SAND2015-6602C

Tunable and Nonlinear Metasurfaces: Metamaterials Meet Optoelectronics

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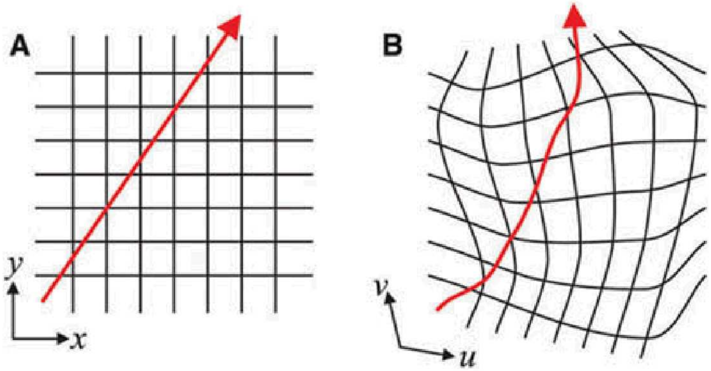
under contract DE-AC04-94AL85000.

Metamaterials



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

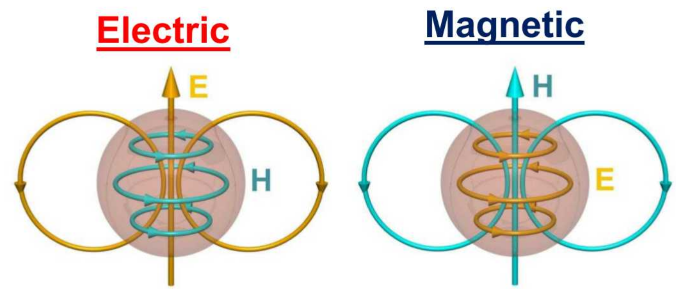
Change

The promise of metamaterials for (IR) applications was great:

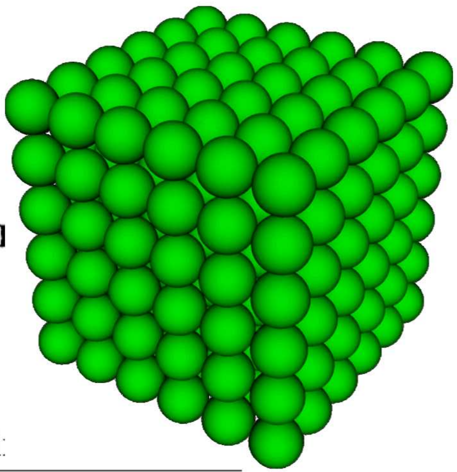
- **Wavefront control (Conformal optics, novel illuminators)**
- **Sub-λ Field Concentration**
- **Absorption / Emission engineering**
- **"Flat" optics (thin, lightweight)**

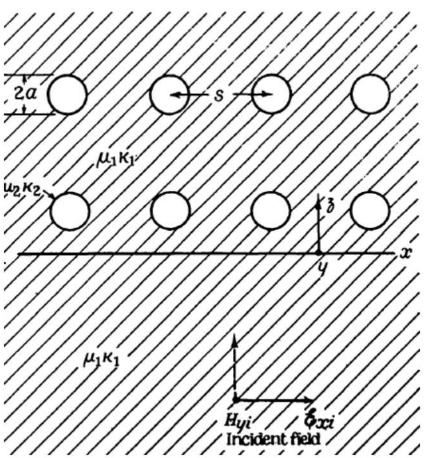
Arbitrary ε and μ Can be Achieved Also With Dielectrics (low loss approach)

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



Images: A. Miroshnichenko





THE ELECTRICAL CONSTANTS OF A MATERIAL LOADI
SPHERICAL PARTICLES*

By L. LEWIN.†

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

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

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

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

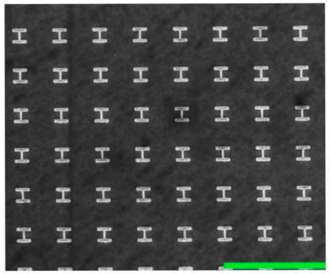
$$\theta = k_0 a\sqrt{\epsilon'_{r2}\mu'_{r2}}$$

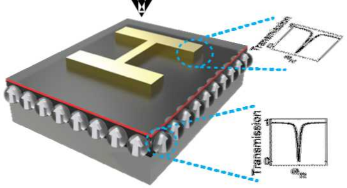
$$b_{\mathrm{e}} = \frac{\epsilon_1}{\epsilon_2}, \qquad b_m = \frac{\mu_1}{\mu_2}$$

Metallic

2D

Planar resonators on III-V substrate

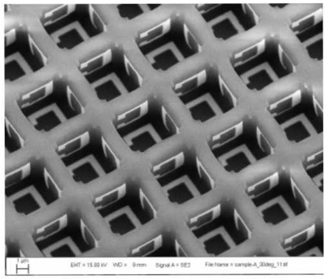




- **Strong coupling to phonons, plasmons, intersubband transitions**
- **Voltage tuning, tunable filters**
- **Nonlinear optics**

3D

Au SRRs on resist “cavities”

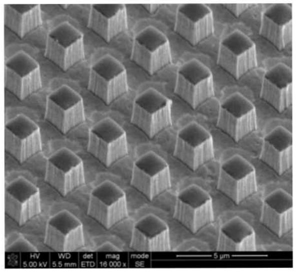


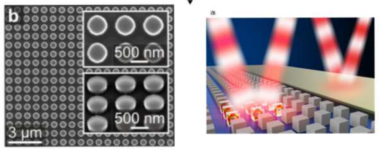
>1 layer:
Incredibly difficult
Too lossy

Dielectric

2D

Tellurium cubes on BaF2

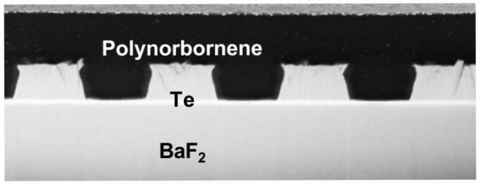




- **Optical magnetism**
- **Unidirectional scattering, Huygens metasurfaces**
- **Nonlinear optics**

3D

multi-layers of Tellurium cubes?



>1 layer:
Incredibly difficult

Metasurfaces

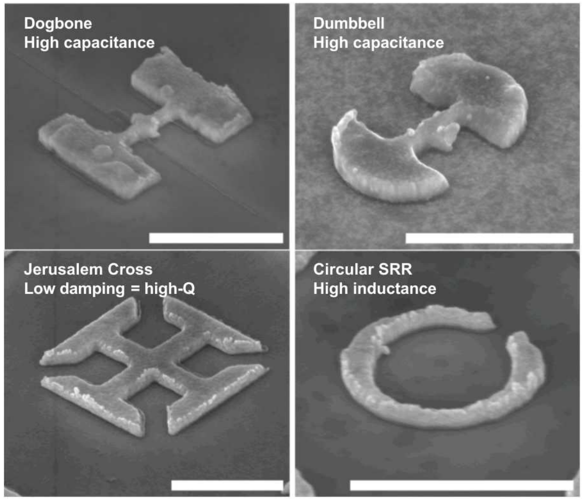
2D Metamaterials ("Metasurfaces")

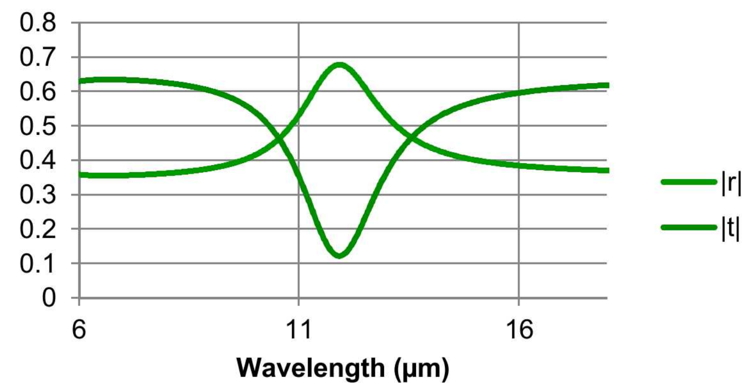
(for some applications, loss is a good thing)

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

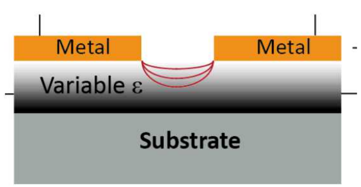
~λ/10

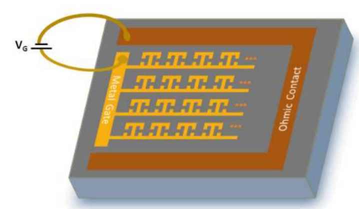
(Sandia)

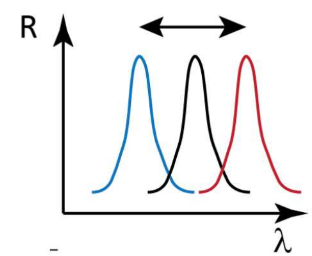




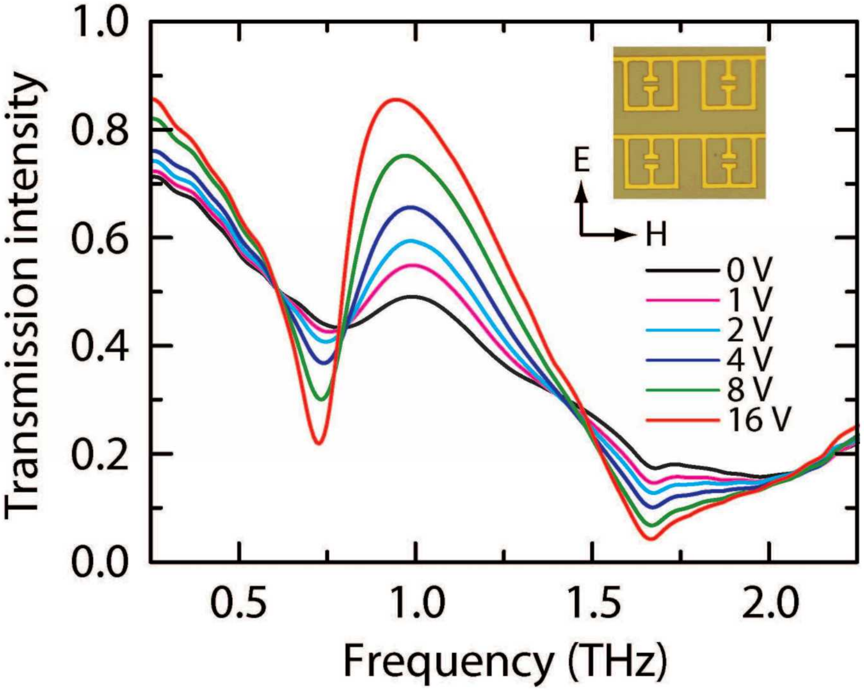
The spectral response is very sensitive to the dielectric environment



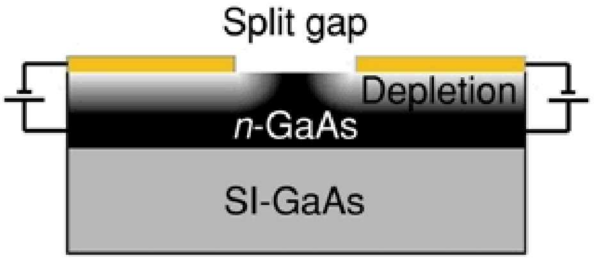




An Example at THz frequencies: Electrically Switchable Metamaterials Using Damping



Chen, Nature 444, 597 (2006).



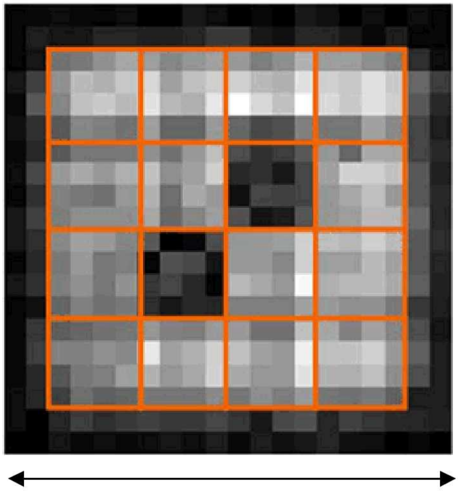
This works by increasing the damping (ε_2).

However: this approach doesn't scale well to shorter wavelengths

0.36 THz,4x4 SLM

(With Rice Univ.)

