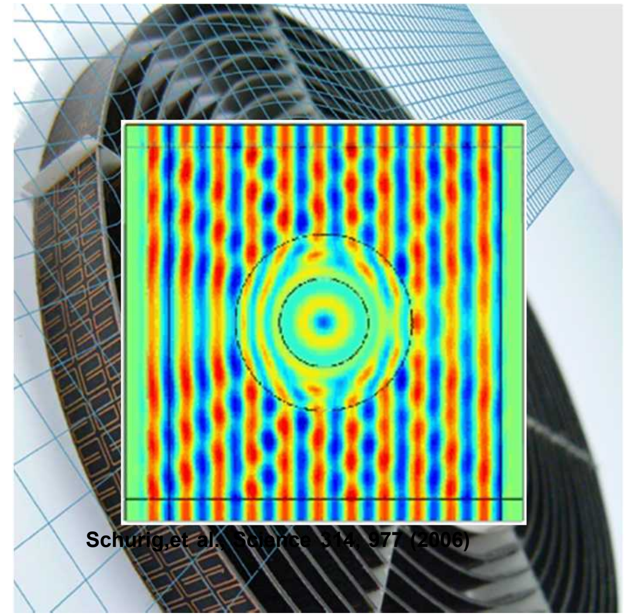
negative index of refraction

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

“Transformation Optics”

Sir John Pendry
circa 2000

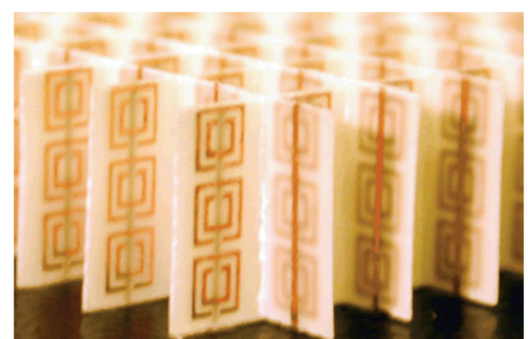




David Smith, Duke

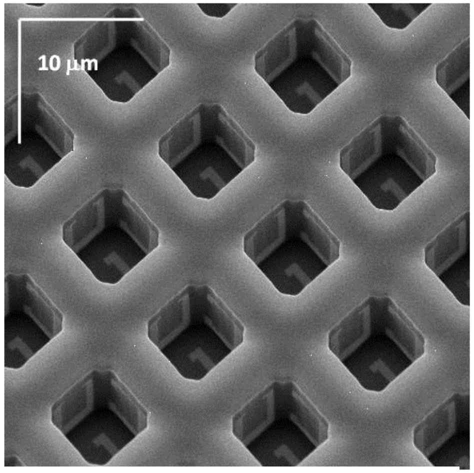
- For **RF** (~3GHz), λ~cm
- We need to create sub-wavelength “inductors” and “capacitors”

~cm’s

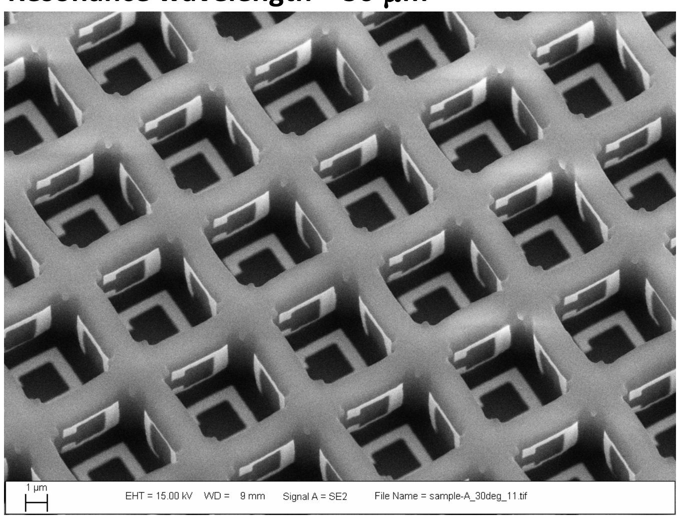


http://www.multitel.be/newsletter/mn72005/images/nl3_Metamaterials_type1.jpg

3D Optical MMs: Membrane Projection Lithography

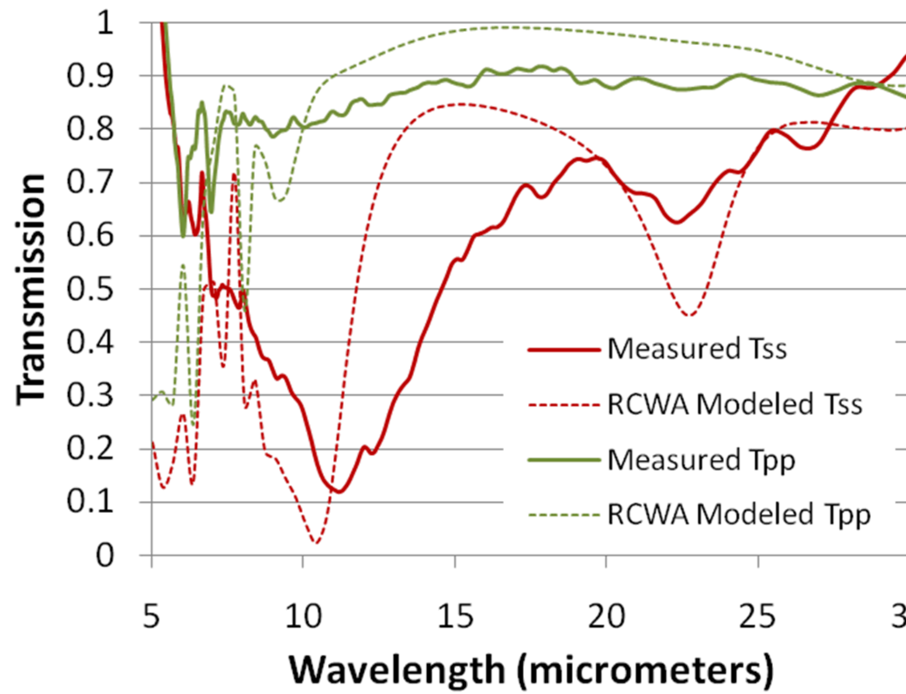


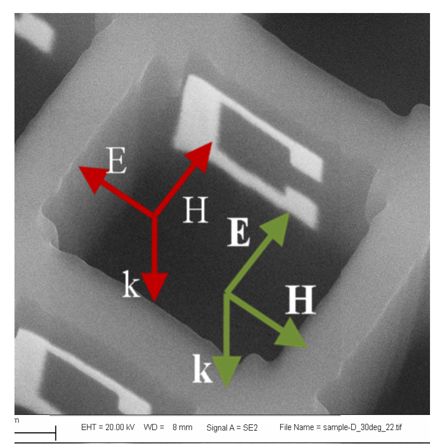
- ➢Unit Cell Dimension = 14 μm pitch
- ➢SRR Dimension = 8 μm
- ➢Resonance wavelength ~ 50 μm



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

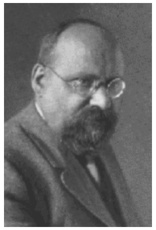
Advanced Materials, 22: 5053–5057 (2010)





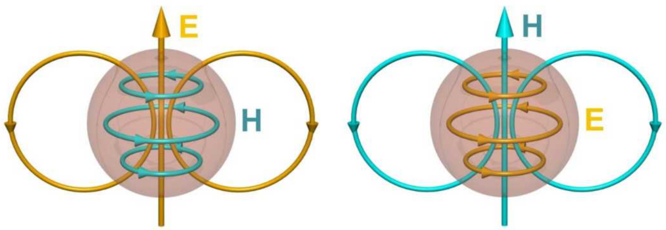
A Non-Metallic Path to Low Loss Metamaterials: Dielectric Resonators

Gustav Mie



Magnetic dipole resonance: tailor μ

Electric dipole resonance: tailor ε



Images: A. Miroshnichenko

3. *Zur Optik kolloidaler Metallösungen;*
von R. Gans und H. Happel.

Annalen der Physik, 1909

Setzen wir (40′), (41) und (43) in die Gleichungen (44) und (45) ein, so ergibt sich die komplexe Dielektrizitätskonstante und Permeabilität der kolloidalen Lösung

$$\varepsilon = \varepsilon_0 \frac{1 + \frac{4\pi N}{3}\left(\frac{\lambda'}{2\pi}\right)^3 (a_1 - a_2)}{1 - \frac{2\pi N}{3}\left(\frac{\lambda'}{2\pi}\right)^3 (a_1 - a_2)}, \quad (46)$$

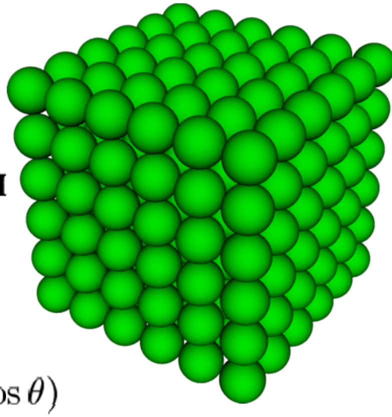
$$\mu = \frac{1 - \frac{4\pi N}{3}\left(\frac{\lambda'}{2\pi}\right)^3 p_1}{1 + \frac{2\pi N}{3}\left(\frac{\lambda'}{2\pi}\right)^3 p_1}. \quad (47)$$

(Ack: Ed Kuester, CU Boulder)

RIAL LOADED WITH

RTICLES*

ed form 27th September, 1946.)



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

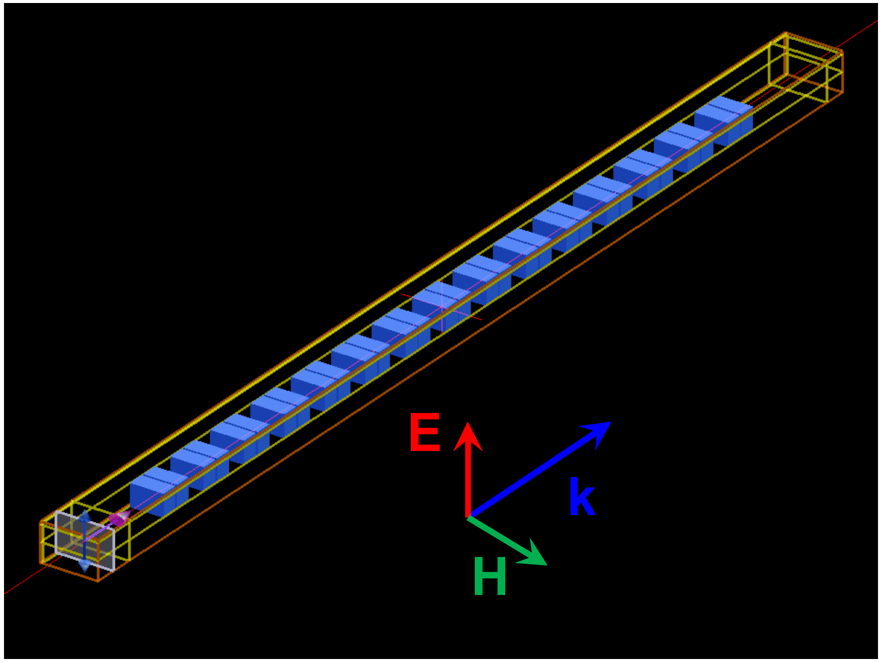
$$\theta = k_0 a\sqrt{\epsilon'_{r2}\mu'_{r2}}$$

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

Full Wave Simulation of Propagation Through Split Cube Array

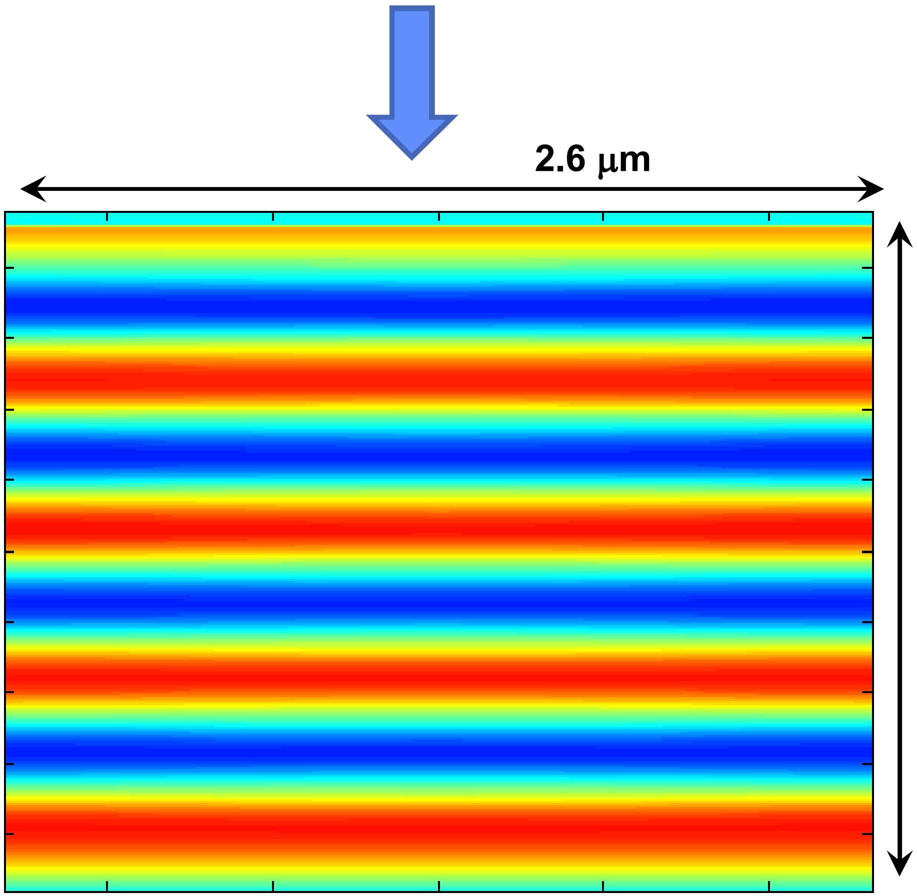
ε=32, edge = 1.53 μm, gap = 100 nm

Lumerical FDTD



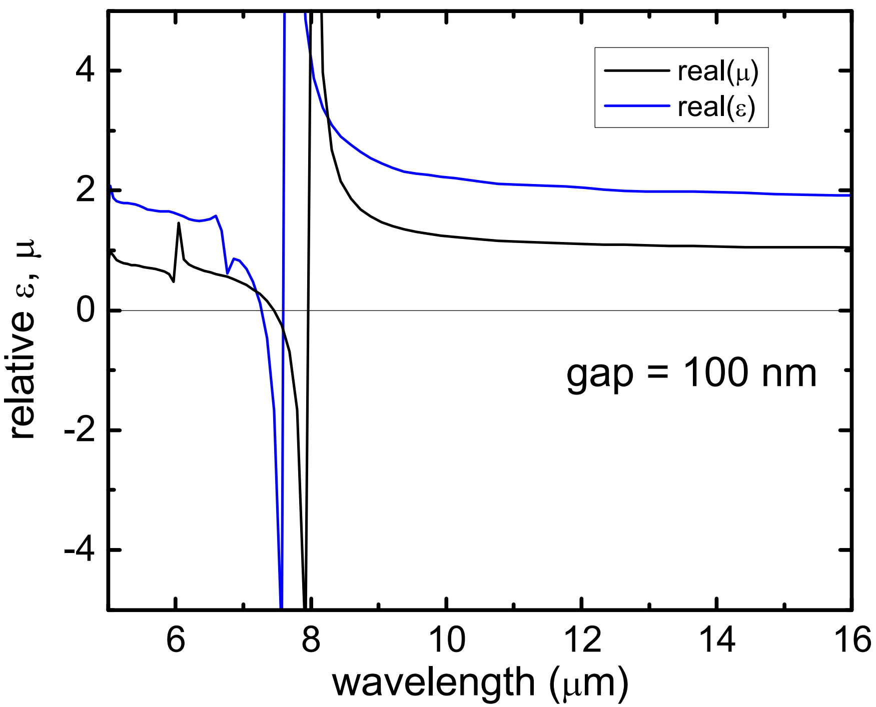
Periodic BC in x & z, 15 cubes thick in y

