SAND2017-10156C

III-V dielectric metasurfaces: enhanced nonlinearities and emission control

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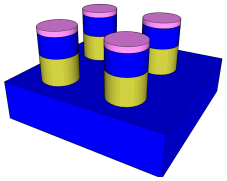
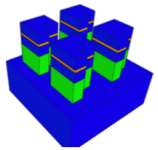
OSA Advanced Photonics Congress, New Orleans

Outline

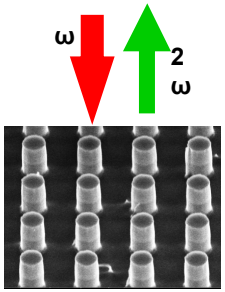
- Background
- All-dielectric metasurfaces from III-V semiconductors



- Coupling of emitters embedded in III-V metasurfaces

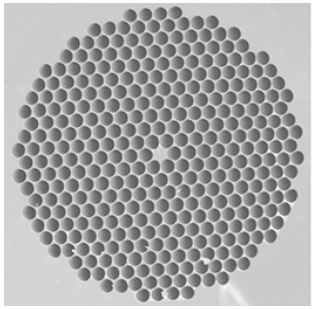


- Harmonic generation and other nonlinearities from III-V metasurfaces

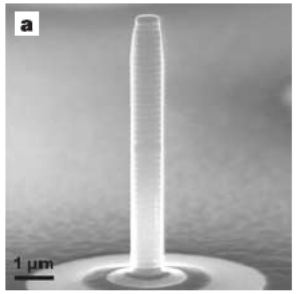


Motivation—enhanced light matter interaction

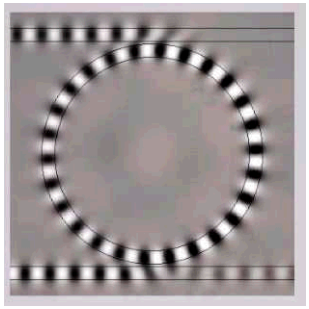
- **Fundamental motivation/interest for nanophotonics**
- **Various platforms**



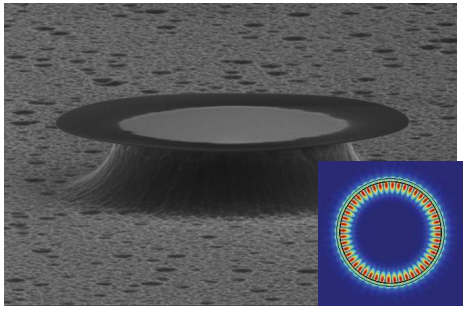
2D Photonic crystal



1D Distributed Bragg-reflector



On-chip microring resonators



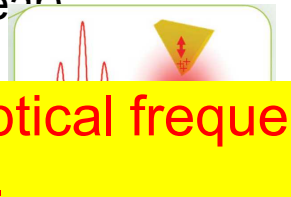
microdisk resonators

NATURE | VOL 432 | 11 NOVEMBER 2004

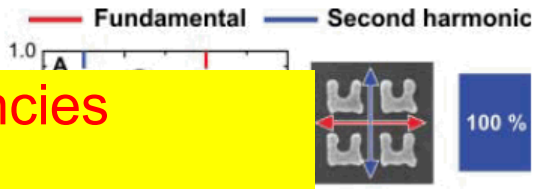
- Plasmonic nano-resonators (linear & nonlinear)

Maiken Mikkelsen (2014)

Niek F. van Hulst (2010)



Seung-Woo Kim (2008)

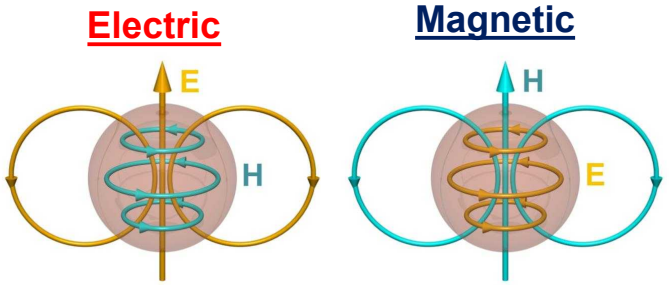


Stefan Linden (2006)

Strong metallic loss at high optical frequencies (reduced quantum efficiency).

Dielectric Resonators 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

THE ELECTRICAL CONSTANTS OF A MATERIAL LOADED WITH SPHERICAL PARTICLES*

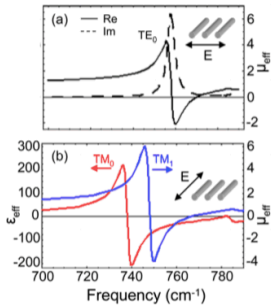
By L. LEWIN.†

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

PRL **99,** 107401 (2007) PHYSICAL REVIEW LETTERS week ending 7 SEPTEMBER 2007

Dielectric Metamaterials Based on Electric and Magnetic Resonances of Silicon Carbide Particles

Jon A. Schuller,[1,*] Rashid Zia,[2] Thomas Taubner,[1] and Mark L. Brongersma[1]
[1]*Geballe Laboratory for Advanced Materials, 476 Lomita Mall, Stanford, California 94305, USA*
[2]*Division of Engineering, Box D, 182 Hope St., Brown University, Providence, Rhode Island 02912, USA*
(Received 21 May 2007; published 7 September 2007)

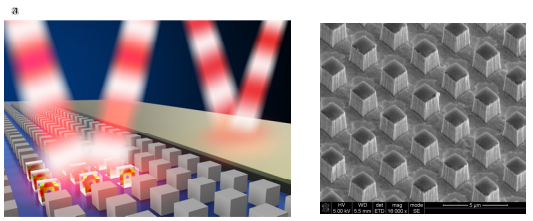


PRL **108,** 097402 (2012) PHYSICAL REVIEW LETTERS week ending 2 MARCH

Realizing Optical Magnetism from Dielectric Metamaterials

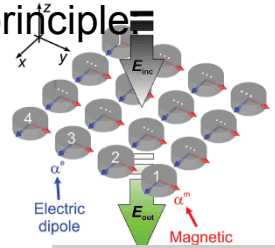
James C. Ginn* and Igal Brener
Sandia National Laboratory, Albuquerque, New Mexico 87185, USA, and Center for Integrated Nanotechnologies, Sandia National Laboratory, Albuquerque, New Mexico 87185, USA

David W. Peters, Joel R. Wendt, Jeffrey O. Stevens, Paul F. Hines, Lorena I. Basilio, Larry K. Warne, Jon F. Ihlefeld, Paul G. Clem, and Michael B. Sinclair
Sandia National Laboratory, Albuquerque, New Mexico 87185, USA
(Received 7 October 2011; published 29 February 2012)

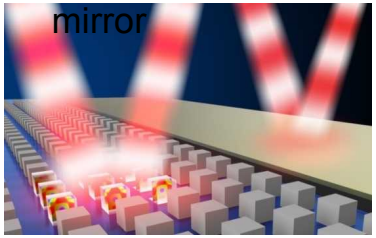


Recent progresses of dielectric metasurfaces

Huygens principle

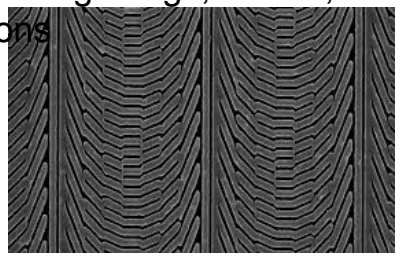


Magnetic mirror



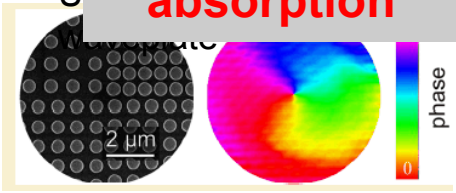
Sheng Liu

Ultrathin gratings, lenses, axicons

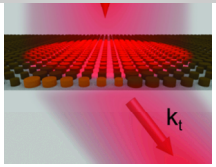


Mostly silicon (easy to fabricate)

- **Indirect bandgap: inefficient light emission and absorption**
- **Centrosymmetric: lack of second-order nonlinearity**
- **Long electron life time: strong free carrier absorption**

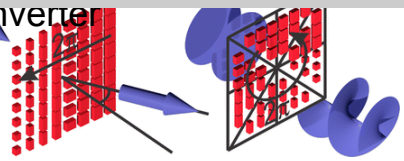


Yuri Kivshar



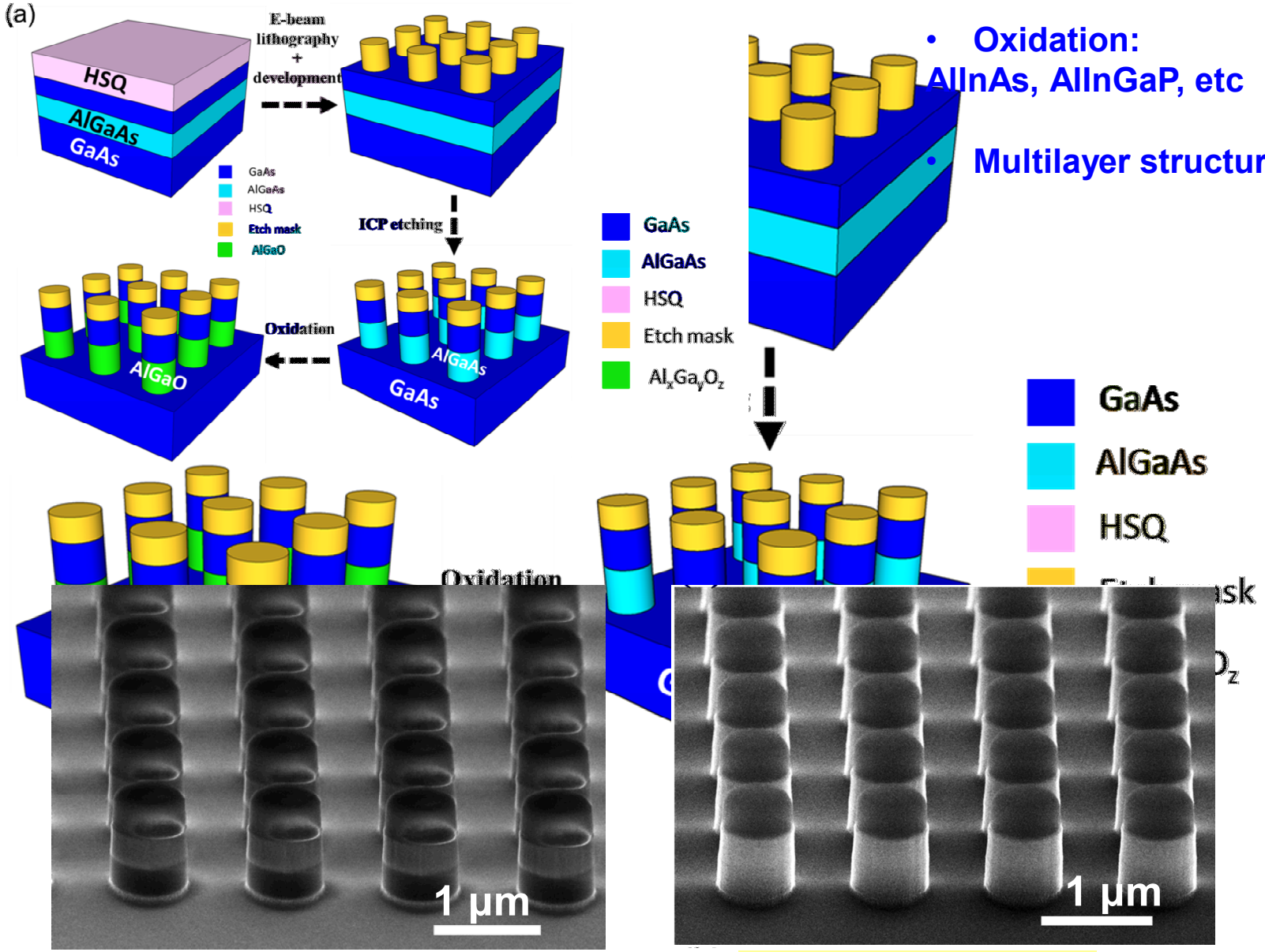
Arseniy I. Kuznetsov

converter



Natalia M. Litchinitser

(Al)GaAs Based Dielectric Metasurfaces



- Oxidation: AlInAs, AlInGaP, etc
- Multilayer structures

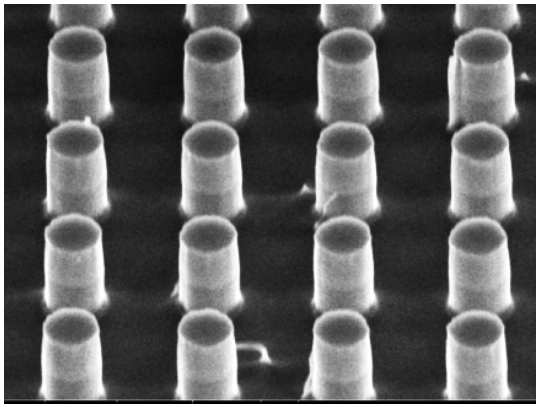
IEEE JSTQE, 3, 916 (1997)