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



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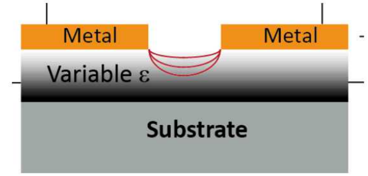
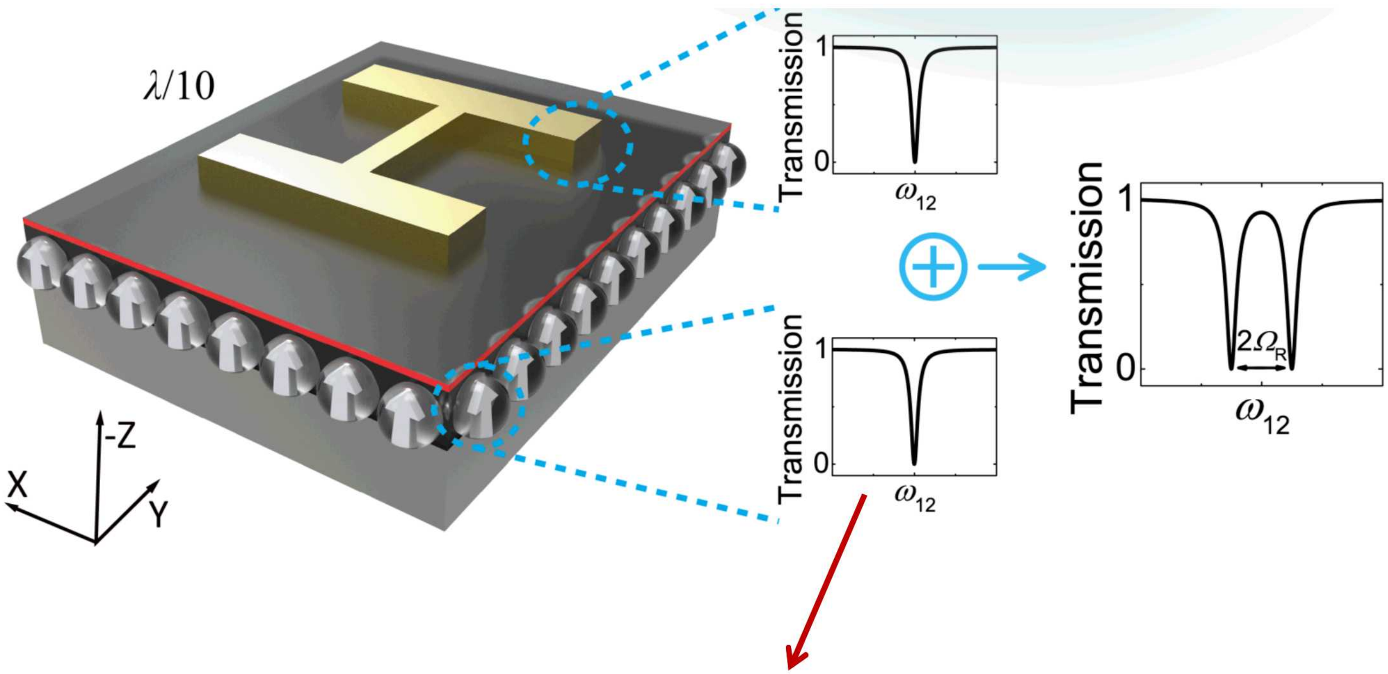
Other Tuning Mechanisms: Coupling

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)

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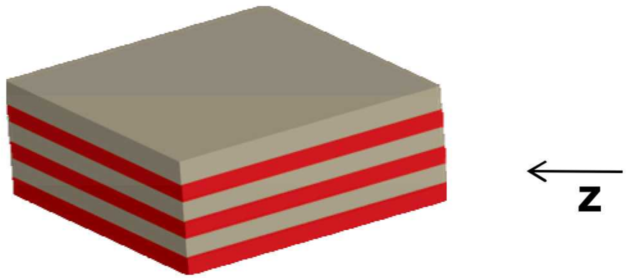
Strong Coupling to Inter-subband Transitions in Quantum Wells

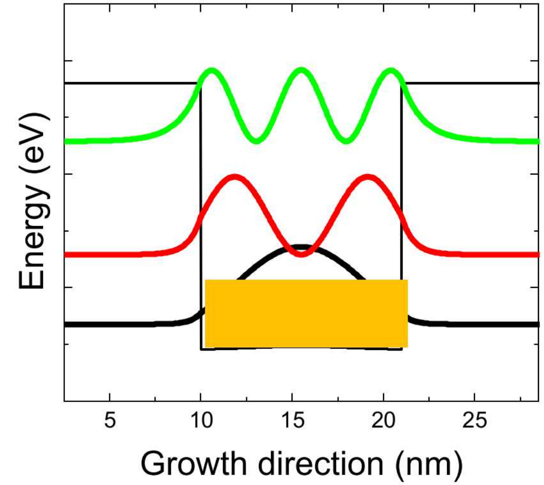
Alex Benz

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

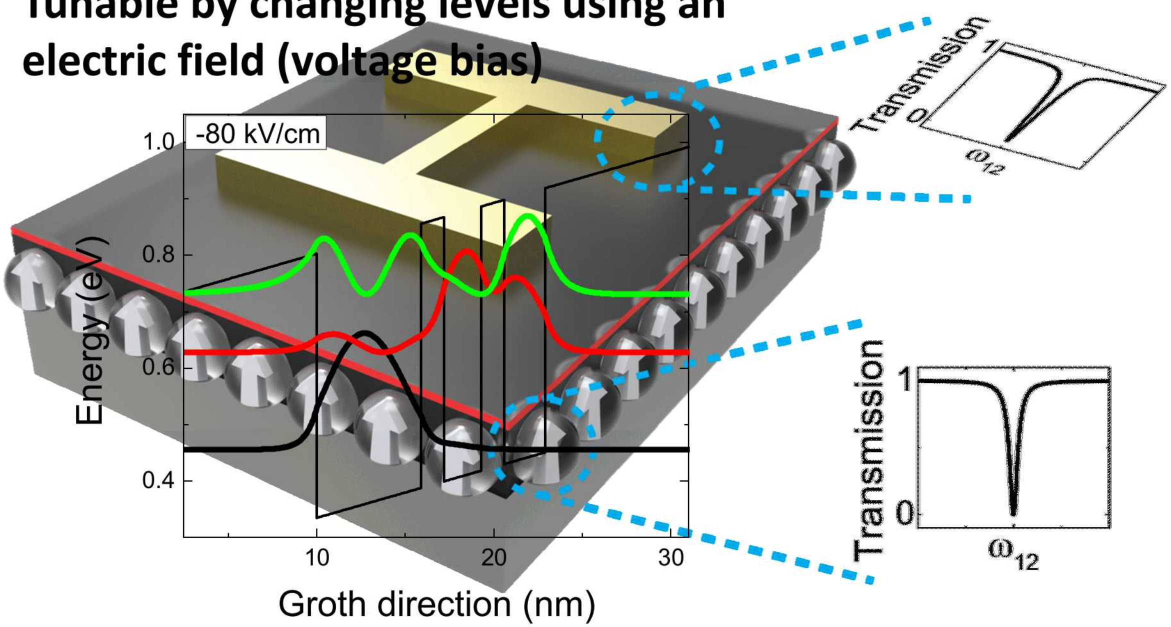
Opt. Express 20, 6584 (2012), APL 98, 203103 (2011)



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

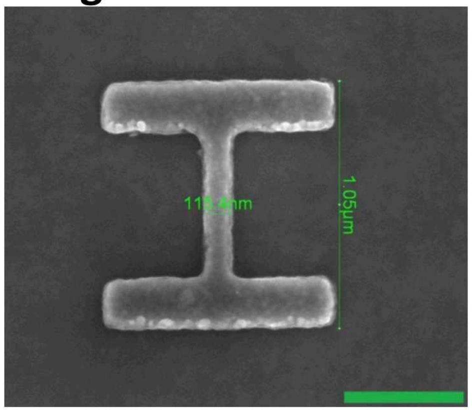


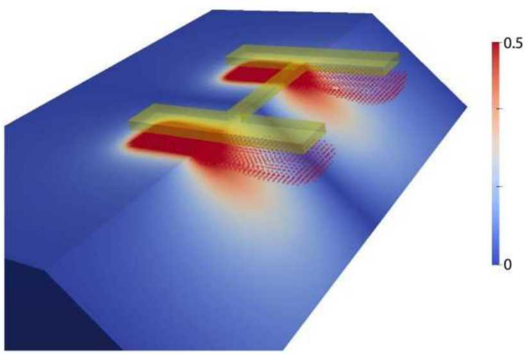
Tunable by changing levels using an electric field (voltage bias)

