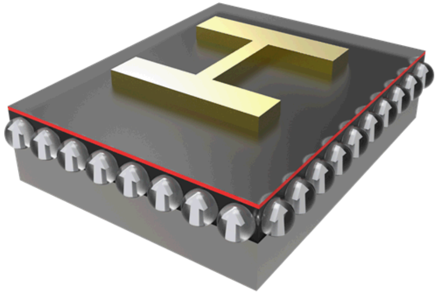
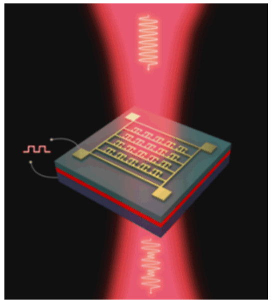
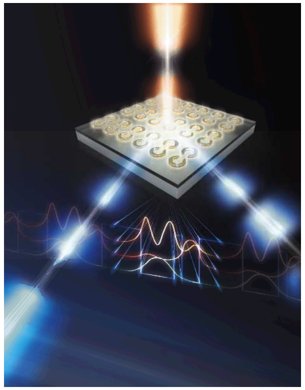
SAND2016-0070C

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







Igal Brener

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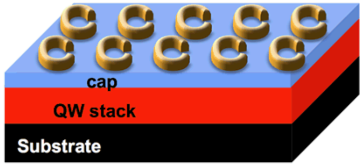
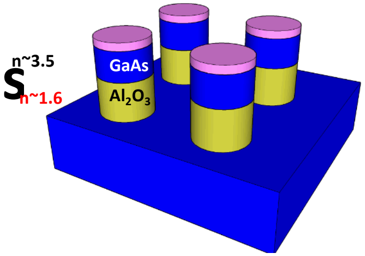
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline

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



- Harmonic generation from all-dielectric metasurfaces

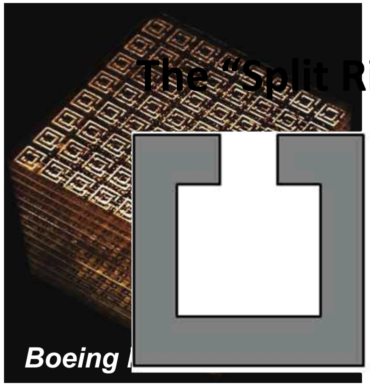


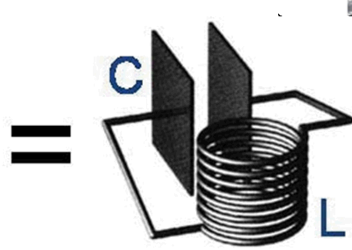
2D Metallic Metamaterials (“Metasurfaces”)

(for some applications, loss is a good thing)

3D

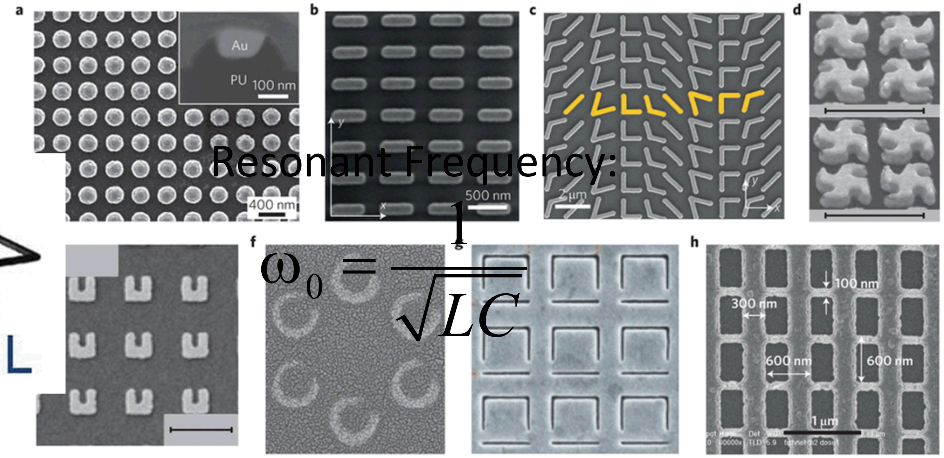
The “Split Ring Resonator”





(Bonn)

2D



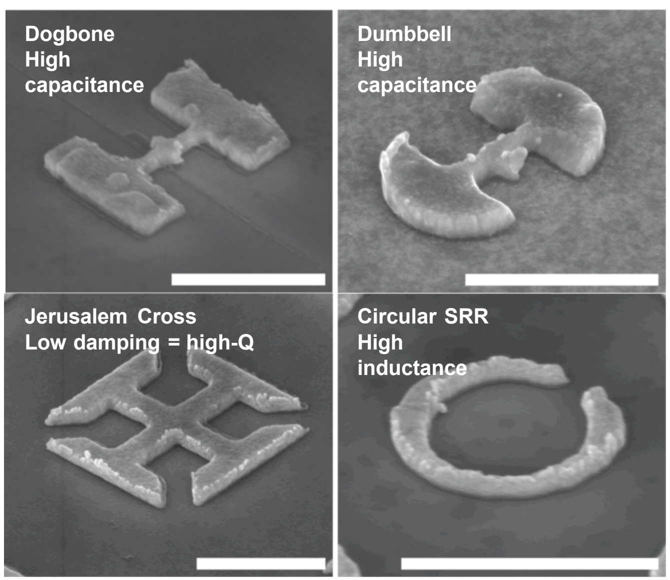
Resonant Frequency:

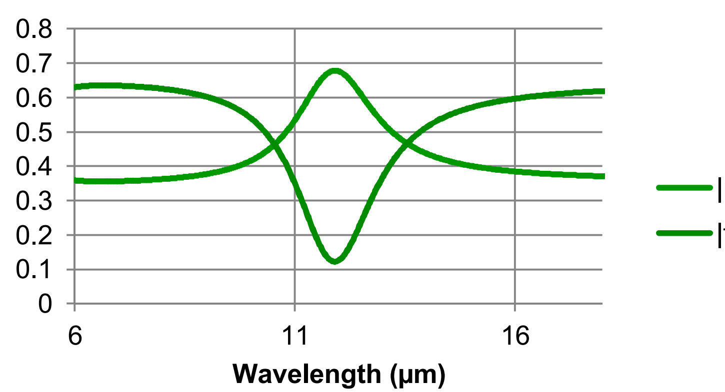
$$\omega_0 = \frac{1}{\sqrt{LC}}$$

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

Even for different shapes, many metallic resonators behave like LCR circuits

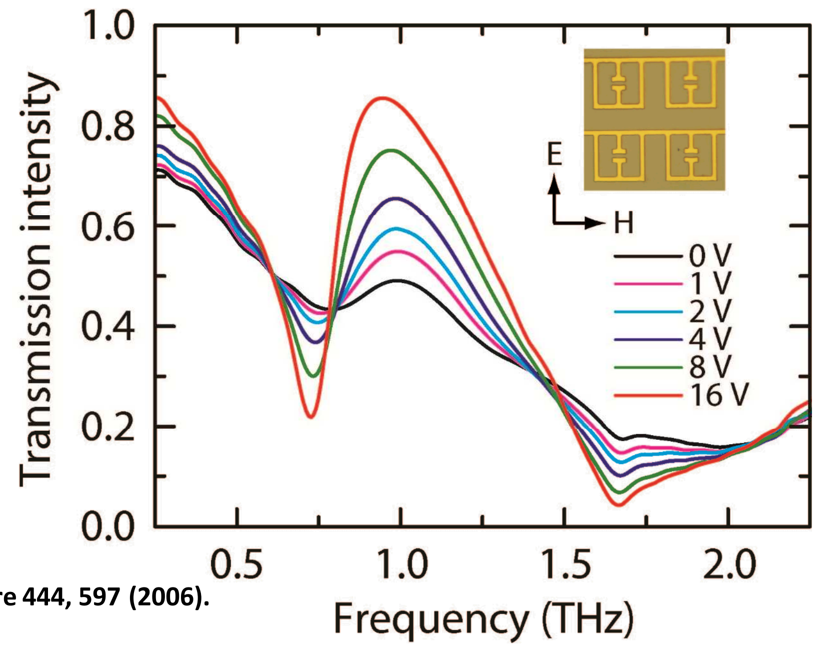
~λ/10



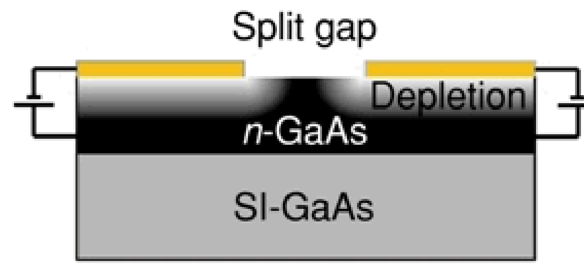


NL 15, 1959 (2015)

Early Days of Tunable Metasurfaces

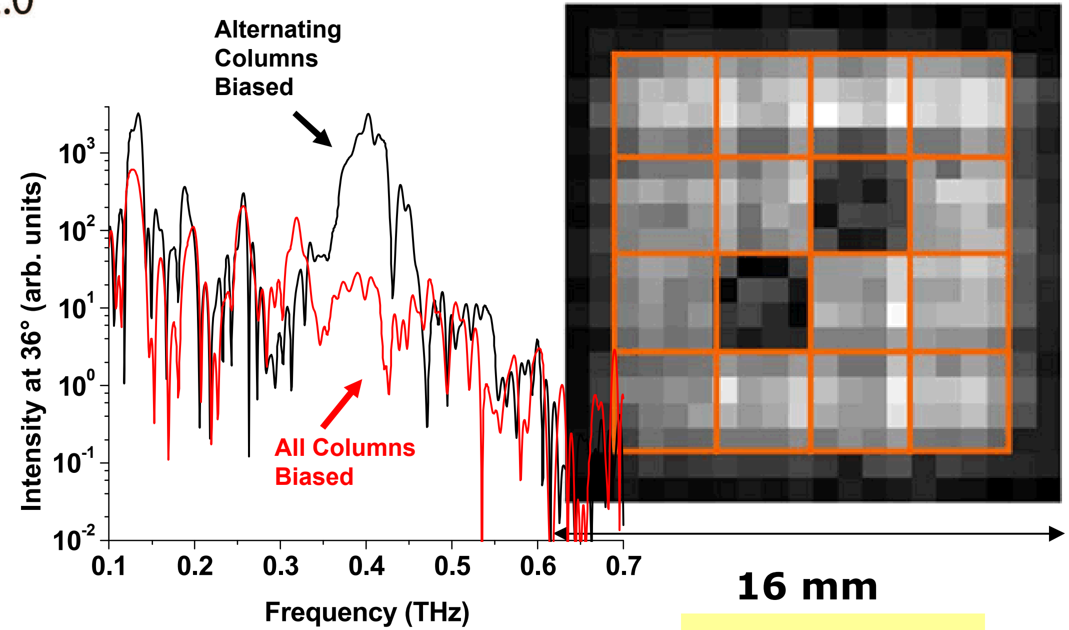


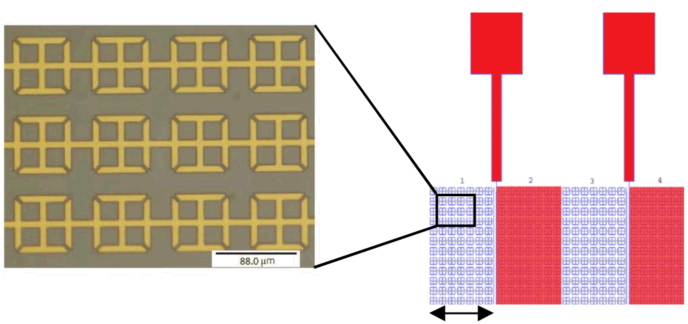
Nature 444, 597 (2006).



This works by increasing the damping (ε_2).

0.36 THz,4x4 SLM



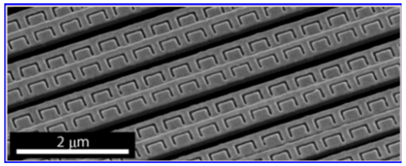


Appl. Phys. Lett., 104, 091115 (2014).

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

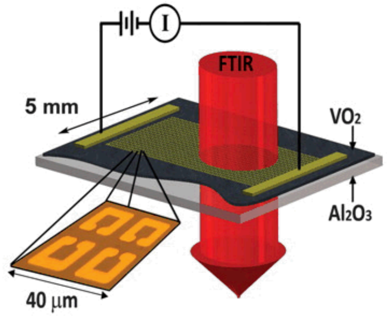
Tunable Metasurfaces: Other Approaches

MEMS approaches



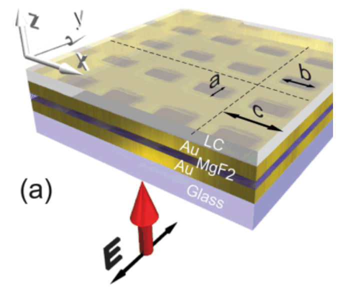
Pryce, NL (2010)
Ou *et. al.* (Zheludev), (2011). *NL 11*, 2142 (2011).

Phase transitions in VO_2



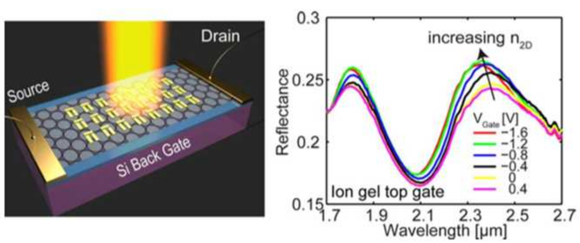
T. Driscoll, Science (2009)

Re-orientation of liquid crystals

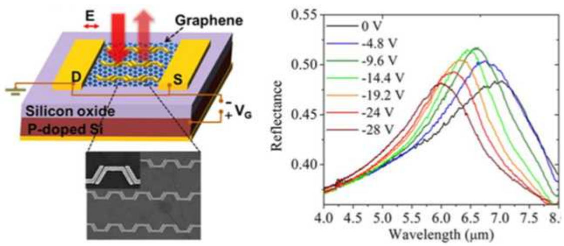


A. Minovich, APL (2012)

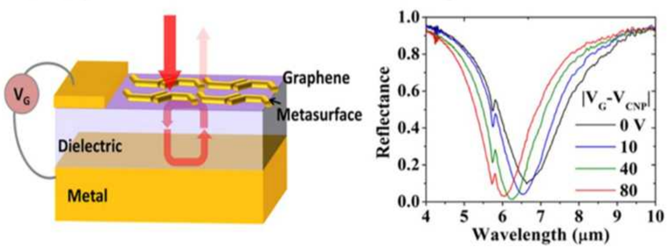
Graphene-based modulation



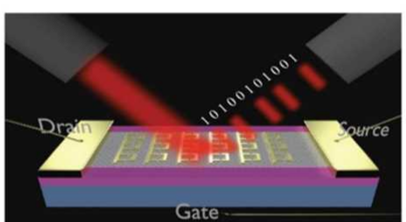
Emani et. al. (Boltasseva), NL **14,** 78 (2014)



Yao et. al. (Capasso), NL **14,** 214 (2014)

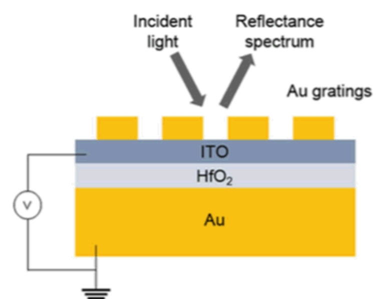


Yao et. al. (Capasso), NL **14,** 6526 (2014)

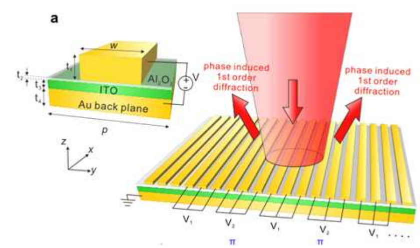


Dabidian et. al. (Shvets), ACS Phot. **2**, 216 (2015) (2015)

Depletion/Accumulation ITO



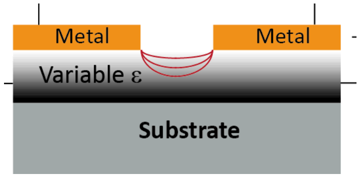
Part *et. al.* (Brongersma), Sci. Rep. 2015

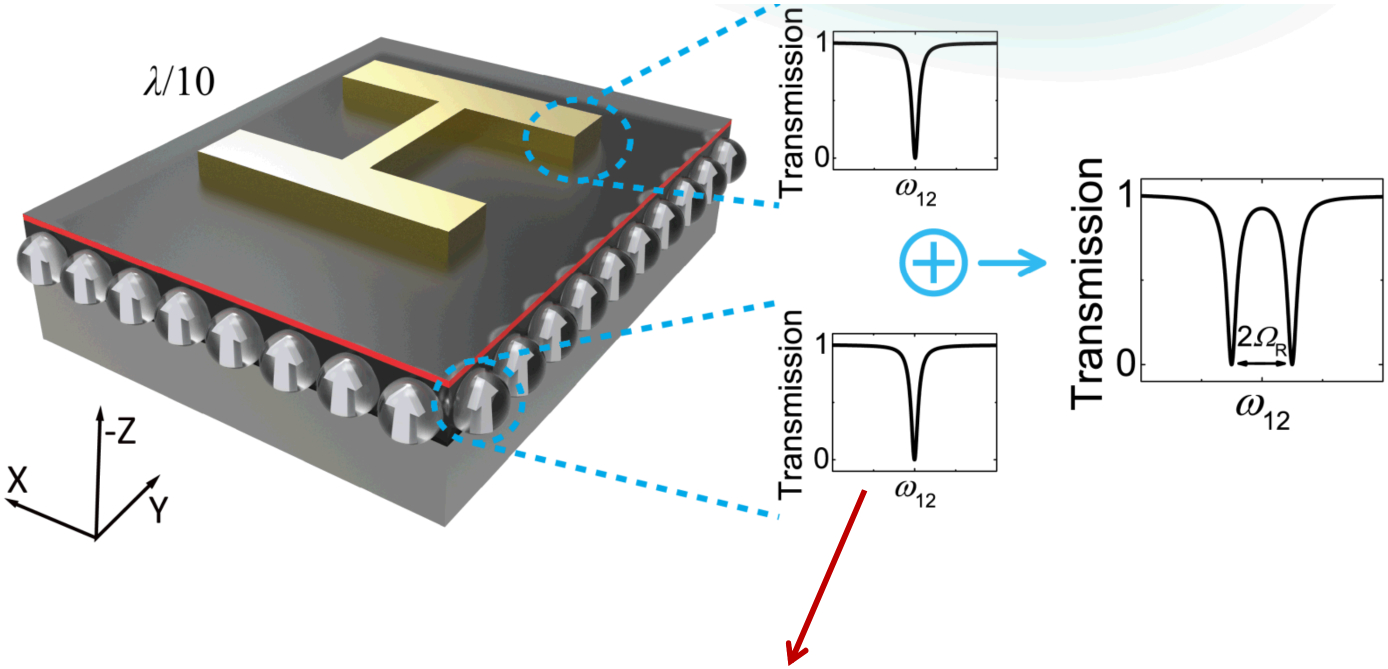


Huang *et. al.*(Atwater), arXiv:1511.09380

Controlled Coupling as Tuning Mechanism

MM resonators create strong optical fields that lead to strong coupling





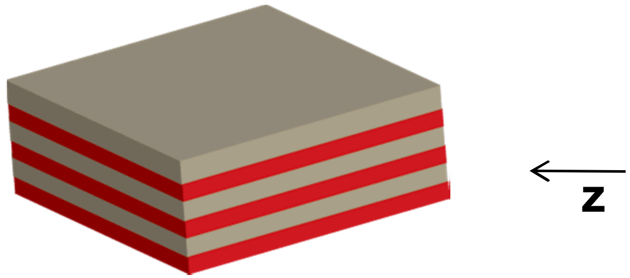
Optical Phonons: Nano Letters 11, 2104 (2011)
Epsilon Near Zero modes: Nano Letters 13, 5391 (2013)
Intersubband Transitions: Nature Communications 4, (2013)

Strong Coupling to Intersubband Transitions in Quantum Wells

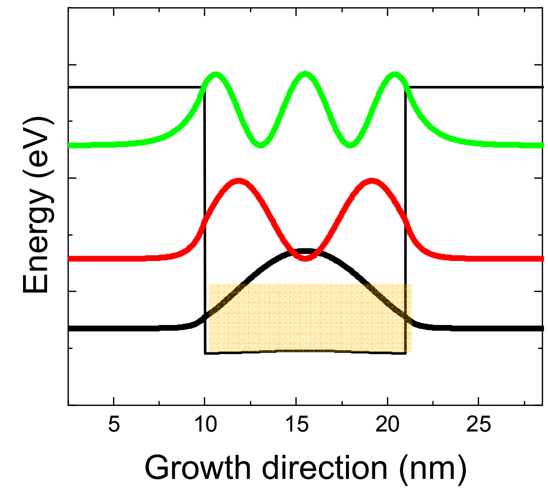
Alex Benz

- **Scalable** (far IR to near IR), **Mature, Versatile**

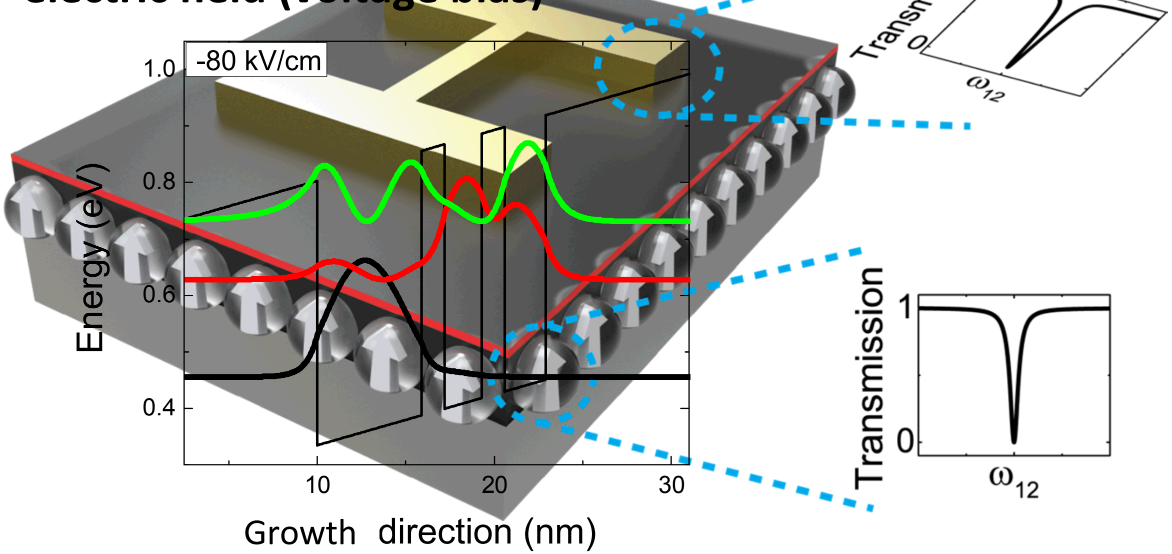
Opt. Express 20, 6584 (2012), APL 98, 203103 (2011)



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

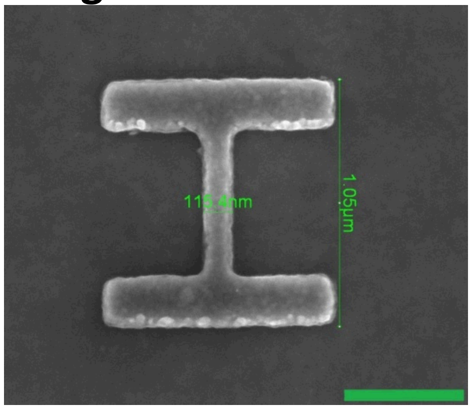


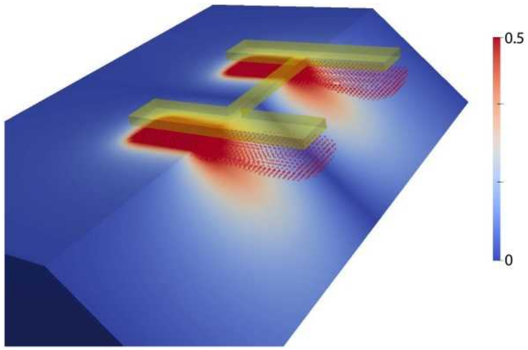
Tunable by changing levels using an electric field (voltage bias)

