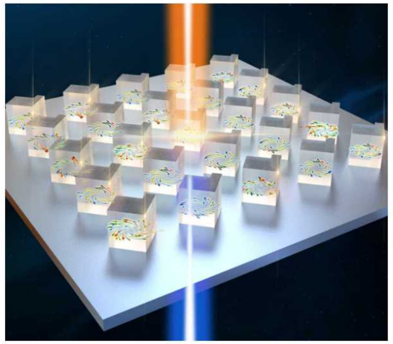
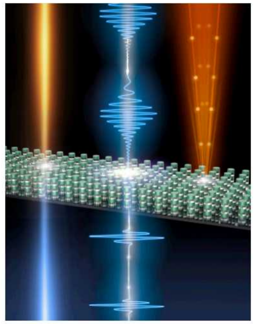
SAND2018-9600C

Recent Advances in Linear and Nonlinear All-Dielectric Metamaterials





Igal Brener

Sandia National Labs &
Center for Integrated Nanotechnologies (CINT)

***ibrener@sandia.gov*, (505) 844-8097**

SPIE 2018, San Diego

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UT Austin: Nish Nookala, Misha Belkin

Moscow State (Russia): Maxim Shcherbakov, Andrey Fedyanin

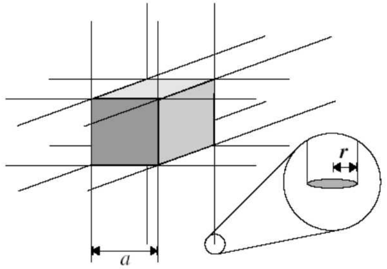
Outline

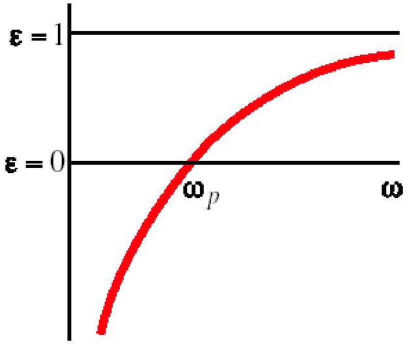
- **Metamaterials & Metasurfaces: refresher, definitions, etc.**
- **Linear Metasurfaces:**
  - **Optical magnetic mirror**
  - **Huygens meta-optics**
- **Emitters + Metasurfaces**
- **Nonlinear optics with all-dielectric metasurfaces:**
- **Outlook on future 3D fabrication**

Refresher: Metamaterials

Controlling ε

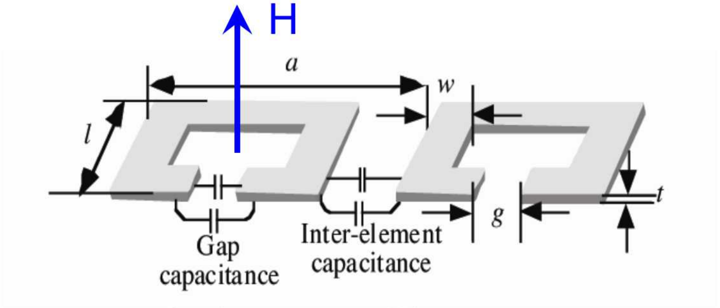
$$\omega_p = \sqrt{\frac{ne^2}{m^* \varepsilon_o}}$$



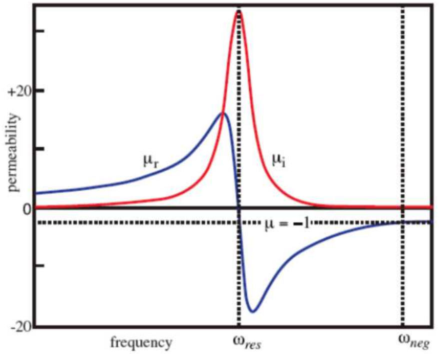


"Diluted Drude" or some electric resonance

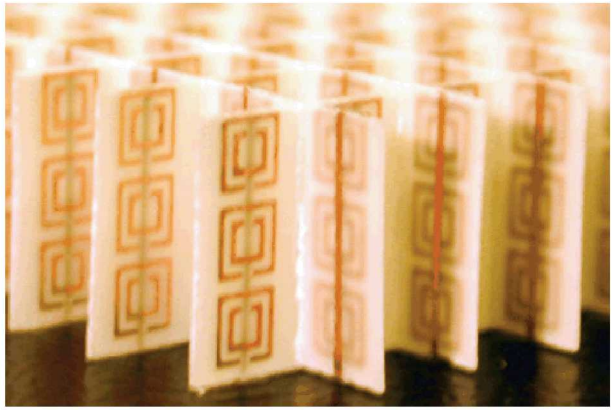
Controlling μ



from; S. McMeekin, Proc. Of SPIE, Vol. 6581



Some magnetic resonance

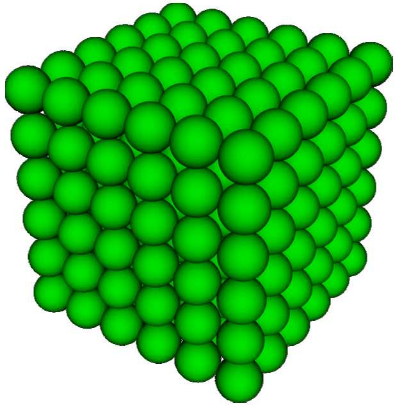


Dielectric Metamaterials

Clausius-Mossoti or Lorentz-Lorenz

Effective medium approximation

$$\varepsilon_{\text{eff}} = \varepsilon_m \frac{2\delta_i(\varepsilon_i - \varepsilon_m) + \varepsilon_i + 2\varepsilon_m}{2\varepsilon_m + \varepsilon_i + \delta_i(\varepsilon_m - \varepsilon_i)}$$



(Ack: Ed Kuester, CU Boulder)

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

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

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

...RIAL LOADED WITH

...ARTICLES*

†

...sed form 27th September, 1946.)

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

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

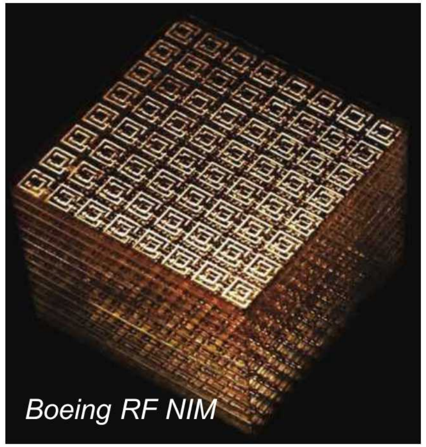
$$b_e = \frac{\epsilon_1}{\epsilon_2}, \qquad b_m = \frac{\mu_1}{\mu_2}$$

What is a “Metasurface”

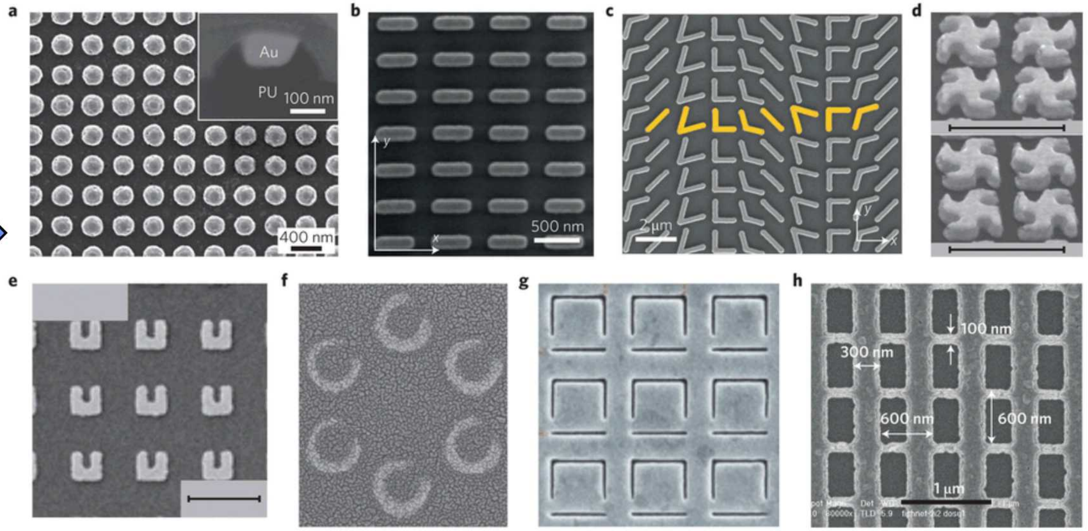
The 2D version of a 3D Metamaterial

- Metallic or Dielectric
- Resonant or non-resonant

3D



2D

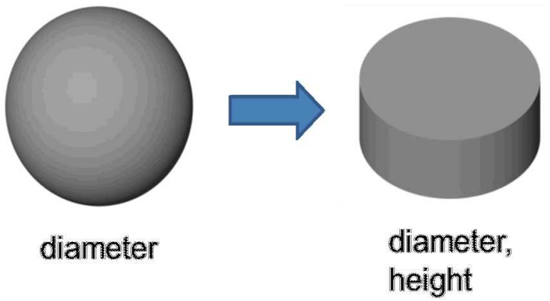


Nature Photonics 8, 889 (2014)

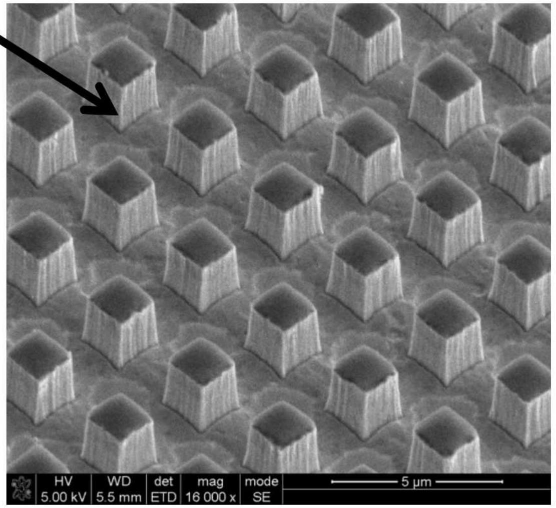
A collection of structures<λ where electric/magnetic reflection, transmission & scattering can be controlled by each element

How to Fabricate Dielectric Metasurfaces

- **Desired: arrays of high index, wavelength scale "particles"**



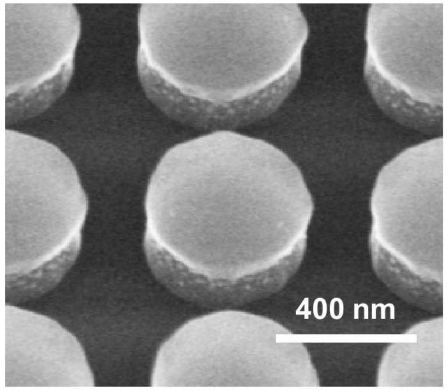
Tellurium
n~5 in the IR



$1.53x1.53x1.7\mu m^3$

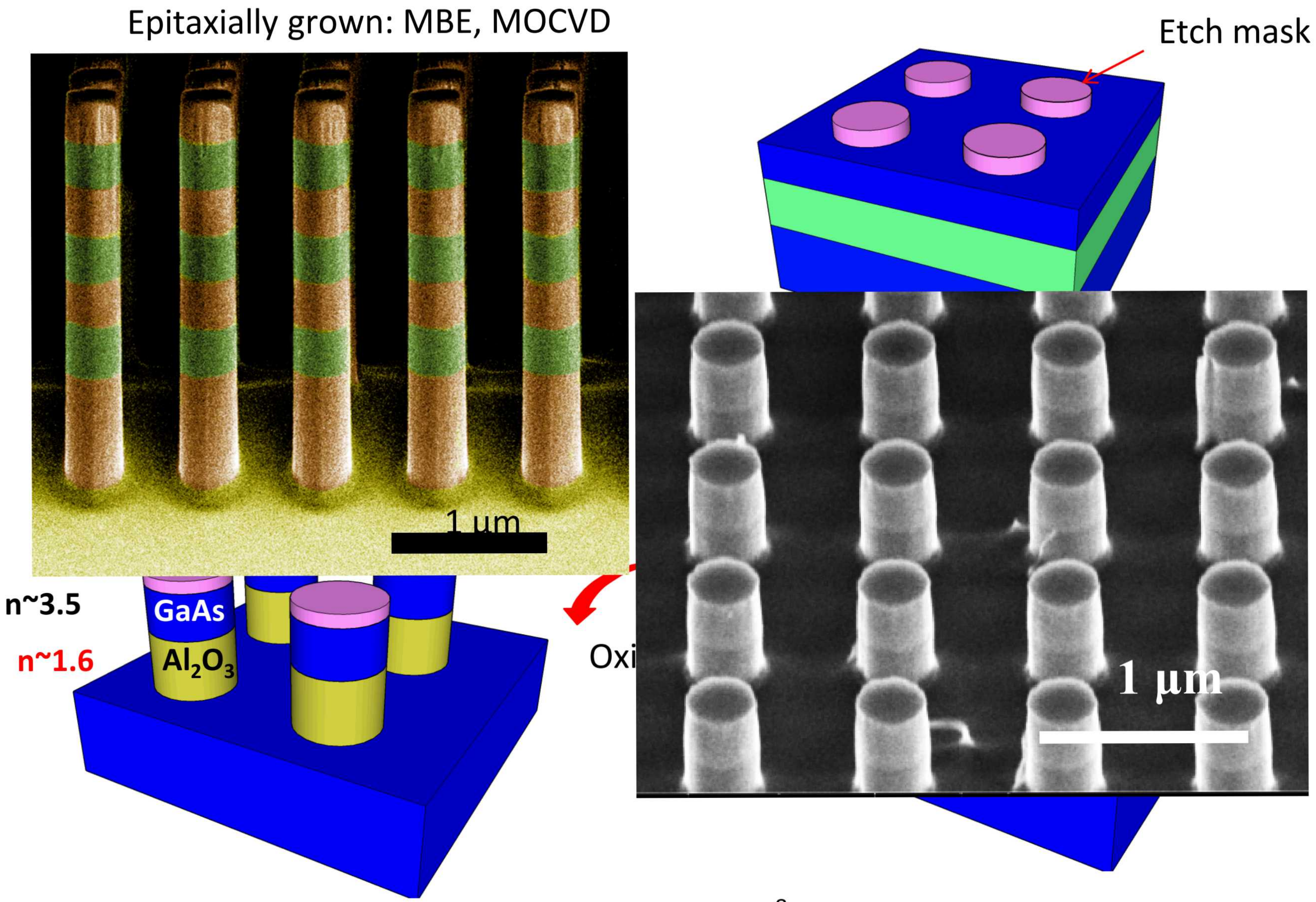
for 10um

Silicon (n~3.8) on glass



for 1.5um

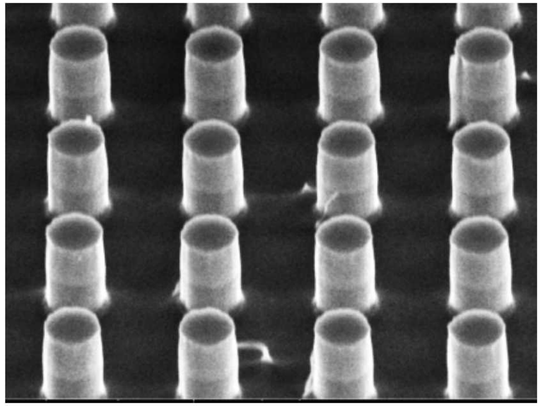
Dielectric Metasurfaces using III-V Semiconductors (n~3.5, near IR)

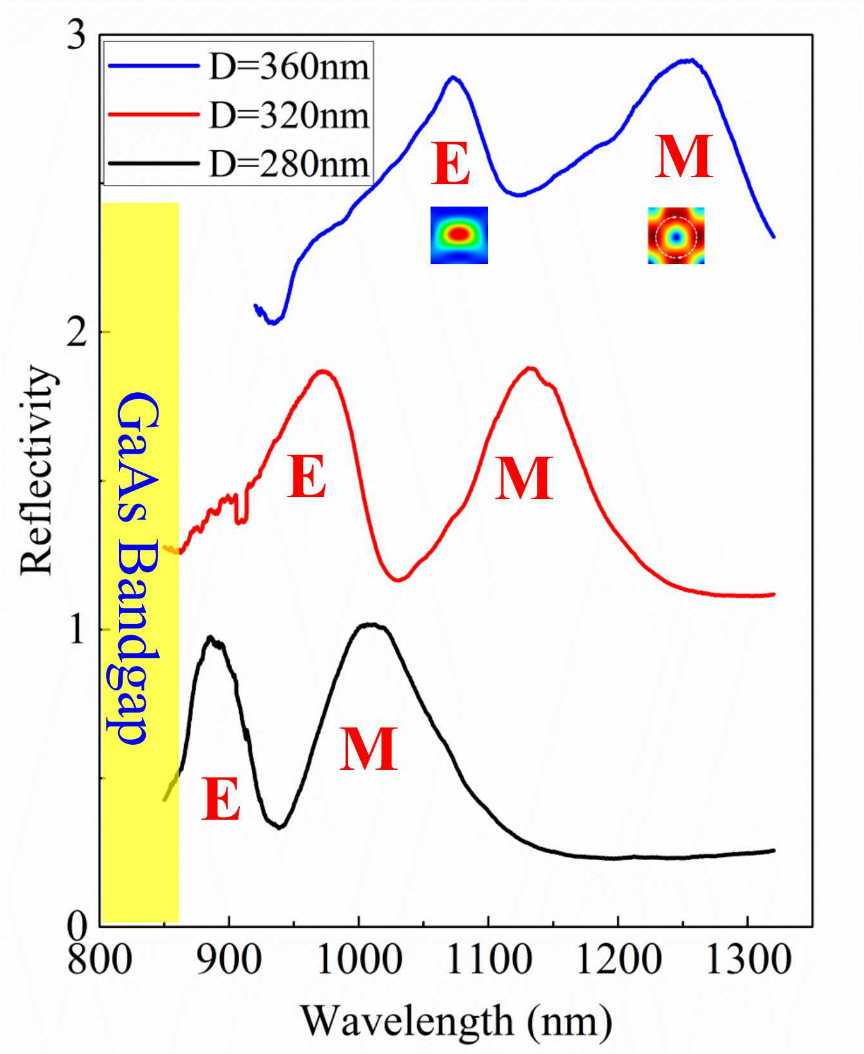


GaAs Dielectric Metasurface

GaAs disk height ~300nm

Different diameters

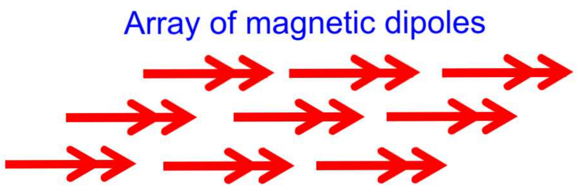




- Extremely low loss below bandgap
- Crystalline

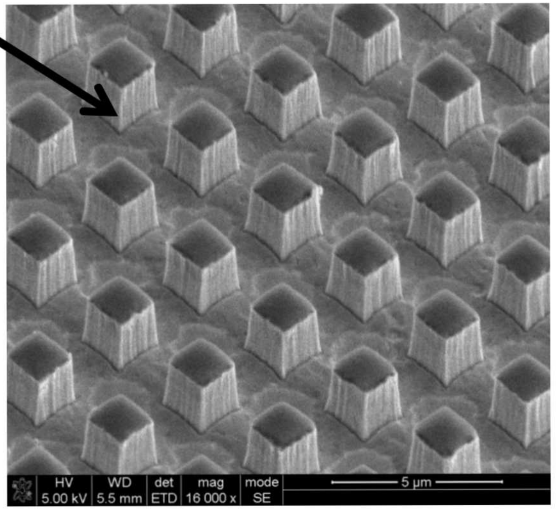
Using Magnetic Resonances: The “Magnetic Mirror”

it does not exist in nature

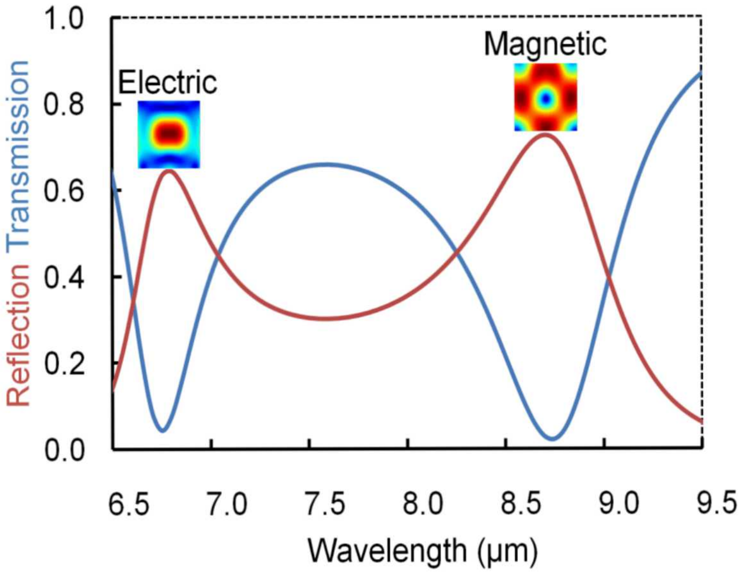


Magnetic dipole responds in phase with the electric field (in microwave language, this represents an **artificial magnetic conductor)**

Tellurium
n~5 in the IR



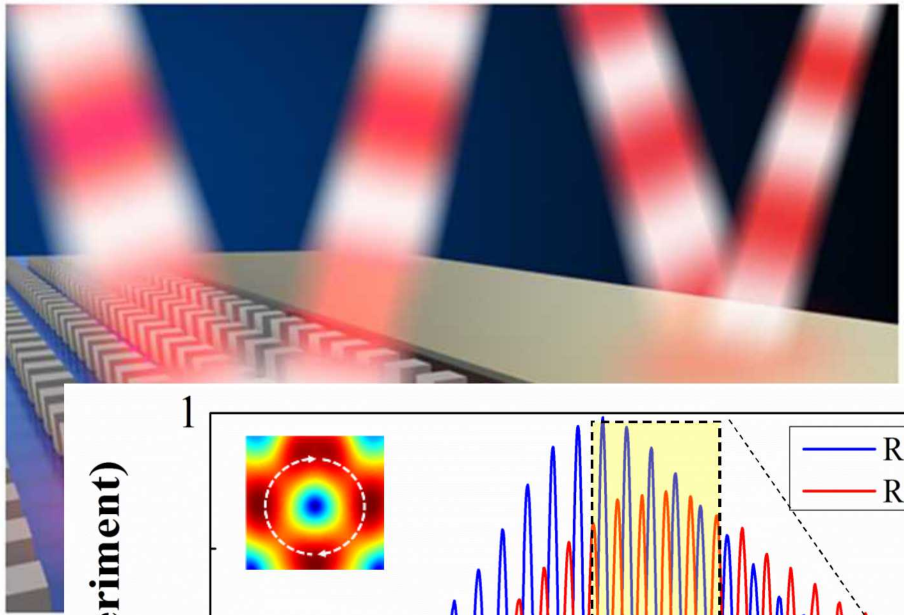
1.53x1.53x1.7μm^3

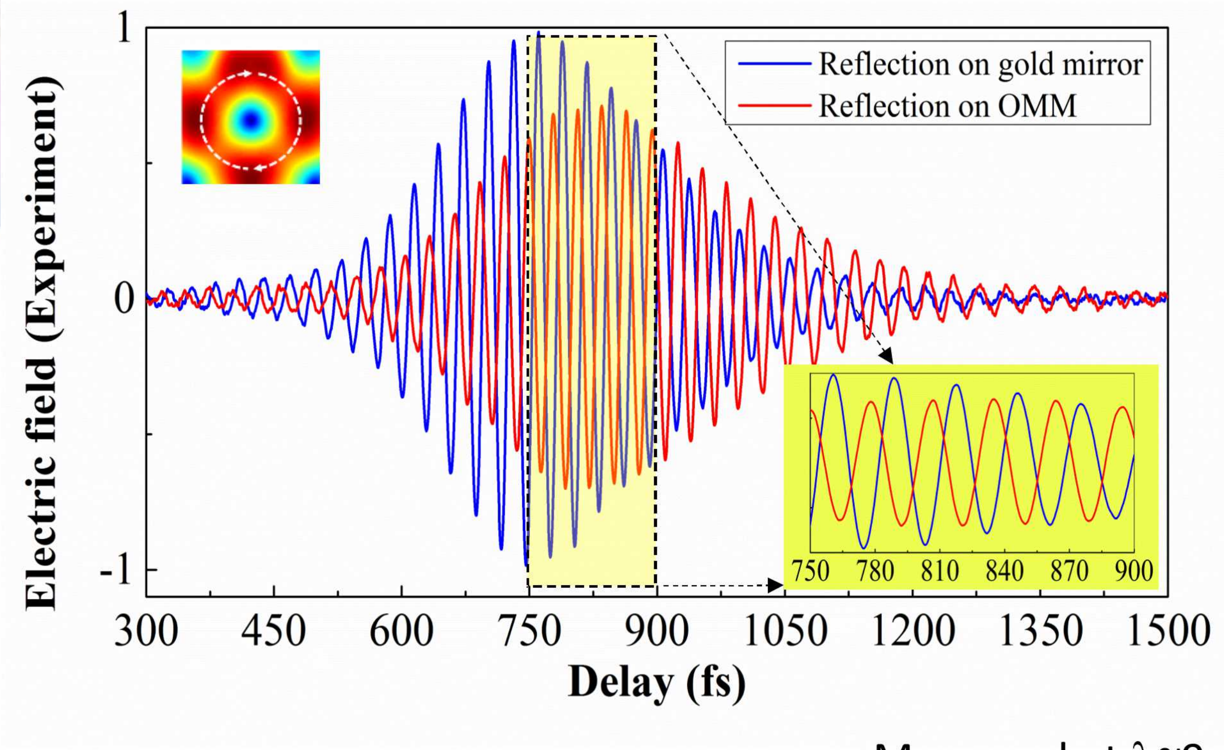


Phys. Rev. Lett. 108, 097402 (2012)