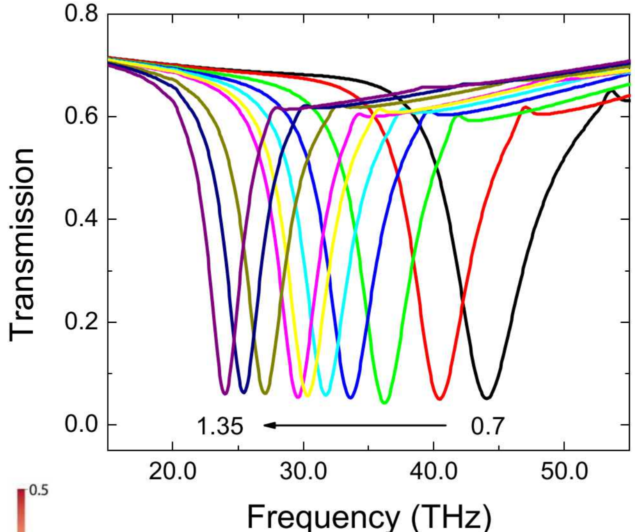


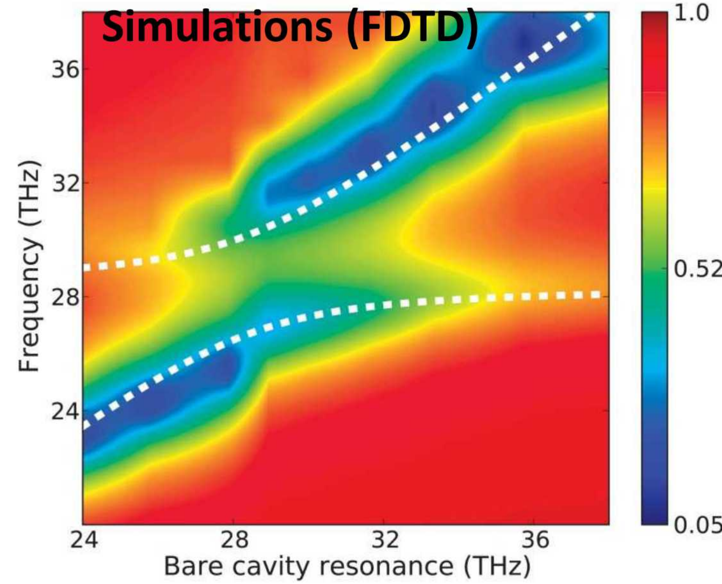
Strong Coupling Theory vs. Experiment

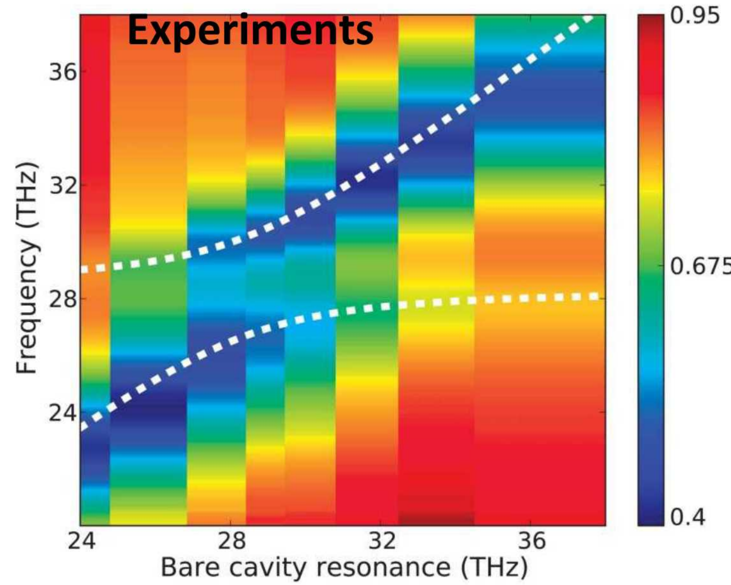
"Dogbone" resonators











Plasma frequency

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

Geometry factor

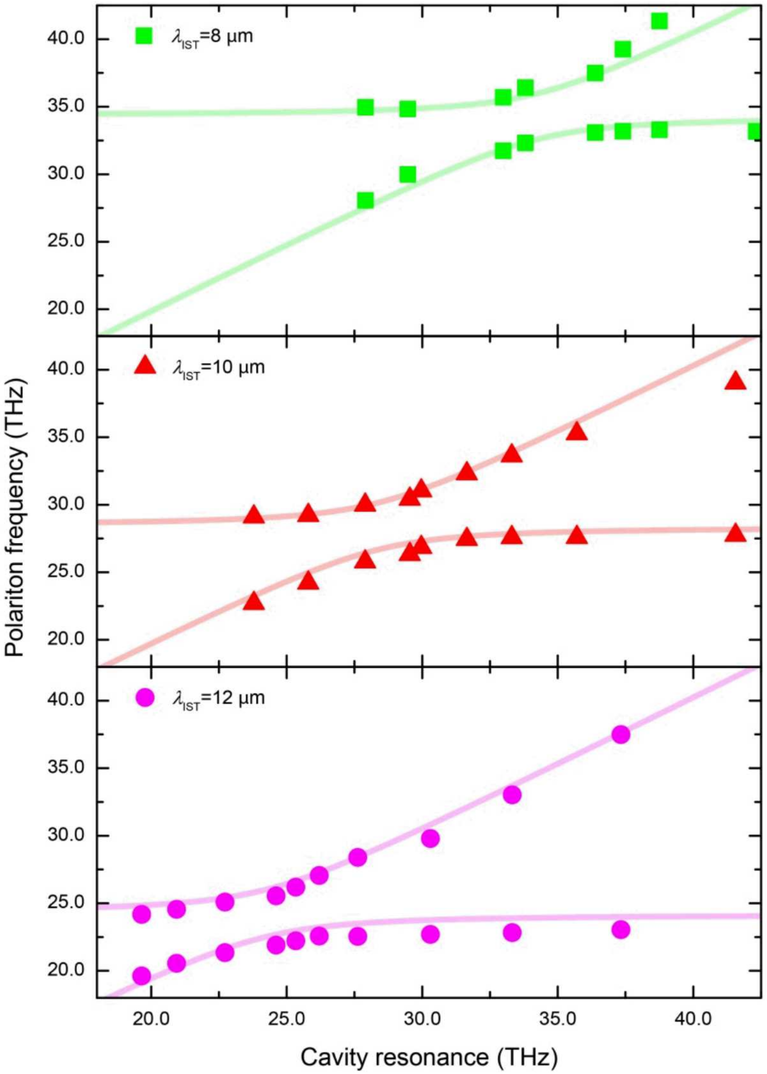
Rabi frequency depends on simple parameters

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

From Mid-IR to Near IR

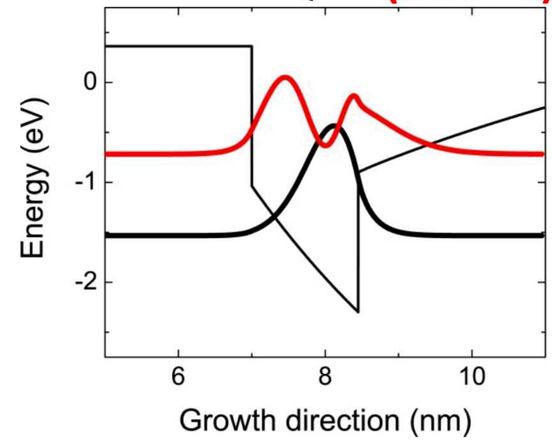
Alex Benz

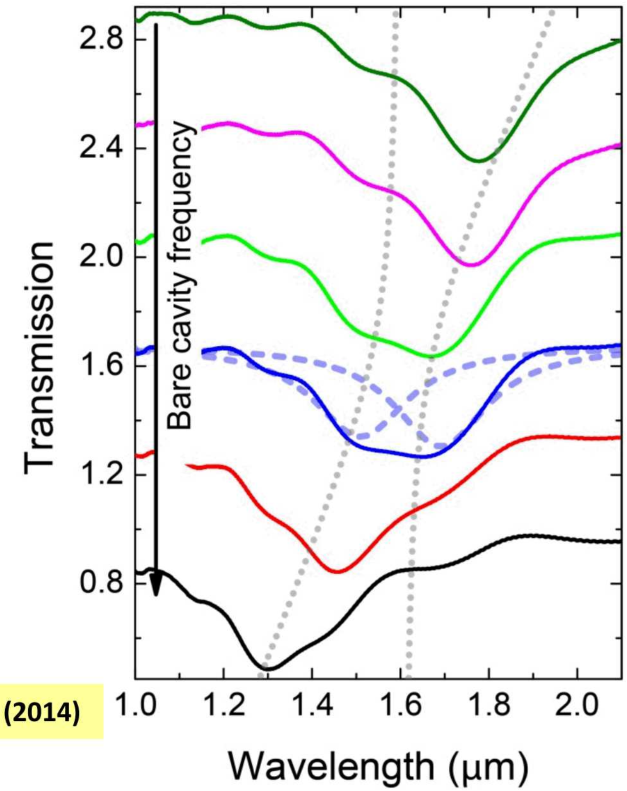
InGaAs QWs (mid IR)



Nature Communications 4, (2013)

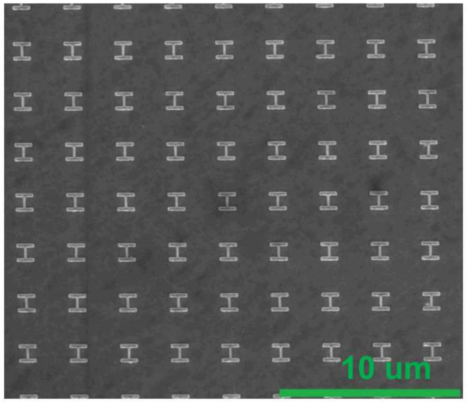
GaN QWs (near IR)

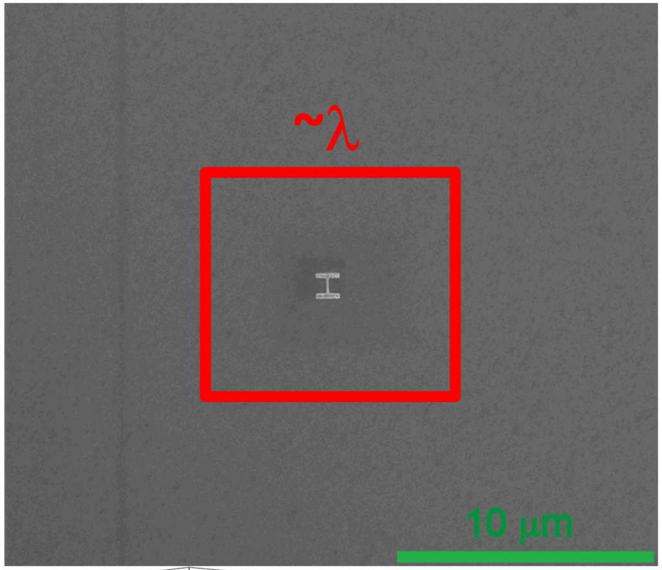


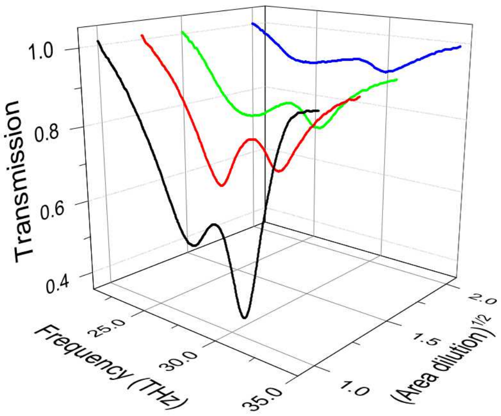


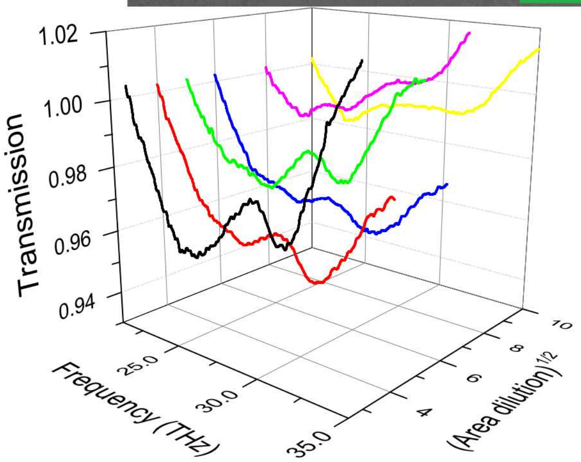
ACS Photonics (2014)

This is a "Single Resonator" Behavior







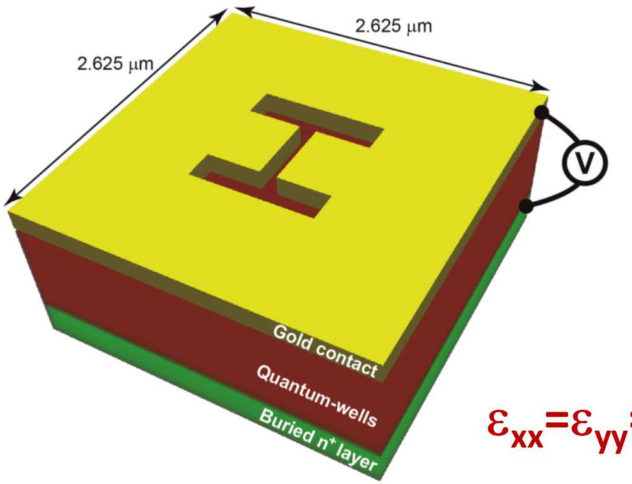


Same Rabi splitting remains down to a single resonator!

Nature communications **4**, (2013)

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

Electrically Tunable Strong Coupling



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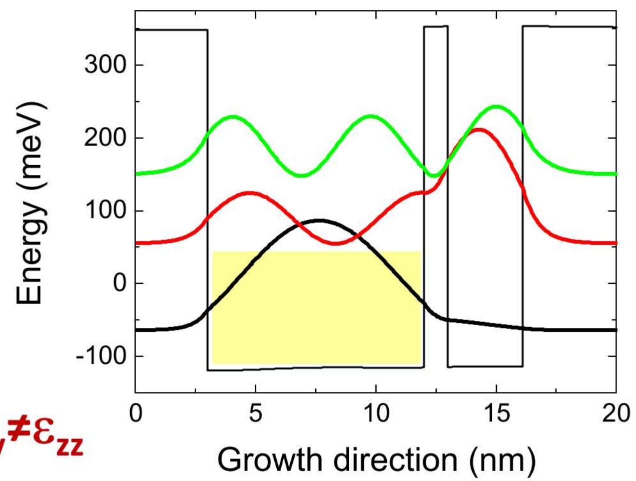
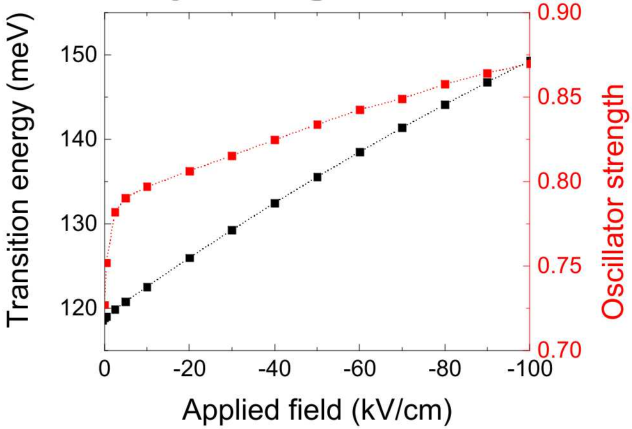
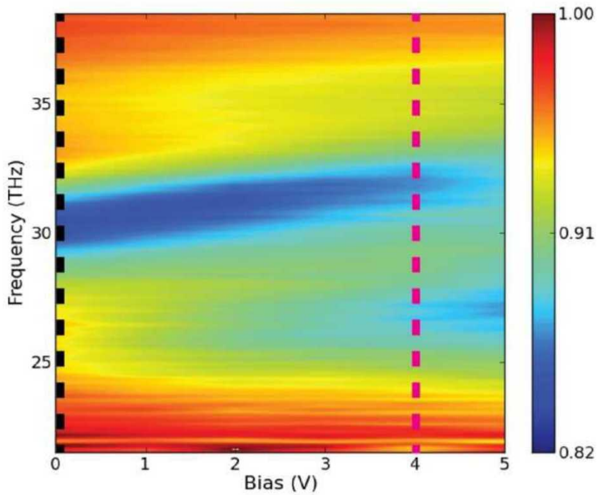
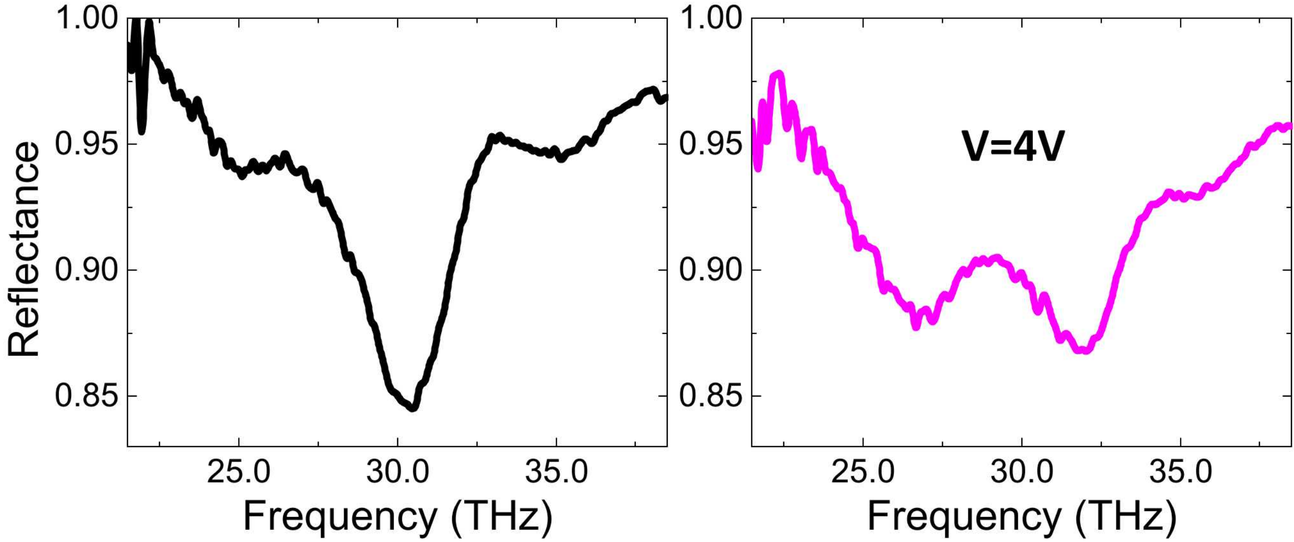




