SAND2016-0046PE

Active Infrared Metasurfaces: Strong Coupling, Spectral Tuning and Optical Nonlinearities

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SAND2015-10658 C

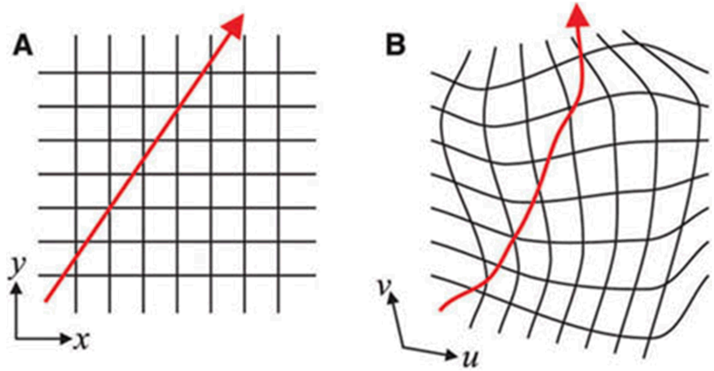
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

Outline

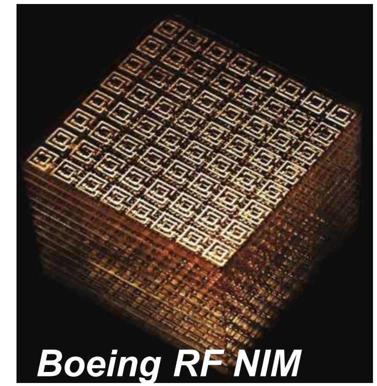
- Electrically tunable metasurfaces
  - Depletion: Thz
  - Scaling to mid IR
  - Tuning by controlling coupling
    - Coupling to “epsilon near zero modes”
    - Coupling to intersubband transitions

- Enhanced optical nonlinearities

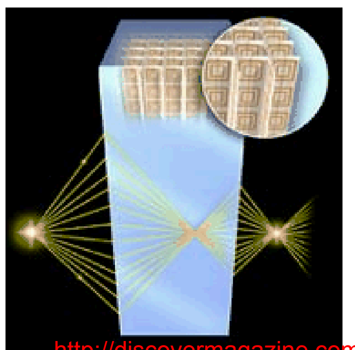
Metamaterials

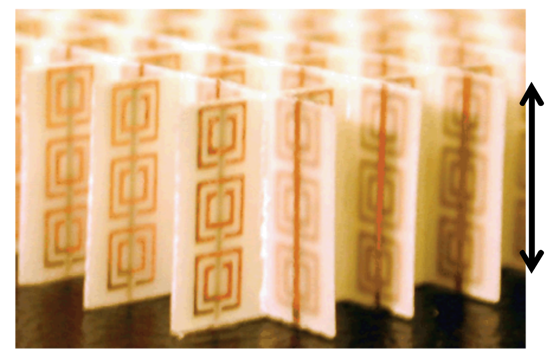


Sir John Pendry
David Smith, etc



Negative Refraction & Perfect Lensing





~cm's

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

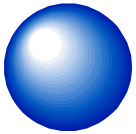
The promise of (IR) applications was great:

- Wavefront control (Conformal optics, novel illuminators)
- Sub-λ Field Concentration
- Absorption / Emission engineering
- "Flat" optics (thin, lightweight)

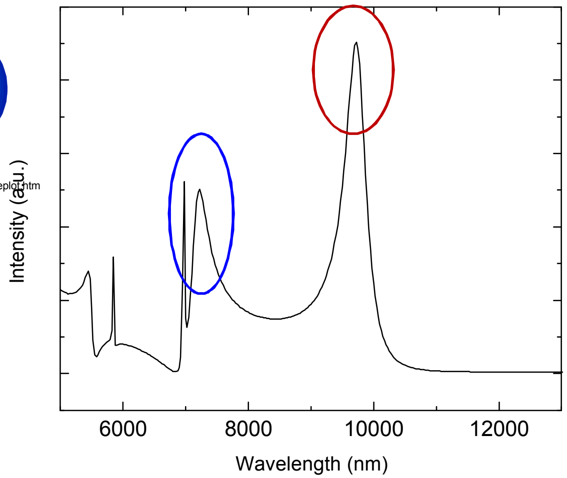
- For RF (~3GHz), λ~cm
- We need to create sub-wavelength "inductors" and "capacitors"

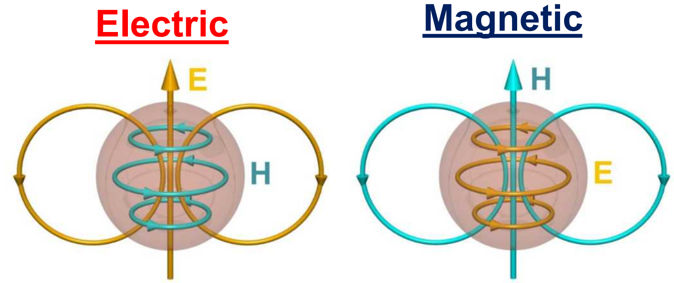
A Non-Metallic Path to Low Loss Metamaterials: Dielectric Resonators

Gustav Mie



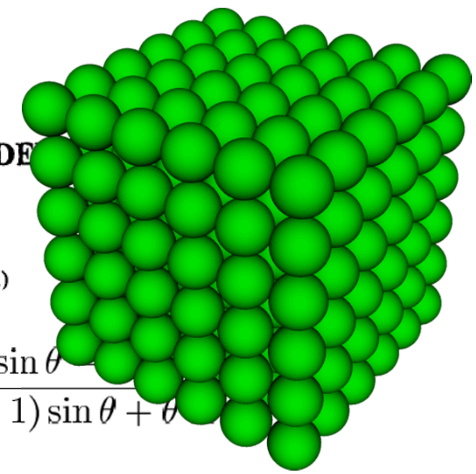
http://www.philiplaven.com/mieplot.htm

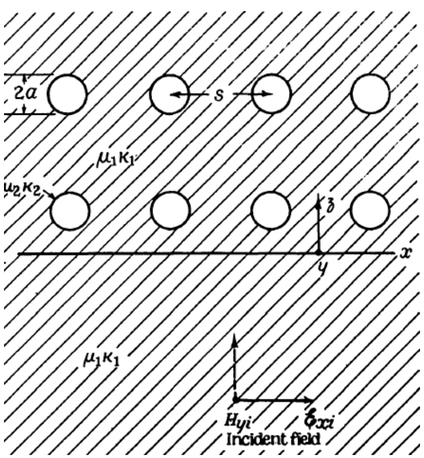




Images: A. Miroshnichenko

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





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

By L. LEWIN.†

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

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

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

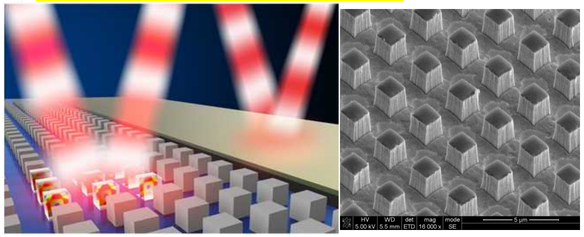
$$F(\theta) = \frac{2(\sin\theta \ldots}{(\theta^2 - 1)\sin\theta + \theta \ldots}$$

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

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

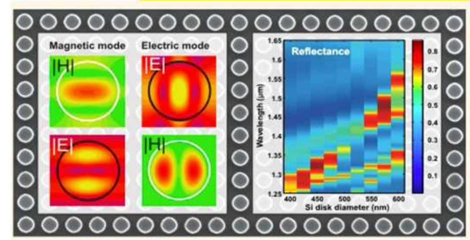
Some Recent Results with Dielectric Metasurfaces (Linear)

Magnetic mirror

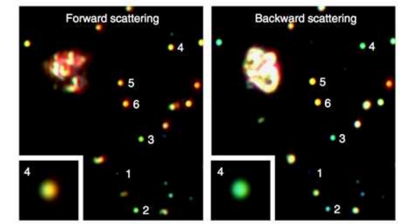


Optica 2015

Tailoring scattering

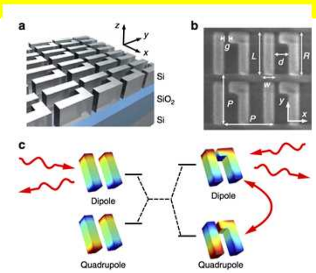


ACS Nano 7, 7824 (2013)

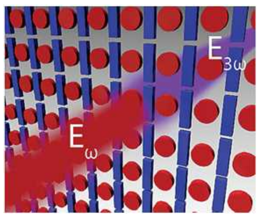


Nat. Comm. 4, 1527 (2013)

Fano resonances

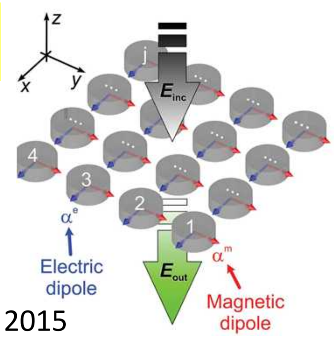


Nature Comm. 2014.



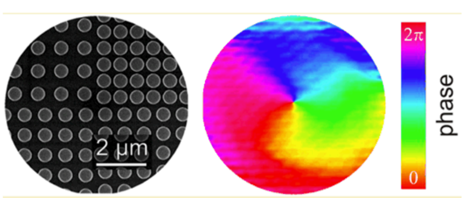
Nano Lett. 15, 7388 (2015)

Huygens Metasurfaces

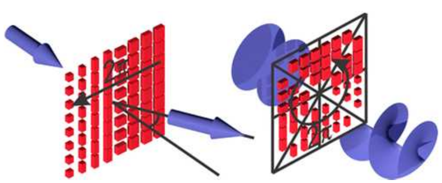


Adv. Optical Mater. 2015

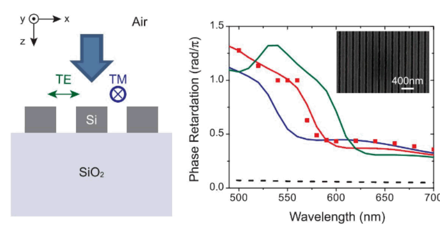
Phase-front manipulation



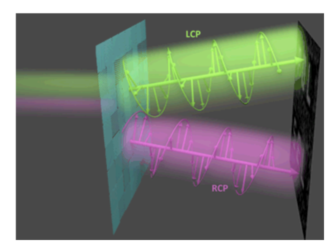
Nano Lett. 15, 5369 (2015)



Nano Lett.15, 6261 (2015)



Science 345, 2015



Opt. Express 23, 22611 (2015)

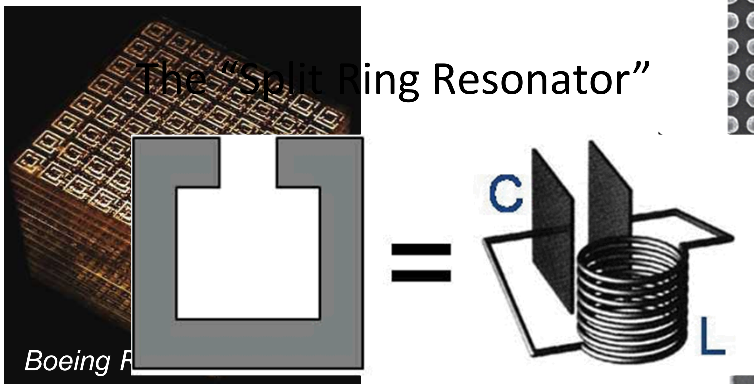
2D Metallic Metamaterials ("Metasurfaces")

(for some applications, loss is a good thing)

3D

2D

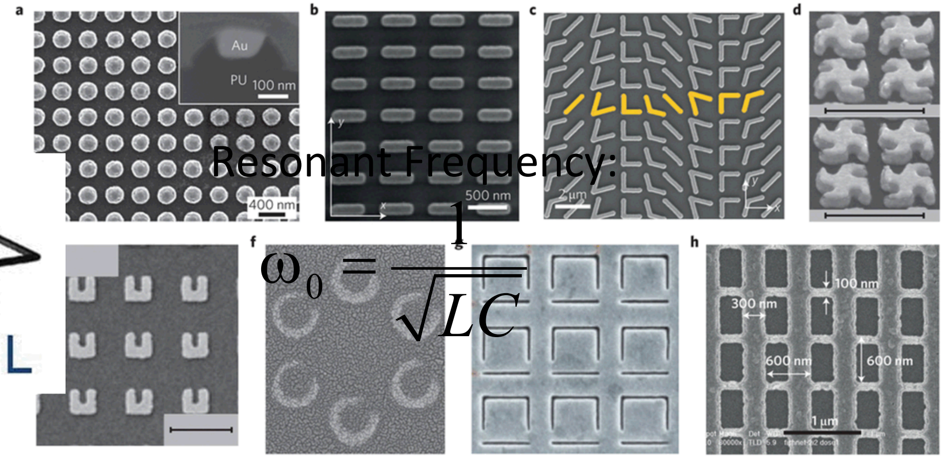
The "Split Ring Resonator"



(Bonn)

Resonant Frequency:

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

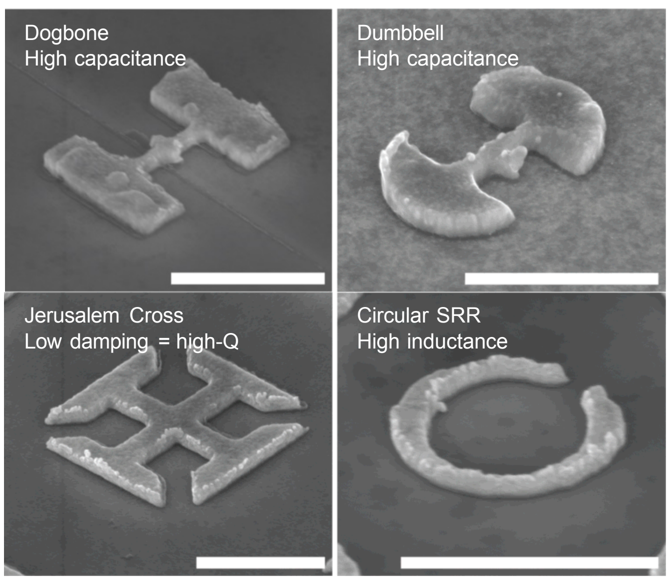


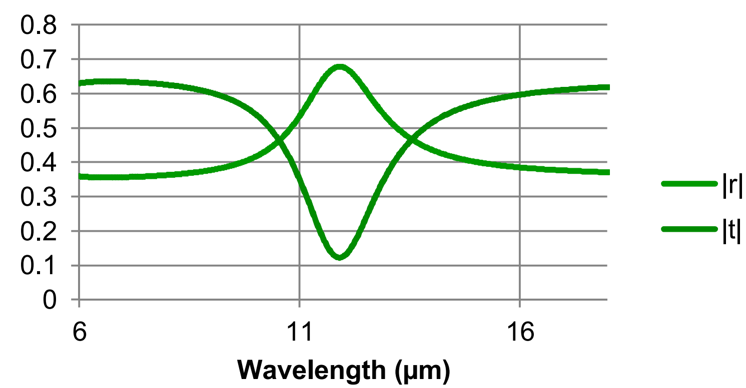
Nature Photonics 8, 889 (2014)

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

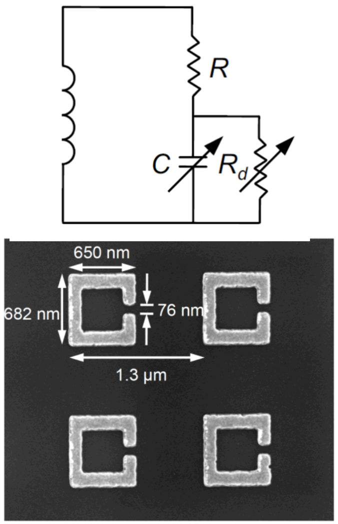
~λ/10

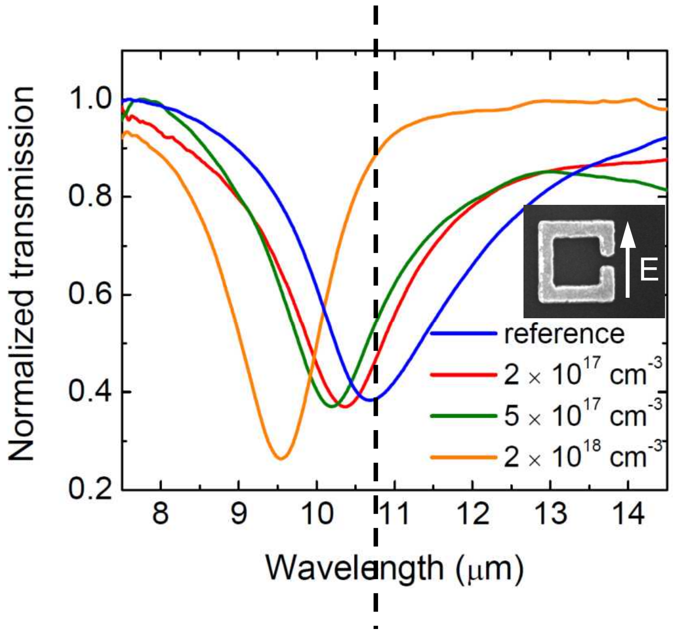
(Sandia)