Liu et al, Adv. Opt. Matt 2016

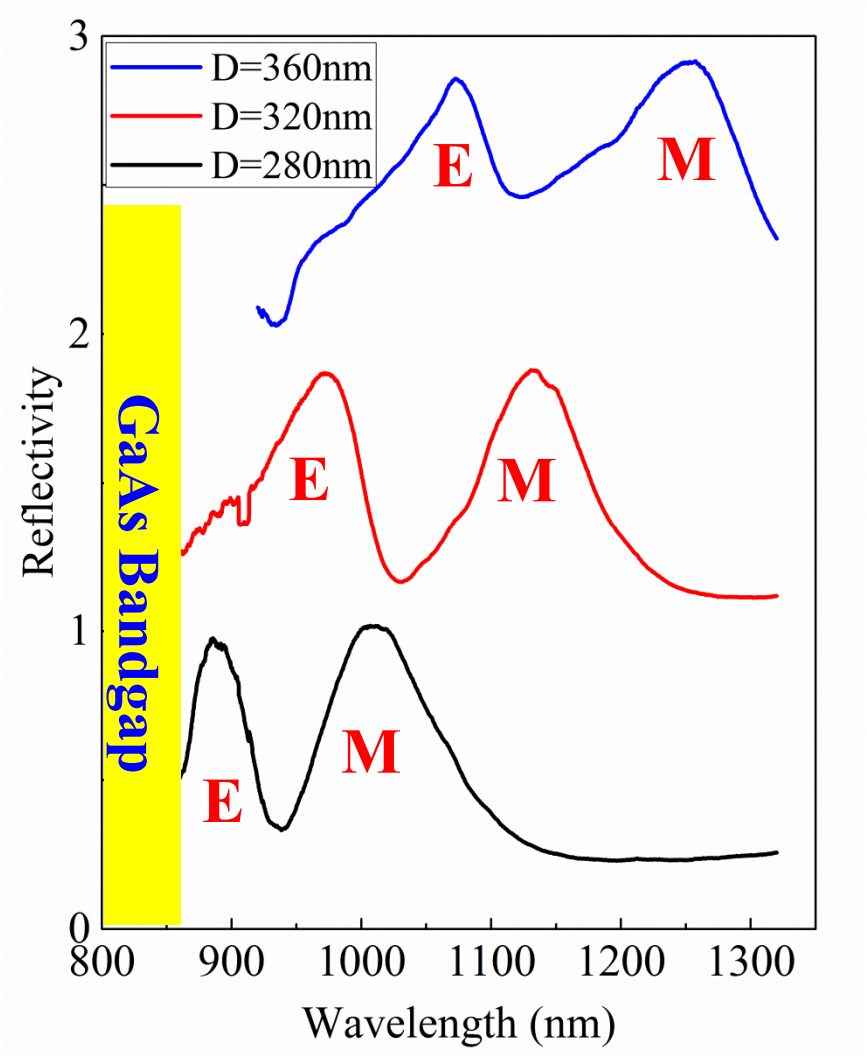
GaAs Dielectric Resonators (1 layer)

GaAs disk height ~300nm

Different diameters

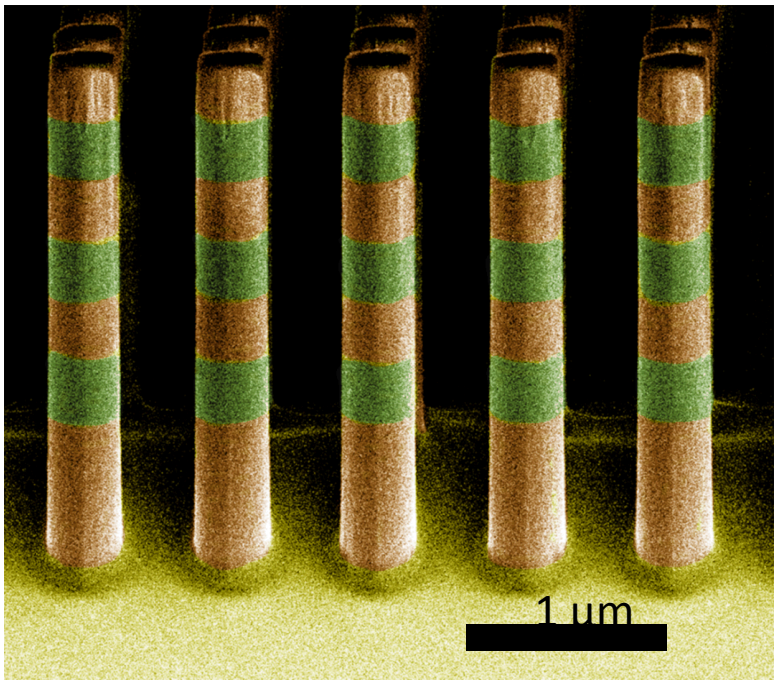


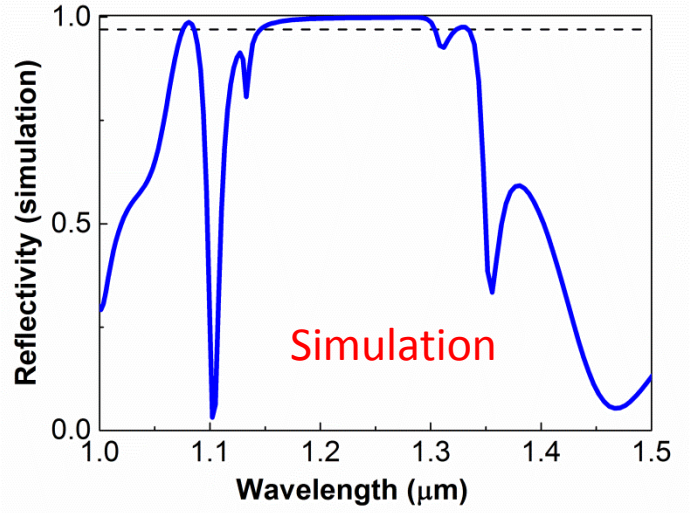
- **Extremely low loss below bandgap**
- **Crystalline**

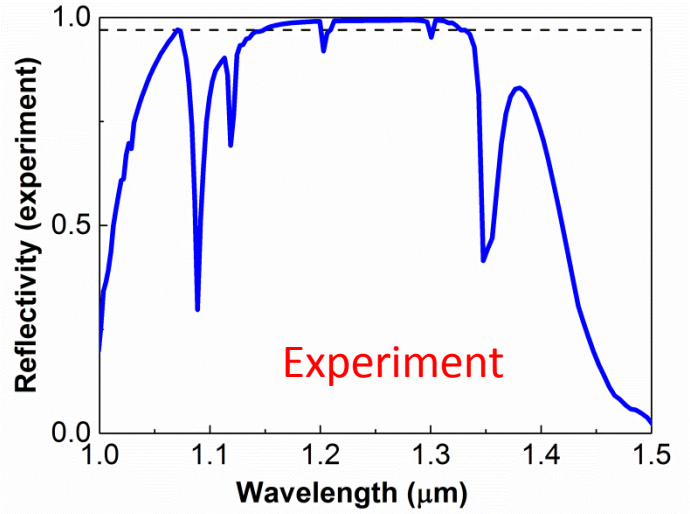


Multi-layer GaAs Dielectric Metasurfaces

- Epitaxially grown 3X (AlGaAs + GaAs)
- Same fabrication steps as 1 layer



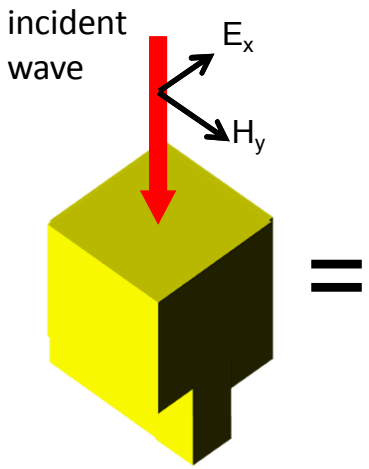




➔**Potential path to 3D dielectric metamaterials**

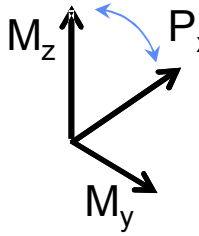
Liu et al, Adv. Opt. Matt 2016

Fano Metasurface: Operating principles



=

weakly coupled
dipole
modes



orthogonal
dipole
modes

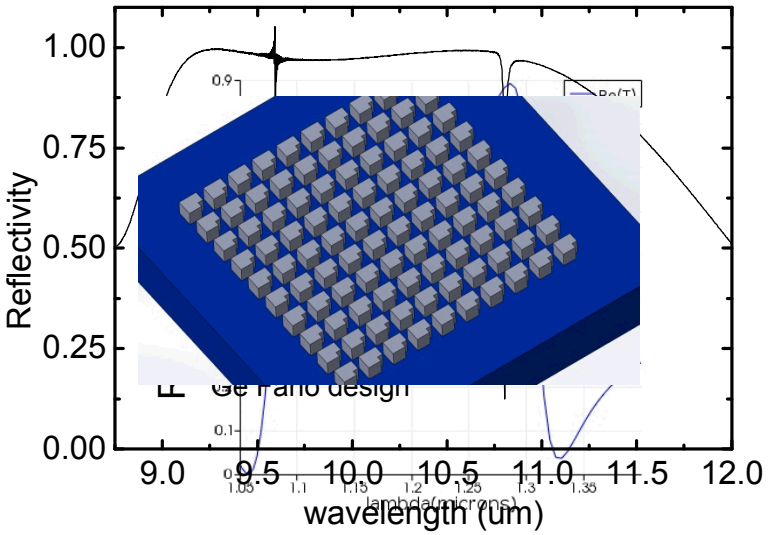
Fano system

External Wave ⟷ P_x ,M_y (low Q)

↕ Cavity perturbation

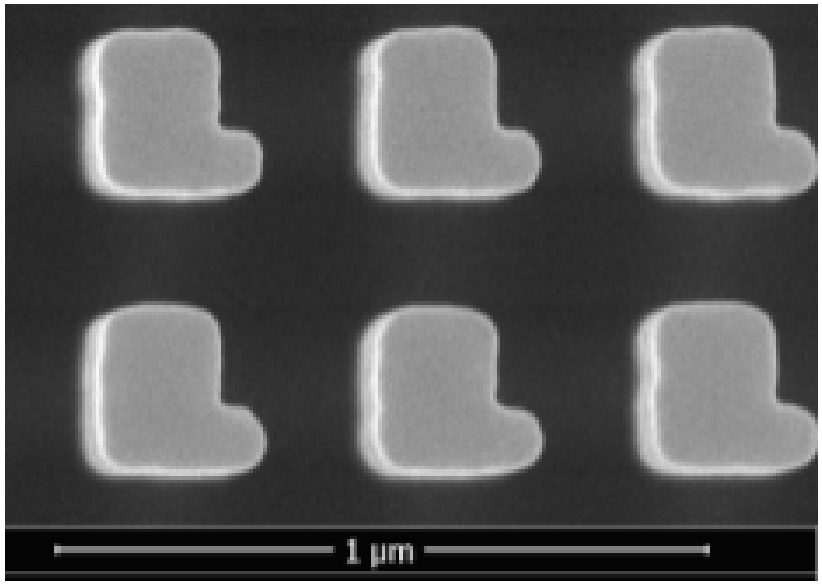
M_z (high Q)

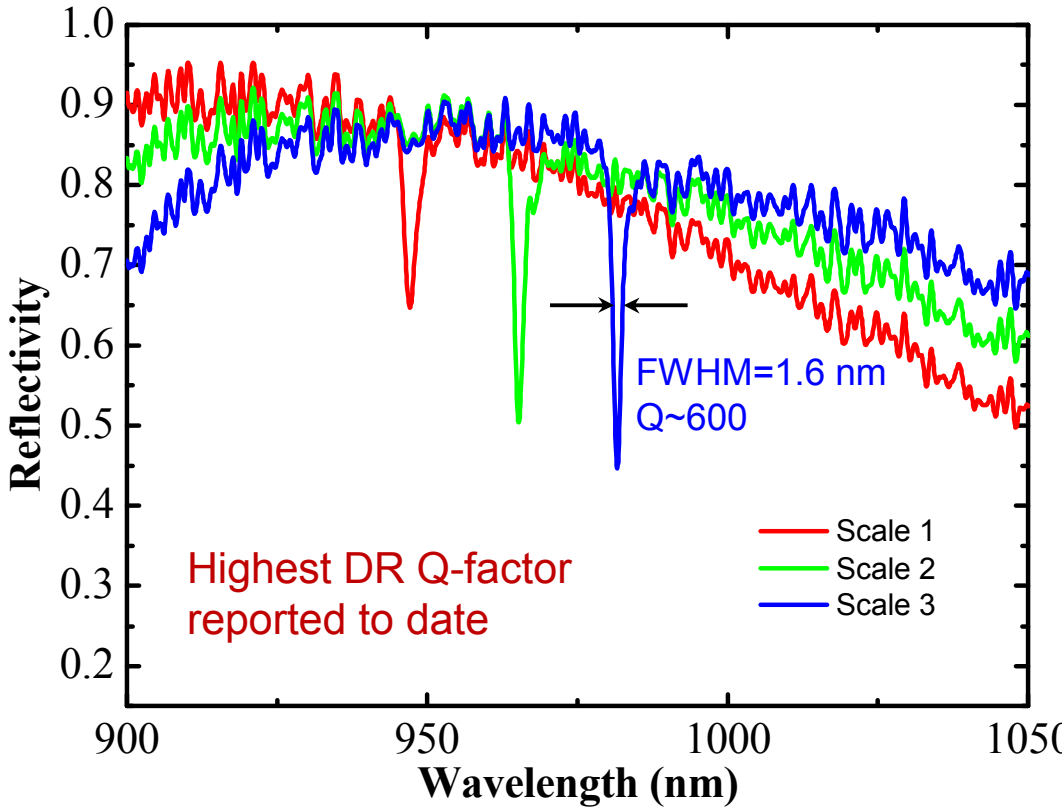
radiative decay is suppressed
due to local field interactions



GaAs Fano Resonators: Q ~ 600!