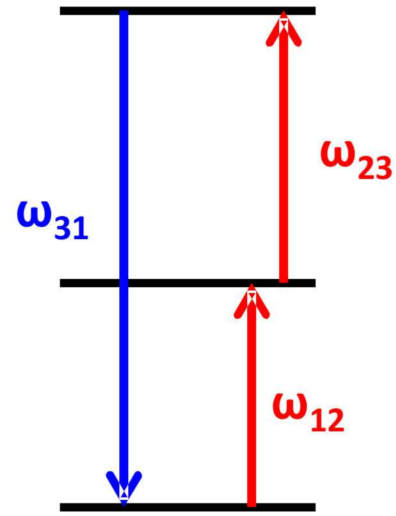


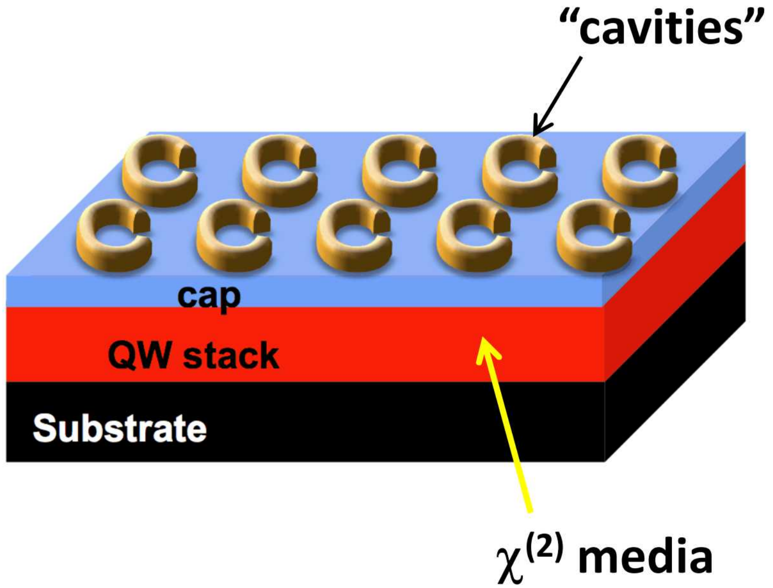


Upper polariton shifted by 2.5 THz (~8% of center frequency)

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

Resonant $\chi^{(2)}$ in a Three-Level System





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

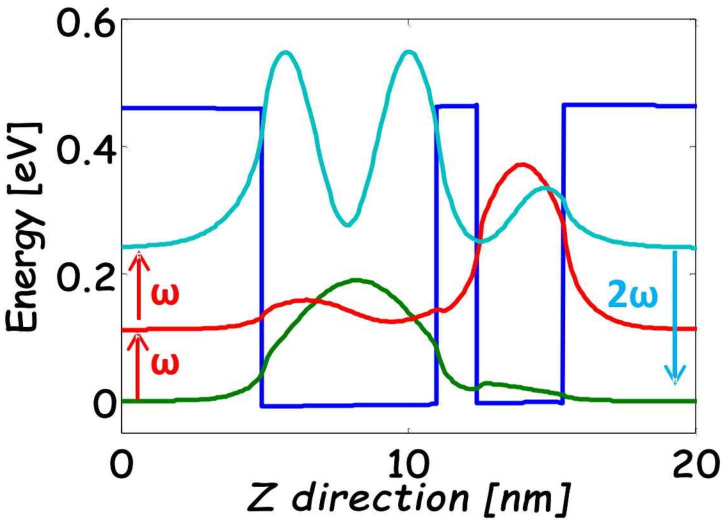
$$z_{ij} \propto \left\langle \Psi_i \middle| \vec{R} \middle| \Psi_j \right\rangle$$

Salvo

Design of the $\chi^{(2)}$ and Resonators

Design: 10µm → 5µm SHG

- InGaAs/AlInAs asymmetric system

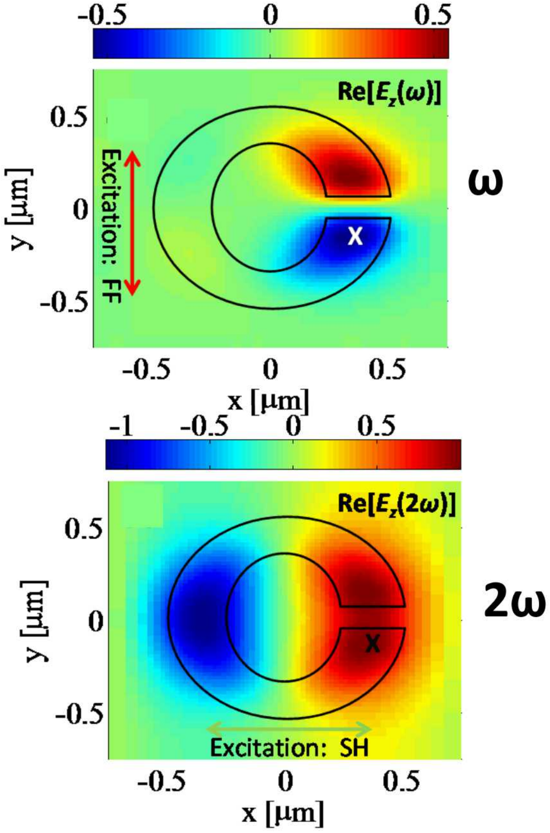


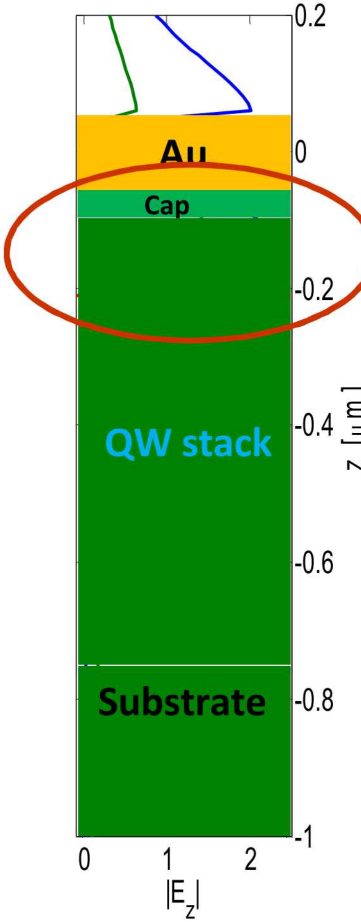
F. Capasso, C. Sirtori, and A.Y. Cho, IEEE J. Quantum Electron. 30, 1313 (1994)

~250 nm/V - QWs

10s of pm/V - $LiNbO_3$

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





APL 104, 131104 (2014)

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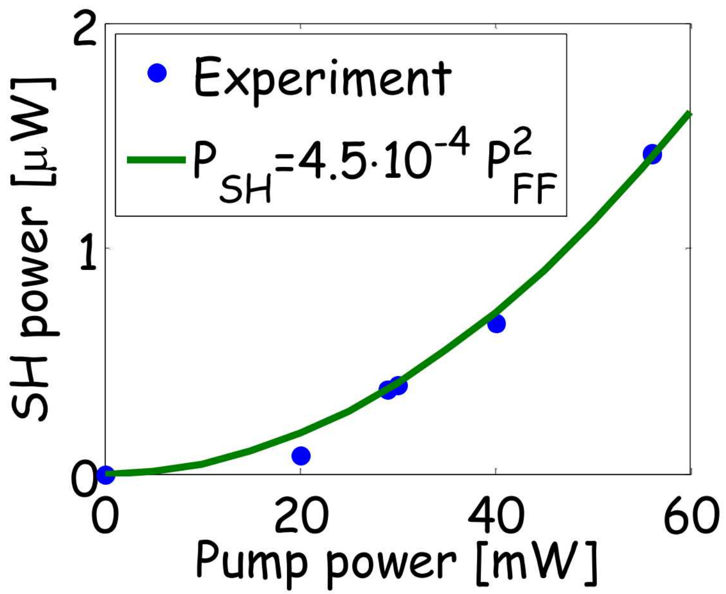
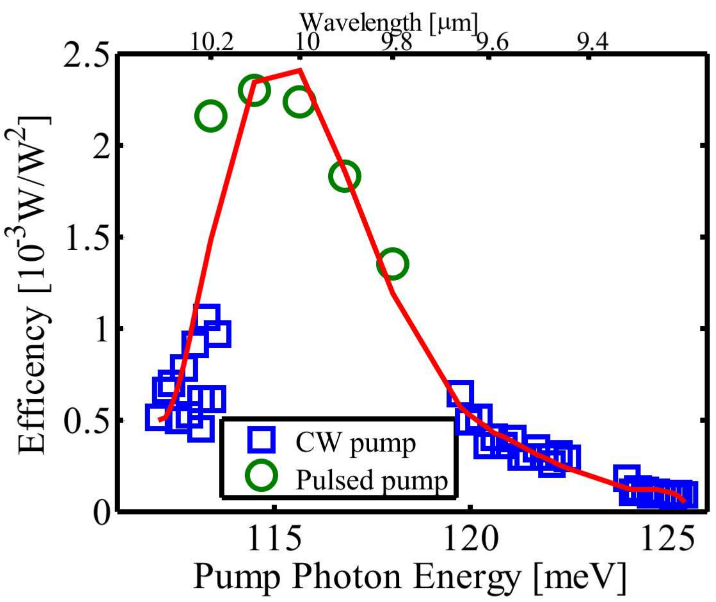
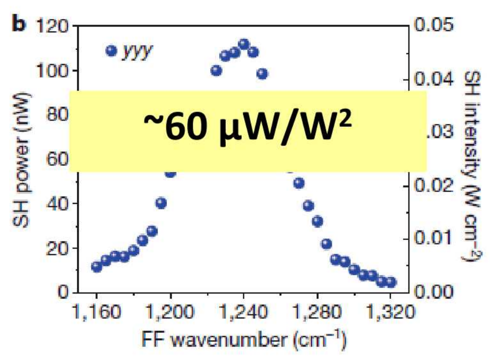
SHG: Power and Frequency Dependence

Pump: CW CO_2 laser



max efficiency: ~2.3 mW/W²

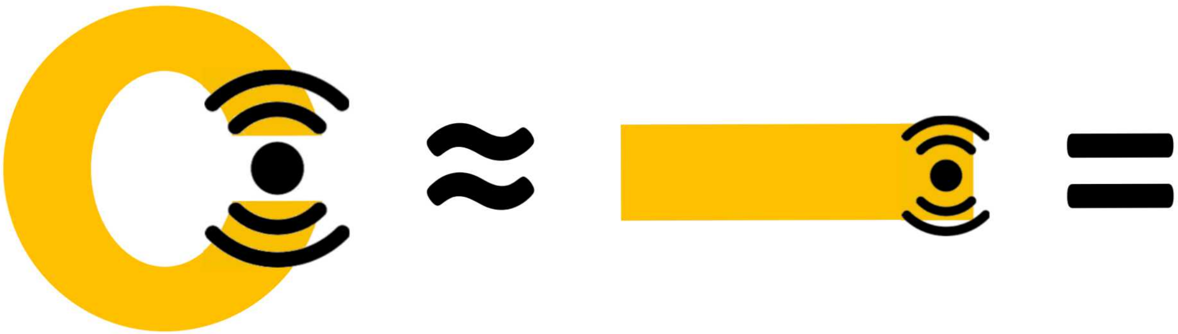




Lee et al. *Nature* 511, 65-69 (2014).