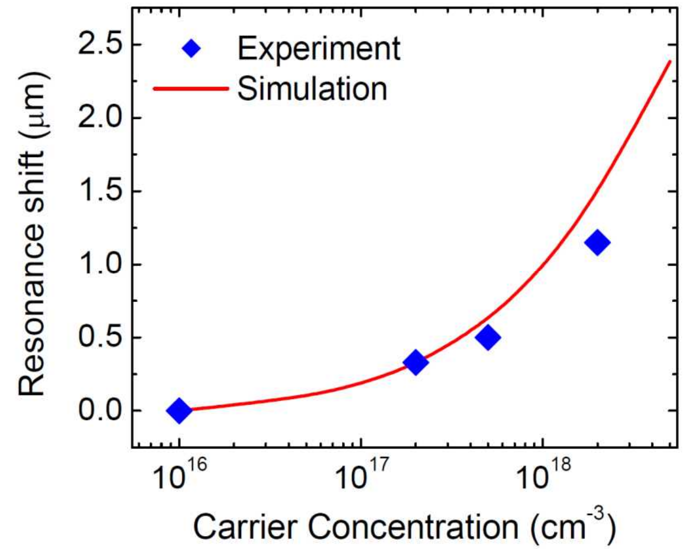




Tuning Metasurfaces Using Semiconductors







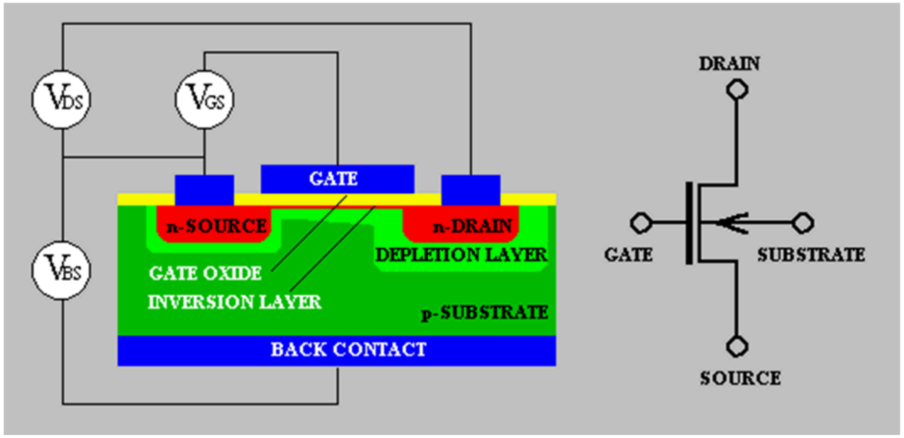
- SRRs made on InSb substrates with different doping
- Experimentally observed doping dependent resonance with <u>no appreciable damping.</u>
    - *A resonance shift of 1.15 um (1×10^{16} cm^{-3} → 2×10^{18} cm^{-3})*

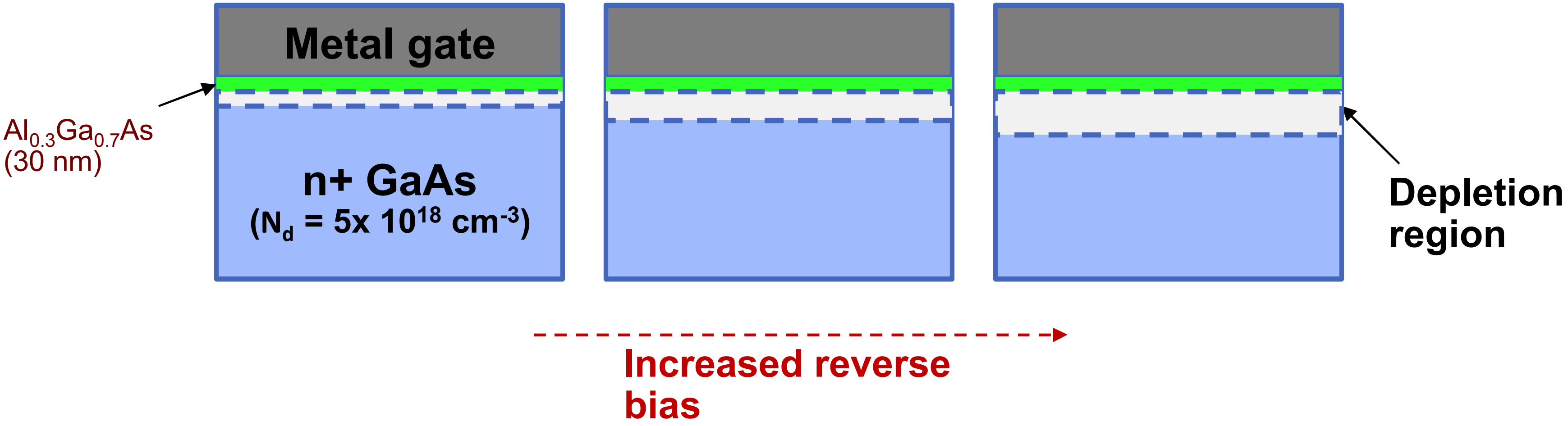
Appl. Phys. Lett. 96, 1 (2010)

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

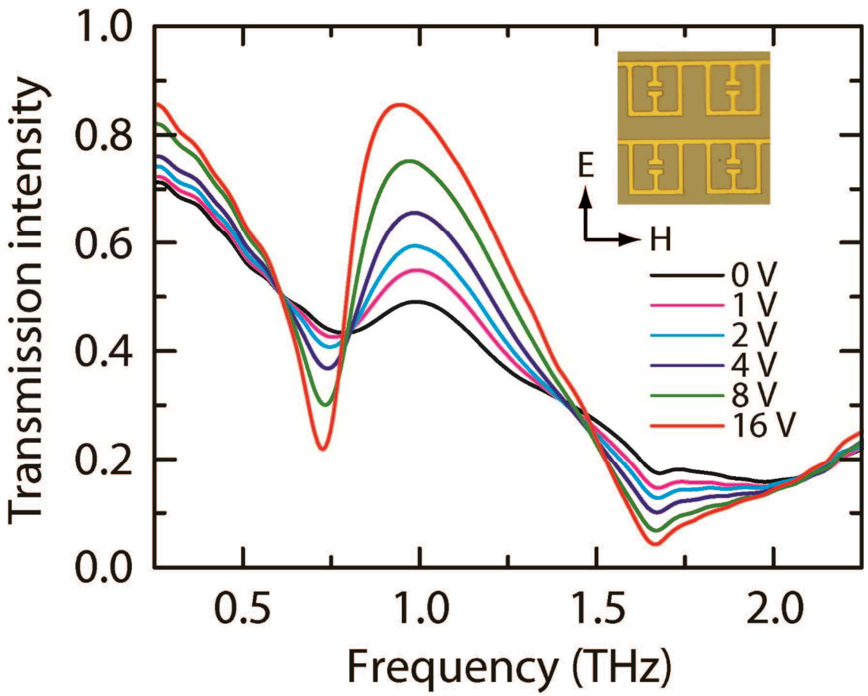
Tuning the Spectral Response by Depletion

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

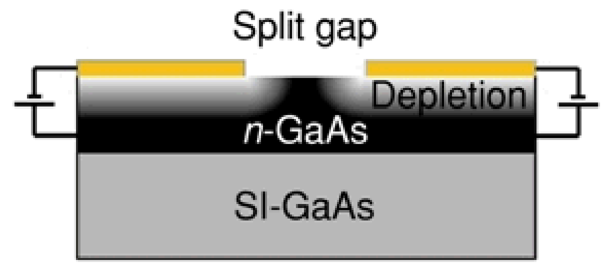




Electrically Switchable THz Metamaterials

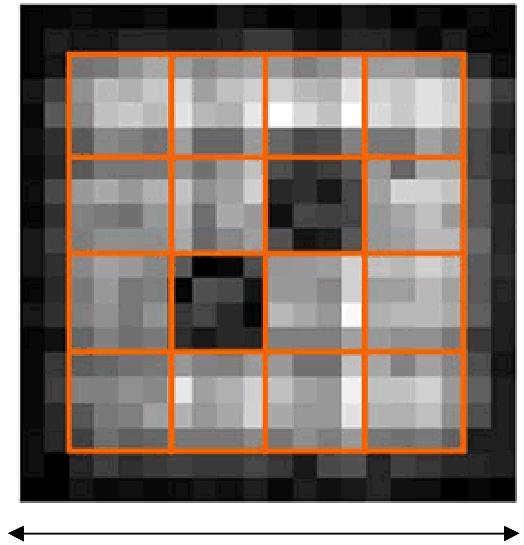


Nature 444, 597 (2006).

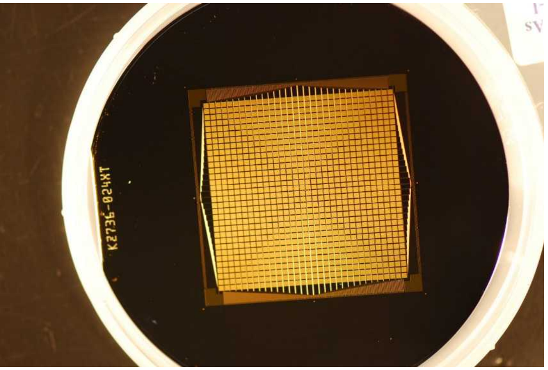


This works by increasing the damping (ε_2). Plasma frequency of doped layer needs to match the MM resonance frequency

0.36 THz,4x4 SLM



16 mm

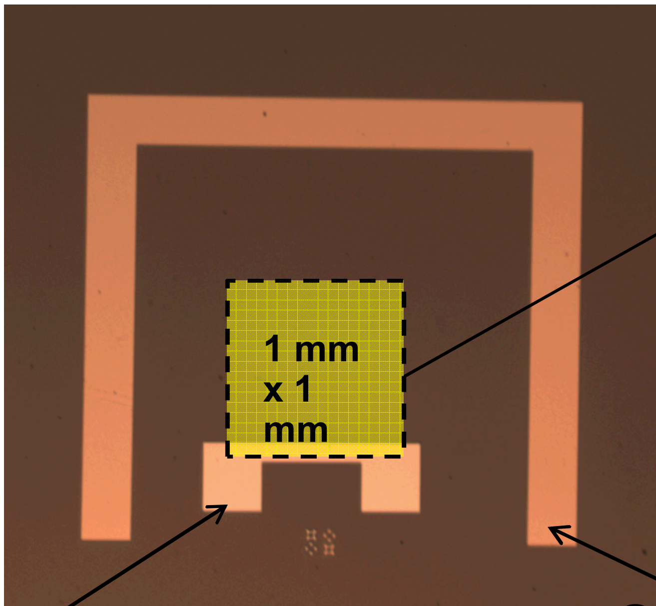


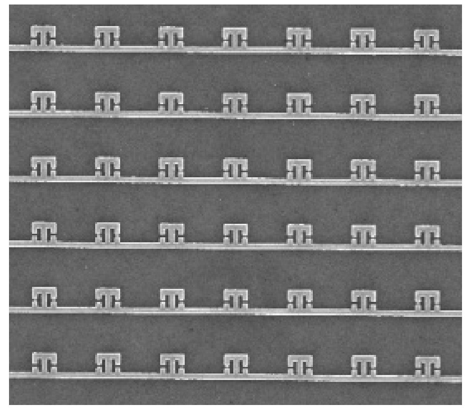
Bigger arrays

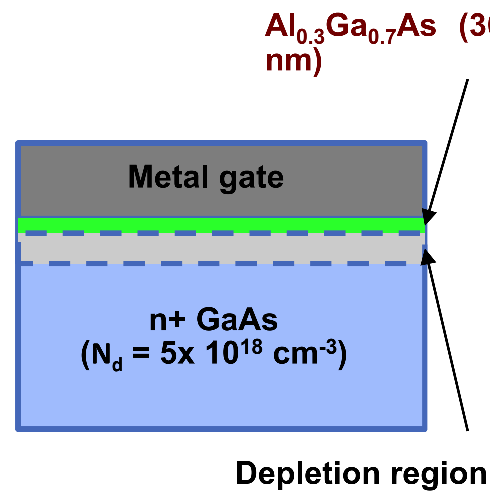
Appl. Phys. Lett. 94, 213511 (2009)

An Attempt to Scale These Active MMs to the mid-IR (from 1THz to 30Thz)

* Metal contacts patterned by optical lithography

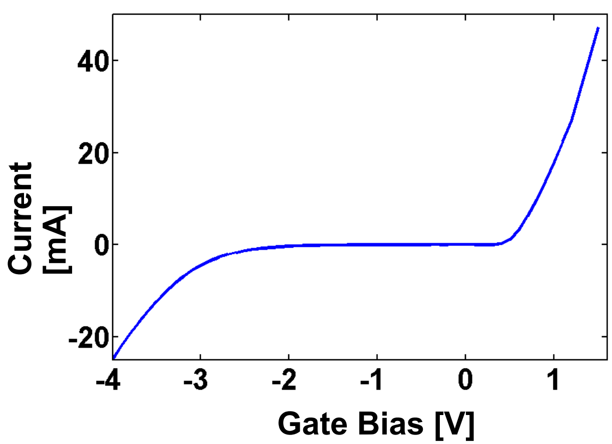


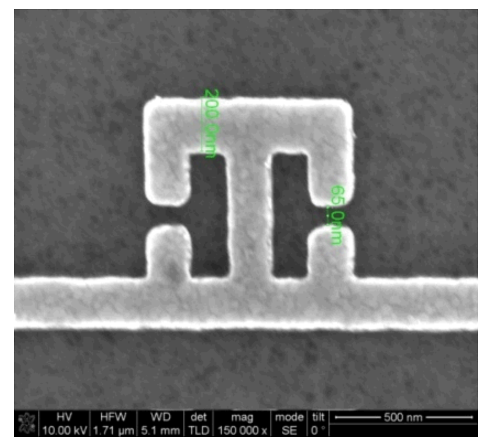




Ohmic contact

Metal gate

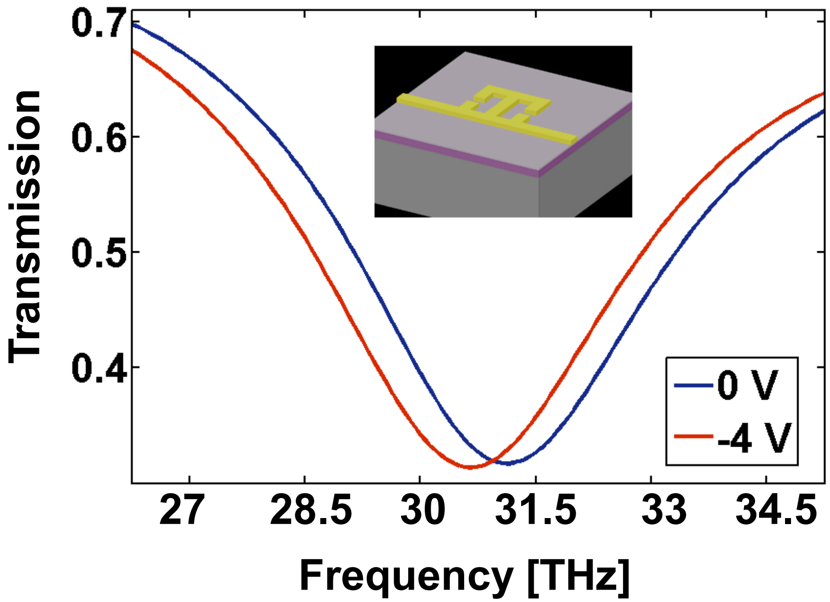




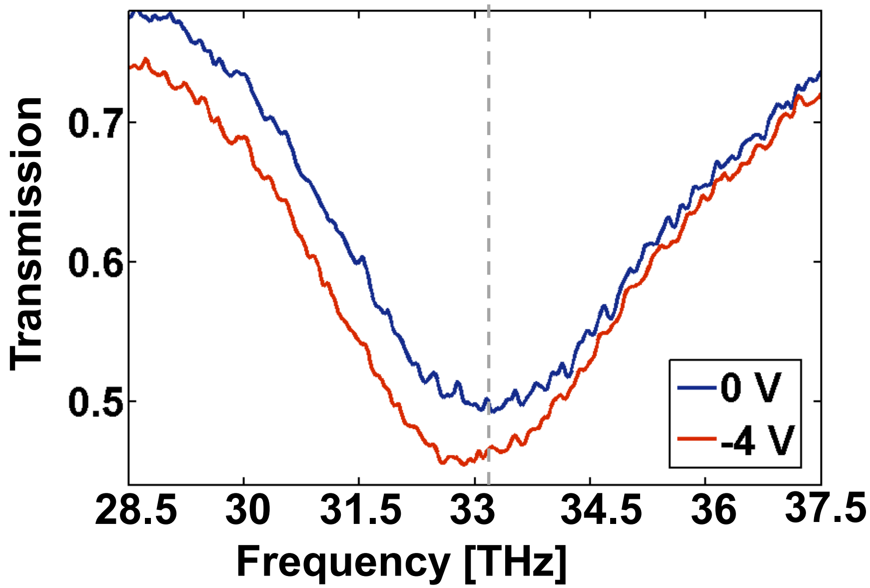
* SRR array patterned by E-beam lithography (connected to Metal gate)