SEM of GaAs Fano resonators

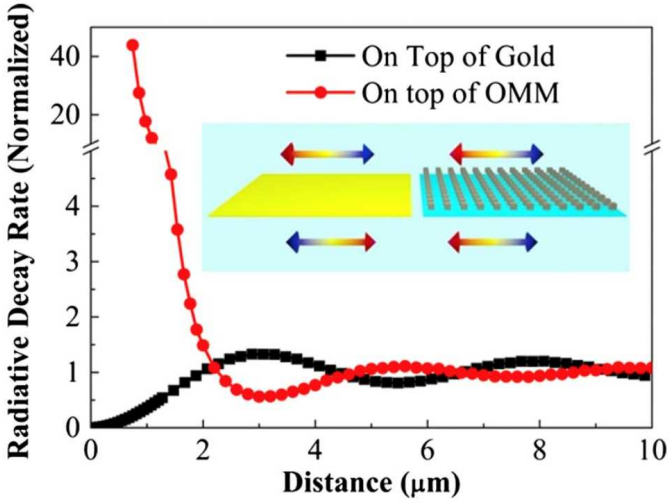


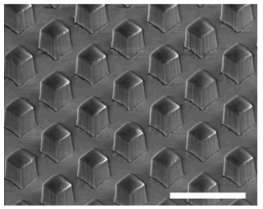


Campione, et al., ACS Photonics 3, 2362 (2016)

Emitters Coupled to Metasurfaces

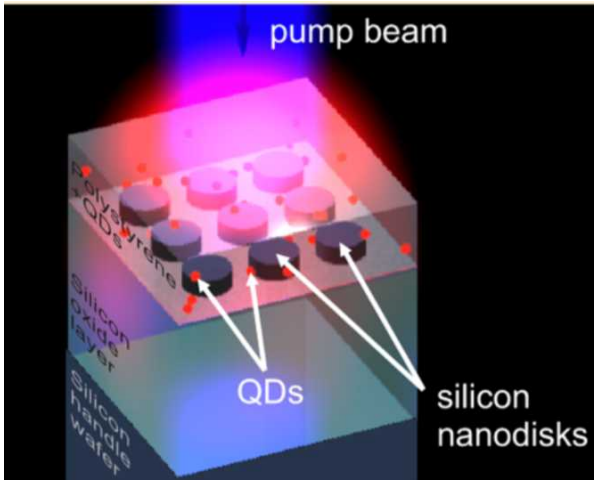
Simulation of emitter very close (~λ) close to dielectric optical mirror showed large radiative enhancement.





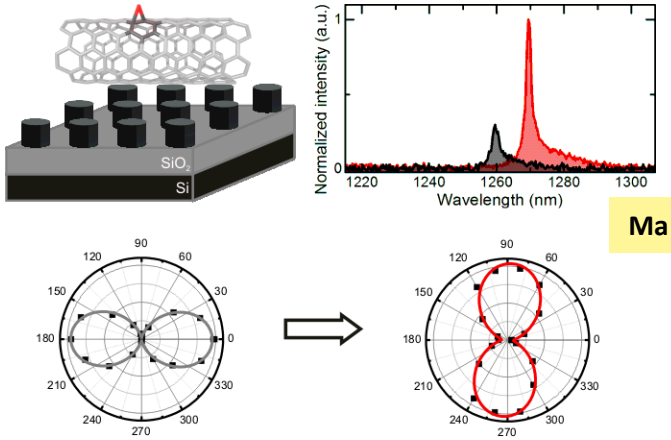
Liu *et al,* Optica 2014

Ensembles of colloidal QDs on top of Si-metasurface: PL reshaping



Staude et al, ACS Photonics 2015

Single photon emitter (dopant in CNT) on top of Si-metasurface: rotation of PL polarization

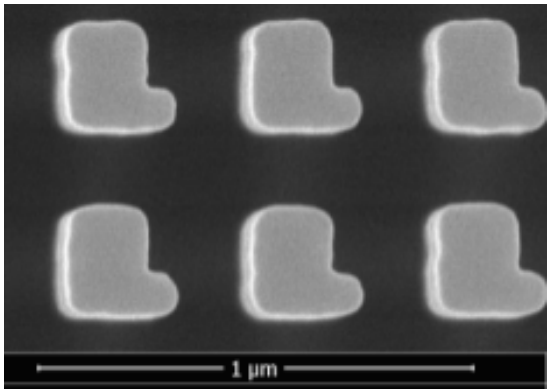


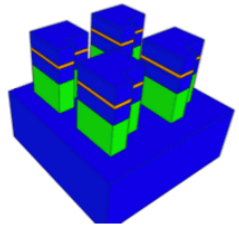
Ma et al, ACS Nano in press

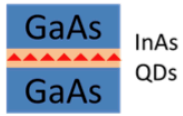
Other groups have investigated coupling of emitters to dielectric nanoresonators/metasurfaces: Hong, Maier, Bonod, Belov, Krasnok, etc.

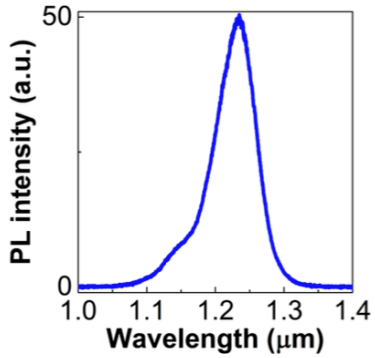
Emitters (QDs) Coupled to Fano Metasurfaces:

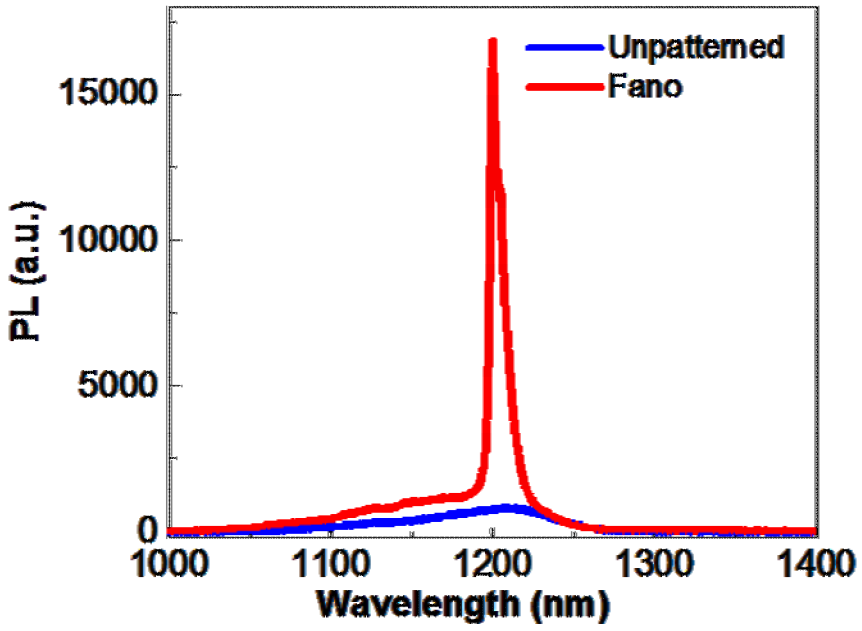
QDs inside, Emission enhancement

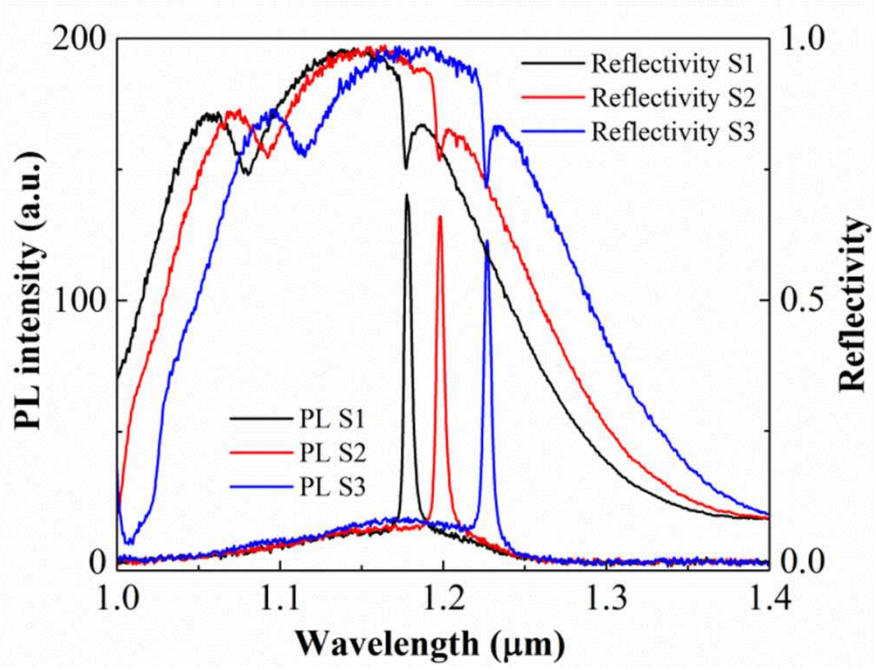




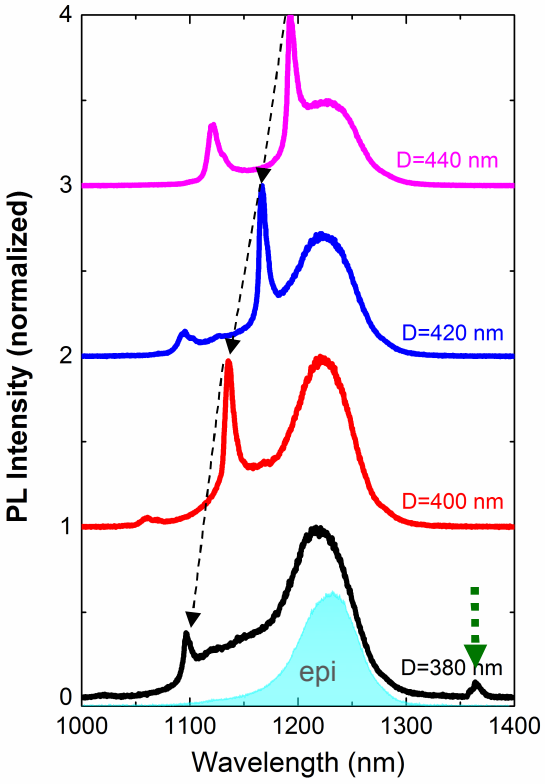


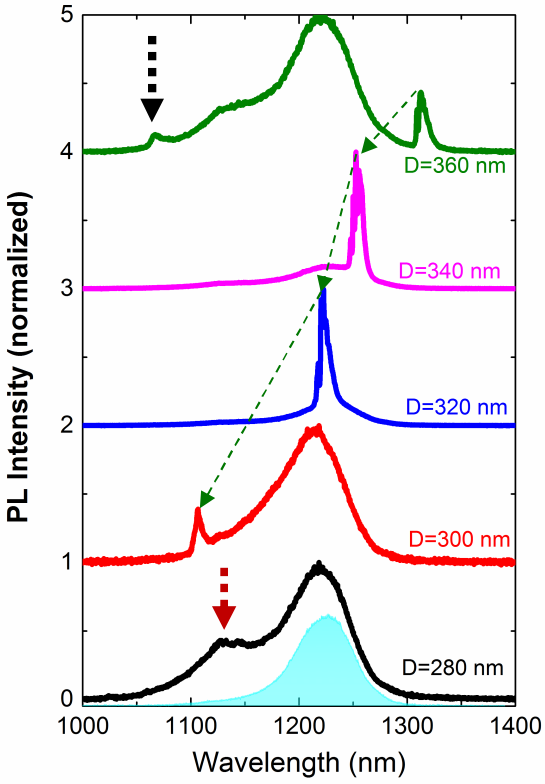


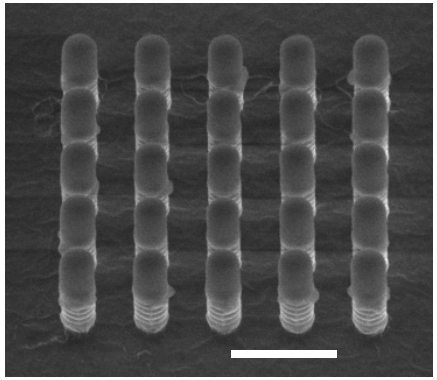


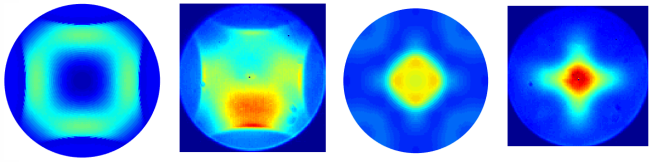


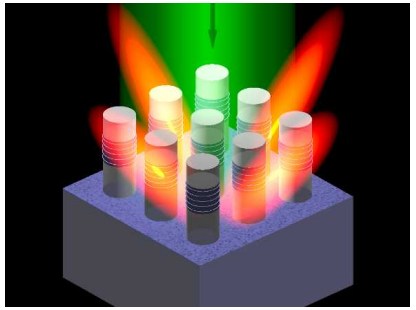
Exploring dark modes in nano-cylinder resonators





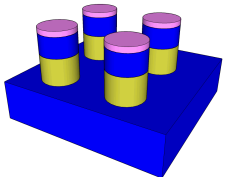




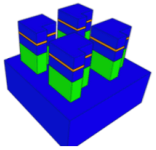


Outline

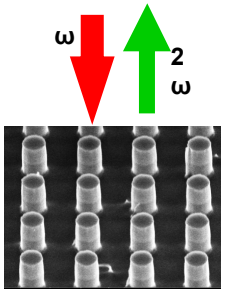
- Background
- All-dielectric metasurfaces from III-V semiconductors



- Coupling of emitters embedded in III-V metasurfaces

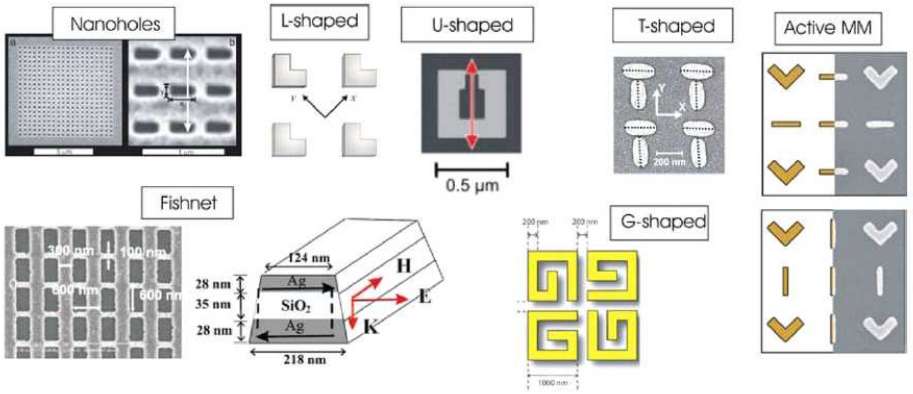


- **Harmonic generation and other nonlinearities from III-V metasurfaces**



Nonlinear optics in nanostructured materials

- **Nonlinear optics is a powerful tool to understand new materials/structures**
- **Nanostructured materials: plasmonic, 2D materials, etc**