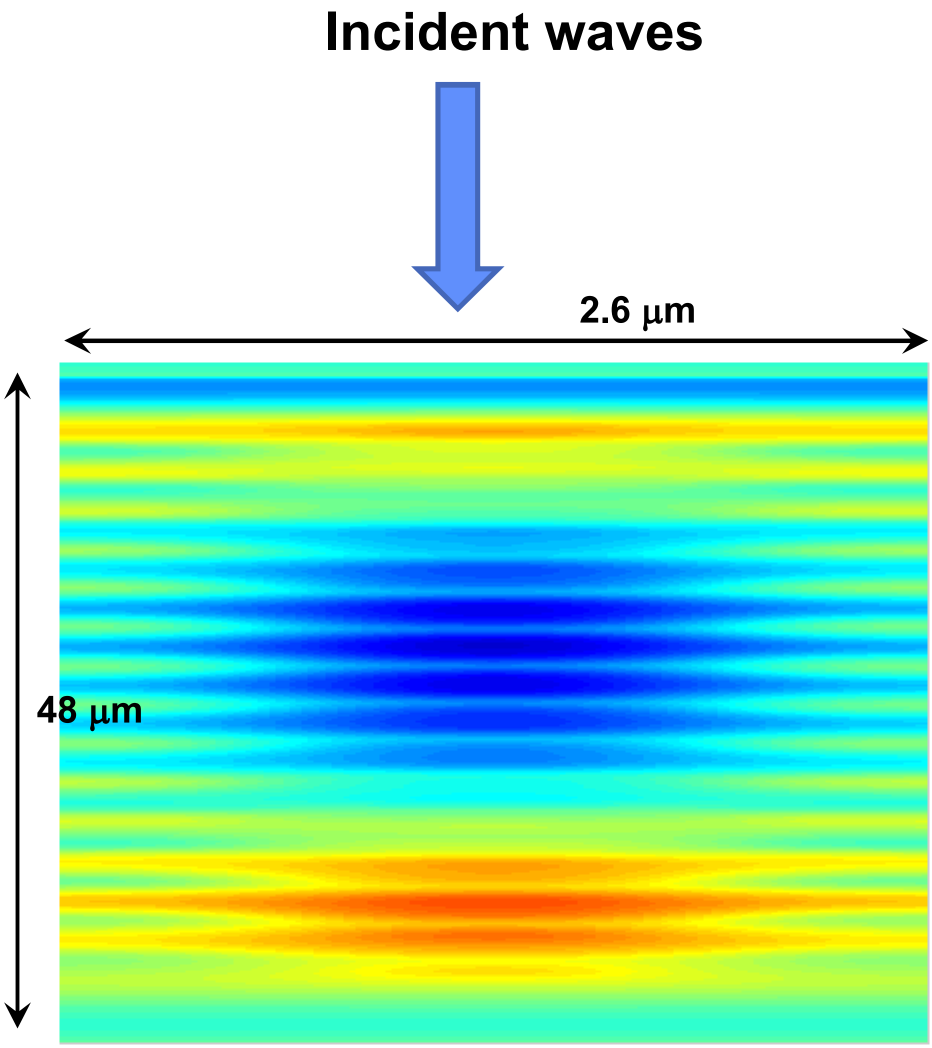
H_x at top of unit cell (z=1.3 μm)
Incident waves



λ = 15 μm

Magnetic Field Movie – 7.5 μm



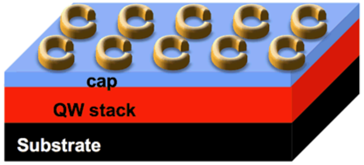


λ = 7.5 μm

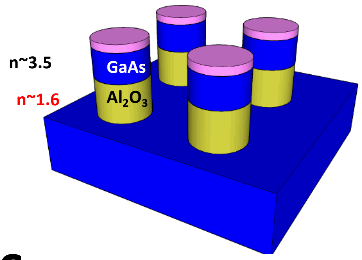
H_x at top of unit cell (z=1.3 μm)

Outline

- Tunable Metasurfaces: overview
- Control of Strong Coupling for tunable behavior
- Harmonic generation from metallic metasurfaces coupled to intersubband transitions in semiconductor quantum wells



- Optical Magnetic Mirrors



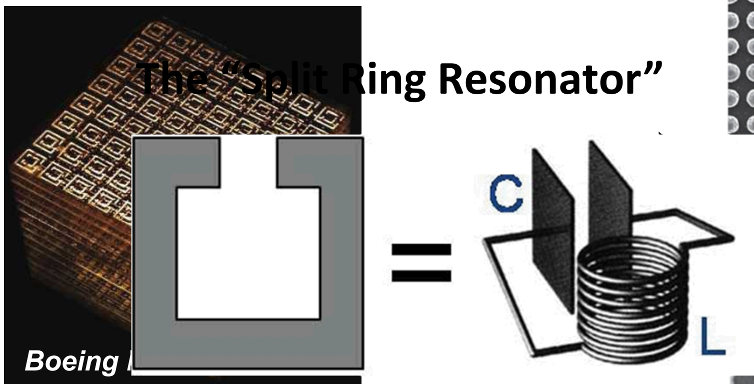
- Harmonic generation from all-dielectric metasurfaces

"Metasurfaces"

3D

2D

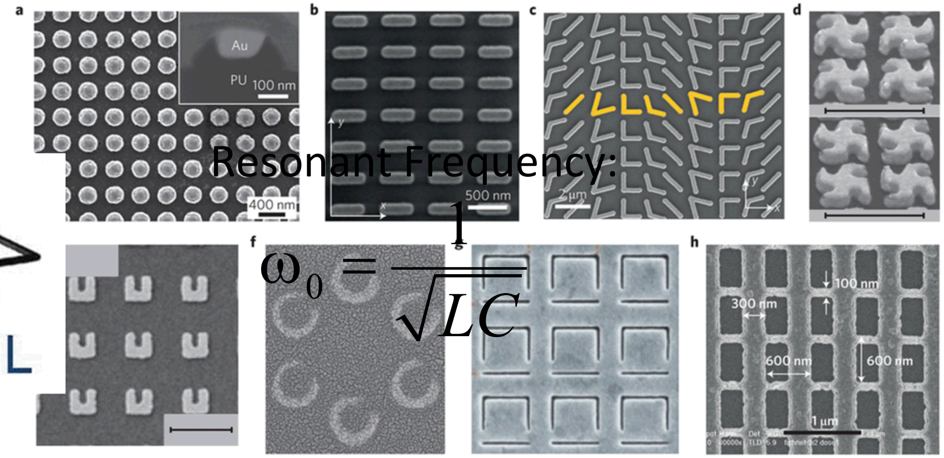
The "Split Ring Resonator"



(Bonn)

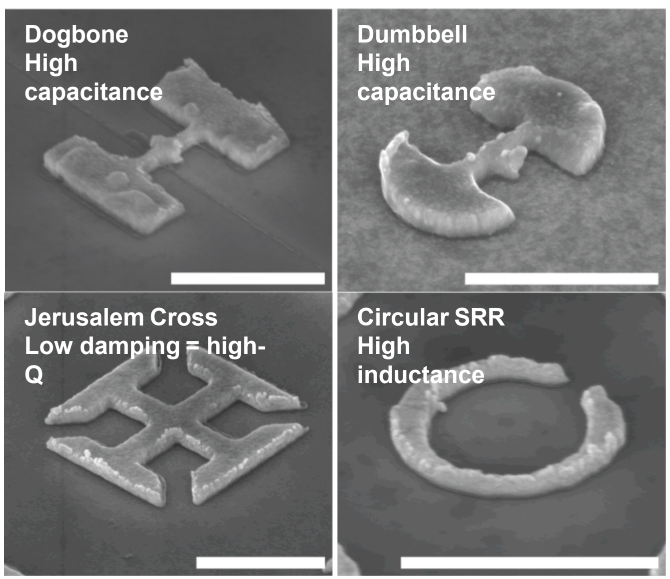
Resonant Frequency:

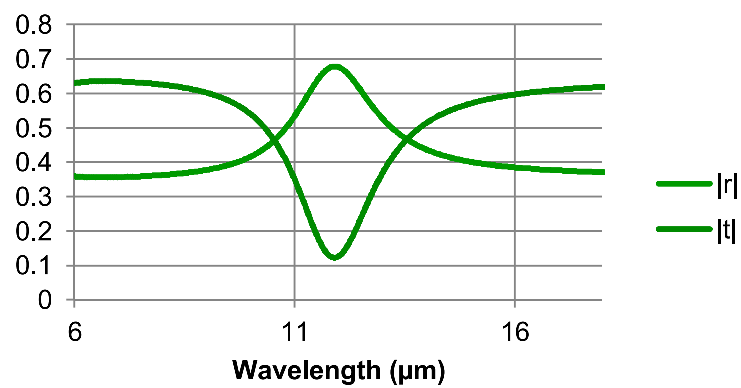
$$\omega_0 = \frac{1}{\sqrt{LC}}$$



***Nature Photonics* 8**, 889 (2014)

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





Optical Modulators, Tunable Filters

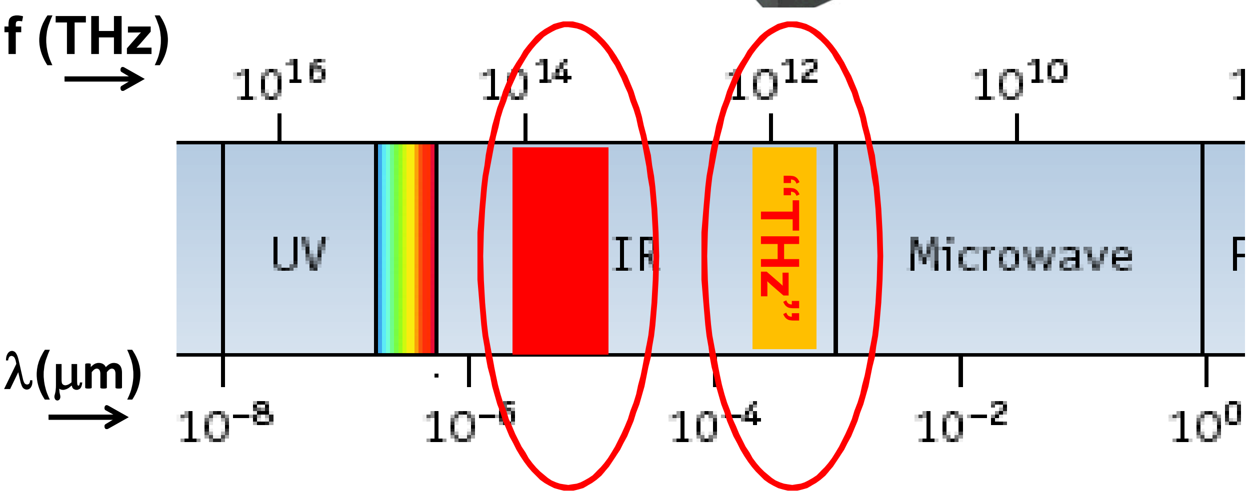
Optical Modulators, Thorlabs

Tunable Filters

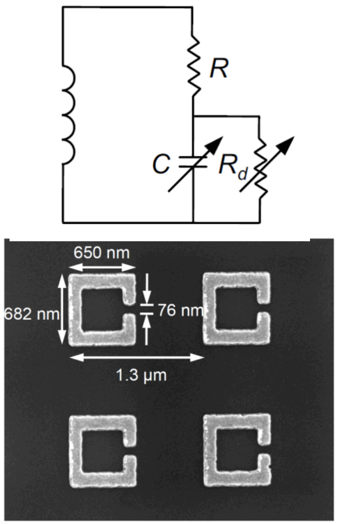
Microwave, Lorch

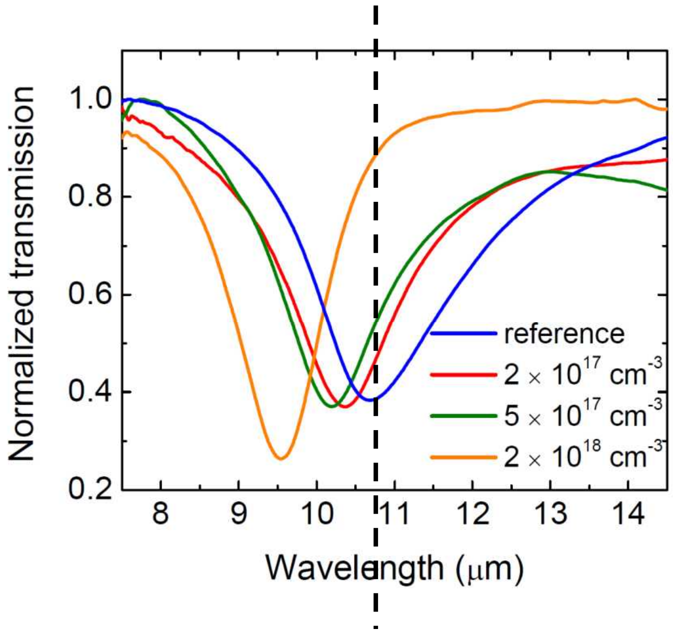
near-IR, Santec

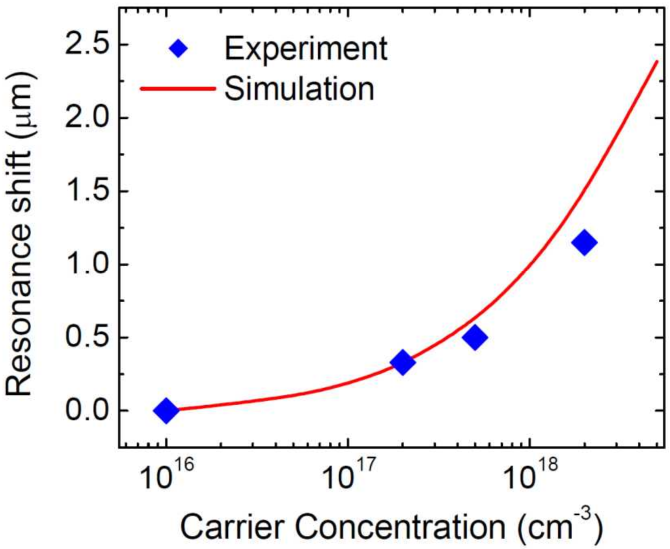
Spatial Light Modulator
Holoeye



Tuning Metasurfaces Using Semiconductors







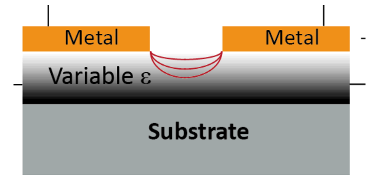
- **SRRs made on InSb substrates with different doping**
- **Experimentally observed doping dependent resonance**
  - ***A resonance shift of 1.15 um (1×10^{16} cm^{-3} → 2×10^{18} cm^{-3})***