Optical Magnetic Mirror

Absolute Phase of Reflected Wave



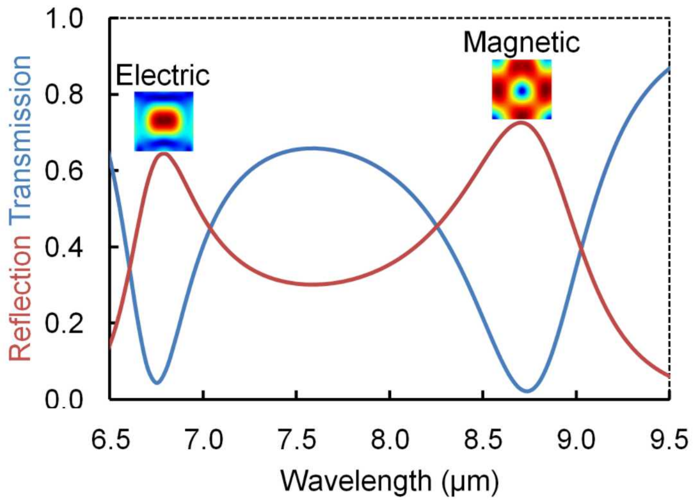


Optica 1, 250 (2014)

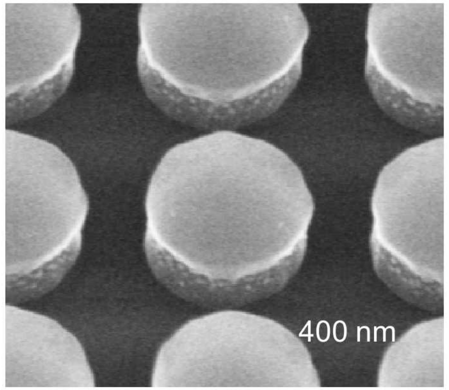
Measured at $\lambda \sim 9 \mu m$

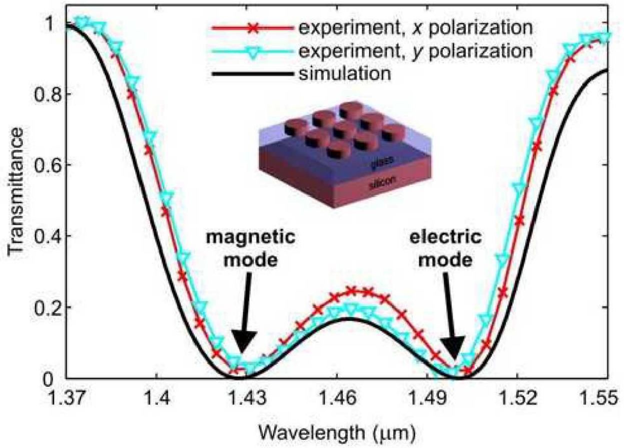
Controlling Spectral Location of Mie Modes

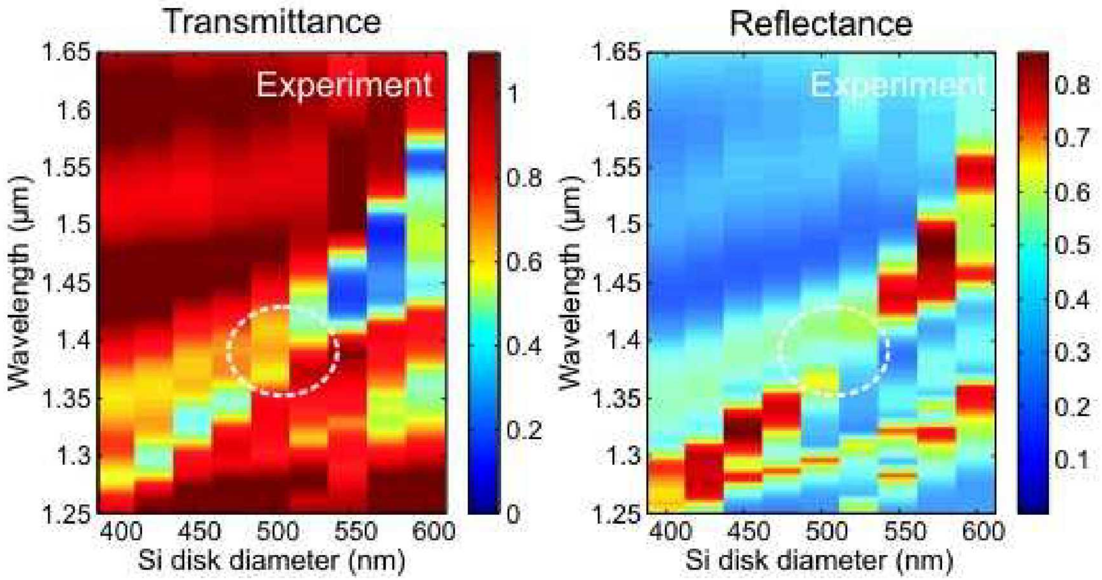
- Change the dielectric environment (liquid crystals: *ACS Nano* 9, 4308 (2015))
- Change aspect ratio of cubes or cylinders
- Introduce a "perturbation" (cut)



Controlling Spetral Location of Mie Modes:
Changing the Aspect Ratio

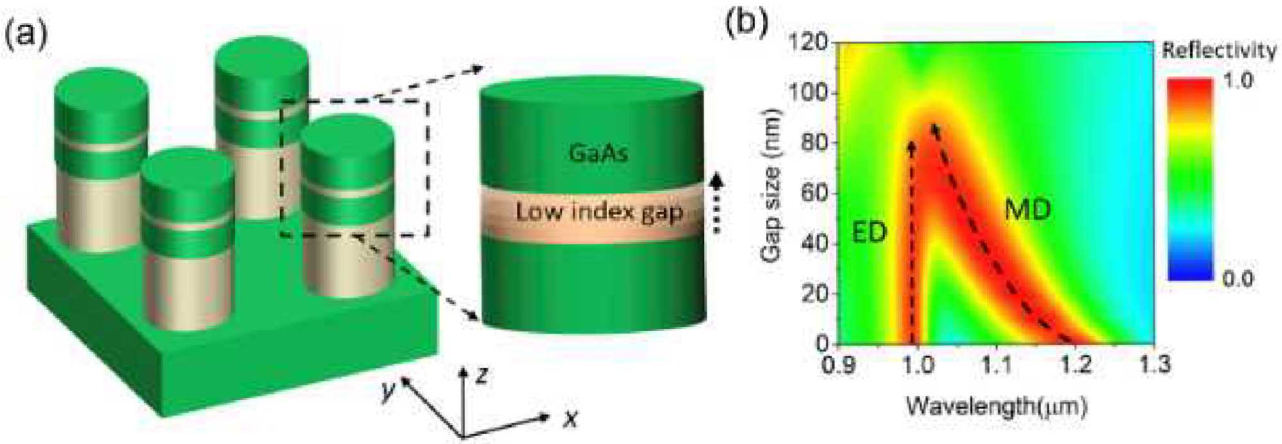


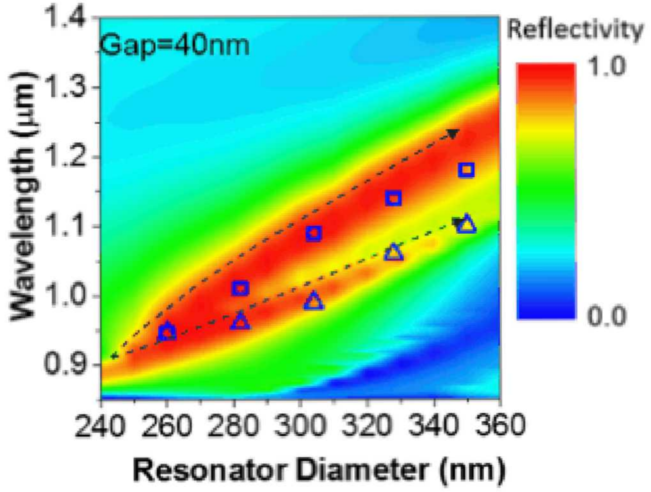


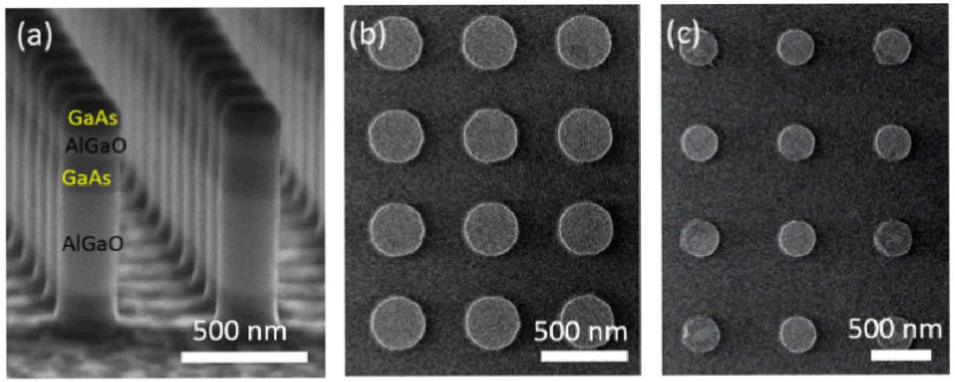


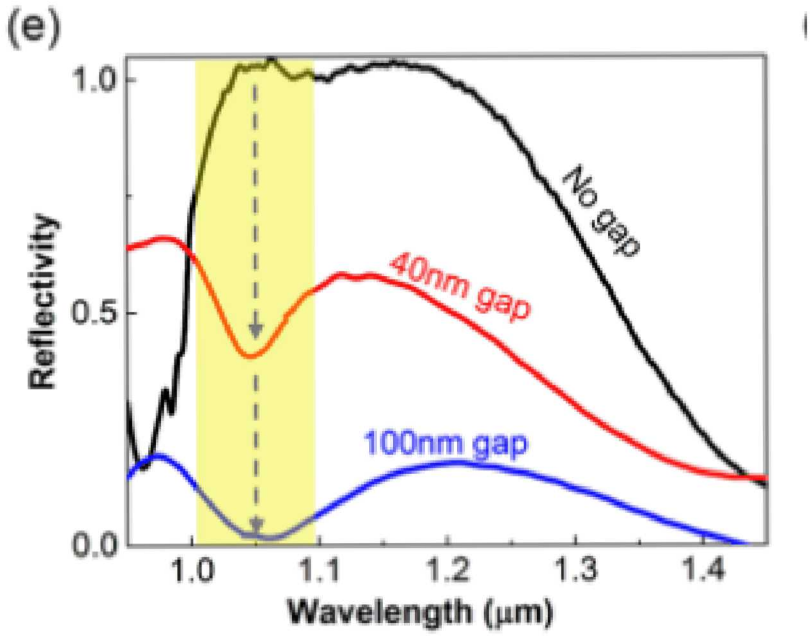
ACS Nano **7**, 7824 (2013).

Controlling Mie Modes: introducing a cut









Nanoletters 2017

Huygens Metasurfaces: Control of Scattering

- Huygens' Principle:
  - Every point on a wavefront is a secondary source of outgoing waves

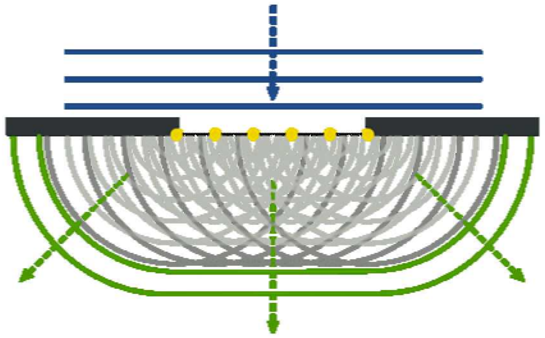
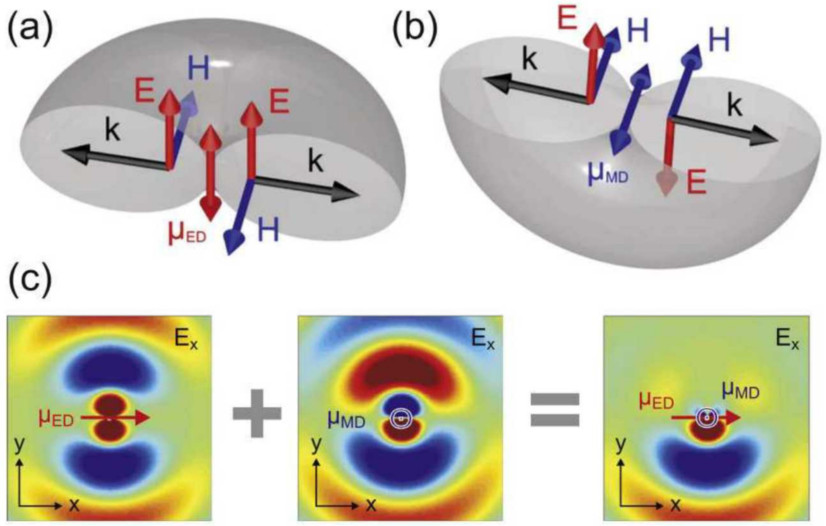


Image: Wikipedia
Huygens, *Traité de la Lumiére*, (1690)
Love, *Phil. Trans. R. Soc. Lond. A* **197**, 1 (1901)

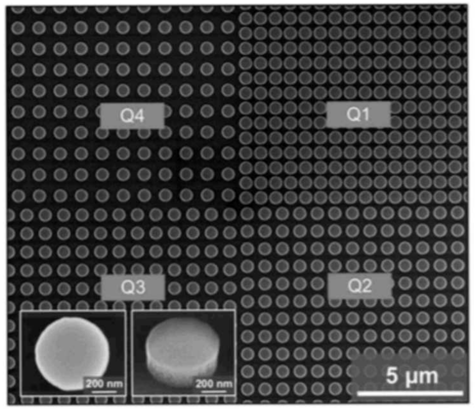
- Huygens' sources
  - **Crossed E & H dipoles (Love's formalism)**
  - Produce **forward-only** propagating elementary waves

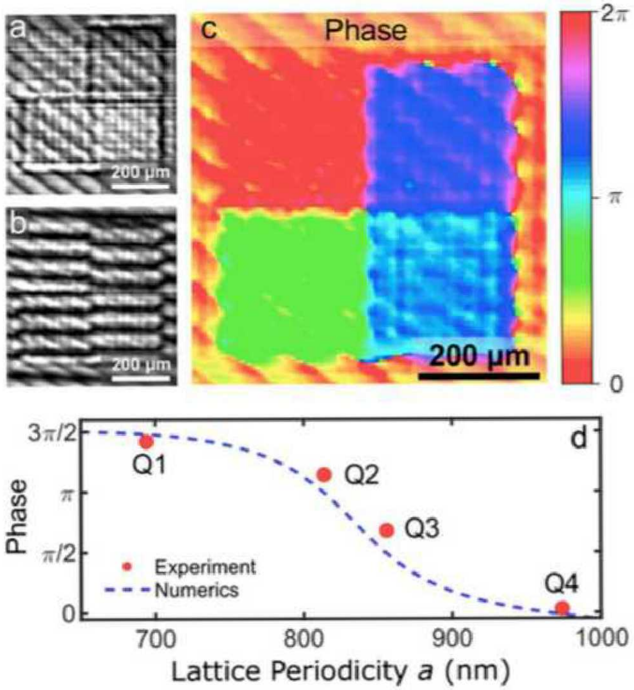


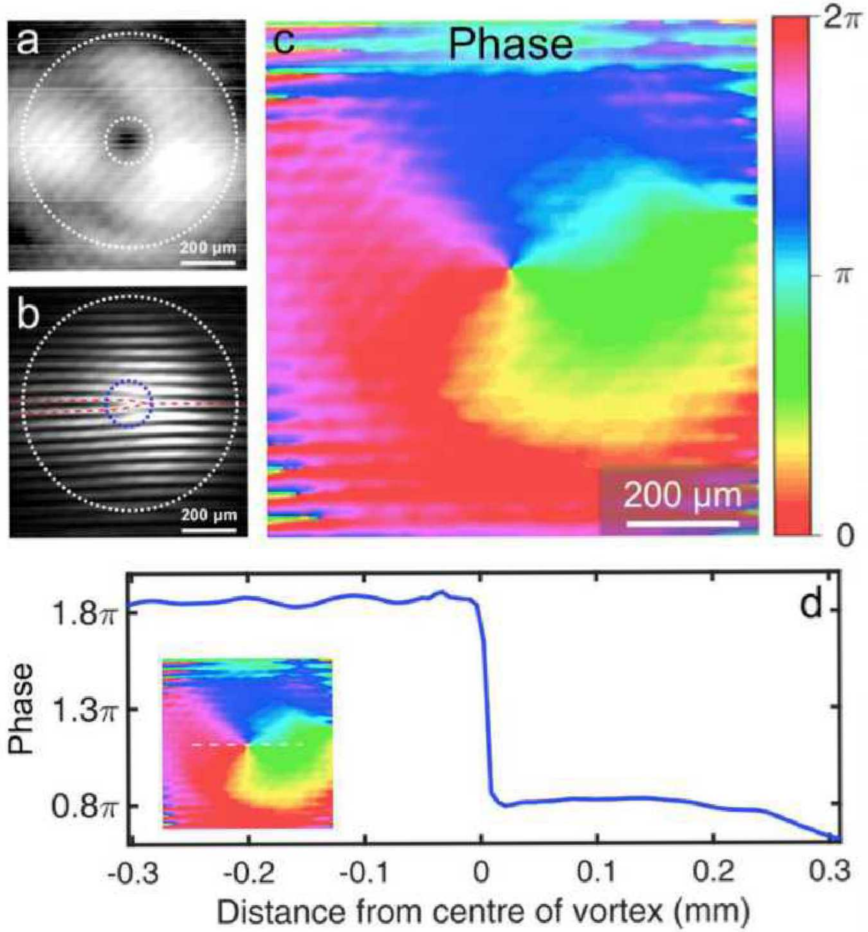
(R. Zia)

IB

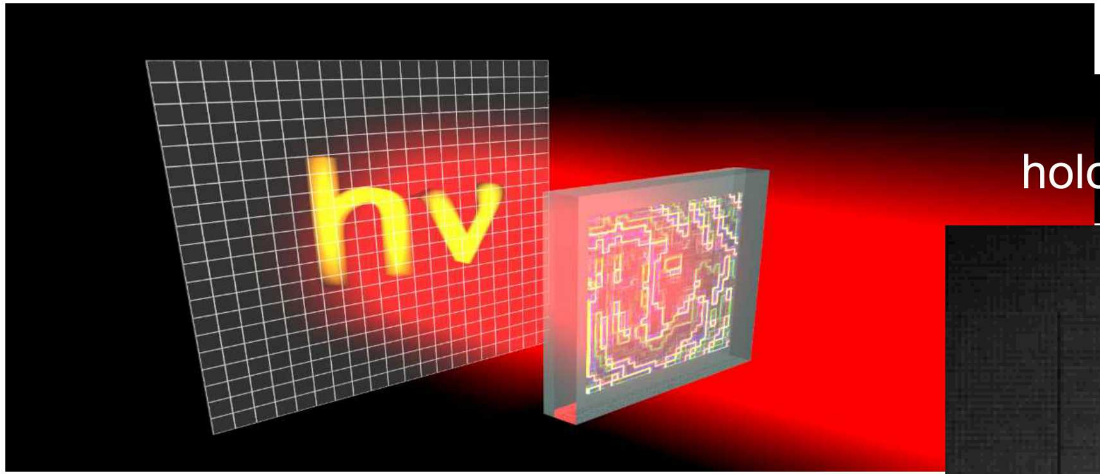
Huygens Metasurface Phase Plate: Vortex Beam

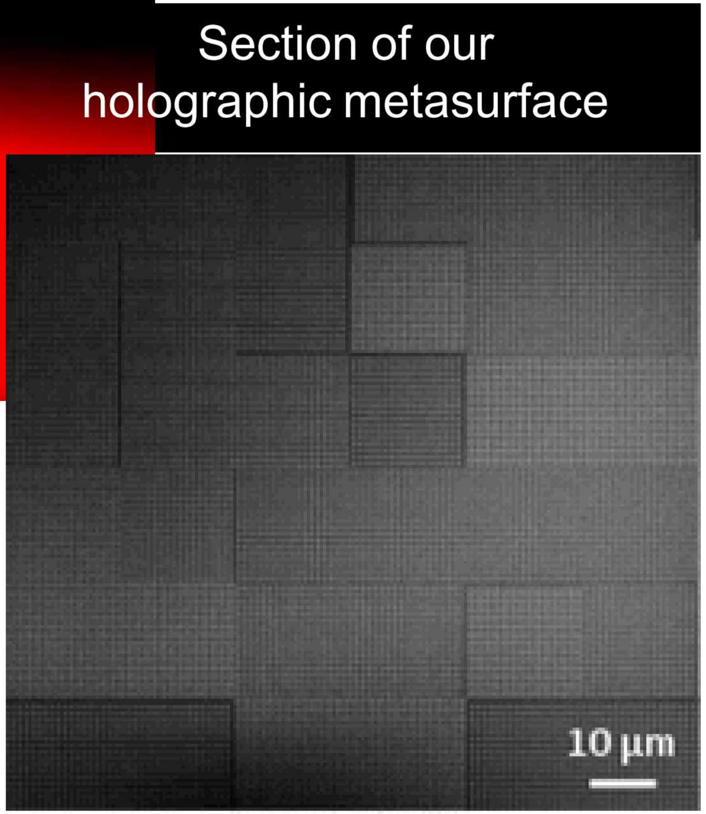


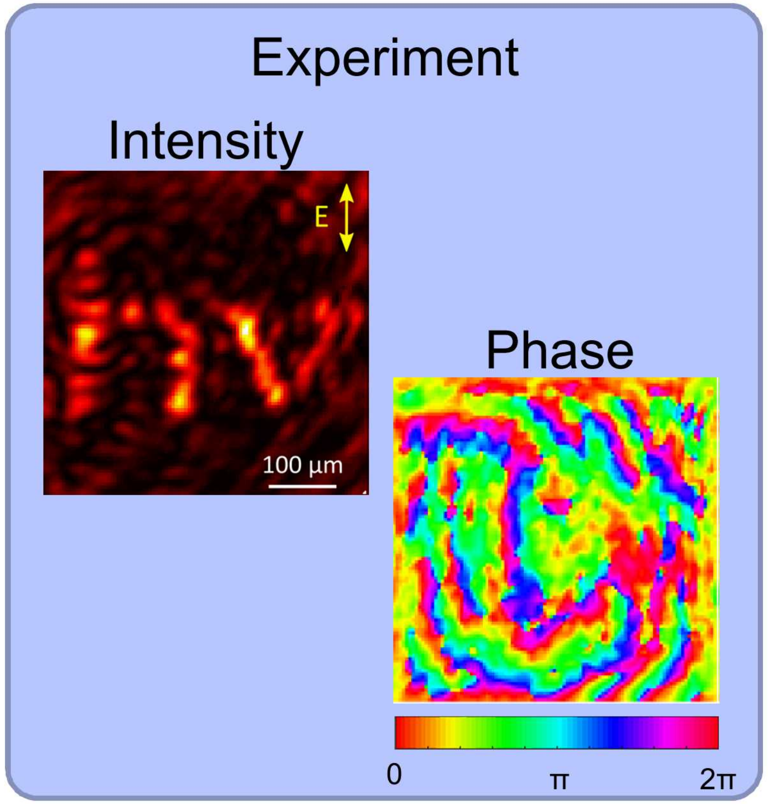




Huygens metasurface hologram demonstrates complex wavefront control







Normal incident 1477nm laser passes through the metasurface to create a 4-phase-level hologram 12 mm behind the sample.

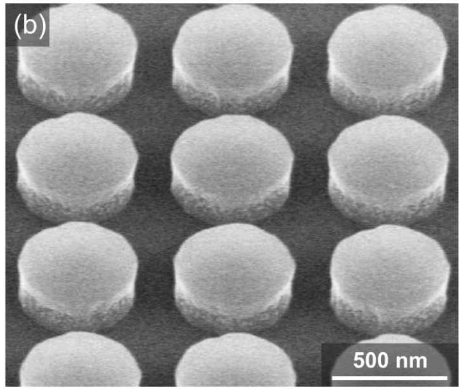
82% transmittance & 40% imaging efficiency

Chong *et al., ACS Photon. (2016)*

Metasurfaces for Flat Optics: Summary

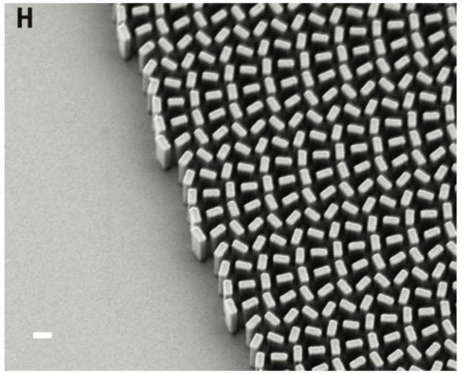
School #1: "Huygens" metasurfaces

(ANU, Sandia, Argonne, Jena,…)



School #2: High aspect ratio elements

(Harvard, Caltech, Technion,…)

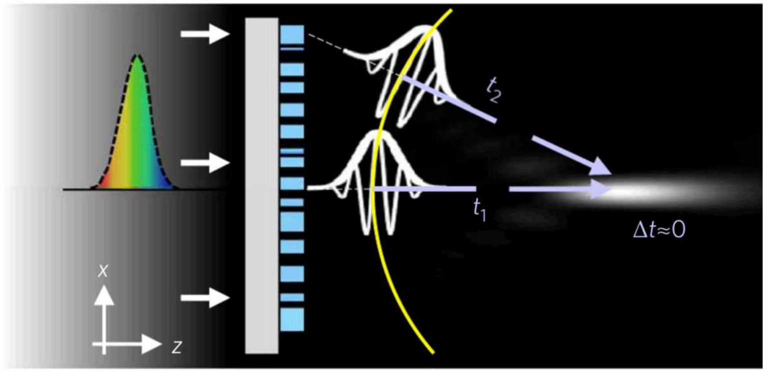


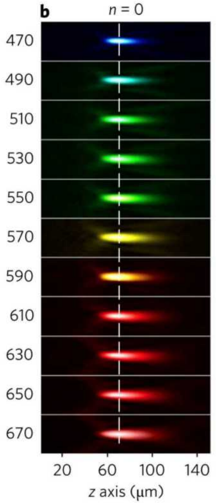
	School #1	School #2
Pros:	**Easy fabrication**	**Phase determined by single element**
Cons:	**Needs small array for a single phase "element"**	**Difficult fabrication**

IB

All-dielectric Metalenses:
Recent Literature

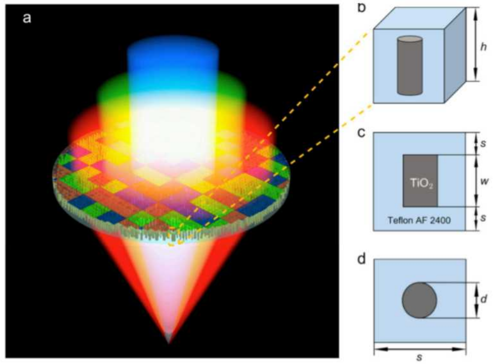
Broadband achromatic metalens



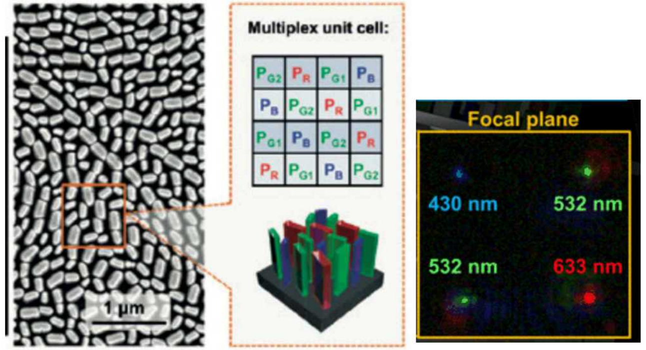


Chen, W. Ti., et al. *Nature nanotechnology* 13.3 (2018): 220.