Y. Kivshar et al, Laser Photonics Review, **9**, 195 (2015)

- Phase matching relaxed
- Tight confinement
- Resonant enhancement of EM field

nature photonics
FOCUS | REVIEW ARTICLES
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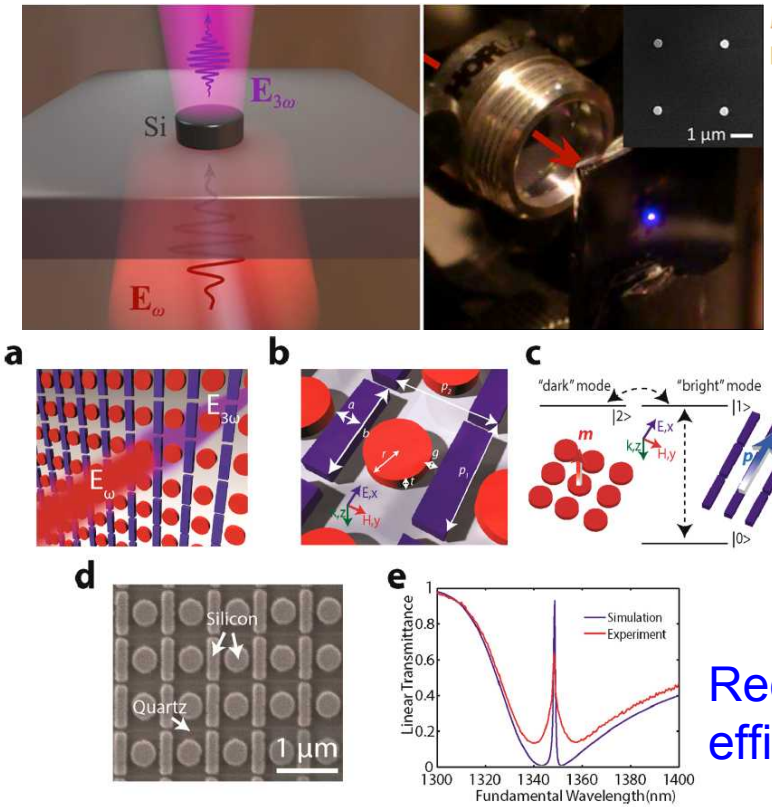
Nonlinear plasmonics

Martti Kauranen[1] and Anatoly V. Zayats[2]

SHG, THG, optical rectification, etc

Plasmonic structure: small modal volume
(usually only use surface nonlinearities)

Third-harmonic generation in Si dielectric metasurfaces



Nano Lett., **2014**, *14* (11), pp 6488–6492
DOI: 10.1021/nl503029j

No second-order nonlinear phenomena observed (silicon: centrosymmetric)

- SHG
- sum-frequency generation
- difference-frequency generation
- Parametric amplification
- Parametric down conversion, etc

Record high efficiencies

Nano Lett. 2015, 15, 7388−7393

GaAs: ~200pm/V

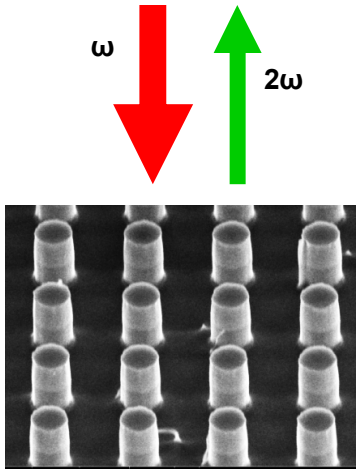
Material	deff (pm/V)
MgO:PPLN	14pm/V (typical)
KTP	3.4pm/V
BBO	2.5pm/V
LBO	0.85pm/V

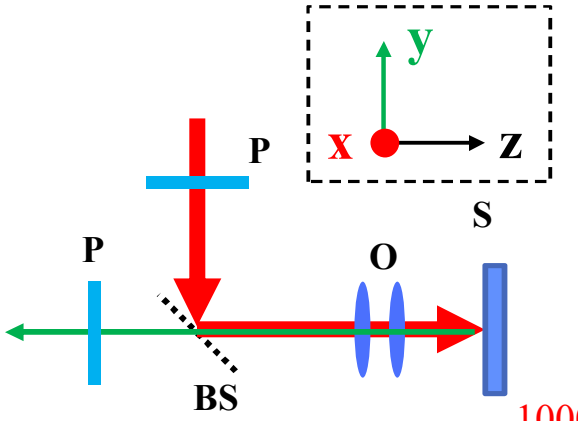
III-V (AlGaAs, InGaAs, GaAs) semiconductors:

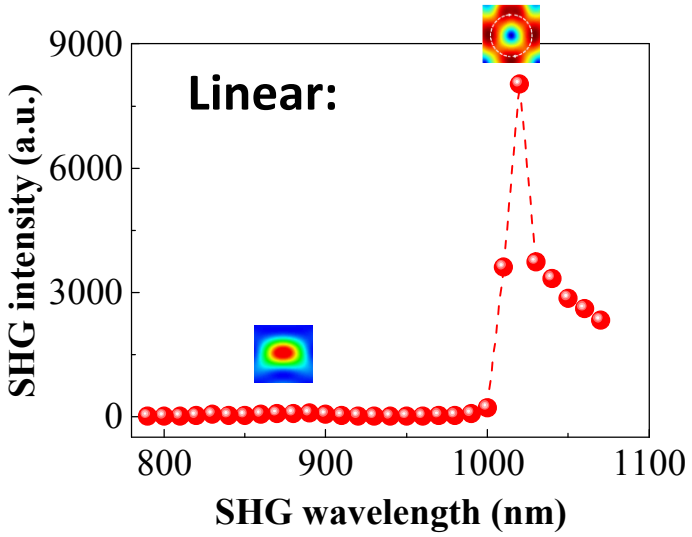
- large nonlinear susceptibilities
- direct bandgap (active devices)
- “3D” & No flip chip bonding

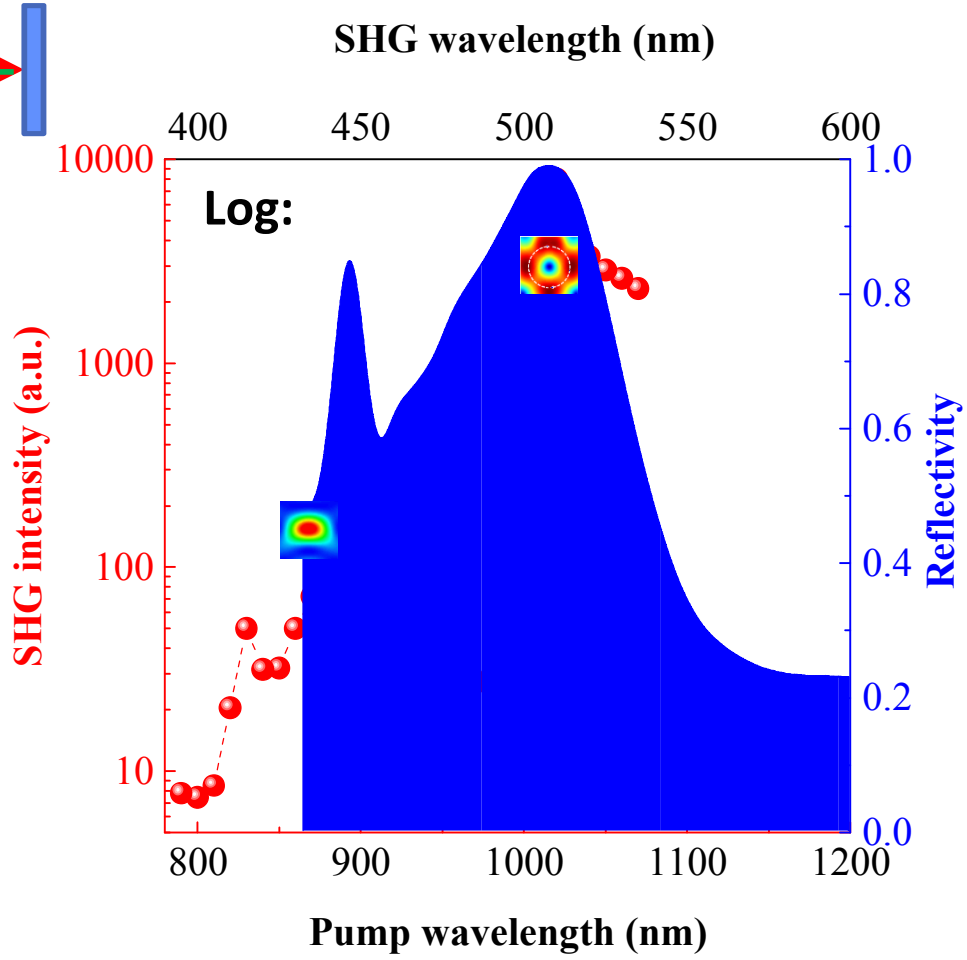
FTh3D.5.