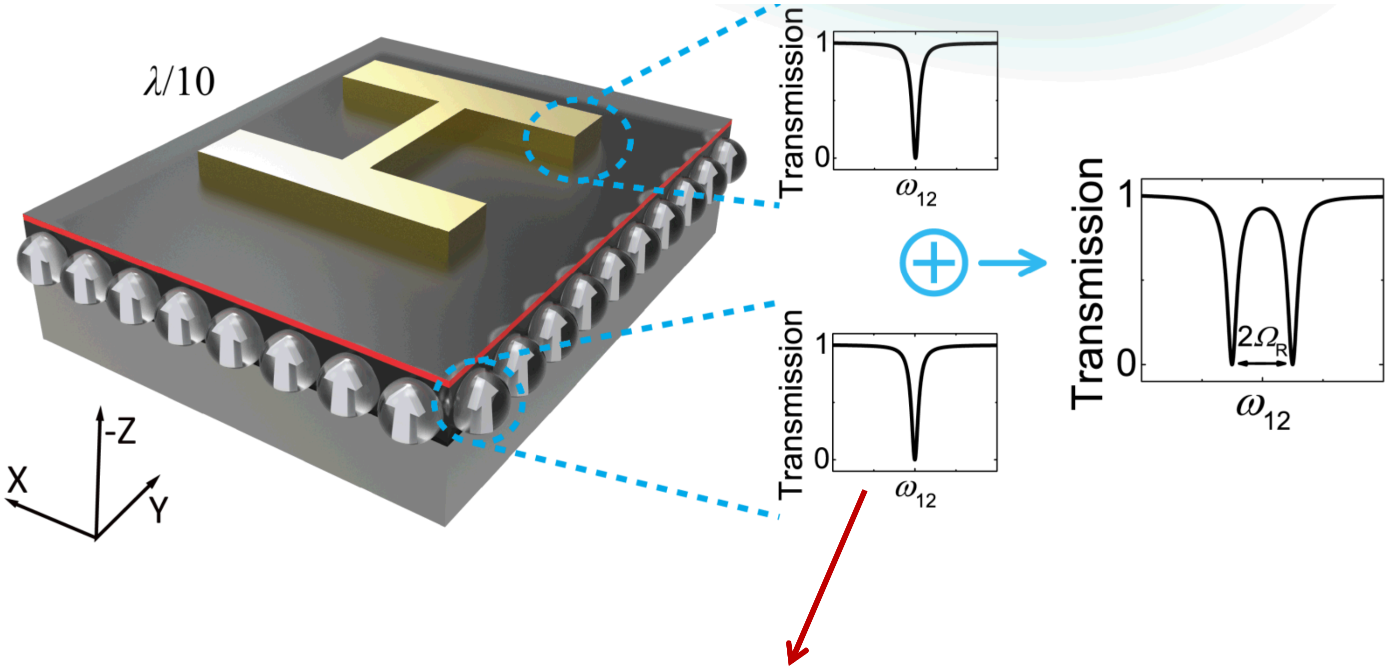
$$\Delta\lambda/\lambda \approx 10.8\%$$

APL 96, 1 2010

Controlled Coupling as Tuning Mechanism

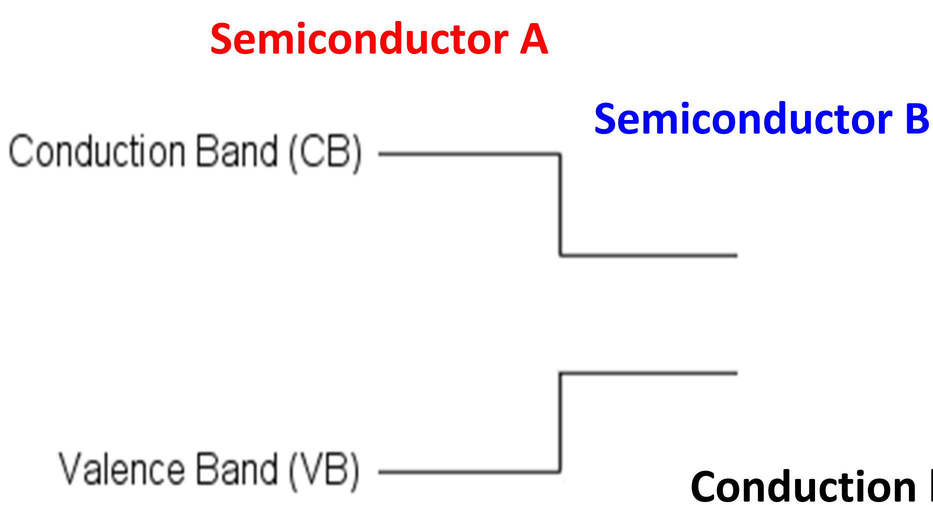
MM resonators create strong optical fields that lead to strong coupling

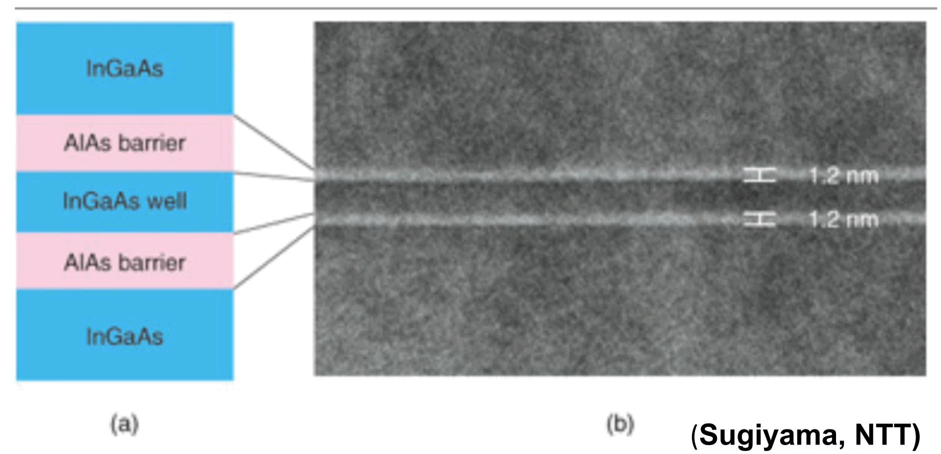




Optical Phonons: Nano Letters 11, 2104 (2011)
Intersubband Transitions: Nature Communications 4, (2013)
Epsilon Near Zero modes: Nano Letters 13, 5391 (2013)

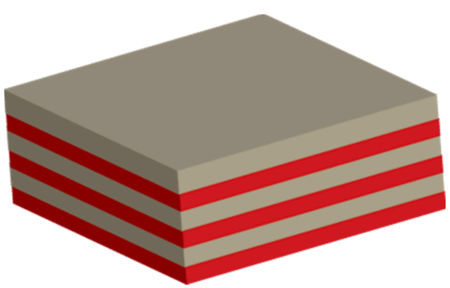
How to Create A Dipole Transition Using Semiconductor Heterostructures

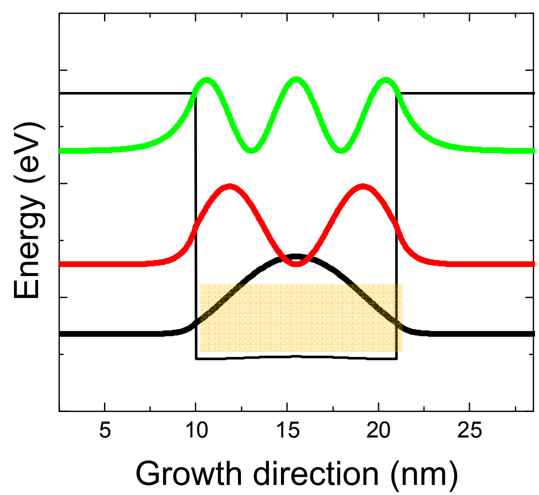




(Sugiyama, NTT)

Conduction band only
Electrons

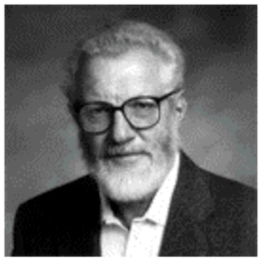




- **<u>Scalable</u> (far IR to near IR), <u>Mature, Versatile</u>**

Interlude 1: Semiconductor Heterostructures are all around us!

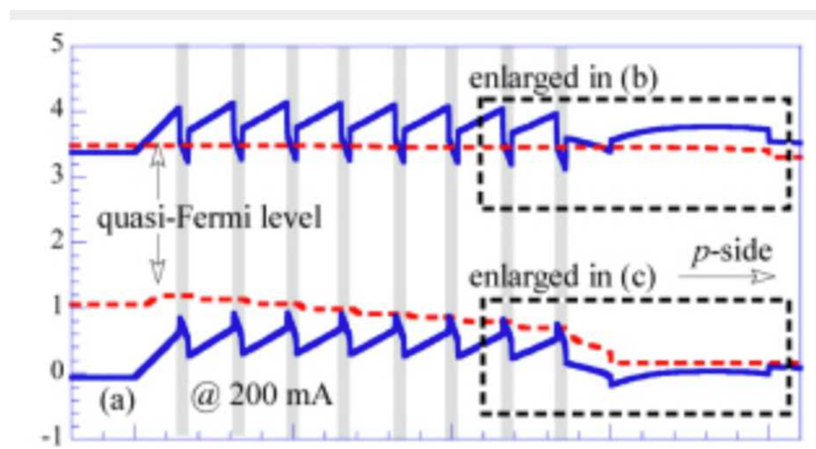
(or quantum mechanics in our daily lives)



Herbert Kroemer (1920-)
Nobel Prize 2000 for the Semiconductor Heterostructure Laser

- **Transistors in every modern chip**
- **All semiconductor lasers**
  - **DVD, Blue-ray**
  - **Every data channel in a fiber is driven by a semiconductor laser (cell phone calls need quantum mechanics)**
- **Every LED!**

Home Depot

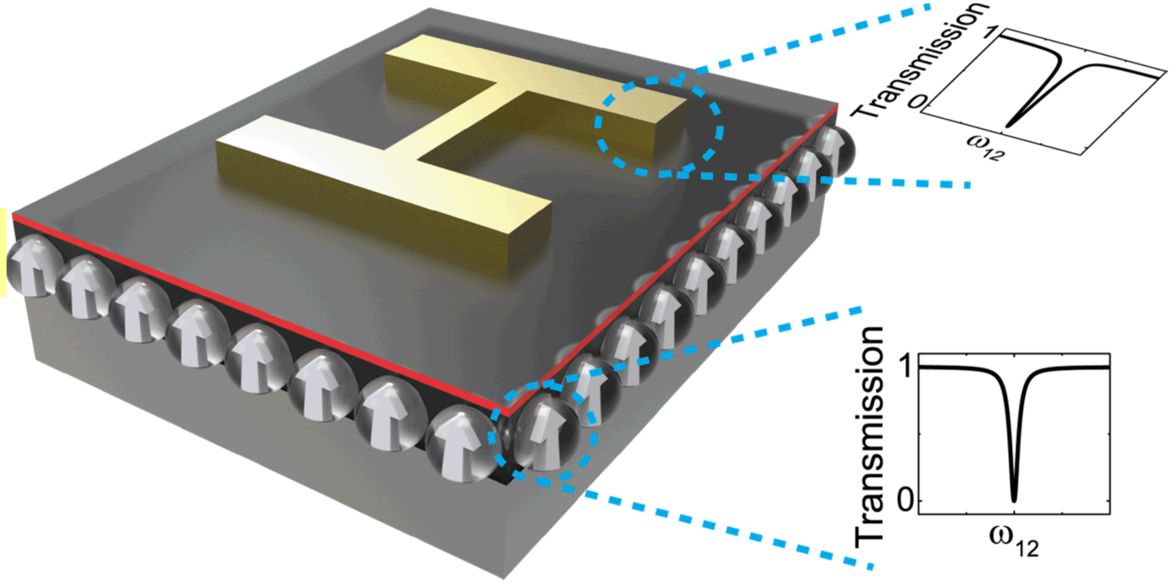


Opt. Exp. **22,** 463 (2014)