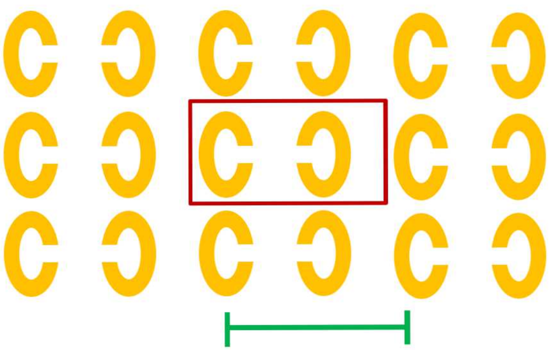
- **Saturation is still an issue**
- **Max. conversion efficiencies of few % are possible**
- **Added functionality is the advantage**

SHG Beam Manipulation

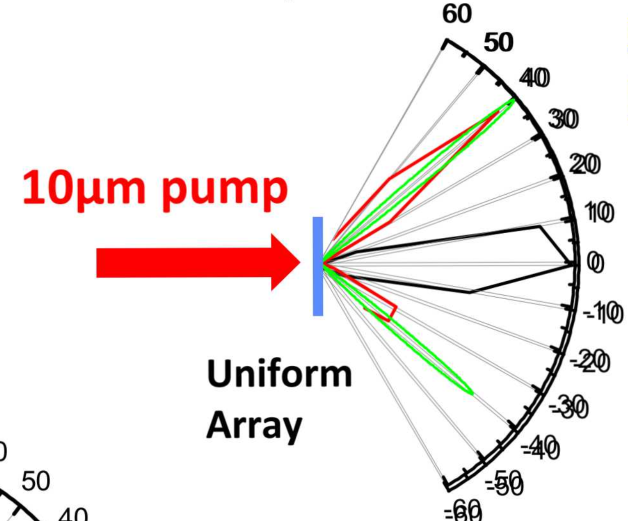


"edge-fed dipole"

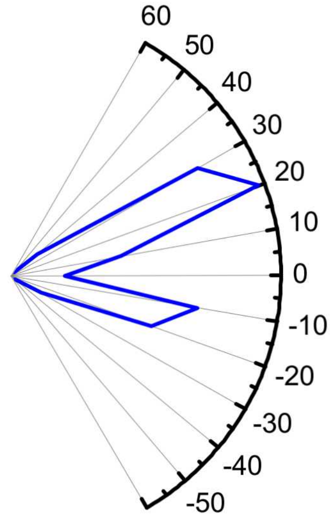
flipping induces π phase shift



Period determines angular separation



5µm beam



2-in-1:

Source +beam splitter

Sandia National Laboratories

Metasurfaces

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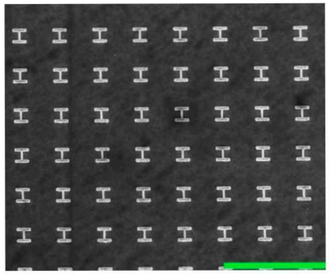
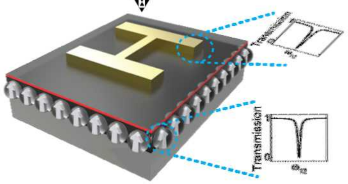
2D

Planar resonators on III-V substrate





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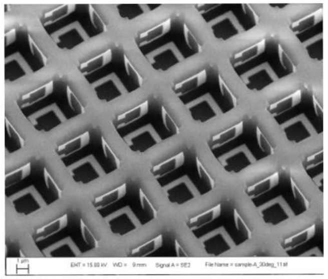
Au SRRs on resist "cavities"



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Incredibly difficult
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STOP

Dielectric

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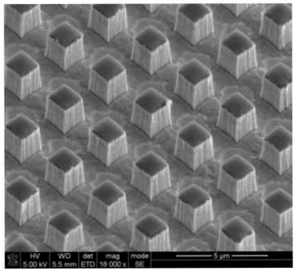
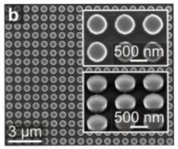
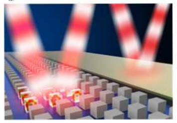


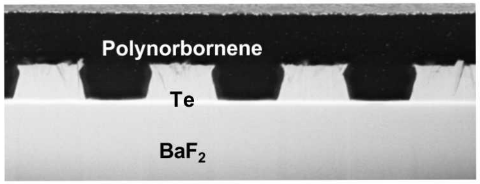




- **Optical magnetism**
- **Unidirectional scattering, Huygens metasurfaces**
- **Nonlinear optics**

3D

multi-layers of Tellurium cubes?

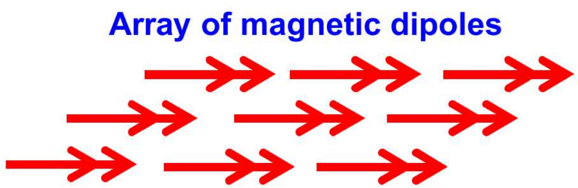


>1 layer:
Incredibly difficult

STOP

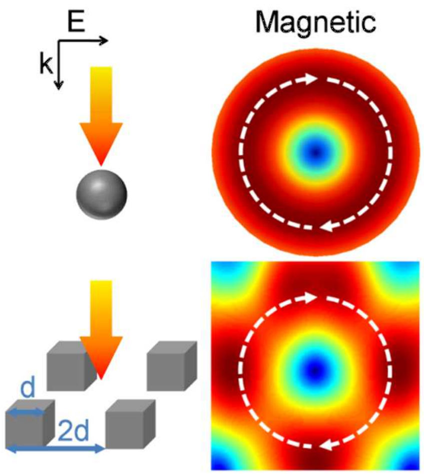
Creating a Magnetic Mirror from a Collection of Magnetic Dipoles

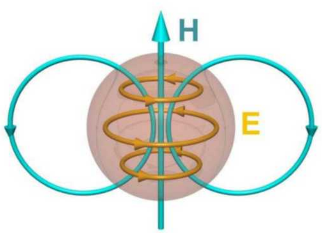
A perfect magnetic conductor does not exist in nature



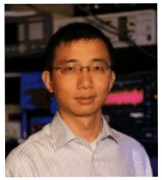
Because the magnetic dipole responds in phase with the electric field, this represents an artificial magnetic conductor