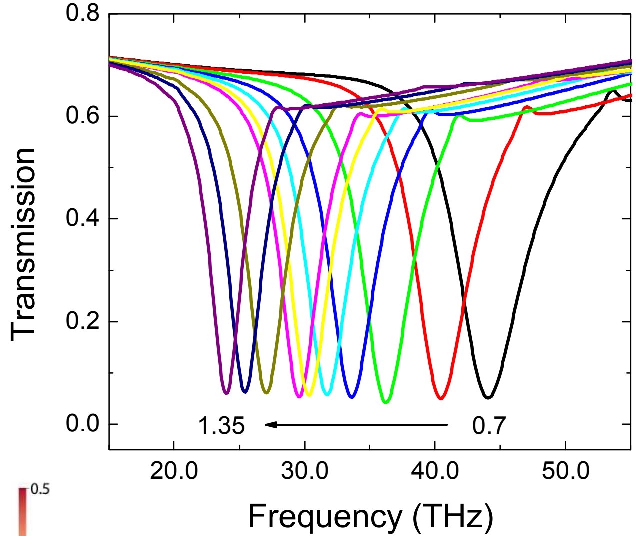


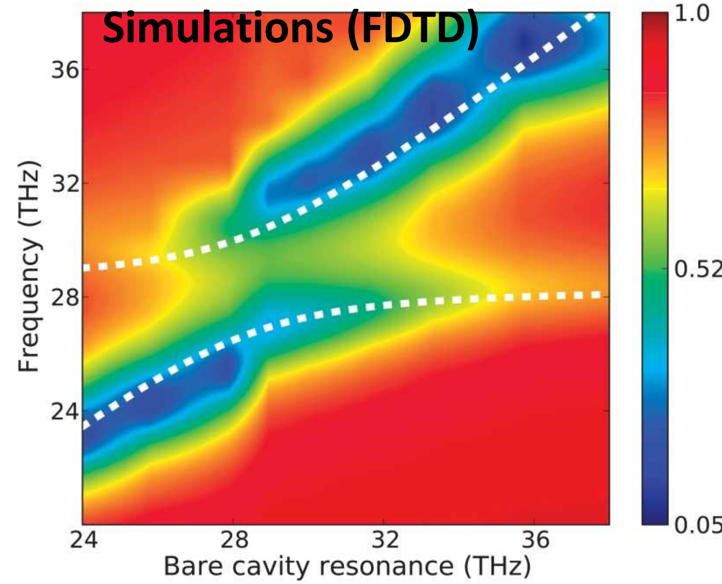
Strong Coupling Theory vs. Experiment

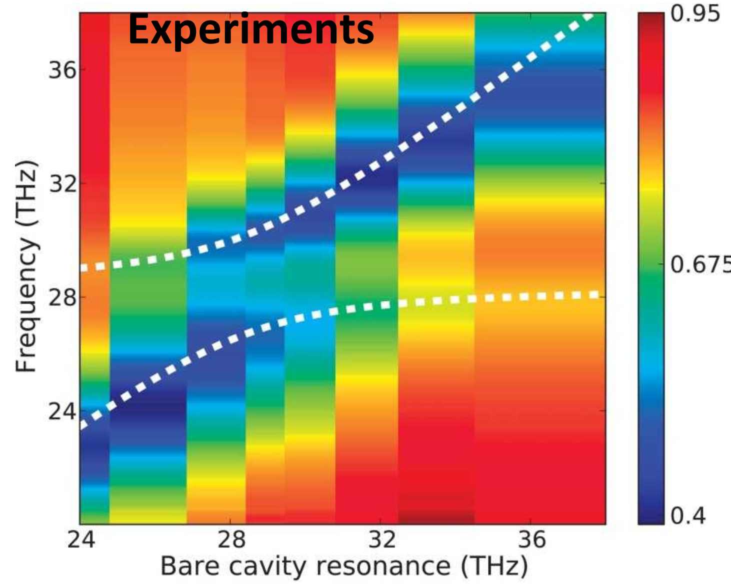
"Dogbone" resonators











Plasma frequency

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

Geometry factor

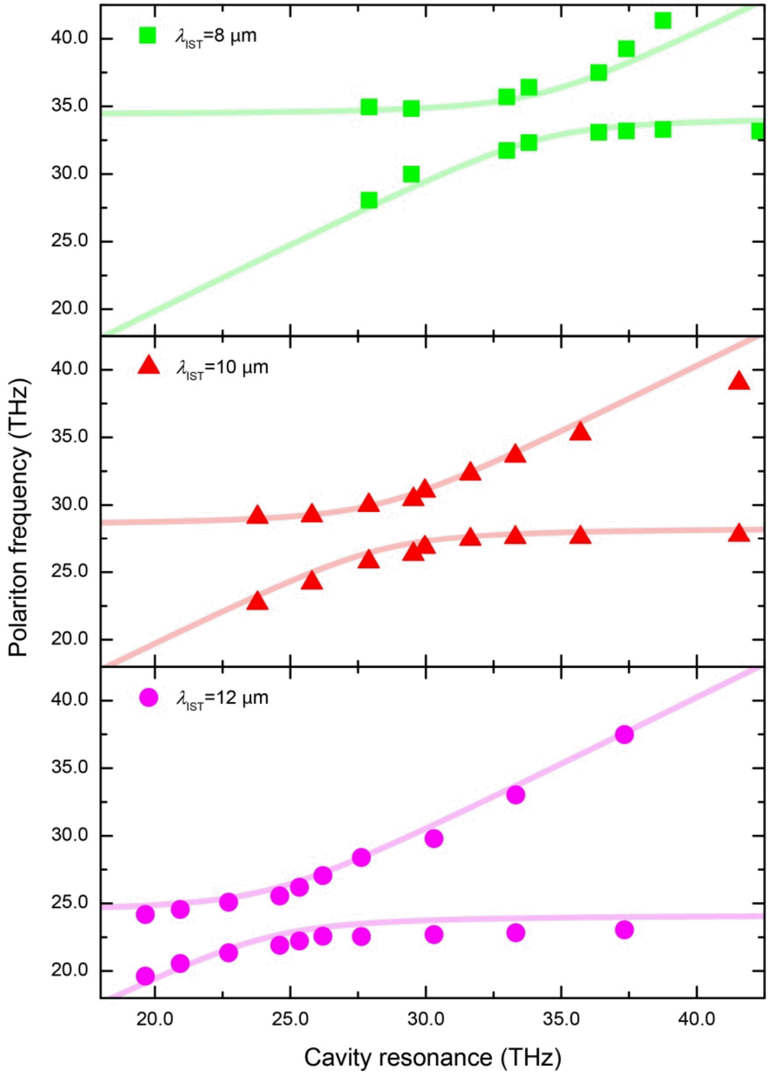
Rabi frequency depends on simple parameters

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

From Mid-IR to Near IR

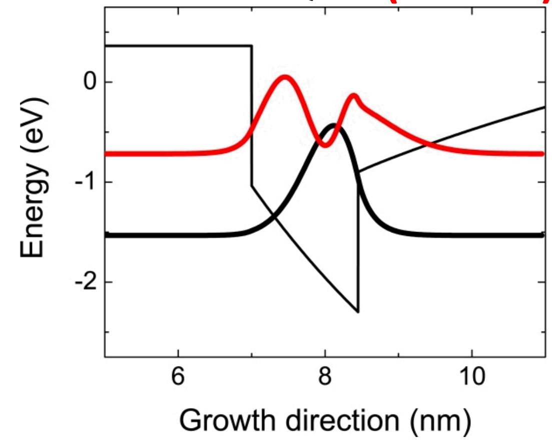
Alex Benz

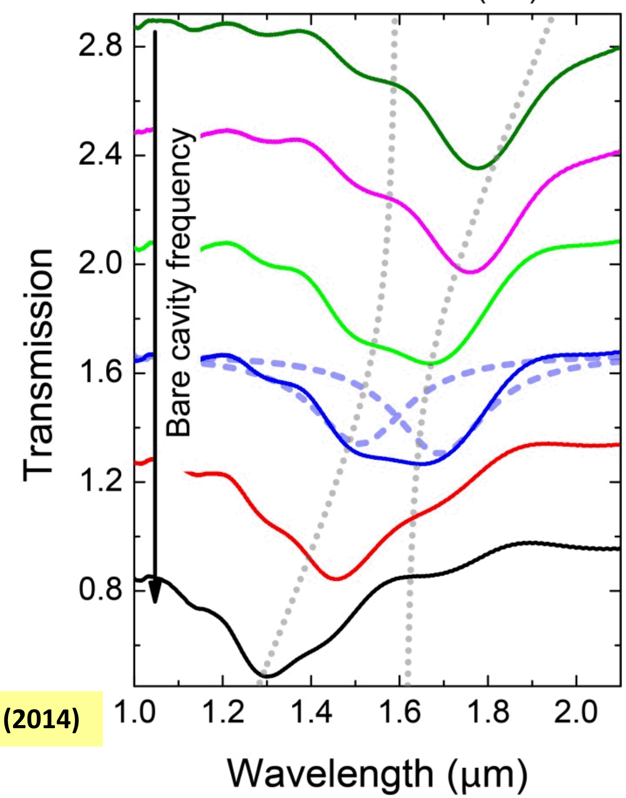
InGaAs QWs (mid IR)



Nature Communications 4, (2013)

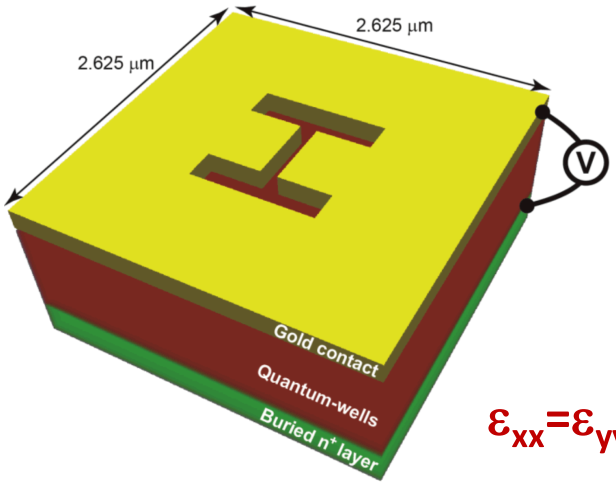
GaN QWs (near IR)



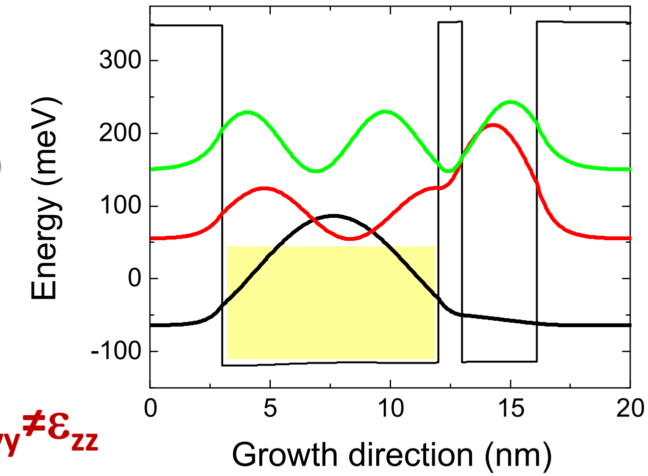


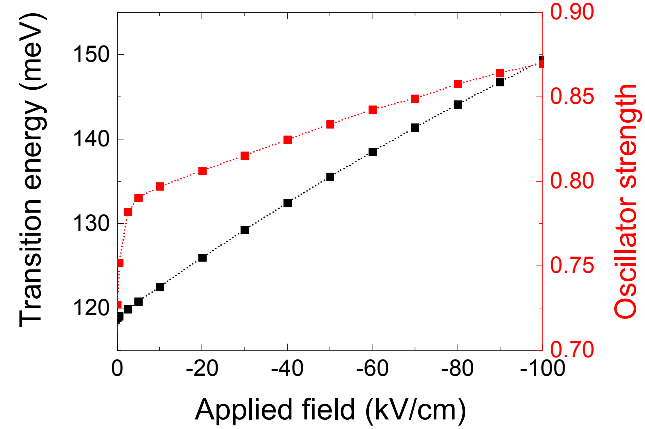
ACS Photonics (2014)

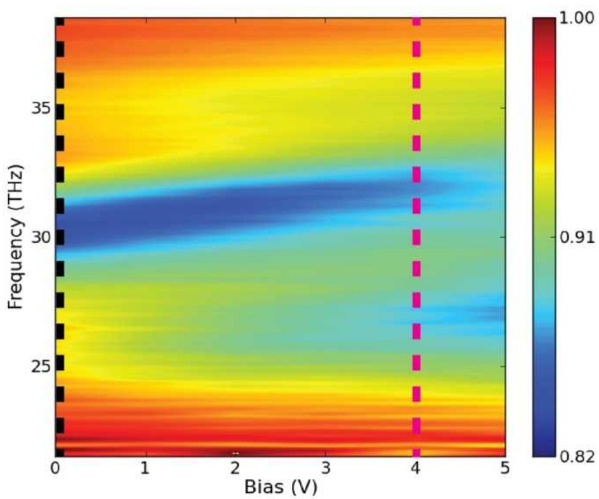
Electrically Tunable Strong Coupling

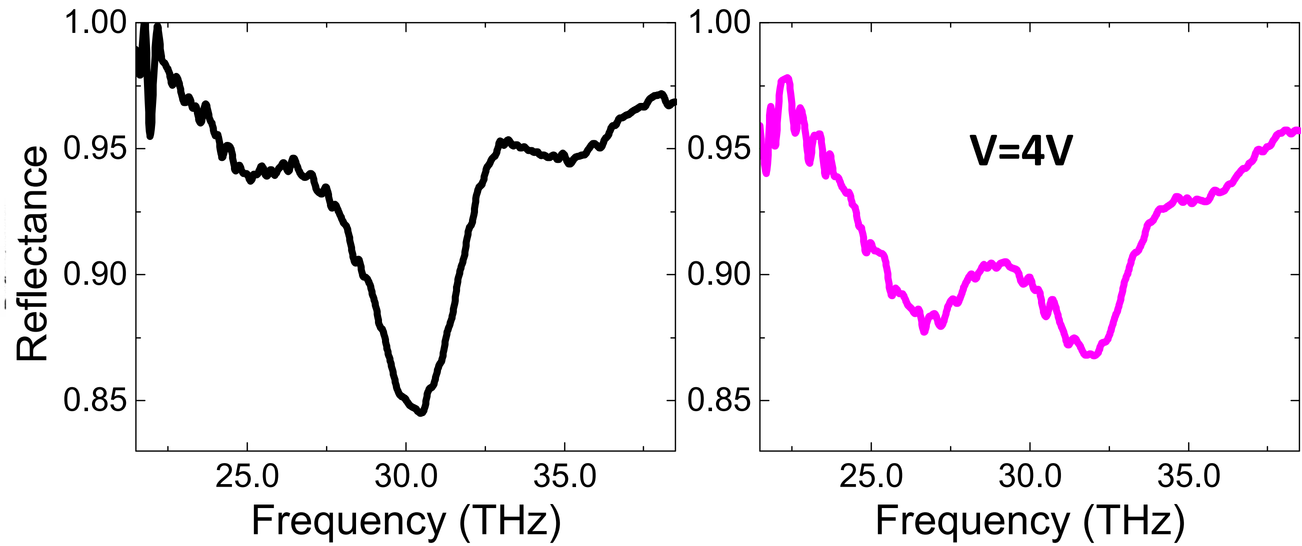


$\varepsilon_{xx}=\varepsilon_{yy}\neq\varepsilon_{zz}$









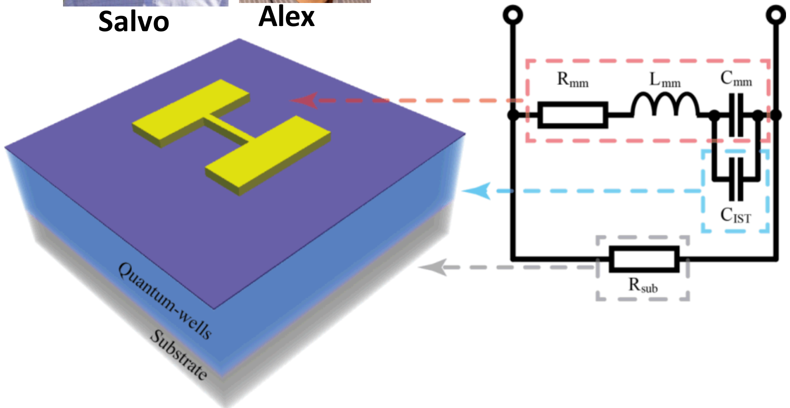
Upper polariton shifted by 2.5 THz (~8% of center frequency)

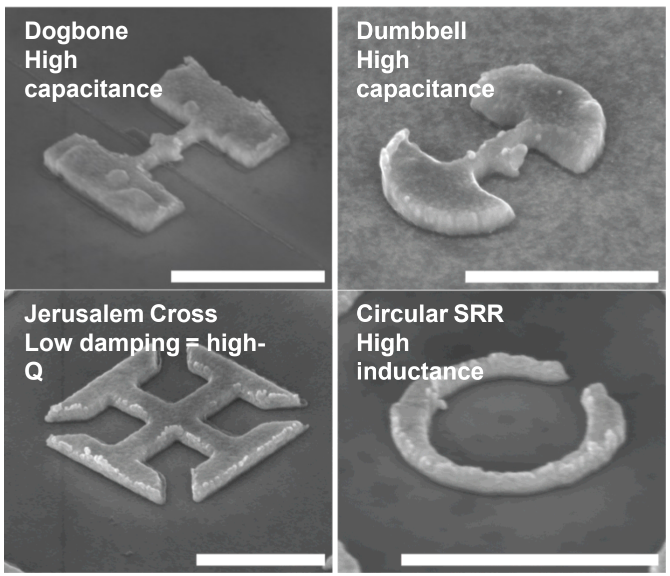
Appl. Phys. Lett. 103, 263116 (2013)

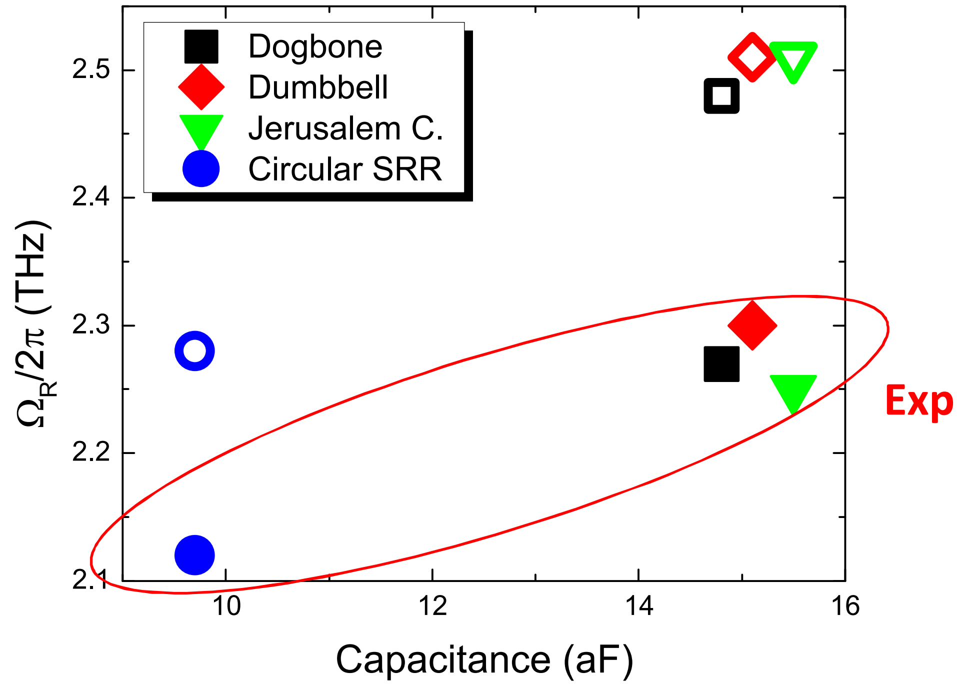
Salvo

Alex

Rabi Frequency vs. Geometry





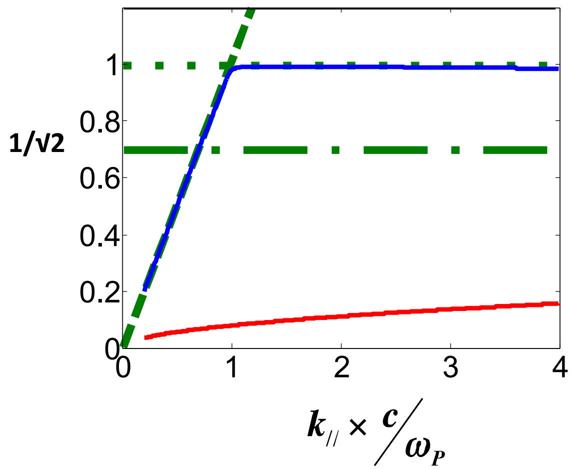


Physical Review B89, 165133 (2014)
NanoLetters 15, 1959 (2015)

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

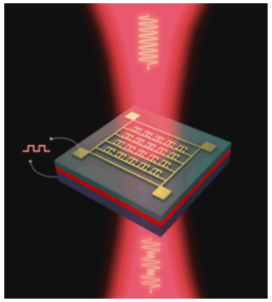
Tunable Metasurfaces: Coupling to Epsilon Near Zero Modes

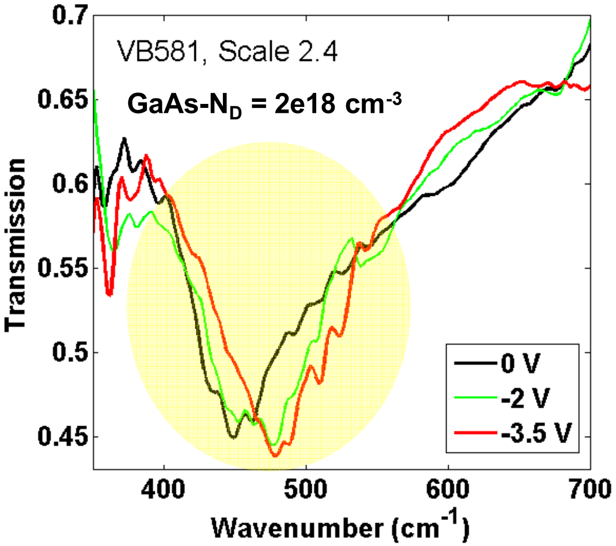
Phys. Rev. B RC. 91, 121408 (2015)

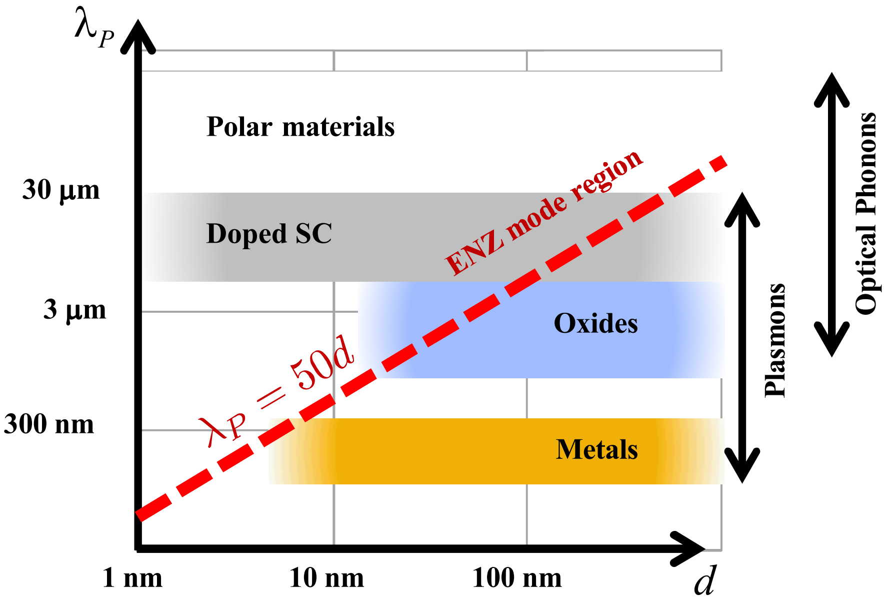


Very thin layers of a Drude material support Epsilon Near Zero modes

$$d <\approx \frac{\lambda_P}{50}$$







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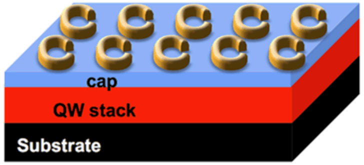
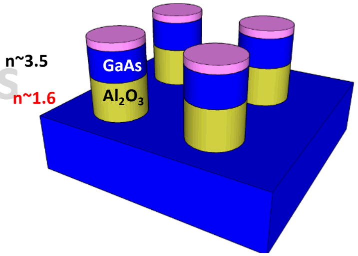
- **Harmonic generation from metallic metasurfaces coupled to intersubband transitions in semiconductor quantum wells**