Experimental Results

Theory



Experiment



- **Metamaterial transmission spectrum red-shifts with external bias (small..)**

Optics Express 20, 1903 (2012)

Depletion Region is Thin (because we work in IR)

Large changes in ε happen near the plasma frequency

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

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

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

Where φ_s is a surface potential which is related to the gate voltage:

$$V_G = \phi_s - \frac{\varepsilon_{GaAs}}{\varepsilon_{AlGaAs}} W_{barrier} \left[\frac{2qN_D}{\varepsilon_{GaAs}\varepsilon_0} |\phi_s| \right]^{1/2}$$

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  - Depletion: Thz
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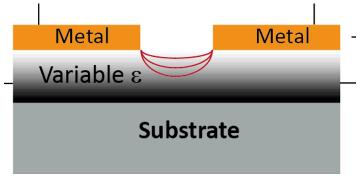
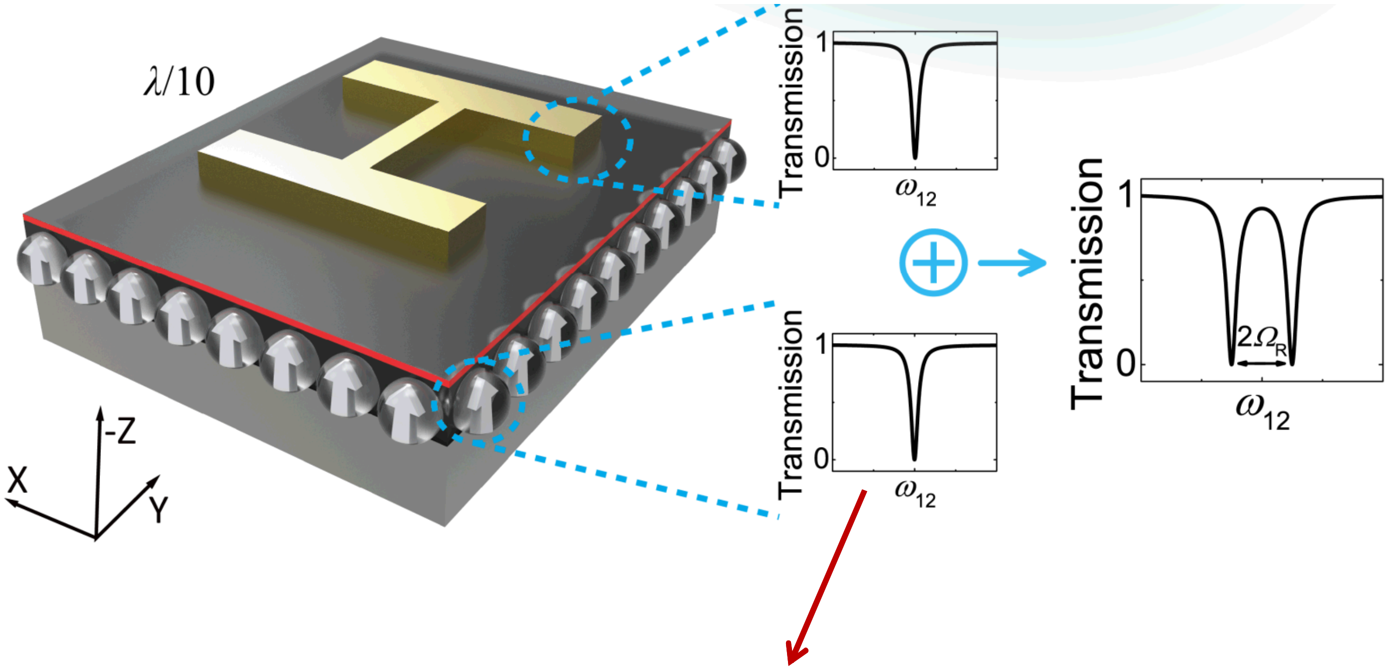
More Tuning Options: Coupling

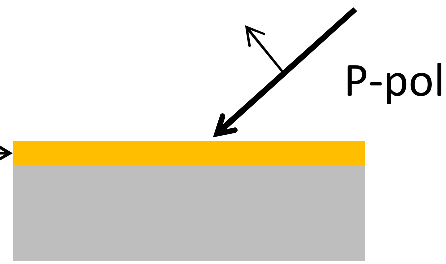
MM resonators create strong optical fields that lead to strong coupling

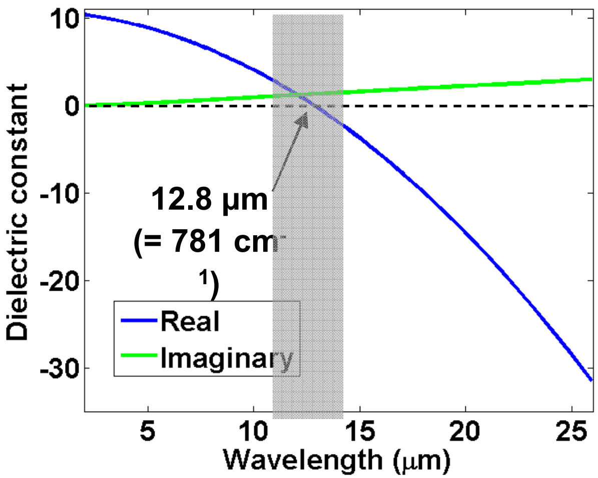




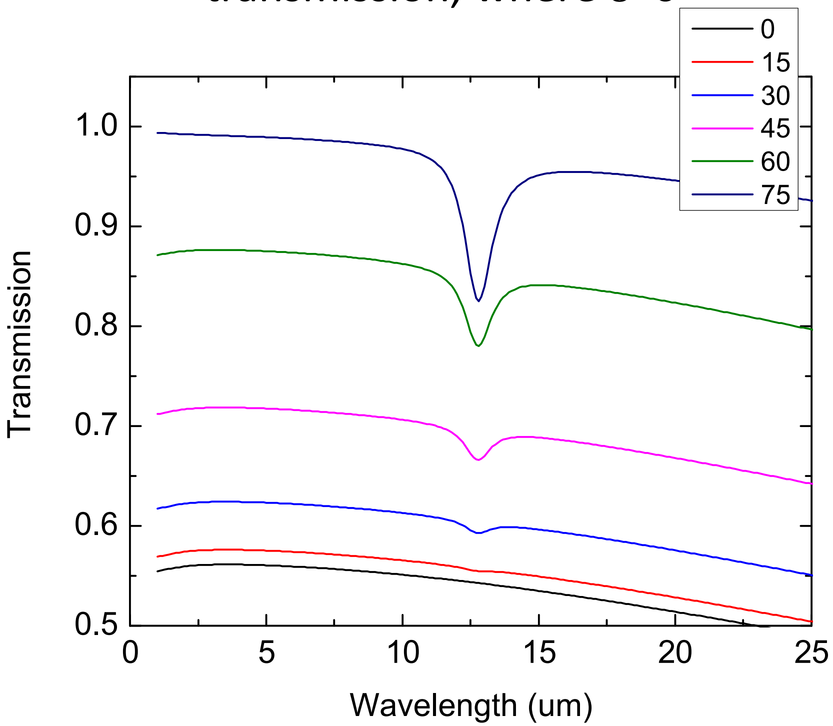
Optical Phonons: Nano Letters 11, 2104 (2011)
Epsilon Near Zero modes: Nano Letters **13**, 5391 (2013)
Intersubband Transitions: Nature Communications 4, (2013)

Coupling Between Metamaterial Resonators and "Epsilon Near Zero" Waves





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

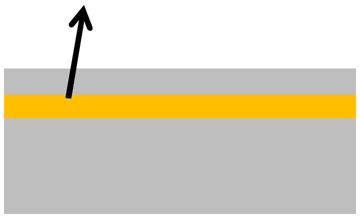


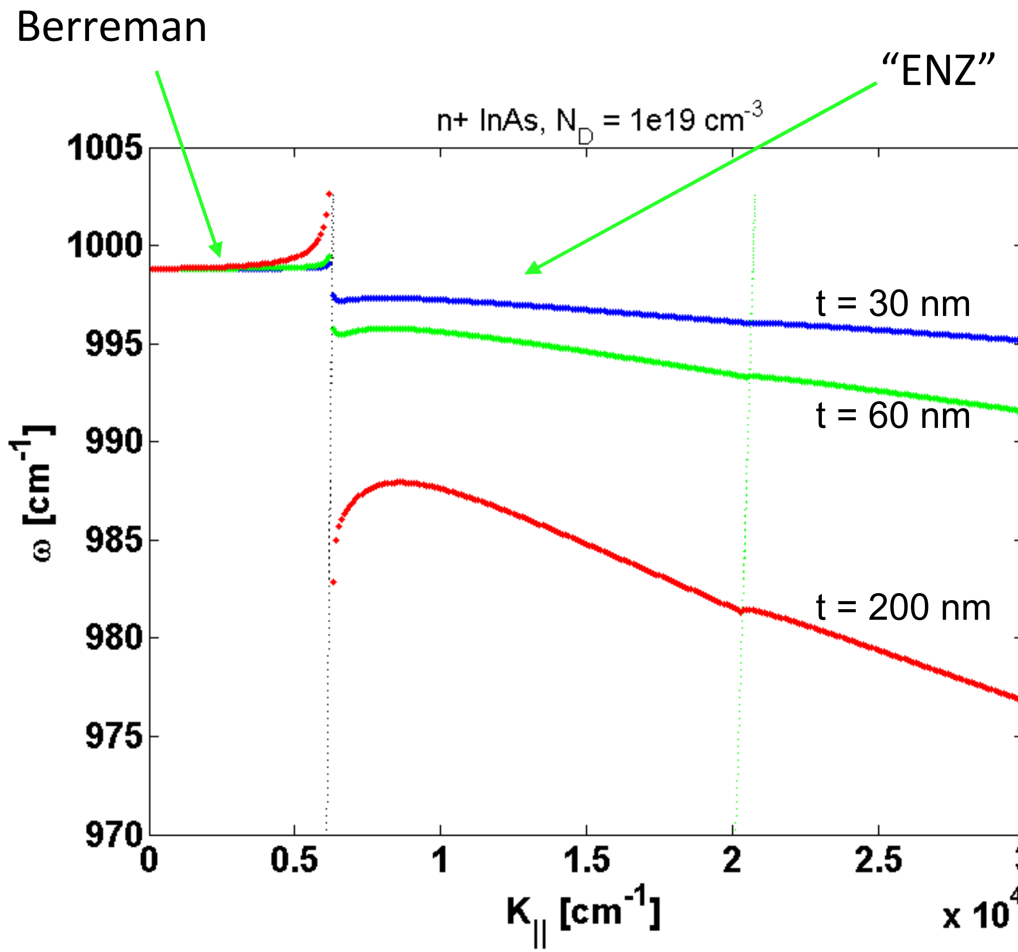
("Berreman" dip)

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

Berreman mode vs ENZ mode in n+ InAs

n+ InAs (Drude)

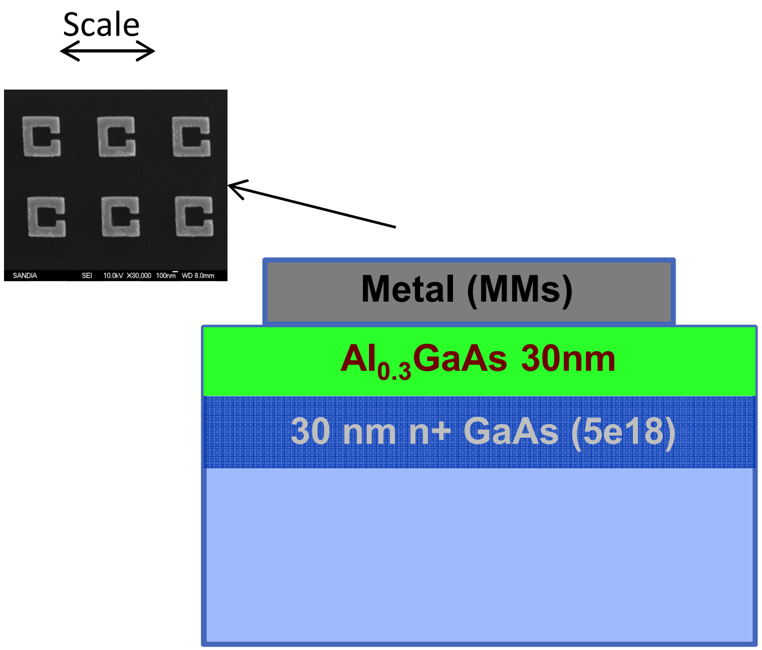


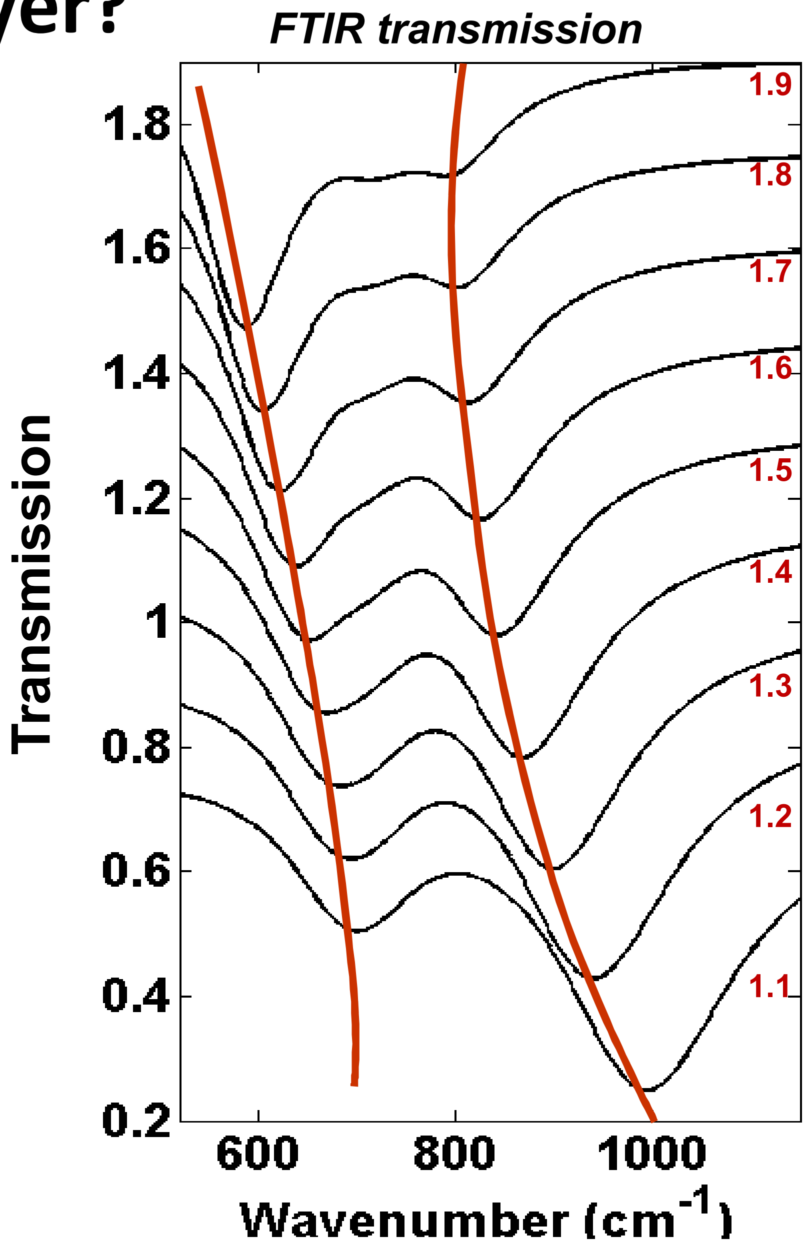


- Berreman mode is very flat for a thin doped layer and leaky into air
- ENZ mode does not couple to free space

