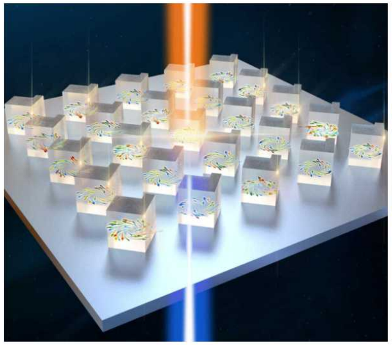
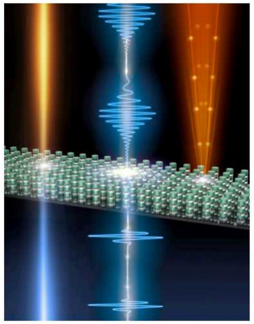
SAND2018-9601C

Ultrafast and Highly Nonlinear Metasurfaces



Igal Brener



Sandia National Labs &
Center for Integrated Nanotechnologies (CINT)

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

MRS 2018

Sandia National Laboratories is a multi mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

SAND2018-2271 C
SAND2017-5558 A

Outline

1. Introduction: all-dielectric metasurfaces

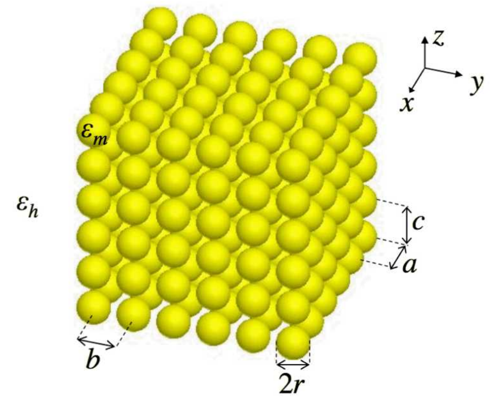
2. Nonlinear Optics using III-V Dielectric Metasurfaces

3. Ultrafast switching using Metasurfaces and Plasmonics

Electromagnetic Properties of a Collection of Dielectric Particles

Clausius-Mossoti or Lorentz-Lorenz

Effective medium approximation



$$\frac{\epsilon_{\mathrm{r}} - 1}{\epsilon_{\mathrm{r}} + 2} = \frac{N\alpha}{3\epsilon_0}$$

polarizability

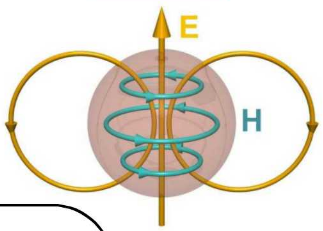
These polarizabilities can come from atoms, molecules or particles

Large changes to polarizabilities typically happen close to resonances

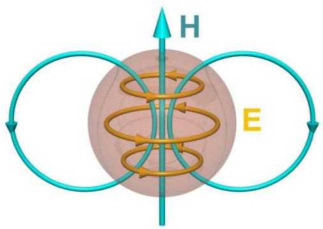
Metamaterials from Dielectric Resonators

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

Electric



Magnetic



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.†

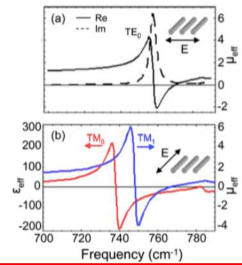
(*The paper was first received* 4*th March, and in revised form* 27*th September*, 1946.)

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 [...] 2 MARC[...]

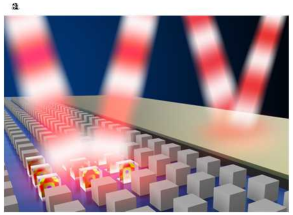
Realizing Optical Magnetism from Dielectric Metamaterials

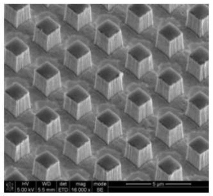
James C. Ginn* and Igal Brener
Sandia National Laboratory, Albuquerque, New Mexico 87185, USA, and Center for Integrated Nanotechnologies, Sandia National Laboratory, Albuquerque, New Mexico 87185, USA

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)