Second Harmonic Generation



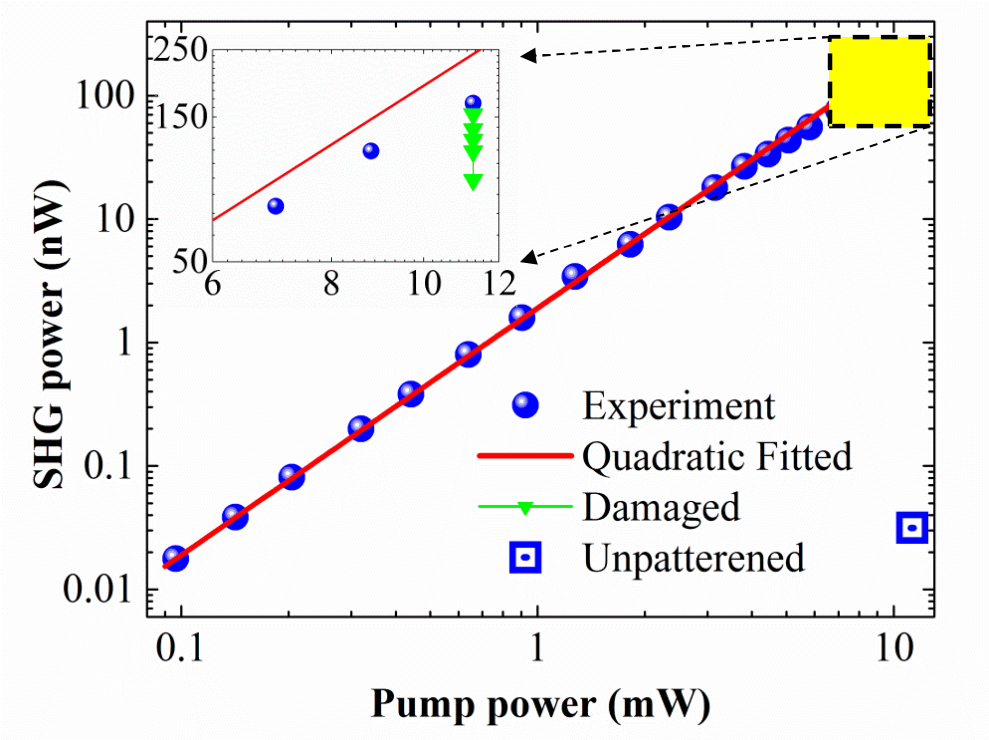


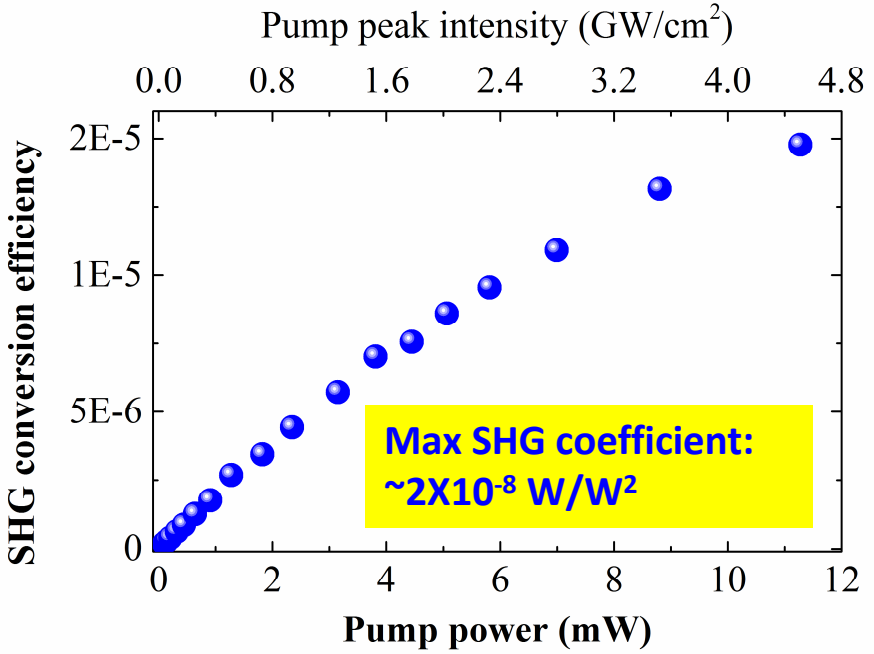




Liu *et al*, Nanoletters 2016

SHG Power Dependence

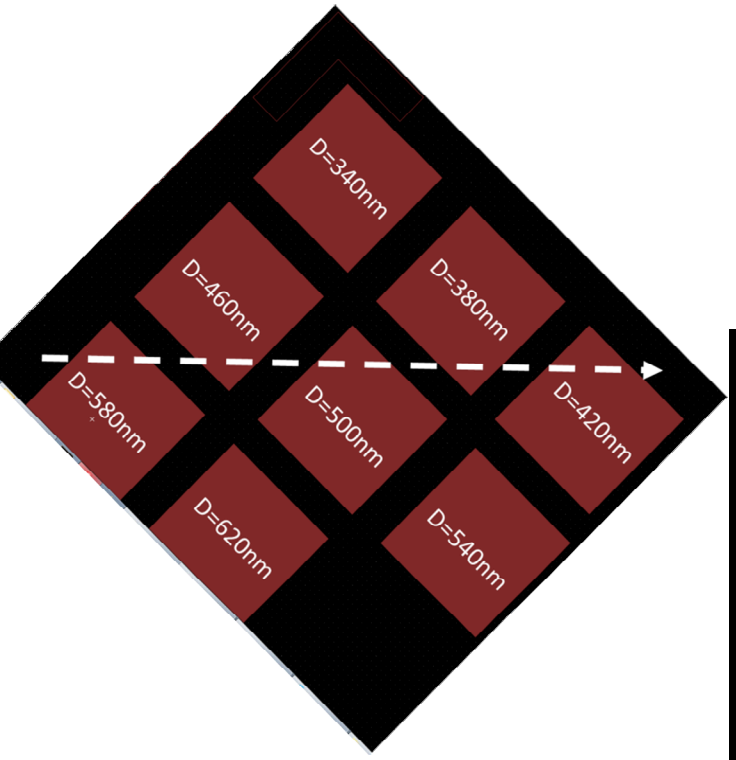


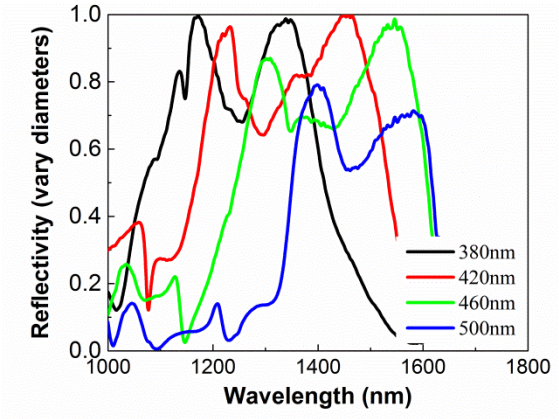


- Quadratic relationship sustained at lower pump power.
- Irreversible damage of resonators > ~1.5 GW/cm².

- Polarization dependence indicates a strong contribution from a surface nonlinearity

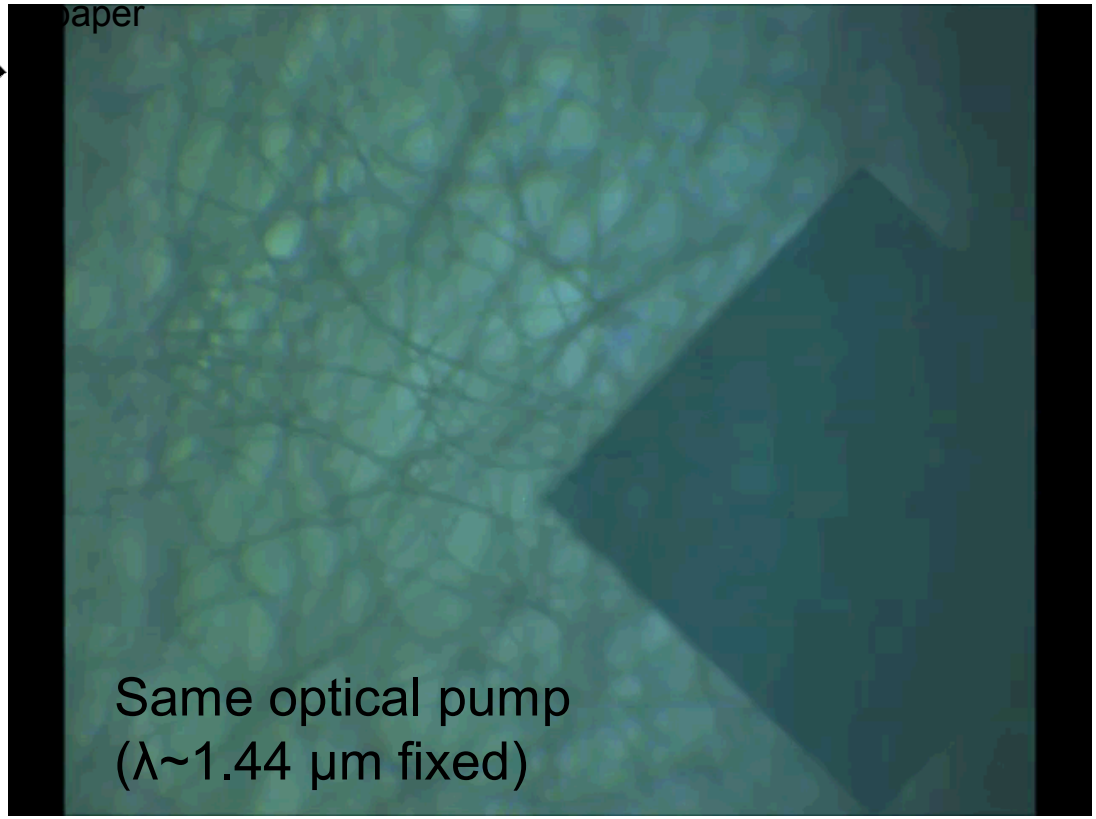
SHG & THG video



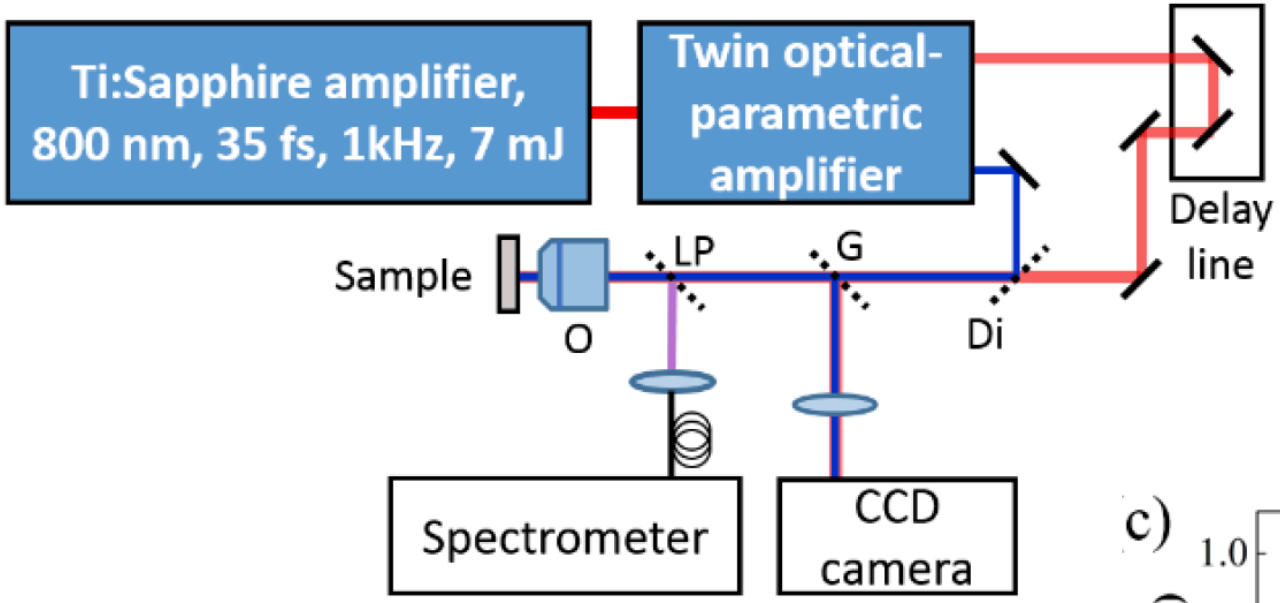


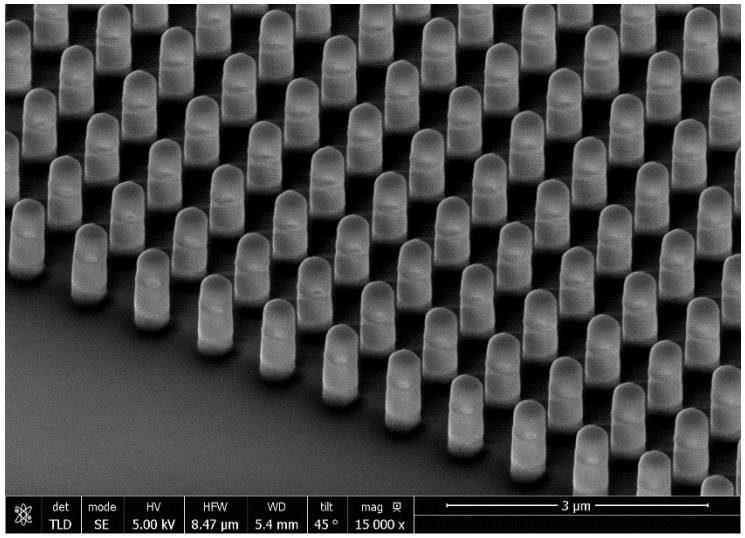
Video just for fun!
Detailed physics needs to be further explored

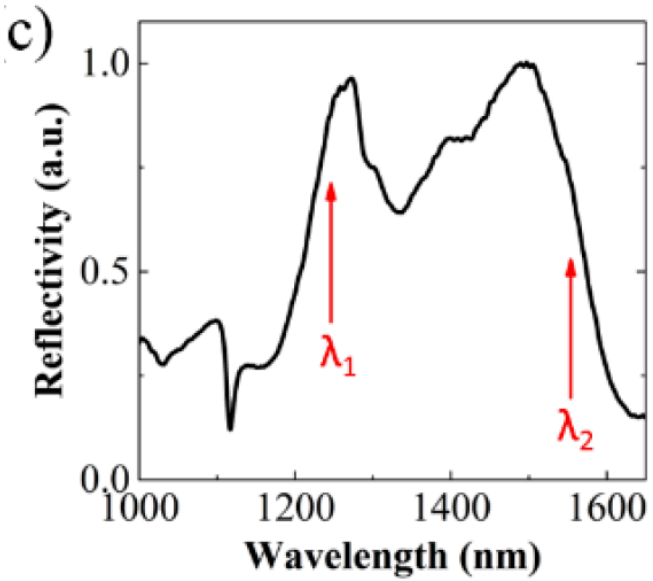
Please ignore the hairy background, it is the image of a lens paper



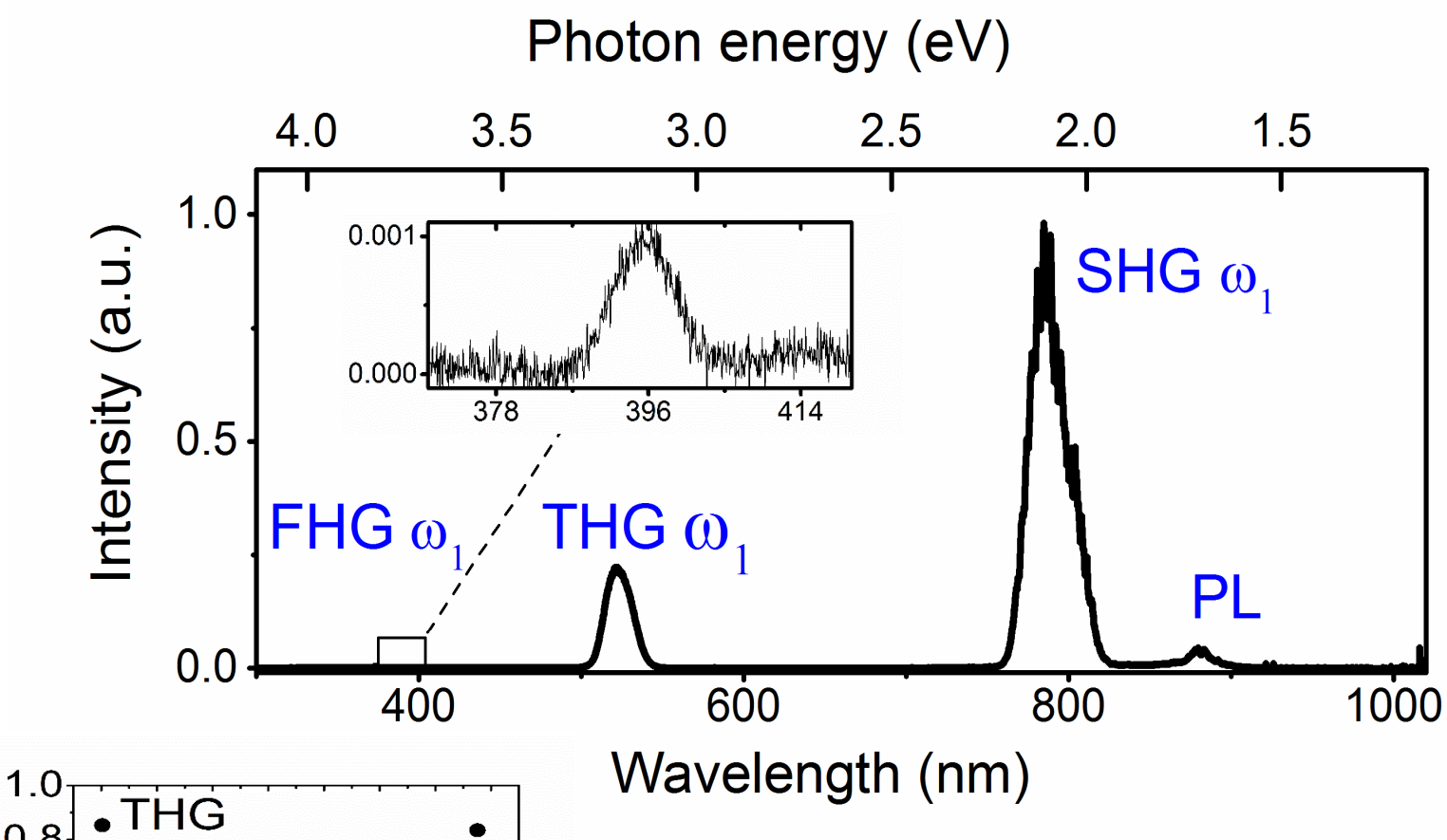
snliu@sandia.gov

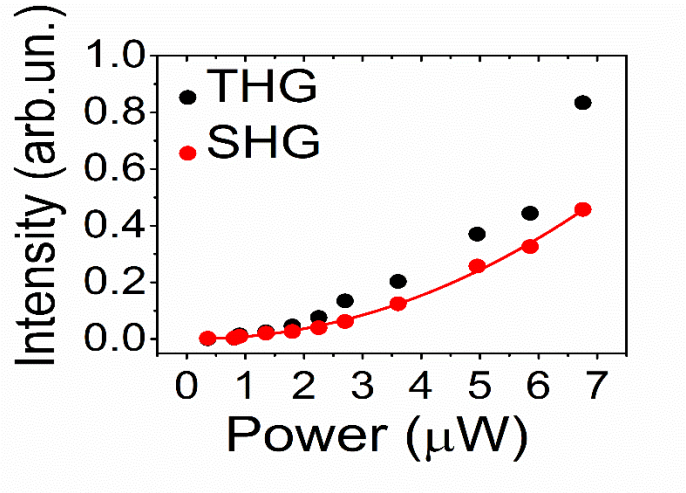

Ti:Sapphire amplifier, 800 nm, 35 fs, 1kHz, 7 mJ
Twin optical-parametric amplifier
Delay line
Sample
LP
G
O
Di
Spectrometer
CCD camera