Greffet et al, PRL 109, 237401 (2012)

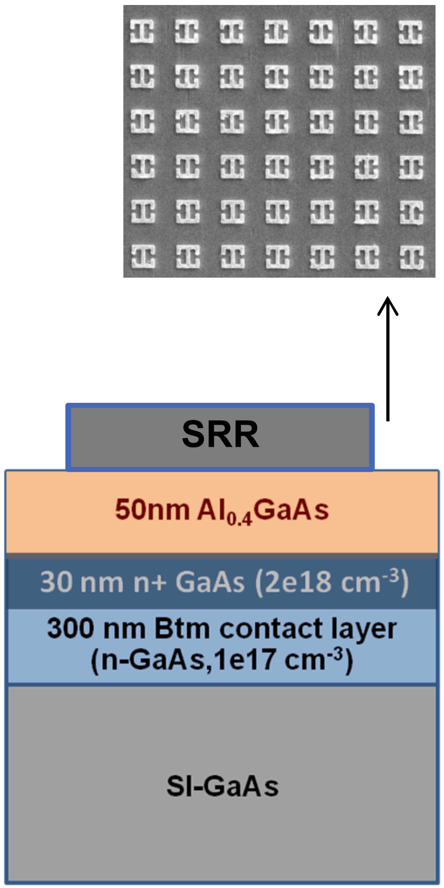
What Happens when MMs Resonate with ε~0 Layer?



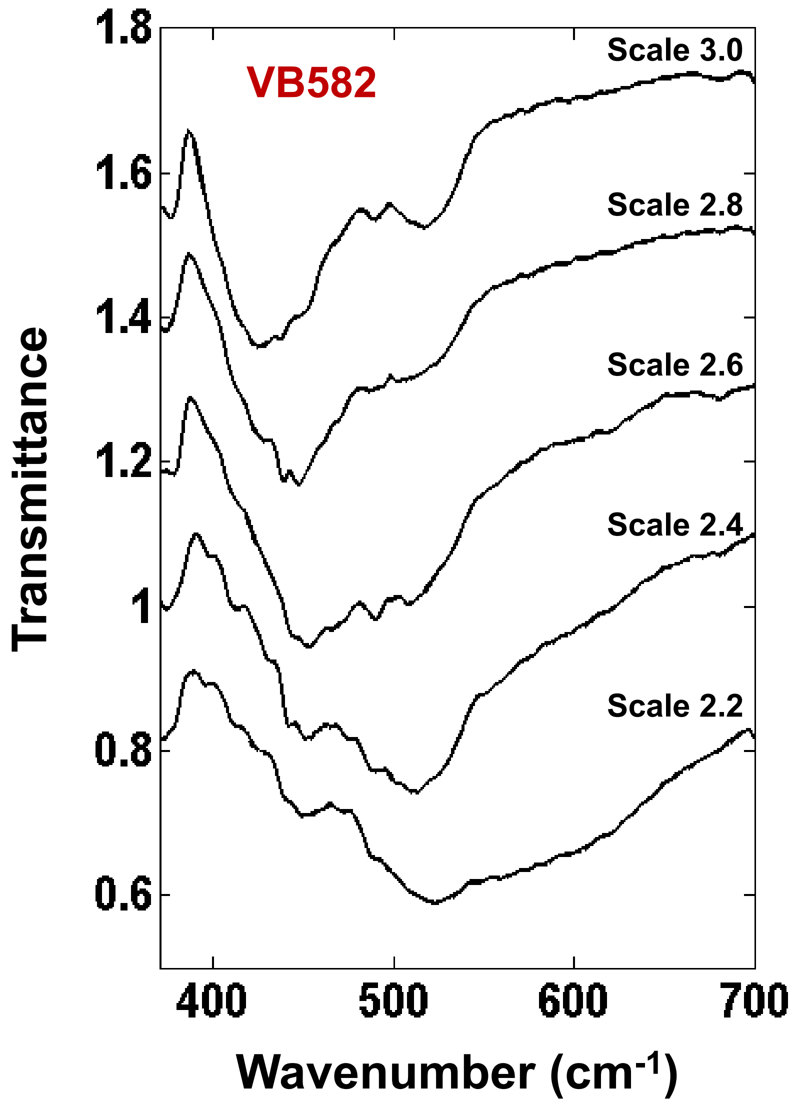


- Strong coupling between the MM resonance and ENZ waves!

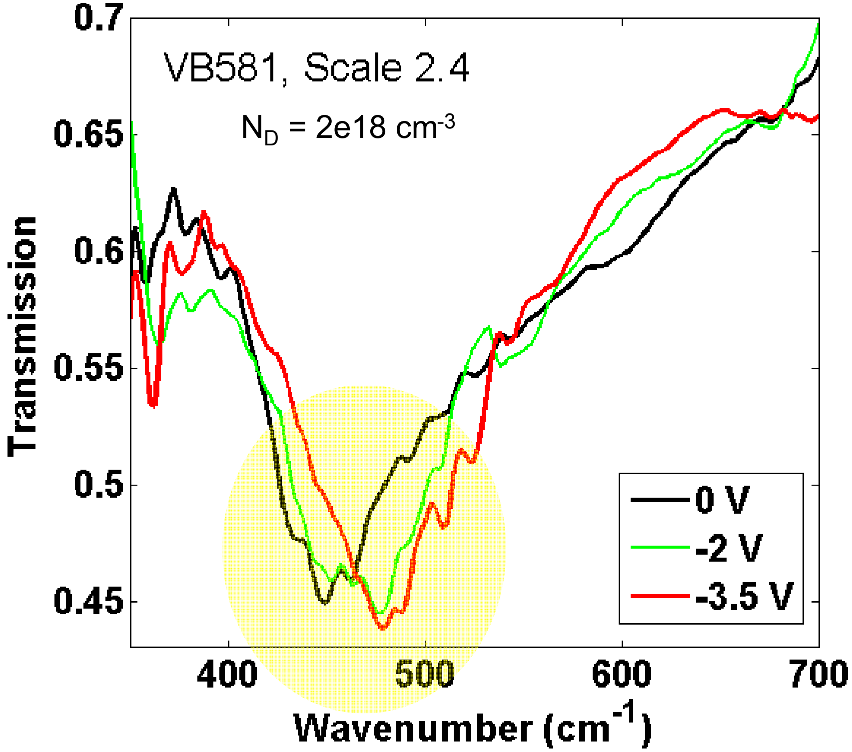
ENZ Strong Coupling ($N_D = 2e18\ cm^{-3}$)

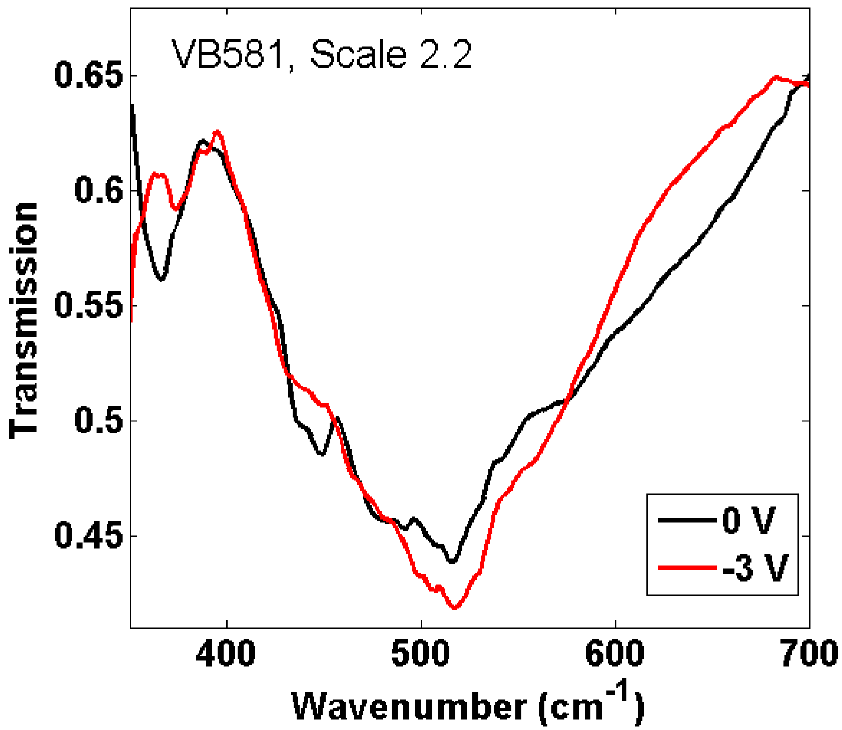


FTIR Transmission spectra



Electrical Tuning the Coupling to the ENZ Mode





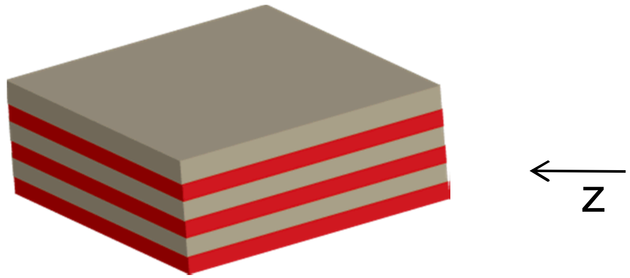
Fundamentally different than tuning just by changing a local permittivity!

Strong Coupling to Inter-subband Transitions in Quantum Wells

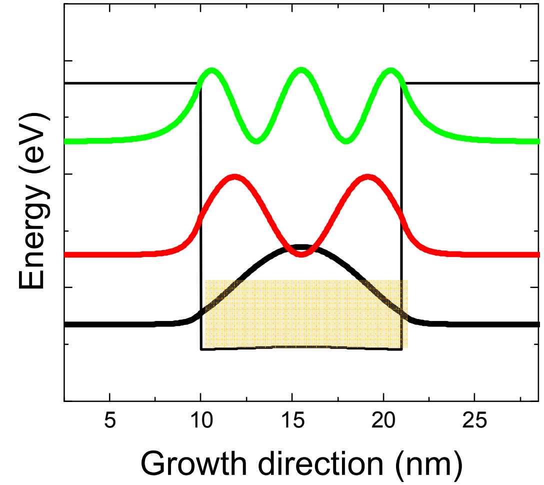
Alex Benz

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

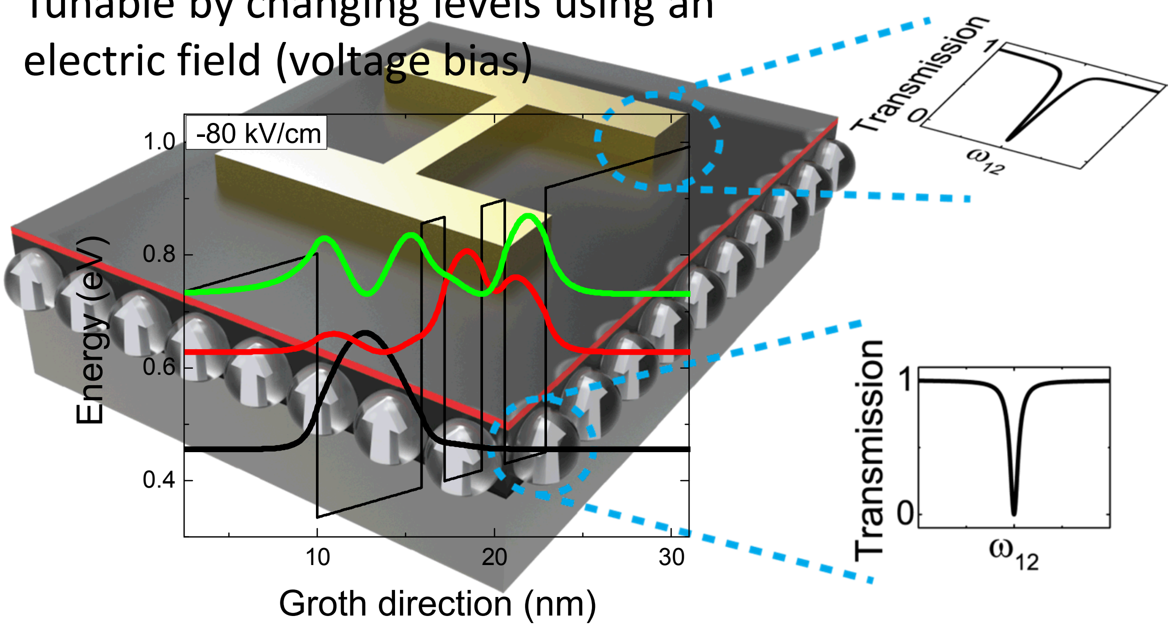
Opt. Express 20, 6584 (2012),
APL 98, 203103 (2011)



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

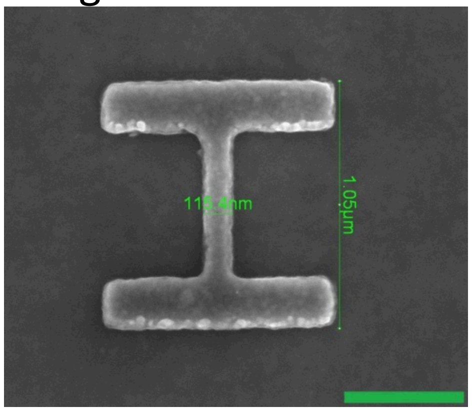


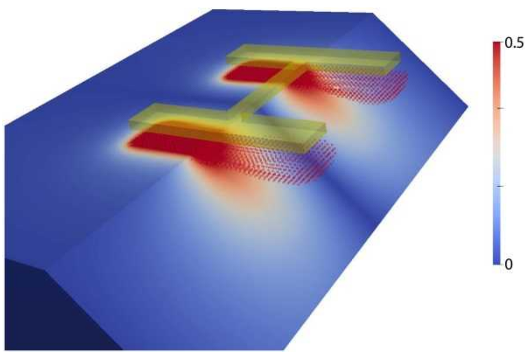
Tunable by changing levels using an electric field (voltage bias)