Multiwavelenght metasurface lenses

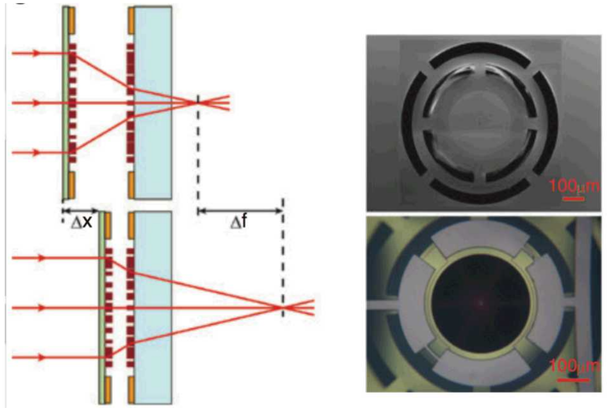


Yuan, J., et al. *Journal of Optics* 19.10 (2017): 105002.



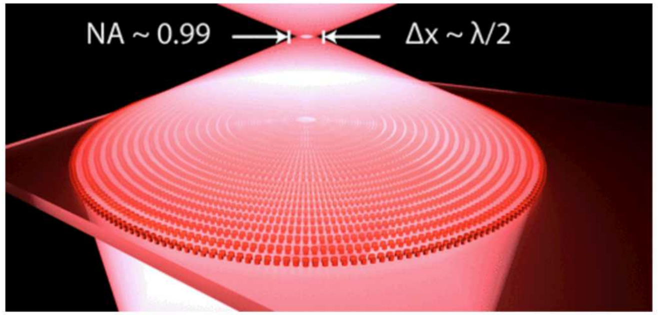
Chen, B. H., et al. *Nano letters* 17.10 (2017): 6345-6352.

Tunable Metalenses



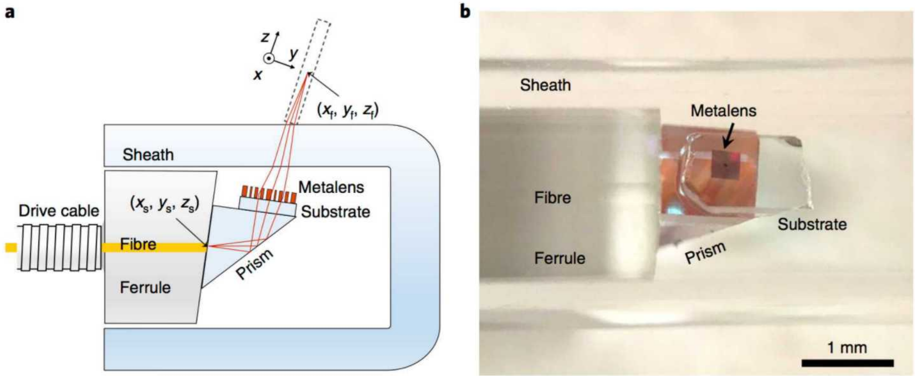
Arbabi, E., et al.
Nature communications 9.1 (2018): 812.

A Metalens with a Near-Unity Numerical Aperture



Paniagua-Dominguez, R., et al.
Nano letters 18.3 (2018): 2124-2132.

Nano-optic endoscope



Pahlevaninezhad, H., et al.
Nature Photonics (2018): 1.

Outline

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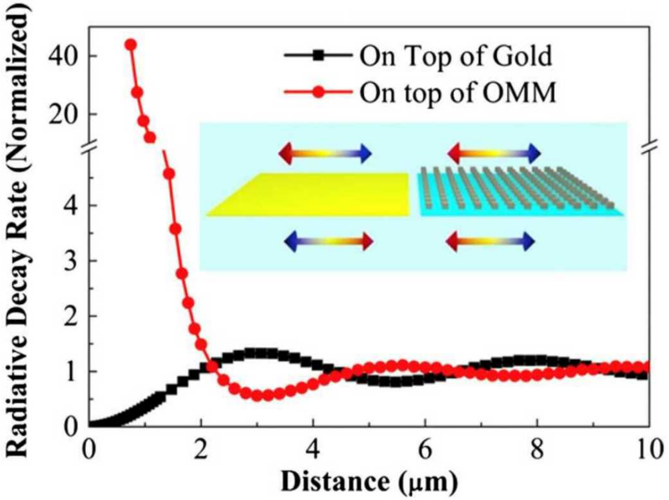
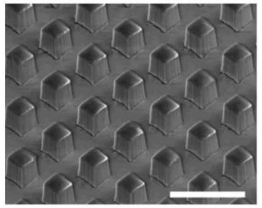
  - Optical magnetic mirror
  - Huygens meta-optics
- **Emitters + Metasurfaces**
- Nonlinear optics with all-dielectric metasurfaces:
- Outlook on future 3D fabrication

Emitters Coupled to Metasurfaces

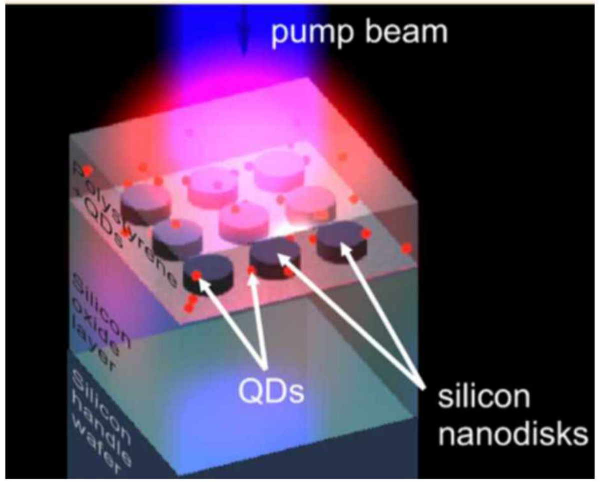
Simulation of emitter very close (~λ) close to dielectric optical mirror showed large radiative enhancement.





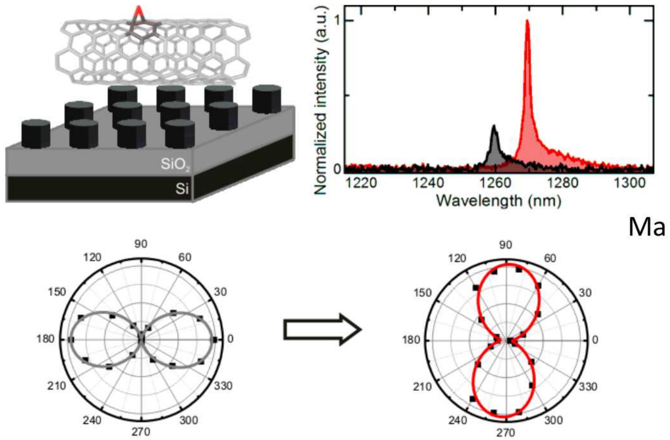
Liu *et al,* Optica 2014

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

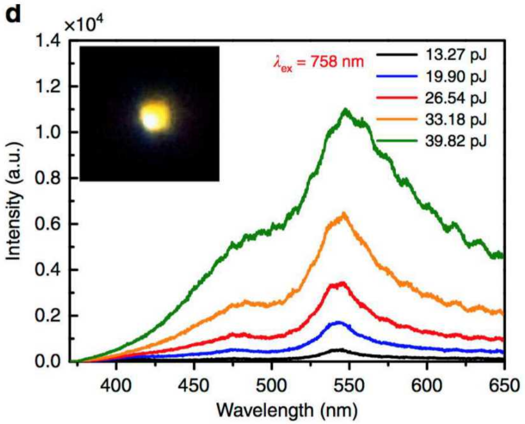


Ma et al, ACS Nano 2017

See also work by Hong, Maier, Bonod, Belov, Krasnok, etc.

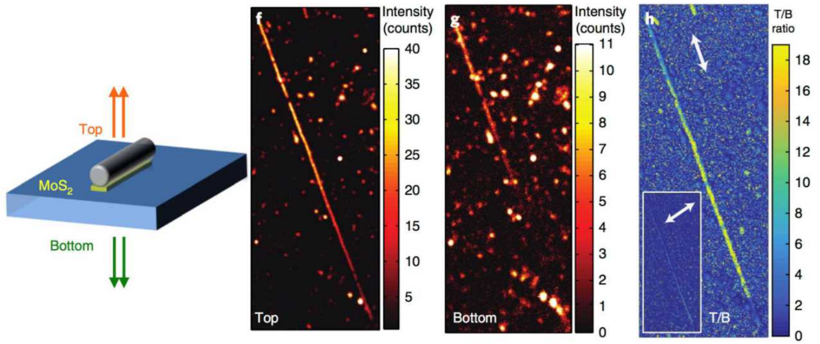
Emission + All-dielectric Metasurfaces: Recent work

White-light emission from silicon nanospheres



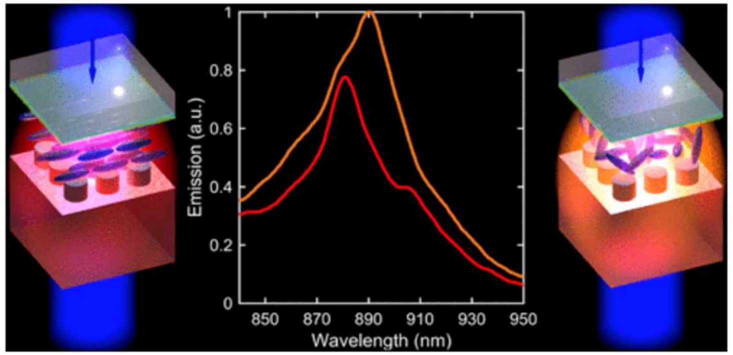
Zhang, C., et al.
Nature communications 9 (2018).

Directional light emission from monolayer MoS2



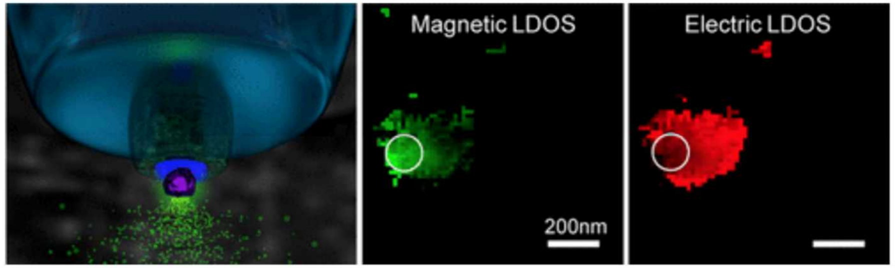
Cihan, A. F., et al.
Nature Photonics 12.5 (2018): 284.

Active Tuning of Spontaneous Emission by Mie-Resonant Dielectric Metasurfaces



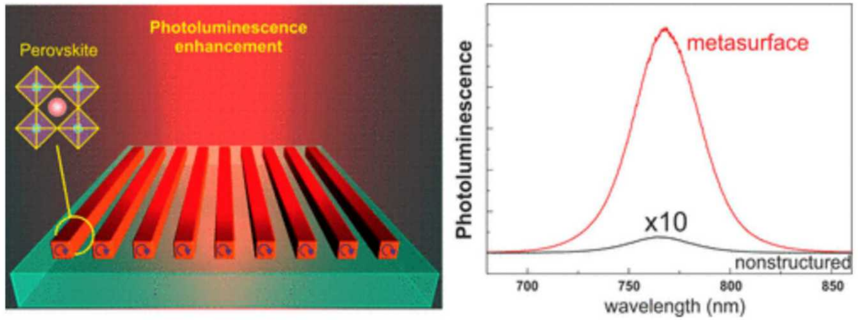
Bohn, J., et al. *Nano letters* 18.6 (2018): 3461-3465.

Enhanced emission of luminescent nanocrystals



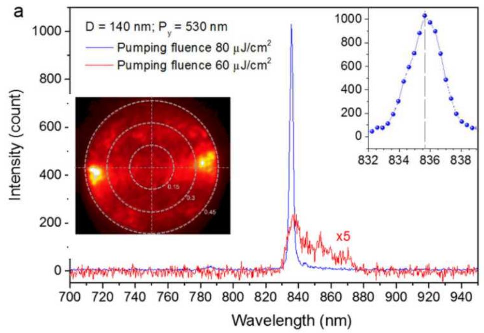
Sanz-Paz, M., et al.
Nano Letters 18.6 (2018): 3481-3487.

Emission enhancement in hybrid perovskite metasurfaces



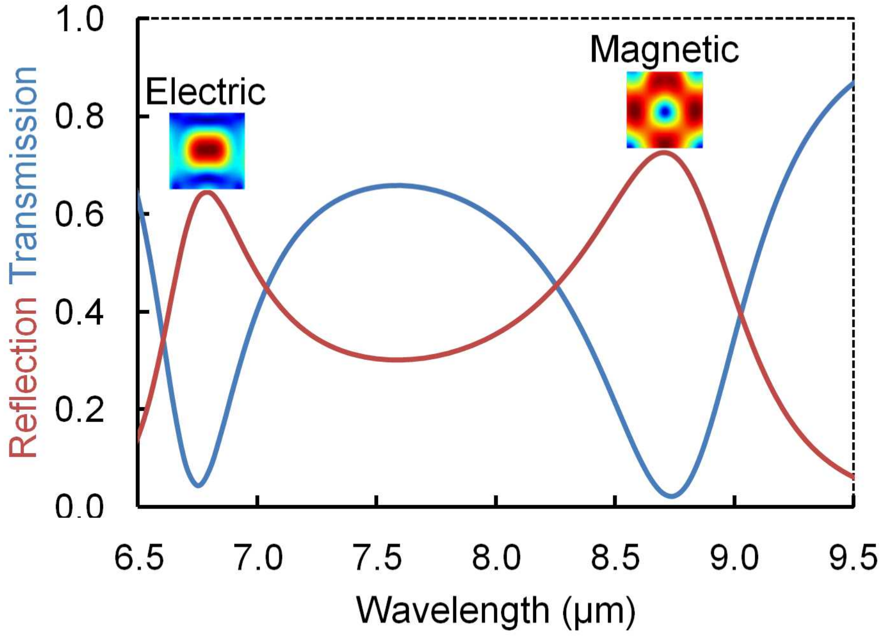
Makarov, S. V., et al. *ACS Photonics* 4.4 (2017): 728-735.

Lasing action in active dielectric nanoantenna arrays



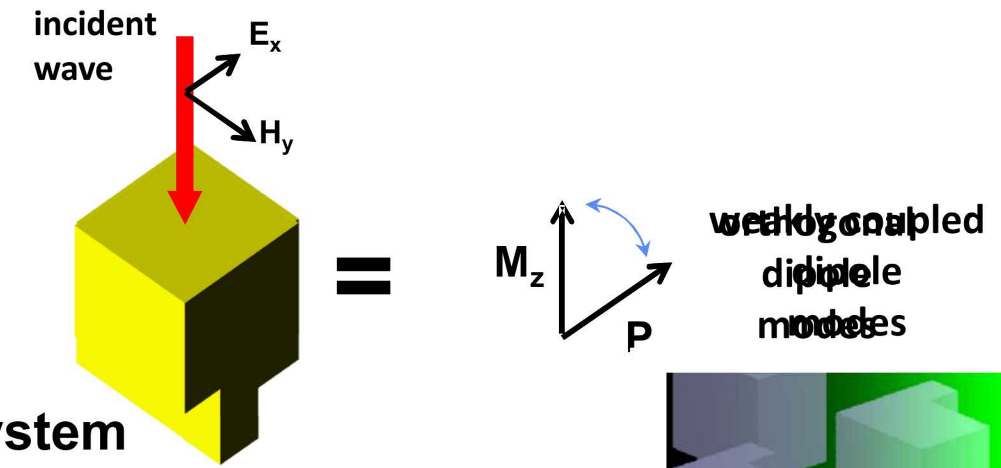
Ha, S. T., et al. *arXiv preprint arXiv:1803.09993* (2018).

Towards High Q: Broken Symmetry Resonators



low Q because these modes couple to free space

High Q modes Using "Broken Symmetry" Resonators



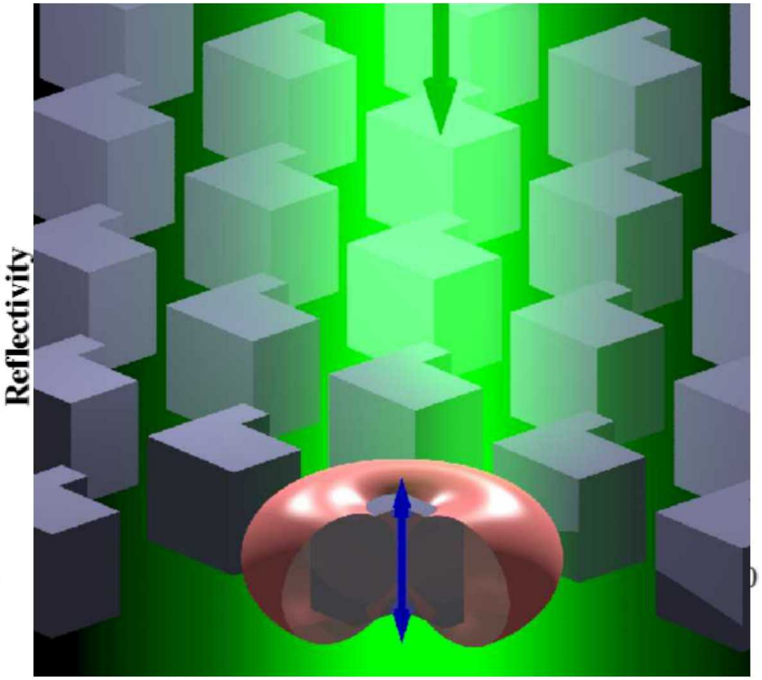
Broken symmetry system

External Wave ⟷ **P_x (low Q)**

Cavity perturbation

M_z (high Q)

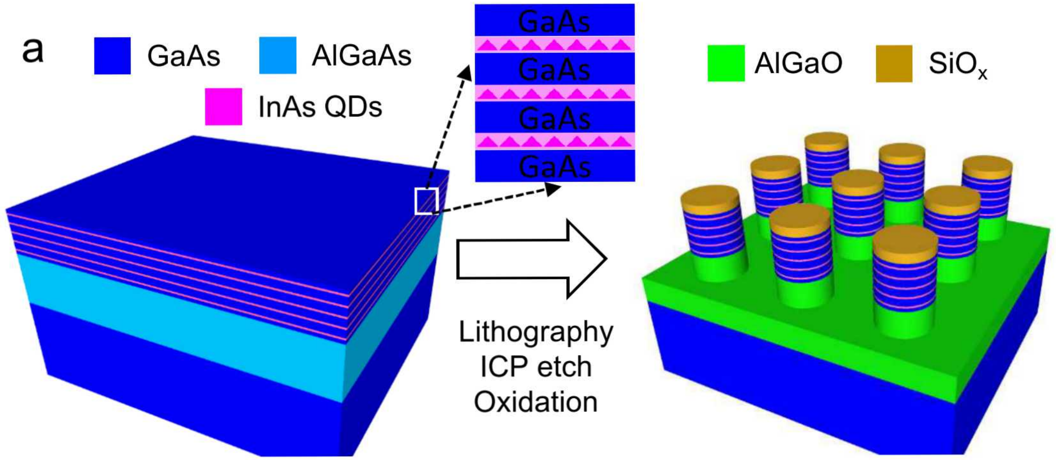
can't radiate in-plane
due to local field interactions



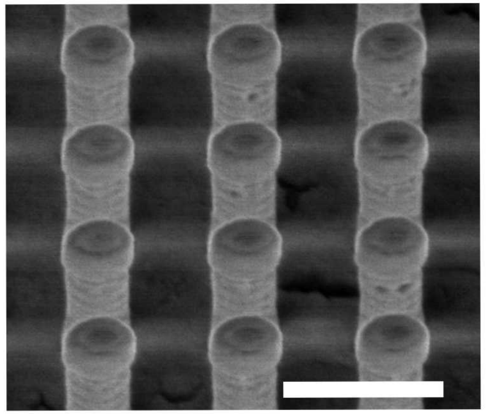
ACS Photonics 2016

Embedding Emitters in Metasurfaces

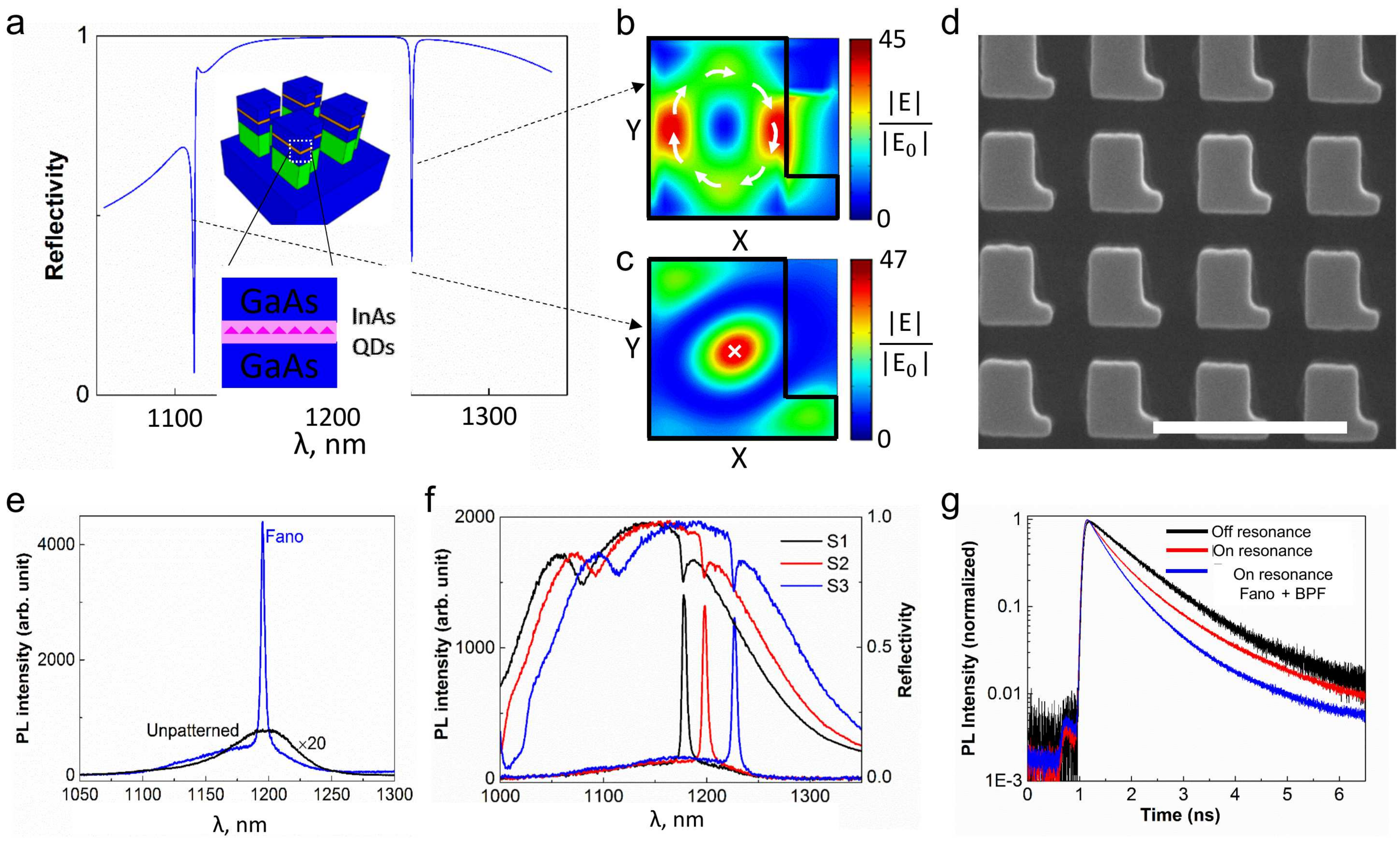
a



b

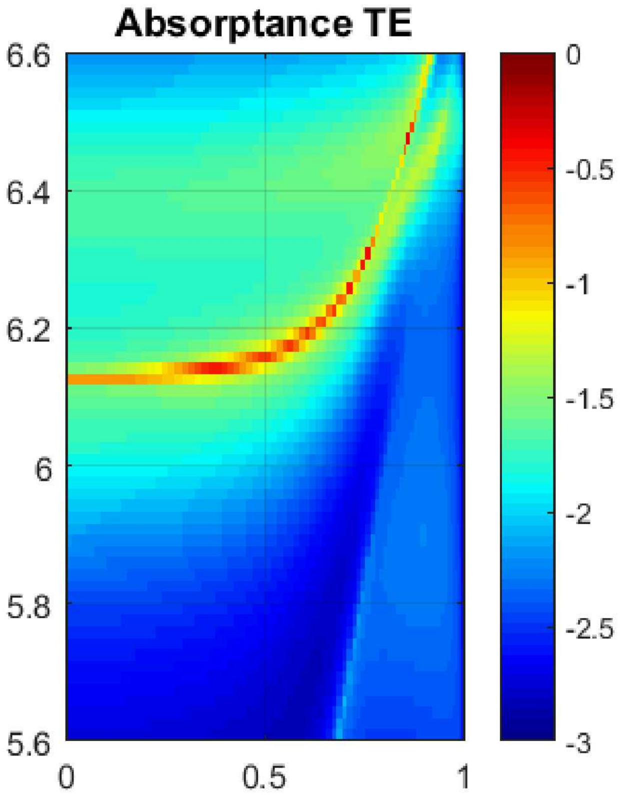


PL: Broken-symmetry Resonators



Back-Focal Plane Emission

(Broken Symmetry Resonators)