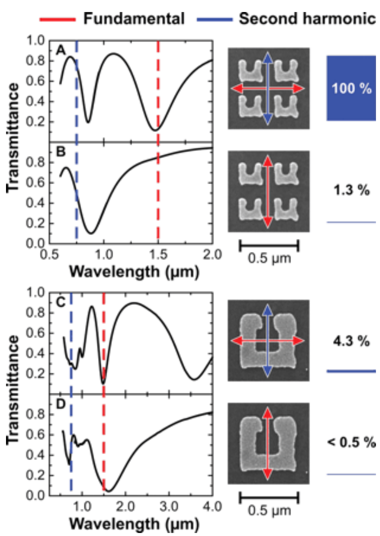
- Harmonic generation from all-dielectric metasurfaces



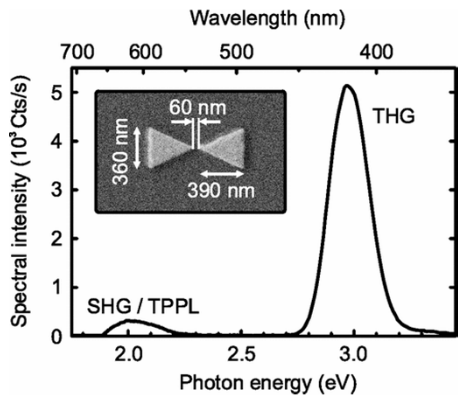
Nonlinear Metasurfaces: Harmonic Generation from Metallic Resonators

- **Harmonic generation has been observed from planar metamaterials ("metasurfaces") and plasmonic arrays.**

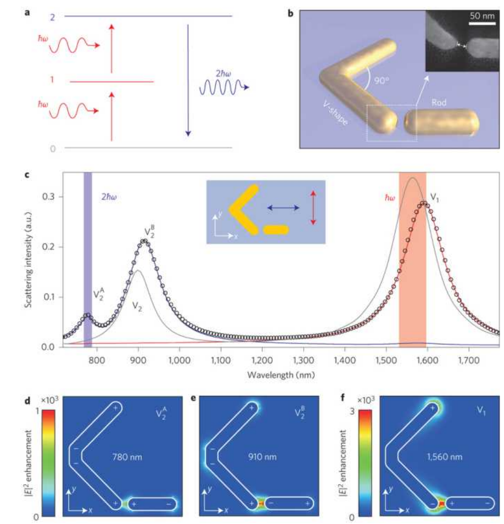
***First reports*: Science 502, 313 (2006)**



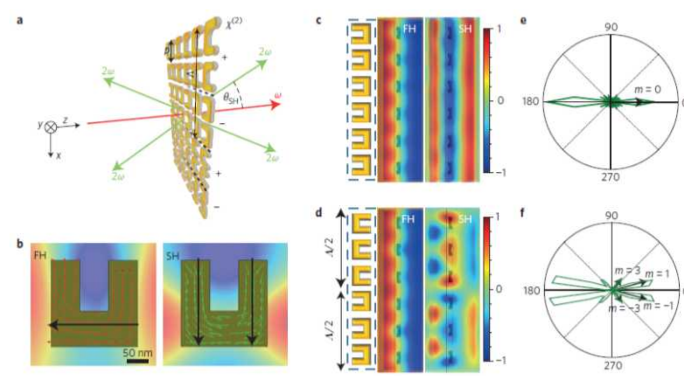
Other geometries:
Phys. Rev. Lett. 103, 257404 (2009)



Mode Matching:
Nature Nanotechnology 10, 412 (2015)



Metamaterials Photonic Crystals:
Nature Photonics 9, 180 (2015)



And many more….

Efficiencies have been very, <u>very</u> low!

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

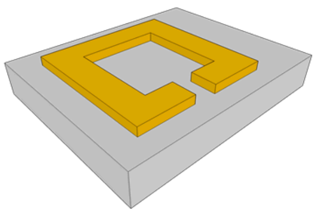
Increase I or L

Cavity-enhanced

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

$\chi^{(2)}$

Coherent Inc.

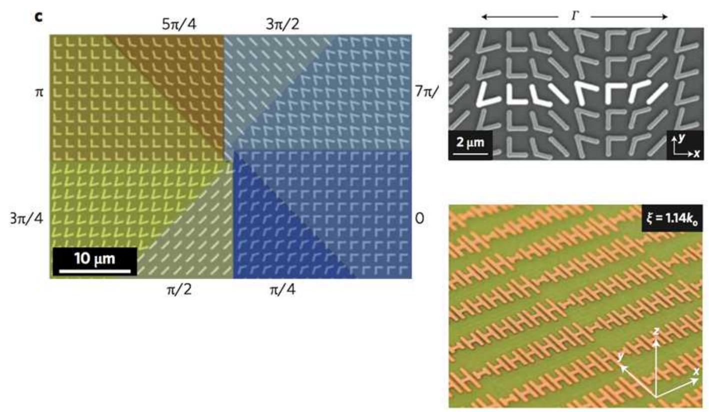


Increase $\chi^{(2)}$

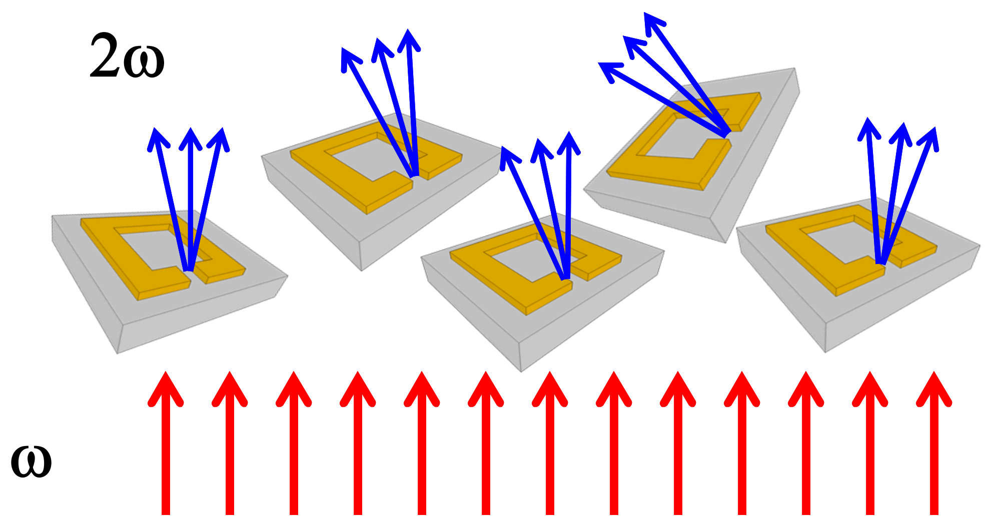
Use resonant $\chi^{(2)}$ with semiconductor heterostructures ~ 10^4 enhancement in $\chi^{(2)}$

Metasurfaces Provide New Functionality for Harmonic Generation

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

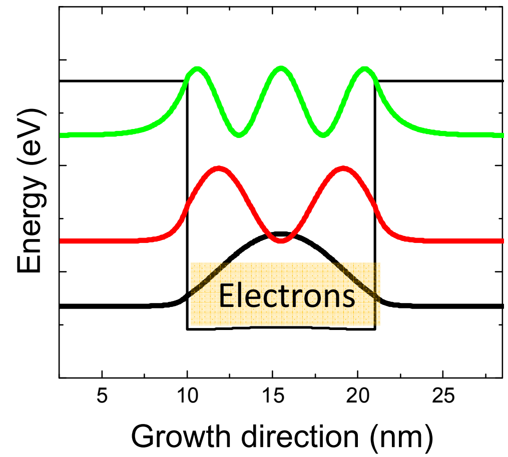


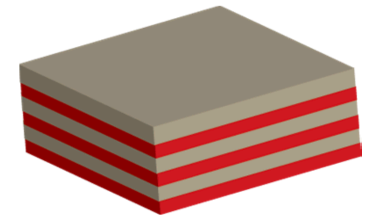
(Shalaev, Capasso, Zhou, Zheludev, etc..)



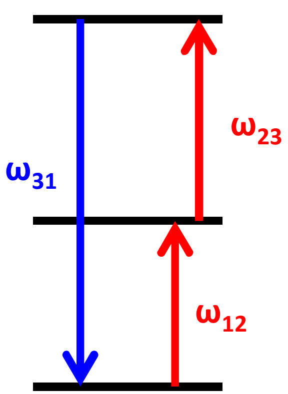
Resonant Optical Nonlinearities: Intersubband Transitions in Quantum Wells

Electronic levels and wavefunctions can be engineered with semiconductor heterostructures





Resonant optical nonlinearities can be engineered too:

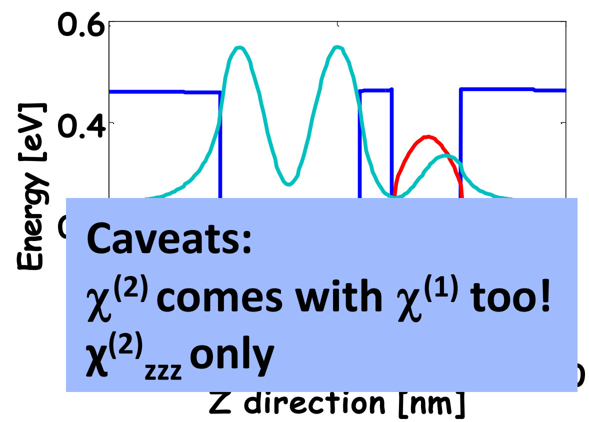


$$\chi^{(2)}(\omega) \propto \frac{N \cdot z_{12} z_{23} z_{13}}{(\omega - \omega_{12} - i\Gamma_{12})(2\omega - \omega_{13} - i\Gamma_{13})}$$

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

~250 nm/V - QWs

10s of pm/V - $LiNbO_3$



Caveats:

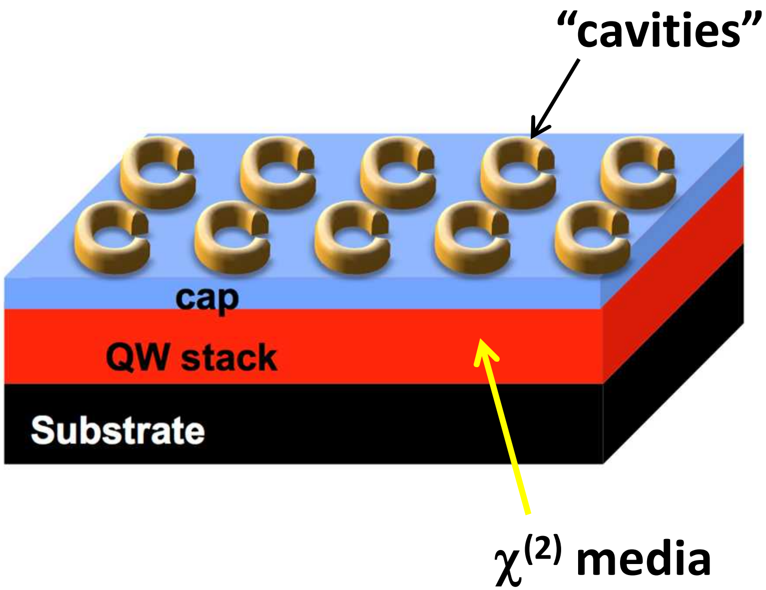
$\chi^{(2)}$ comes with $\chi^{(1)}$ too!

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

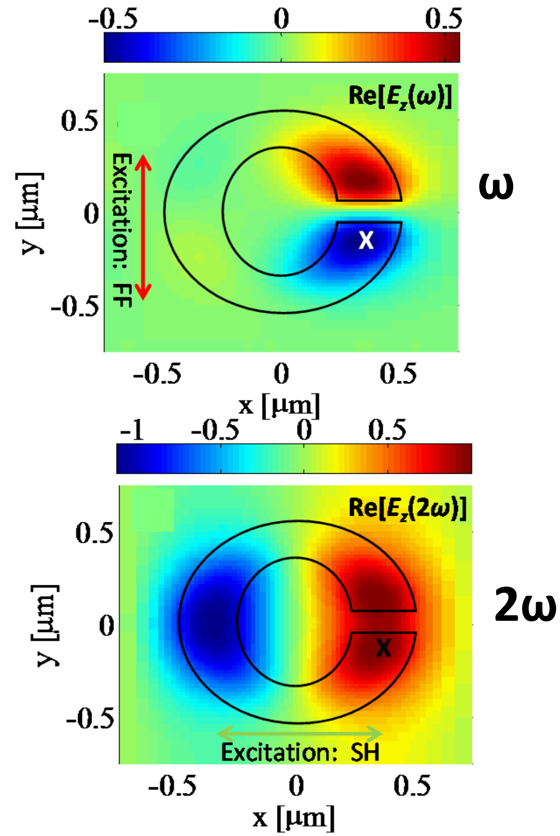
F. Capasso, C. Sirtori, and A.Y. Cho, IEEE J. Quantum Electron. 30, 1313 (1994)

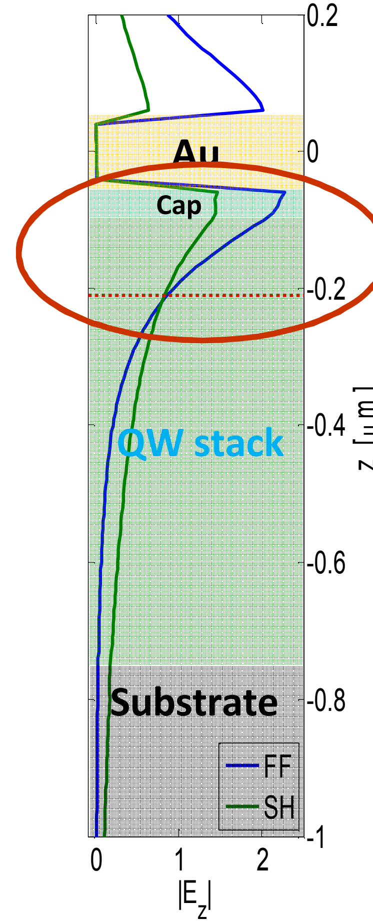
Salvo Campione

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



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





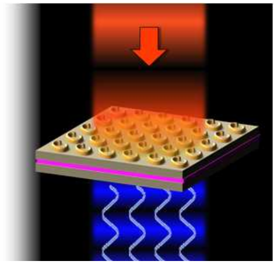
APL 104, 131104 (2014)


Omri

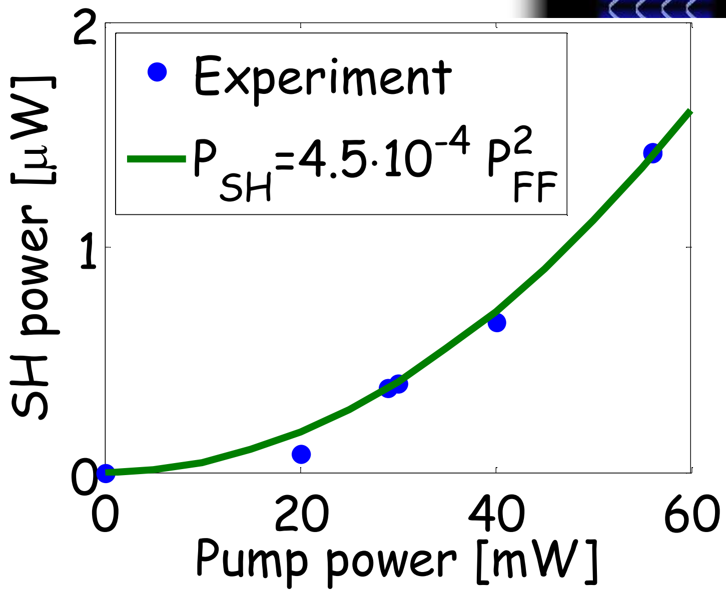

Salvo

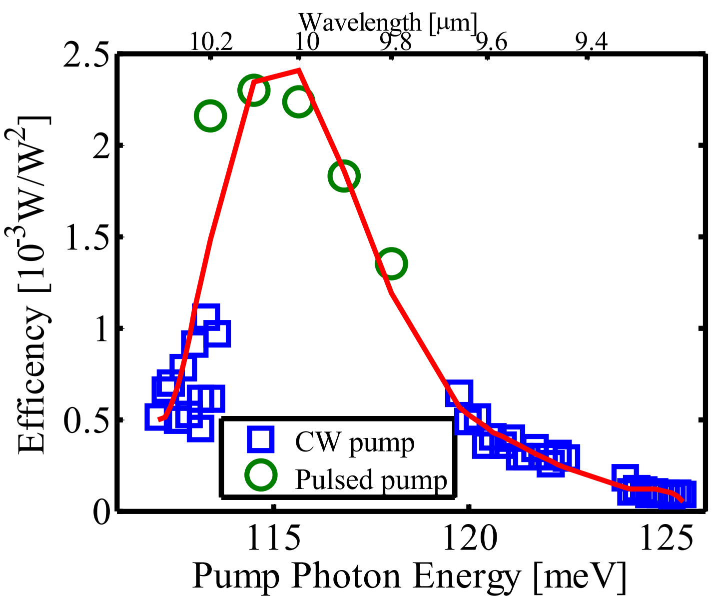
SHG: Power and Frequency Dependence

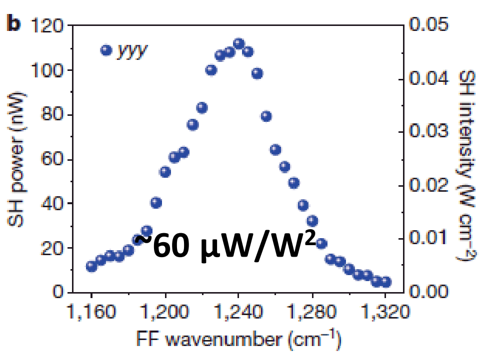
Pump: CW CO_2 laser



max efficiency: ~2.3 mW/W²







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

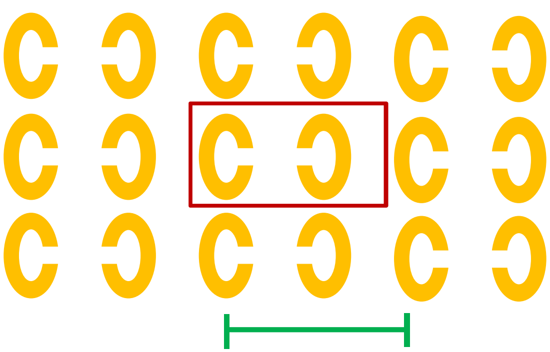
- **Saturation is an issue**
- **Max. conversion efficiencies of few % are possible**
- **Added functionality is the advantage**

Nature Communications 6, 7667 (2015)

SHG Beam Manipulation

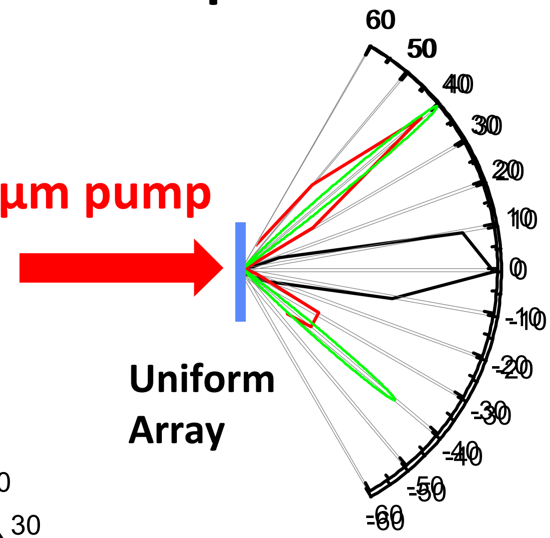
“edge-fed dipole”

flipping induces π phase shift



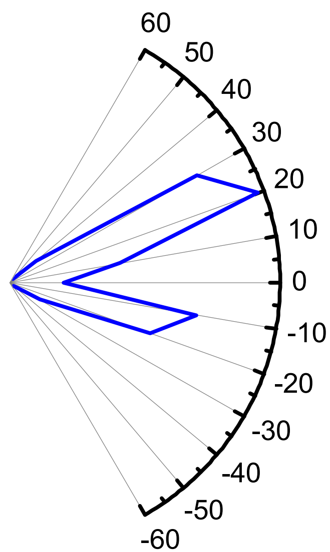
Period determines angular separation

10μm pump



5μm beam

Uniform Array



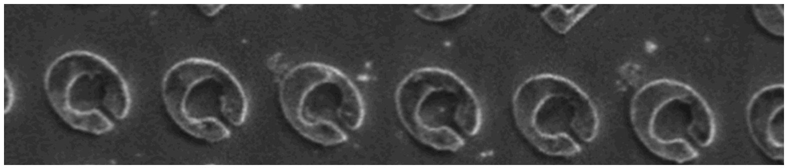
2-in-1:

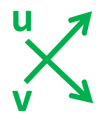
Source +beam splitter

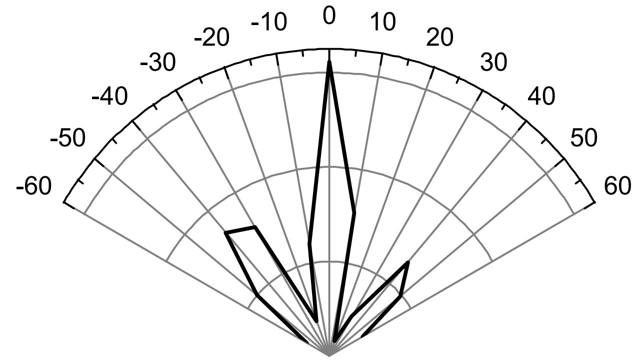
Nature Communications 6, 7667 (2015)

SHG Beam Manipulation II

- Cavities radiate polarized light

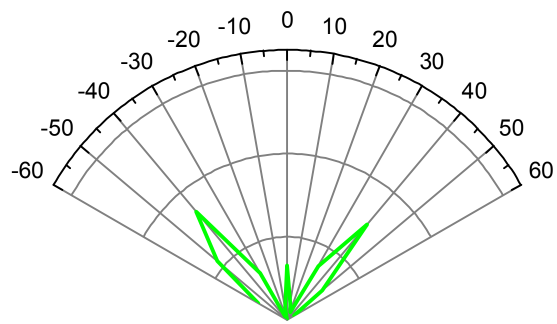




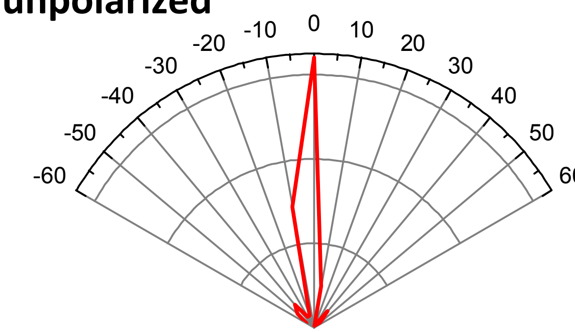


unpolarized

Pump polarization



v polarized

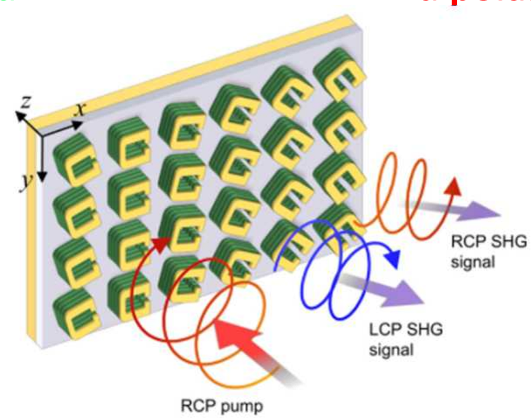


u polarized

3-in-1:

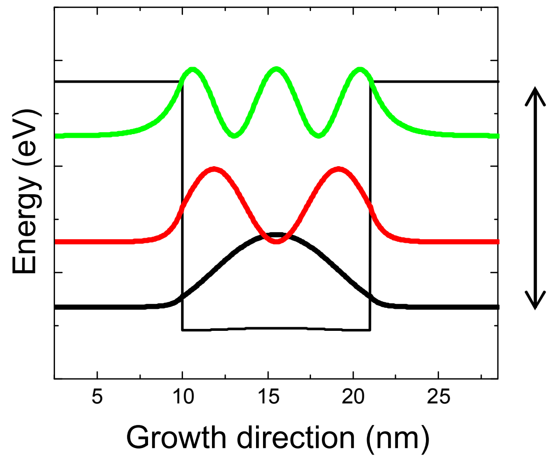
Source + Polarizer + Beam Splitter

Belkin & Alu, PRL 2015



Scaling This Approach to Shorter Wavelengths

Material 1 Material 2 Material 1



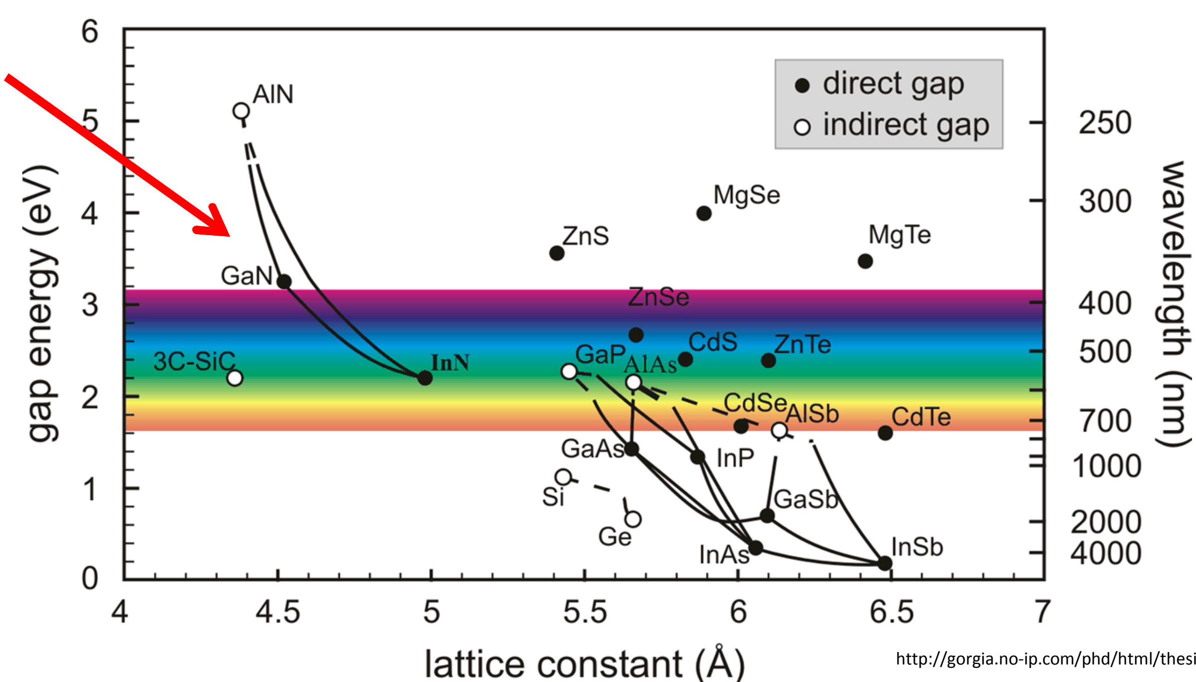
10um to 5um: AlInAs barriers
InGaAs wells

2ω ~ 0.24eV

How about 1.55um to 0.75um?