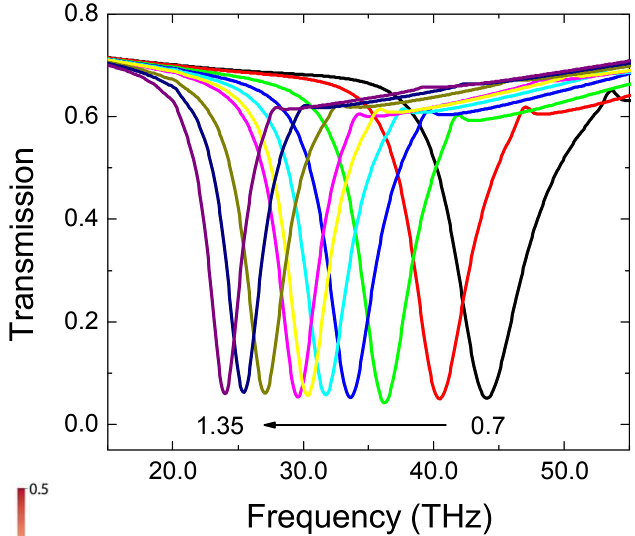


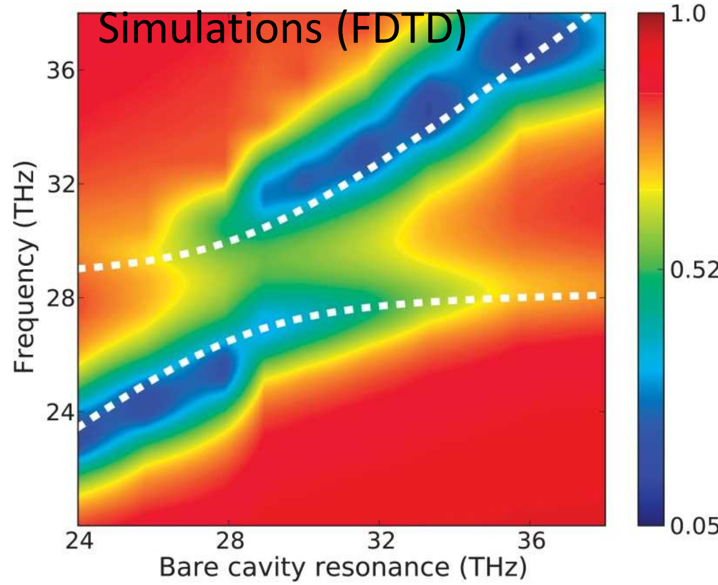
Strong Coupling Theory vs. Experiment

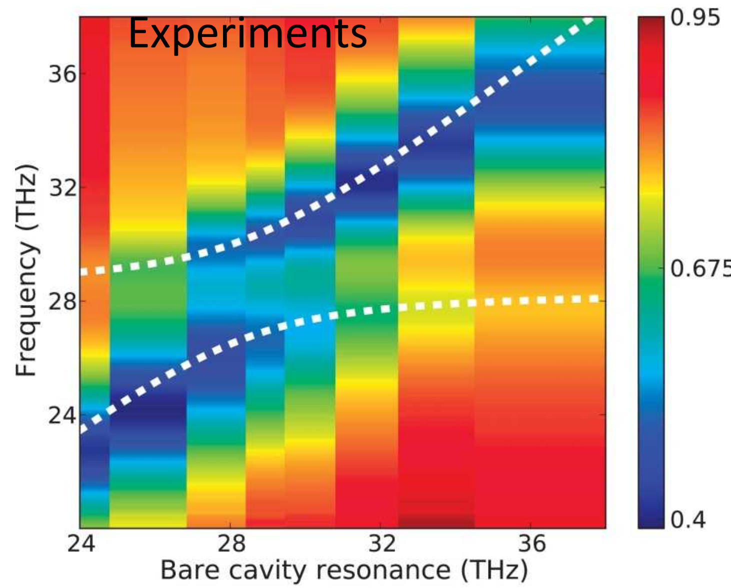
"Dogbone" resonators











Rabi frequency depends on simple parameters

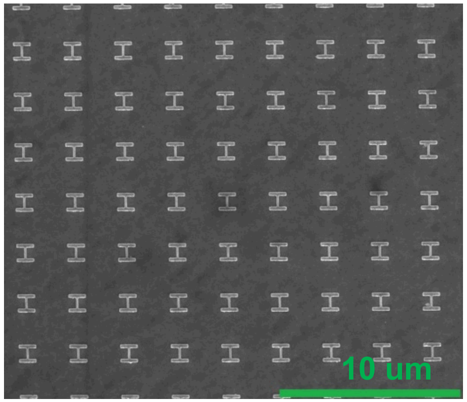
Plasma frequency

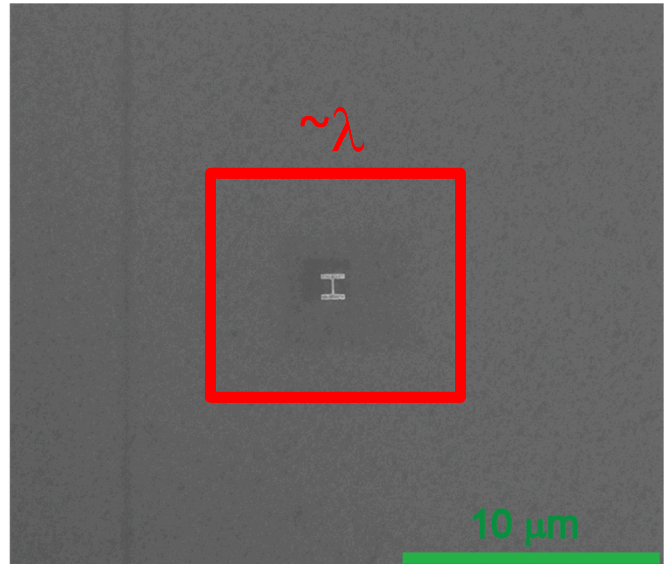
$$\Omega_R = \sqrt{f_W}\,\omega_p/2$$

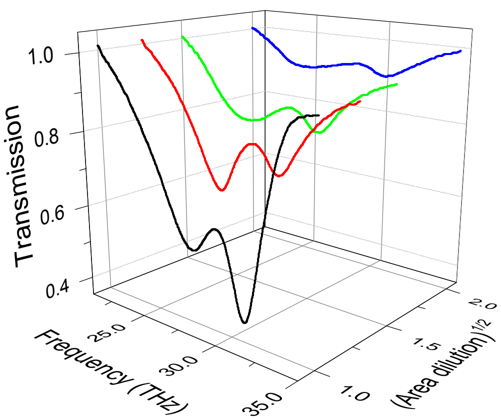
Geometry factor

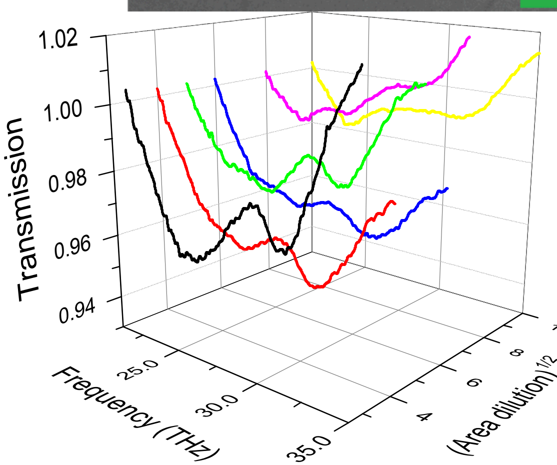
Nature Communications 4, (2013)
Phys. Rev. B 89, 165133

This is a "Single Resonator" Behavior









Same Rabi splitting remains down to a single resonator!

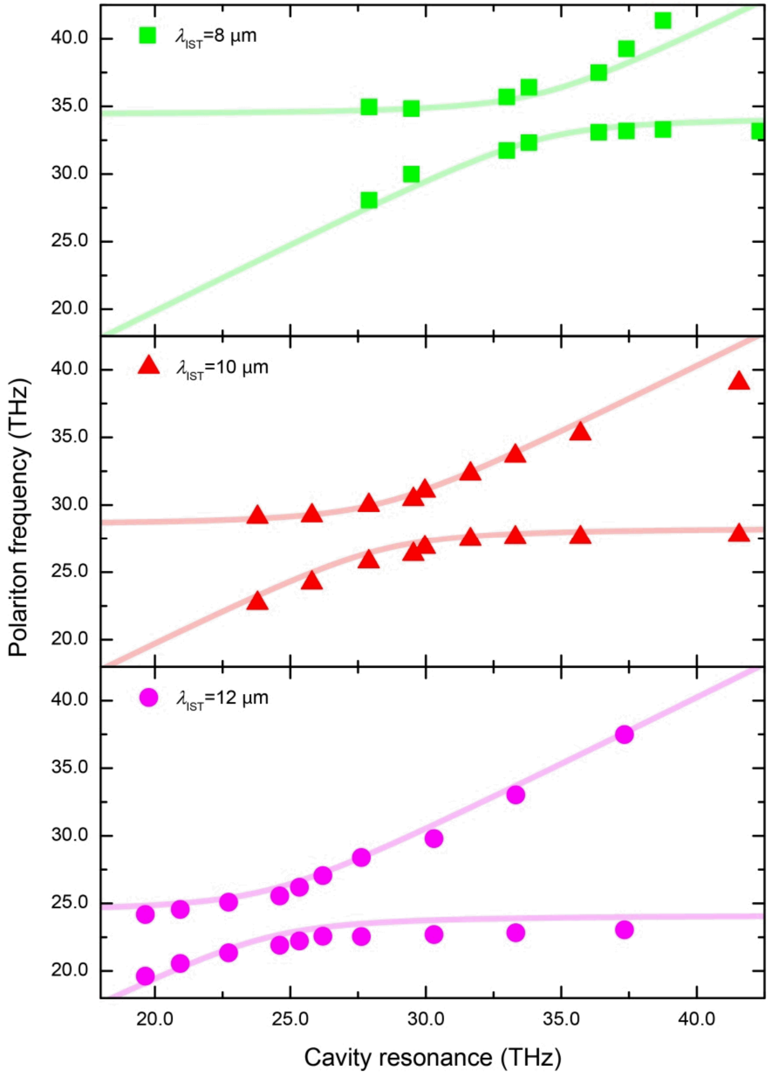
Nature communications 4, (2013)

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

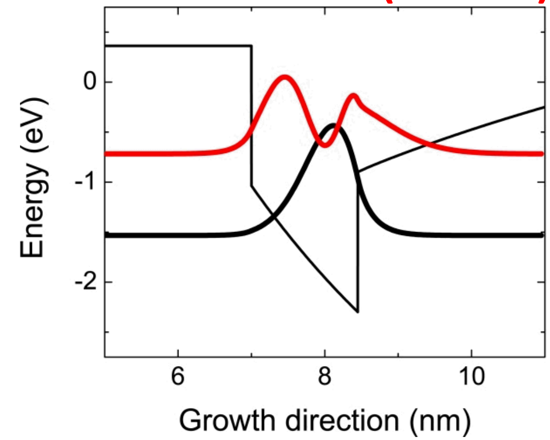
From Mid-IR to Near IR

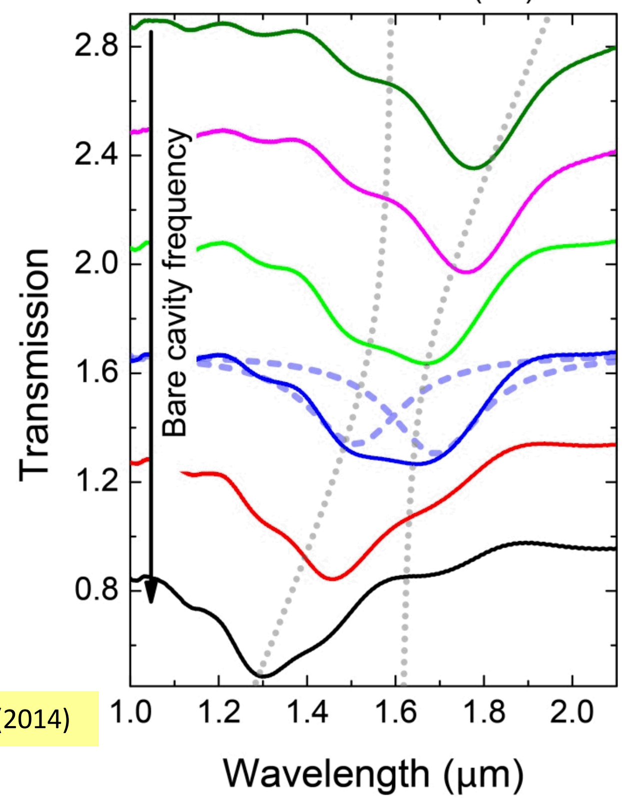
Alex Benz

InGaAs QWs **(mid IR)**



GaN QWs **(near IR)**

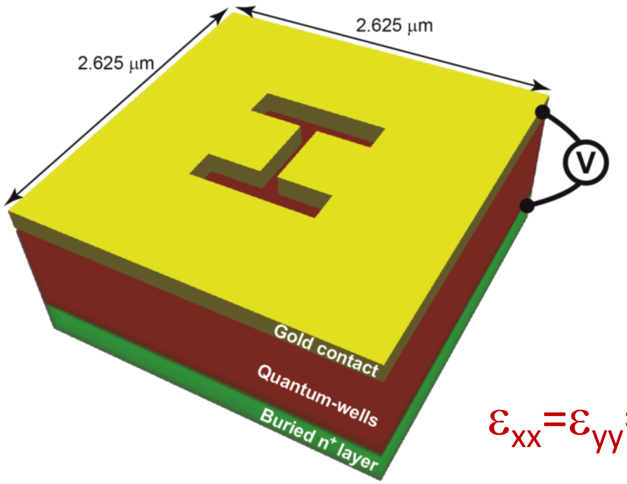




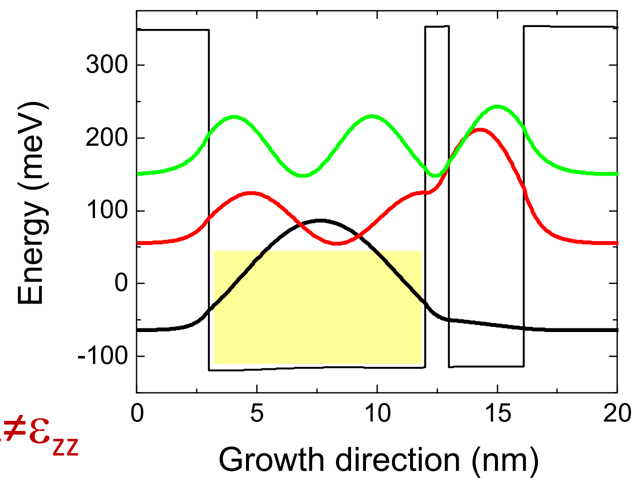
ACS Photonics (2014)

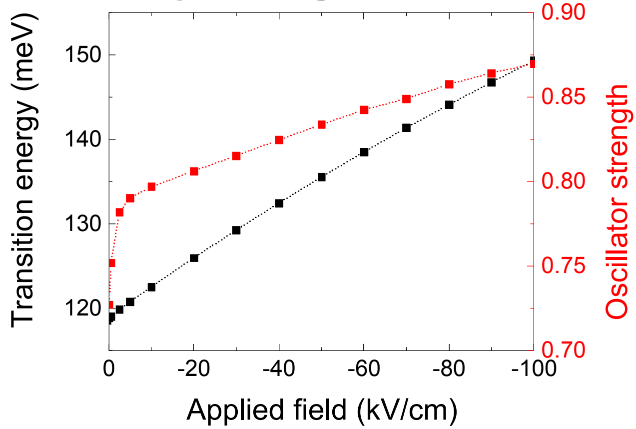
Nature Communications 4, (2013)