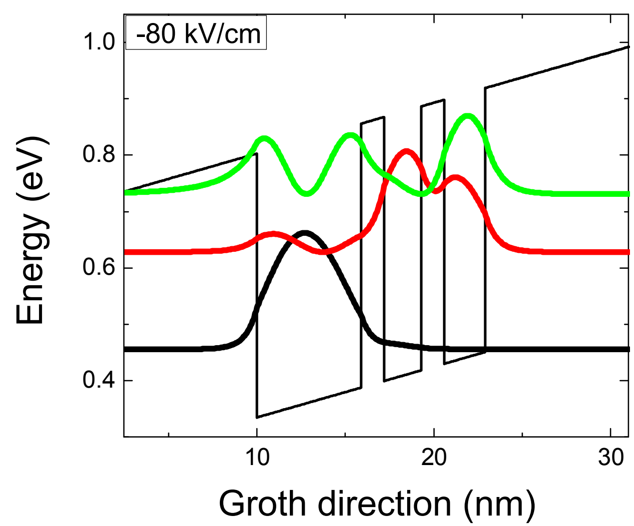
Strong Coupling to Intersubband Transitions in Quantum Wells

Alex Benz

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

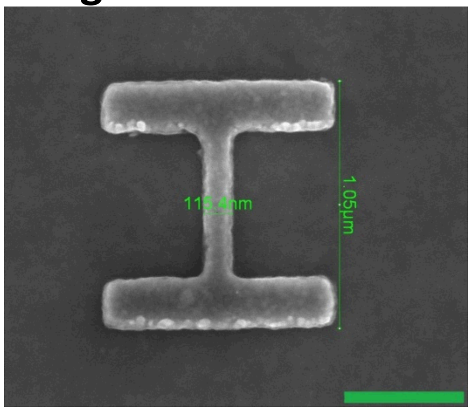


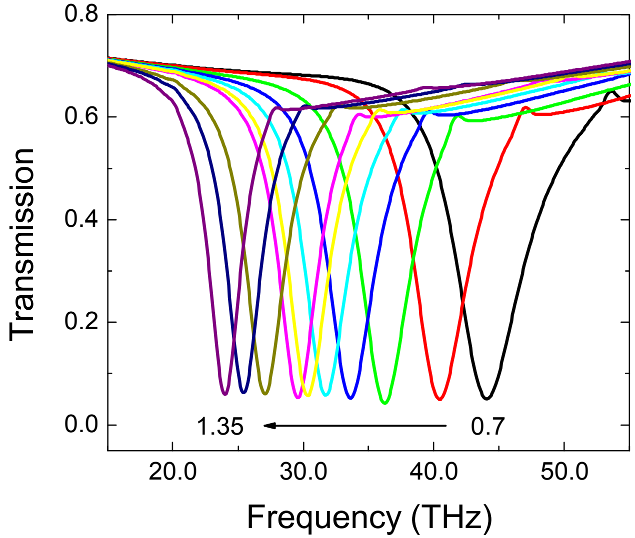
Tunable by changing levels using an electric field (voltage bias)

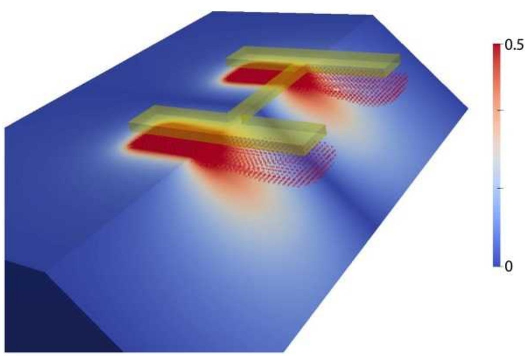


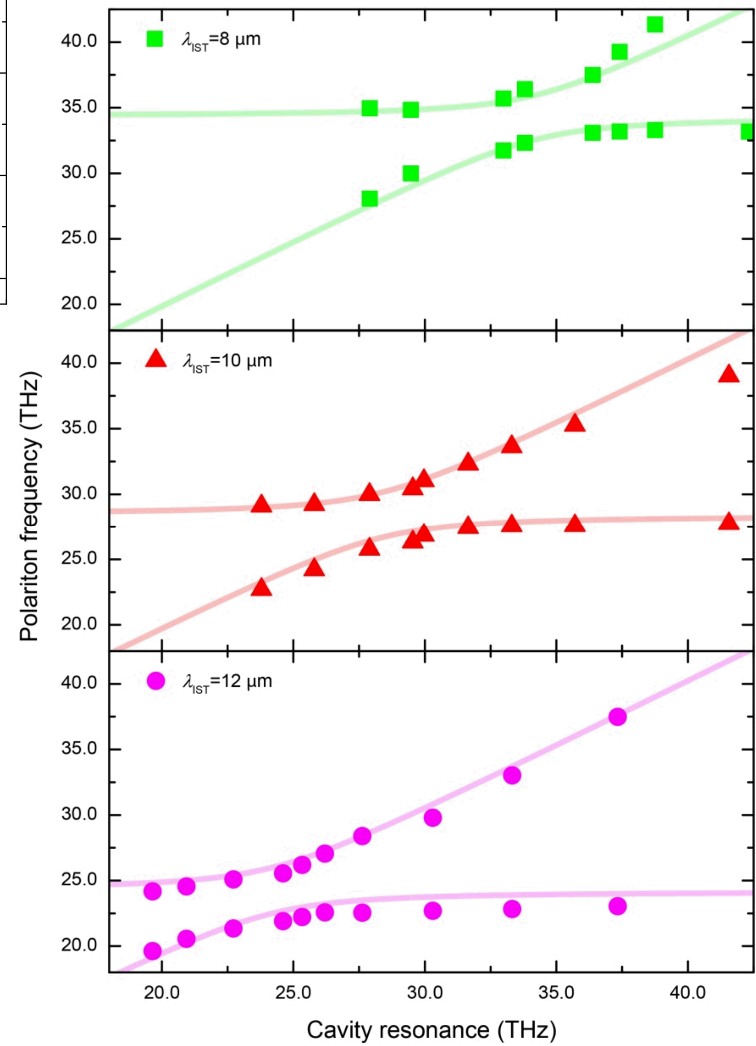
Strong Coupling Results

“Dogbone” resonators



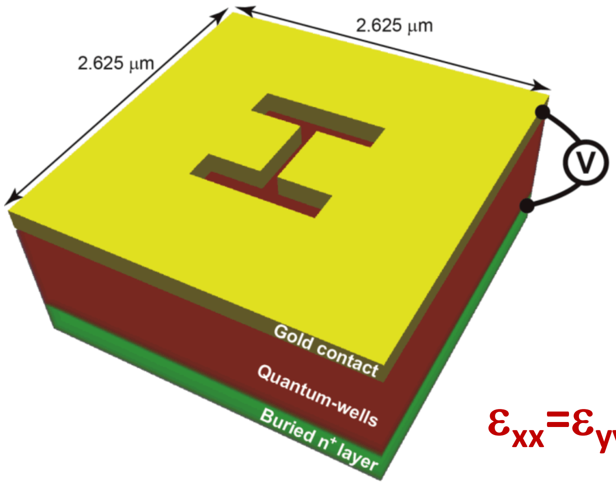




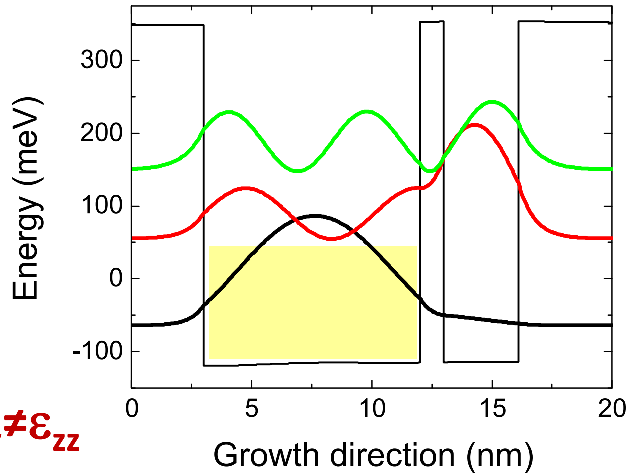


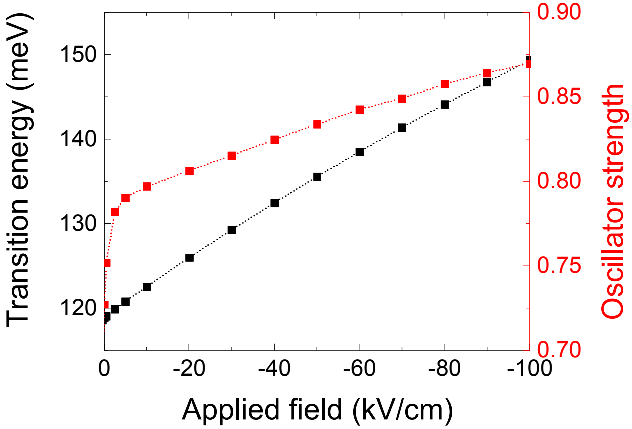
Nature Communications 4, (2013)
Phys. Rev. B 89, 165133 (2015)
Nanolett.15, 1959 (2015)

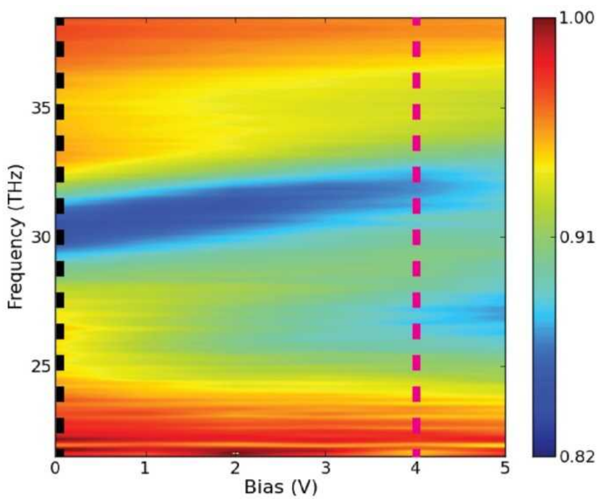
Electrically Tunable Strong Coupling

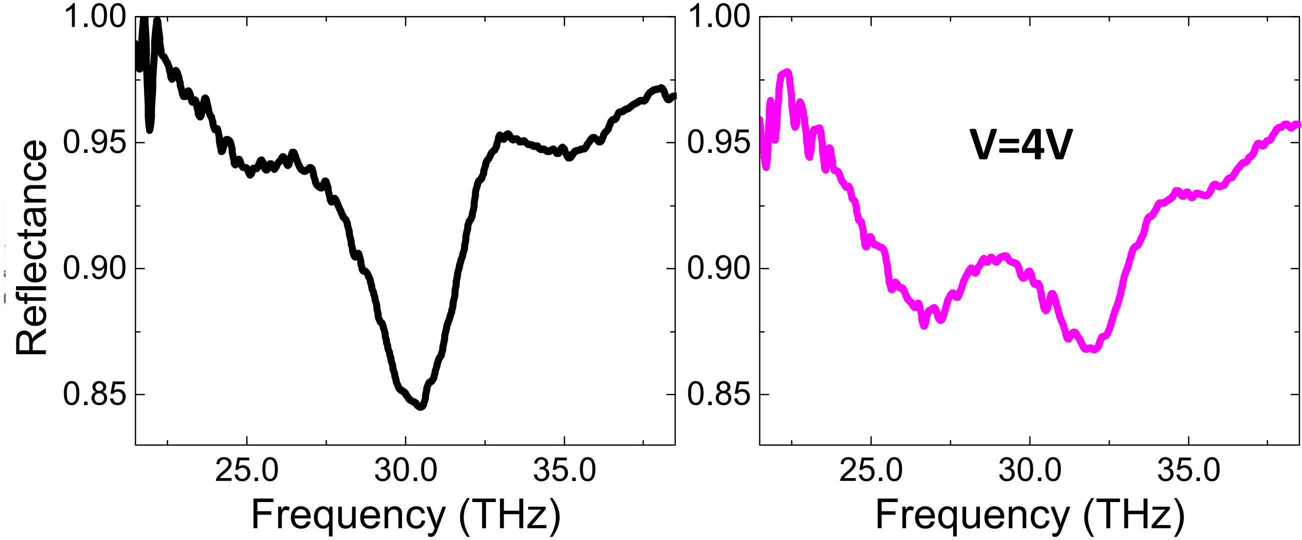


$\varepsilon_{xx}=\varepsilon_{yy}\neq\varepsilon_{zz}$







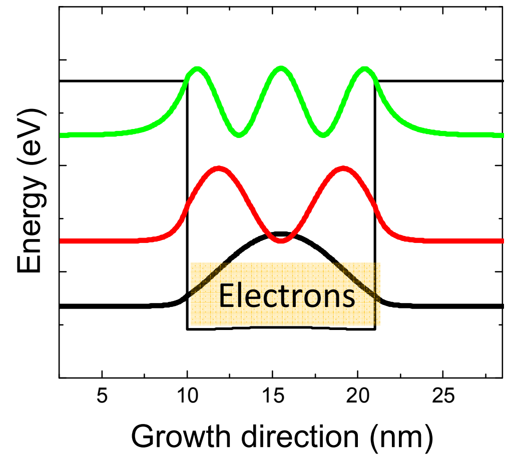


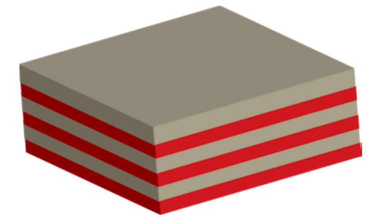
Upper polariton shifted by 2.5 THz (~8% of center frequency)

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

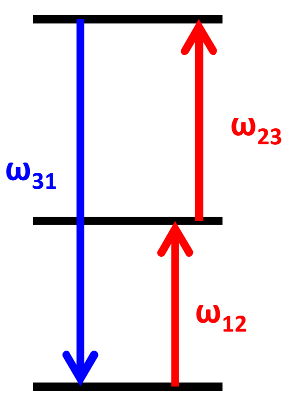
Resonant Optical Nonlinearities: Intersubband Transitions in Quantum Wells

Electronic levels and wavefunctions can be engineered with semiconductor heterostructures





***Resonant* optical nonlinearities can be engineered too:**

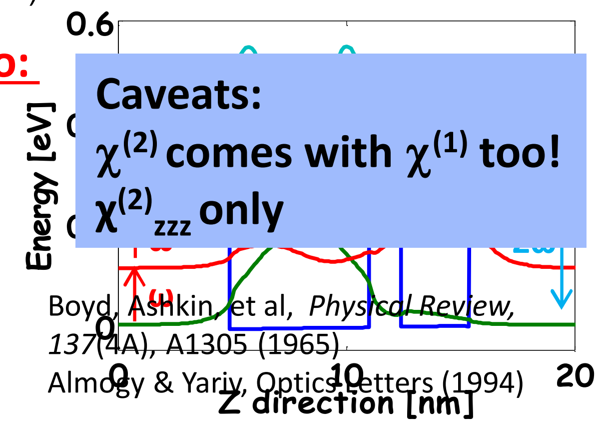


$$\chi^{(2)}(\omega) \propto \frac{N\cdot z_{12}z_{23}z_{13}}{(\omega-\omega_{12}-i\Gamma_{12})(2\omega-\omega_{13}-i\Gamma_{13})}$$

$$z_{ij} \propto \langle \Psi_i | \vec{R} | \Psi_j \rangle$$

~250 nm/V - QWs

10s of pm/V - $LiNbO_3$



Caveats:

$\chi^{(2)}$ comes with $\chi^{(1)}$ too!