Outline

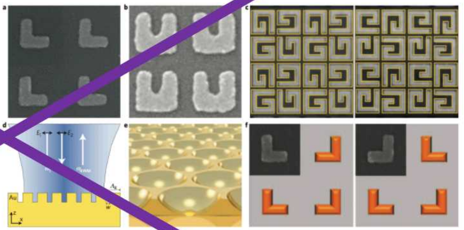
- Metamaterials & Metasurfaces: refresher, definitions, etc.
- Linear Metasurfaces:
  - Optical magnetic mirror
  - Huygens meta-optics
- Emitters + Metasurfaces
- **Nonlinear optics with all-dielectric metasurfaces**
- Outlook on future 3D fabrication

Paths to Nonlinear Metasurfaces

Metallic/Plasmonic

Using metal nonlinearity:

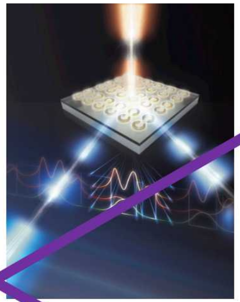
Nature Photonics, 6(11), 737

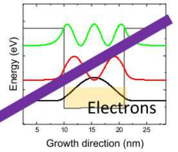


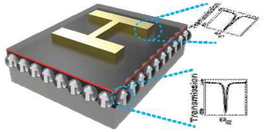
+: Small mode volume
-: Low efficiency

Combined with an "engineered" nonlinearity:

Metallic metasurfaces on III-V heterostructures





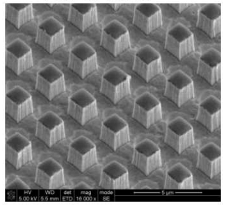


Nat. Comm. 2013, 2015

+: Record high SHG
-: Saturation

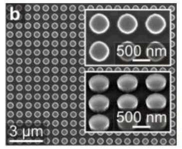
Dielectric

Tellurium



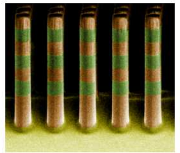
PRL 2012

Silicon



Adv. Opt. Mat. 2015, NL 2015, ACS Phot. 2016

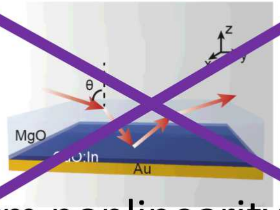
GaAs



Adv. Opt. Mat. 2016, NL 2016

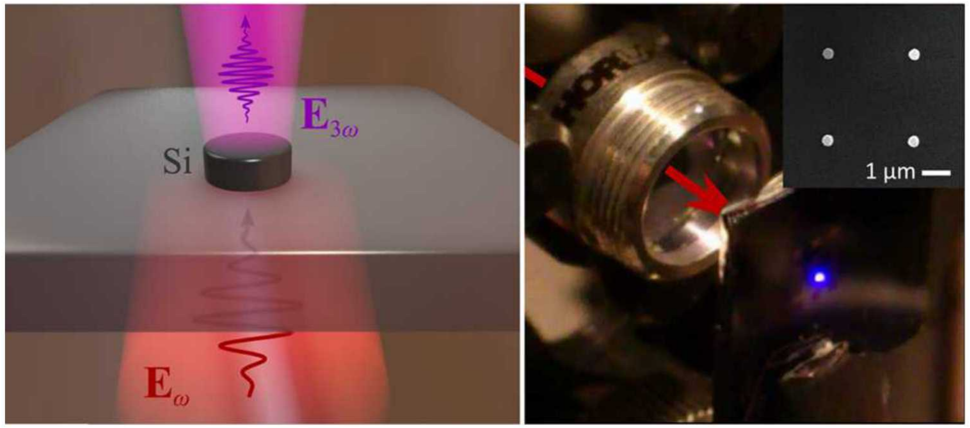
+: High nonlinear coefficient materials (GaAs: ~200pm/V)
+: large mode volume
-: medium to low efficiency

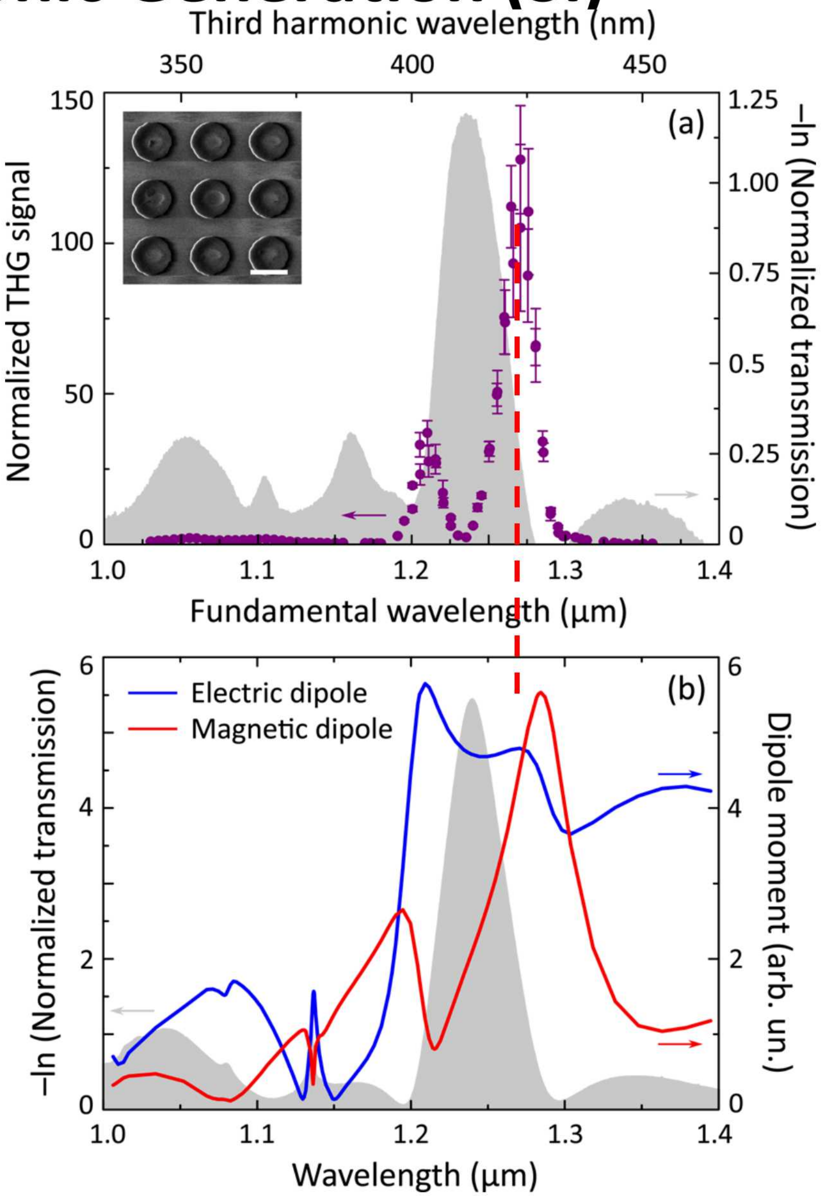
Epsilon Near Zero



+: uniform nonlinearity, high field
-: ??

Optical Nonlinearities from Dielectric Metasurfaces: Third Harmonic Generation (Si)





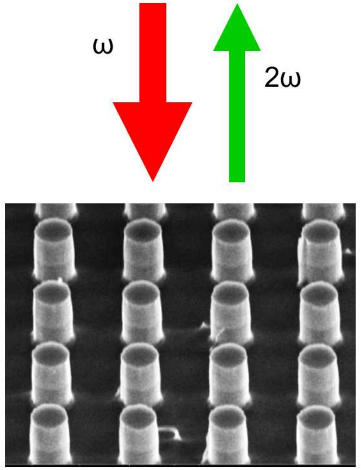
Strong enhancement near magnetic dipole resonance

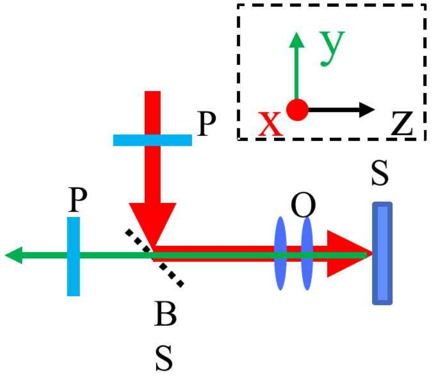
Silicon is passive & has no $\chi^{(2)}$

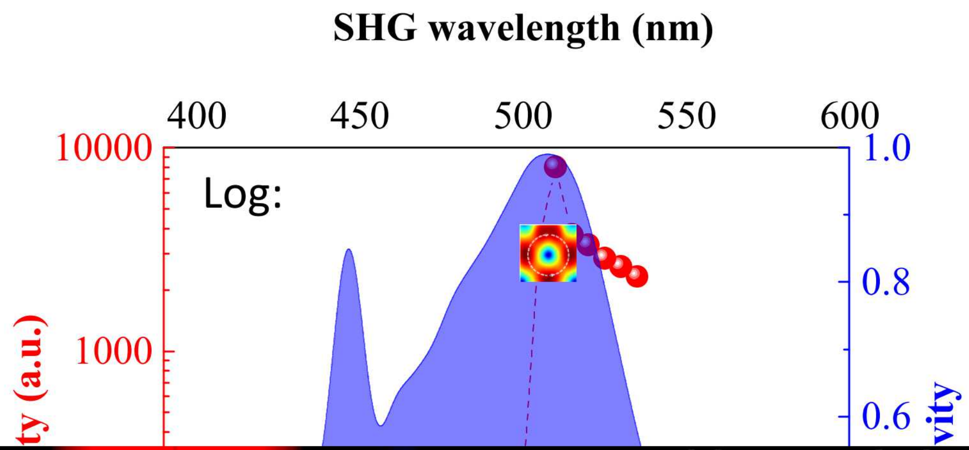
Nano Letters (2015)

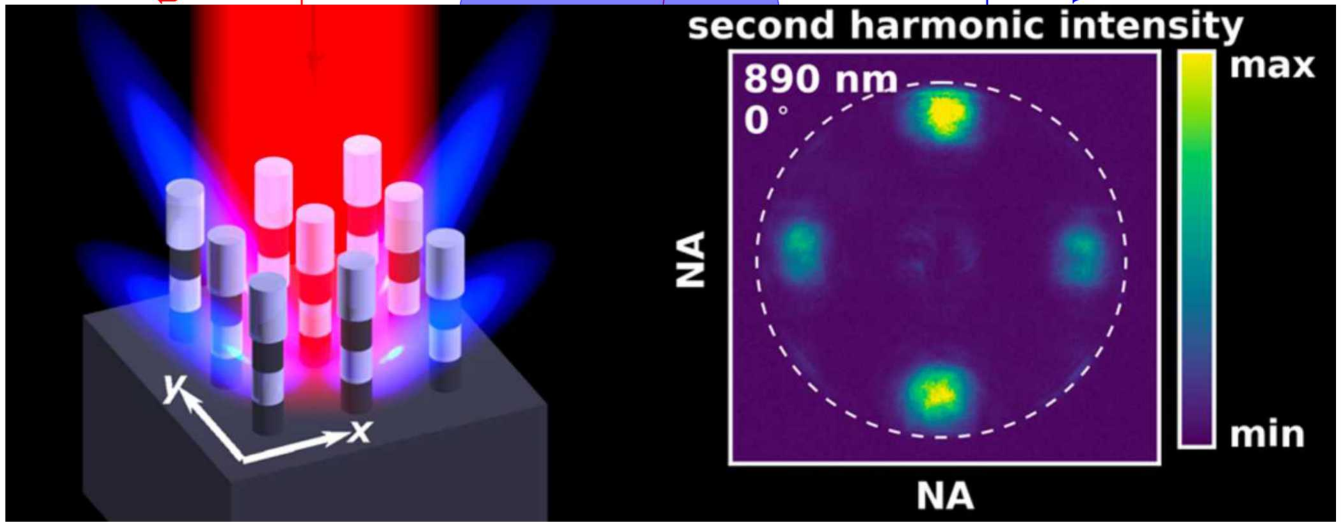
(With ANU & Moscow State

Second Harmonic Generation from GaAs Metasurfaces





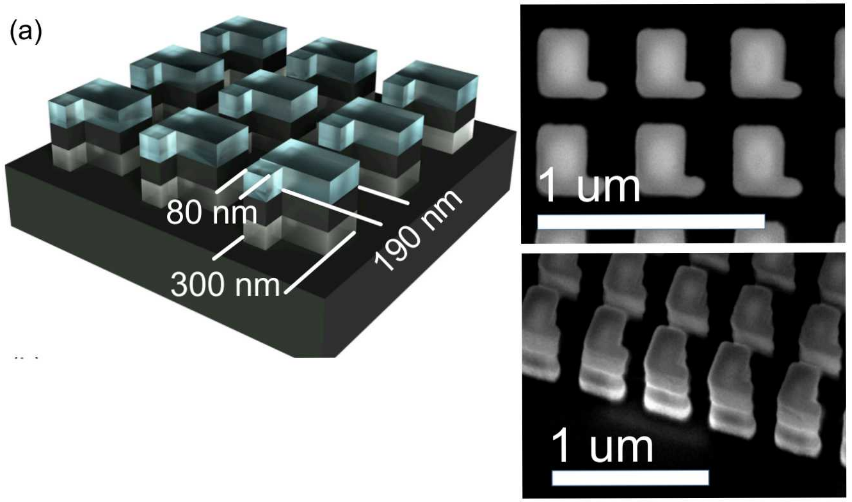


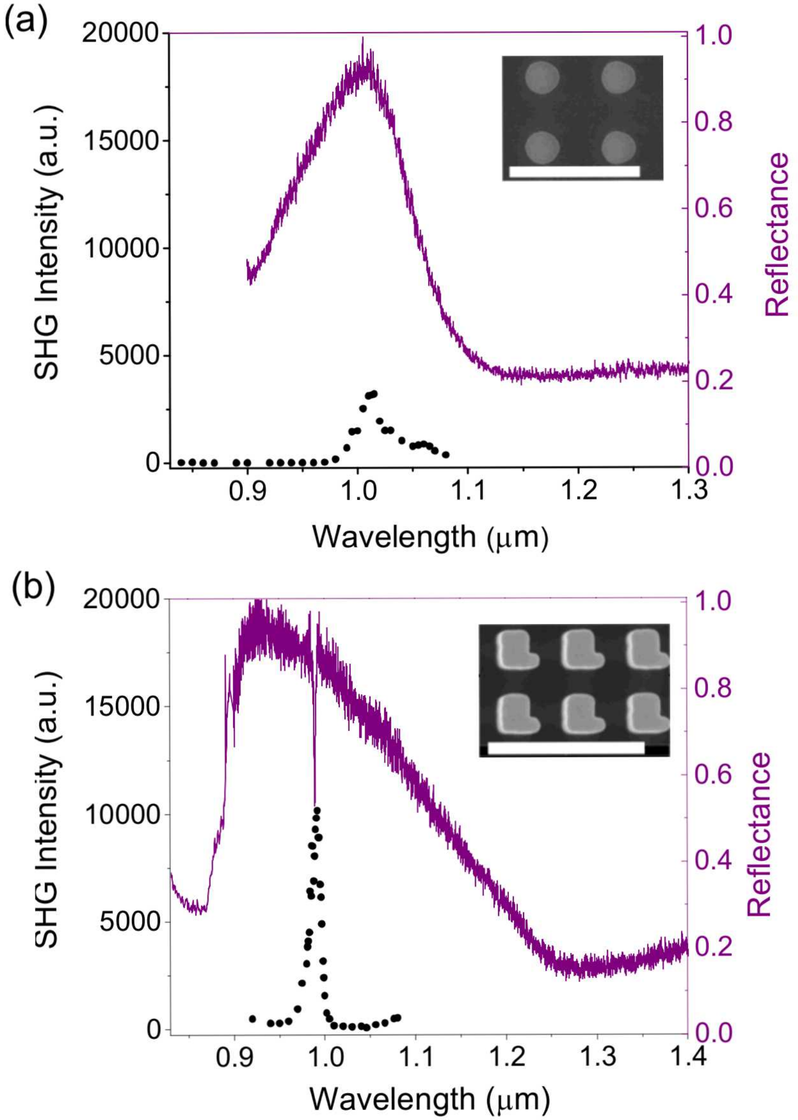


ACS Photonics 2018, 5, 1786−1793

Nano Letters 2016
Also ANU, Costa (Italy)

Higher Q: SHG from Broken Symmetry Metasurfaces

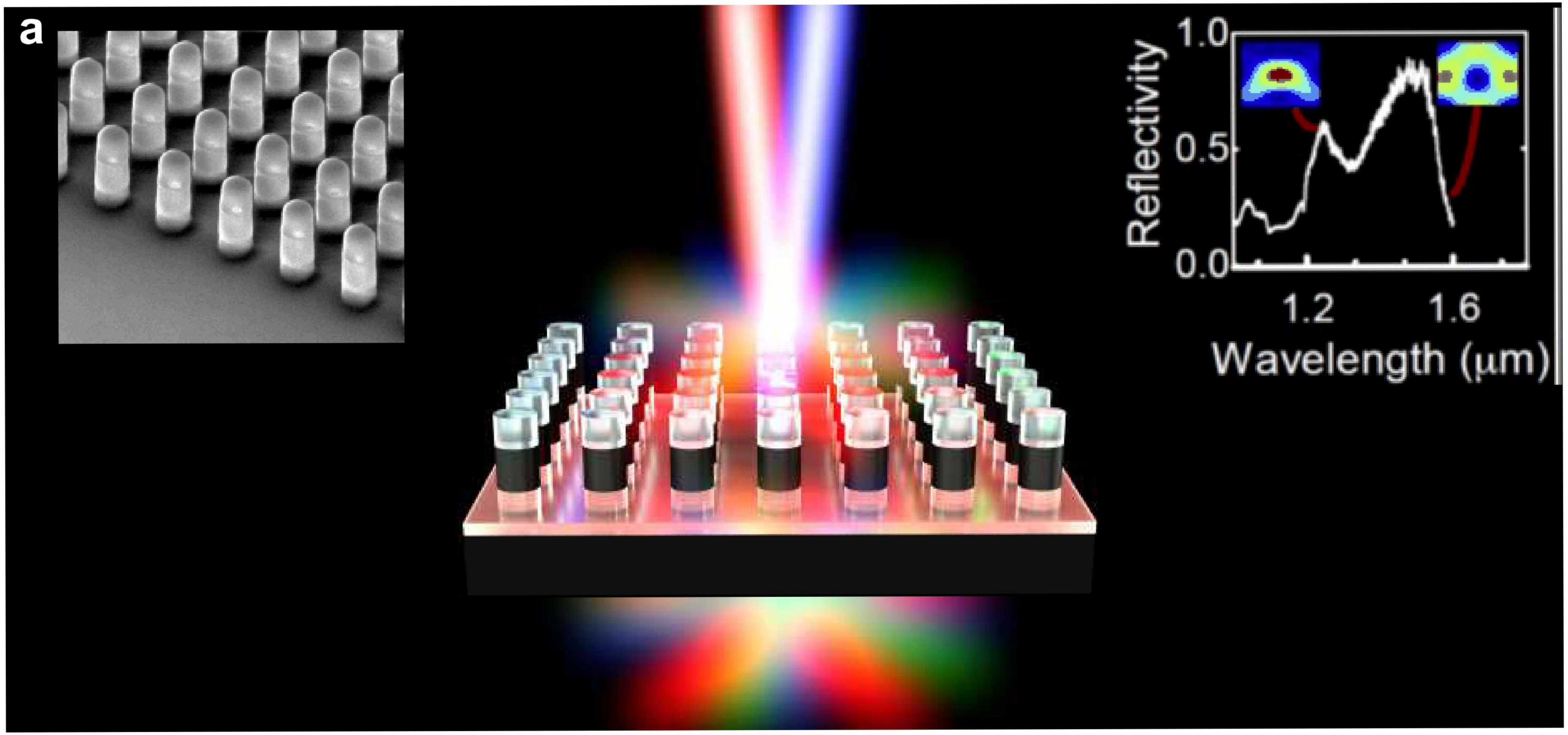




13-fold enhancement of SHG in Fano metasurface compared with the nanodisk metasurface

ACS Photonics 2018

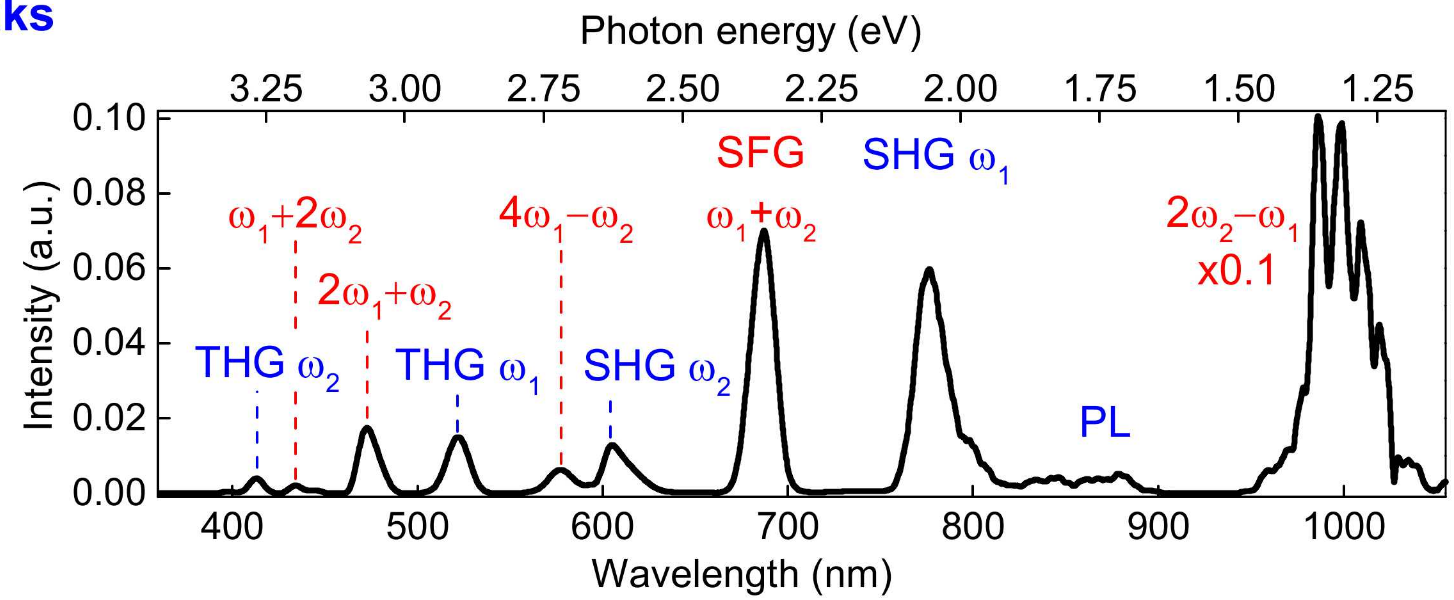
Higher Harmonics:
The "Optical Metamixer"

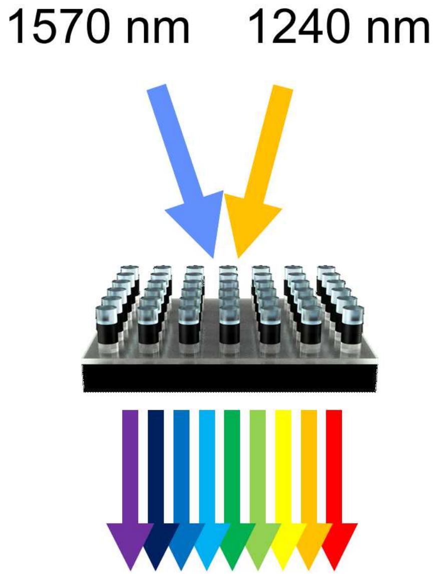


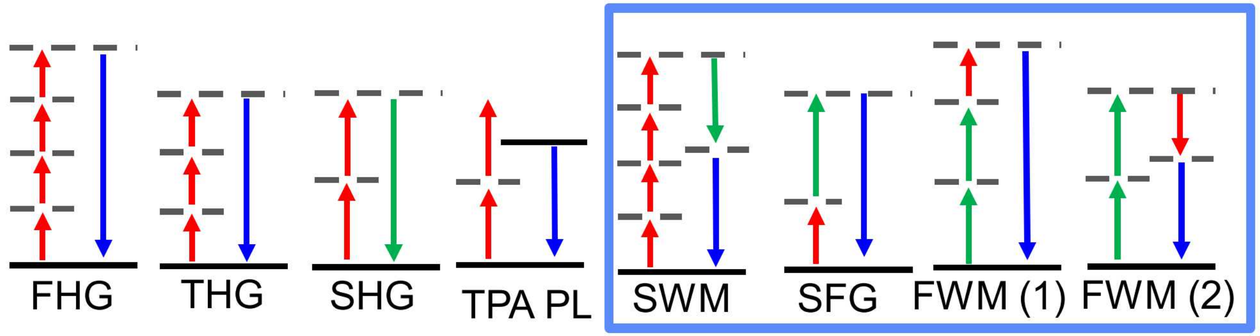
Nature Comm. 2018

Frequency mixing spectra

11 peaks





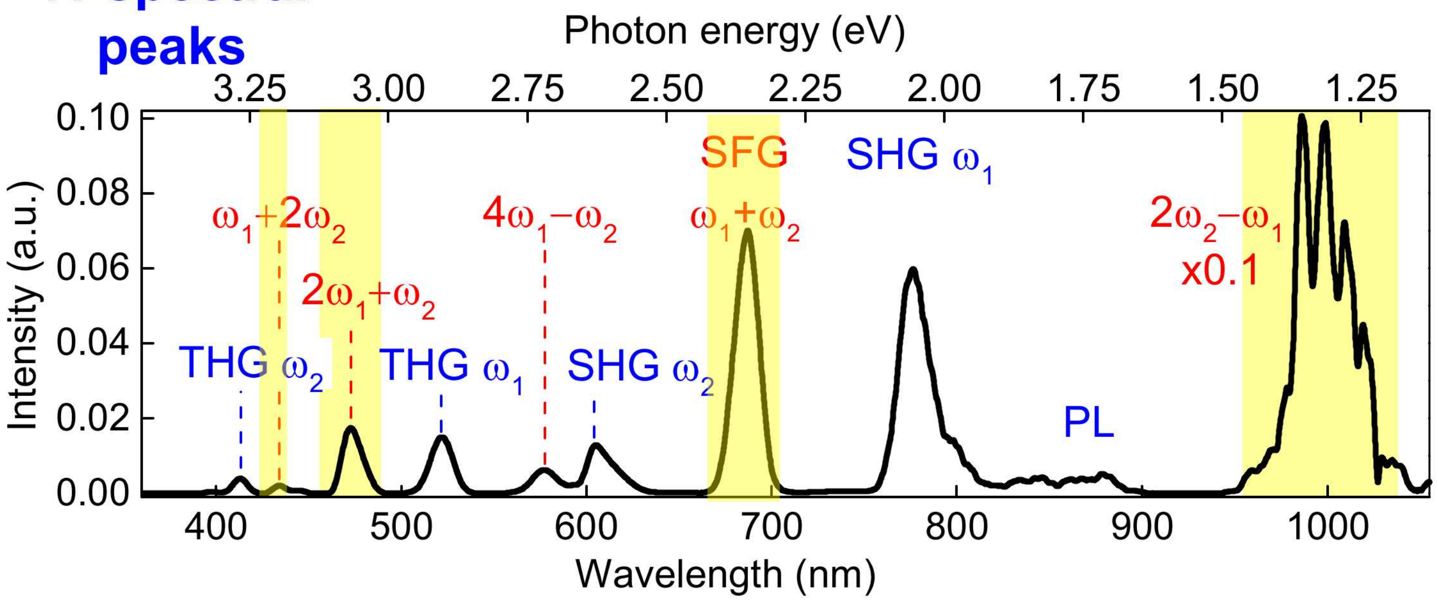


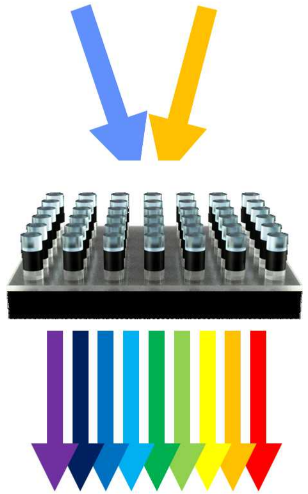
7 different nonlinear processes: 2nd, 3rd, 4th harmonics, sum frequency generation, 4 wave-mixing, six-wave mixing….