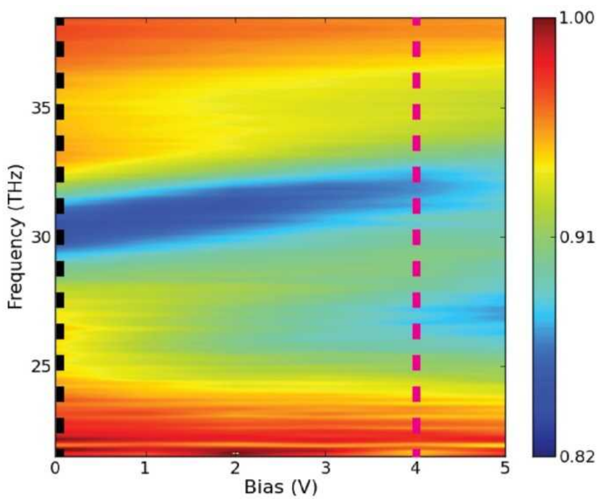
Electrically Tunable Strong Coupling

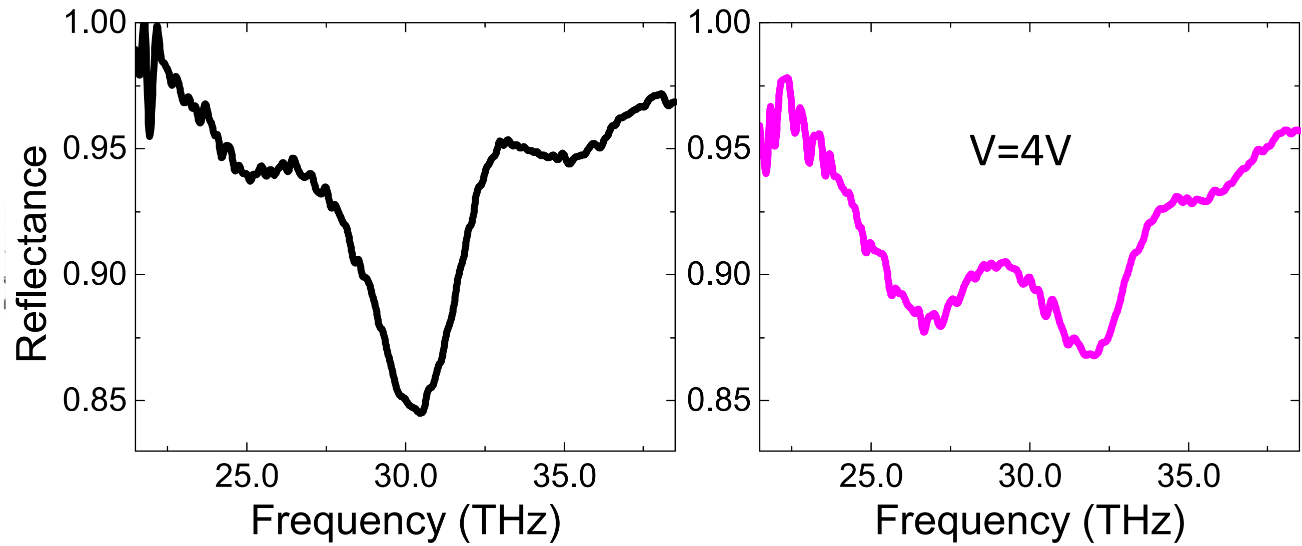


$\varepsilon_{xx}=\varepsilon_{yy}\neq\varepsilon_{zz}$









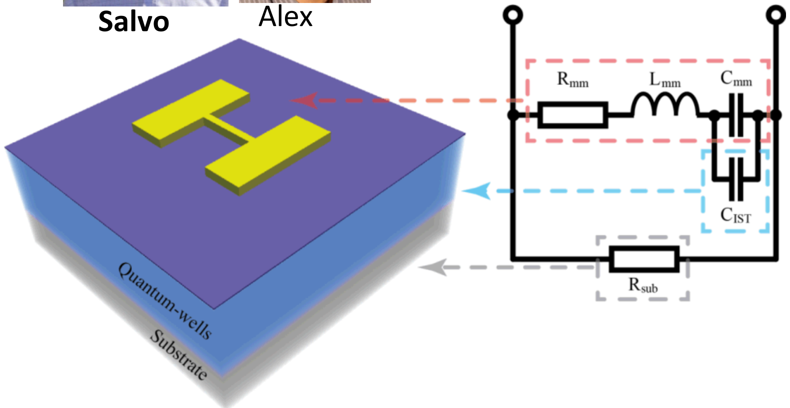
Upper polariton shifted by 2.5 THz (~8% of center frequency)

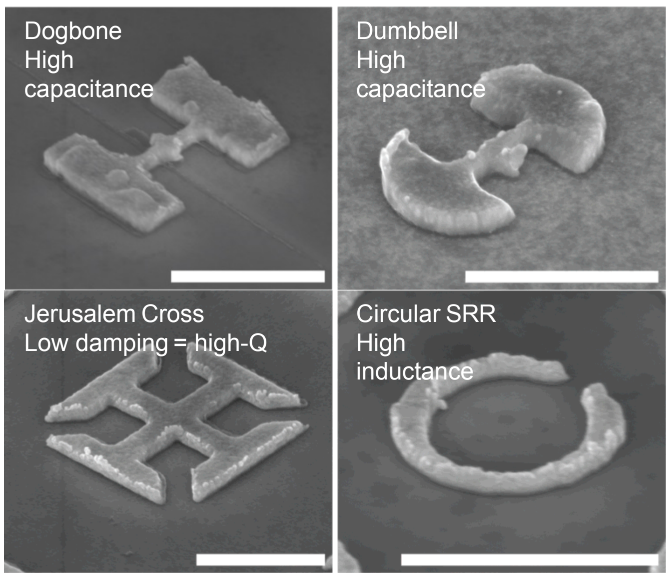
Appl. Phys. Lett. 103, 263116 (2013)

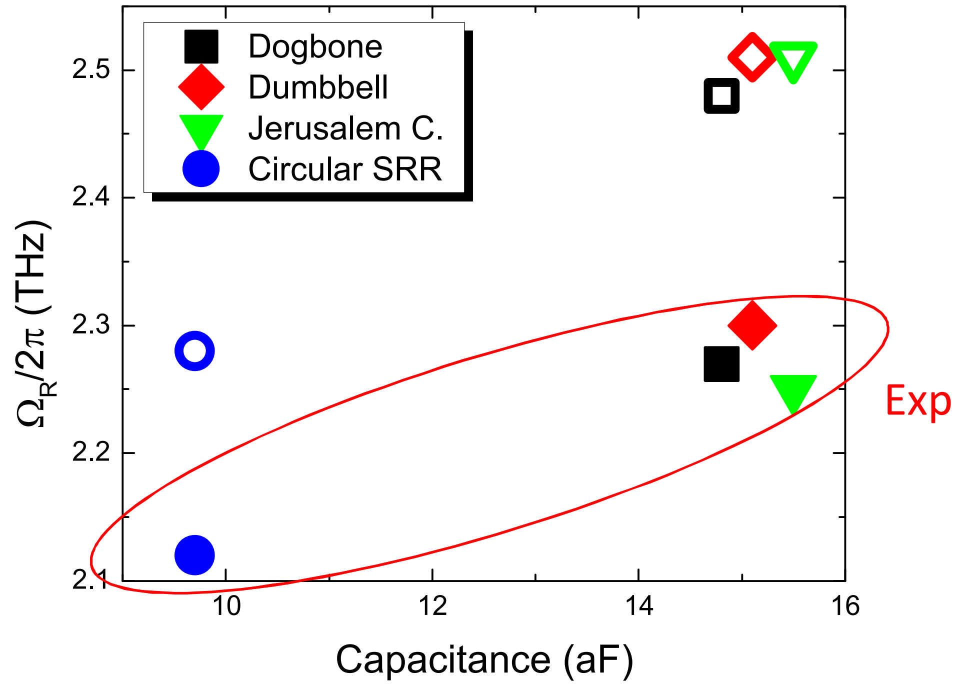
Salvo

Alex

Rabi Frequency vs. Geometry







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

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

Outline

- Electrically tunable metasurfaces
  - Depletion: Thz
  - Scaling to mid IR
  - Tuning by controlling coupling
    - Coupling to "epsilon near zero modes"
    - Coupling to intersubband transitions
- Enhanced optical nonlinearities

How Metasurfaces on Semiconductors Can Be Used for Enhanced Optical Nonlinearities

Conventional SHG, perfect phase-matching

$I_{2\omega} \sim (I_{\omega}\,\chi^{(2)} L)^2$

$\chi^{(2)}$

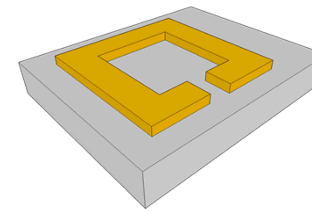
L

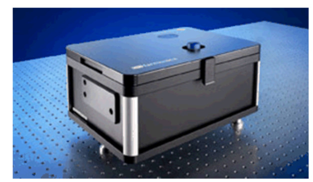
Increase I or L

Cavity-enhanced

$I_{2\omega} \sim Q^2$

$\chi^{(2)}$





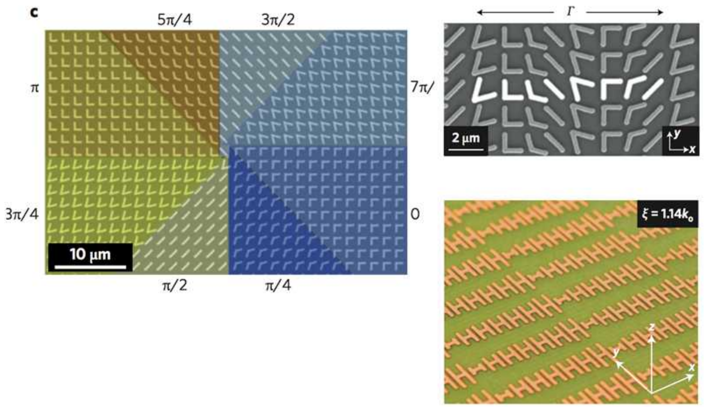
Coherent Inc.

Increase $\chi^{(2)}$

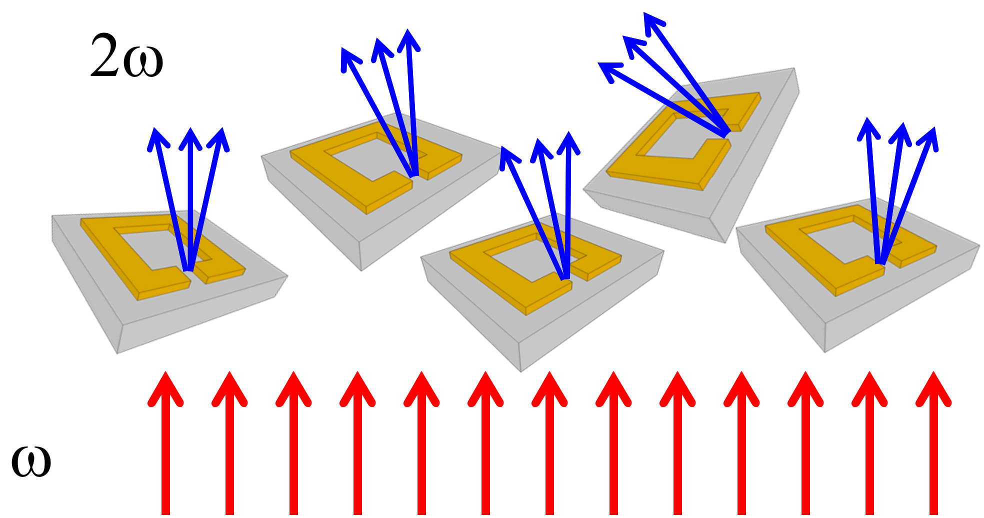
Use <u>resonant</u> $\chi^{(2)}$ with semiconductor heterostructures ~ 10^4 enhancement in $\chi^{(2)}$

Metasurfaces Provide New Functionality for Harmonic Generation

Metallic Metasurfaces have been used extensively for beam/phasefront/polarization manipulation: *this is all degenerate*

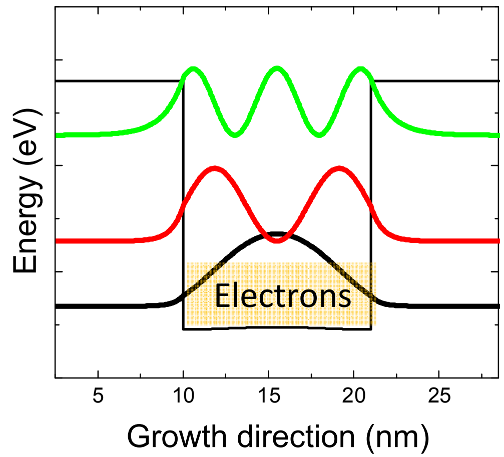


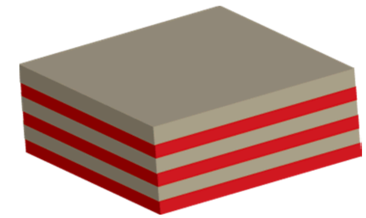
(Shalaev, Capasso, Zhou, Zheludev, etc..)



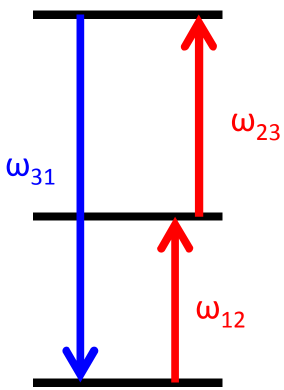
Resonant Optical Nonlinearities: Intersubband Transitions in Quantum Wells

Electronic levels and wavefunctions can be engineered with semiconductor heterostructures





Resonant optical nonlinearities can be engineered too:

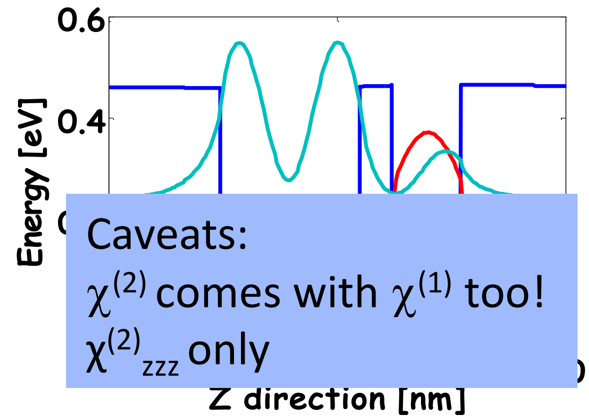


$$\chi^{(2)}(\omega) \propto \frac{N \cdot z_{12} z_{23} z_{13}}{(\omega - \omega_{12} - i\Gamma_{12})(2\omega - \omega_{13} - i\Gamma_{13})}$$

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

~250 nm/V - QWs

10s of pm/V - $LiNbO_3$



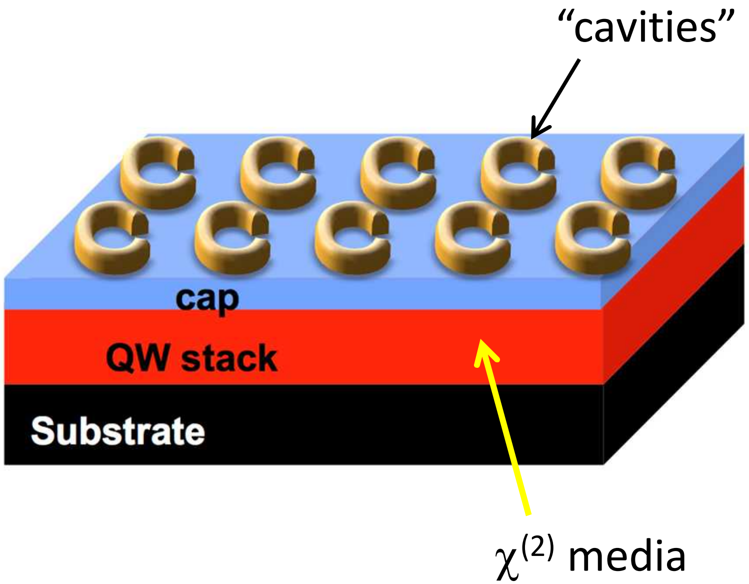
Caveats:
$\chi^{(2)}$ comes with $\chi^{(1)}$ too!
$\chi^{(2)}_{zzz}$ only

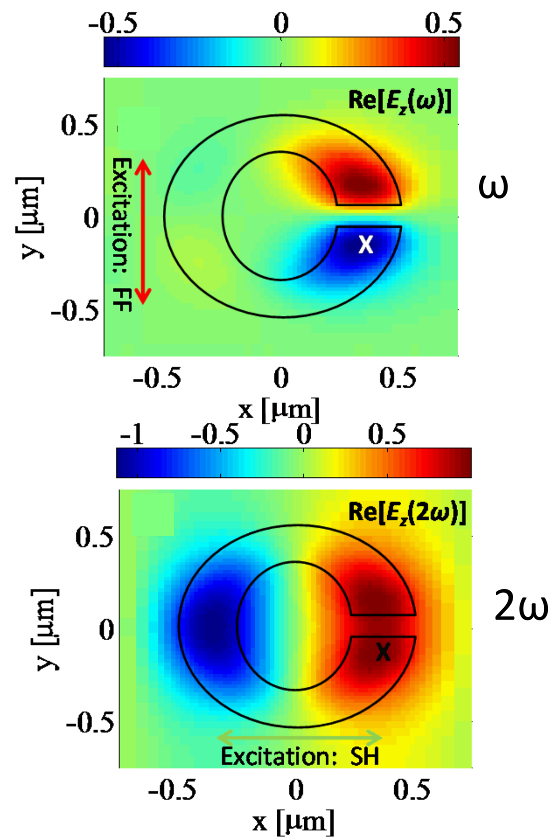
F. Capasso, C. Sirtori, and A.Y. Cho, IEEE J. Quantum Electron. 30, 1313 (1994)