$\chi^{(2)}_{zzz}$ only

Boyd, Ashkin, et al, *Physical Review, 137*(4A), A1305 (1965)

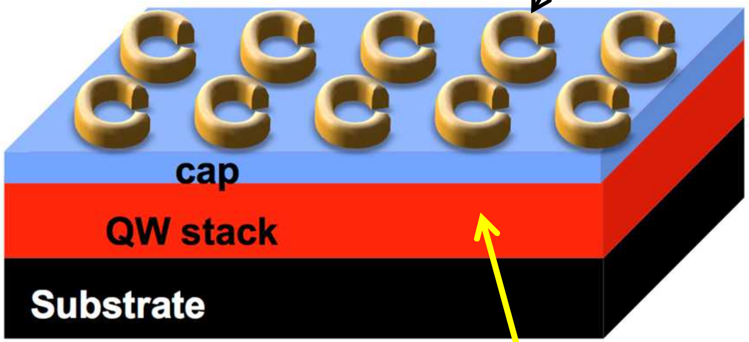
Almogy & Yariv, Optics Letters (1994)

No SHG for L>~ 1/α

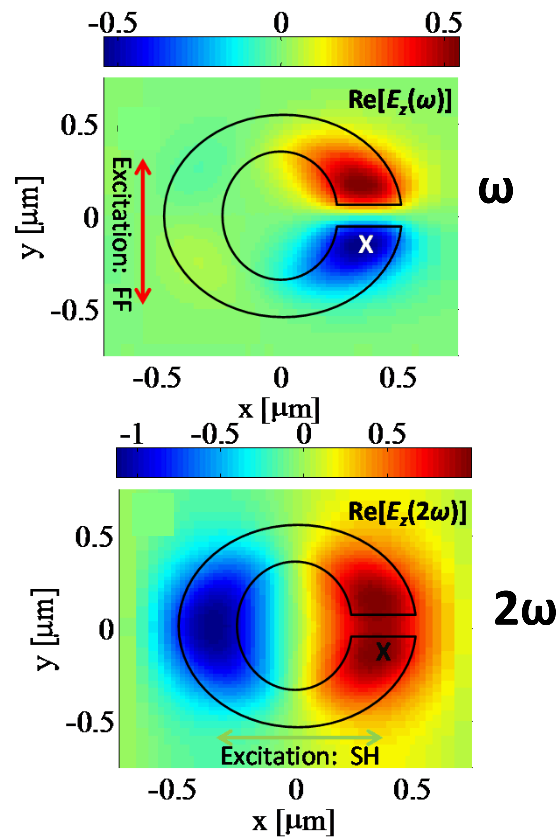
F. Capasso, C. Sirtori, and A.Y. Cho, IEEE J. Quantum Electron. 30, 1313 (1994)

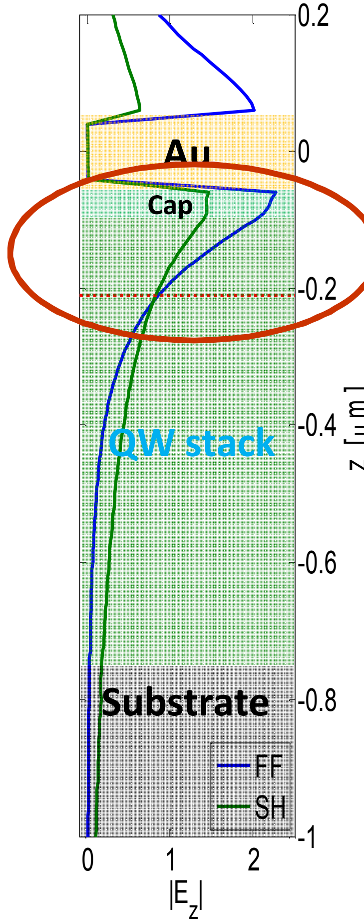
Salvo Campione

Metasurfaces Coupled to Resonant $\chi^{(2)}$



Resonators are designed to have resonances at 30 & 60 THz (5&10um)





APL 104, 131104 (2014)

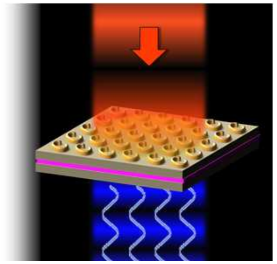
Omri

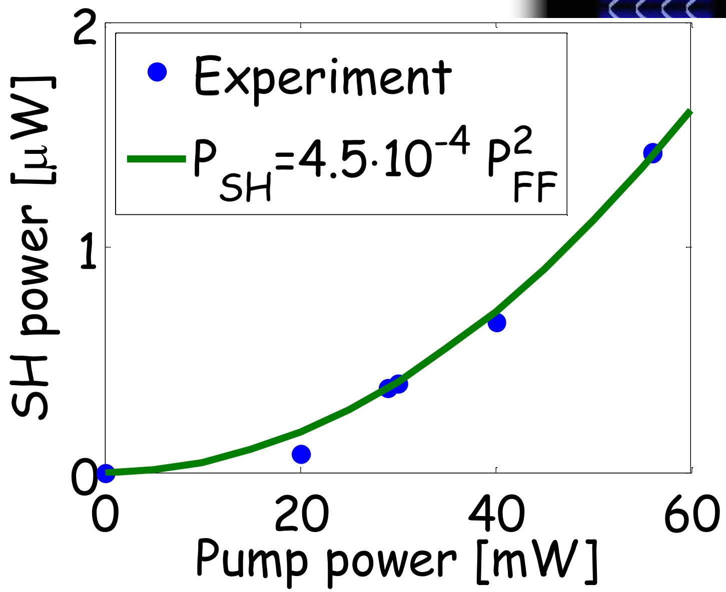
Salvo

Sandia National Laboratories

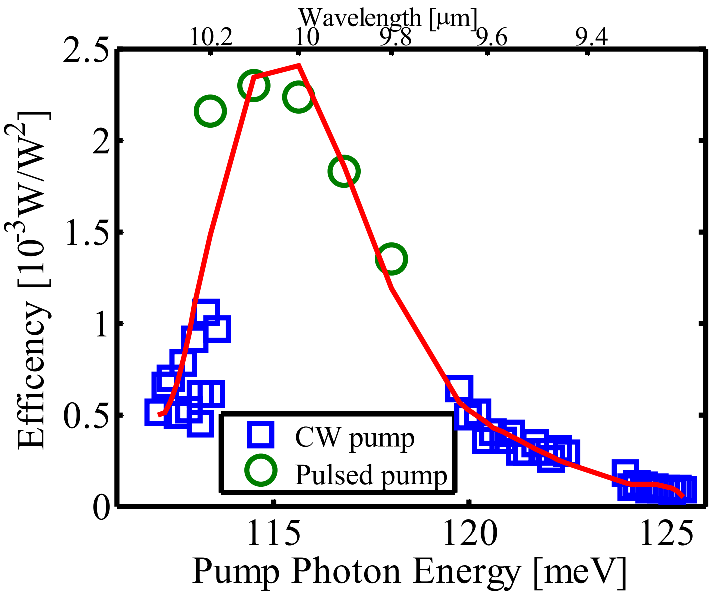
SHG: Power and Frequency Dependence

Pump: CW CO_2 laser





max efficiency: ~2.3 mW/W²



- **Saturation is an issue**
- **Max. conversion efficiencies of few % are possible**
- **Added functionality is the advantage**

Nature Communications 6, 7667 (2015)

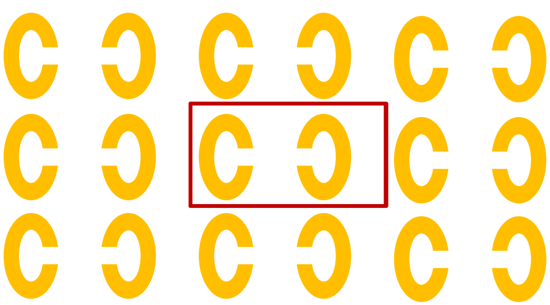
SHG Beam Manipulation

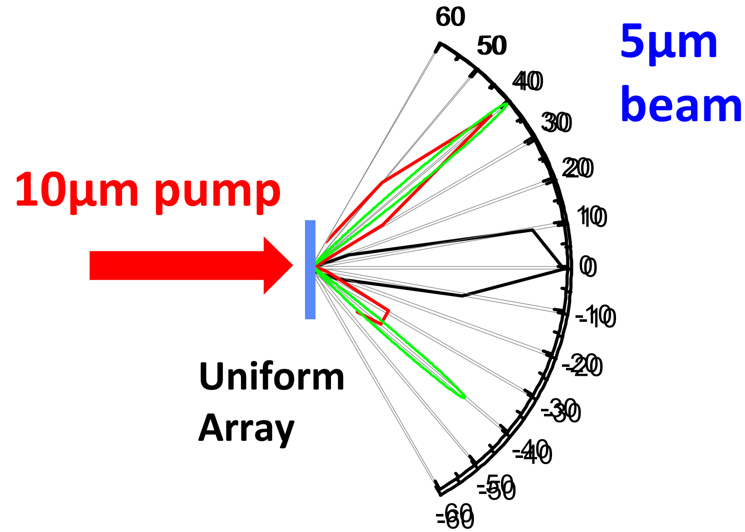
Omri

Salvo

"edge-fed dipole"

flipping induces π phase shift





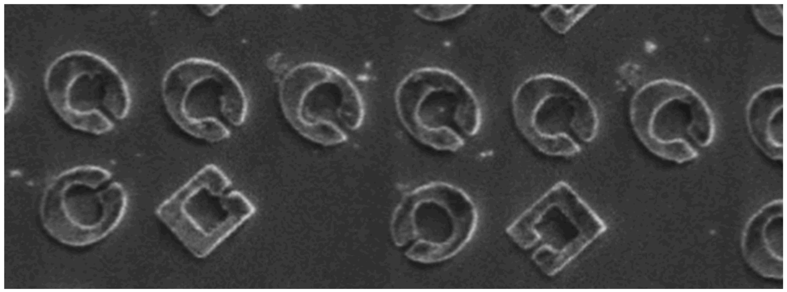
2-in-1:

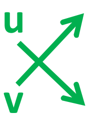
Source +beam splitter

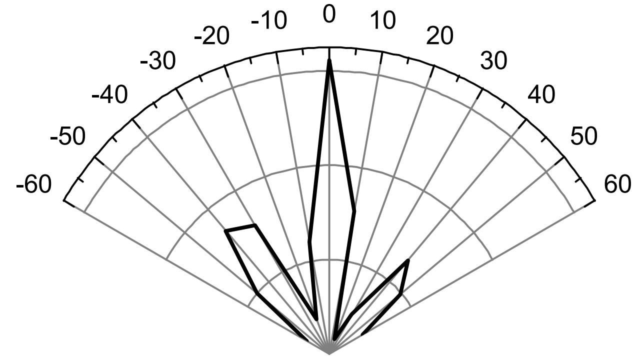
Nature Communications 6, 7667 (2015)

SHG Beam Manipulation II

- **Cavities radiate polarized light**

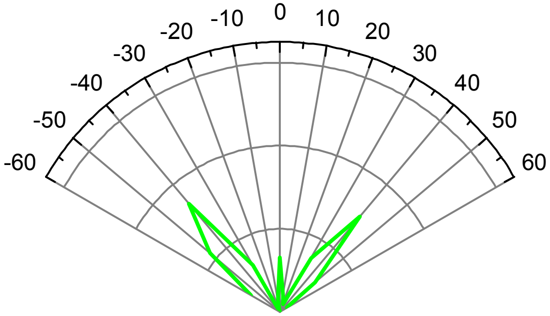




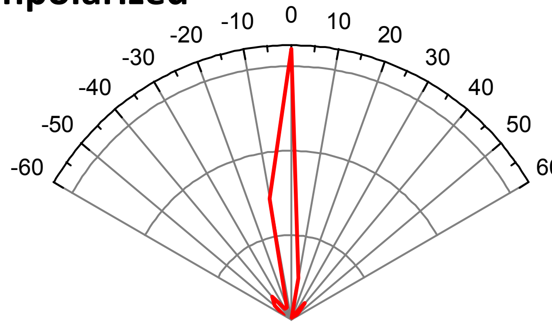


unpolarized

Pump polarization



v polarized



u polarized

3-in-1:

Source + Polarizer + Beam Splitter

Dielectric Metasurfaces…

Interlude.....

What is a mirror?