Nature Comm. 2018

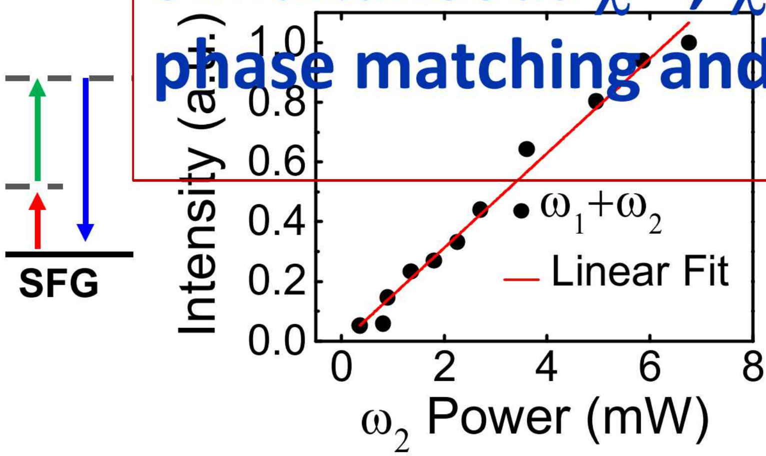
Frequency mixing spectra

11 spectral peaks

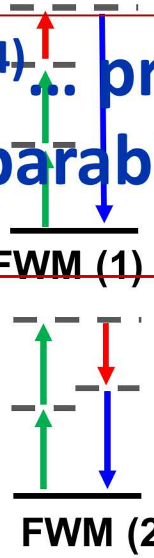




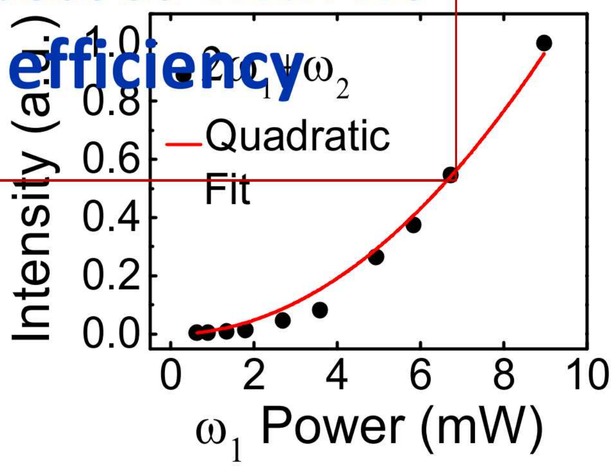
SFG power dependence



Simultaneous $\chi^{(2)}$, $\chi^{(3)}$, $\chi^{(4)}$ … processes with no phase matching and comparable efficiency



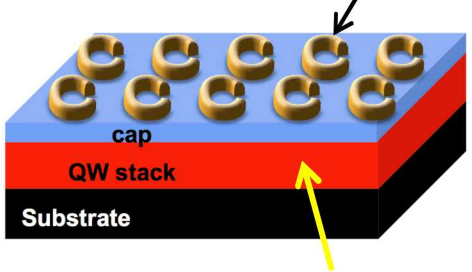
FWM power dependence

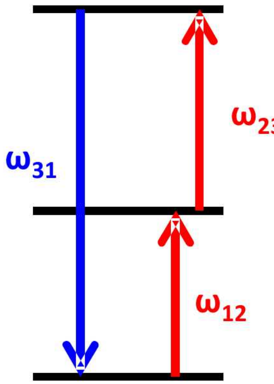


Nature Comm. 2018

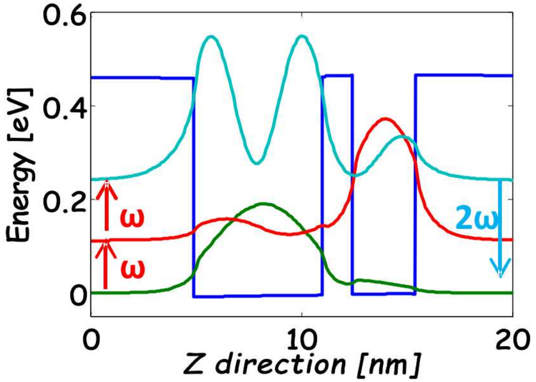
Interlude: The Highest Nonlinearity from Metasurfaces (SHG)

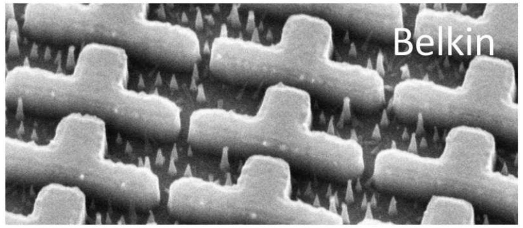
“Nanoantennas”/metasurface





Resonant $\chi^{(2)}$ media
Quantum wells





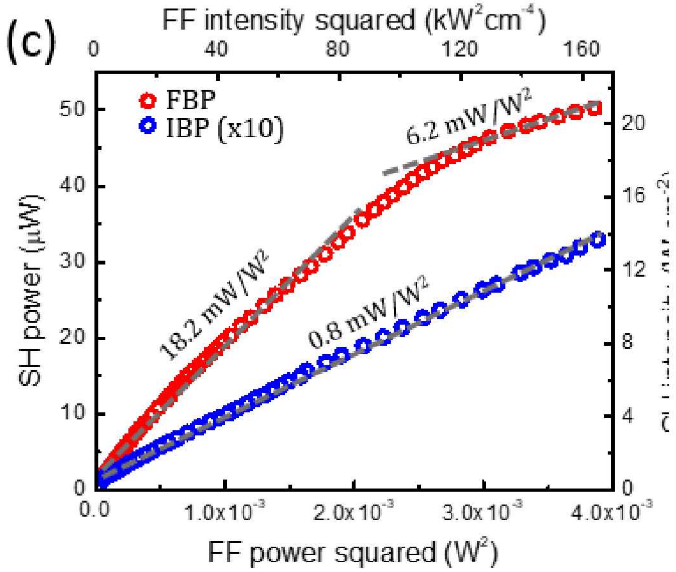
<u>Max efficiency:</u>

Brener (transmission): 2.3 mW/W^2

Belkin (reflection, etched resonators): 17 mW/W^2

Belkin & Brener 2018, 18.2 mW/W^2

$\chi^{(2)}_{eff\sim}$ $1.31\times10^{6}\,pmV^{-1}$



Brener: Nature Communications 6, 7667 (2015)
Belkin & Alu, Nature 511, 65-69 (2014).

Nonlinear Metasurfaces: Comparison

	Metallic MS + Quantum Wells	Mie Resonator MS
Reported nonlinearity	~10^{-2} W/W^2	~10^{-8} W/W^2
"Material" chi(2)	~200 **nm**/V	~200 pm/V
Mode Depth	~λ/20	~λ/n
Mode overlap and chi(2) utilization	**	* **(**)**
Q	~10	~10 **(1000)**
Saturation and damage threshold	Low	High
Wavelength scaling	>3-5 um	visible to far IR
>3rd order	No (in mid IR)	Yes

(PPLN ~ 10^{-1})

$I_{SHG} \sim (\chi^{(2)})^2$

$I_{SHG} \sim Q^2$ or Q^4

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- Metamaterials & Metasurfaces: refresher, definitions, etc.
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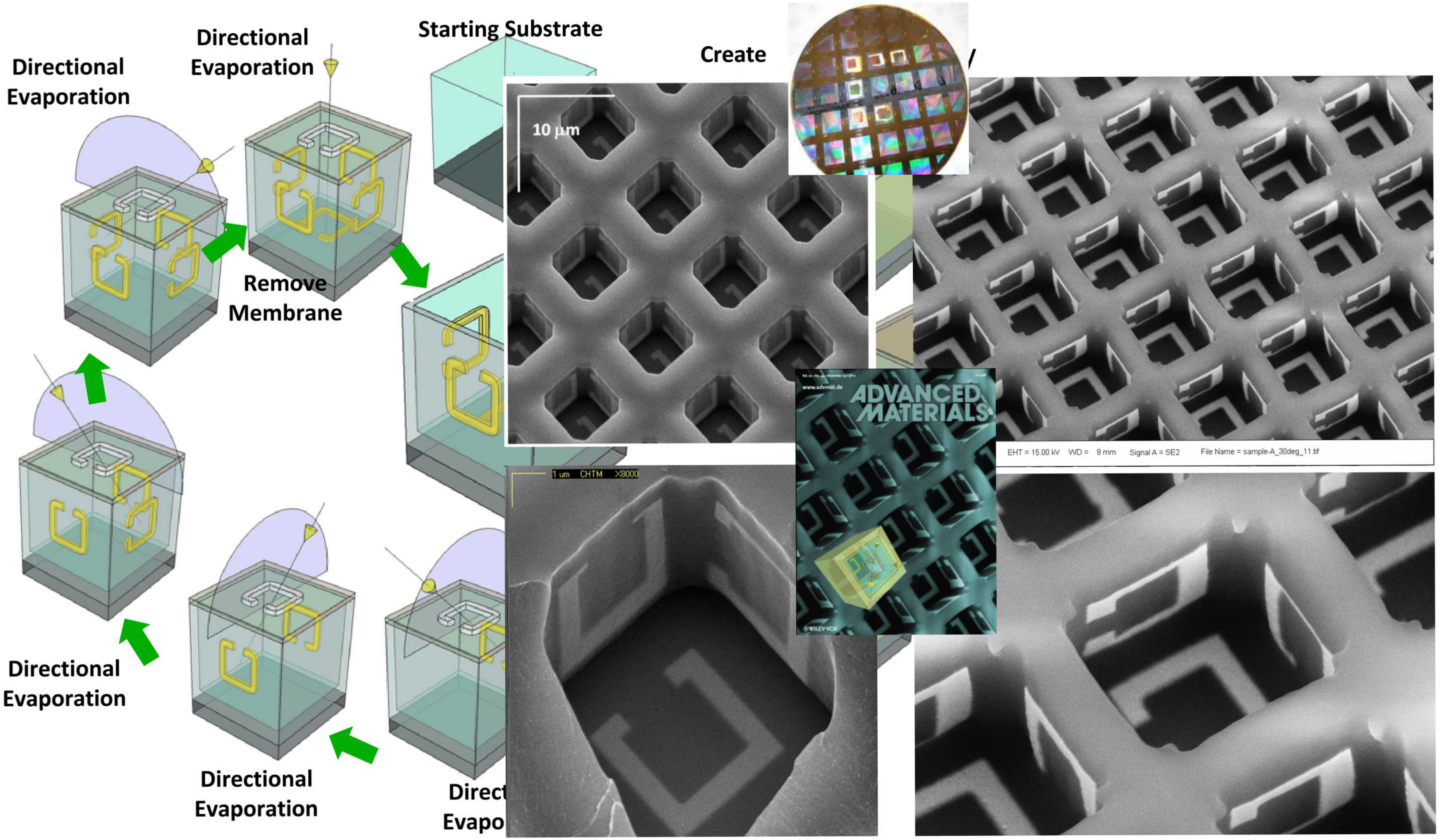
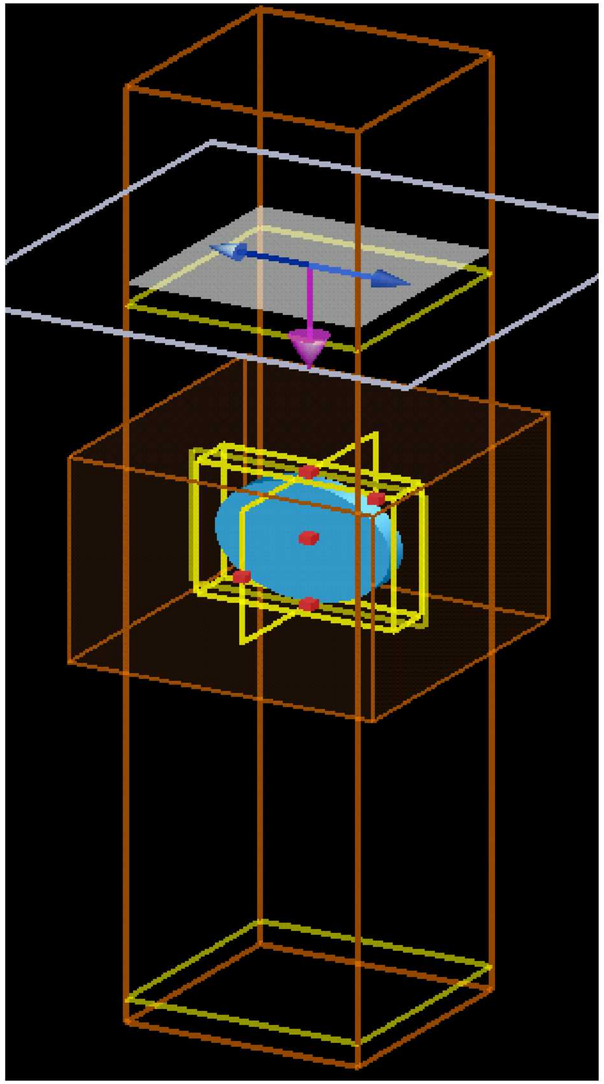
  - Huygens meta-optics
- Emitters + Metasurfaces
- Nonlinear optics with all-dielectric metasurfaces
- **Outlook on future (quasi) 3D fabrication**

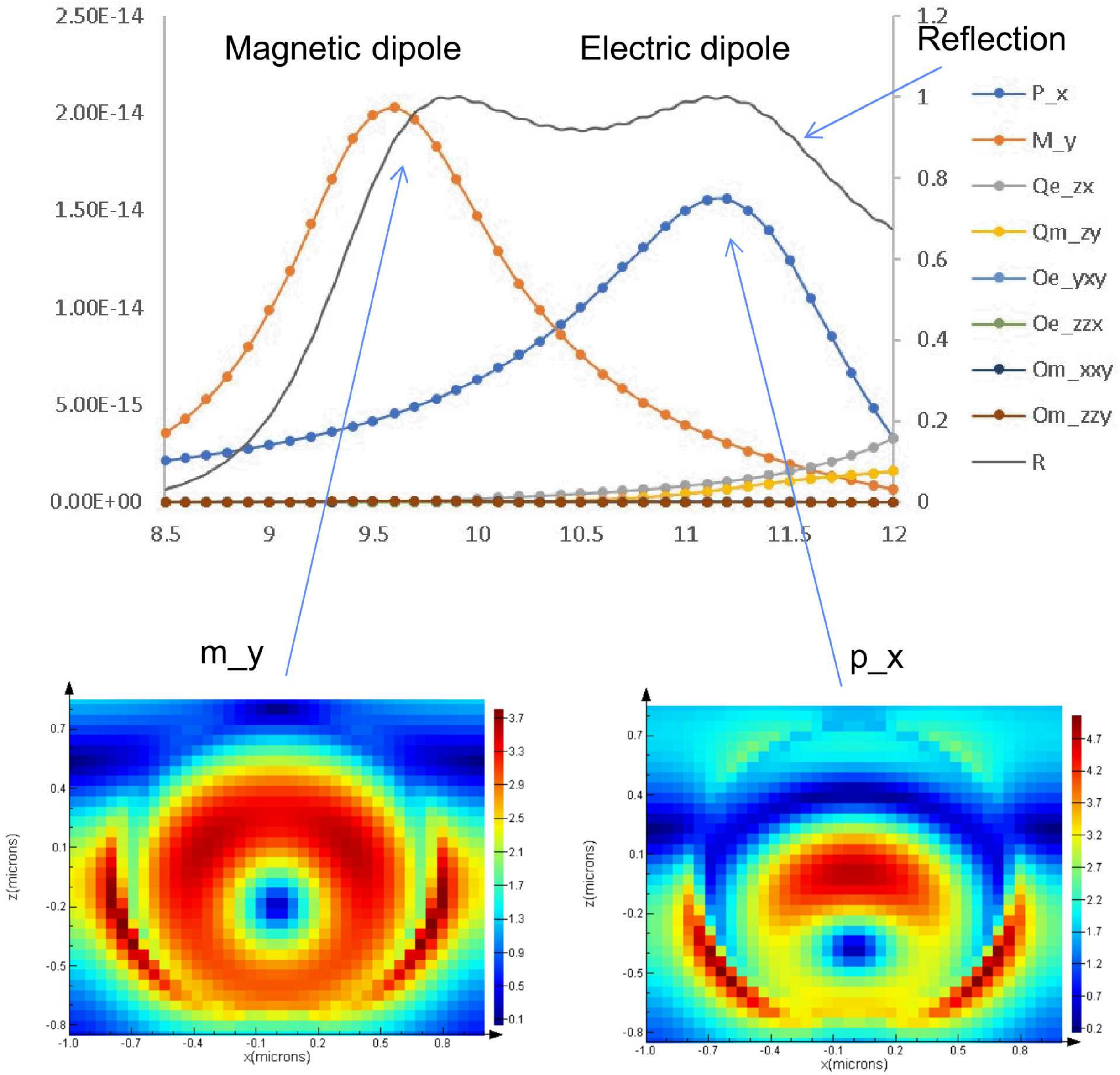
Fabrication of 2D Metamaterials
Membrane Projection Lithography



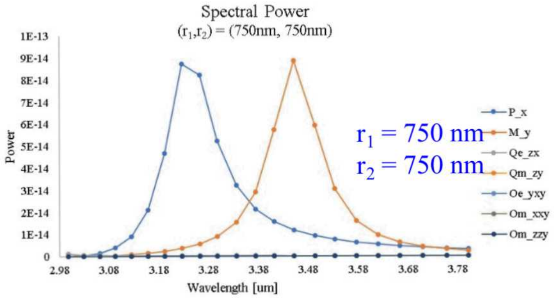
Burckel et al, Adv. Mat. 2010

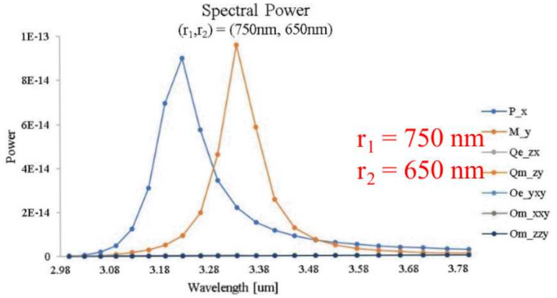
“Vertical” Dielectric Resonators

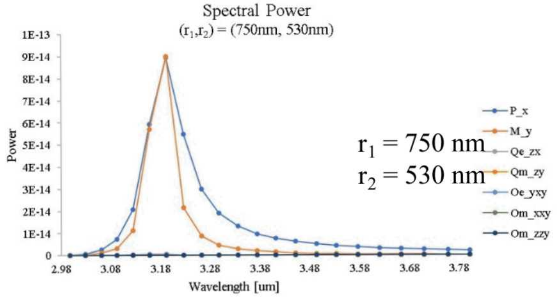


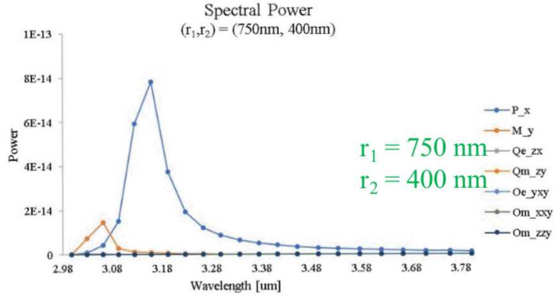


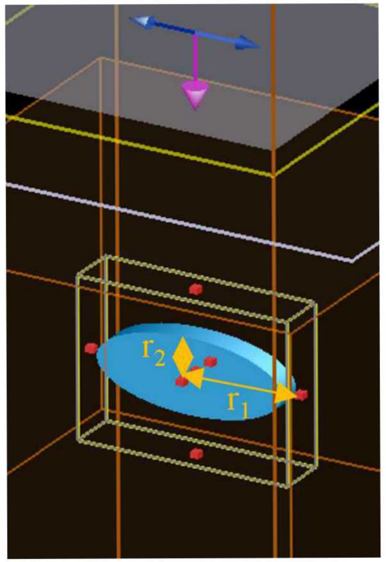
Achieving Huygens Point



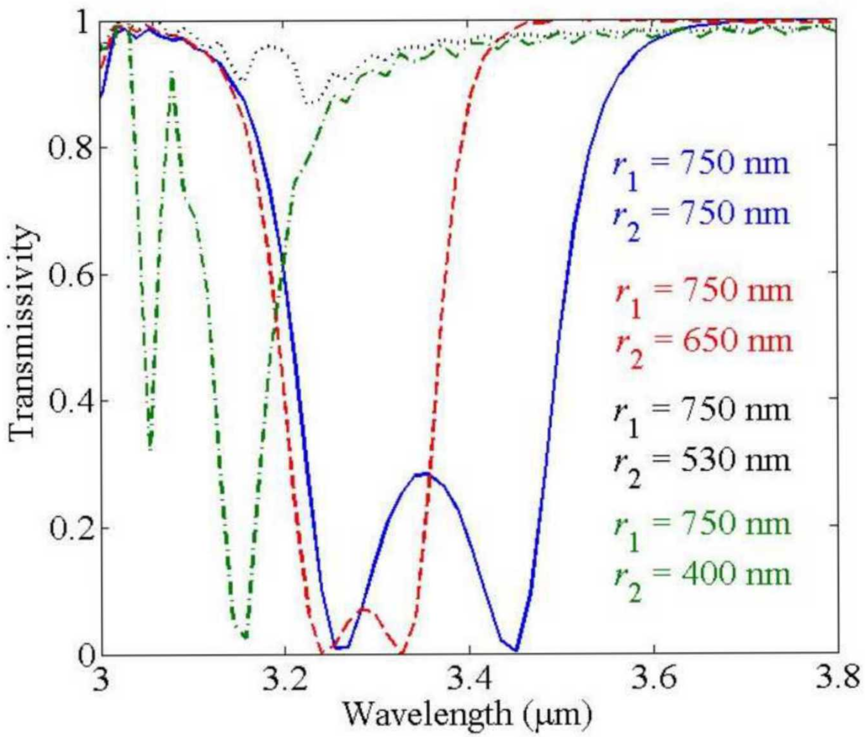




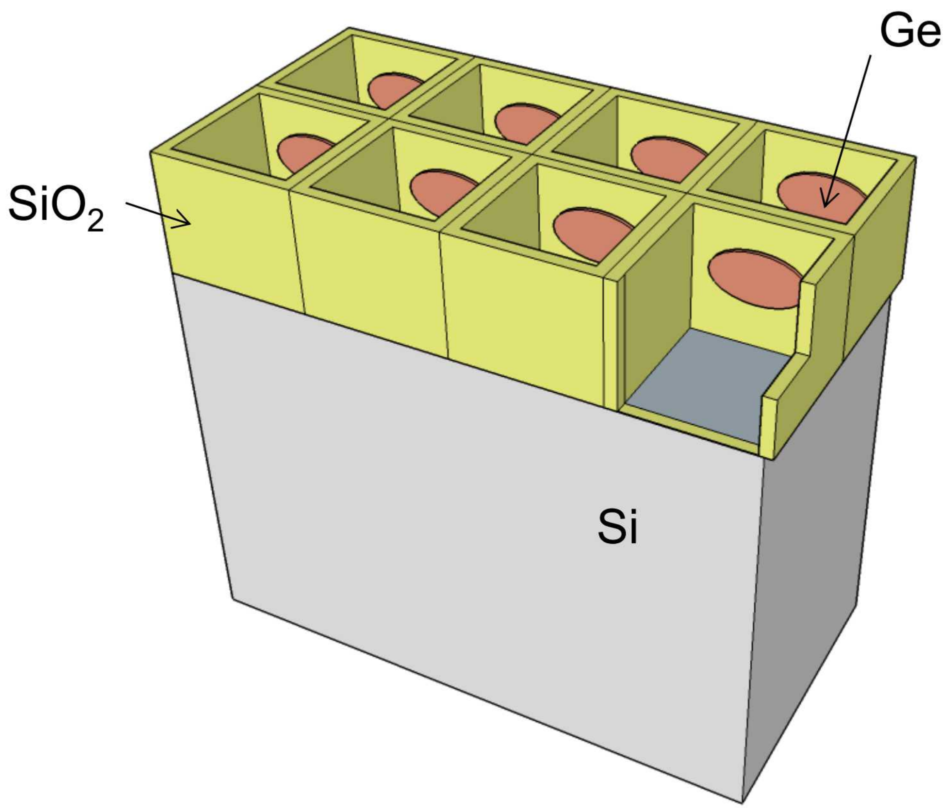




3 um period
Resonator in free space



Huygens Metasurfaces Using Out of Plane Resonators



- Elliptical resonators: Huygens behavior.
- Maybe we can stack several vertical resonators: $>2\pi$ phase shift
- All CMOS compatible, 1st devices in ~1 month

Summary

- Metamaterials & Metasurfaces: refresher, definitions, etc.