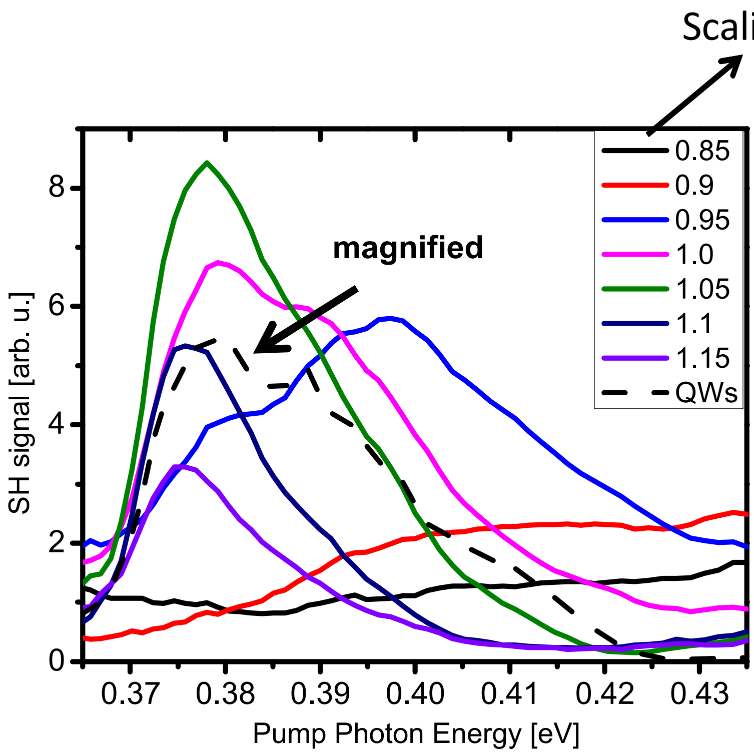
This requires a conduction band offset of ~1.6eV!!

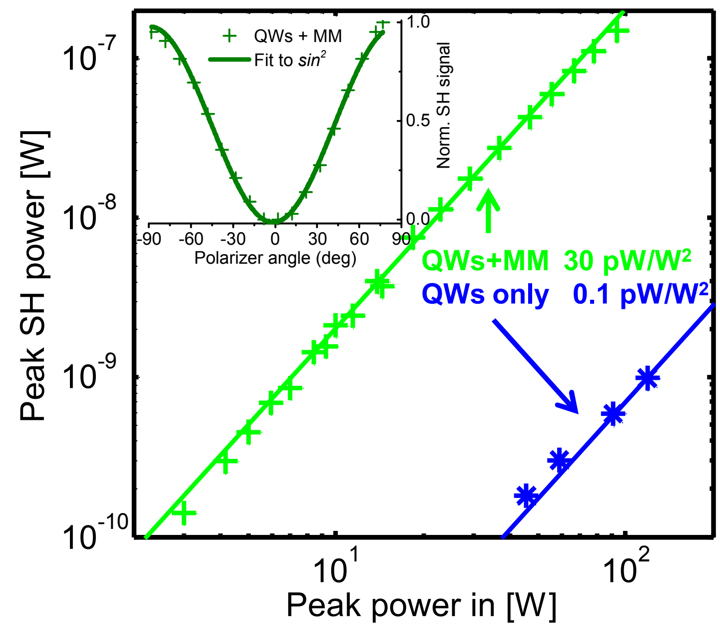
III-Nitrides

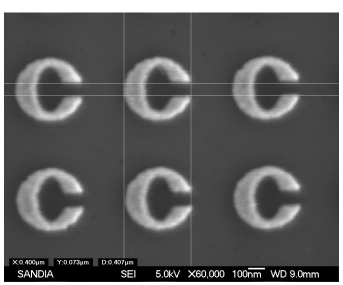


http://gorgia.no-ip.com/phd/html/thesis/phd_html/simone-jbook.html

SHG (3.2μm>1.6μm) Using AlGaN/GaN QWs





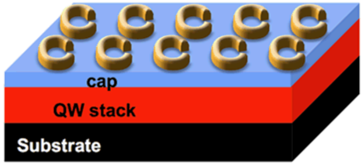


In a III-N heterostructure, metamaterials increase efficiency by over 2 orders of magnitude

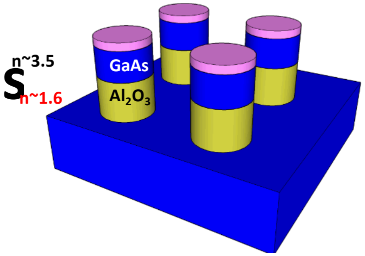
APL 107, 151108 (2015)

Outline

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

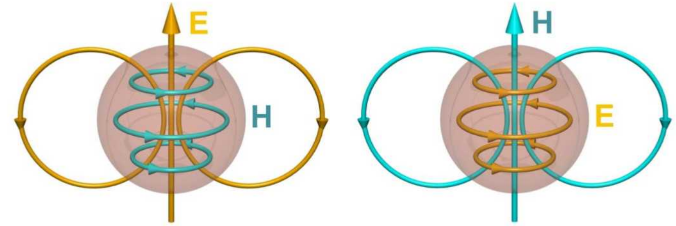


- **Harmonic generation from all-dielectric metasurfaces**



Dielectric Resonators for Metamaterials

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



Images: A. Miroshnichenko

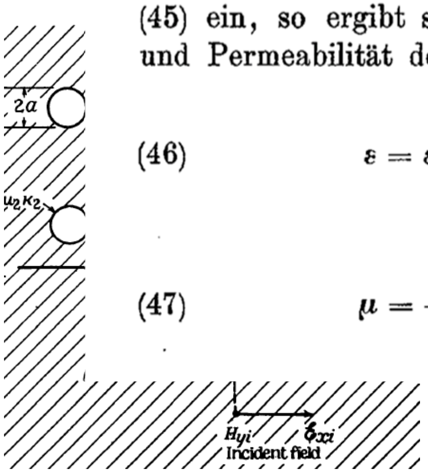
3. *Zur Optik kolloidaler Metallösungen;*
von R. Gans und H. Happel.

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

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

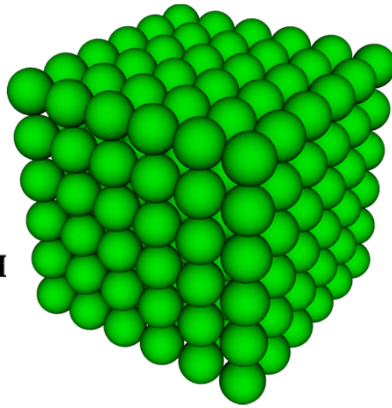
$$(47)\qquad \mu = \frac{1 - \frac{4\pi N}{3}\left(\frac{\lambda'}{2\pi}\right)^3 p_1}{1 + \frac{2\pi N}{3}\left(\frac{\lambda'}{2\pi}\right)^3 p_1}.$$



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

(Ack: Ed Kuester, CU Boulder)

MATERIAL LOADED WITH
ICLES*
†
ed form 27th September, 1946.)



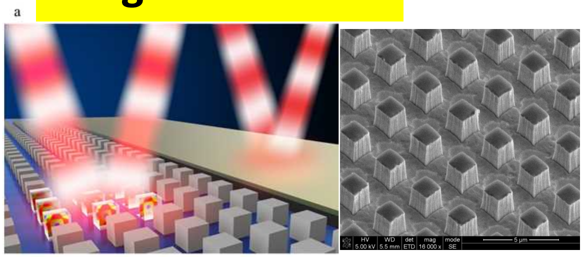
$$F(\theta) = \frac{2(\sin\theta - \theta\cos\theta)}{(\theta^2 - 1)\sin\theta + \theta\cos\theta}$$

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

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

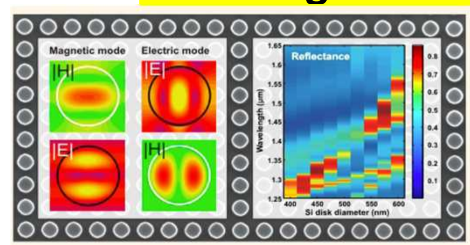
Some Recent Results with Dielectric Metasurfaces (Linear)

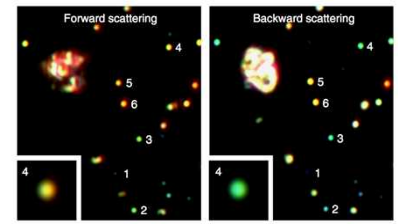
Magnetic mirror



Optica 2015

Tailoring scattering

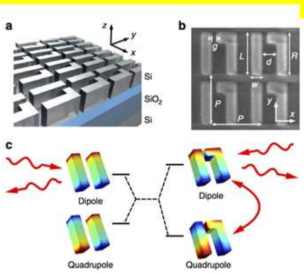


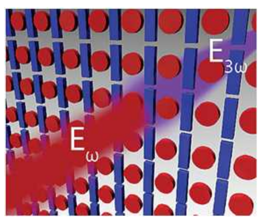


***ACS Nano 7**, 7824 (2013)*

***Nat. Comm. 4**, 1527 (2013)*

Fano resonances

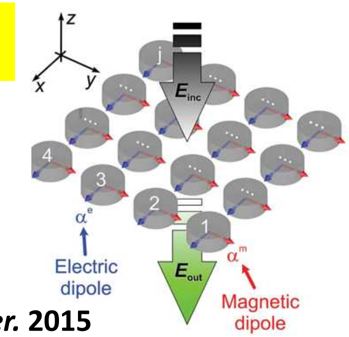




***Nature Comm**. 2014.*

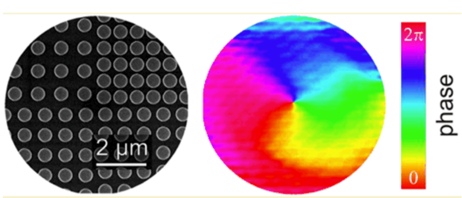
Nano Lett. 15, 7388 (2015)

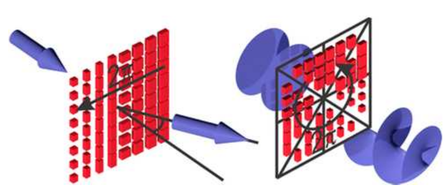
Huygens Metasurfaces

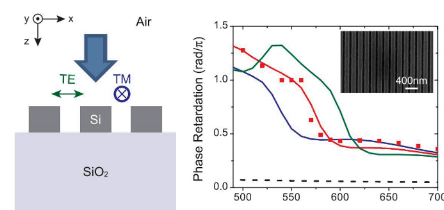


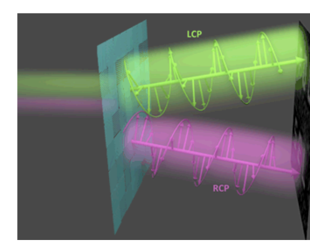
Adv. Optical Mater. **2015**

Phase-front manipulation









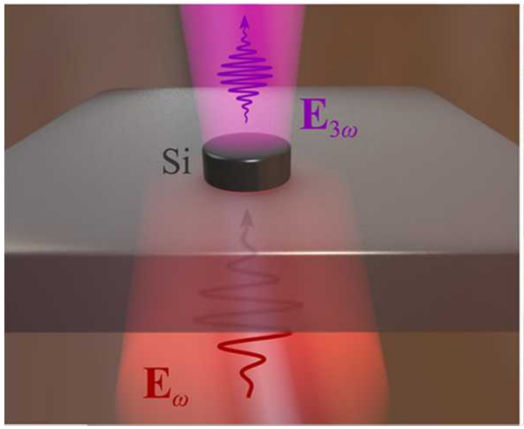
Nano Lett. 15, 5369 (2015)

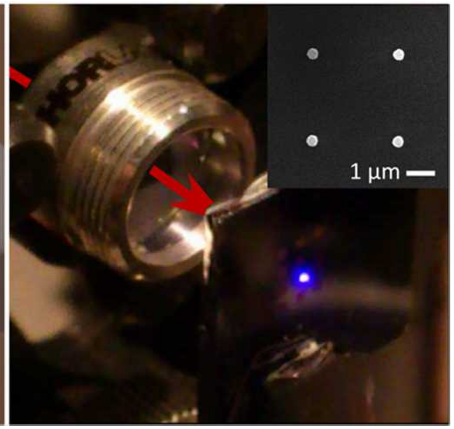
Nano Lett.15, 6261 (2015)

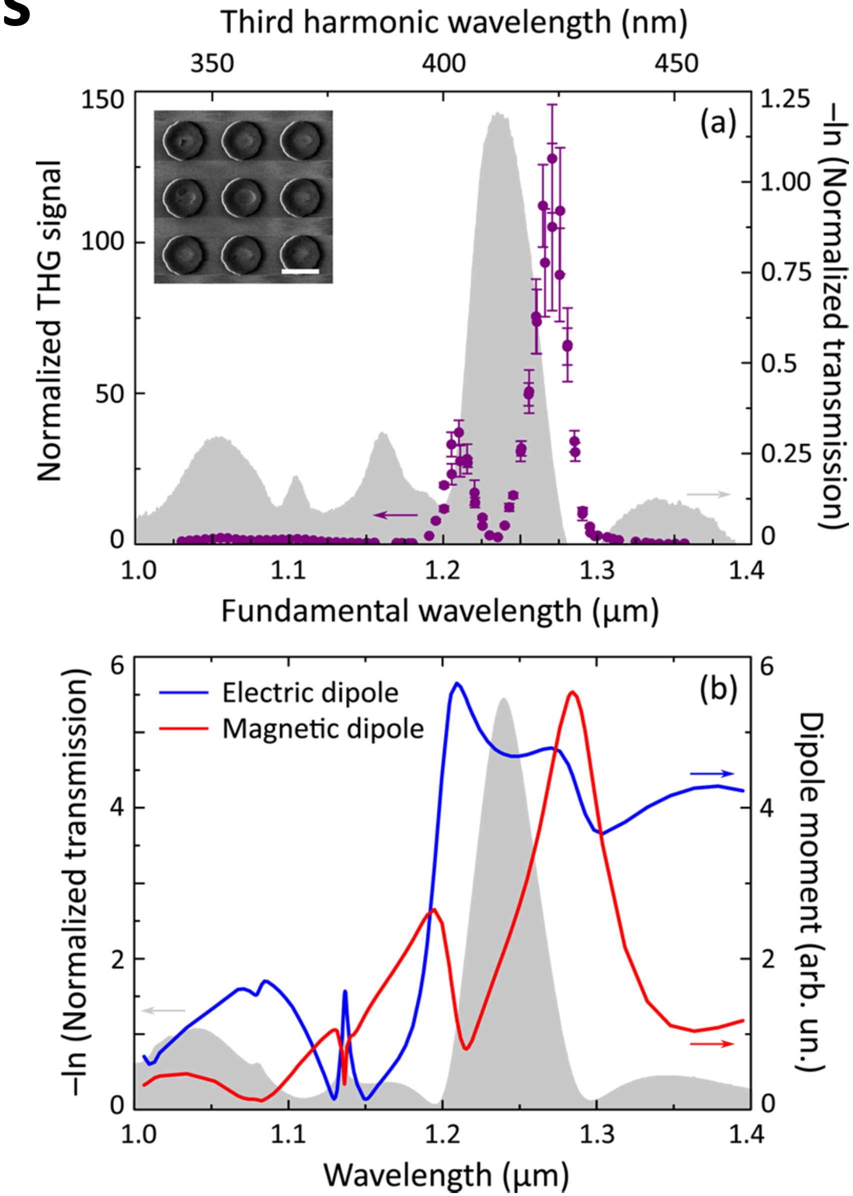
***Science 345,** 2015*

***Opt. Express 23,** 22611 (2015)*

Optical Nonlinearities (THG) in Si Dielectric Metasurfaces







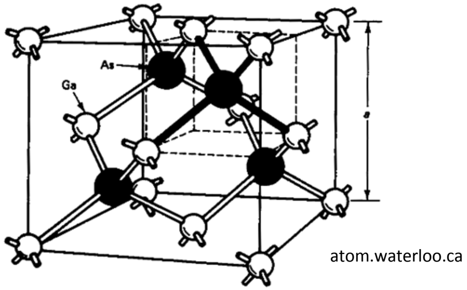
Strong enhancement near magnetic dipole resonance

(With ANU & Moscow State
Maxim R. Shcherbakov, Alexander S. Shorokhov, Dragomir N. Neshev, Ben Hopkins, Isabelle Staude, Elizaveta V. Melik-Gaykazyan, Alexander A. Ezhov, Andrey E. Miroshnichenko, Igal Brener, Andrey A. Fedyanin, and Yuri S. Kivshar)

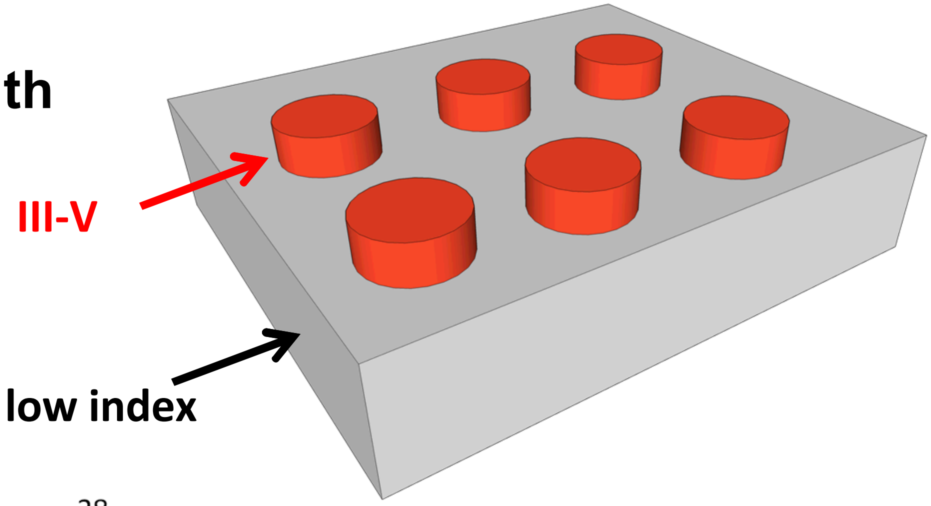
Nano Letters (2015)

Silicon is "limited" for Optical Nonlinearities

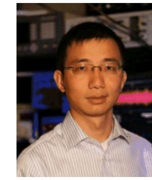
- Silicon is centrosymmetric → NO second order nonlinearity
- Lots of III-V semiconductors have $\chi^{(2)}$
- Example, GaAs:

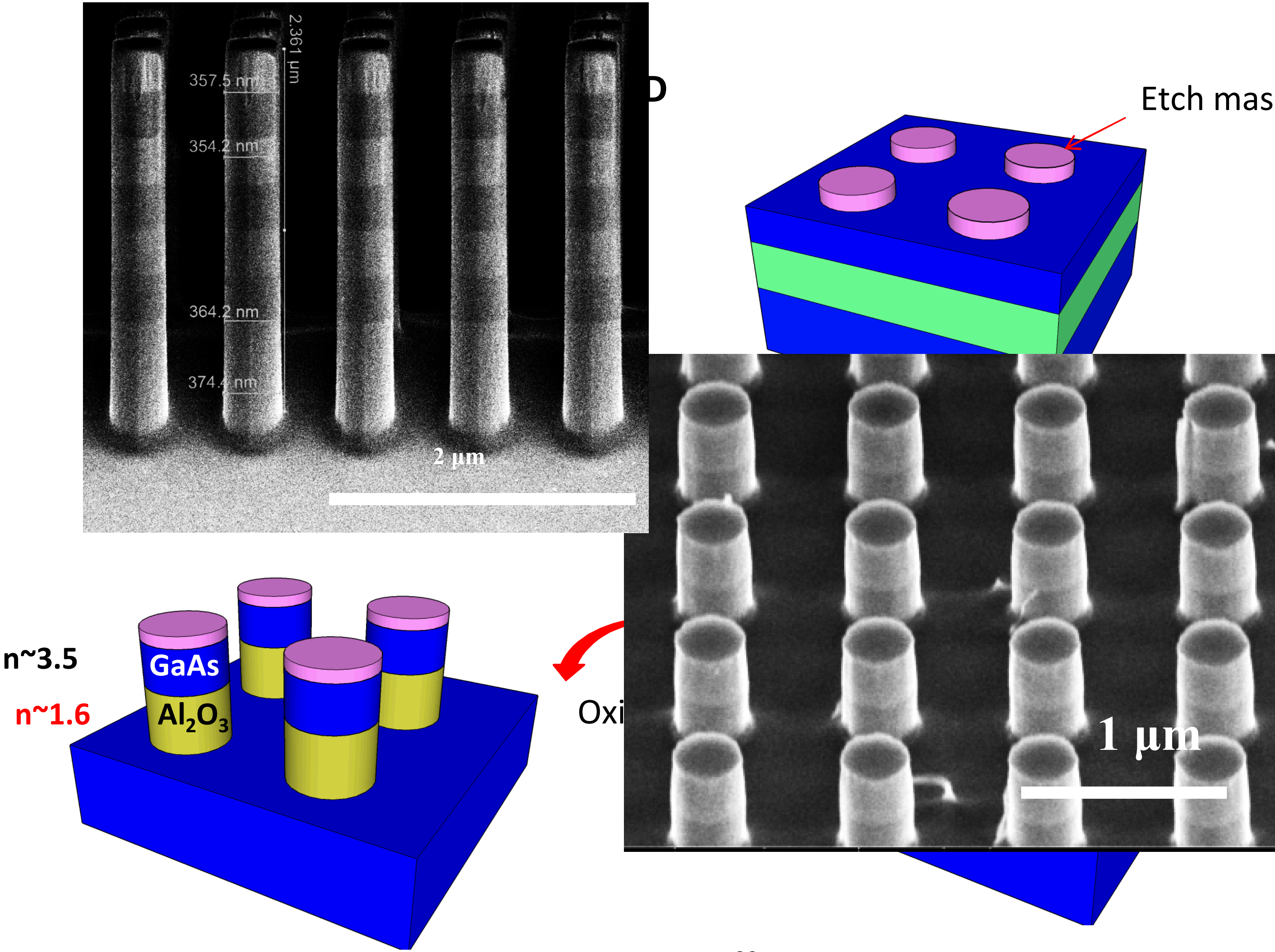


How to obtain high index dielectric nanoresonators with III-V semiconductors??