det TLD
mode SE
HV 5.00 kV
HFW 8.47 µm
WD 5.4 mm
tilt 45 °
mag 15 000 x
3 µm

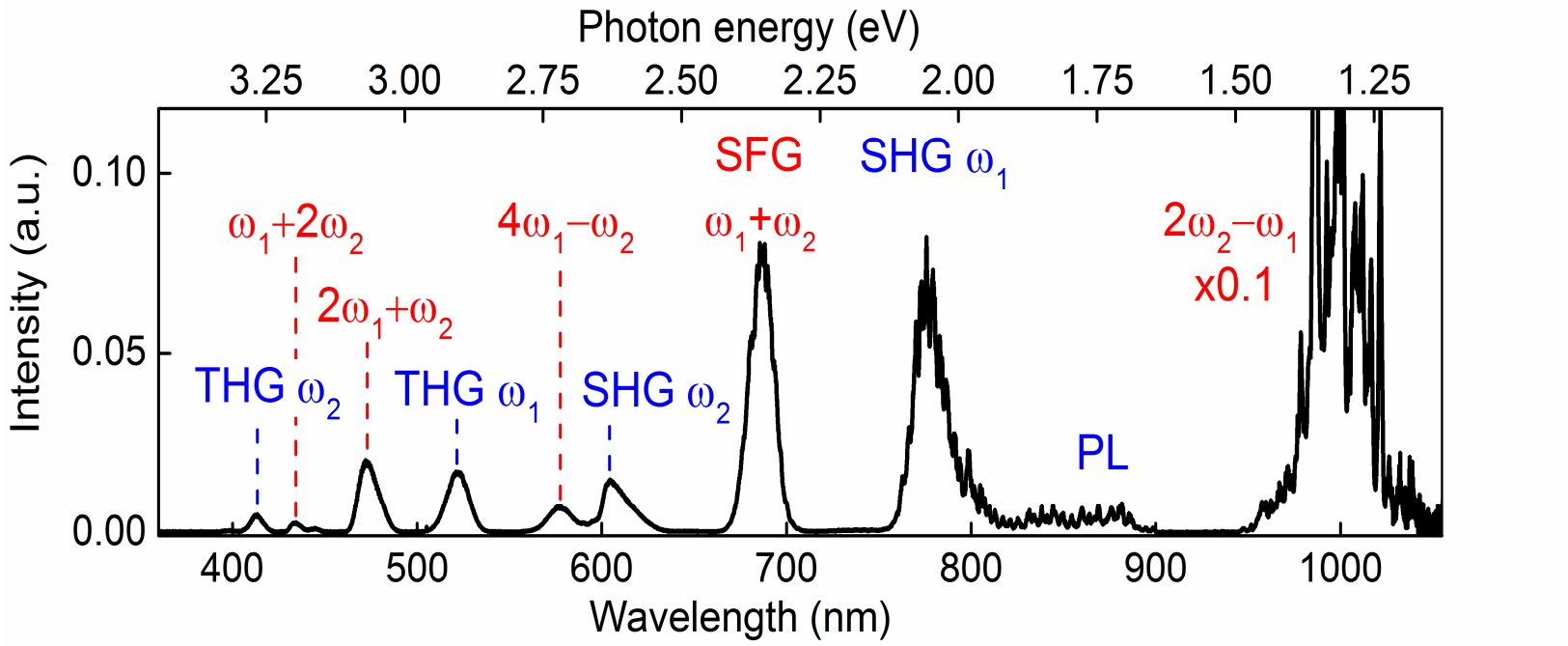

c)
Reflectivity (a.u.)
1.0
0.5
0.0
λ1
λ2
1000
1200
1400
1600
Wavelength (nm)

Single beam harmonic generation (2nd, 3rd, 4th harmonic)

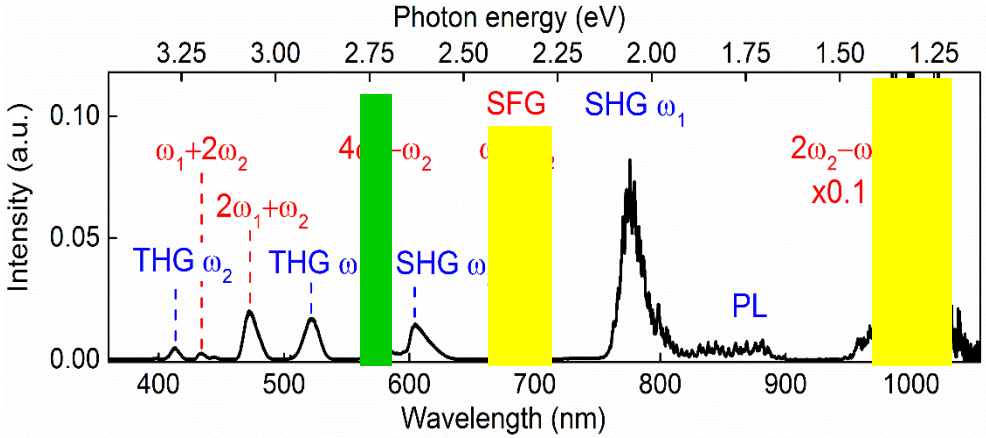


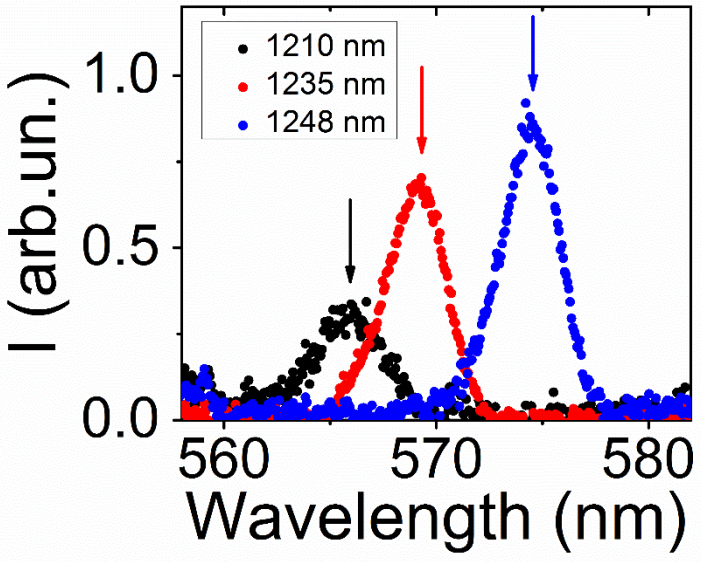


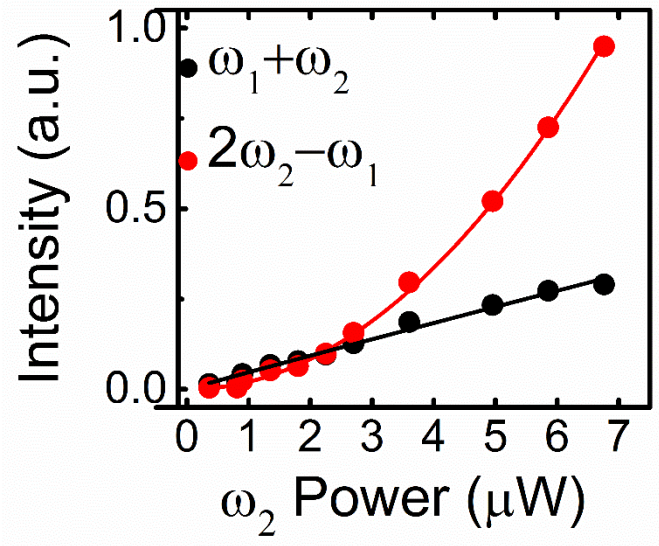
Frequency “super” mixing

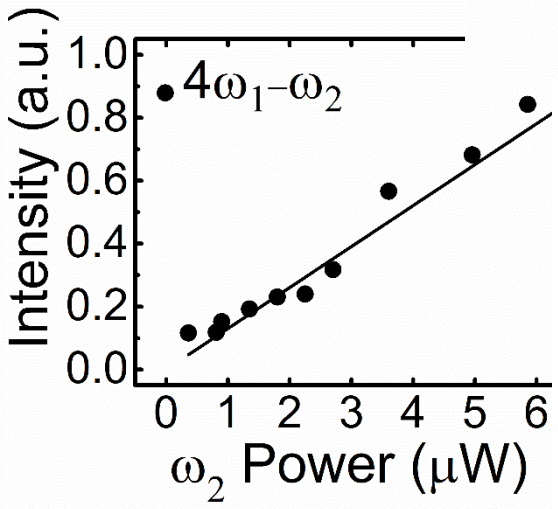


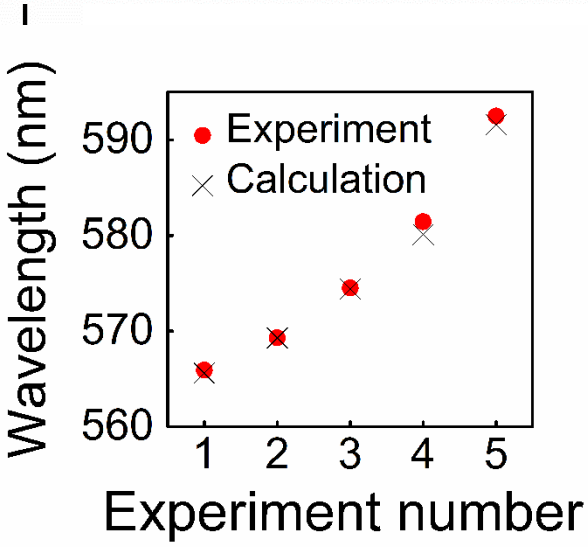
- **11 spectral peaks**
- **7 different nonlinear processes: 2nd, 3rd, 4th harmonics, sum frequency generation, 4 wave-mixing, six-wave mixing, PL induced by two-photon absorption**


Photon energy (eV)
3.25
3.00
2.75
2.50
2.25
2.00
1.75
1.50
1.25
Intensity (a.u.)
0.10
0.05
0.00
ω1+2ω2
2ω1+ω2
THG ω2
THG ω
SHG ω
SFG
SHG ω1
PL
2ω2−ω
x0.1
400
500
600
700
800
900
1000
Wavelength (nm)

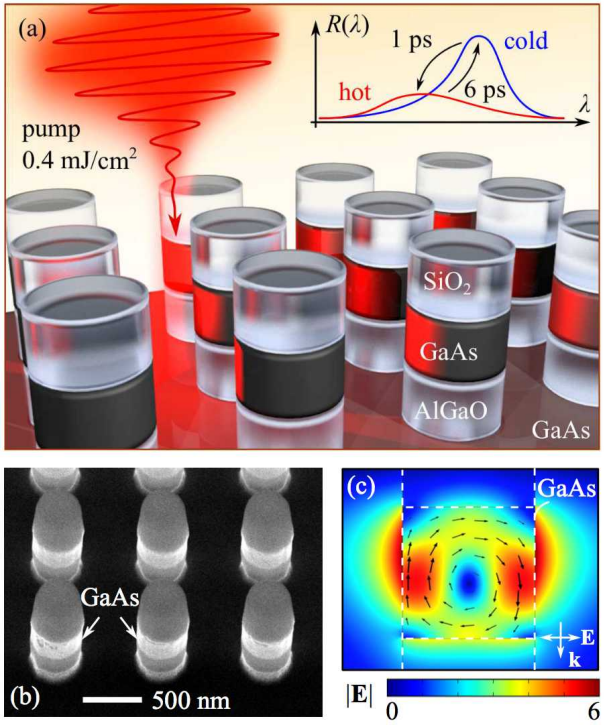

1210 nm
1235 nm
1248 nm
I (arb.un.)
1.0
0.5
0.0
560
570
580
Wavelength (nm)


Intensity (a.u.)
1.0
0.5
0.0
ω1+ω2
2ω2−ω1
0
1
2
3
4
5
6
7
ω2 Power (μW)

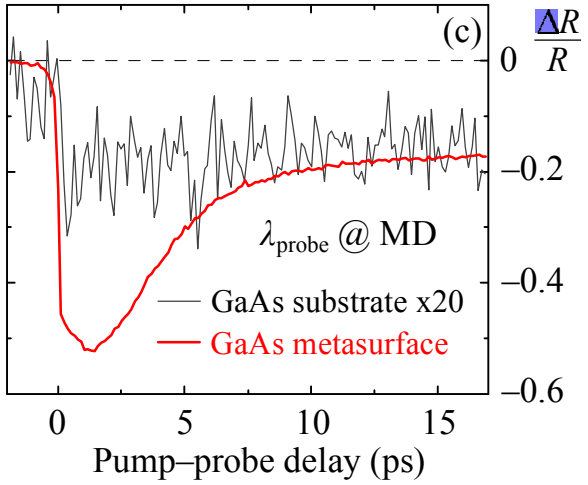

Intensity (a.u.)
1.0
0.8
0.6
0.4
0.2
0.0
4ω1−ω2
0
1
2
3
4
5
6
ω2 Power (μW)