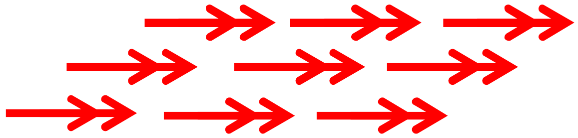
“Regular” mirrors invert the phase of the reflected wave

A “magnetic mirror” <u>does not</u>

How to Create a "Magnetic Mirror"

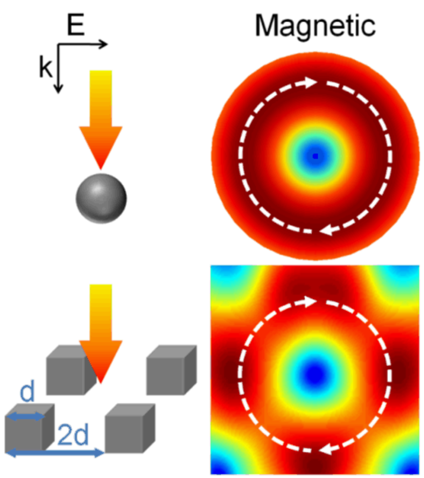
We need a "perfect magnetic conductor"; it does not exist in nature

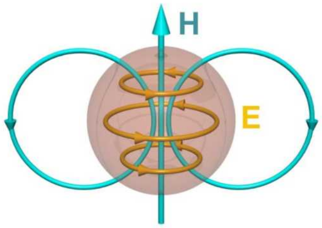
Array of magnetic dipoles



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

I can create magnetic dipoles with Dielectric Resonators operating at the magnetic dipole resonance

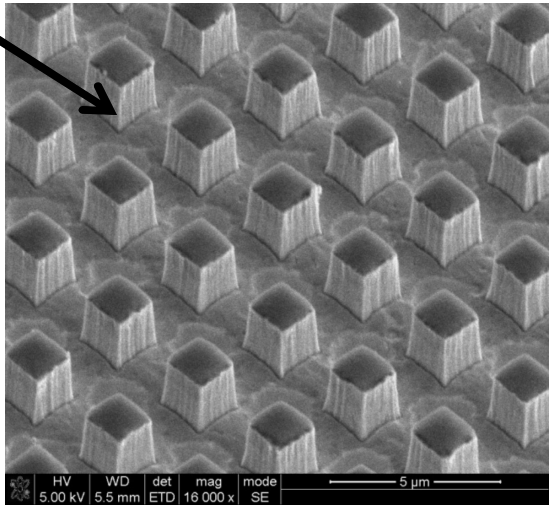




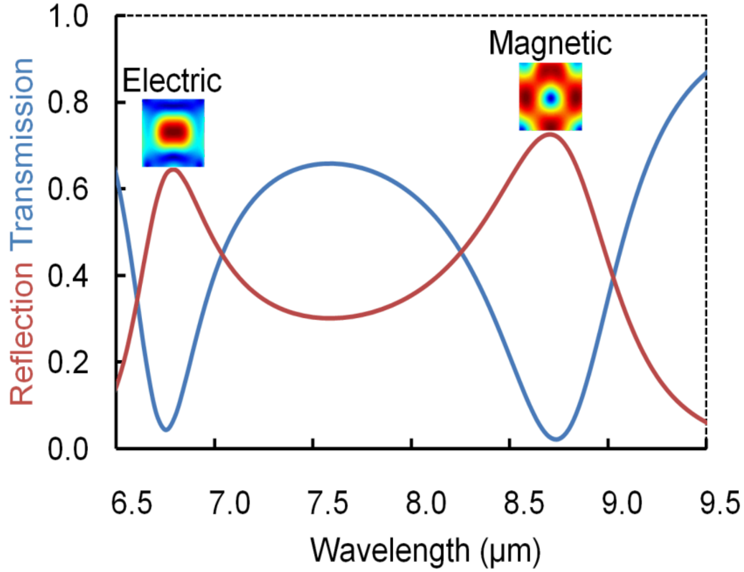
Optical Magnetic Mirror

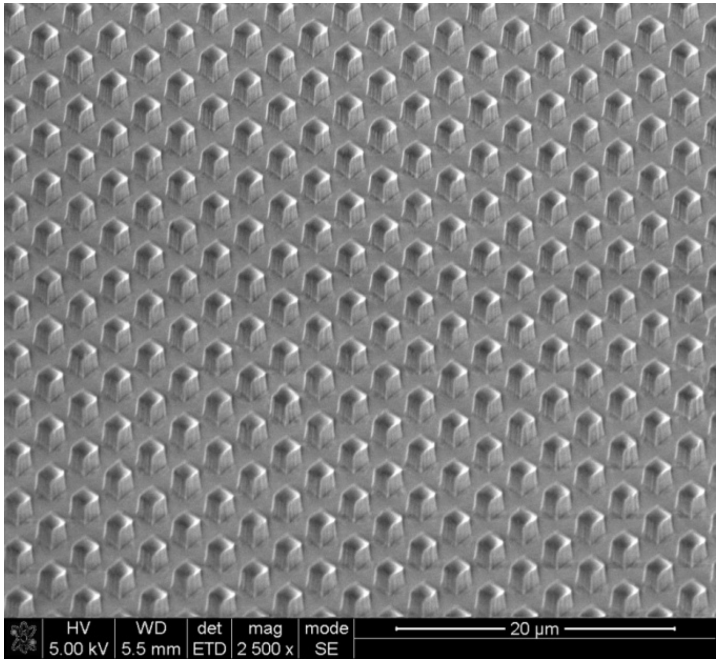
Tellurium

n~5 in the IR



1.53x1.53x1.7μm^3



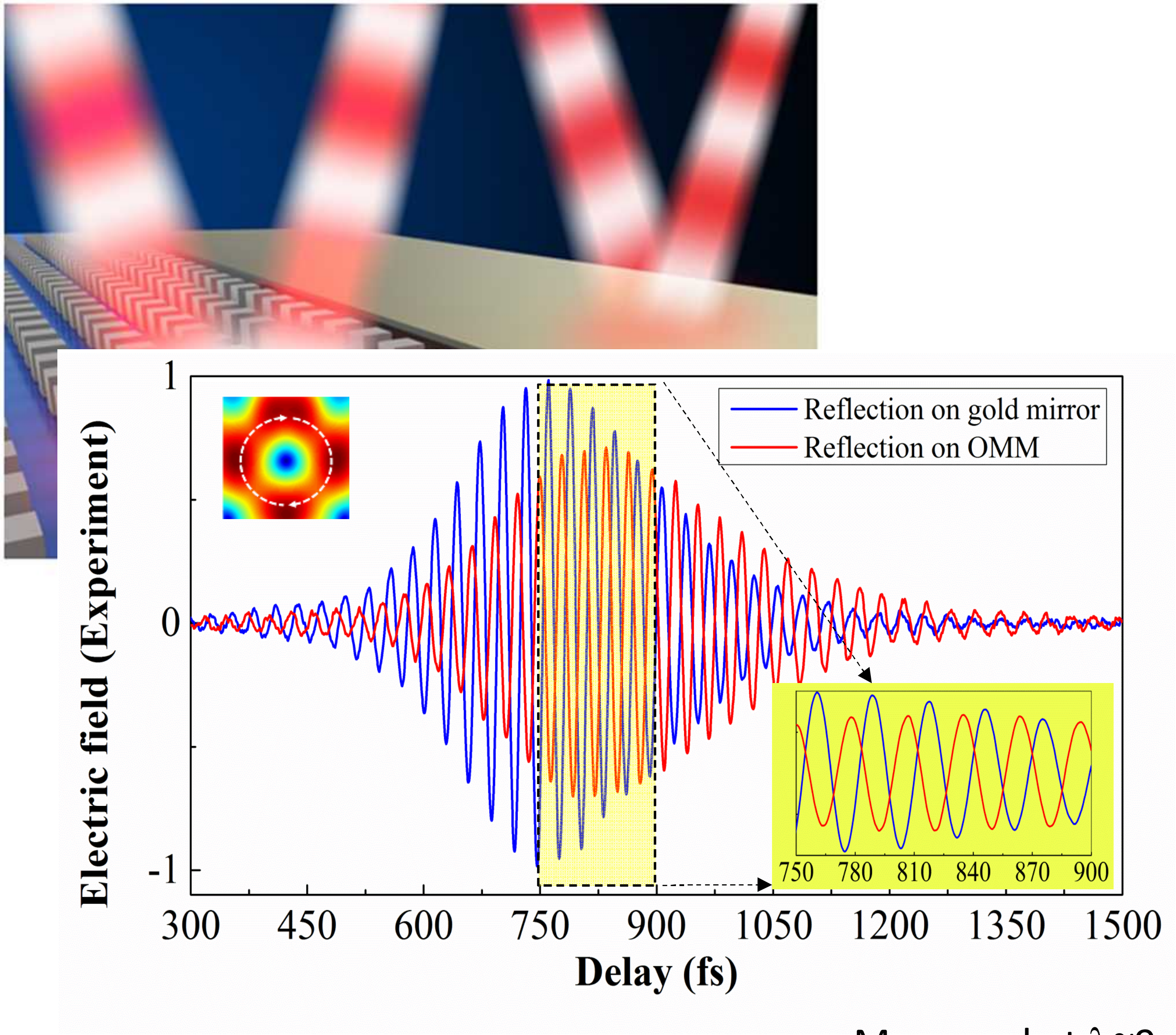


A Metasurface (dielectric)

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

Optical Magnetic Mirror

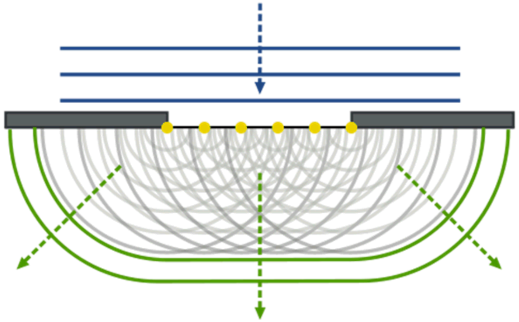
Measure Absolute Phase of Reflected Wave



Optica **1**, 250 (2014)

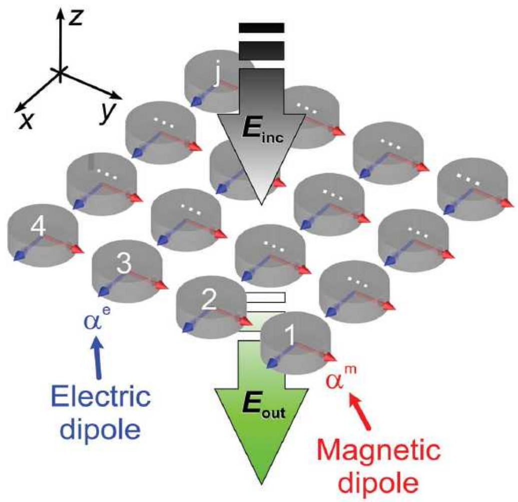
Measured at λ~9μm

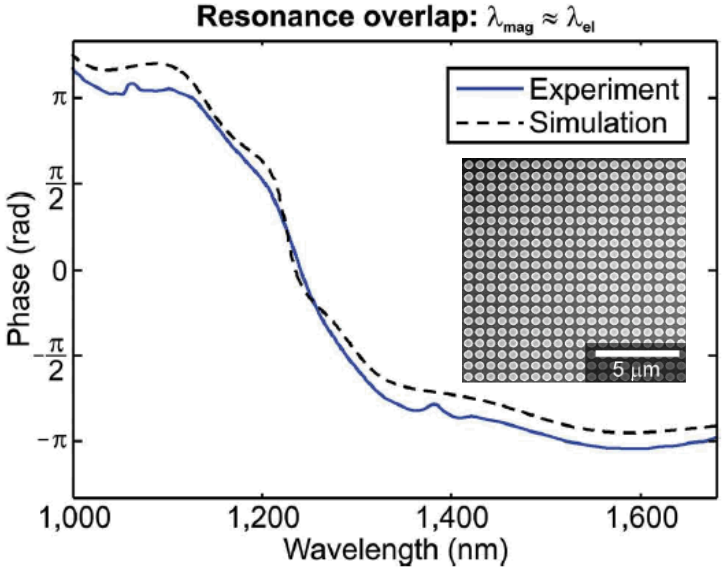
Huygens Metasurface



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

Using dielectric resonators, we can achieve this

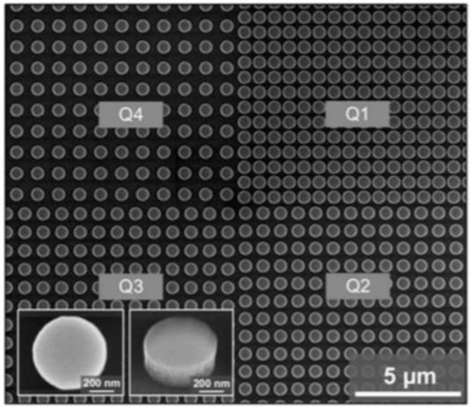


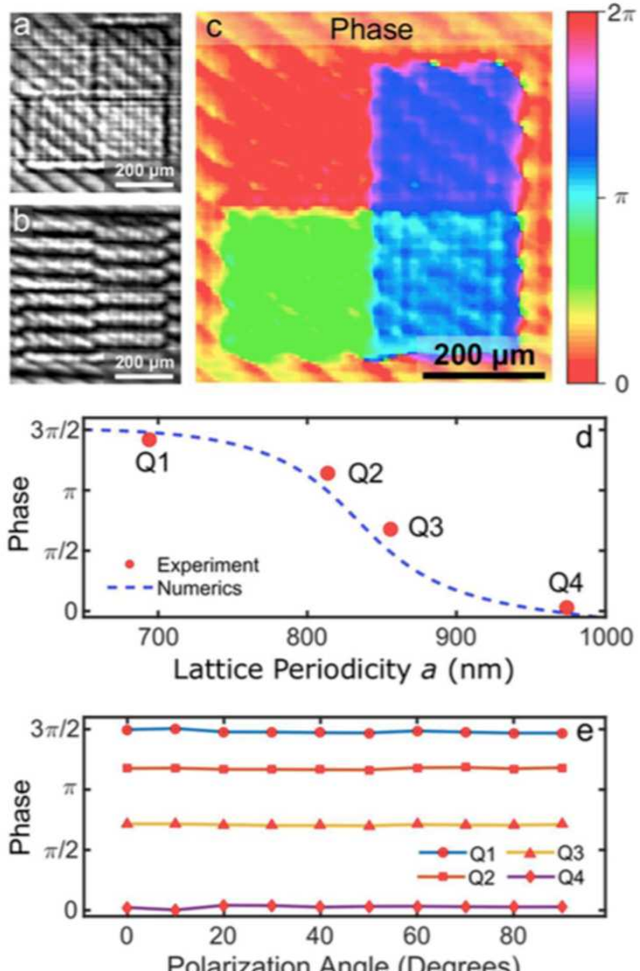


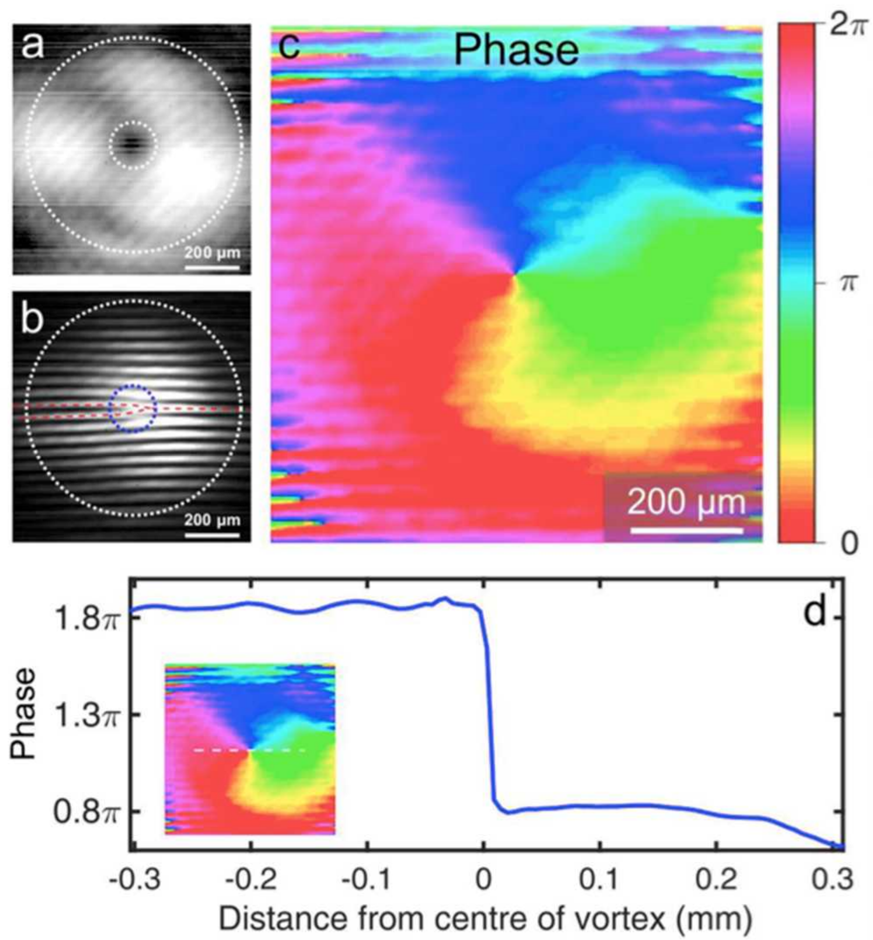
- **Complete 2π phase range in transmission**
- **Near-unity transmittance for ideal MS**
- **No reflection losses, no absorption losses (NIR)**
- **No polarization conversion losses**
- **Single step lithography fabrication**