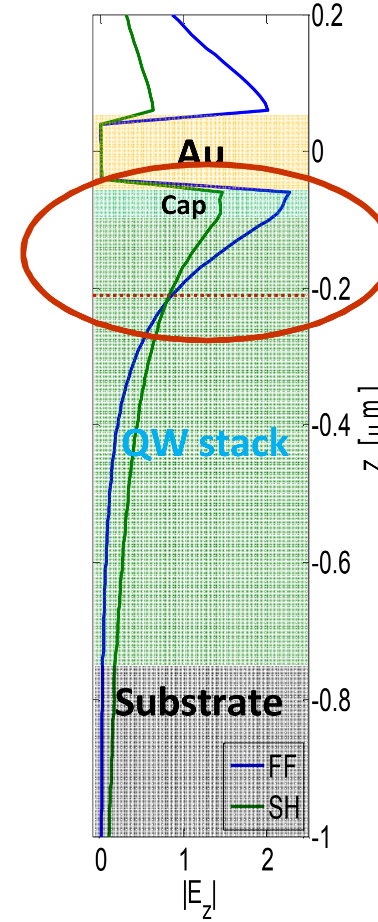
Salvo Campione

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

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



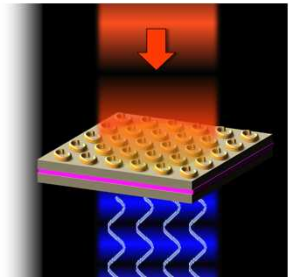


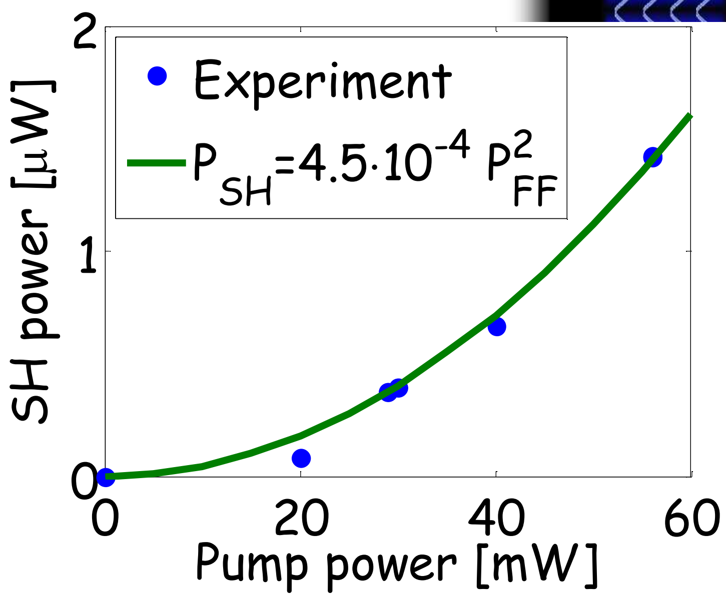


APL **104**, 131104 (2014)

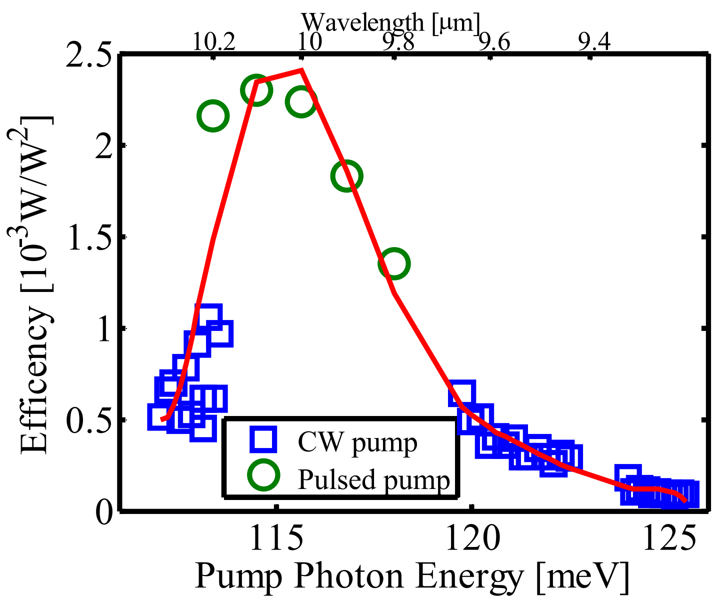
SHG: Power and Frequency Dependence

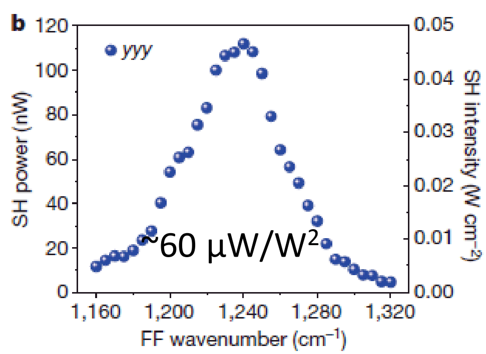
Pump: CW CO_2 laser





max efficiency: ~2.3 mW/W^2



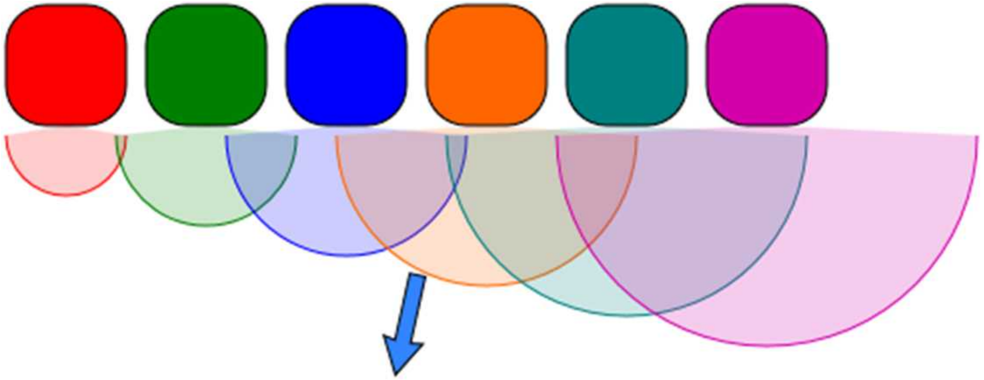


Lee, Belkin, Alu, et al. *Nature* 511, 65-69 (2014).

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

Nature Communications 6, 7667 (2015)

Phased Arrays



Identical point sources

+

Radiating with controllable phase difference

==

Full control over beam direction and shape

Image from Wikipedia

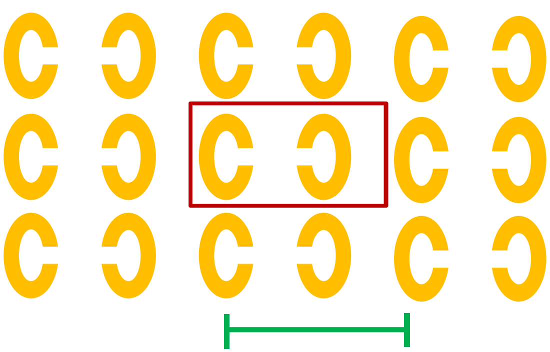
SHG Beam Manipulation


Omri


Salvo

“edge-fed dipole”

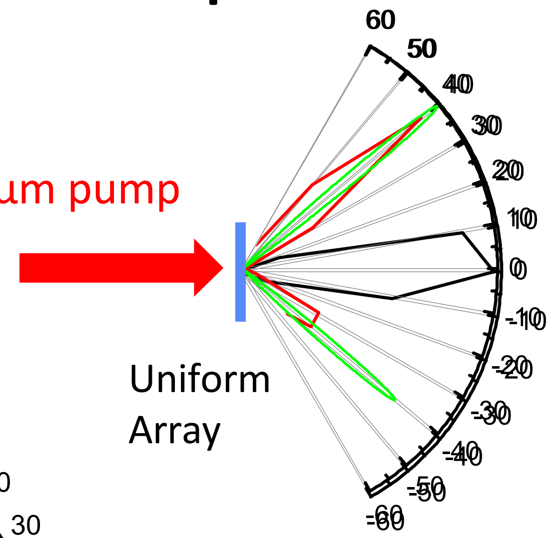
flipping induces π phase shift



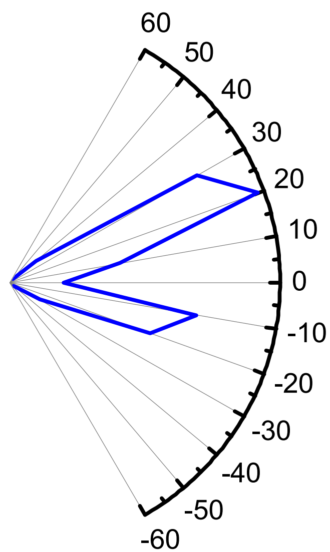
Period determines angular separation

10μm pump

5μm beam



Uniform Array



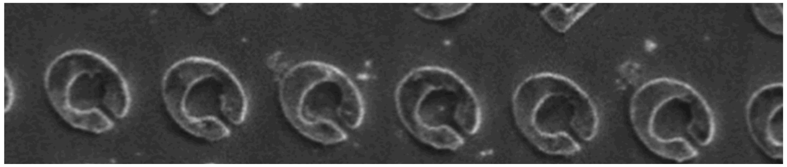
2-in-1:

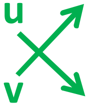
Source +beam splitter

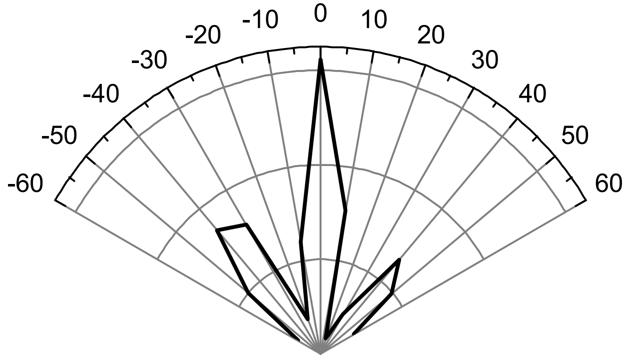
Nature Communications 6, 7667 (2015)

SHG Beam Manipulation II

- **Cavities radiate polarized light**

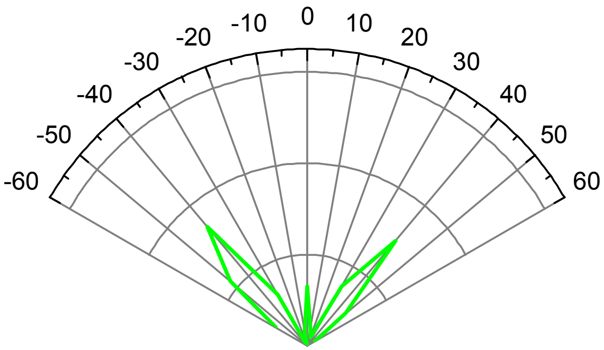




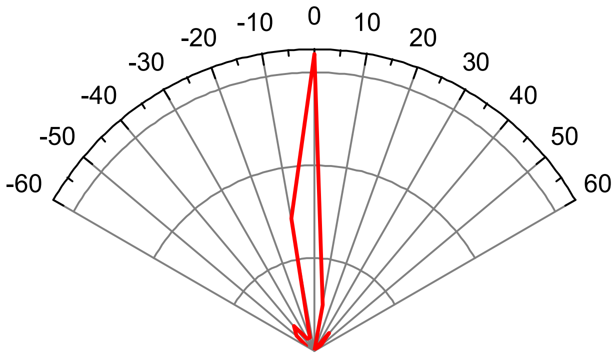


unpolarized

Pump polarization



v polarized

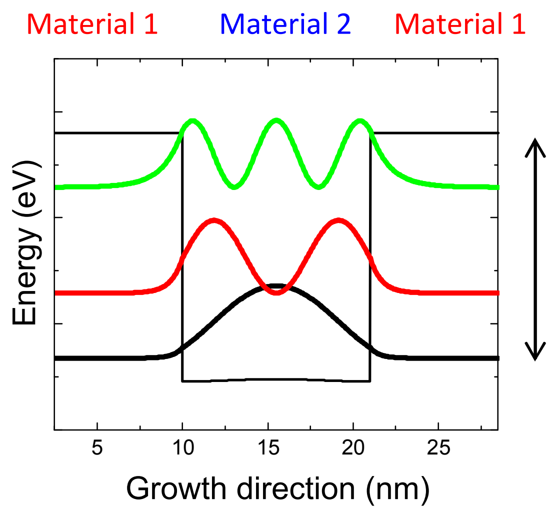


u polarized

3-in-1:

Source + Polarizer + Beam Splitter

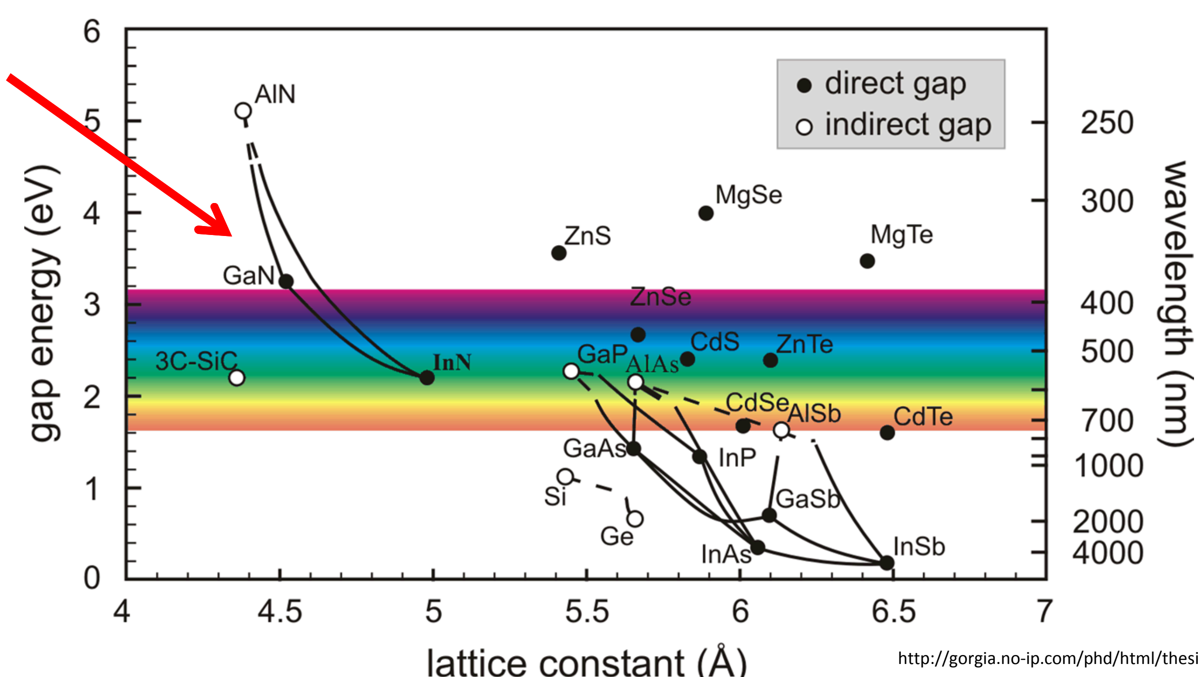
Scaling This Approach to Shorter Wavelengths



10um to 5um: AlInAs barriers
InGaAs wells
2ω ~ 0.24eV

How about 1.55um to 0.75um?
This requires a conduction band offset of ~1.6eV!!