We can create magnetic dipoles with Dielectric Resonators

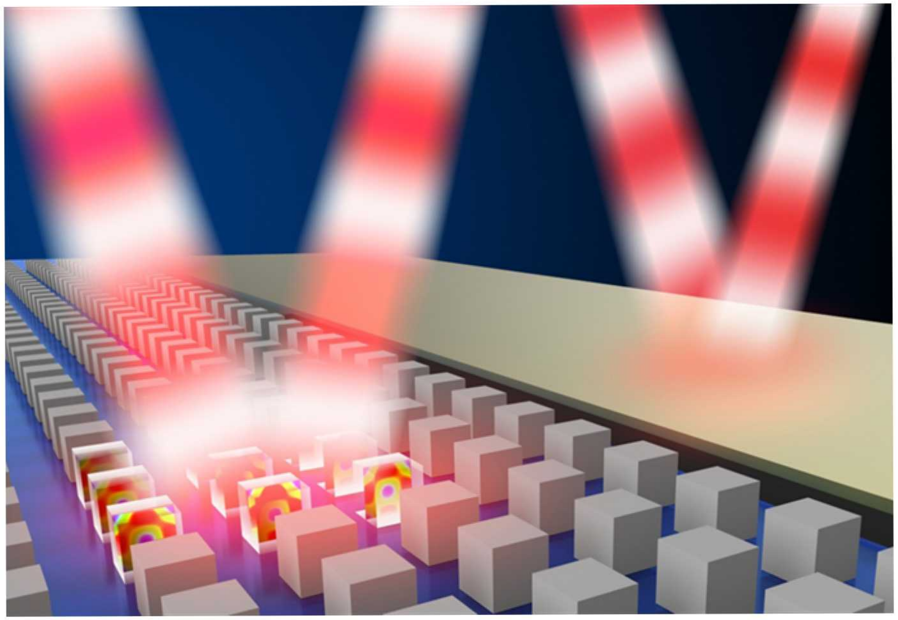


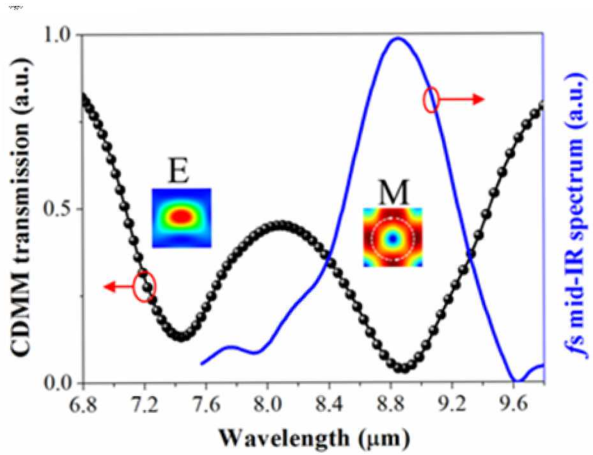


Proving Optical Magnetism:
Measure Absolute Phase of Reflected Wave


Sheng Liu

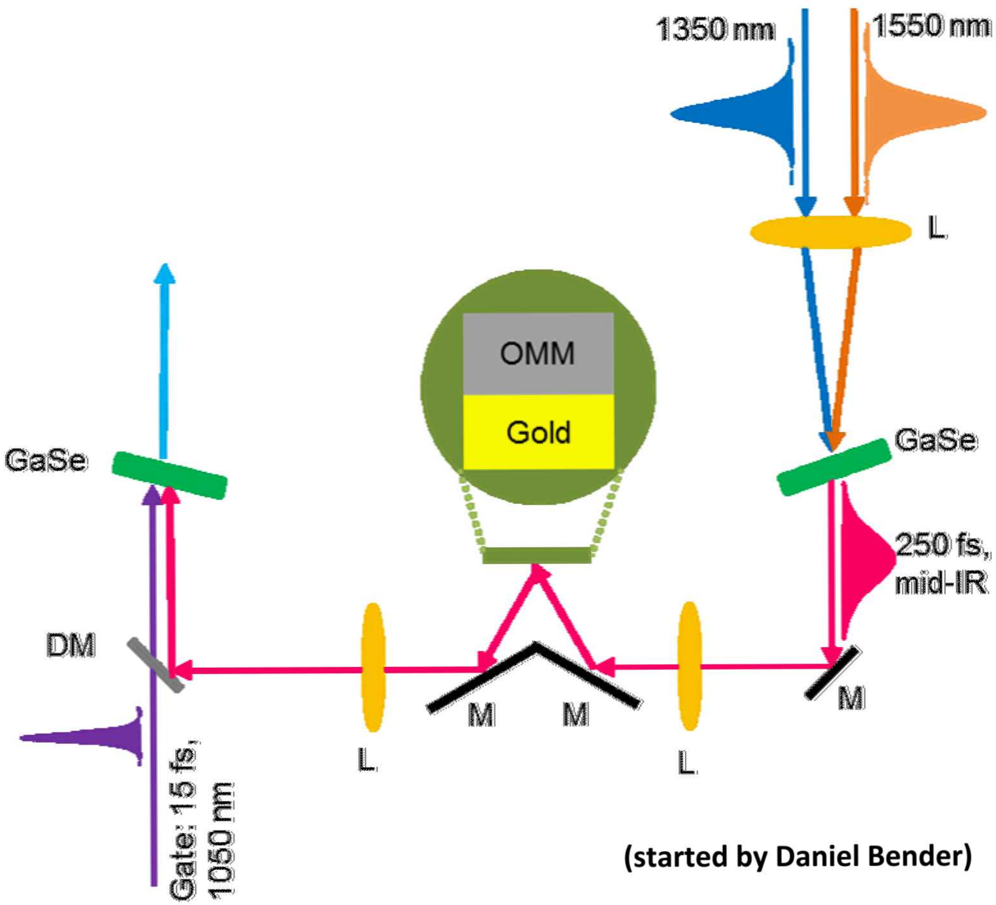
a





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

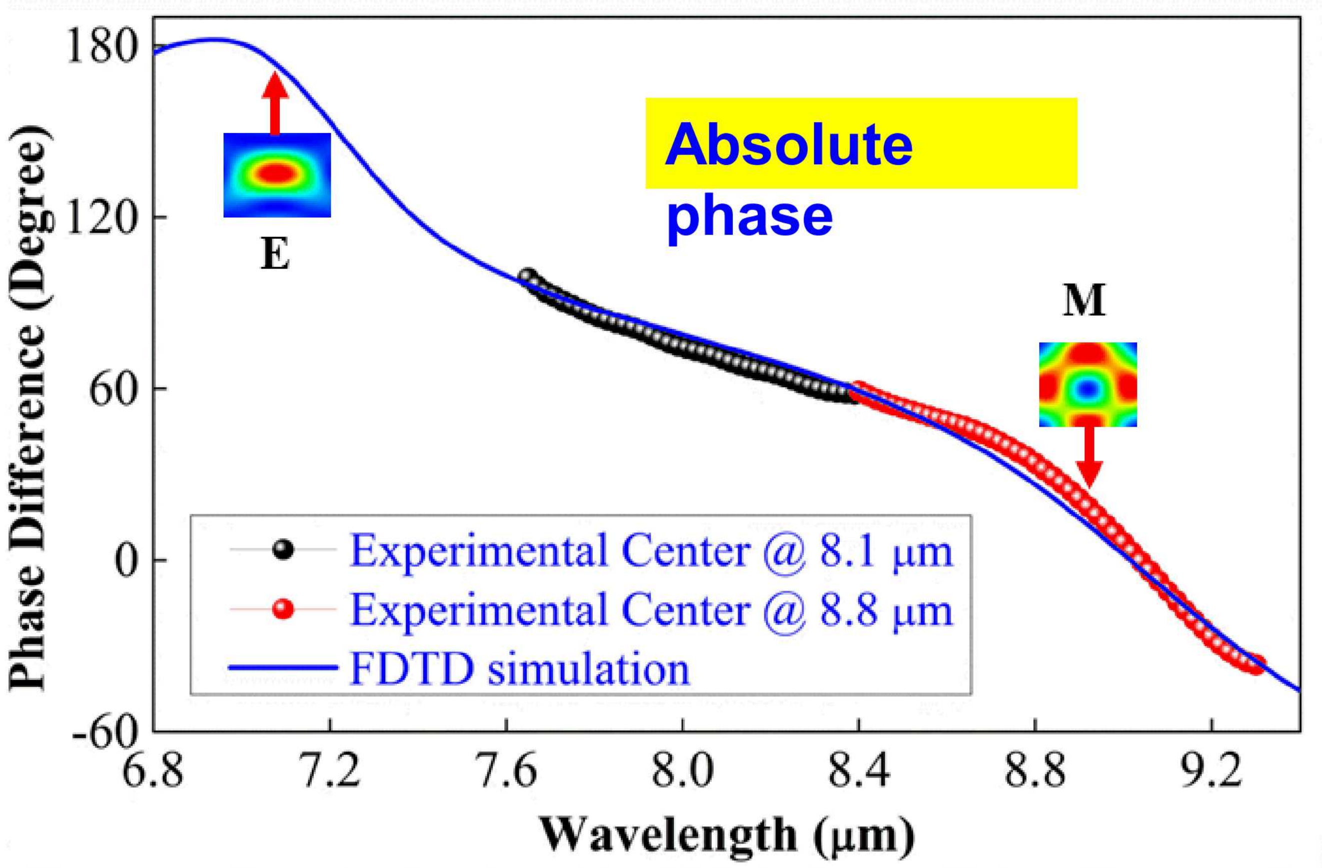
Phase-locked Time Domain Spectroscopy



(started by Daniel Bender)

Optica (2014)

Fourier Transform of Experimental Results (Phase)



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

Optica, 1, 250 (2014)

Shorter Wavelengths: Limitations of Si for Dielectric Metamaterials

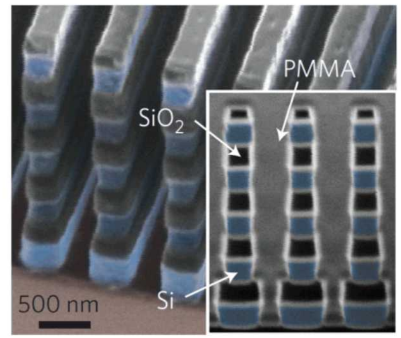
- Challenging to realize real 3D metamaterials (multi-layers)—different etchant for Si and SiO2


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*]

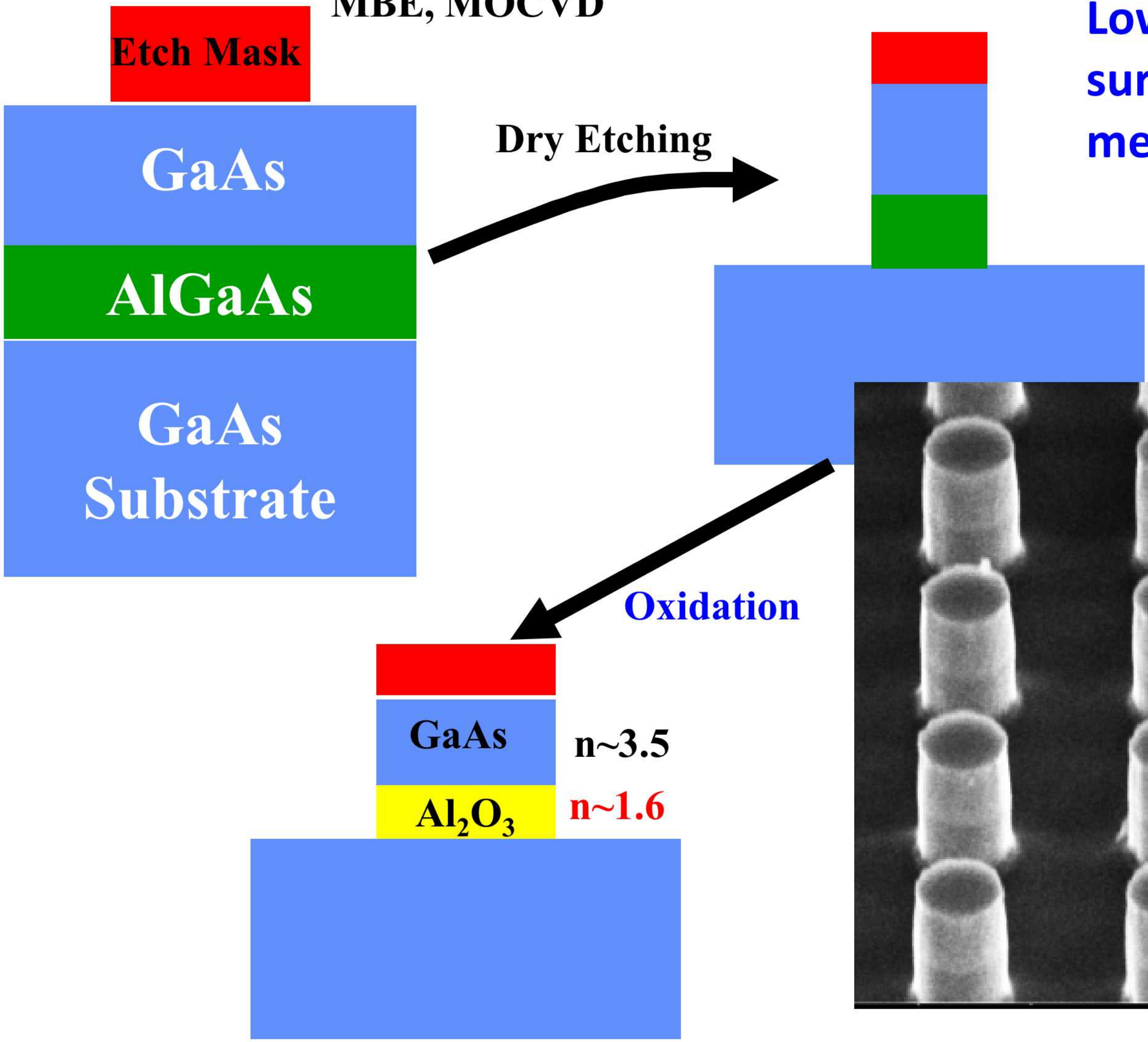


- Free carrier absorption of Silicon (long electron lifetime)
- Silicon is centrosymmetric ➔ NO second order nonlinearity
- Inefficient light emission (hard to incorporate active media)

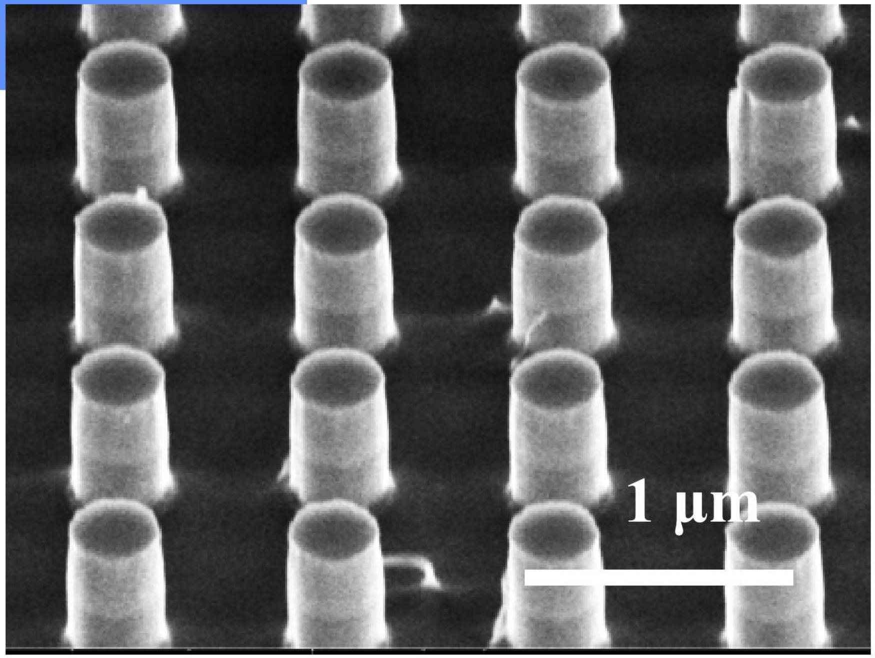
Direct bandgap semiconductors: III-V (AlGaAs, InGaAs, GaAs)

Fabrication of Al(In)GaAs Based Dielectric MM

Epitaxially grown:
MBE, MOCVD

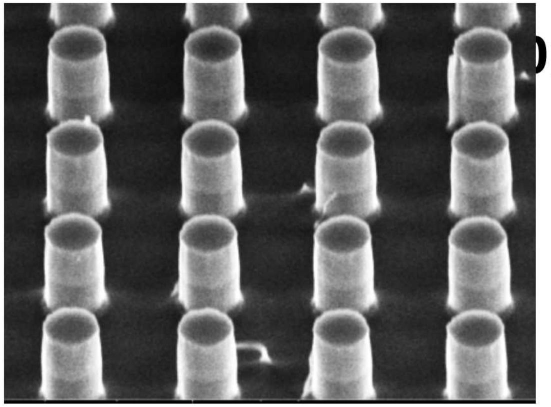


Low refractive index surrounding hig index medium is needed!