- Linear Metasurfaces:
  - Optical magnetic mirror
  - Huygens meta-optics

- Emitters + Metasurfaces

- Nonlinear optics with all-dielectric metasurfaces:

- Outlook on future 3D fabrication

Acknowledgments

Departed postdocs: Omri Wolf
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ANU (Australia): Yuri Kivshar, Dragomir Neshev, Katie Chong

Jena (Germany): Isabelle Staude, Aleks Vaskin

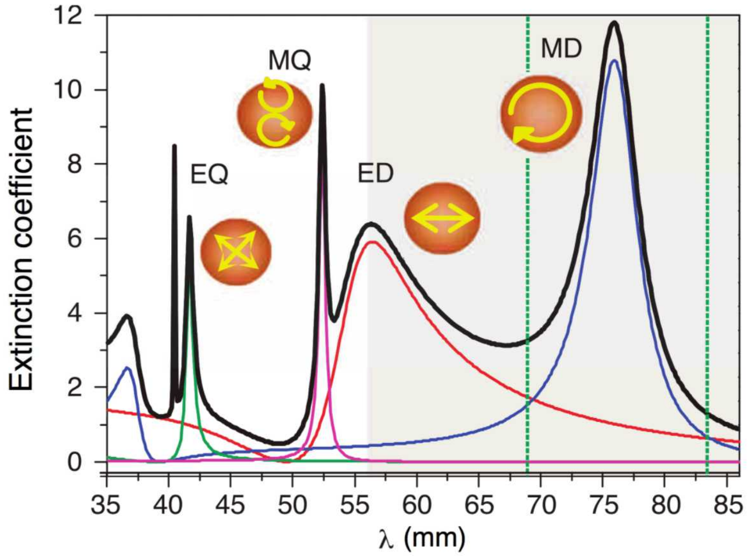
UT Austin: Nish Nookala, Misha Belkin

Moscow State (Russia): Maxim Shcherbakov, Andrey Fedyanin

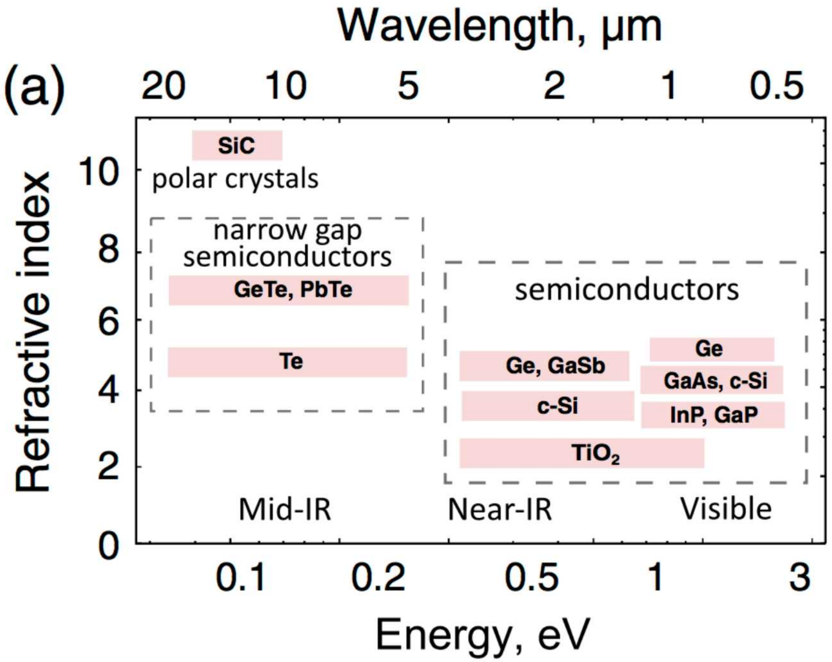
U.S. DEPARTMENT OF ENERGY | Office of Science

Mie-resonance Dielectric Metasurfaces

Mie resonances in Dielectric spheres

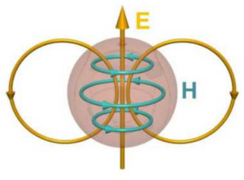


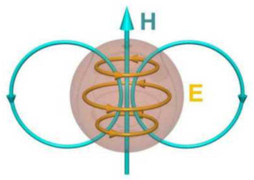
Geffrin, J.-M., et al. *Nat. Commun.* 3, 1171, **2012**



Baranov, D.G., et al. *Optica* 4.7, 814-825, **2017**

Electric Dipole Magnetic Dipole

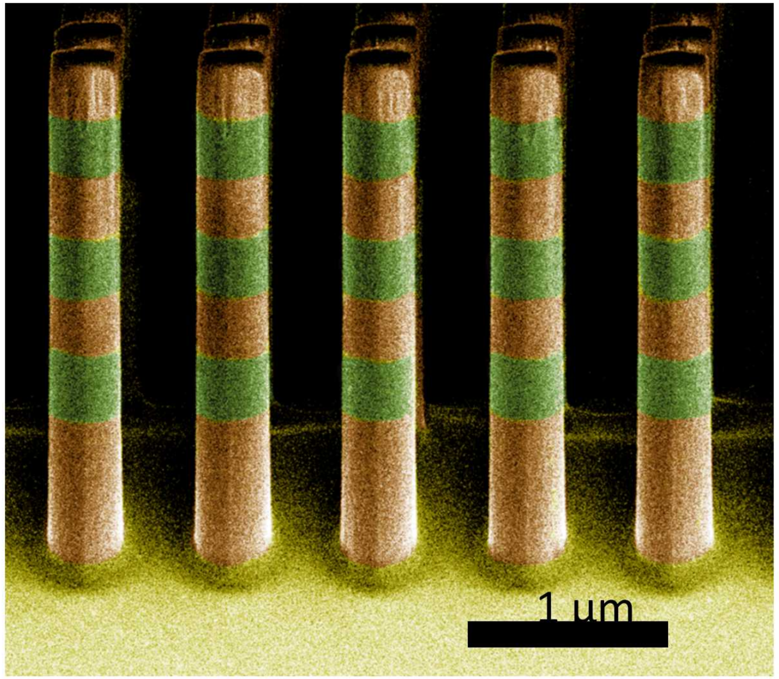


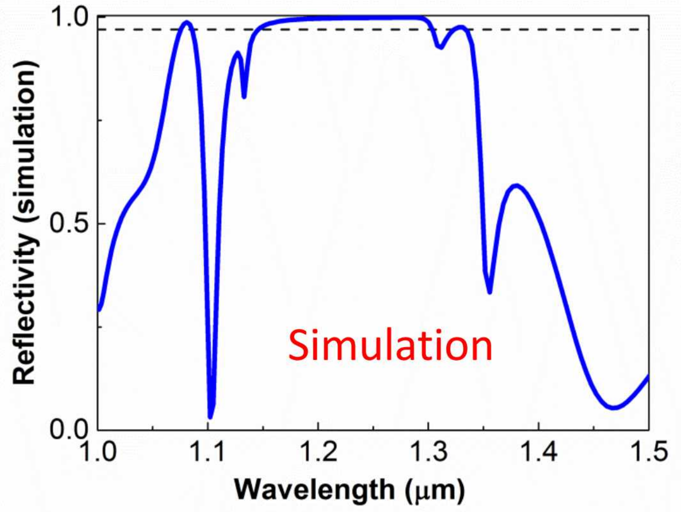


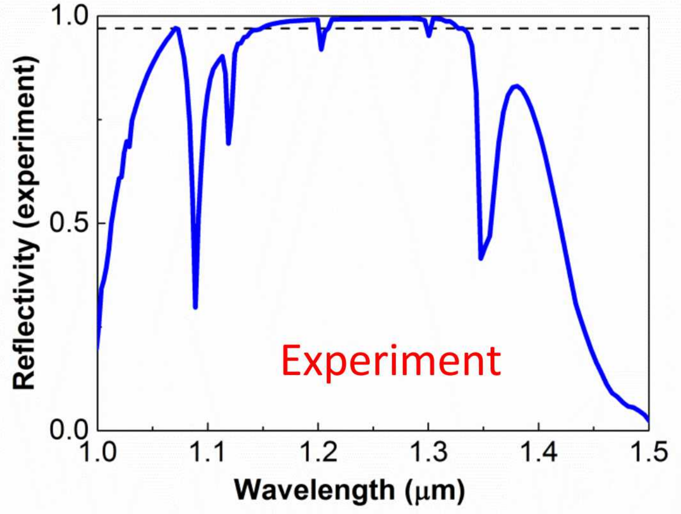
Images: A. Miroshnichenko

Multi-layer GaAs Dielectric Metasurfaces

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







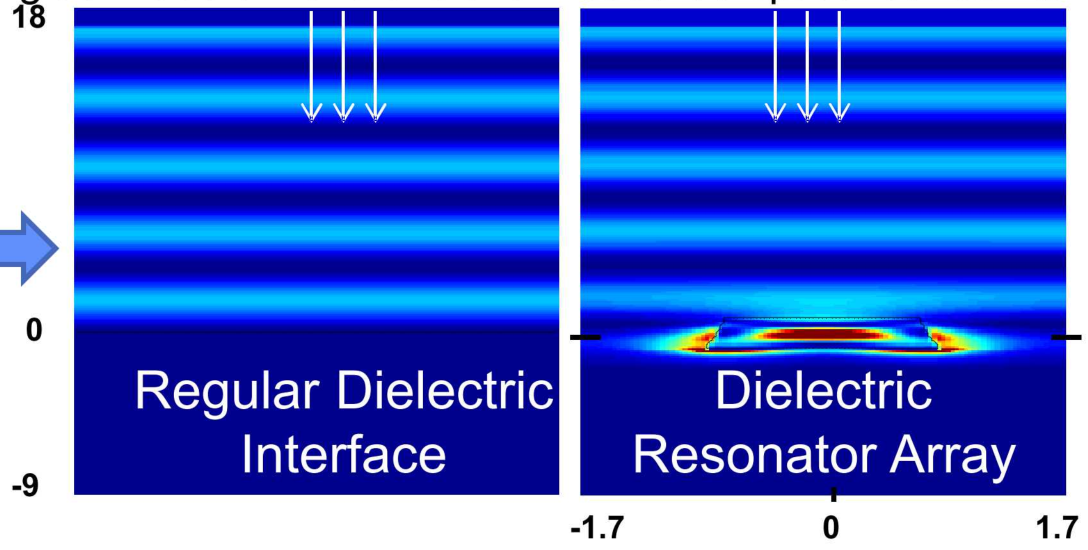
➔Potential path to 3D dielectric metamaterials

Liu et al, Adv. Opt. Matt 2016

Tellurium Cubic Resonators:
FDTD Simulation of the Reflected Wave

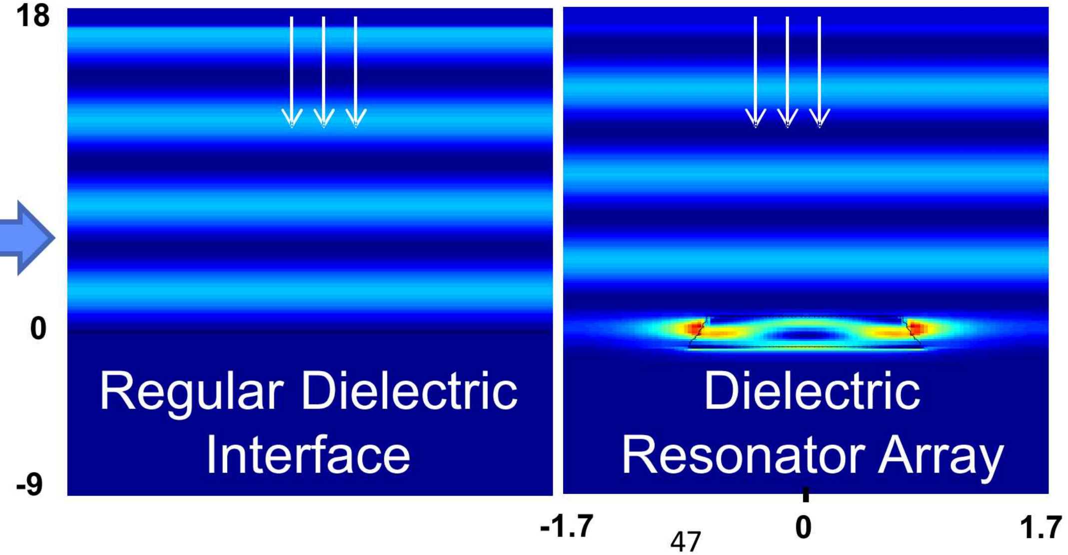
Simulated using as-made dimensions and measured optical constants

Electric Resonance λ=7.4μm



$$E_r \propto -E_i$$

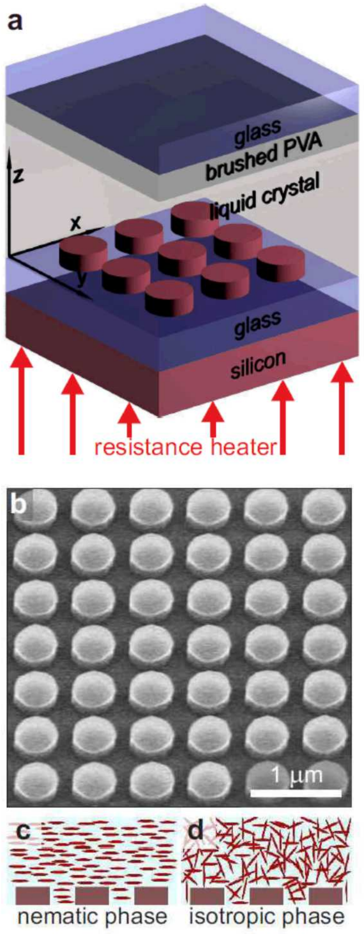
Magnetic Resonance λ=9.5μm

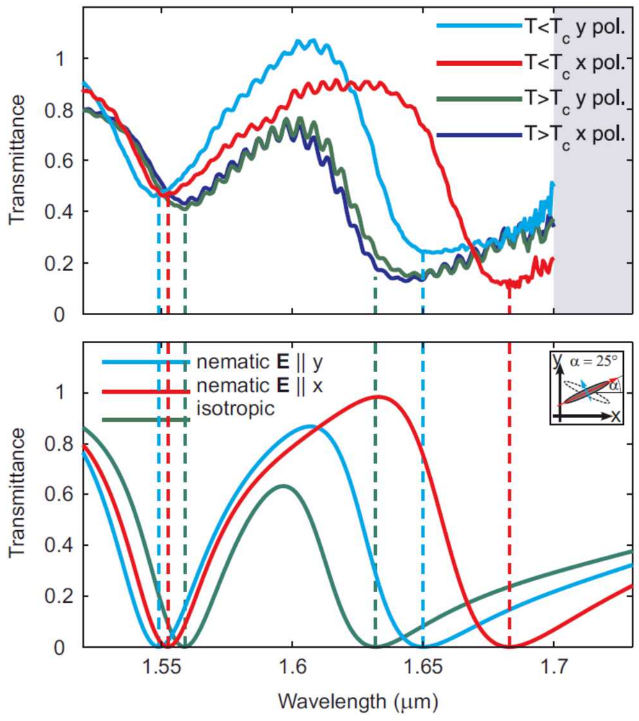


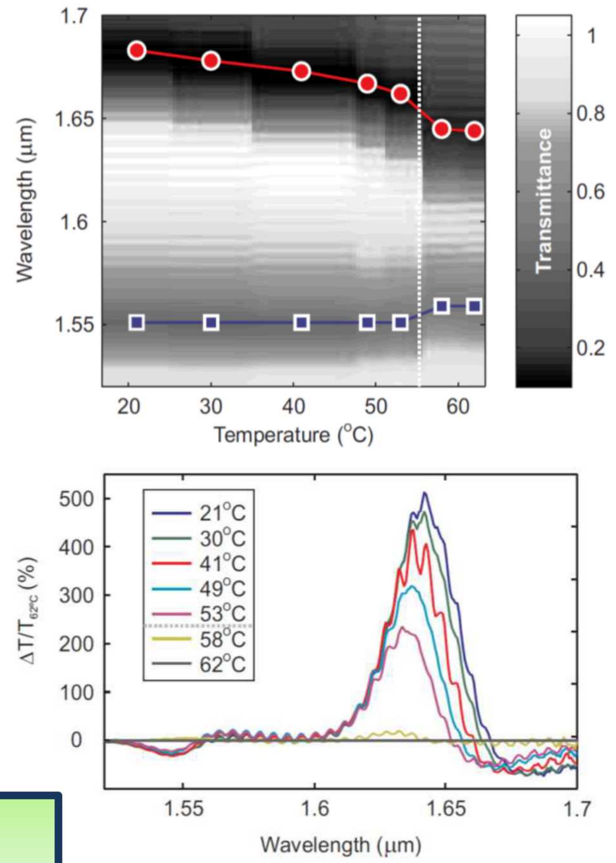
$$E_r \propto +E_i$$

"magnetic" mirror

Dynamic Control Using Liquid Crystals



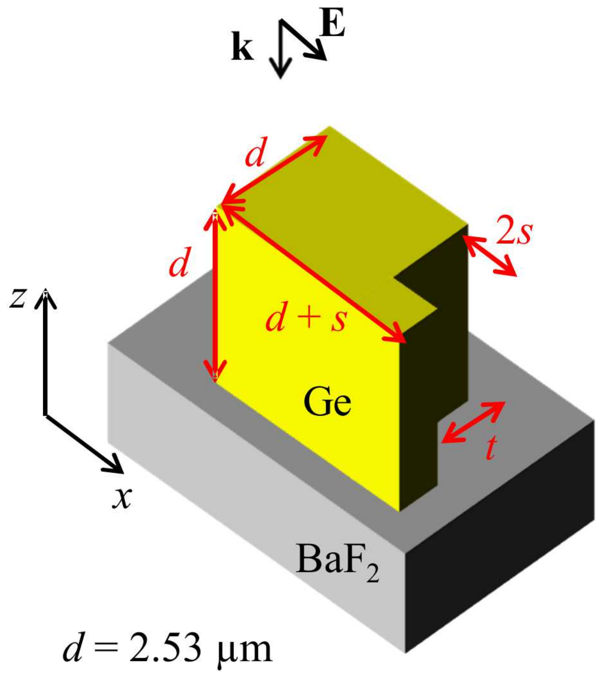




- Tuning range 40 nm
- Tuning contrast 500%

J. Sautter *et al*., *ACS Nano* **9**, 4308 (2015).

Ge-based Fano metasurface design



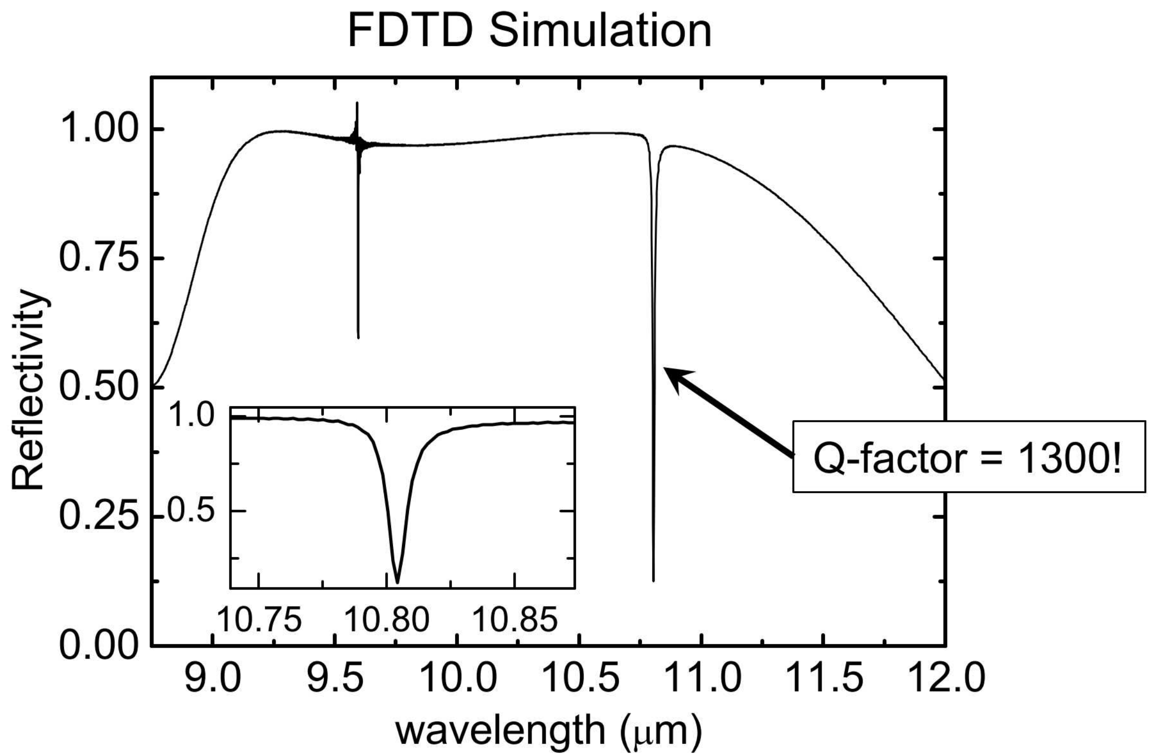
$d = 2.53\ \mu m$

$s = d / 5$

$t = 1.5\ \mu m$

Array Pitch:

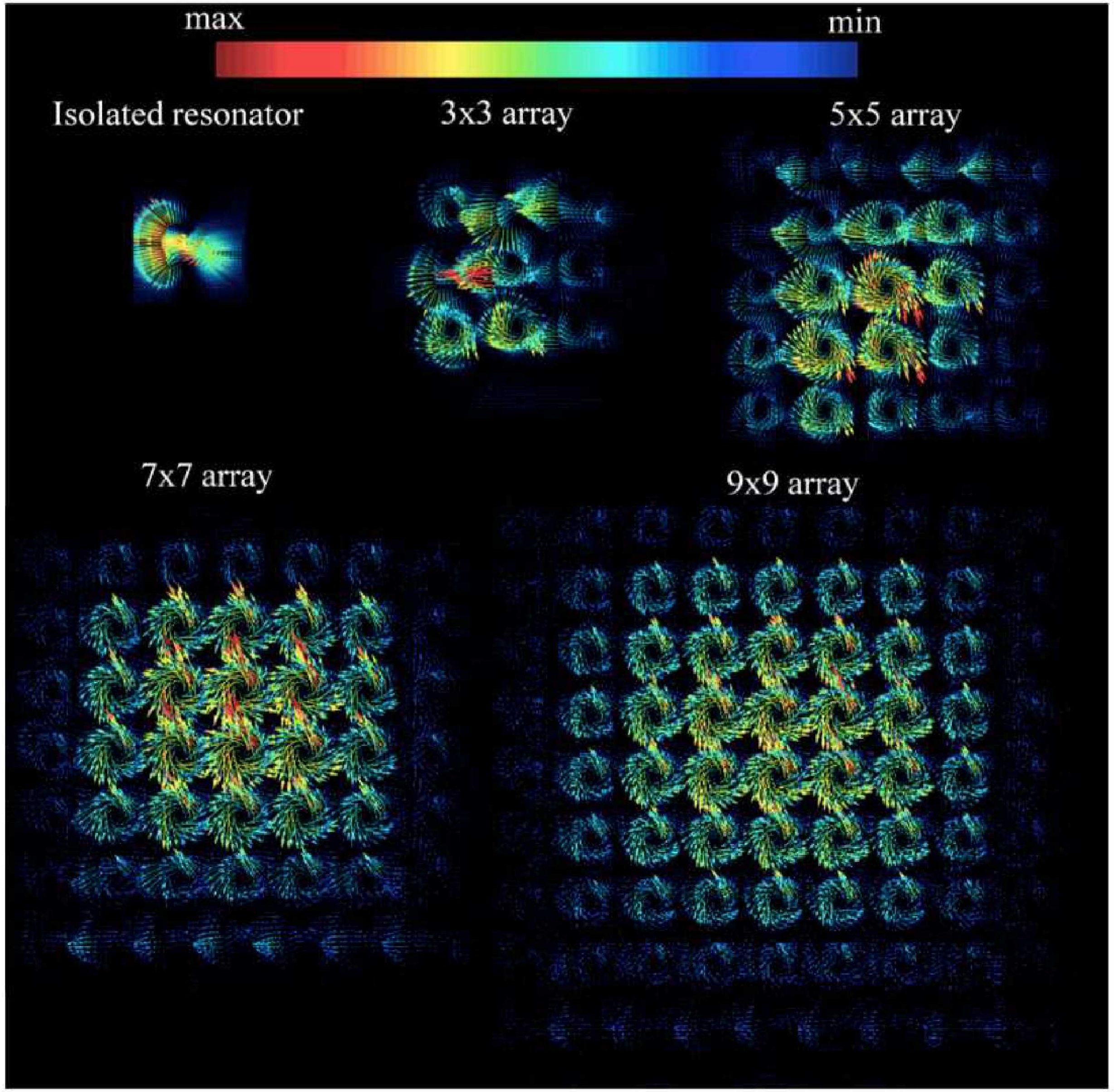
$a = b = 4.2\ \mu m$



Design is scalable from near infrared through RF

ACS Photonics 2016

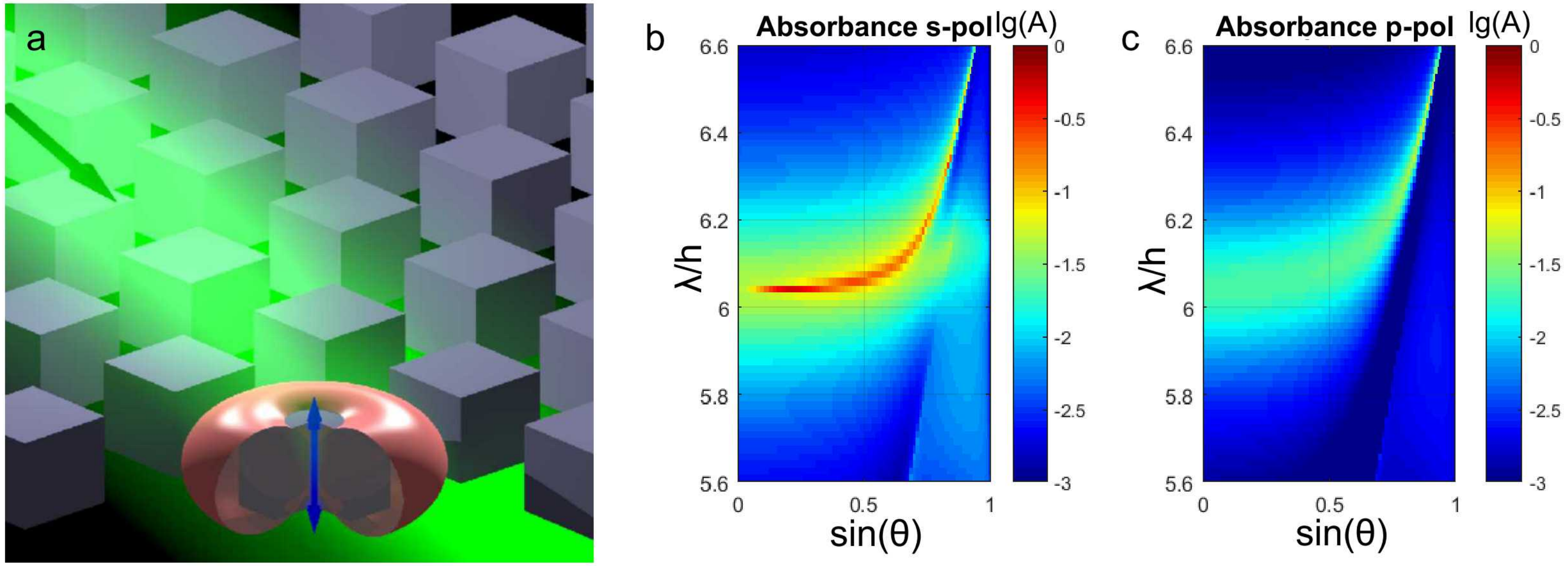
High Q: Only a small array is needed



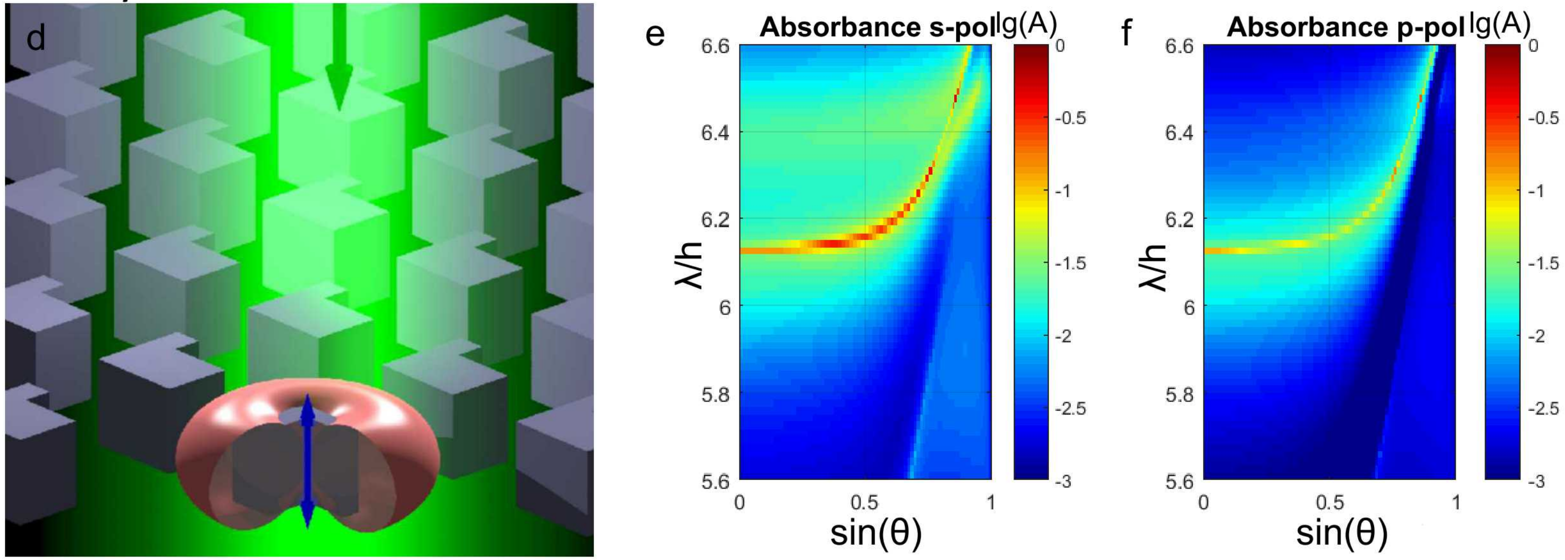
Campione, et al., ACS Photonics 3, 2362 (2016)

Out of Plane Dipole Modes

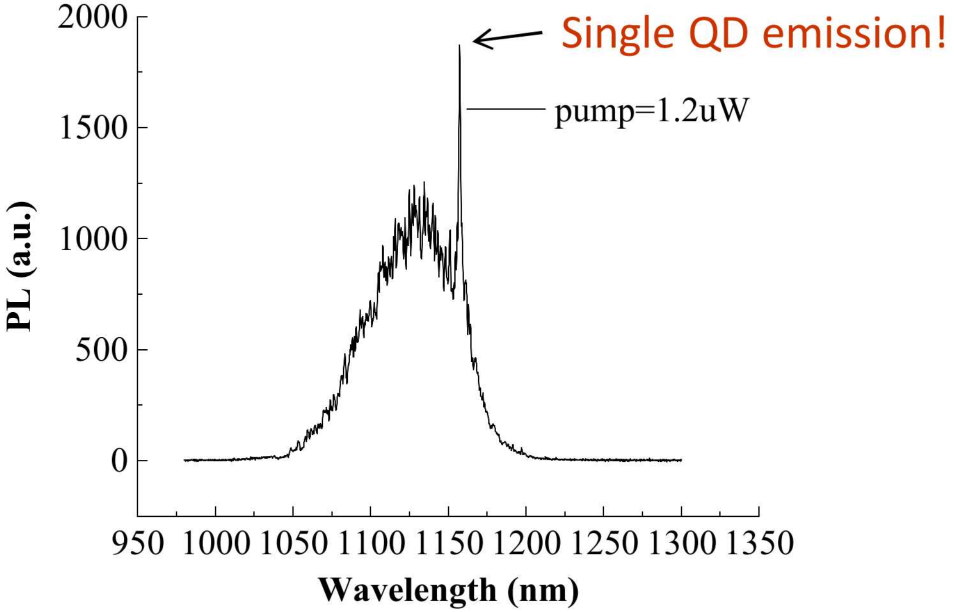
Symmetric Resonators

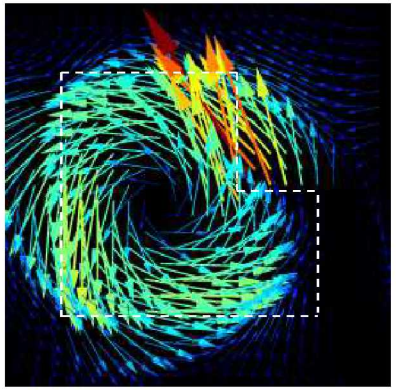


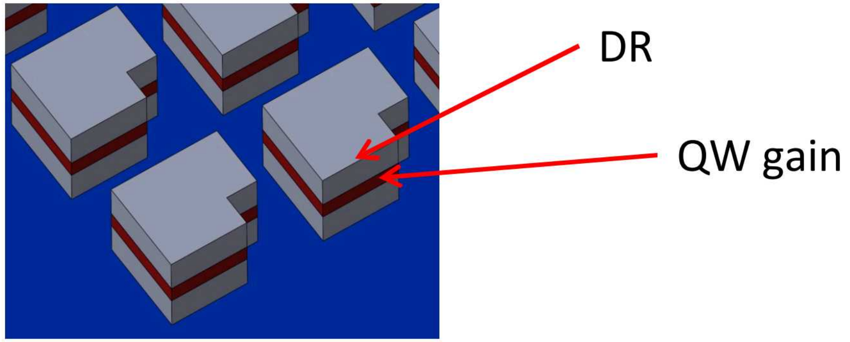
Broken-symmetry Resonators



Low temperature
PL

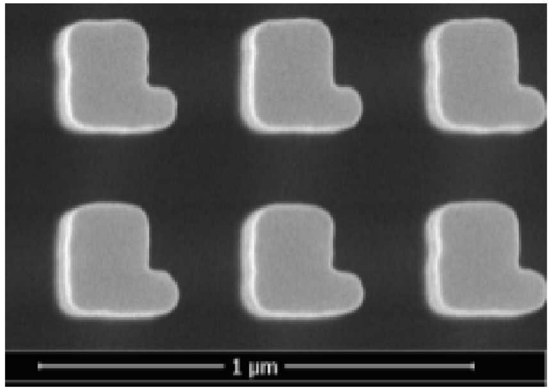


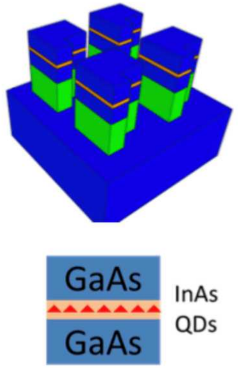


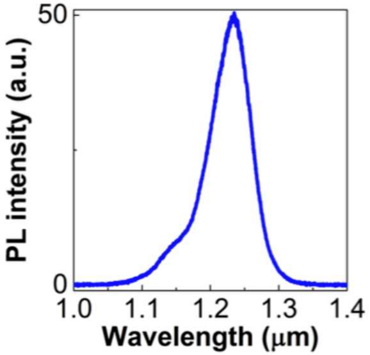


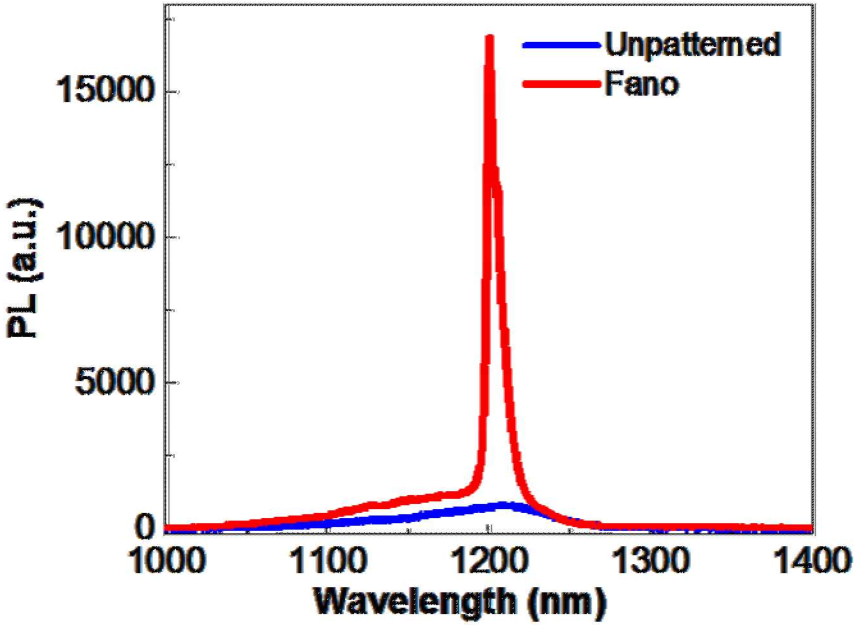
Emitters (QDs) Coupled to “Fano” Metasurfaces:

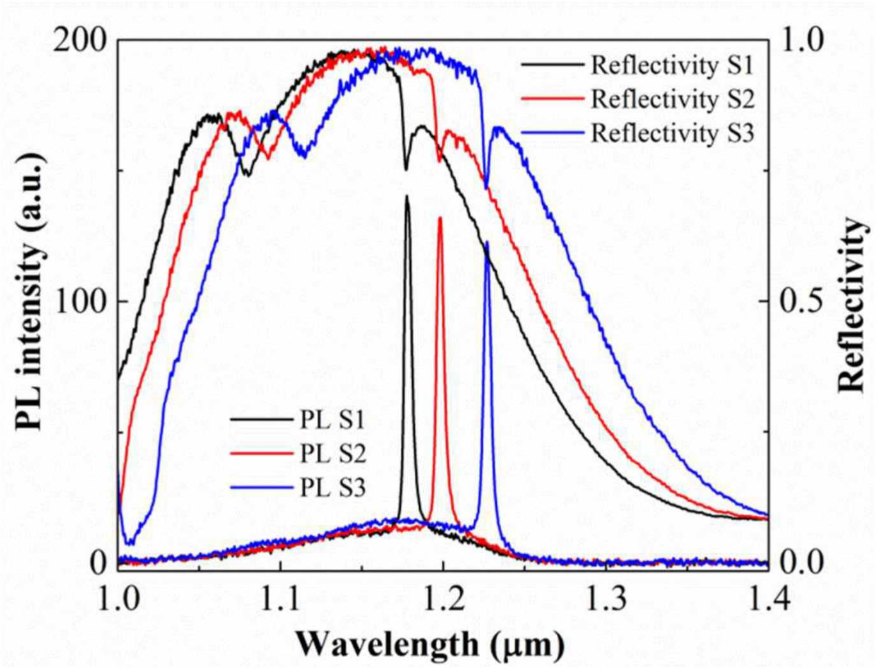
QDs inside, Emission enhancement









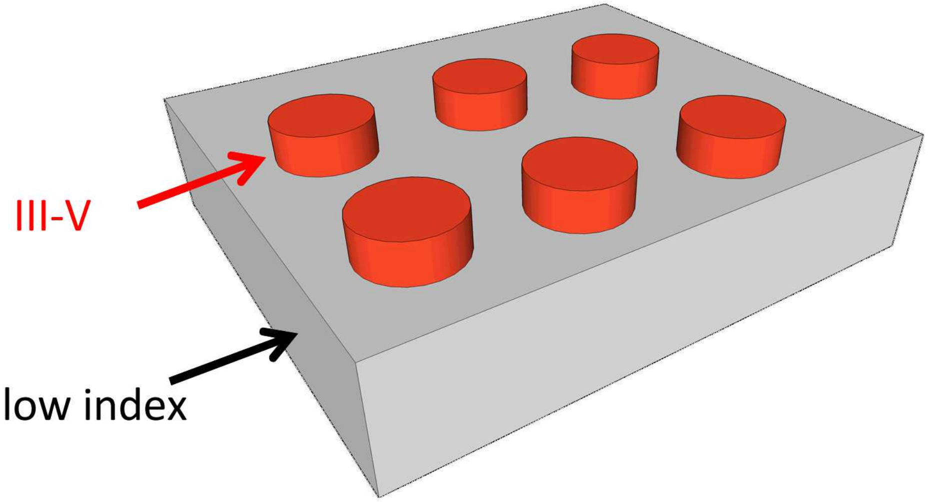


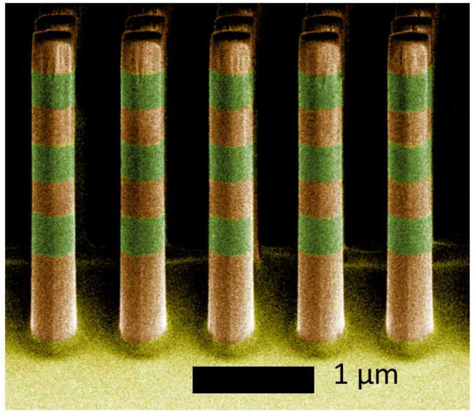
Nonlinear Metasurfaces: Silicon vs III-V's

- **Silicon is centrosymmetric ➔ NO second order nonlinearity**
- **Lots of III-V semiconductors have $\chi^{(2)}$**

GaAs: ~200pm/V

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



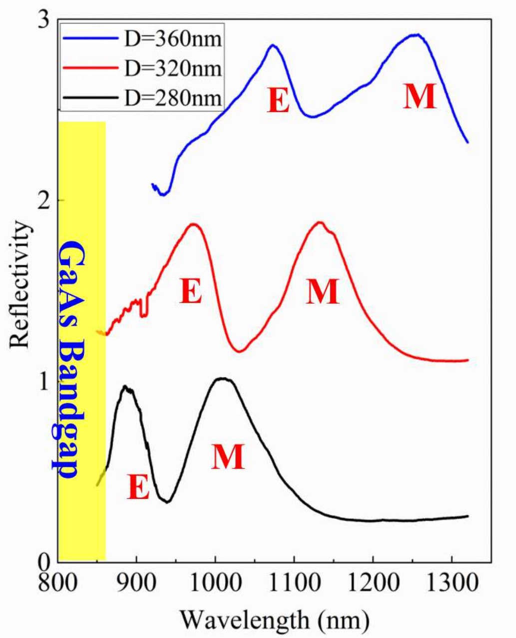


How to Increase SHG Efficiency from all-Dielectric Metasurfaces

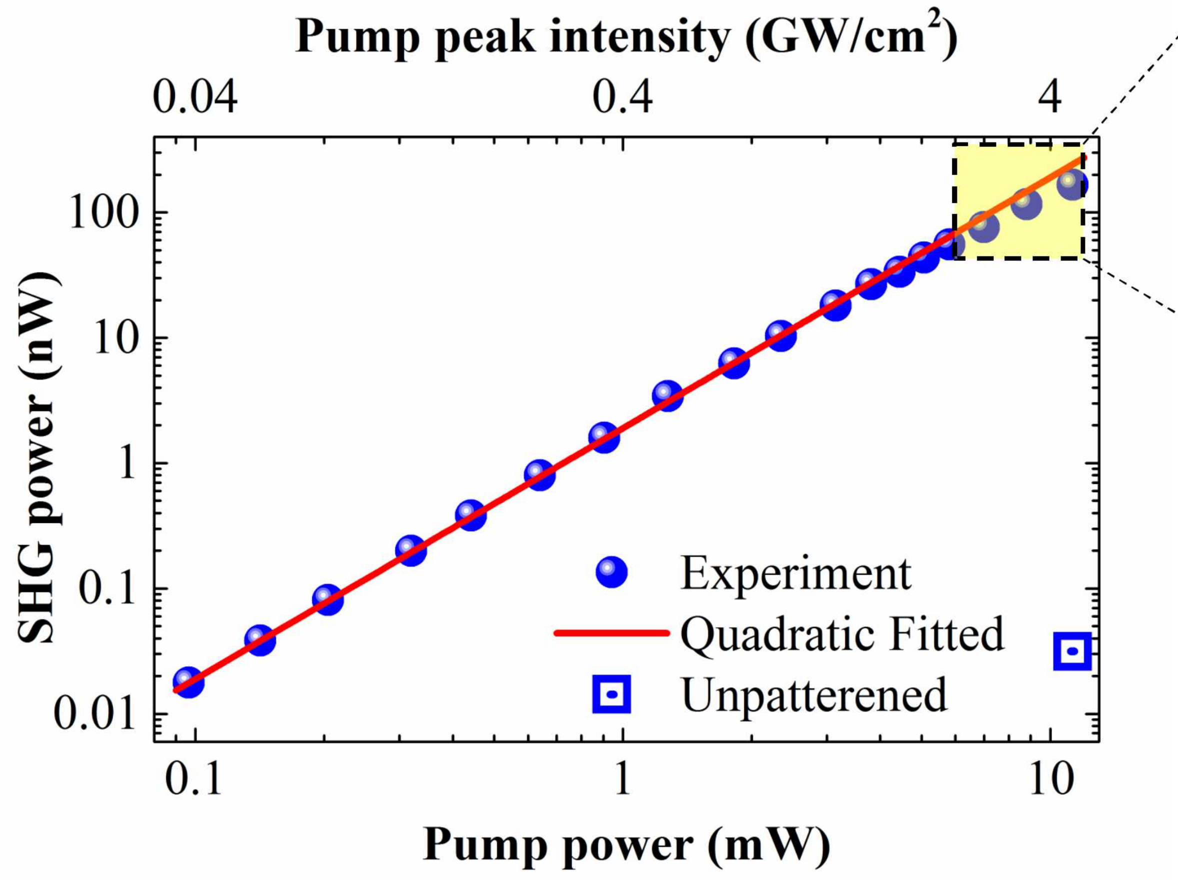
- **Find another high index material with higher $\chi^{(2)}$**
  - **GaAs already has $\chi^{(2)}$> 200pm/V**

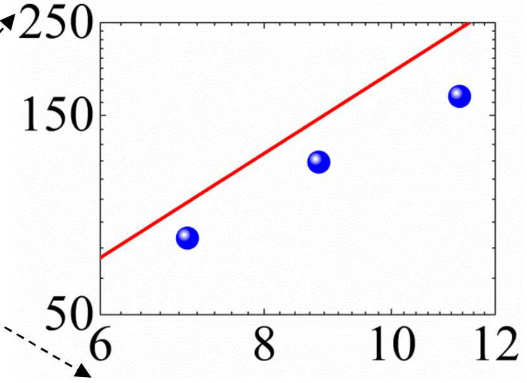
- **Find combination of modes and symmetry that maximize nonlinear polarization** $P^{2\omega}_{NL,x} \propto 2\chi^{(2)}_{xyz} E^{\omega}_{y} E^{\omega}_{z}$**,...**

- **Increase Q of resonances ($E_{inside} \propto Q$)**

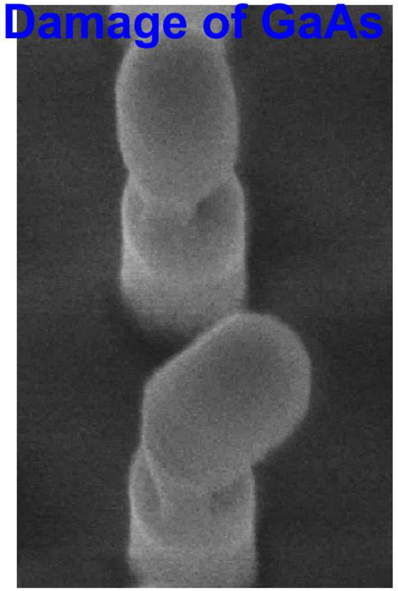


SHG power vs pump power





Pump of ~10GW/cm^2 Damage of GaAs



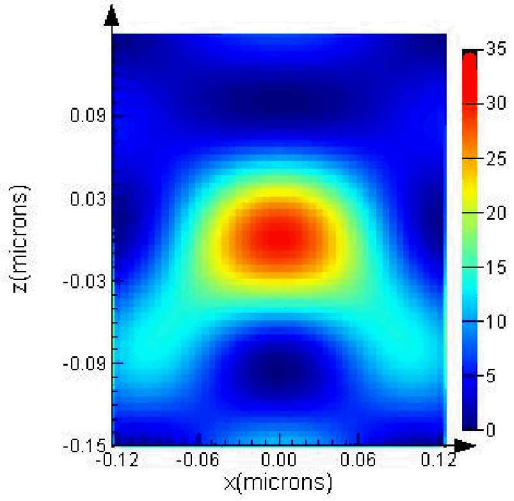
- Quadratic relationship sustained at lower pump power.
- Irreversible damage of GaAs occurred > ~1.5 GW/cm^2.
- Two-photon-absorption of GaAs followed by thermal damage due increased free carrier absorption

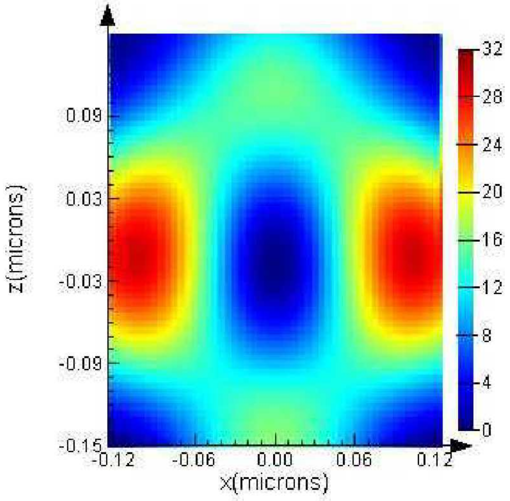
Sheng Liu, et al, in preparation

Polarization, Selection Rules

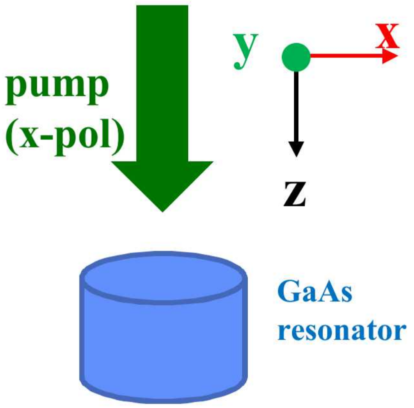
$|E|^2$ enhancement for both electric and magnetic dipole resonance.

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





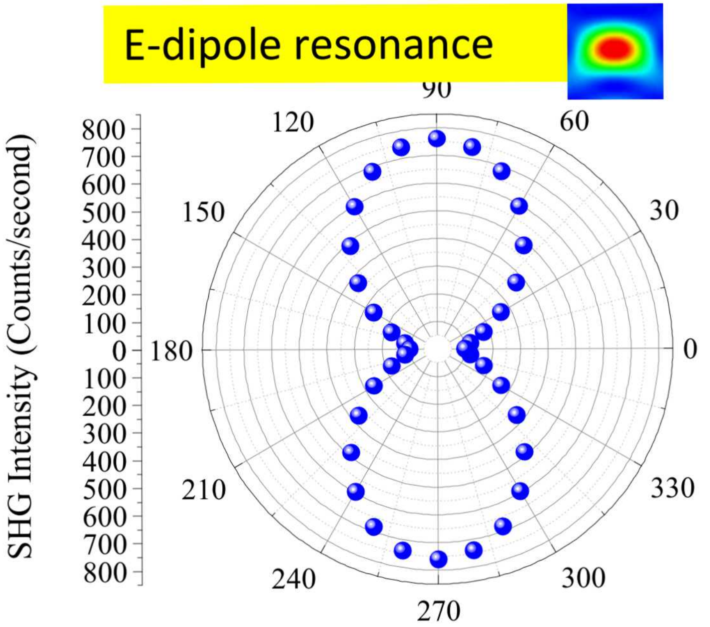
There are only E_x and E_z component inside the GaAs resonators.

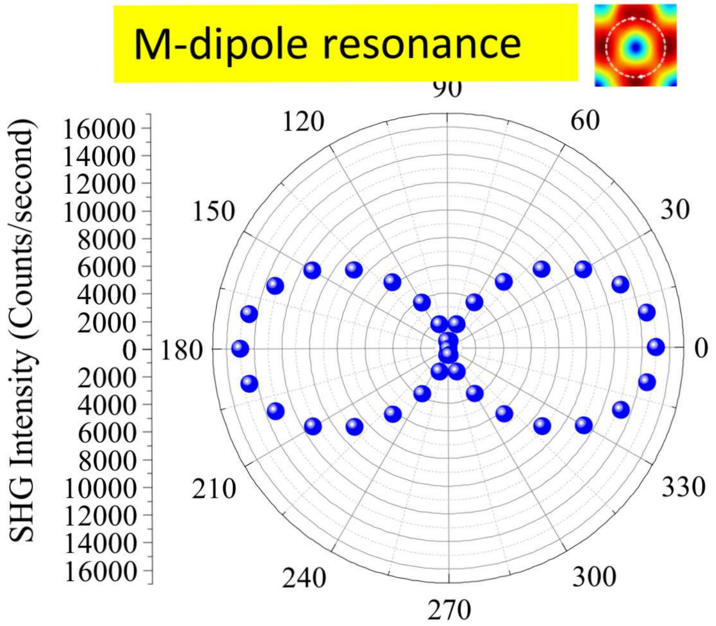


$$E_y^{2\omega} = 2\chi_{xxy}^{(2)} E_x^{\omega} E_z^{\omega}$$

Orthogonal SHG polarization compared to the pump is expected

Pump





!!!