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

Huygens Metasurface Phase Plate: Vortex Beam

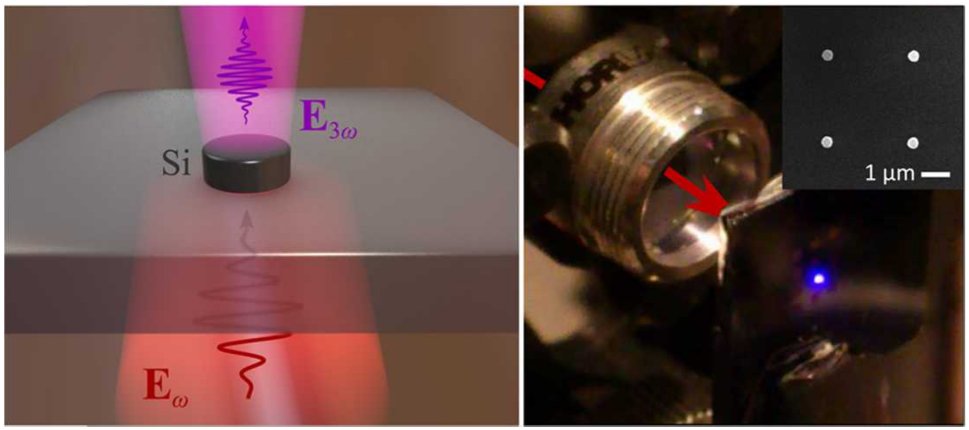


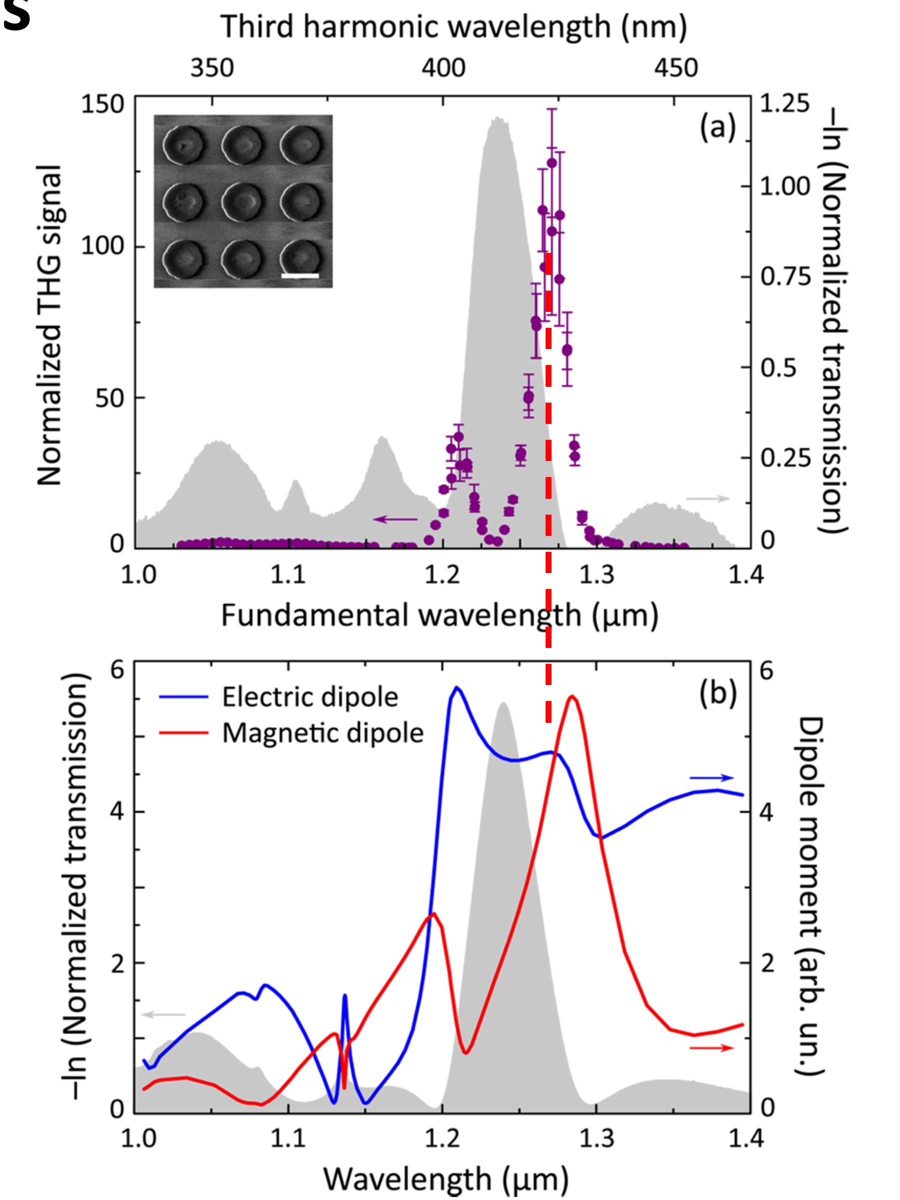




Nonlinear Optics with Dielectric Metasurfaces

Optical Nonlinearities (THG) in Si Dielectric Metasurfaces





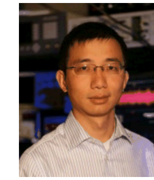
Strong enhancement near magnetic dipole resonance

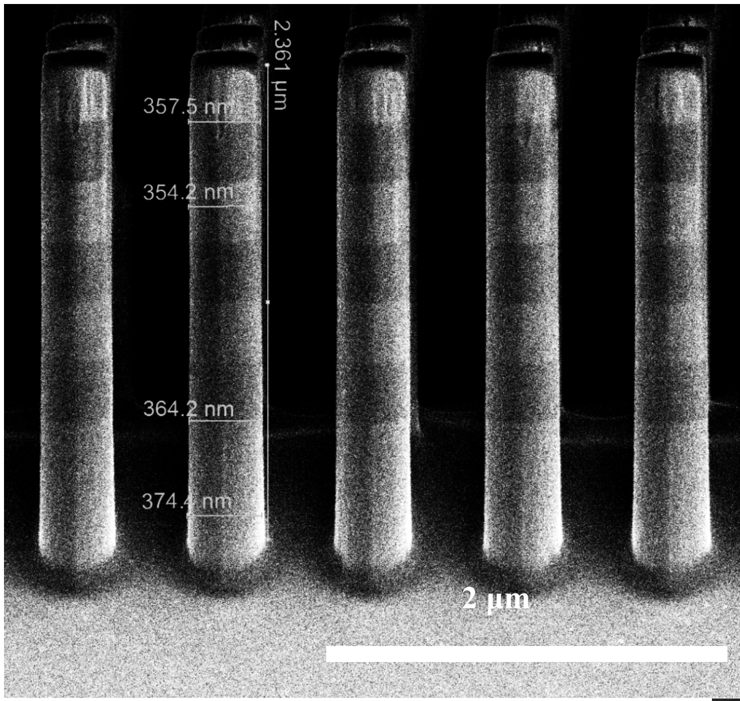
Silicon is passive & has no $\chi^{(2)}$

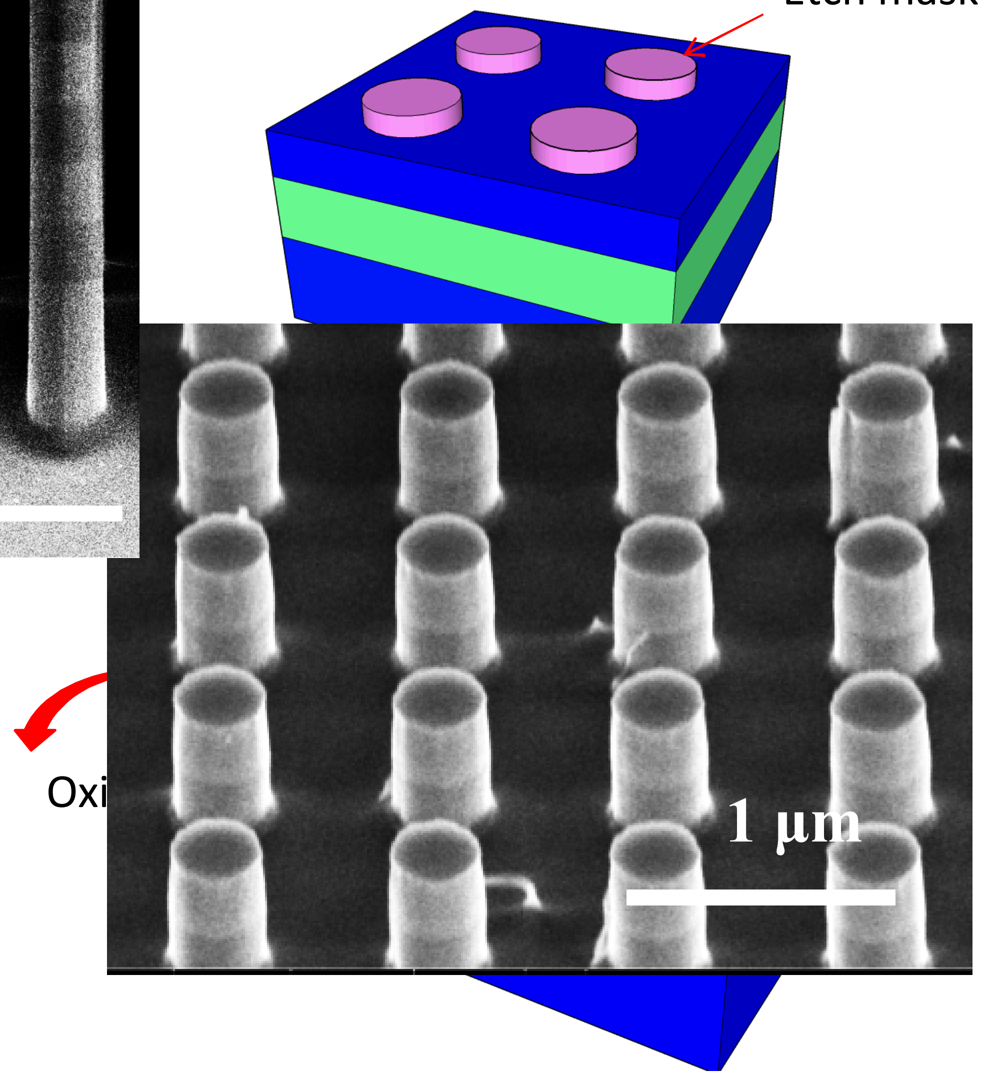
Nano Letters (2015)