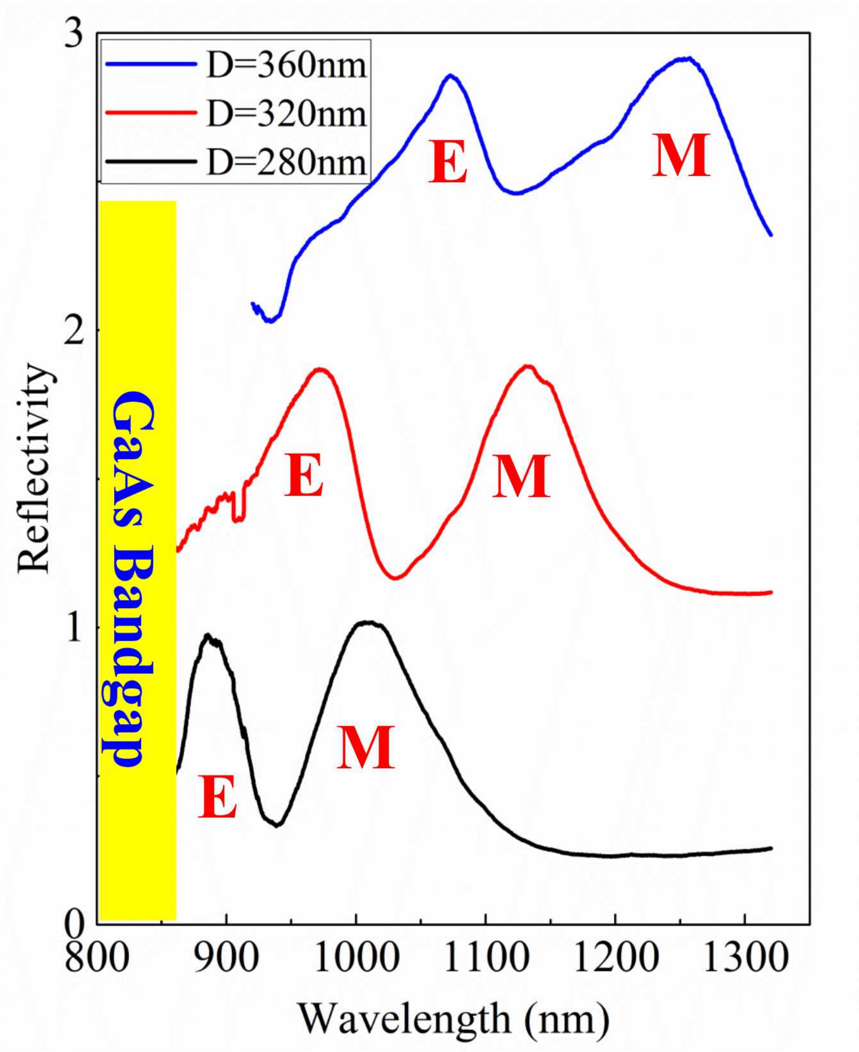
Sandia VCSEL: IEEE JSTQE, 3, 916 (1997)

GaAs Dielectric Resonators (1 layer)

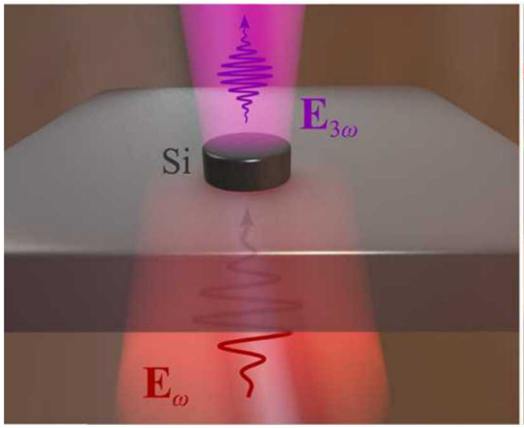


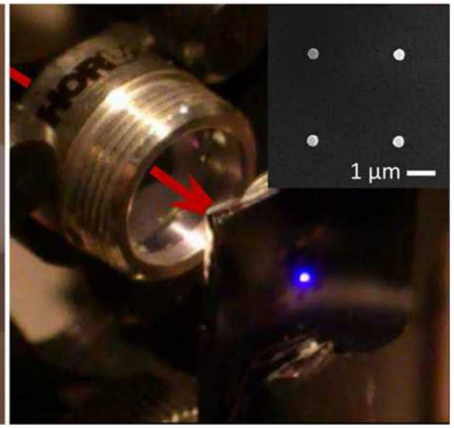
)nm

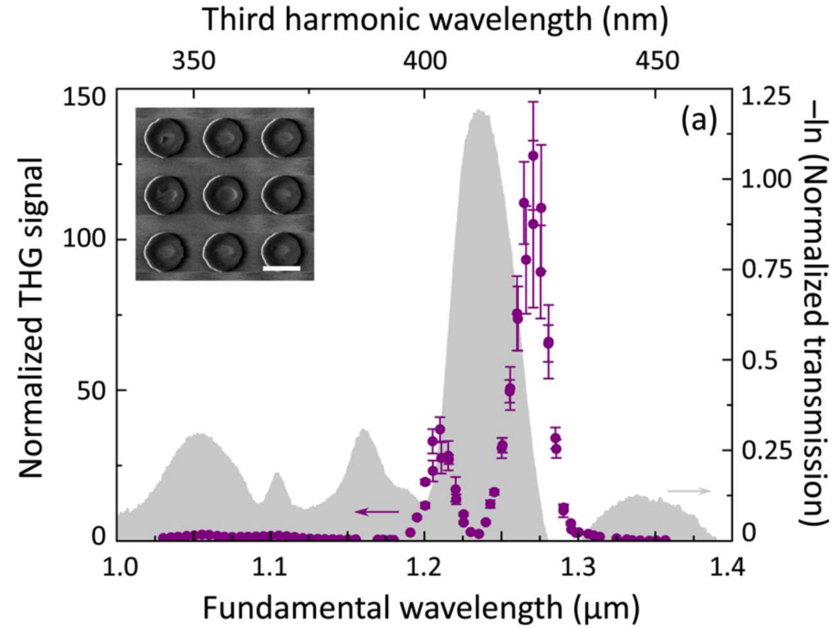
- **Extremely low loss below bandgap**
- **Crystalline**

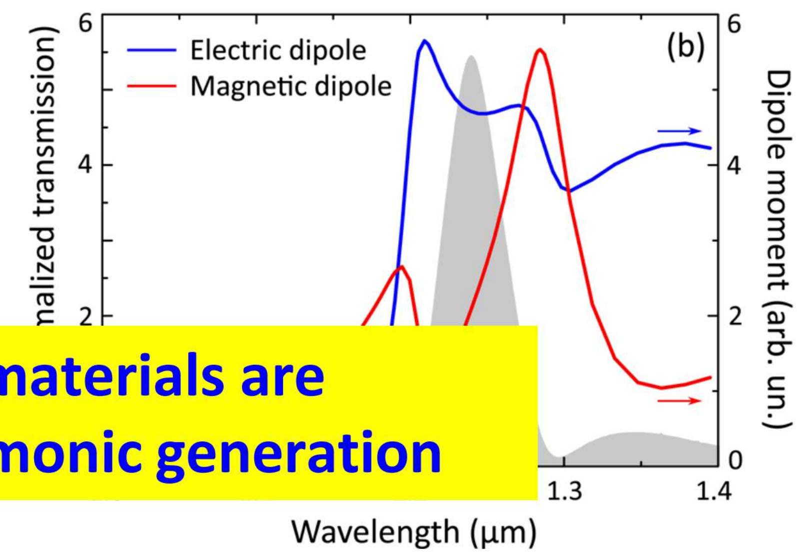


Optical Nonlinearities in Dielectric Metasurfaces







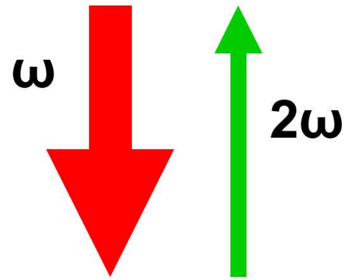


(With ANU & Moscow State)

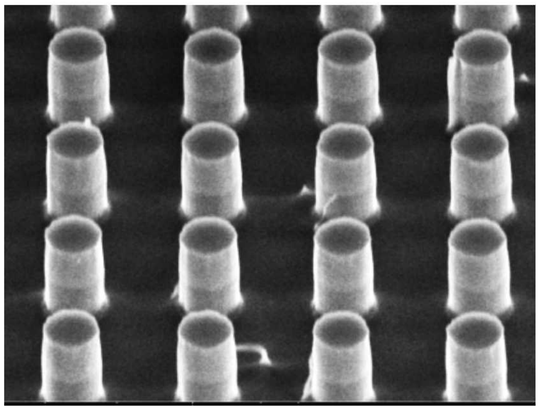
Non-centrosymmetric materials are needed for second harmonic generation

Nano Letters (2015)

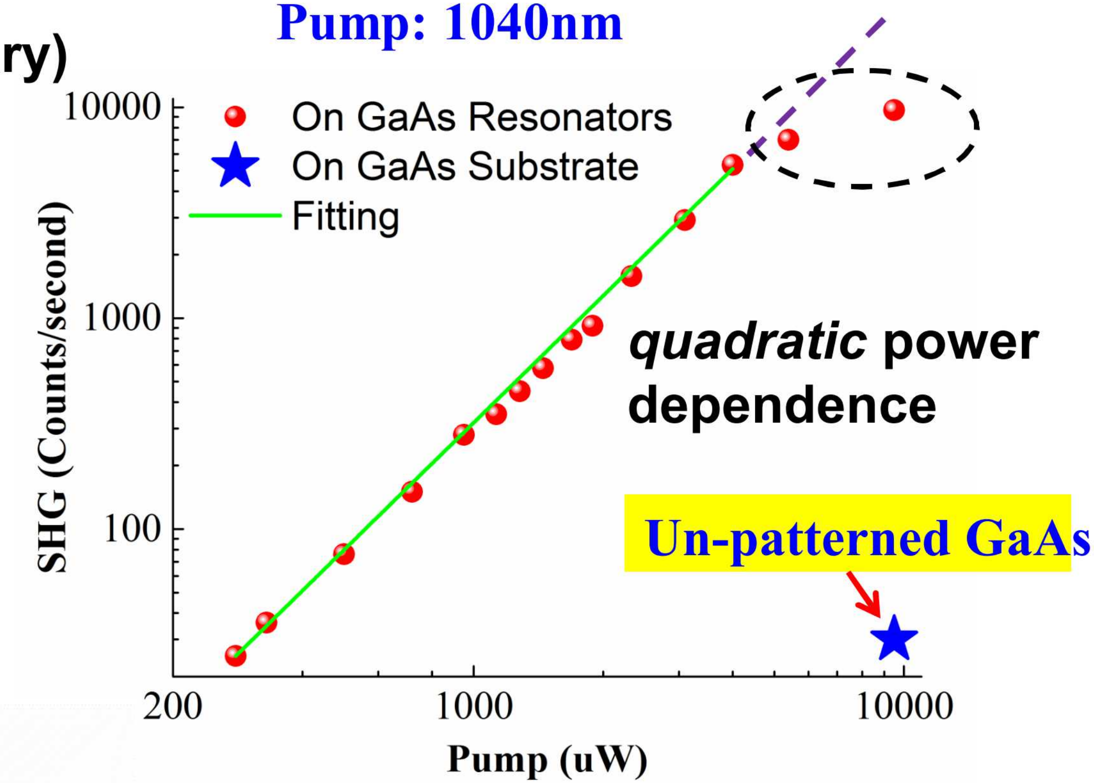
Nonlinear Harmonic Generation using III-V Metasurfaces

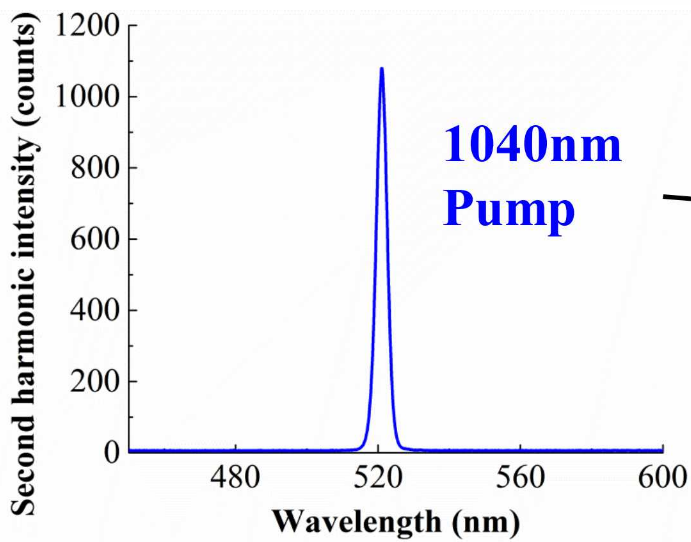


(preliminary)