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

What happens at the M-dipole resonance?

1. Surface nonlinearity changes symmetry to mm2

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

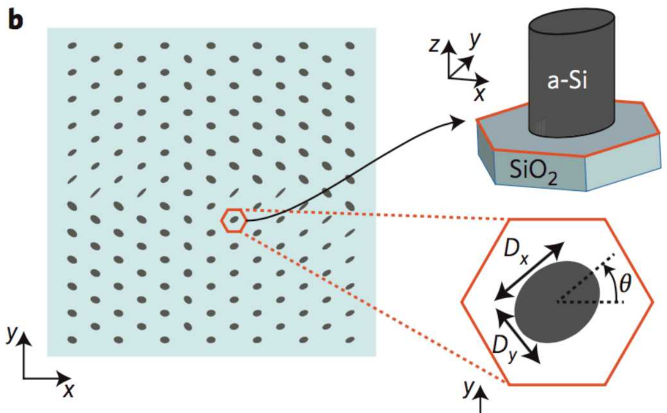
can be large, considering the large field enhancement at the surface for this mode.

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

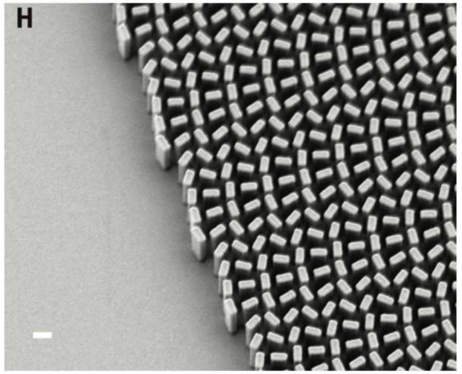
Not predicted: Carletti *et al*,: "Enhanced second-harmonic generation from magnetic resonance in AlGaAs nanoantennas", *Optics Express*, *23*, 26544 (2015)

School #2: High Aspect Ratio Dielectric Metasurfaces for Flat Optics

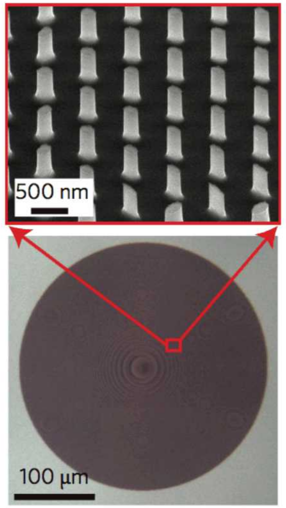
Use “tiny waveguides”, birefrigent because of asymmetrical cross section.
Phase given by orientation (Faraon, Hasman, Capasso)

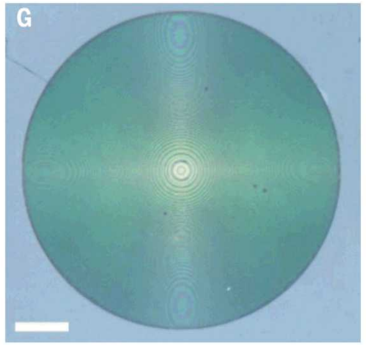


Faraon et al, Nat. Nanotech 2015



Capasso et al, Science 2016

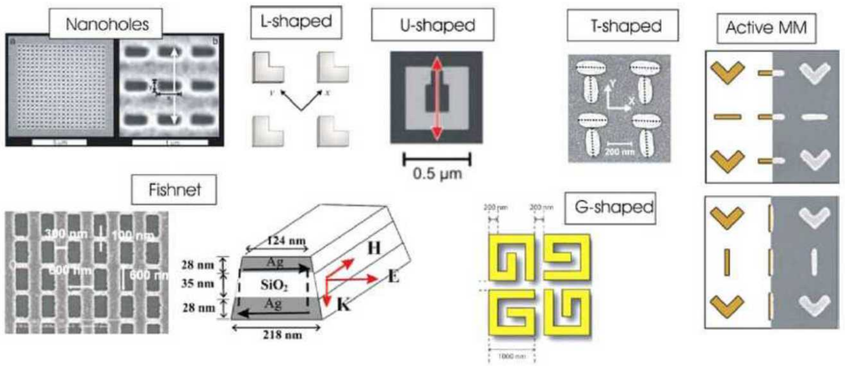




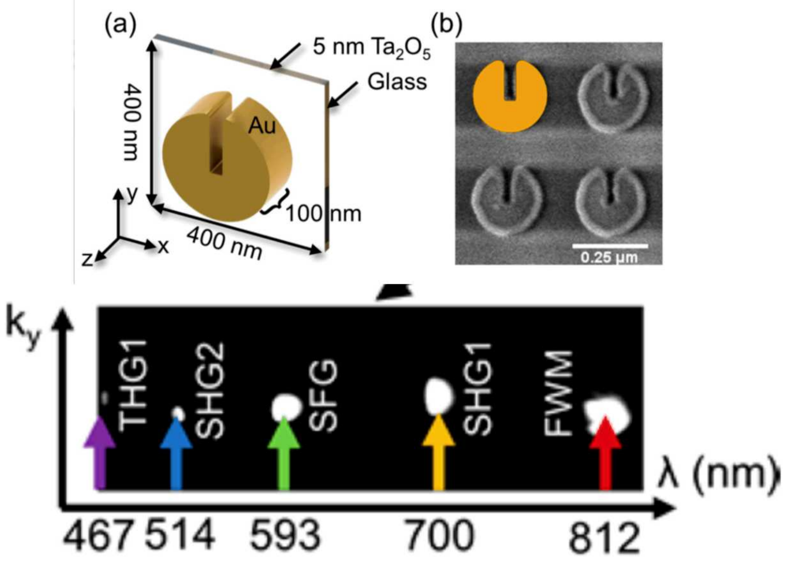
IB

Nonlinear Optics from Plasmonic Metasurfaces

- **Relaxed phase matching conditions**
- **Resonant enhancement of EM field induced by Plasmon excitation**



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



Sartorello, et al. *ACS Photonics* 3.8 (2016): 1517-1522.

nature photonics
FOCUS | REVIEW ARTICLES
PUBLISHED ONLINE: 31 OCTOBER 2012 | DOI: 10.1038/NPHOTON.2012.244

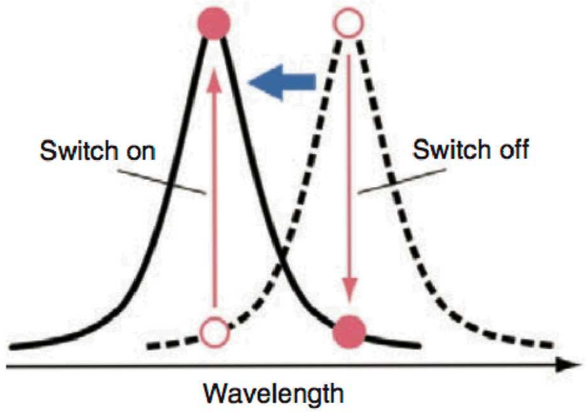
Nonlinear plasmonics

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

SHG efficiency ~ 10^{-9}

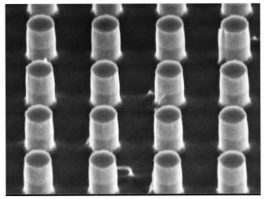
Plasmonic structure: small mode volume (usually only uses surface nonlinearities)

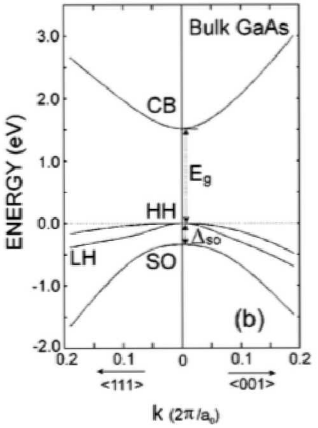
Ultrafast Switching Using Metasurfaces



NTT Tech. Rev.

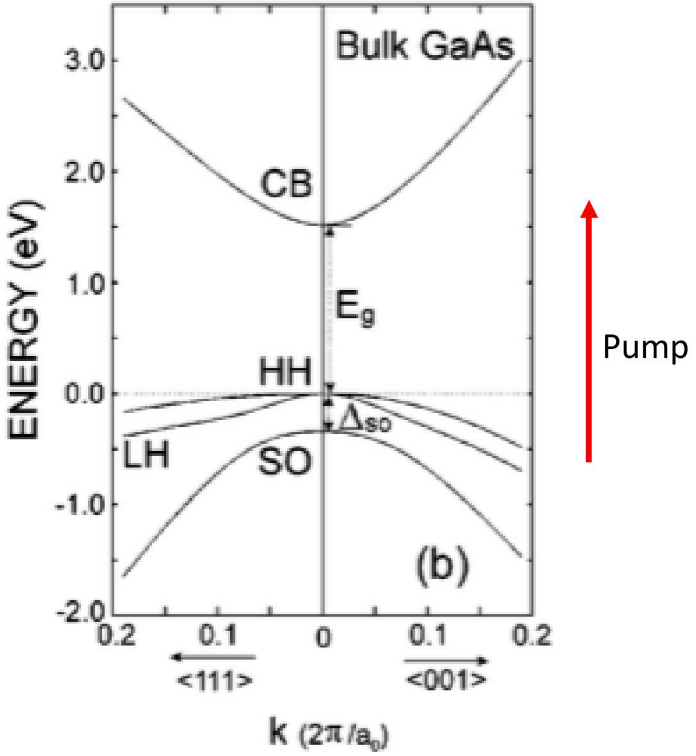
- **Dielectric Metasurfaces**





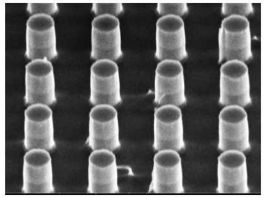
Pump

Vurgaftmana
JAPN (2001)

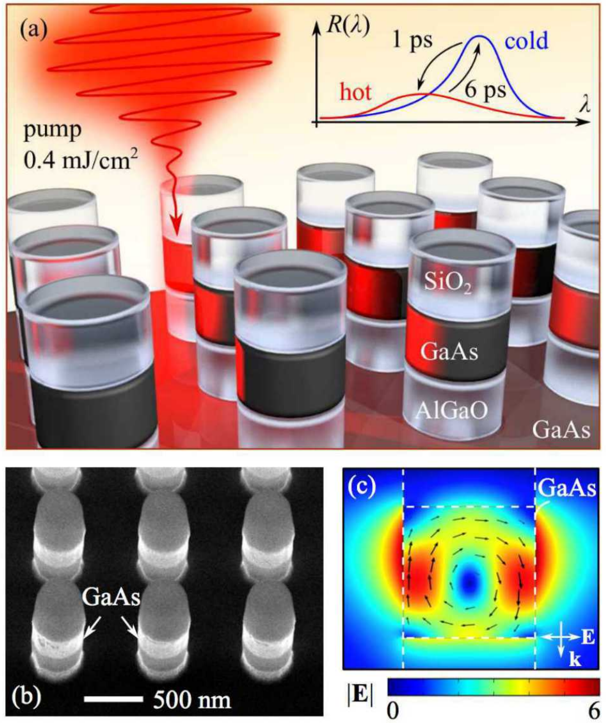


To first order, the laser beam gets absorbed, generates electrons and holes, and these cause a refractive index change.

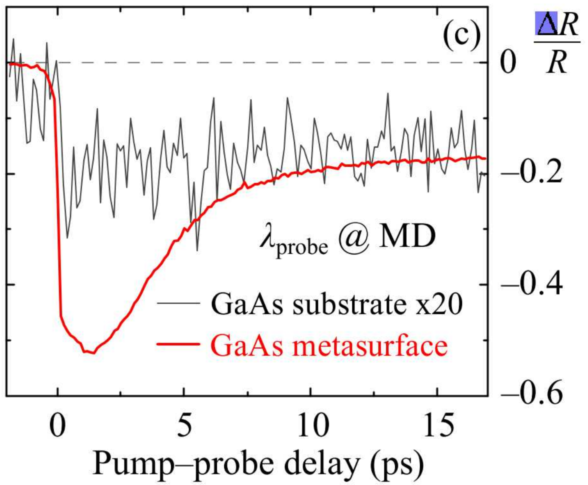
Then the Mie resonances will change (spectrally) since resonances occur at ~λ/n



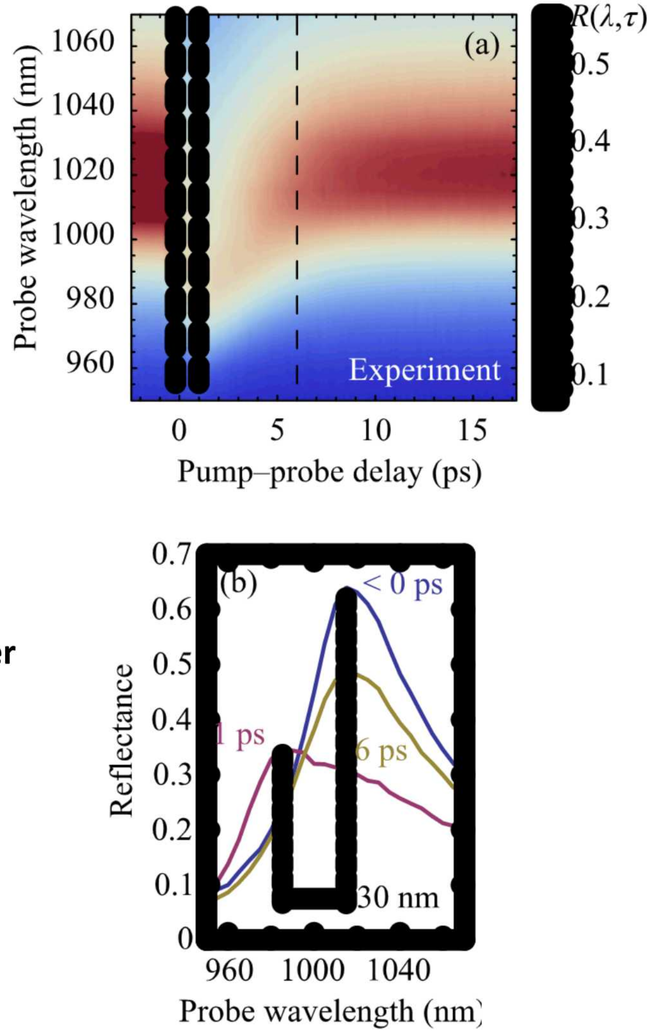
Dielectric Metasurface: Ultrafast Tuning of Magnetic Dipole Mode



Modulation 50x of substrate



Resonance tuning by 30 nm

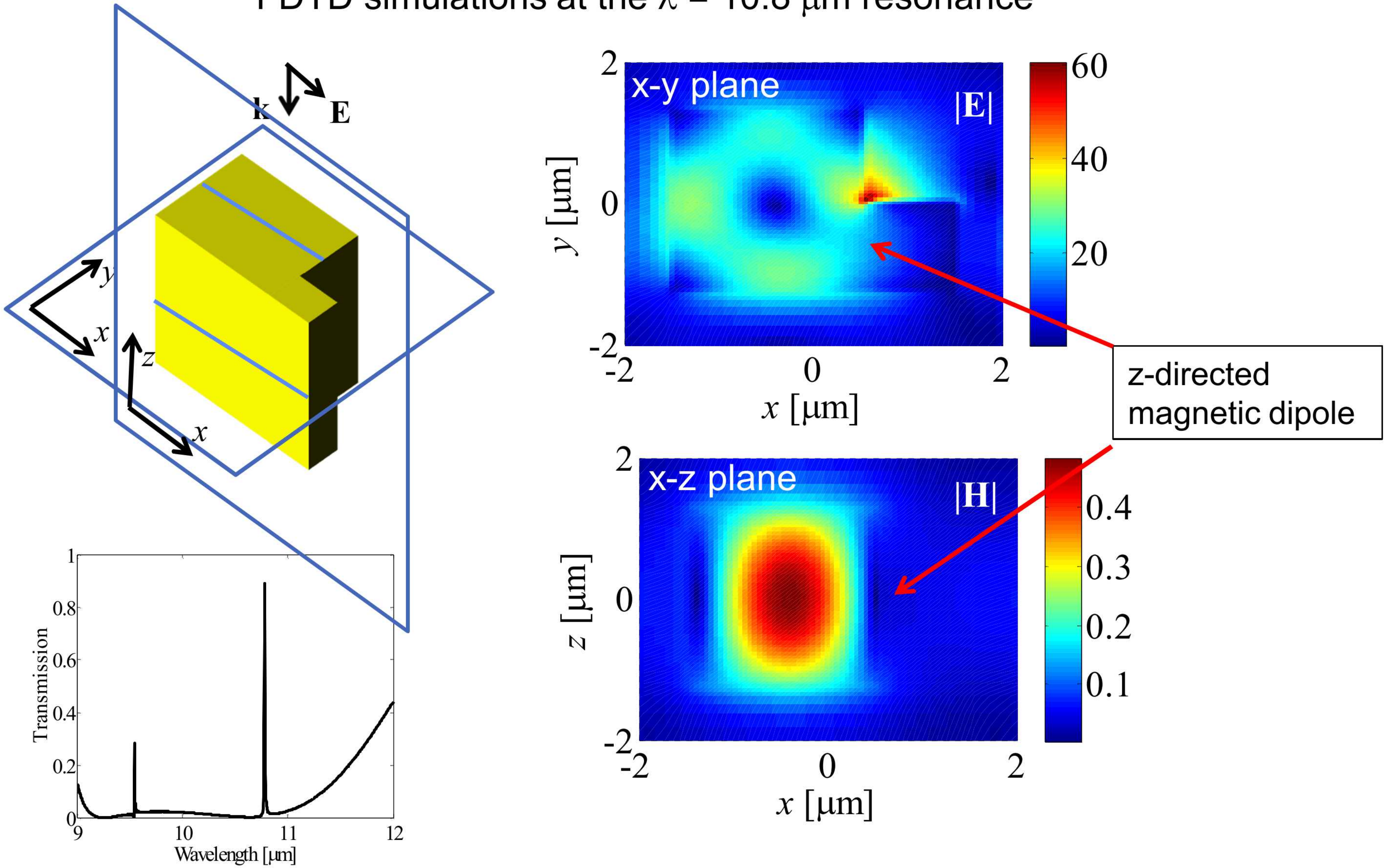


- **Fast recovery due to surface recombination (~2.5 ps from low power expts)**
- **Maximum index modulation is –0.14 due to Drude dispersion and band filling effects**

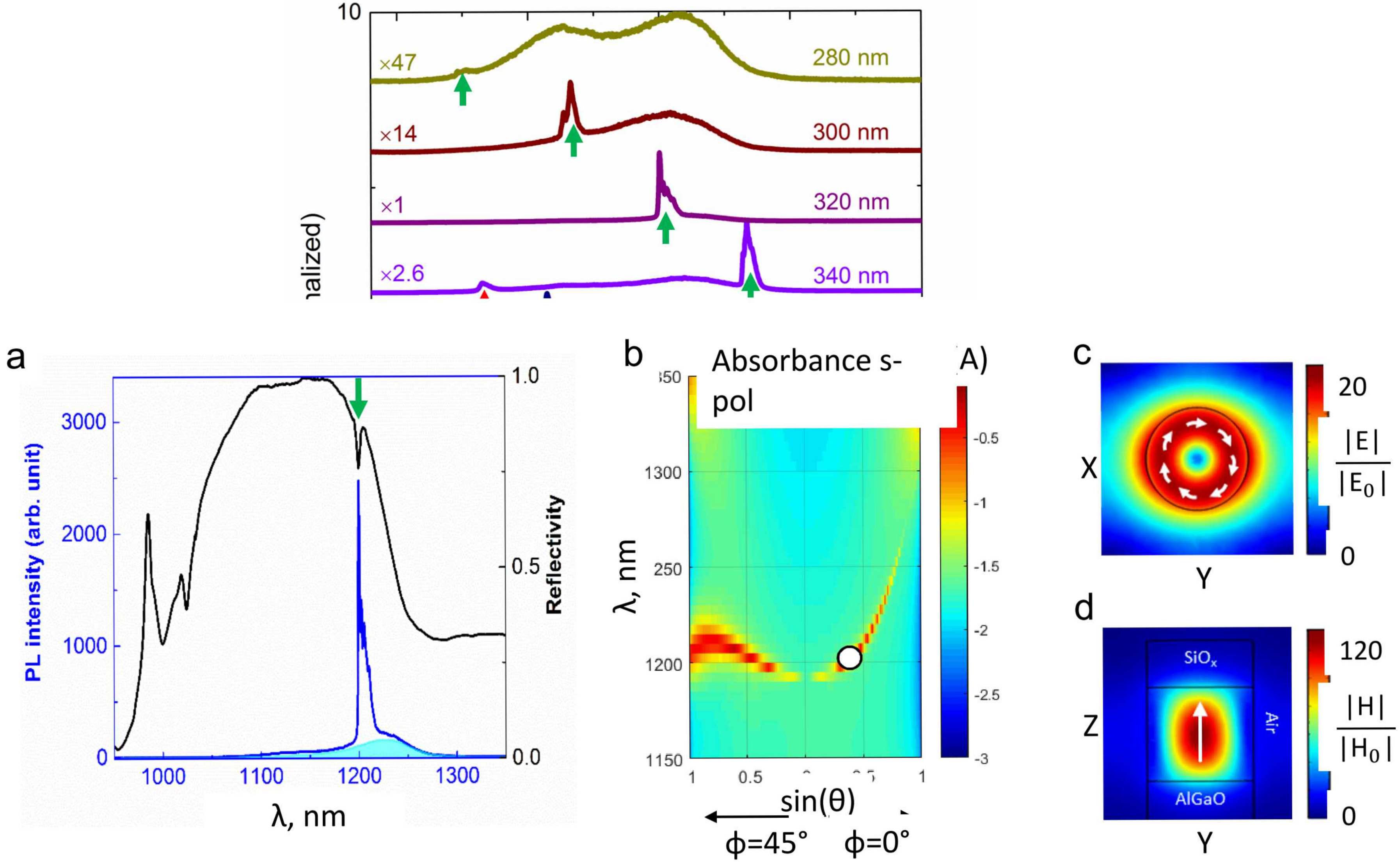
Nat. Comm. 2017

Resonant Mode Field Profiles

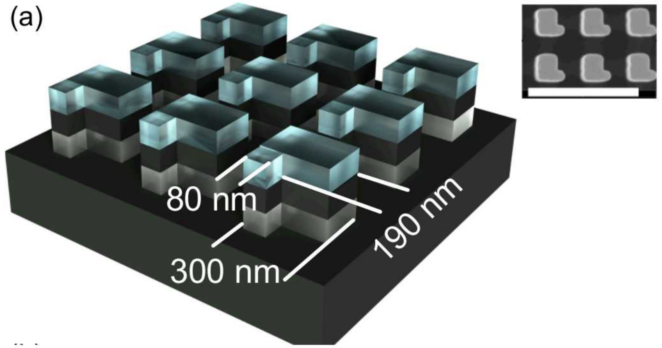
FDTD simulations at the λ = 10.8 μm resonance

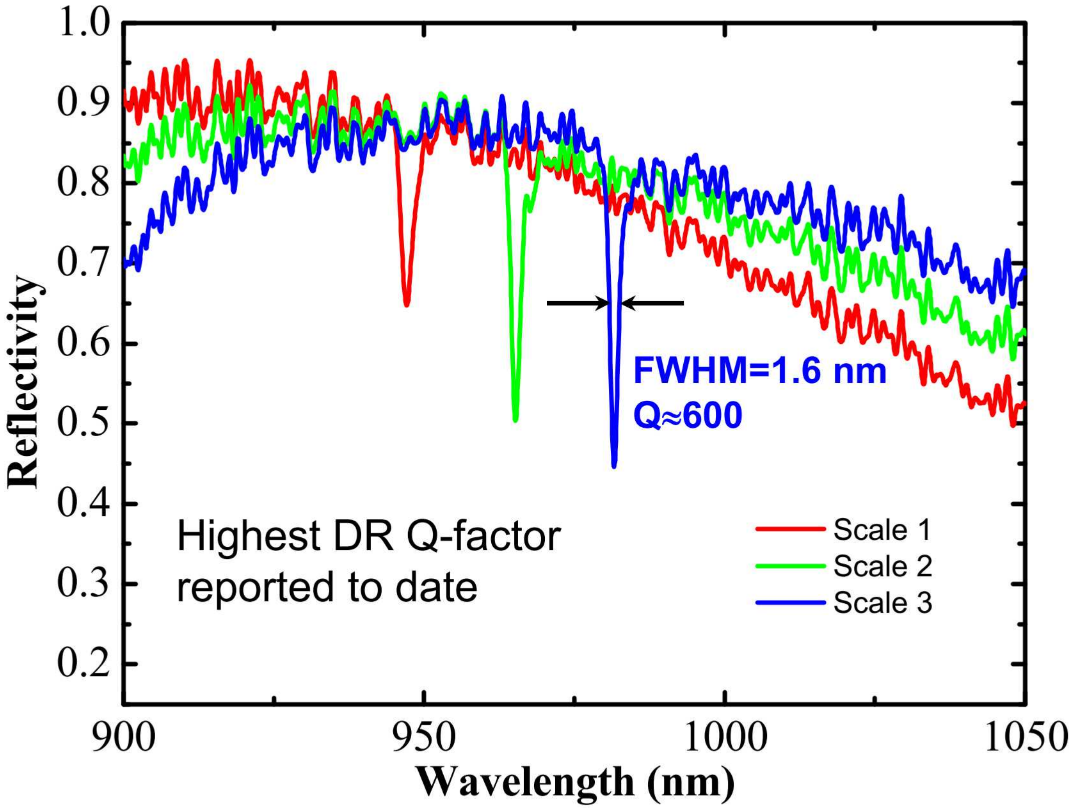


Photoluminescence



GaAs Fano Resonators: Q ≈ 600!





- GaAs is direct bandgap → lower absorption losses
- GaAs has a large $\chi^{(2)}$ → nonlinear devices (SHG, down-conversion, etc.)
- Can incorporate InGaAs quantum wells for gain and photon detection