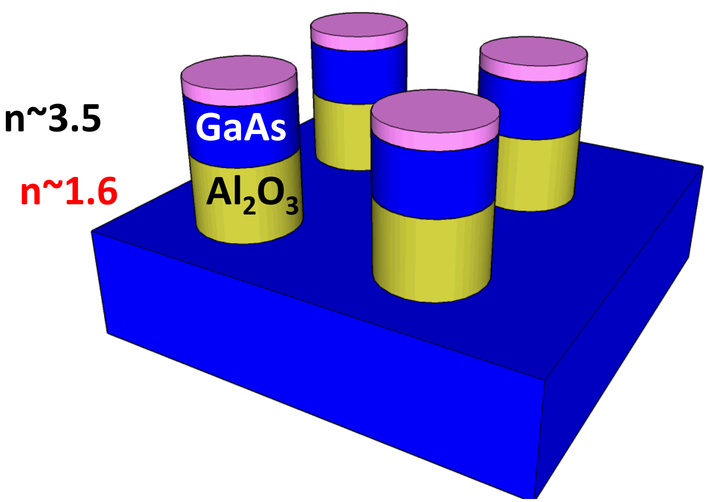
(With ANU & Moscow State

All III-V Dielectric Metasurfaces





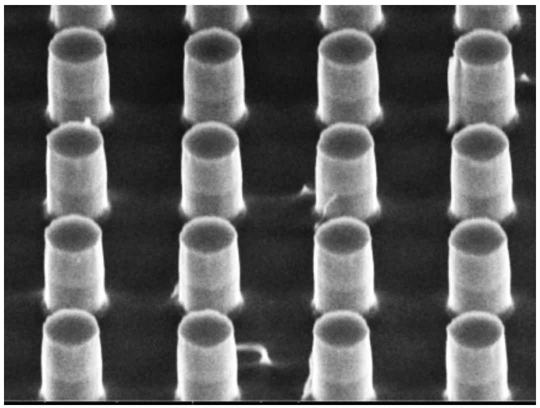




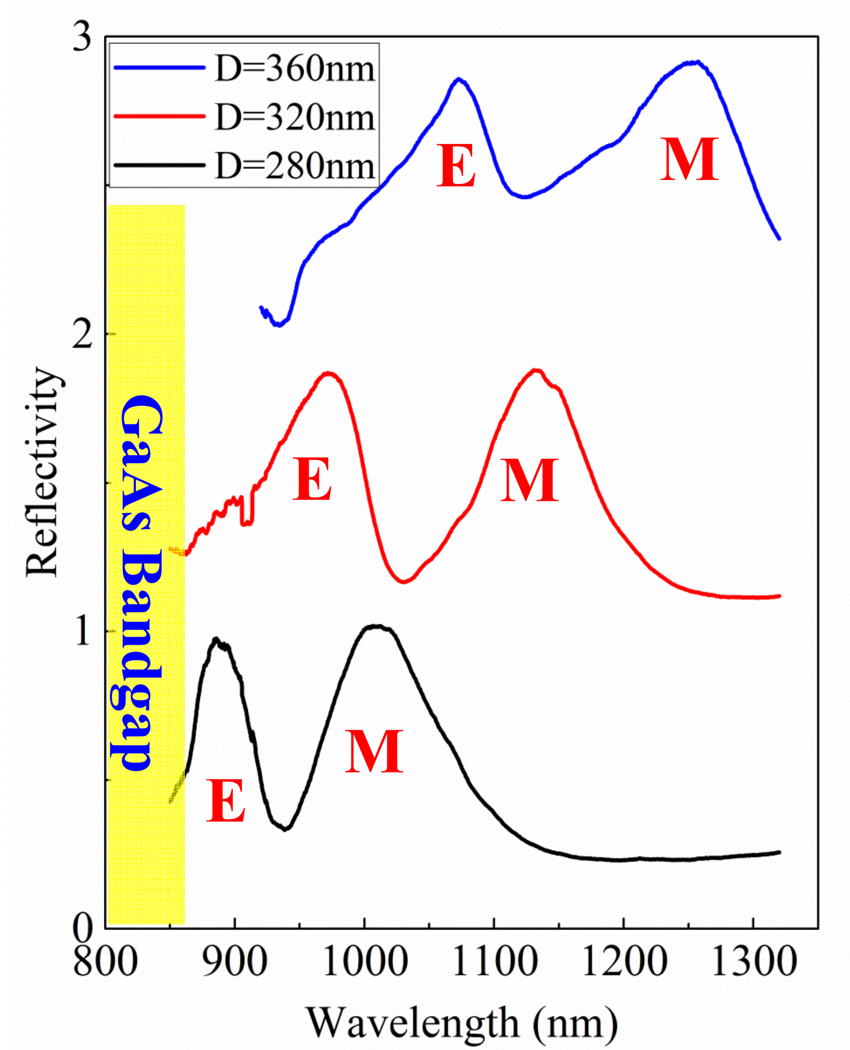
GaAs Dielectric Resonators (1 layer)

GaAs disk height ~300nm

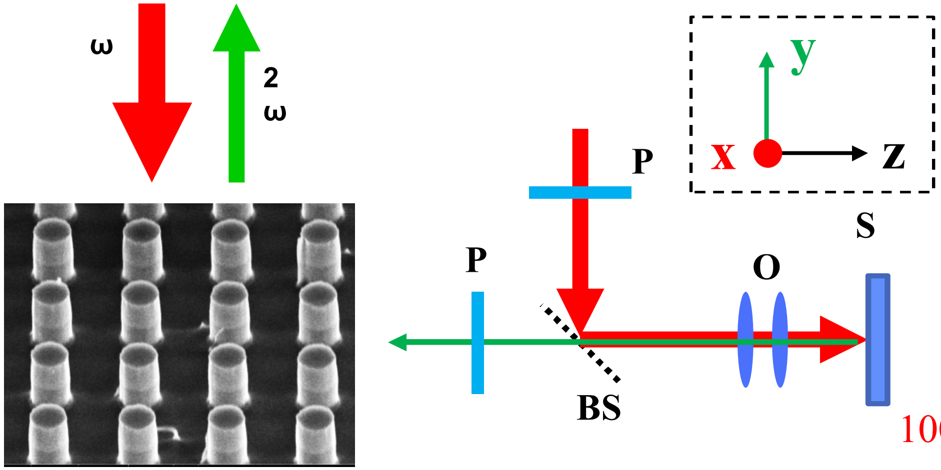
Different diameters

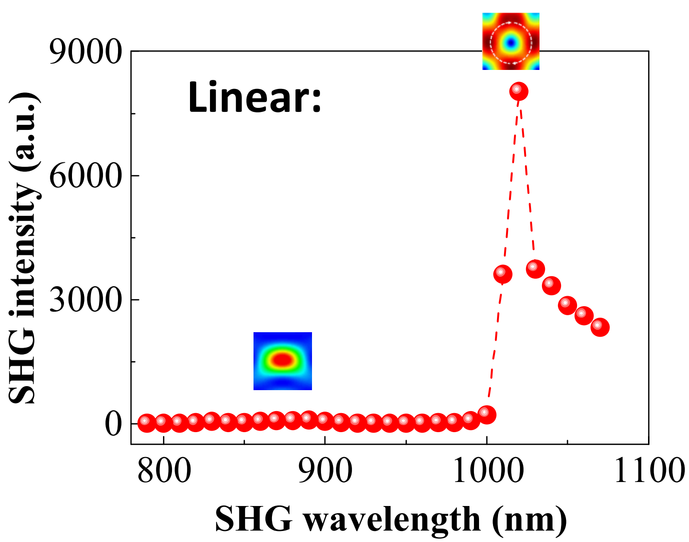


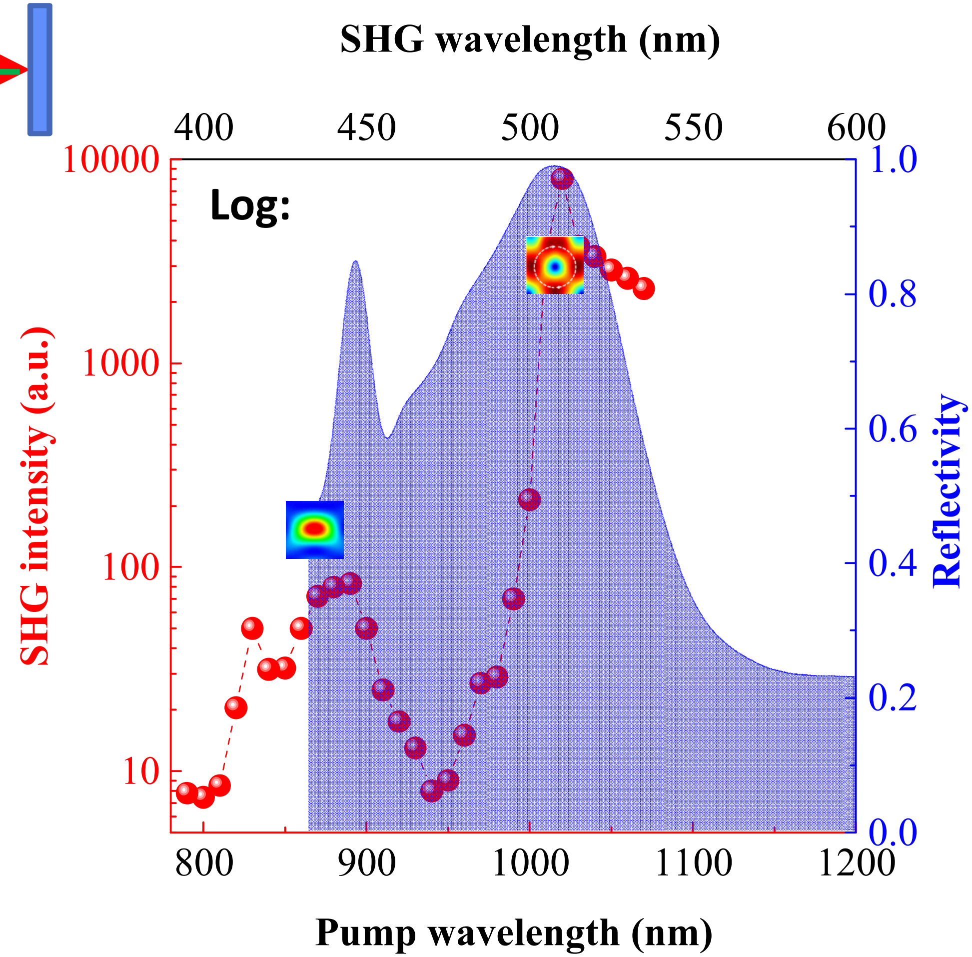
- Extremely low loss below bandgap
- Crystalline



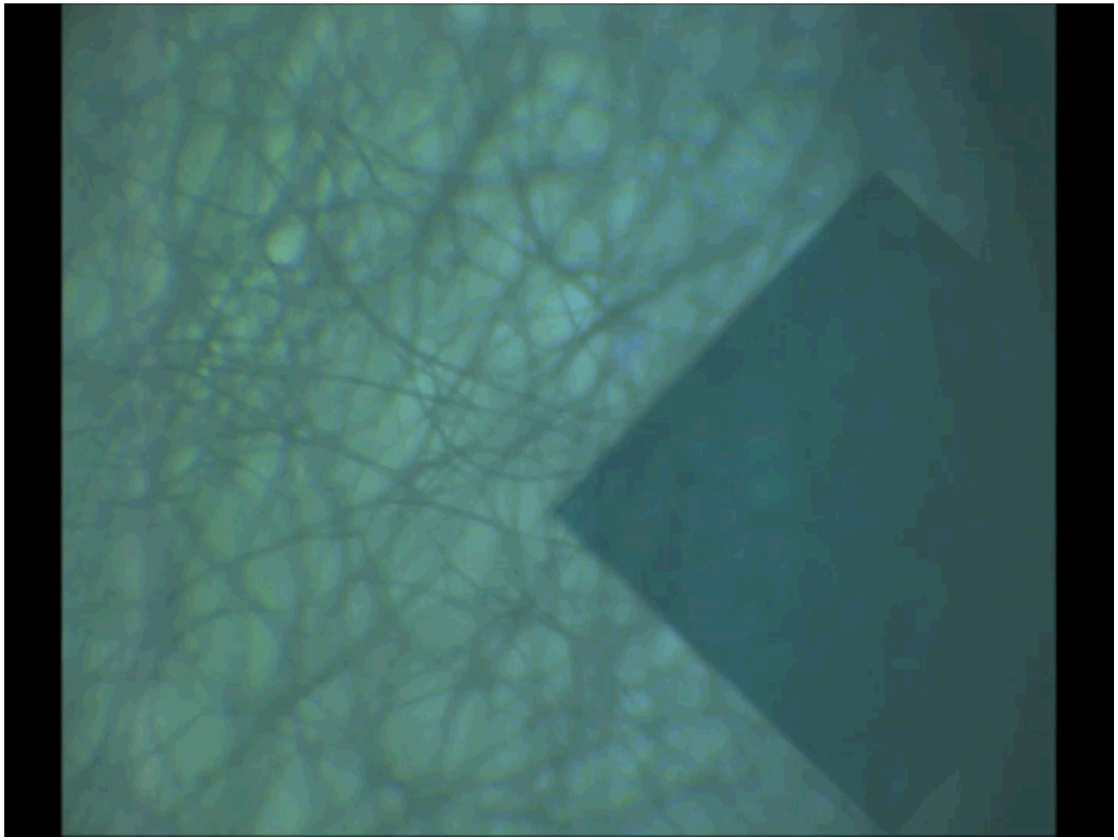
Second Harmonic Spectral Dependence

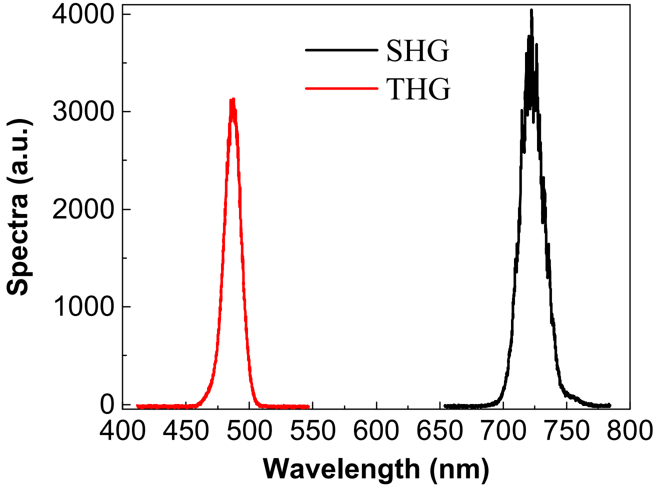




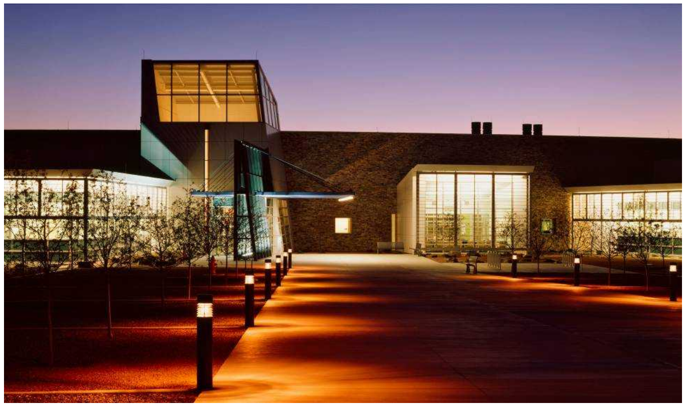


Simultaneous SHG & THG….





Center for Integrated Nanotechnologies: CINT



Center for Nanoscale Materials
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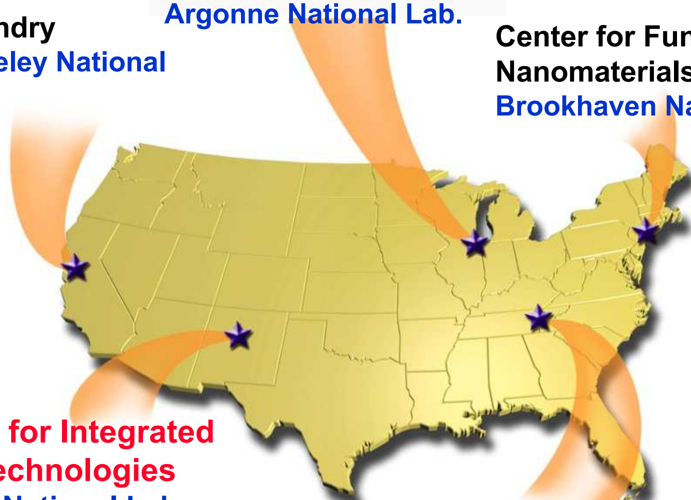
Molecular Foundry
Lawrence Berkeley National Lab.

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

Acknowledgments

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

I. d'Optique: Francois Marquier, Jean-Jacques Greffet

UNM: Ganesh Balakrishnan (QD samples)


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