Fabrication of Al(In)GaAs Based Dielectric MMs

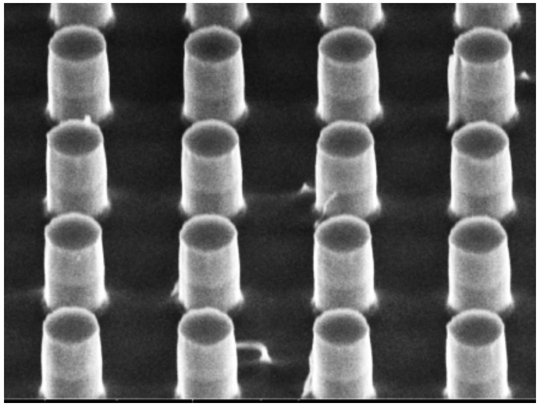

Sheng Liu



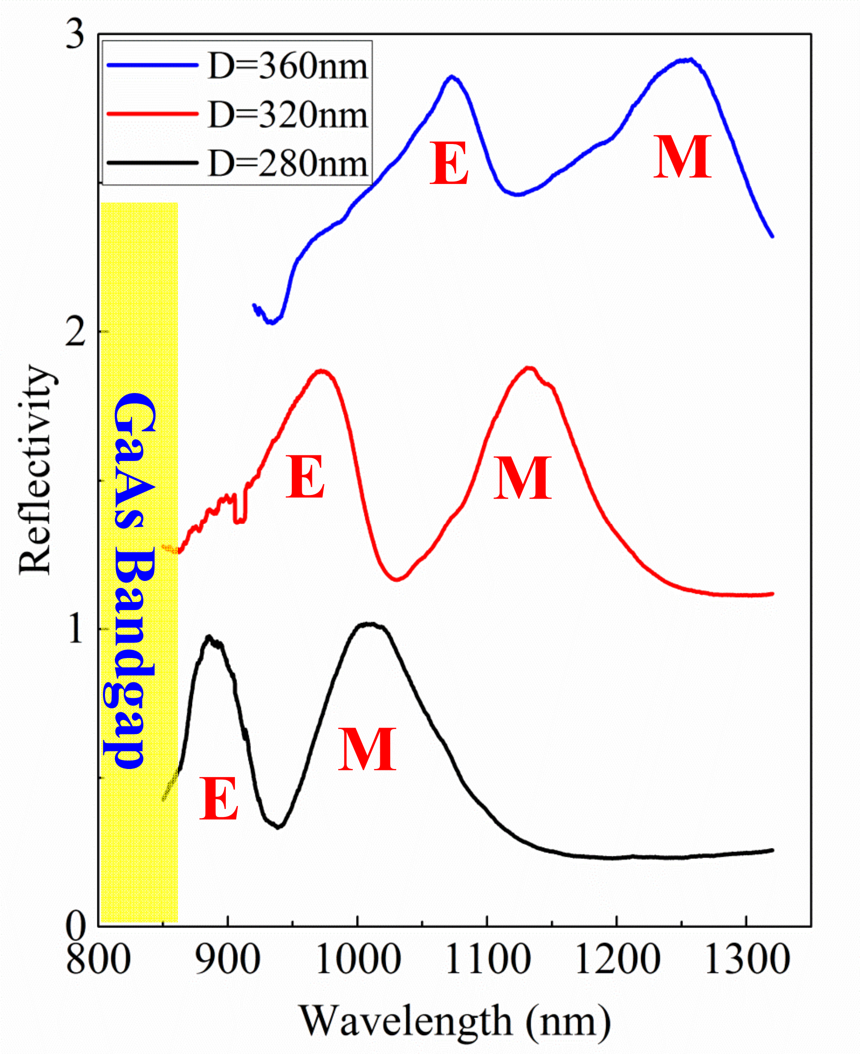
GaAs Dielectric Resonators (1 layer)

GaAs disk height ~300nm

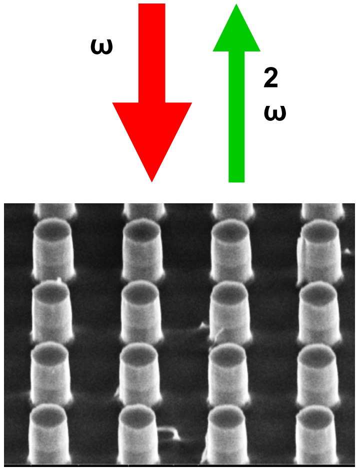
Different diameters

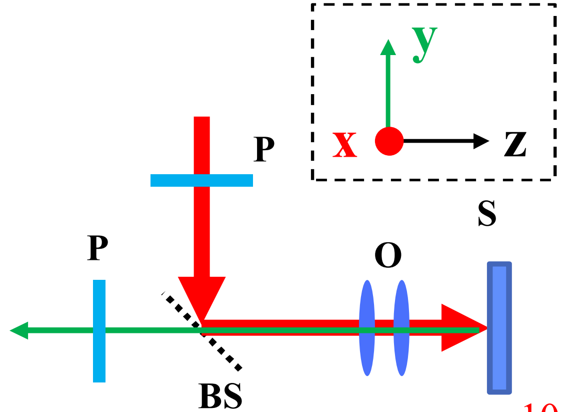


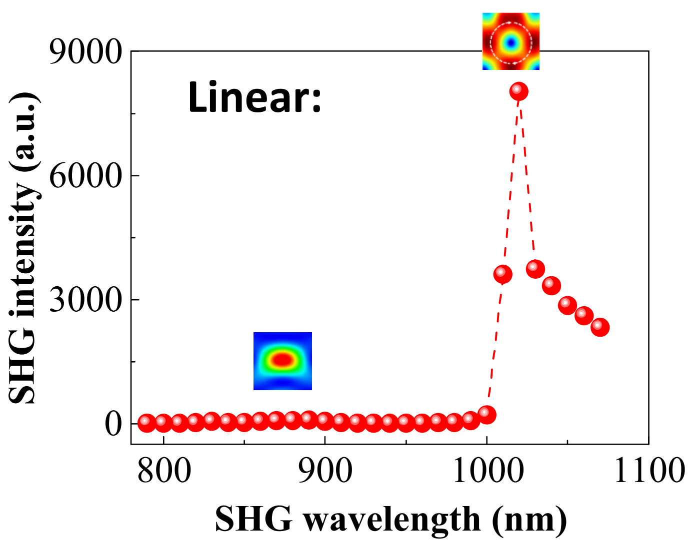
- Extremely low loss below bandgap
- Crystalline

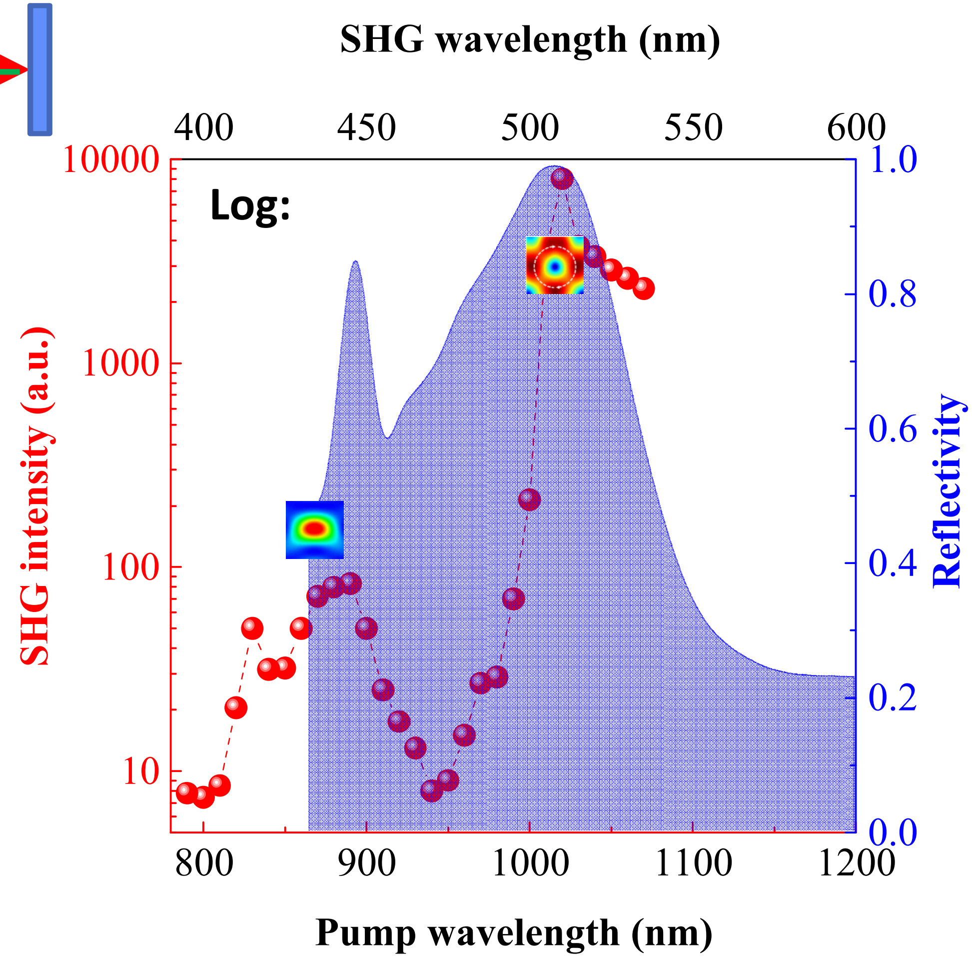


Second Harmonic spectral dependence





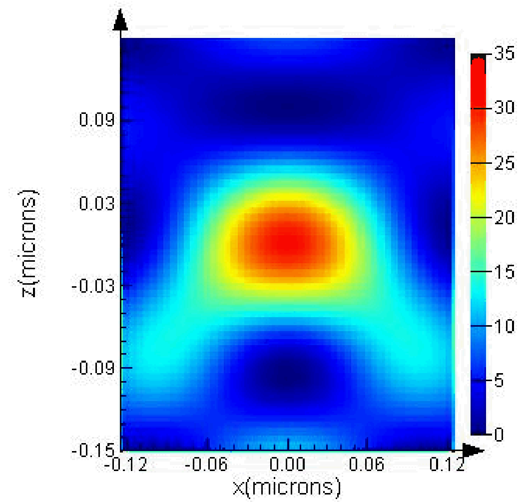


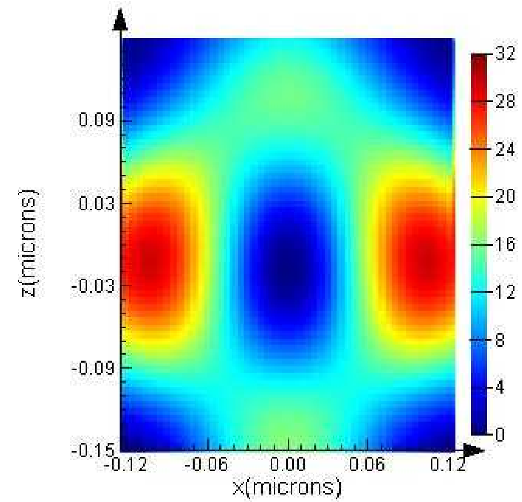


Polarization, Selection Rules

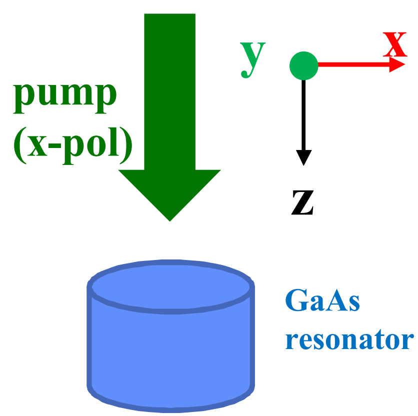
$|E|^2$ enhancement for both electric and magnetic dipole resonance.

($I_{2\omega}$ proportional to I_{ω}^2)





There are only E_x and E_z component inside the GaAs resonators.

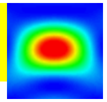


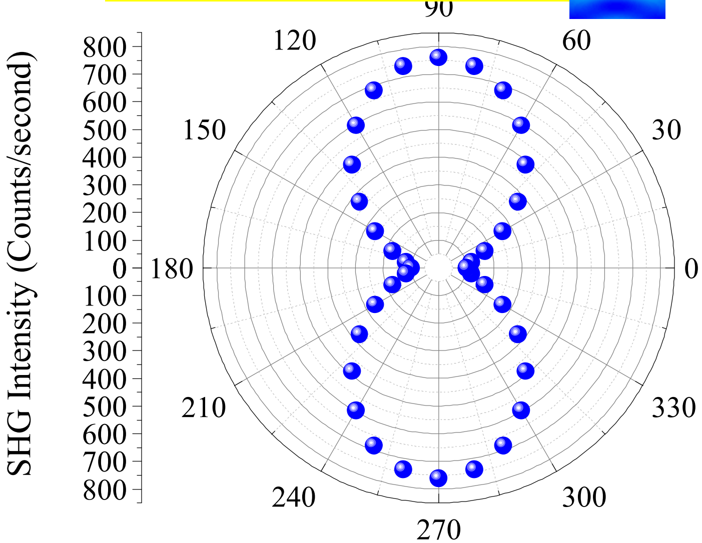
$$E_y^{2\omega} = 2\chi_{xxy}^{(2)} E_x^{\omega} E_z^{\omega}$$

Orthogonal SHG polarization compared to the pump is expected

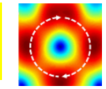
Pump ←

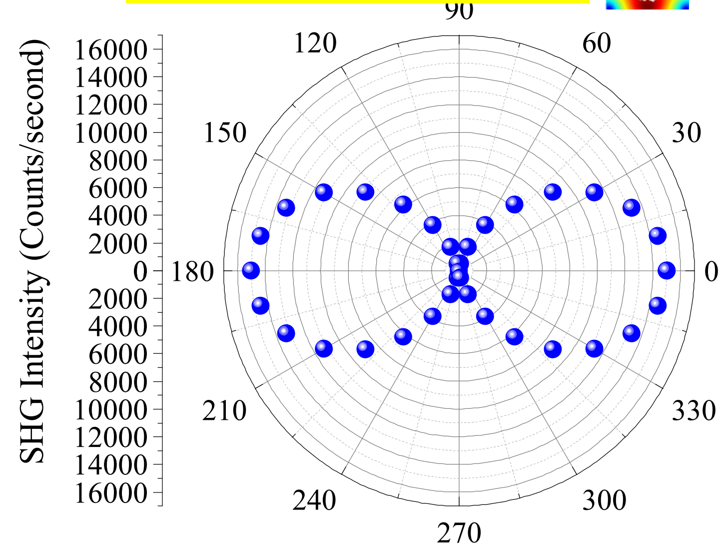
E-dipole resonance

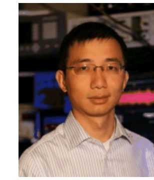




M-dipole resonance







Sheng Liu

!!!

This is not consistent with bulk $\chi^{(2)}$

What happens at the M-dipole resonance?

1. Surface nonlinearity changes symmetry to mm2

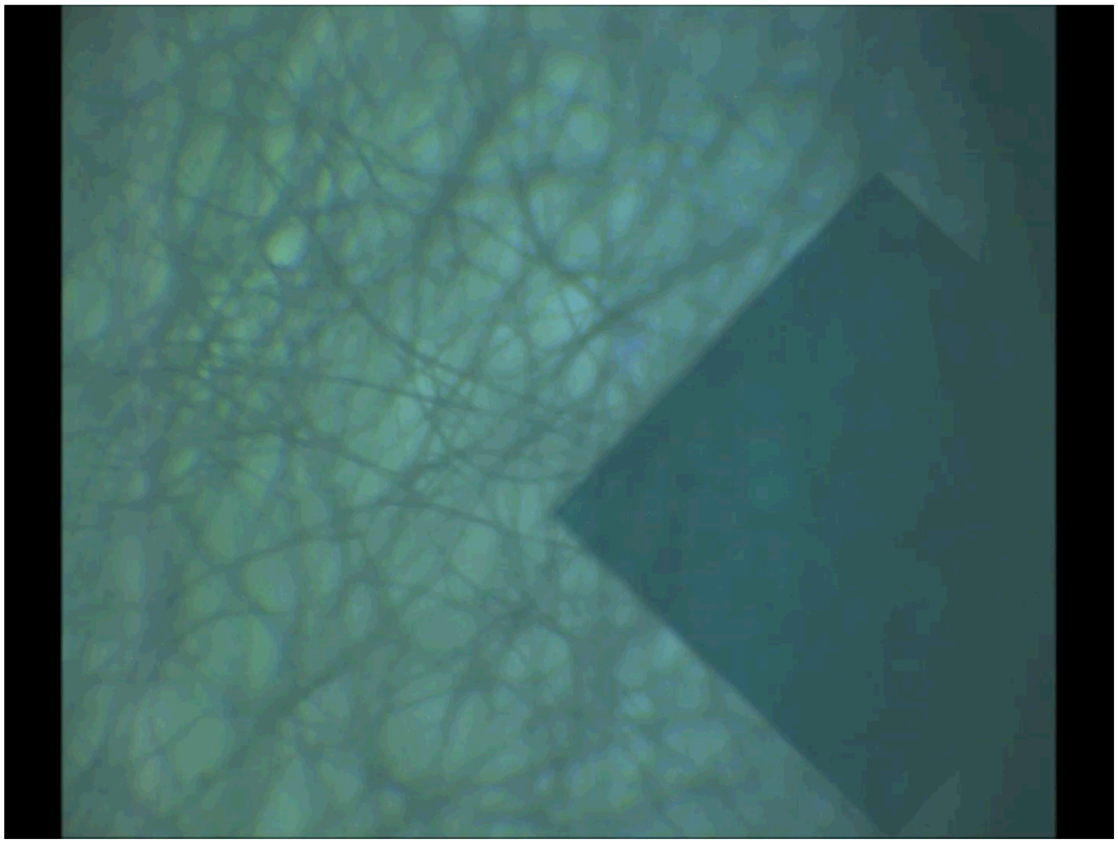
$$E_x^{2\omega} = 2\chi_{xxz}^{(2)} E_x^{\omega} E_z^{\omega}$$

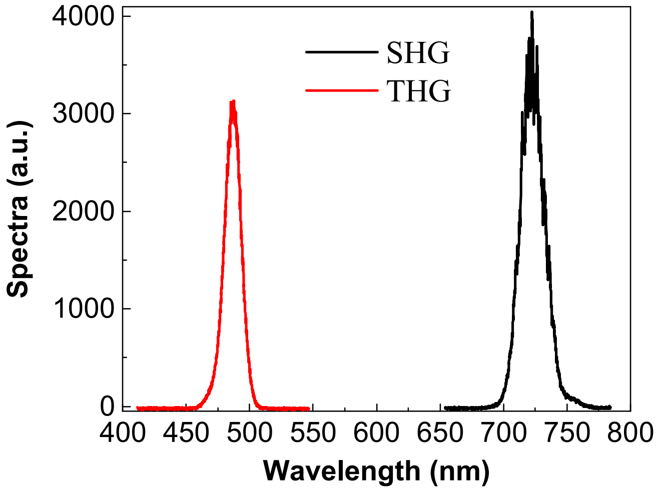
can be large, considering the large field enhancement at the surface for this mode.

2. SHG is above bandgap of GaAs, absorption favors SHG generated at the surface.

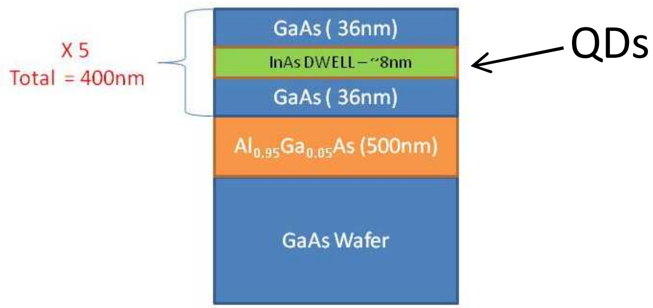
Not predicted: Carletti *et al*,: “Enhanced second-harmonic generation from magnetic resonance in AlGaAs nanoantennas”, *Optics Express*, *23*, 26544 (2015)

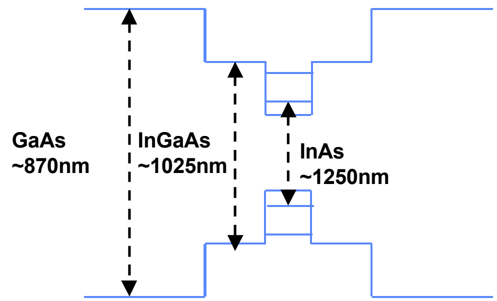
Simultaneous SHG & THG….