Wavelength (nm)
590
580
570
560
Experiment
Calculation
1
2
3
4
5
Experiment number

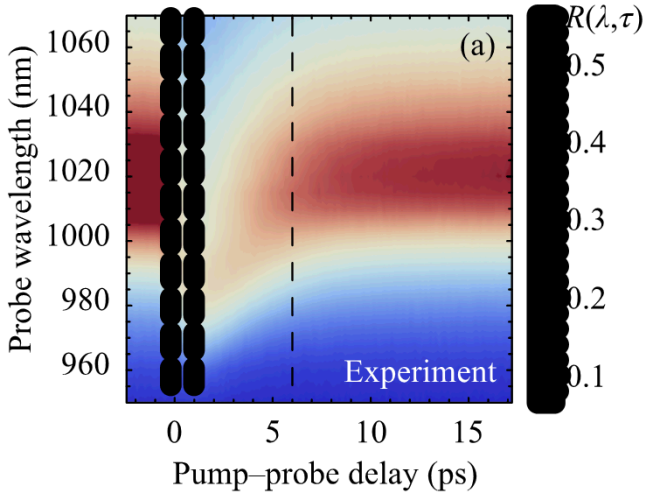
Ultrafast Active Tuning of the Magnetic Dipole Resonance



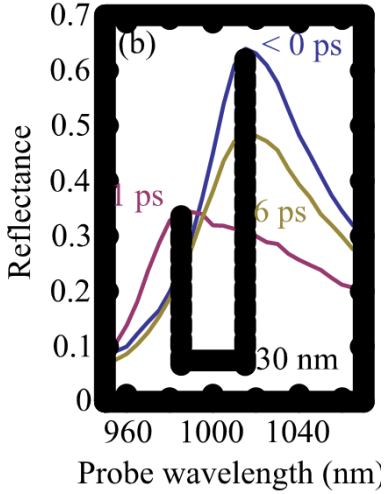
Modulation 50x of substrate



Resonance tuning by 30 nm



- **Fast recovery due to surface recombination (~2.5 ps from low power expts)**
- **Maximum index modulation is –0.14 due to Drude dispersion and band filling effects**



M. R. Shcherbakov et al., Nat. Comm. 2017

Summary & Acknowledgments

- **All-dielectric metasurfaces from III-V semiconductors**
- **Coupling of emitters embedded in III-V metasurfaces**
- **Harmonic generation and other nonlinearities from III-V metasurfaces**

CINT + Sandia: Sheng Liu, Salvo Campione, John Reno, Mike Sinclair, John Klem, Willie Luk, Joel Wendt, Jason Domingues, Greg Peake.

Jena: Isabelle Staude, Sina Saravi, Frank Setzpfandt, Thomas Pertsch

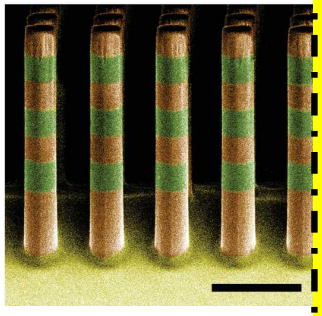
Moscow State: Maxim Shcherbakov, Varvara Zubyuk, Polina Vabishchevich Andrey A. Fedyanin

University of New Mexico: Ganesh Balakrishna

Slides from MRS
ACS Galveston
Photonics West 2017

III-V dielectric metamaterials

- **Multilayer**
  MBE/MOC
  monolithic

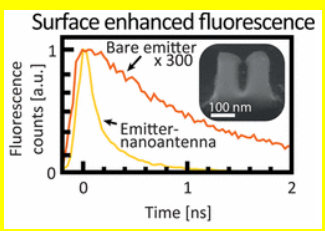


- **Direct band**
  absorption

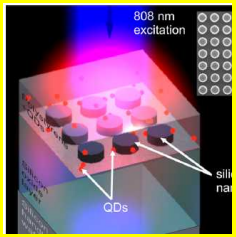
Ultrafast resonance shift ~30nm

Maxim, Nature Comm. **8**, article 17 (2017)

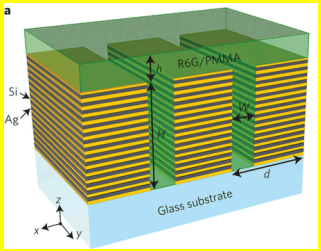
- **Enhanced light emission**



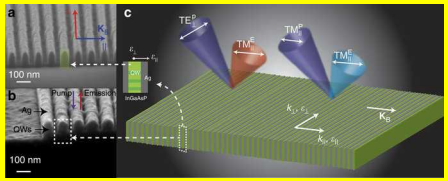
Stefan Maier (2017)



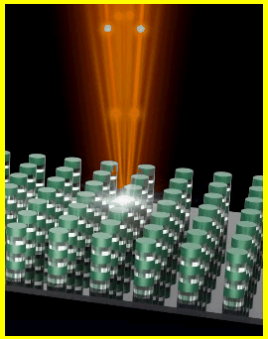
Isabelle (2014)



Zhaowei Liu (2014)



Luminescent hyperbolic metasurfaces Joseph Smalley, UCSD

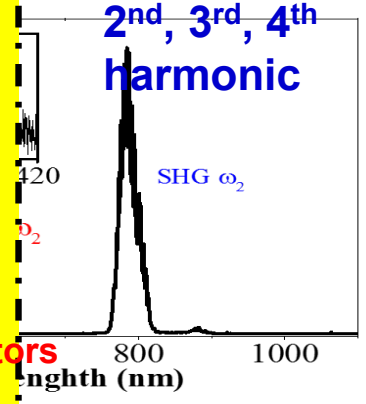


Embedding emitters inside resonators

- **Resonantly enhanced**
  ic generation

g Liu, et al, Nano Letters, **16**, 5426,
)
Giuseppe
16)
Kivshar, Dragomir Neshev,
o Letters (2016)

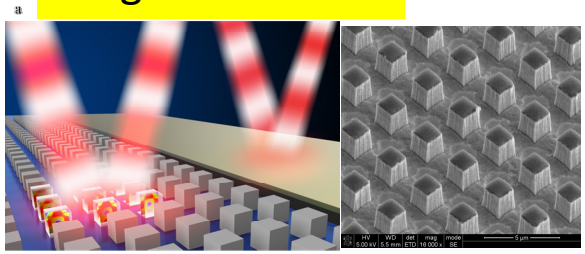
2nd, 3rd, 4th harmonic



Pump–probe delay (ps)

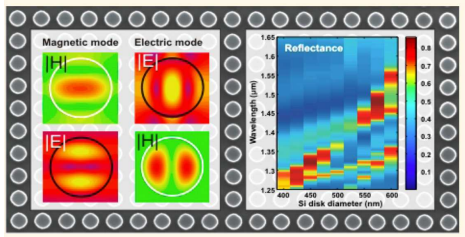
Examples of Dielectric Metasurfaces (Linear)

Magnetic mirror

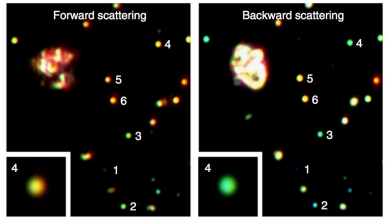


Optica 2015

Tailoring scattering

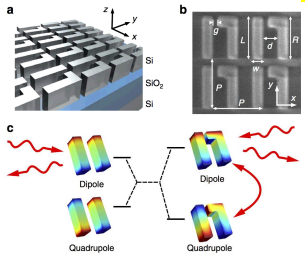


ACS Nano 7, 7824 (2013)

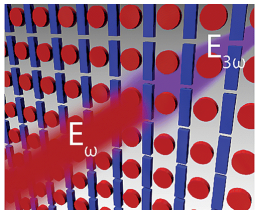


Nat. Comm. 4, 1527 (2013)

Fano resonances

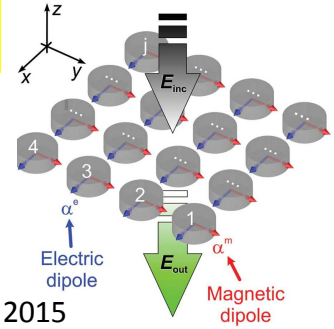


Nature Comm. 2014.



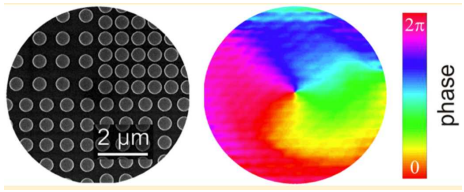
Nano Lett. 15, 7388 (2015)

Huygens Metasurfaces

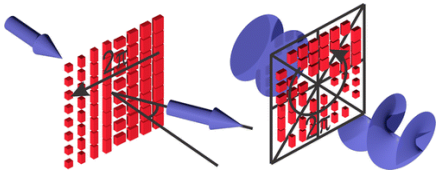


Adv. Optical Mater. 2015

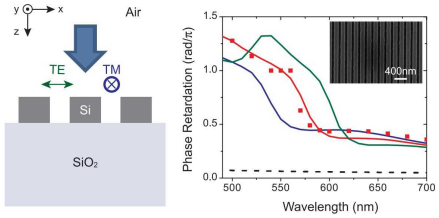
Phase-front manipulation



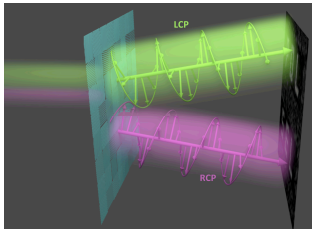
Nano Lett. 15, 5369 (2015)



Nano Lett.15, 6261 (2015)



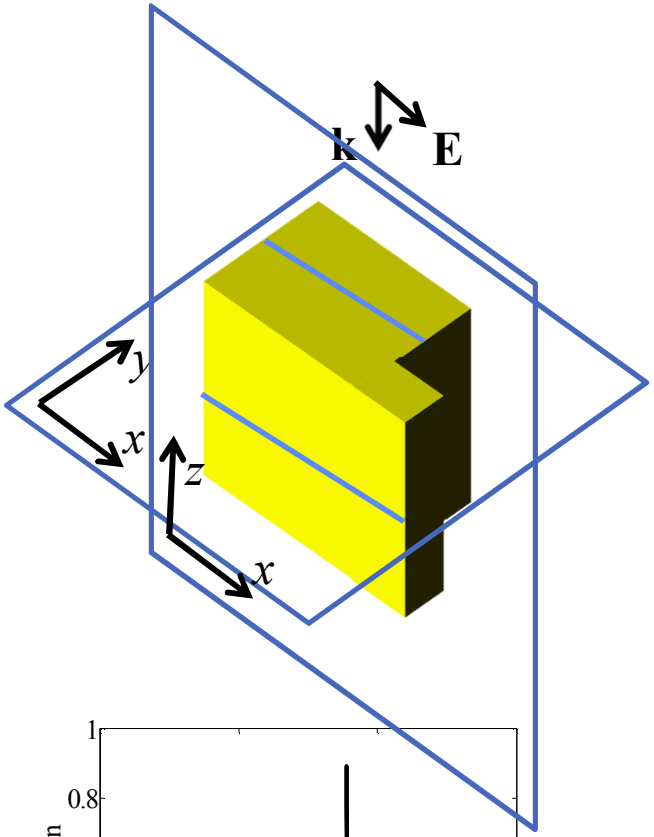
Science 345, 2015

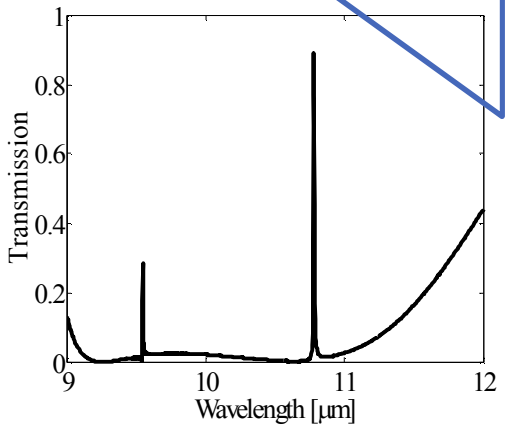


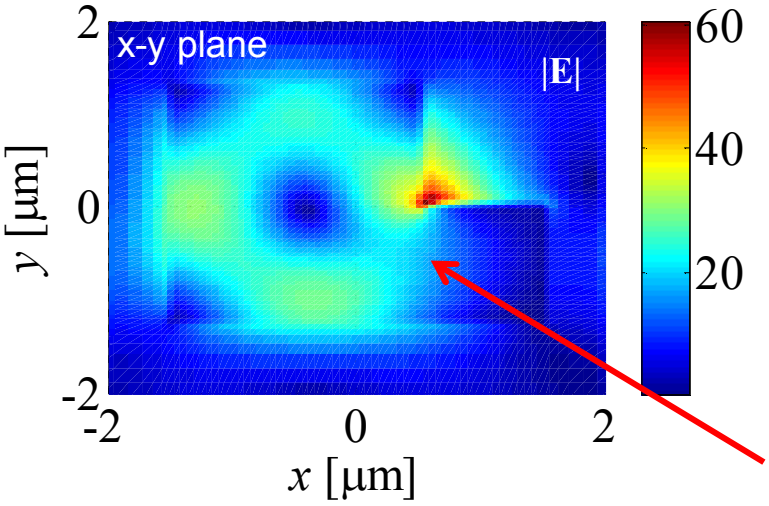
Opt. Express 23, 22611 (2015)