III-Nitrides

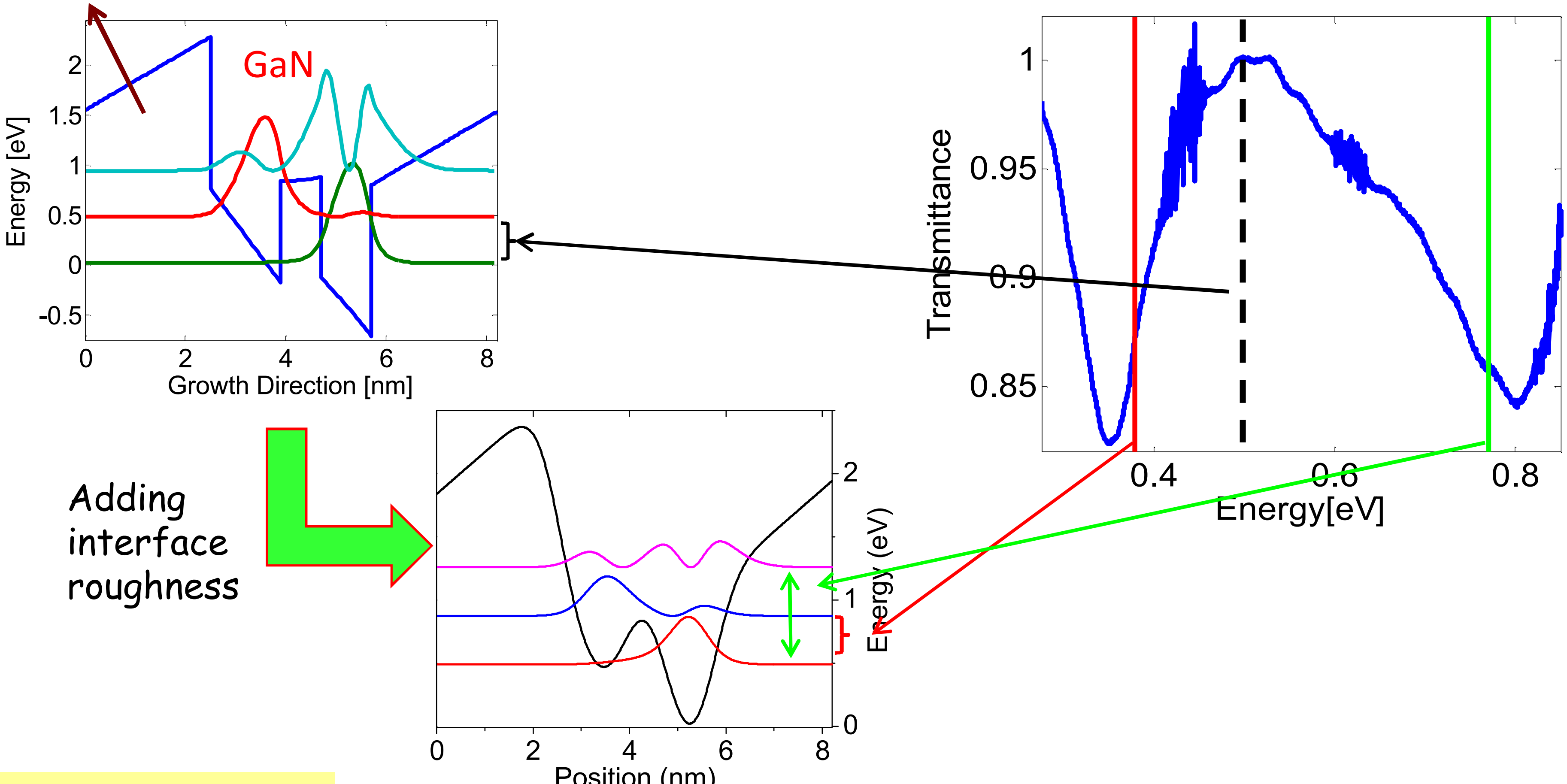


http://gorgia.no-ip.com/phd/html/thesis/phd_html/simone-jbook.html

Omri Wolf

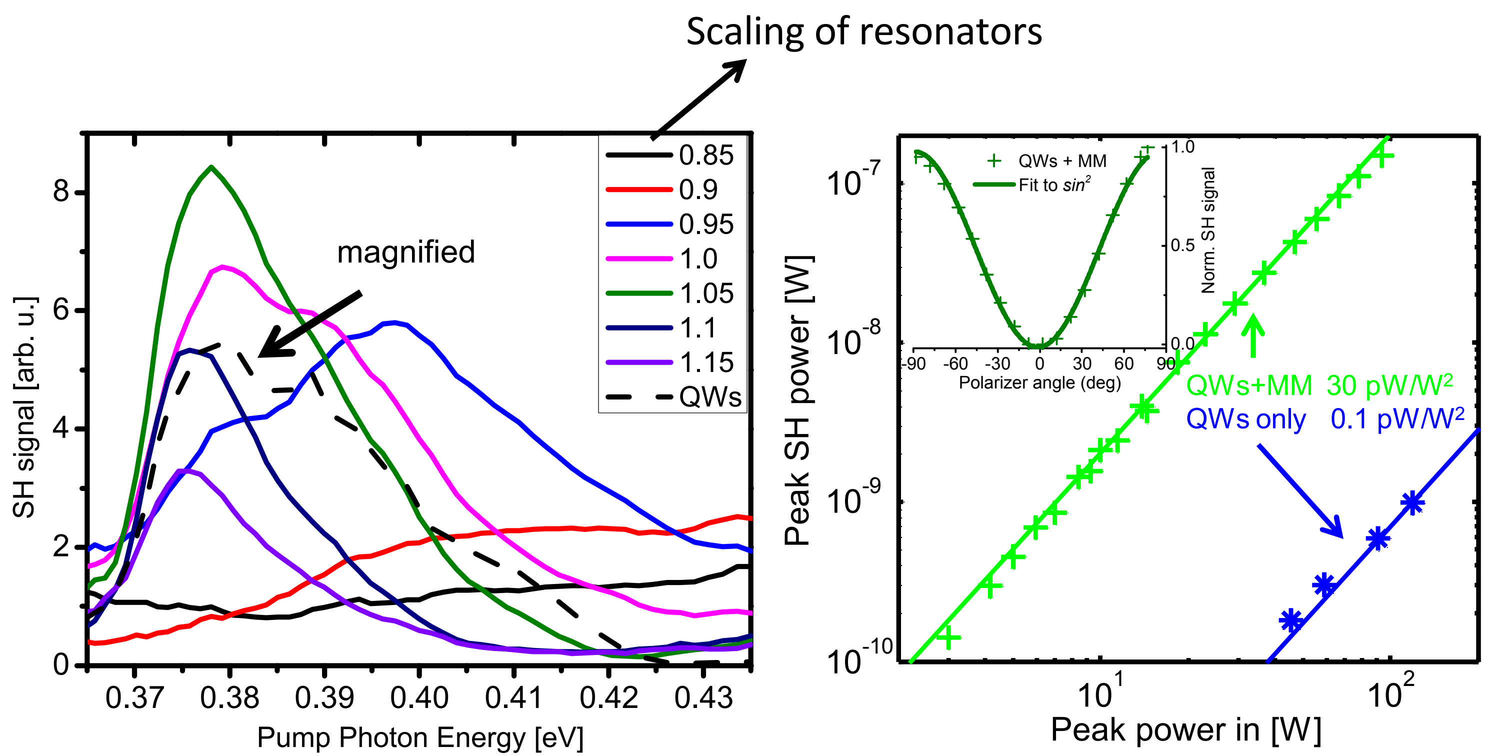
SHG (3.2μm>1.6μm) Using AlGaN/GaN QWs

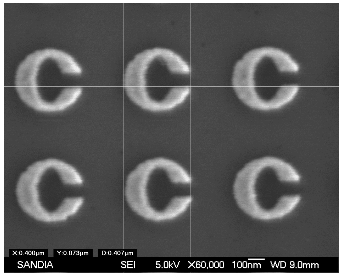
- **Design: SHG 3 μm → 1.5 μm (0.4 eV → 0.8 eV)**
- **Traditional band structure calculation <u>not enough</u>**
  - **Over estimation of IST**



O. Wolf et al. APL 2015

SHG (3.2μm>1.6μm) Using AlGaN/GaN QWs





In a III-N heterostructure, metamaterials increase efficiency by over 2 orders of magnitude

Summary & Acknowledgments

Metasurfaces **in conjunction with semiconductor heterostructures can enhance and provide new functionality for linear and nonlinear optics:**

- **Field Concentration**
- **Electrically tunable spectral filters**
- **Enhanced and more functional optical nonlinearitiess**

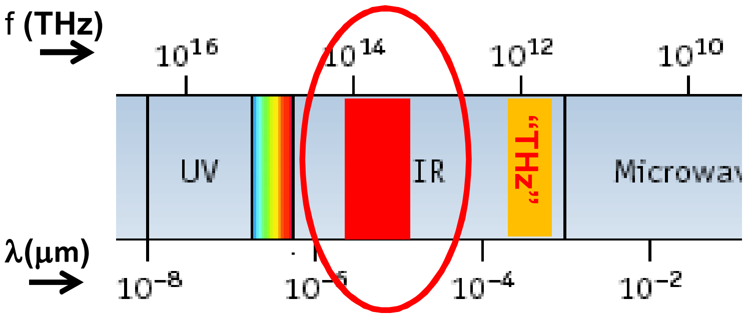
Postdocs: Salvo Campione, Omri Wolf, Sheng Liu

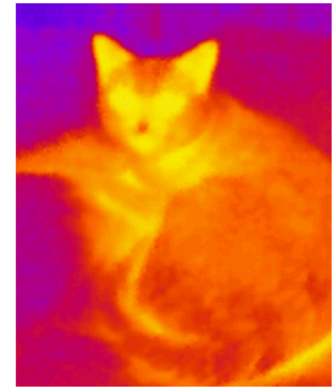
GaAs　　　　　　　　　　　　InGaAs

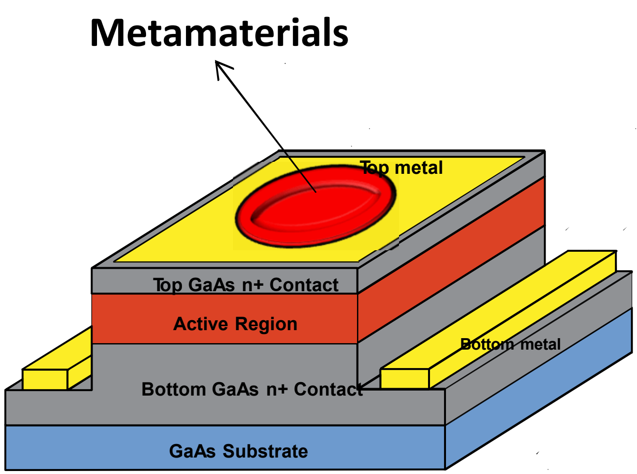
CINT + Sandia: John Reno, Mike Sinclair, Ines Montano, John Klem, Eric Shaner, Mike Wanke, Joel Wendt, Paul Clem, Jon Ihlefeld, Bruce Burckel, Jason Domingues, Andy Allerman, Sally Samora, Jon Wierer, ……

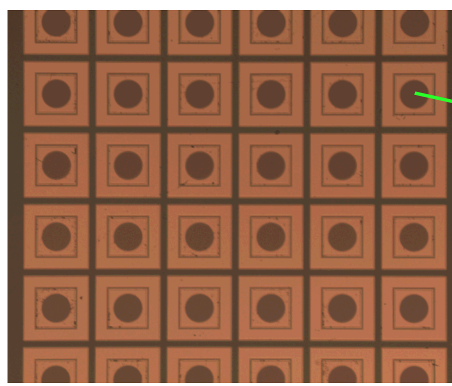
GaN

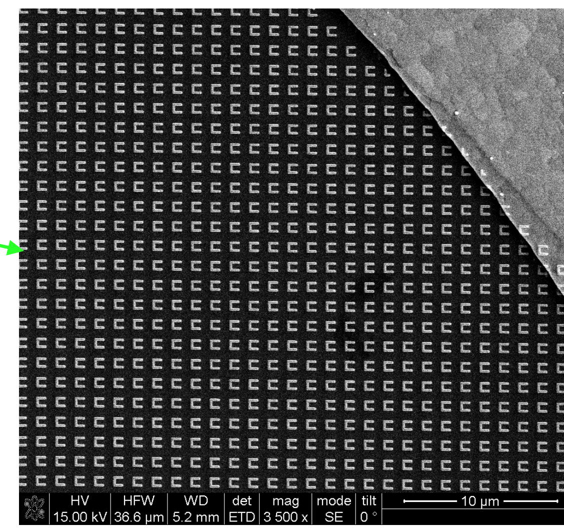
Metasurfaces for Improved Infrared Detectors







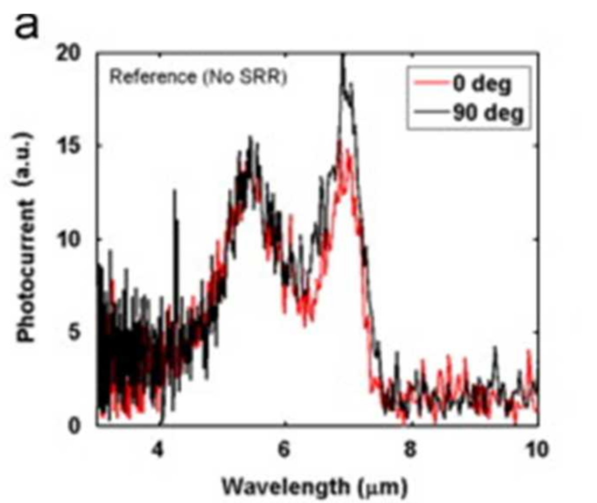


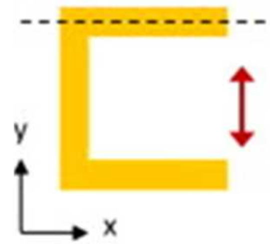


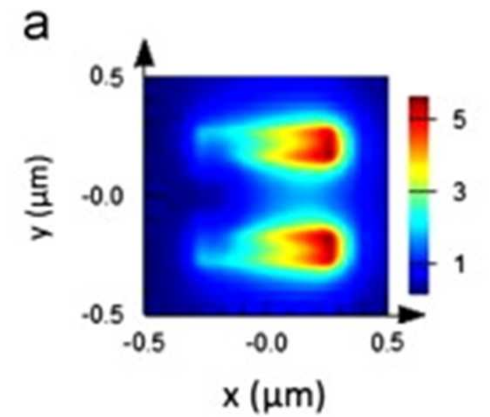
UNM (Krishna) & Sandia

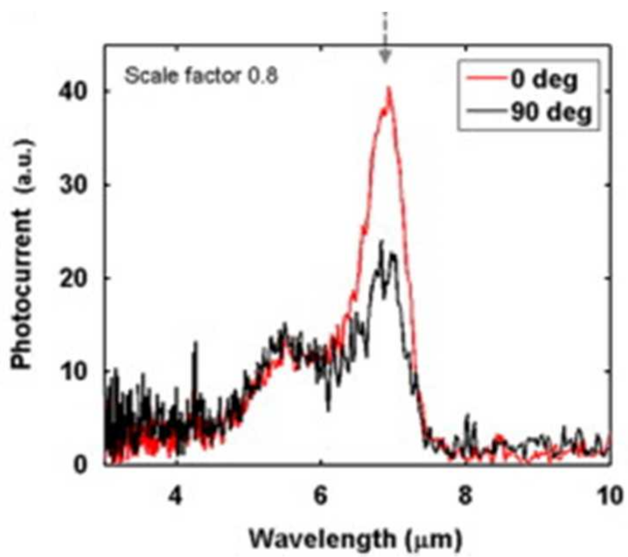
Optics Communications 312 (2014) 31–34

Improved IR Responsivity









UNM & Sandia

Other Related Topics

- **Equivalent circuit model in the strong coupling regime:** Physical Review B89, 165133 (2014)
- **Strong coupling to intersubband transitions in the near IR:** ACS Photonics 2014, DOI: 10.1021/ph500192v
- **Maximizing strong coupling by changing the metallic resonators:** *Nano Letters* Article ASAP, DOI: 10.1021/nl504815c
- **Integration of MM resonators with IR detectors:** Optics Communications 312, 31-34, 2014
- **Enhancing strong coupling with a doped backplane:** Optics Express 21 (26), 32572-32581,2013

Other Related Topics

- **Shaping PL from QDs:** ACS Photonics 2, 172-177 (2015) (with ANU)
- **Near field mapping of modes:** ACS Photonics 2014, Article ASAP, DOI: 10.1021/ph500232u (with ANU & UNM)
- **Tuning Dielectric metasurfaces with Liquid Crystals:** ACS Nano 2015, DOI: 10.1021/acsnano.5b00723, (with ANU)
- **Chiral and high Q Fano metasurfaces:** Nature Communications 5, (2014), doi:10.1038/ncomms4892 (with UT)
- **Third harmonic from Si metasurfaces:** ACS Photonics Article ASAP, DOI: 10.1021/acsphotonics.5b00065, Nano Letters 14, 6488-6492 (2014). (with ANU+Moscow State)
- **Near field modes, THz Mie resonances:** Optics express 22, 23034 (2014) (with UCL)