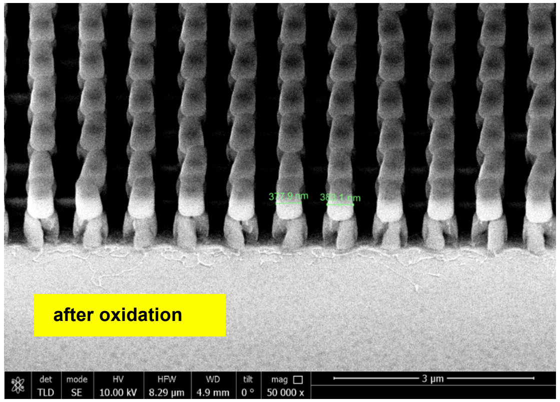




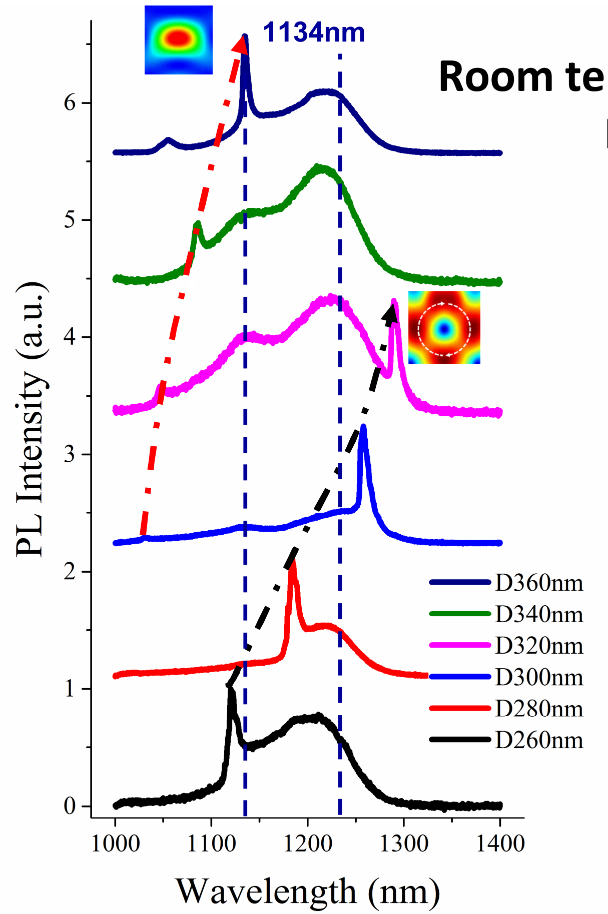
“Active” All-Dielectric Metasurfaces



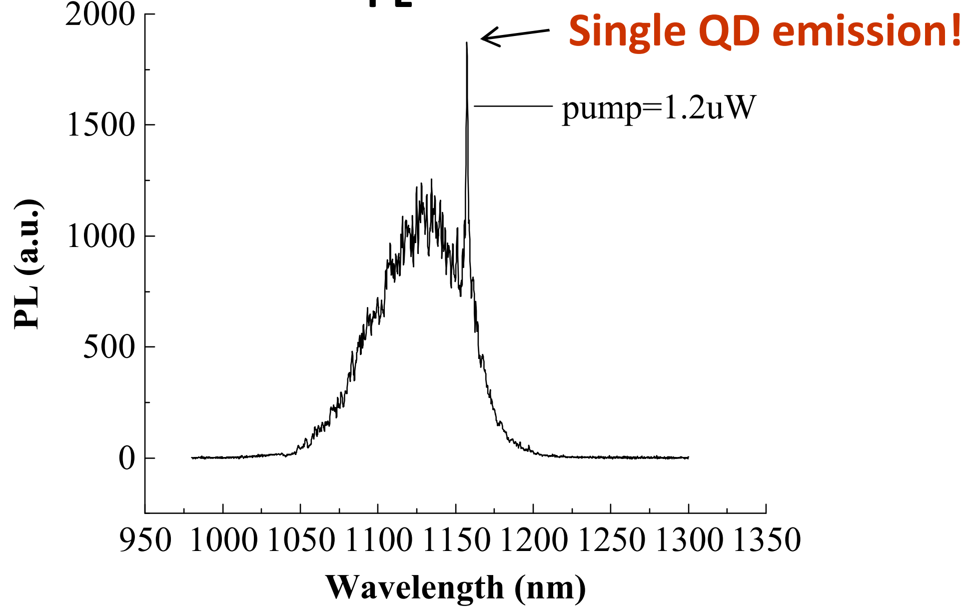




Room temperature PL



Low temperature PL



Summary & Acknowledgments

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

Departed postdocs: Young-Chul Jun, Alex Benz, Alon Gabbay
Current 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 Dominguez, Andy Allerman, Sally Samora, Jon Wierer, ……

GaN

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

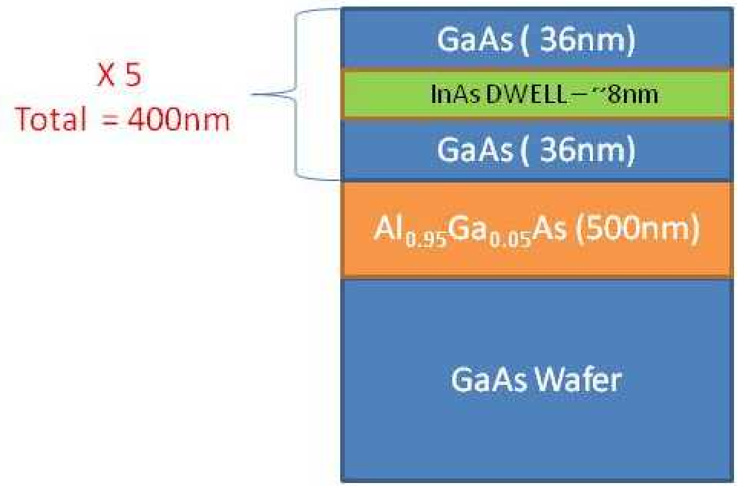
UNM: Ganesh Balakrishnan (QD samples)

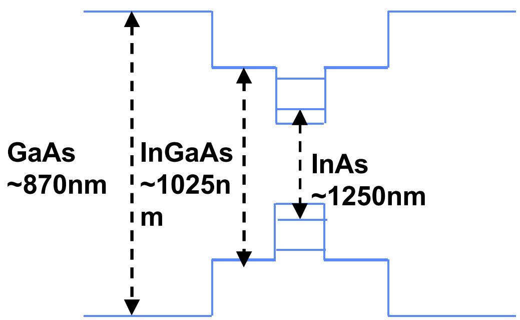
U.S. DEPARTMENT OF ENERGY | Office of Science

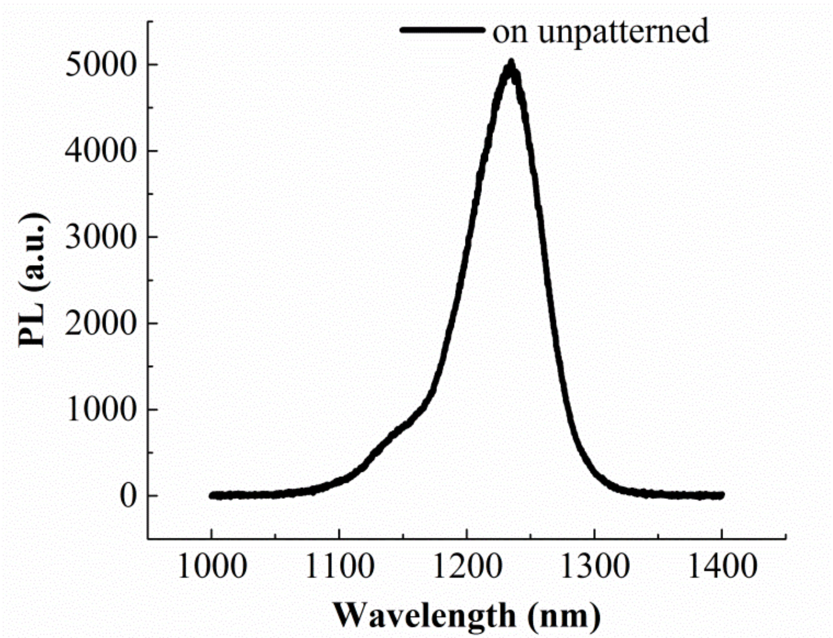
Outline

- Record optical nonlinearities in the infrared obtained from metallic metasurfaces coupled to intersubband transitions
- Progress in second harmonic generation from III-V semiconductor dielectric metasurfaces
- New Fano designs for all-dielectric metasurfaces
- **Coupling of epitaxial quantum dot emitters to dielectric resonators**

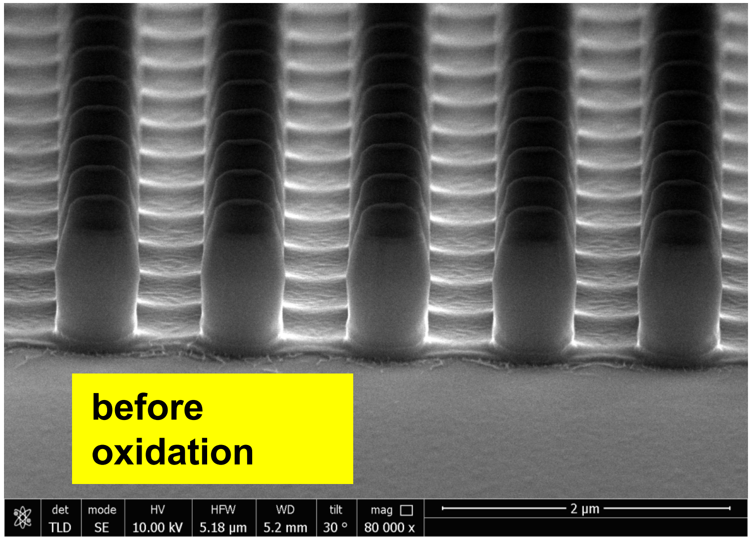
Active III-V Dielectric Resonators

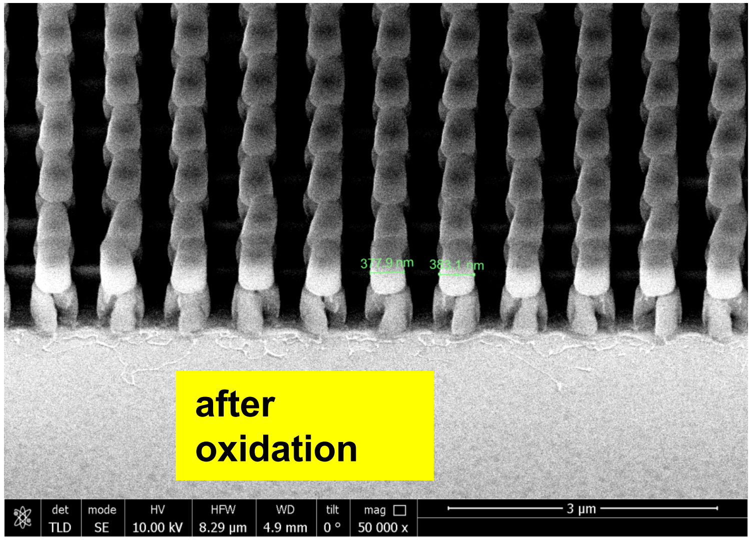


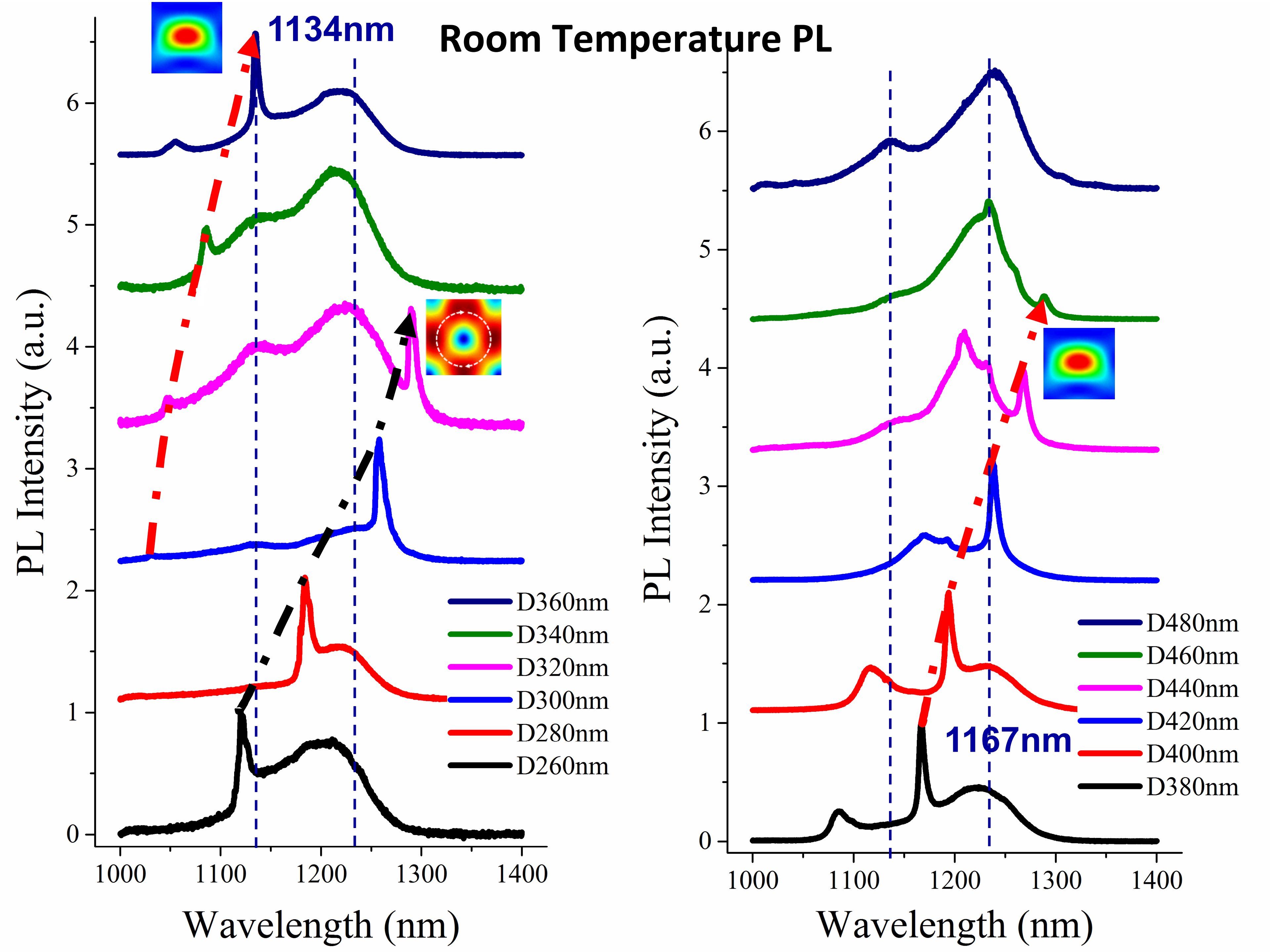




Fabrication

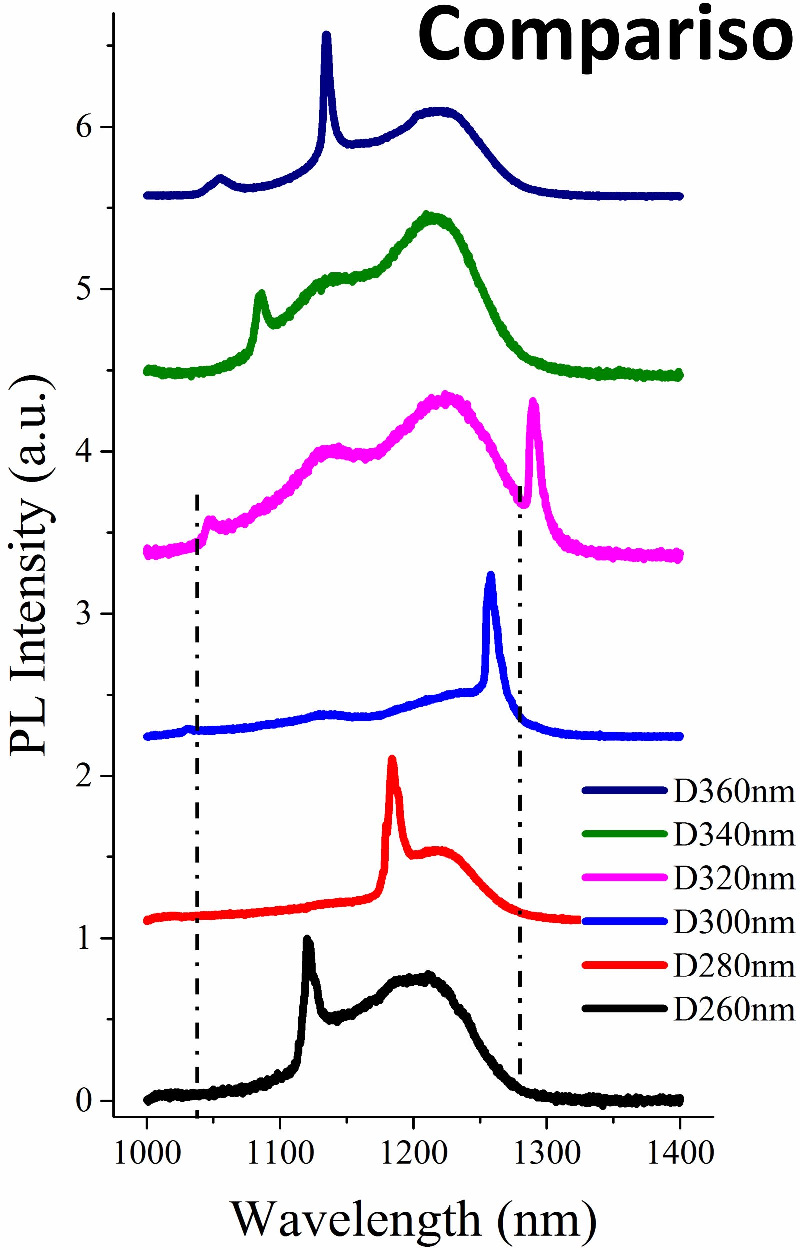


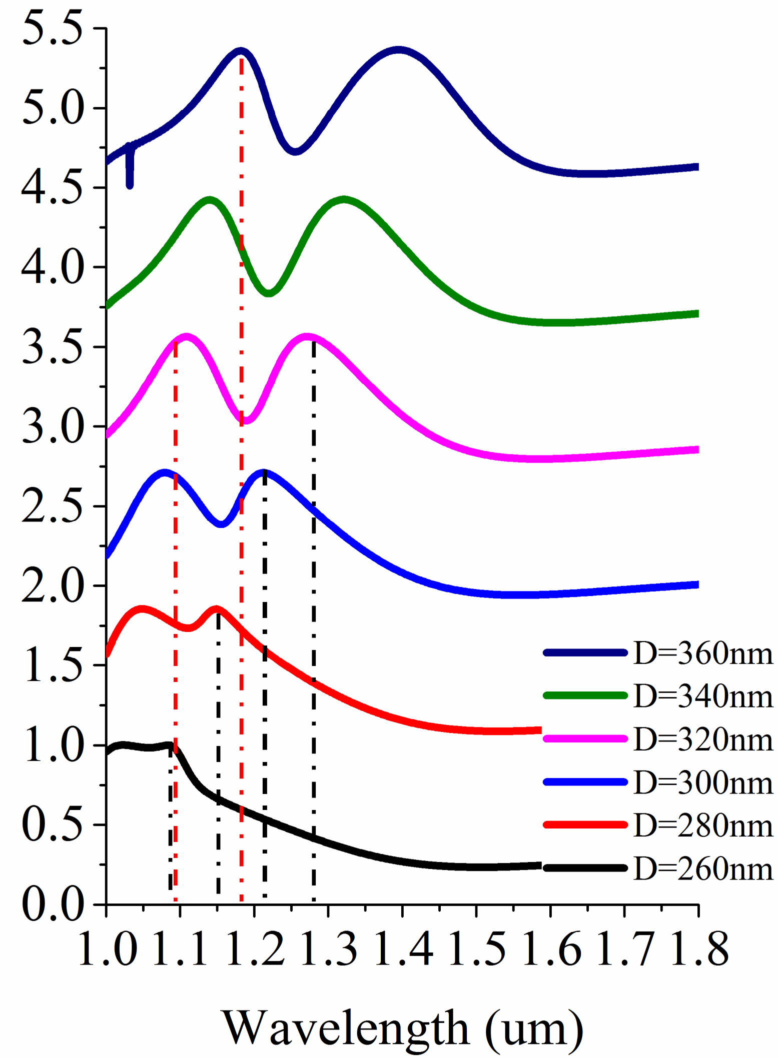


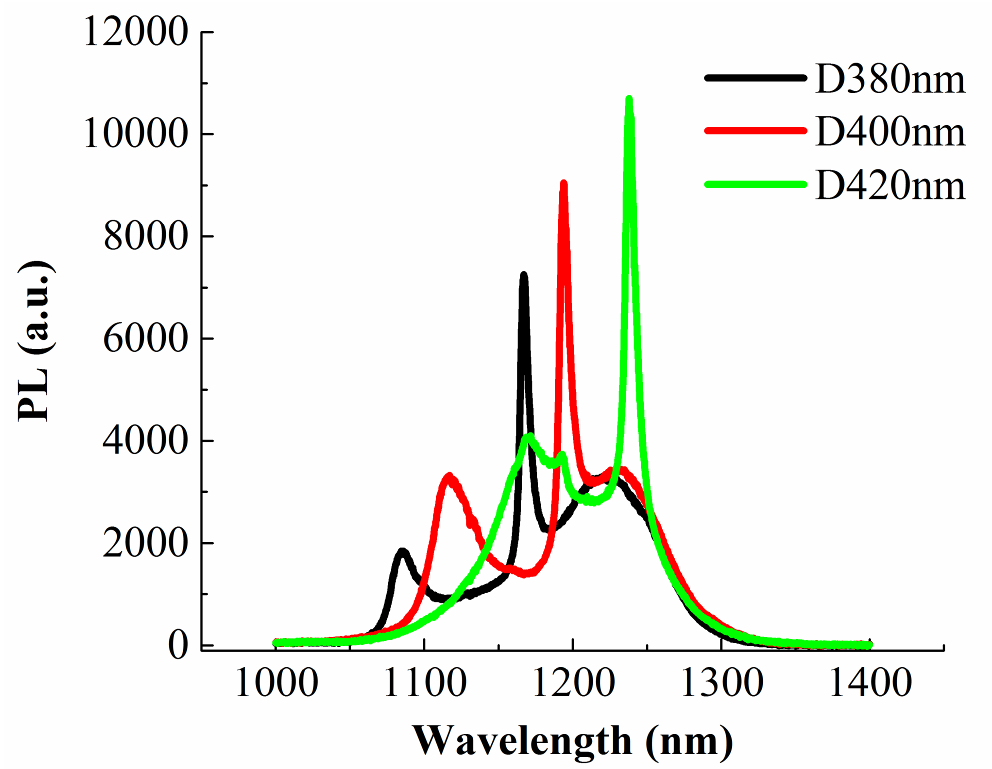


Room Temperature PL
1134nm
1167nm
PL Intensity (a.u.)
Wavelength (nm)
D360nm
D340nm
D320nm
D300nm
D280nm
D260nm
D480nm
D460nm
D440nm
D420nm
D400nm
D380nm
0
1
2
3
4
5
6
1000
1100
1200
1300
1400

Comparison to FDTD Modeling

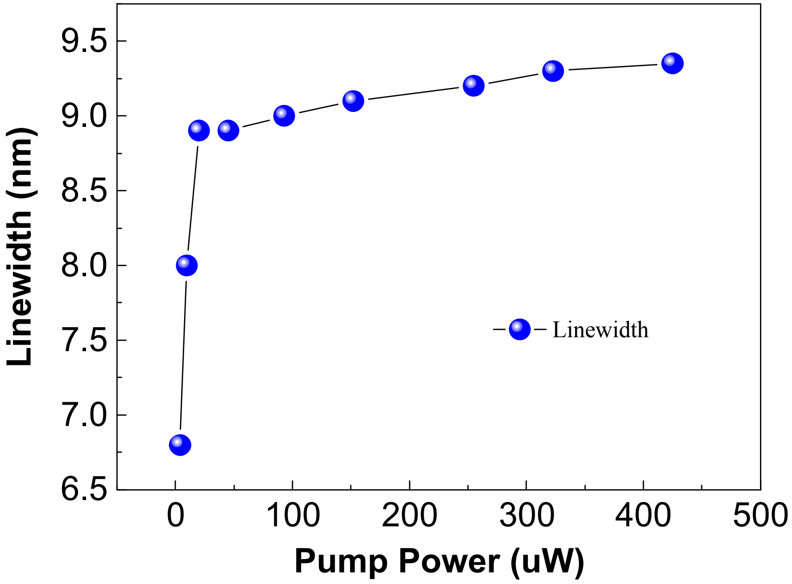


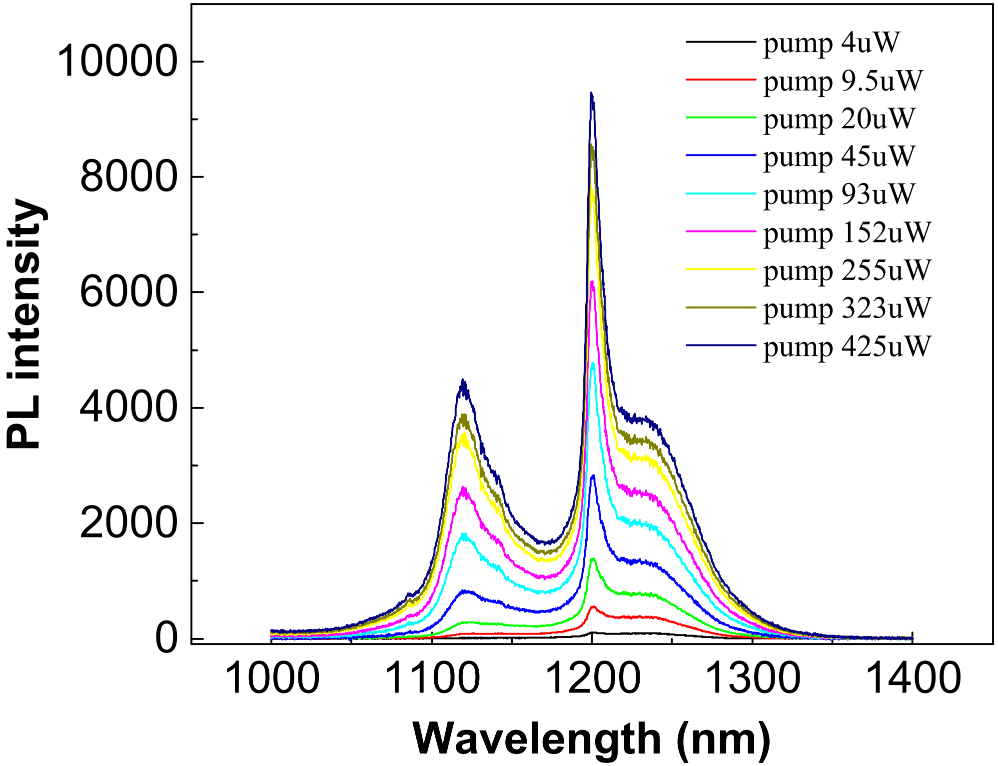




The PL intensity enhancement is larger at electric dipole resonance than at the magnetic dipole resonance.