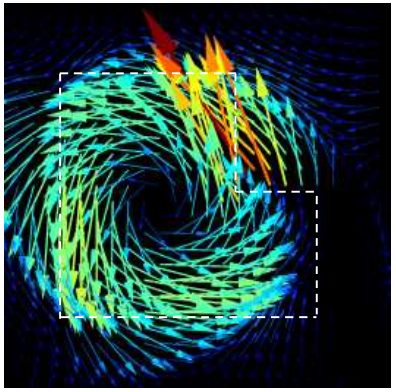
Resonant Mode Field Profiles

FDTD simulations at the λ = 10.8 μm resonance

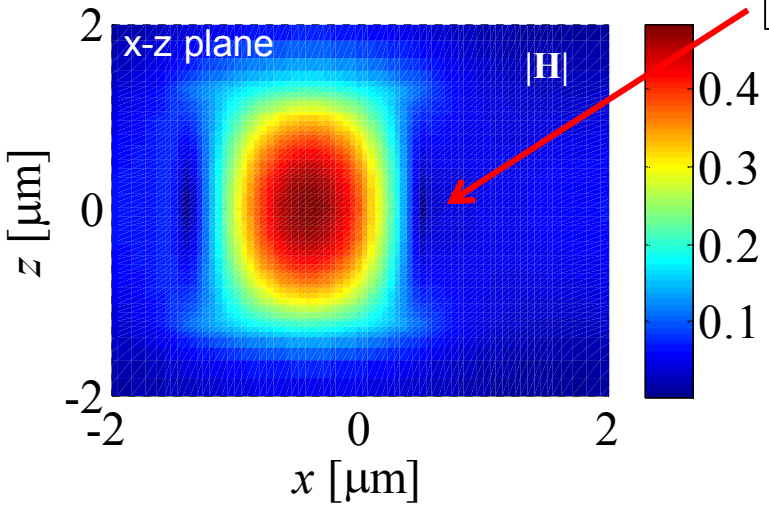




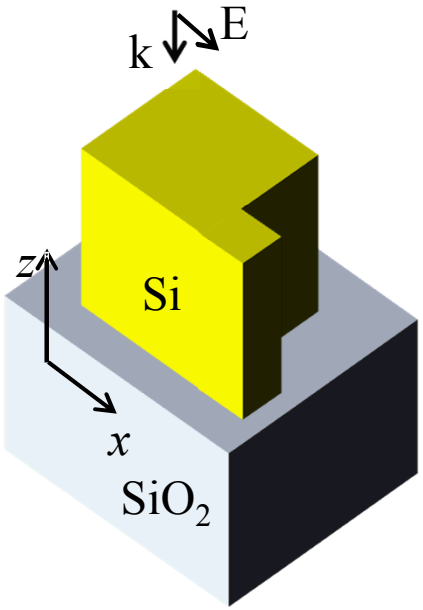




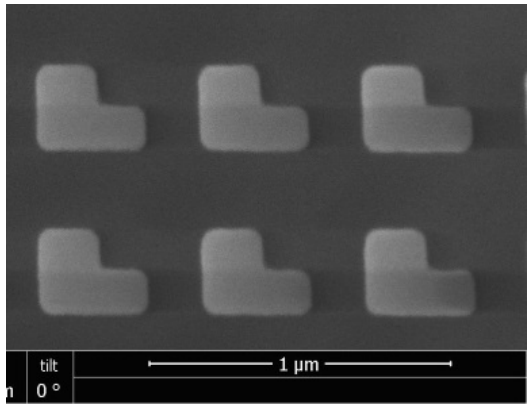
z-directed magnetic dipole

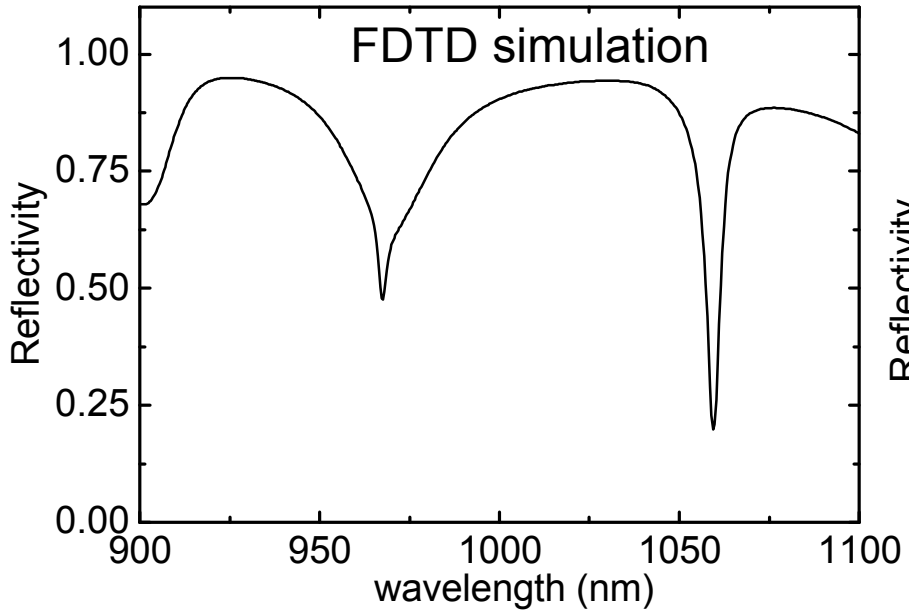


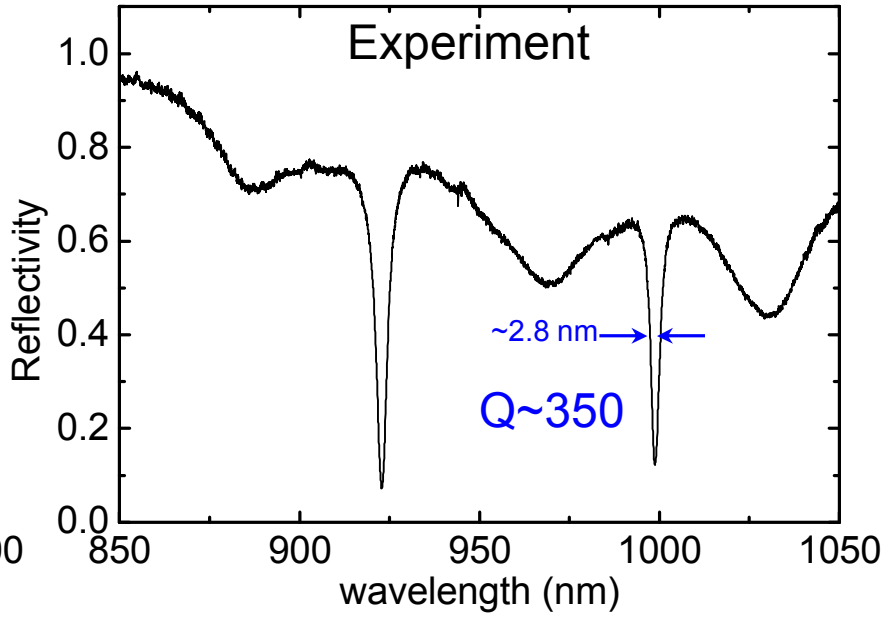
Experimental verification: Silicon Fano Resonators



Thickness = 250 nm
Side length = 280 nm
Array pitch = 550 nm

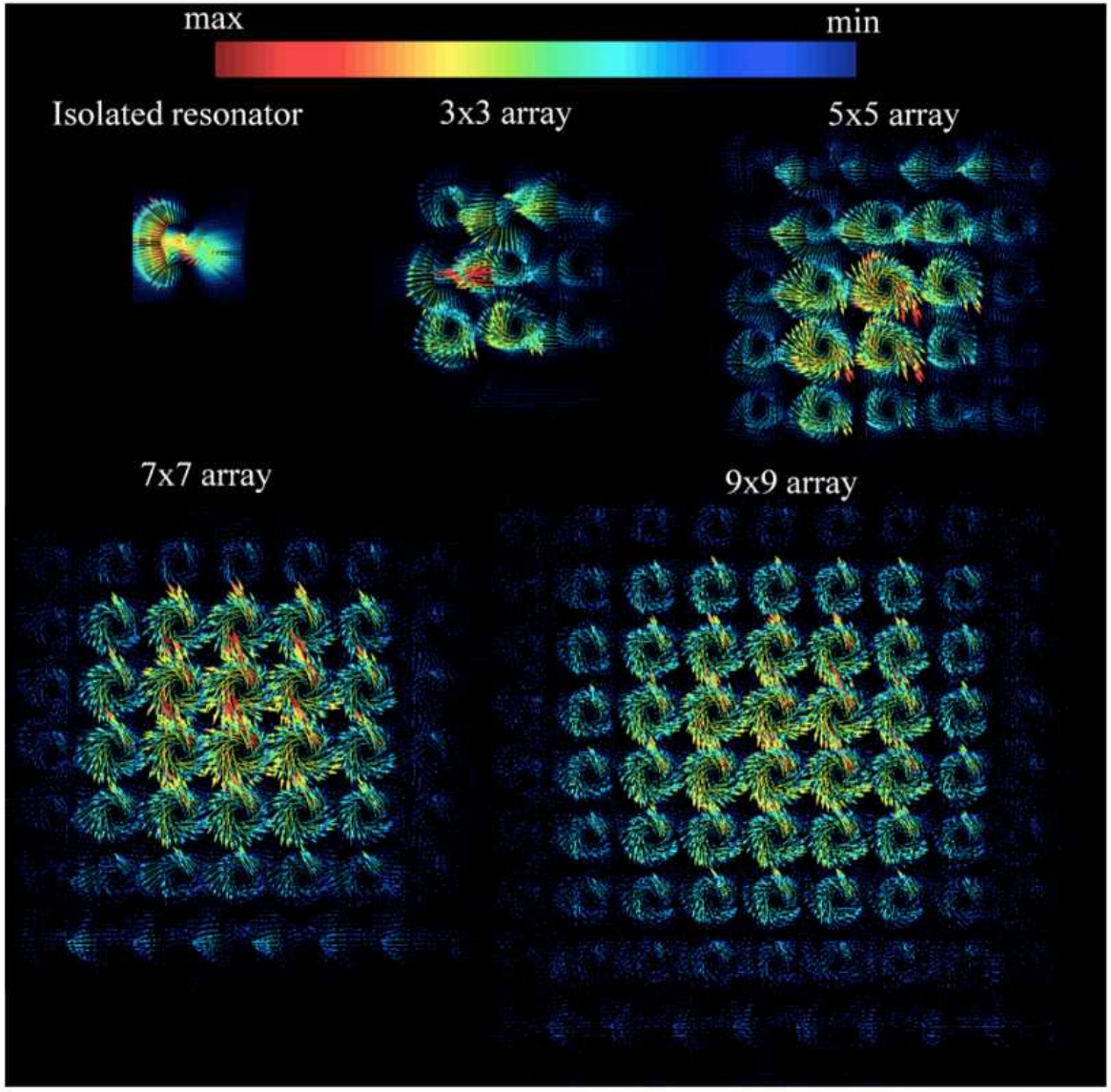






Campione, et al., ACS Photonics 3, 2362 (2016)

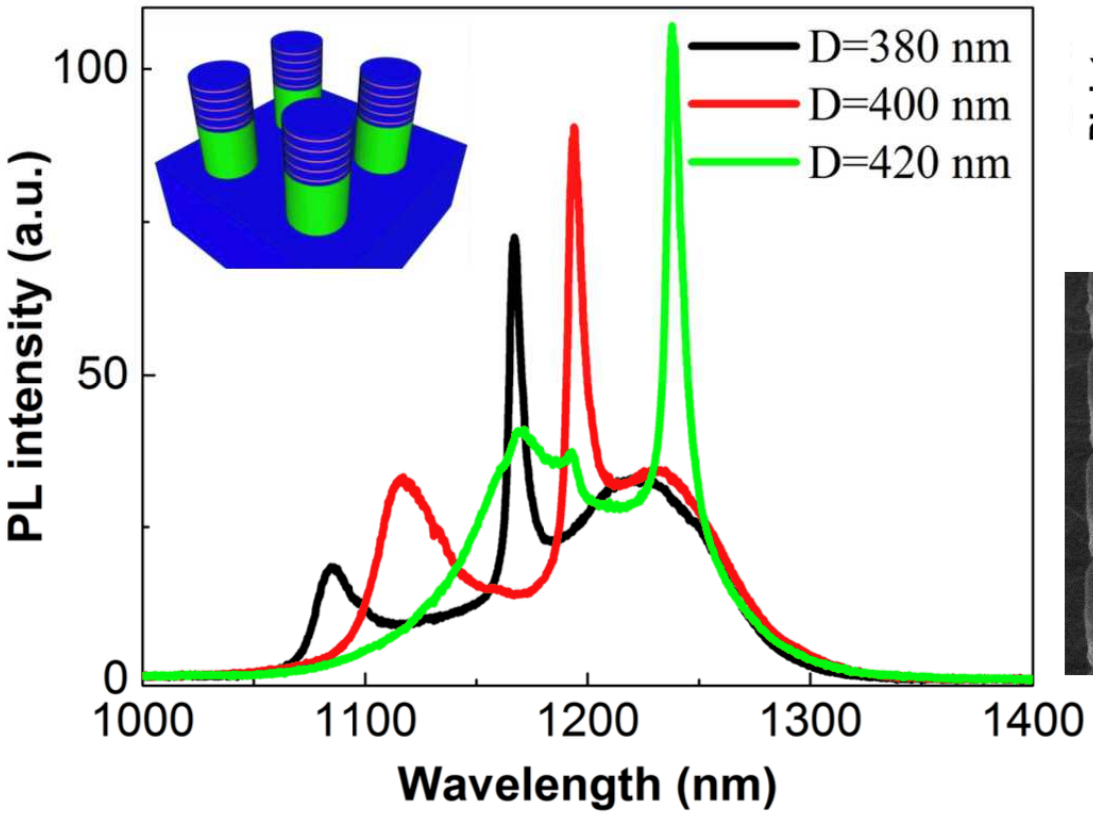
High Q: Only a small array is needed



Campione, et al., ACS Photonics 3, 2362 (2016)

Quantum Dots + Symmetrical Metasurfaces

QDs still couple to a high Q, vertical dipole mode



QD PL