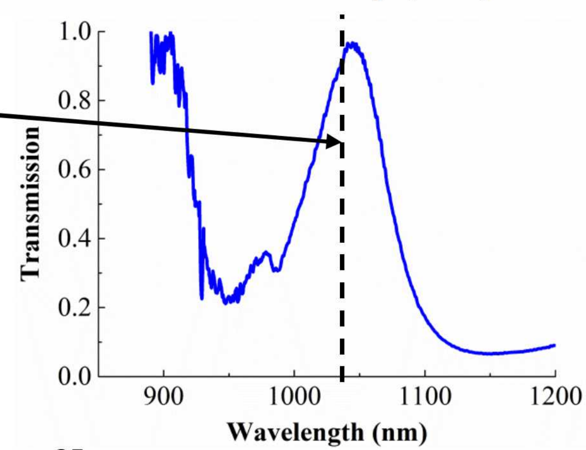


Pump: 1040nm



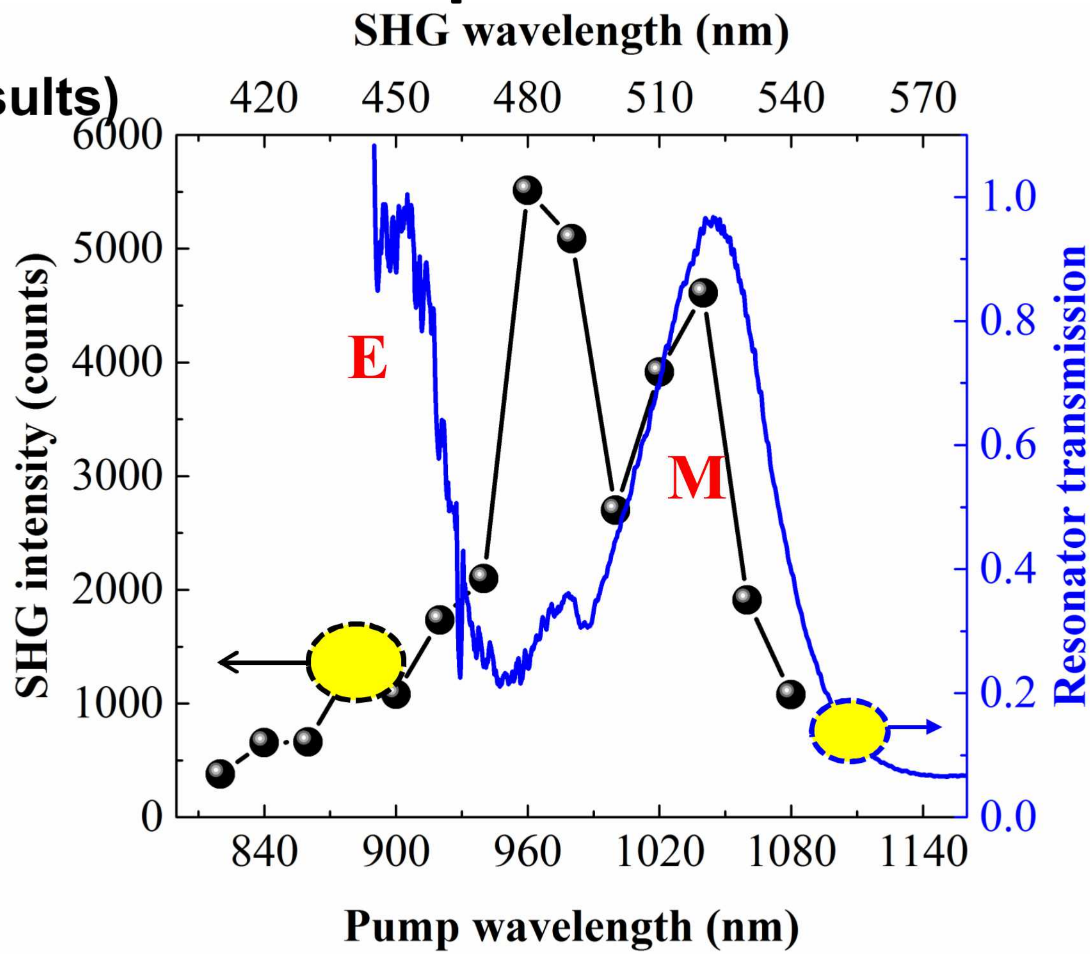


1040nm Pump



Second Harmonic– Pump Wavelength Dependence

(preliminary results)



- Strong pump wavelength dependence—resonant enhancement
- @ same pump wavelength—different diameter resonators show different SHG efficiency
- More work is under way

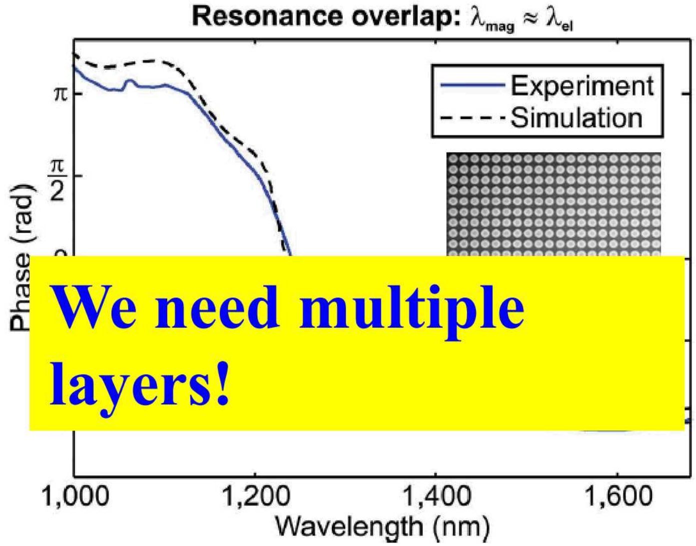
Multilayer Dielectric Metamaterials: Example, Femtosecond Pulse Compression

Huygens sources radiate unidirectional as superposition of electric and magnetic dipoles

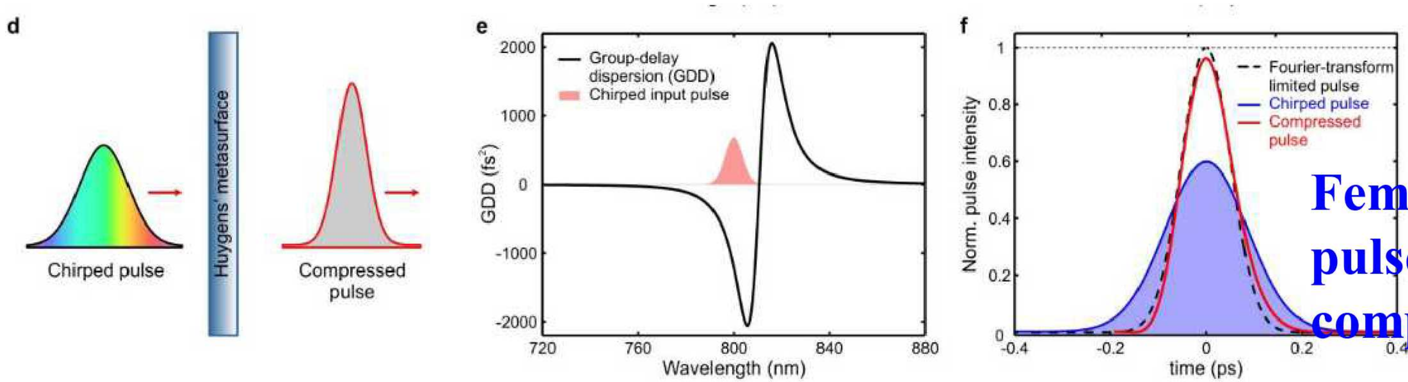
Single layer is not enough to generate sufficient phase difference within the spectrum of femtosecond pulses.

Huygens Metasurface

Complete 2π phase range in transmission



We need multiple layers!

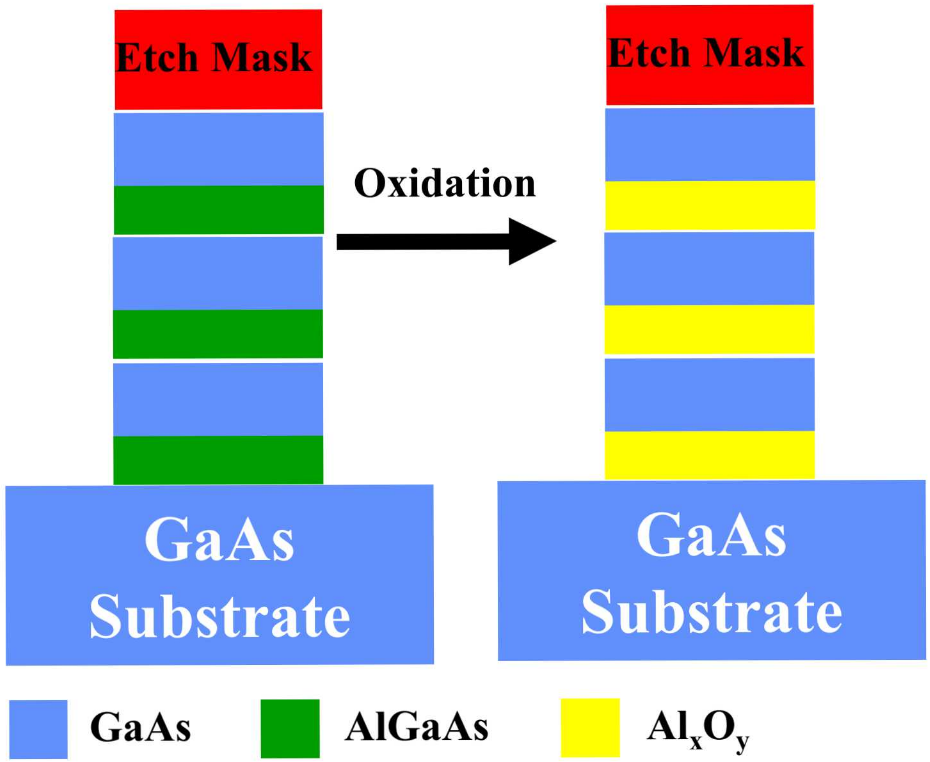


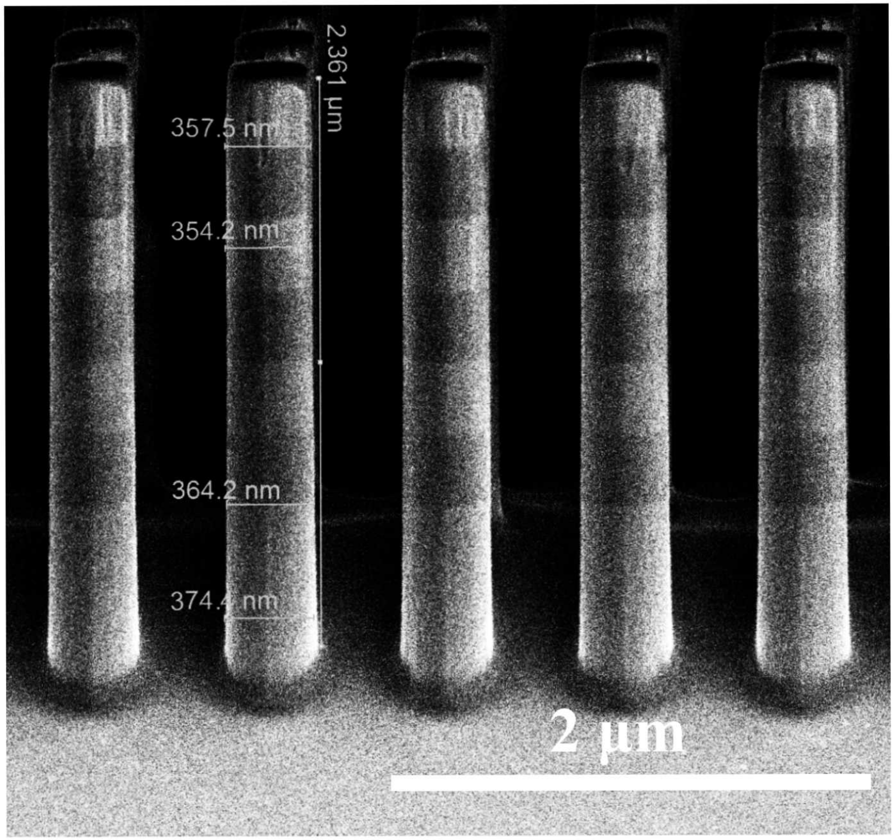
Femtosecond pulse compression

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

Multilayer III-V Dielectric Metamaterials

Epitaxially grown multi-layer
GaAs/AlGaAs





Predictions…. Thoughts…

- Voltage tunable metasurfaces will be incorporated with III-V devices and will enable next generation of focal plane arrays
- Work in nonlinear metasurfaces will increase: opportunities in quantum information science, etc.
- Advances in low-loss dielectric metasurfaces could enable practical optical devices in most of the IR (phase plates, holographic elements, etc)
- New types of III-V devices that combine dielectric metasurfaces and III-V optoelectronics?

Acknowledgments

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

Lomonosov Moscow State: M. Shcherbakov,…


THAT CONCLUDES MY TWO-HOUR PRESENTATION. ANY QUESTIONS?
DID YOU INTEND THE PRESENTATION TO BE INCOMPREHENSIBLE, OR DO YOU HAVE SOME SORT OF RARE "POWERPOINT" DISABILITY?
ARE THERE ANY QUESTIONS ABOUT THE CONTENT?
THERE WAS CONTENT?
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