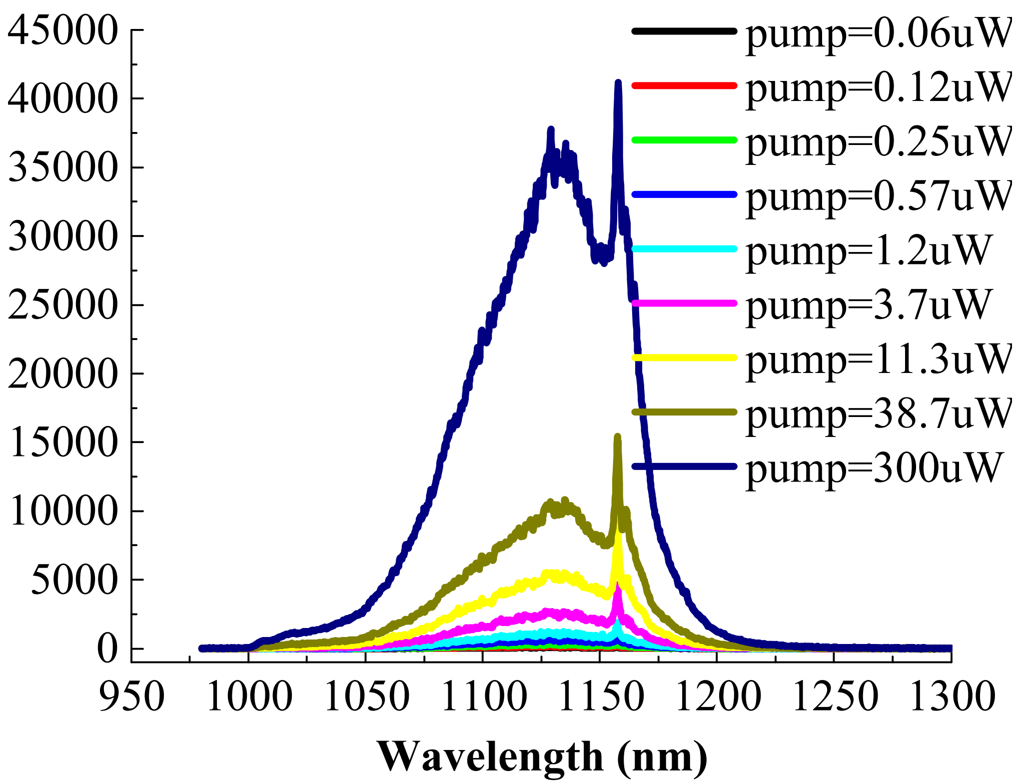
This is not Lasing!

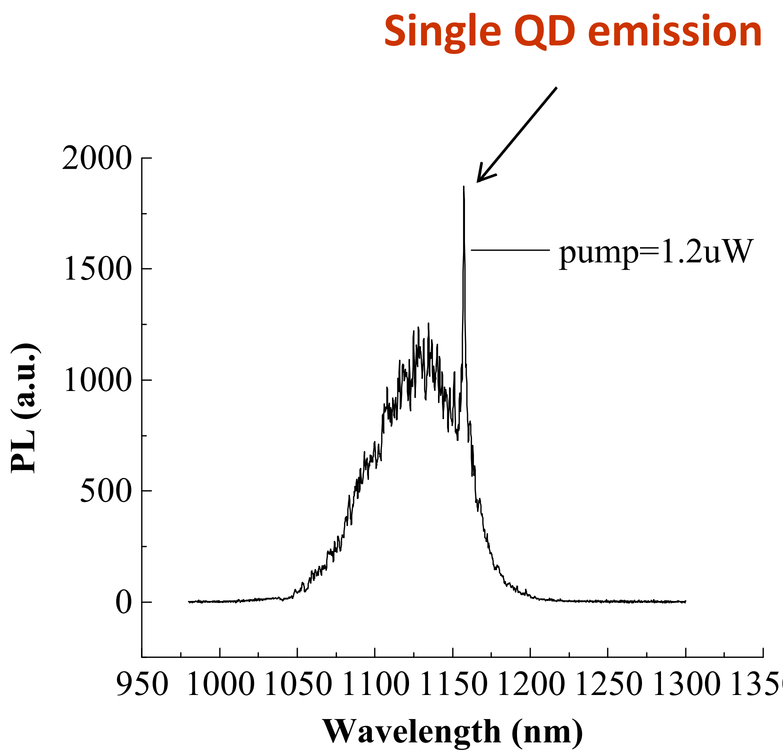




T=8K Results

At low powers it is quite easy to see *very* narrow peaks





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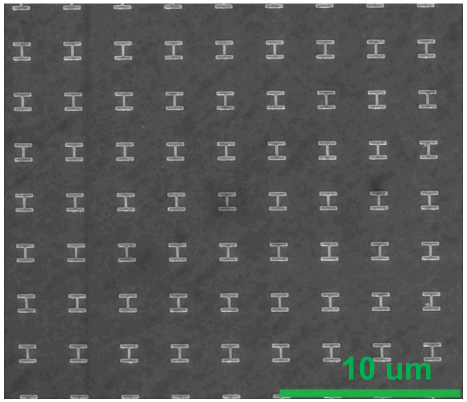
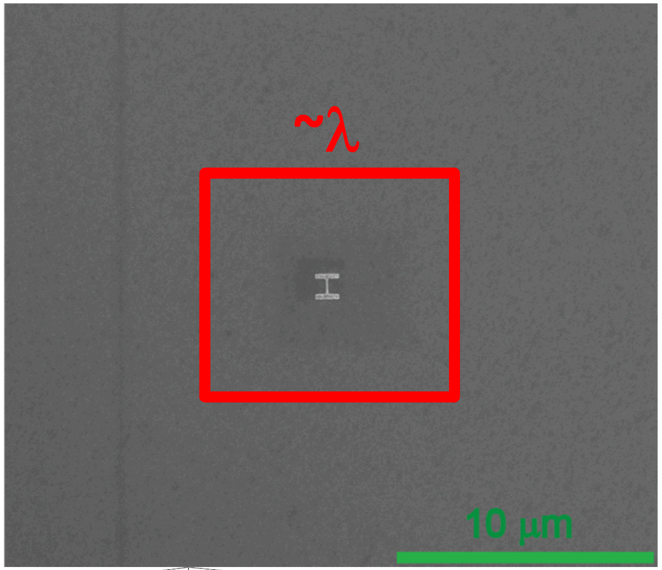
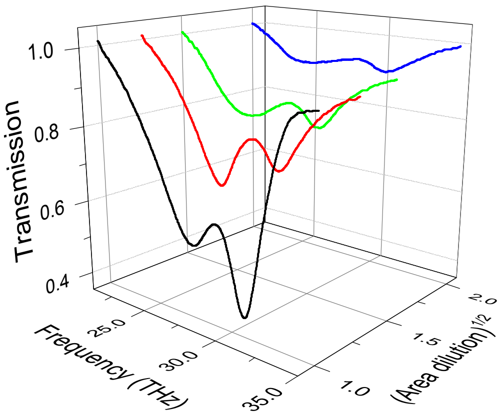
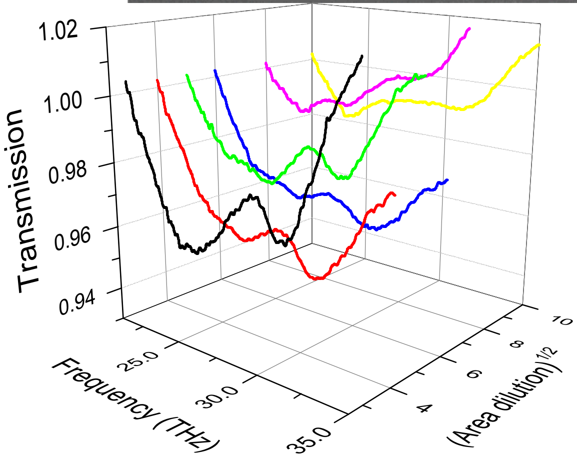
- Record optical nonlinearities in the infrared obtained from metallic metasurfaces coupled to intersubband transitions
- **Progress in second harmonic generation from III-V semiconductor dielectric metasurfaces**
- New Fano designs for all-dielectric metasurfaces
- Coupling of epitaxial quantum dot emitters to dielectric resonators

This is a “Single Resonator” Behavior







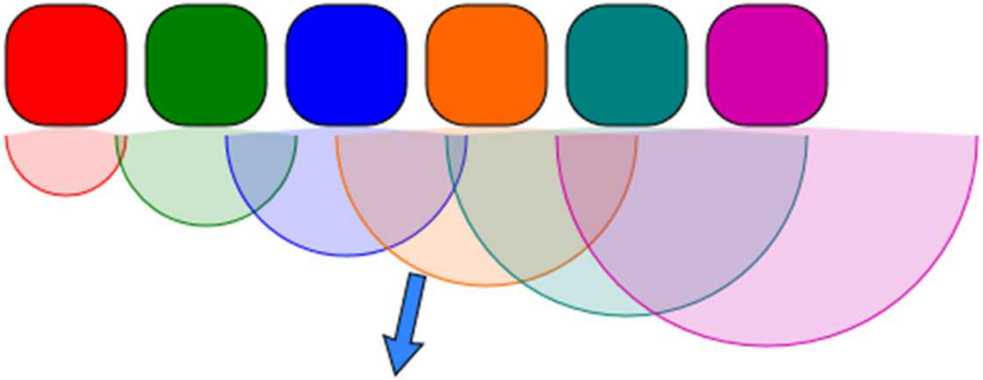


Same Rabi splitting remains down to a single resonator!

Nature communications **4**, (2013)

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

Phased Arrays



Identical point sources

+

Radiating with controllable phase difference

==

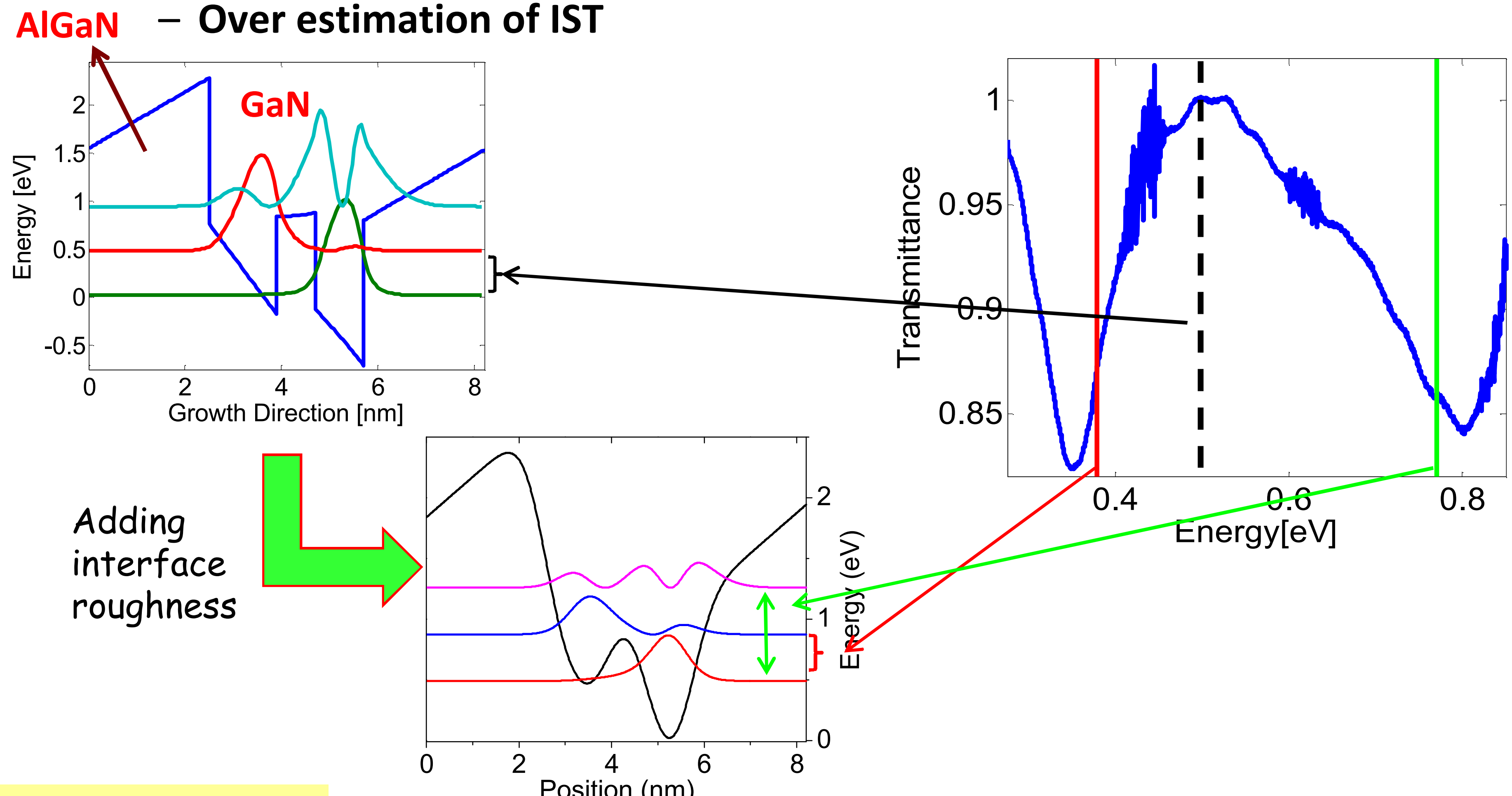
Full control over beam direction and shape

Image from Wikipedia

Omri Wolf

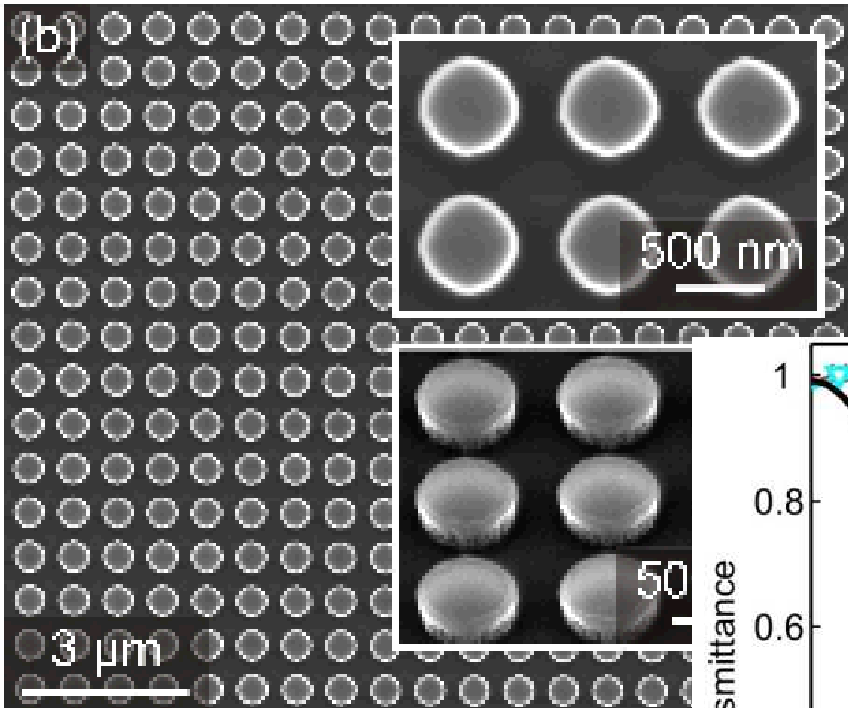
SHG (3.2μm>1.6μm) Using AlGaN/GaN QWs

- **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**

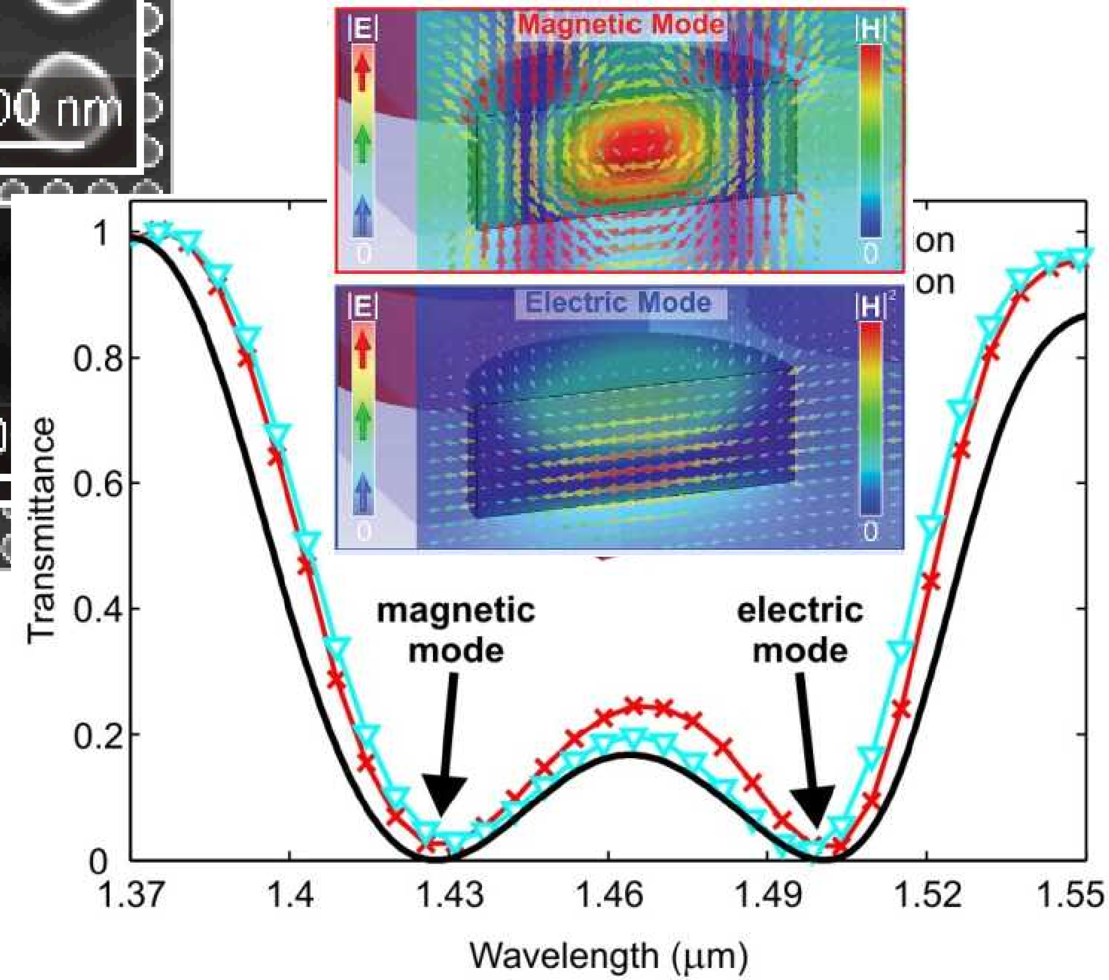


O. Wolf et al. APL 2015

LC tunable dielectric MSs

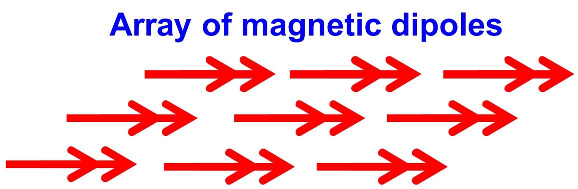


EBL and dry etching on SoI wafer



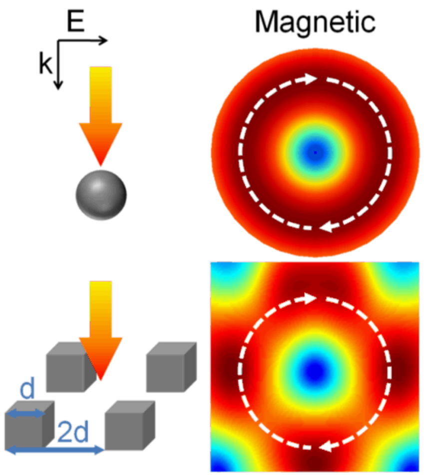
Creating a Magnetic Mirror from a Collection of Magnetic Dipoles

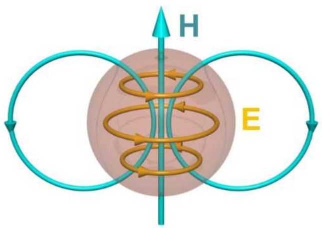
A perfect magnetic conductor does not exist in nature



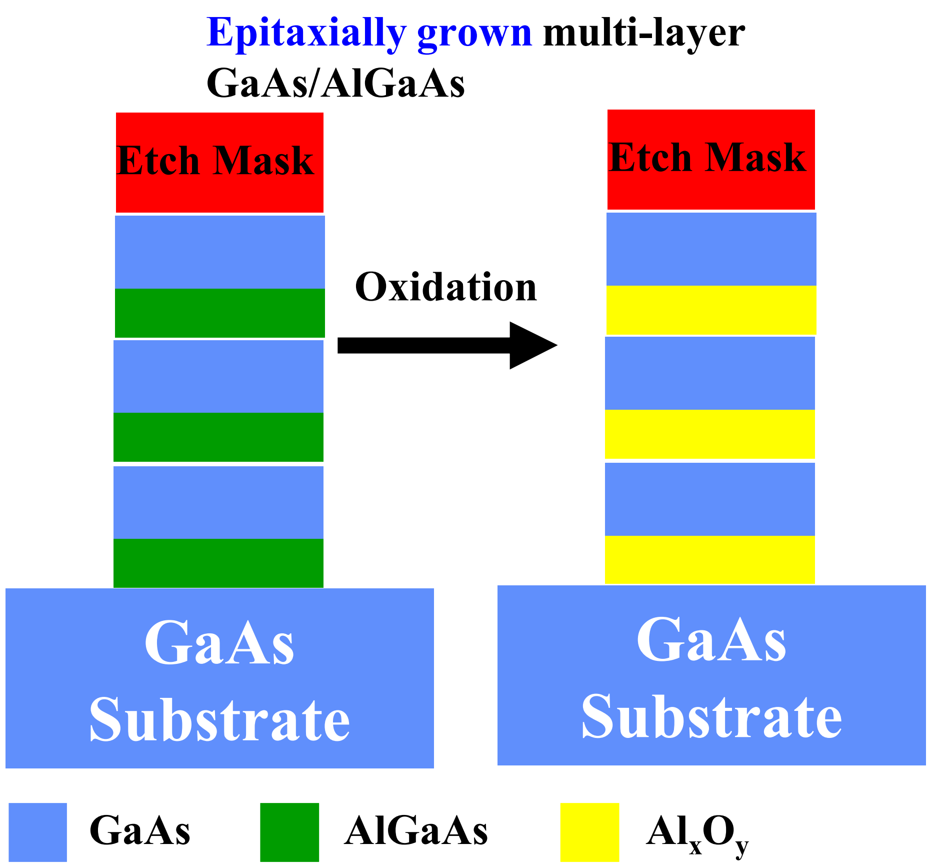
Because the magnetic dipole responds in phase with the electric field, this represents an artificial magnetic conductor

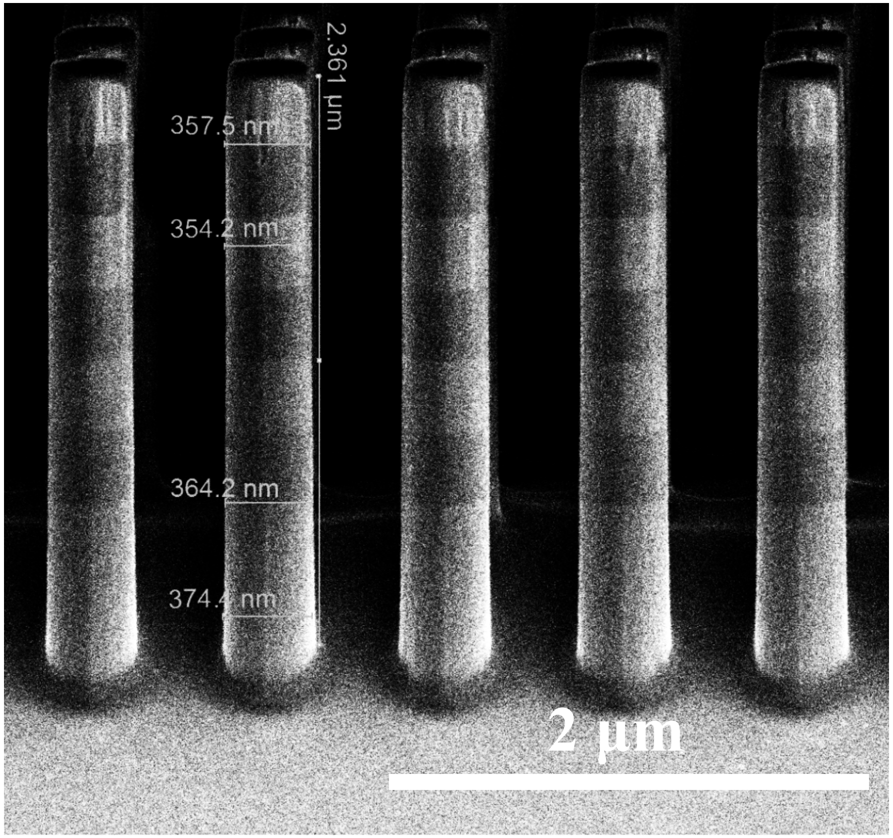
We can create magnetic dipoles with Dielectric Resonators



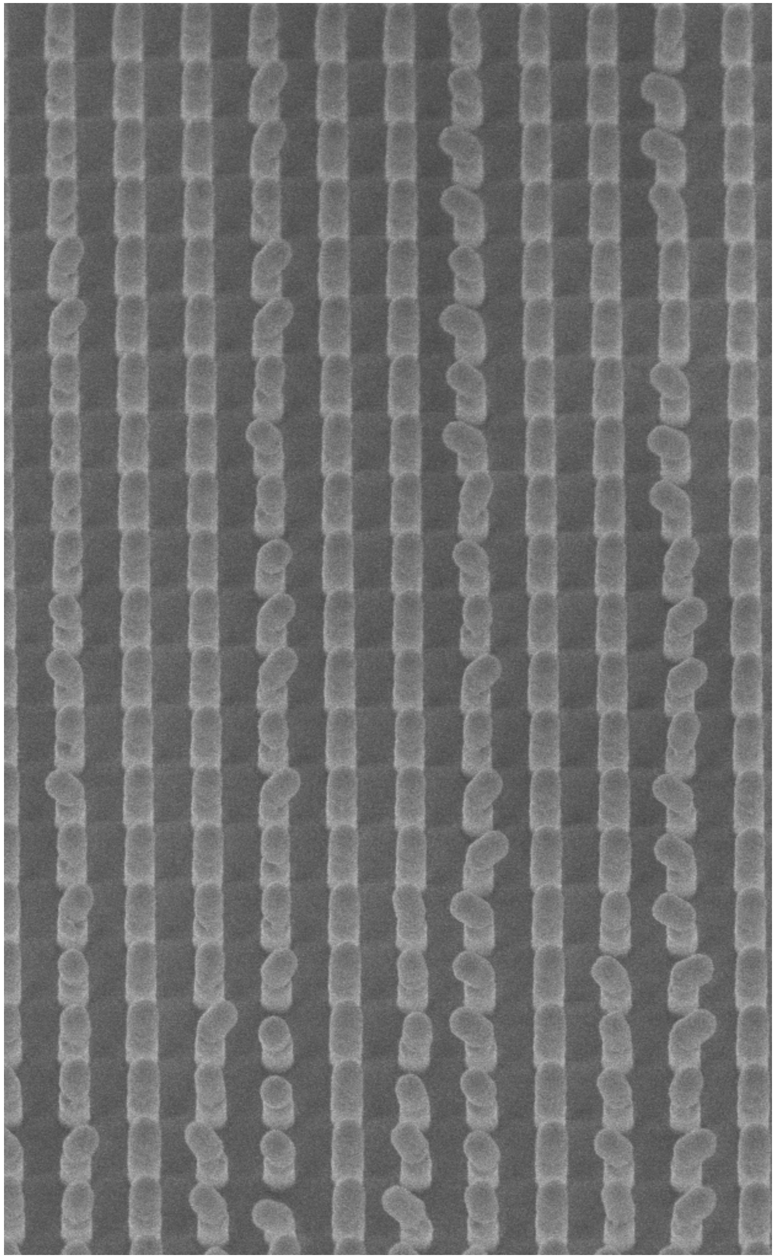


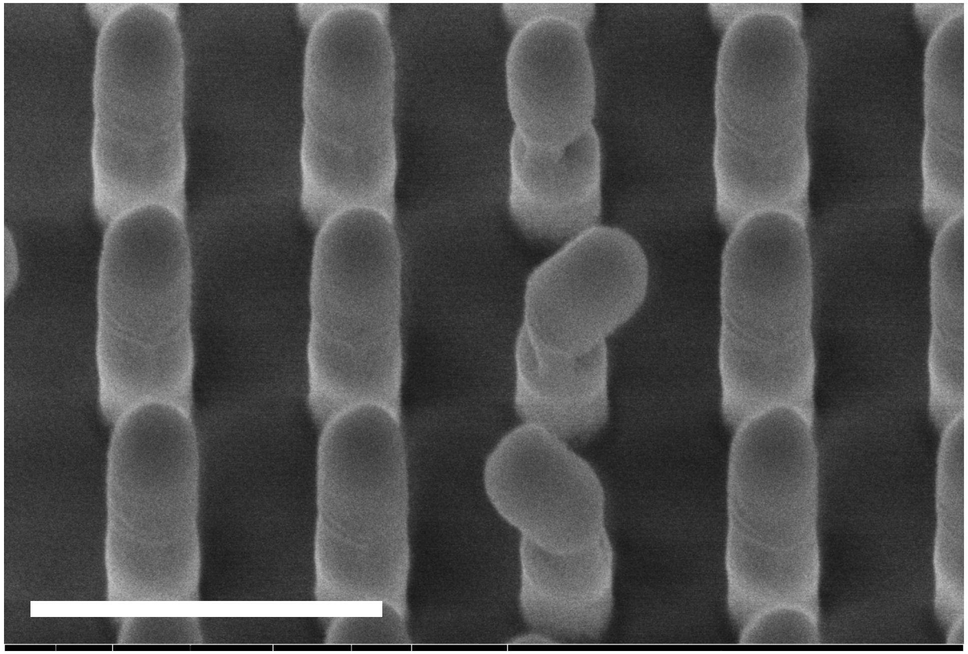
Multilayer III-V Dielectric Metamaterials





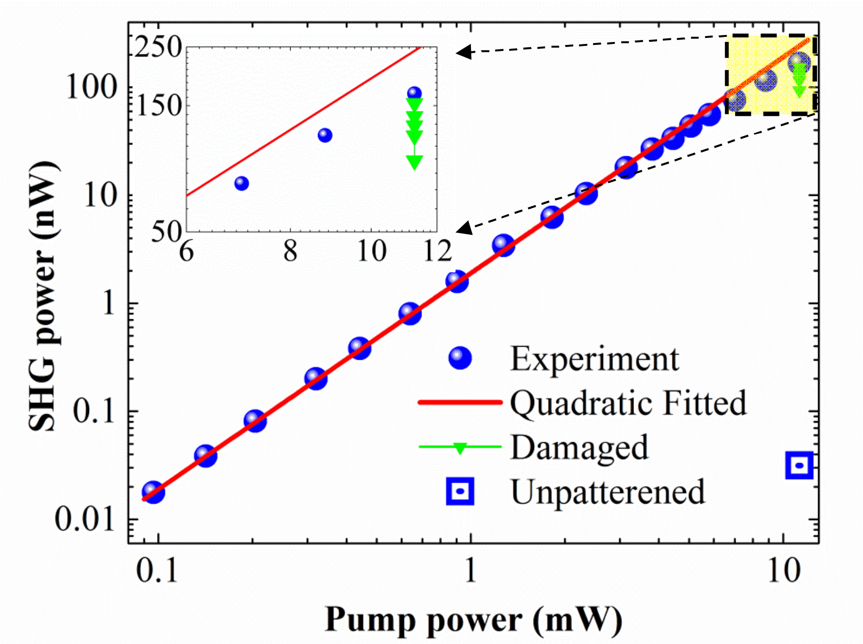
Sample damaged by strong pump and SEM images showing damage.

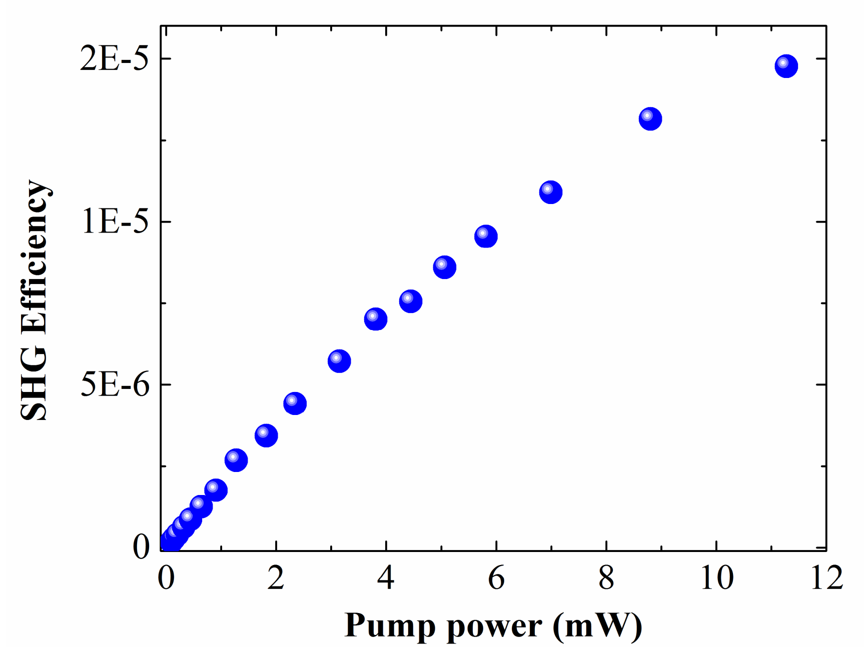




Low damage threshold, maybe due to etching induced defect on the surface.

Power Dependence





Effect of Absorption on SHG

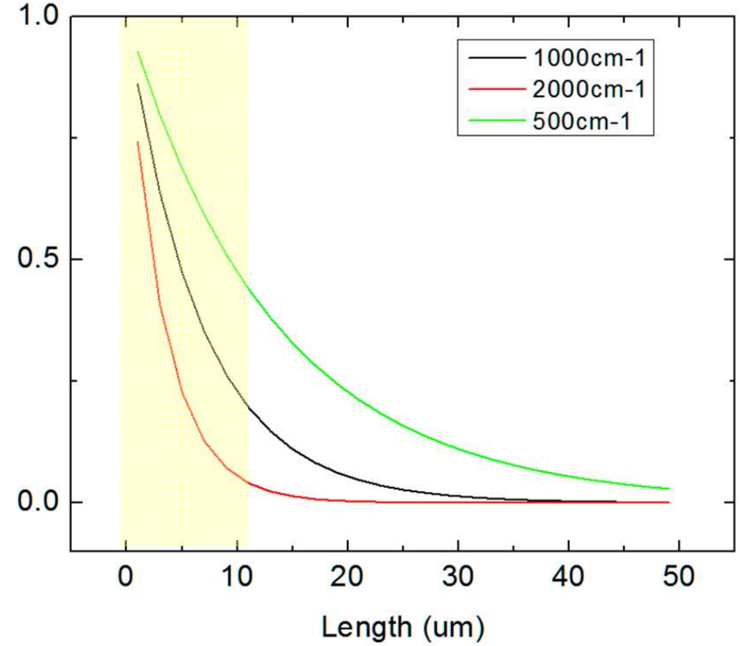
$$E(2\omega) \propto e^{\frac{-\alpha_{2\omega} l}{2}} \int_0^l e^{\alpha' z} \quad , \quad \alpha' = \alpha_\omega - \frac{\alpha_{2\omega}}{2}$$

$$I_{2\omega}(l) \propto e^{-\alpha_{2\omega} l} \frac{\left(e^{-\alpha' l} - 1\right)^2}{\alpha'^2}$$

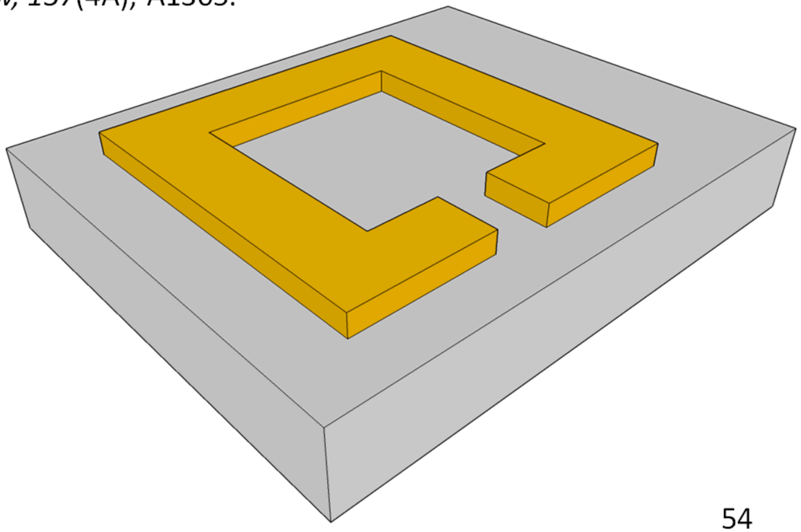
$$\alpha_\omega \approx \alpha_{2\omega} \approx \alpha$$

$$I_{2\omega}(l) \propto e^{-\alpha l} \frac{\left(e^{\frac{-\alpha l}{2}} - 1\right)^2}{\left(\frac{-\alpha l}{2}\right)^2}$$

Boyd, Ashkin, Dziedzic, & Kleinman, (1965). *Physical Review, 137*(4A), A1305.



For α~1000cm[-1], "effective length" (*QxL*) needs to be <few microns

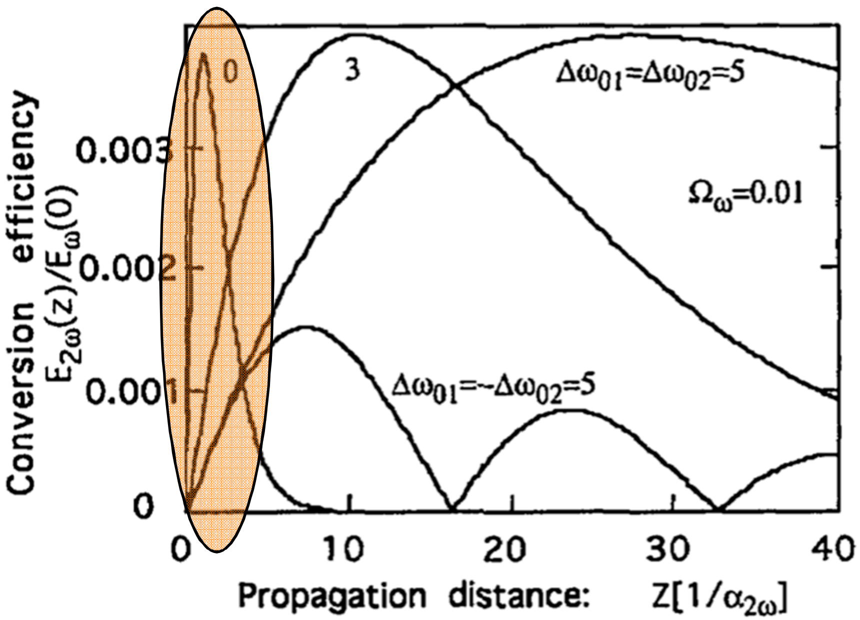


Q~10

Field decay length (*L*) ~200nm

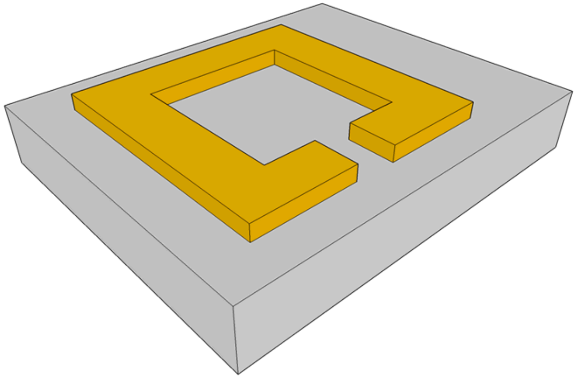
QxL~2um….

Effect of Absorption on SHG (unavoidable when using resonant $\chi^{(2)}$)



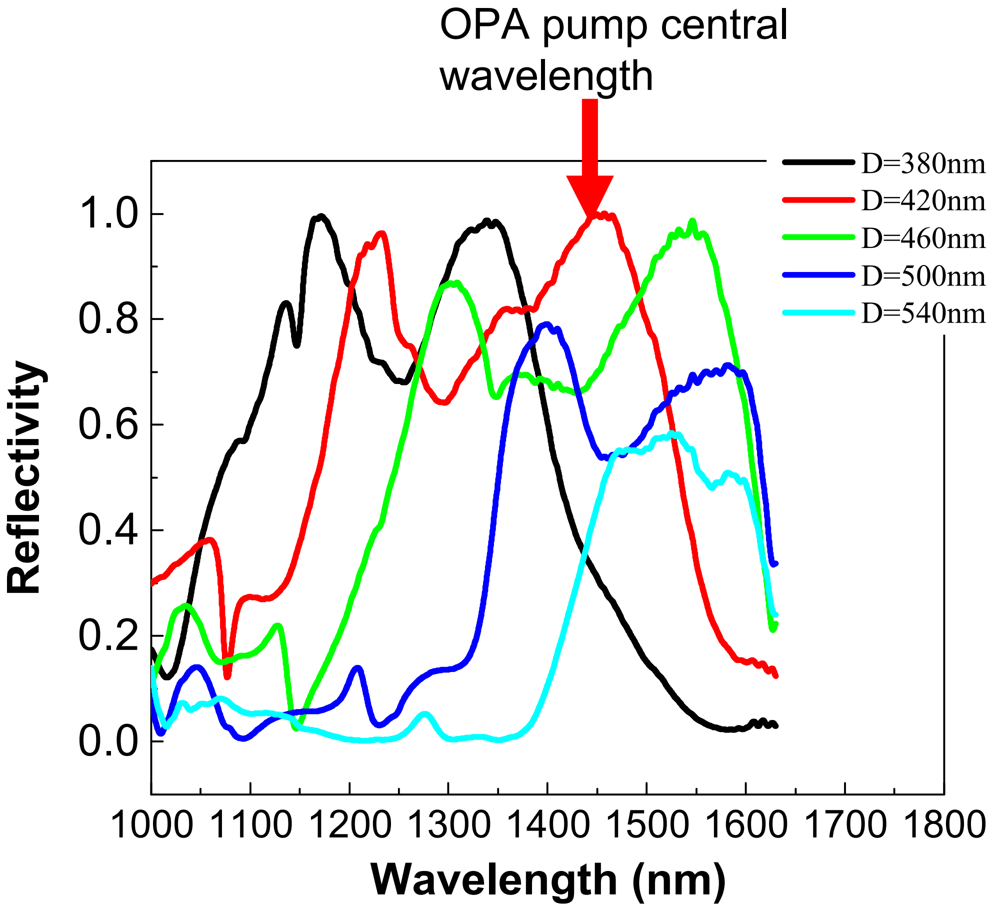
Almogy&Yariv, *Optics Letters* (1994)

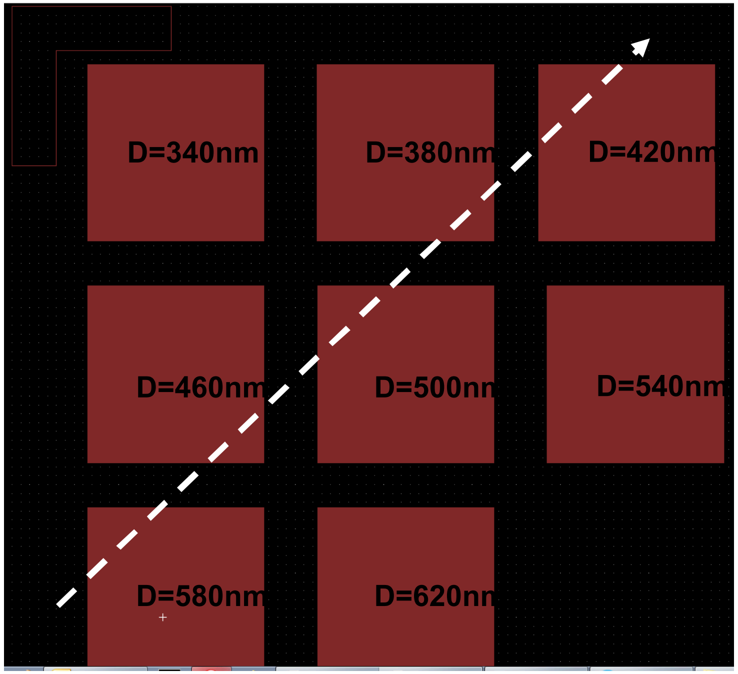
Dealt first by Boyd, Ashkin, Dziedzic, & Kleinman, (1965). *Physical Review, 137*(4A), A1305.



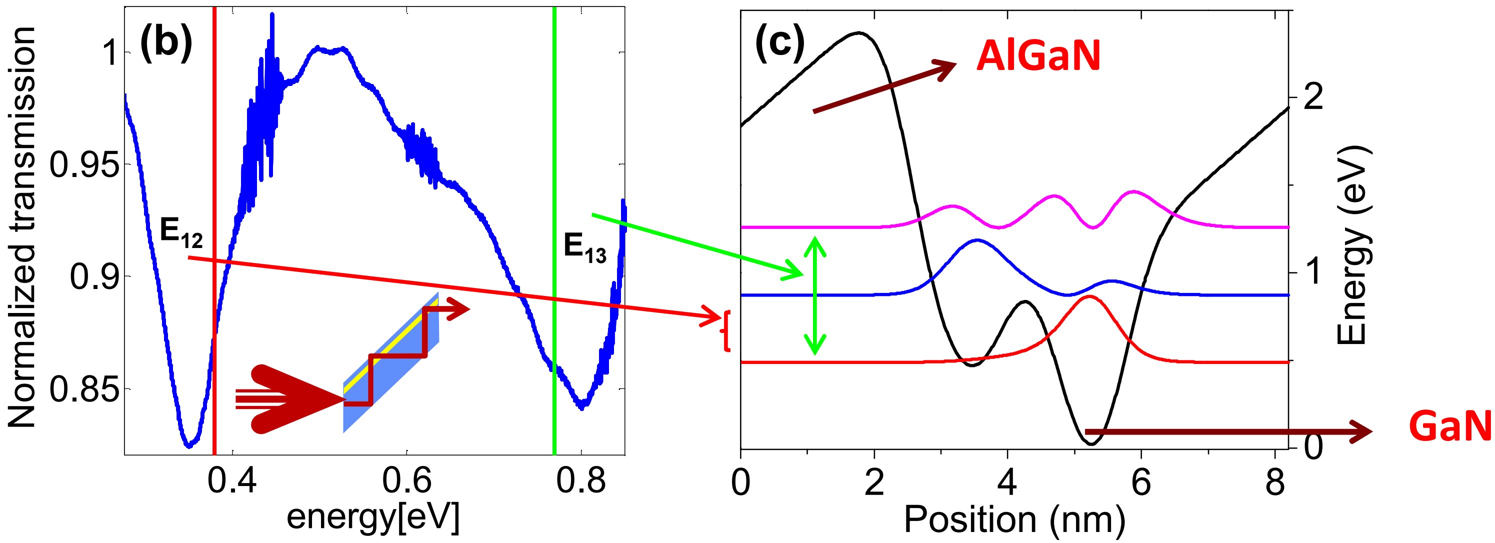
For α~1000cm^{-1} (1/α~10um), <u>"effective length" (*QxL*) needs to be <~10 microns</u>

"Cavity" with Q~10
Field decay length (*L*) ~200nm
***QxL*~2um…. >> OK,**
We cannot gain too much more by increasing Q!


OPA pump central wavelength
D=380nm
D=420nm
D=460nm
D=500nm
D=540nm
Reflectivity
1.0
0.8
0.6
0.4
0.2
0.0
1000 1100 1200 1300 1400 1500 1600 1700 1800
Wavelength (nm)


D=340nm
D=380nm
D=420nm
D=460nm
D=500nm
D=540nm
D=580nm
D=620nm

SHG (3.2μm>1.6μm) Using AlGaN/GaN QWs



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