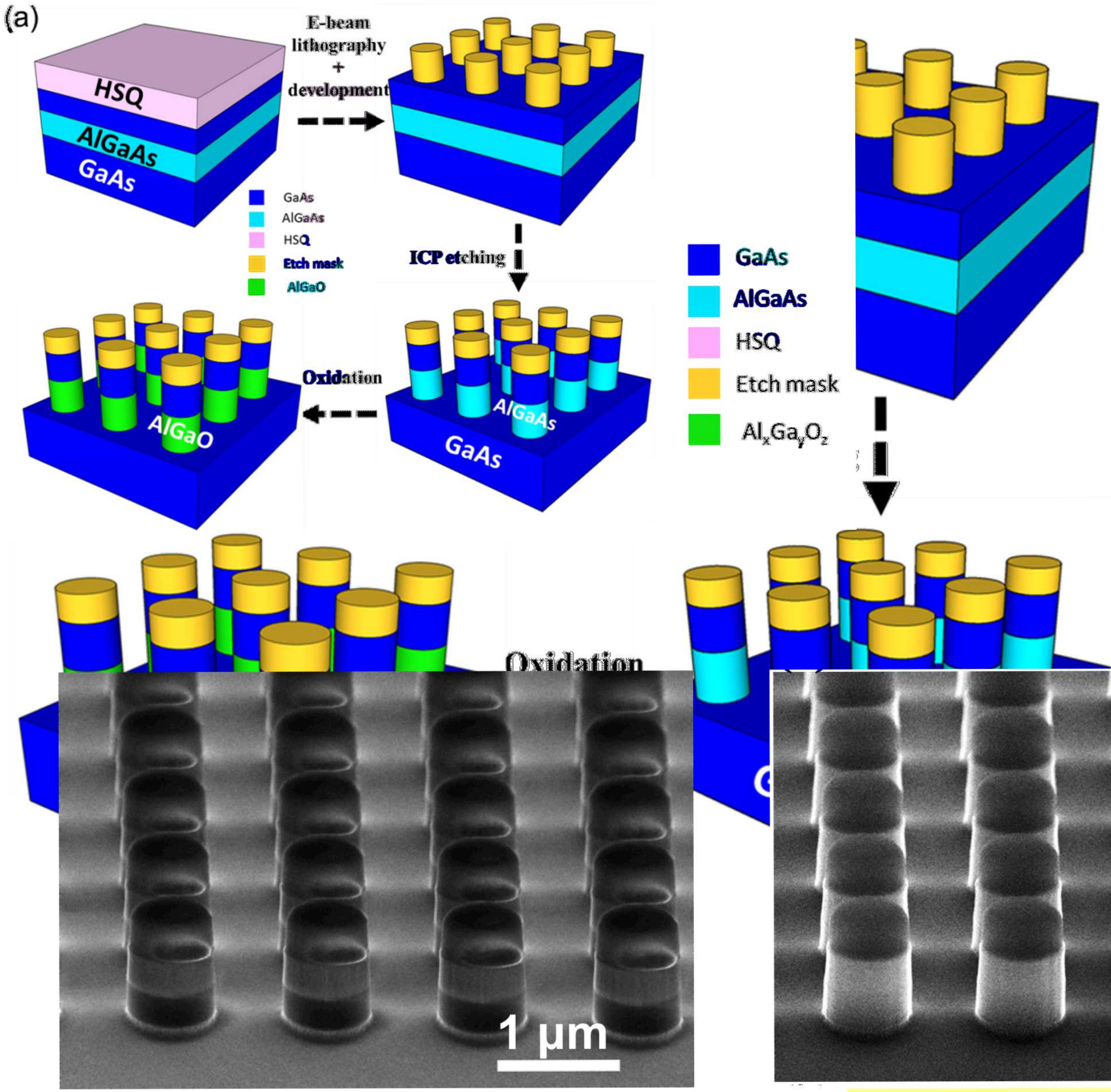
a

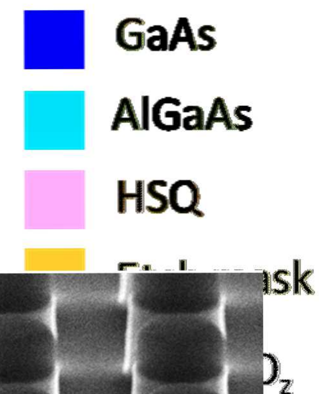


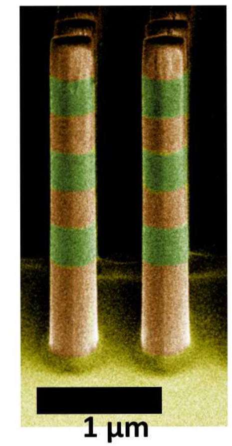


(Al)GaAs based dielectric Metasurfaces

- **Oxidation: AlInAs, AlInGaP, etc**
- **Multilayer structures**







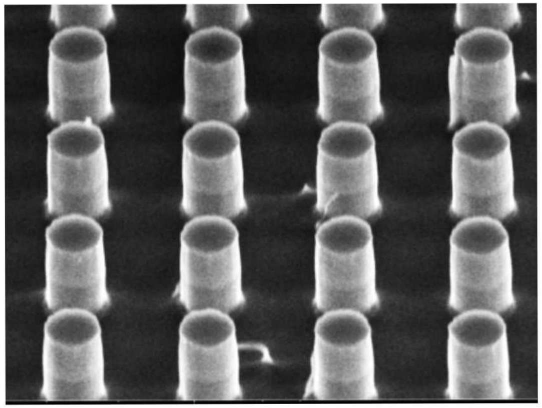
IEEE JSTQE, 3, 916 (1997)

Liu et al, Adv. Opt. Matt 2016

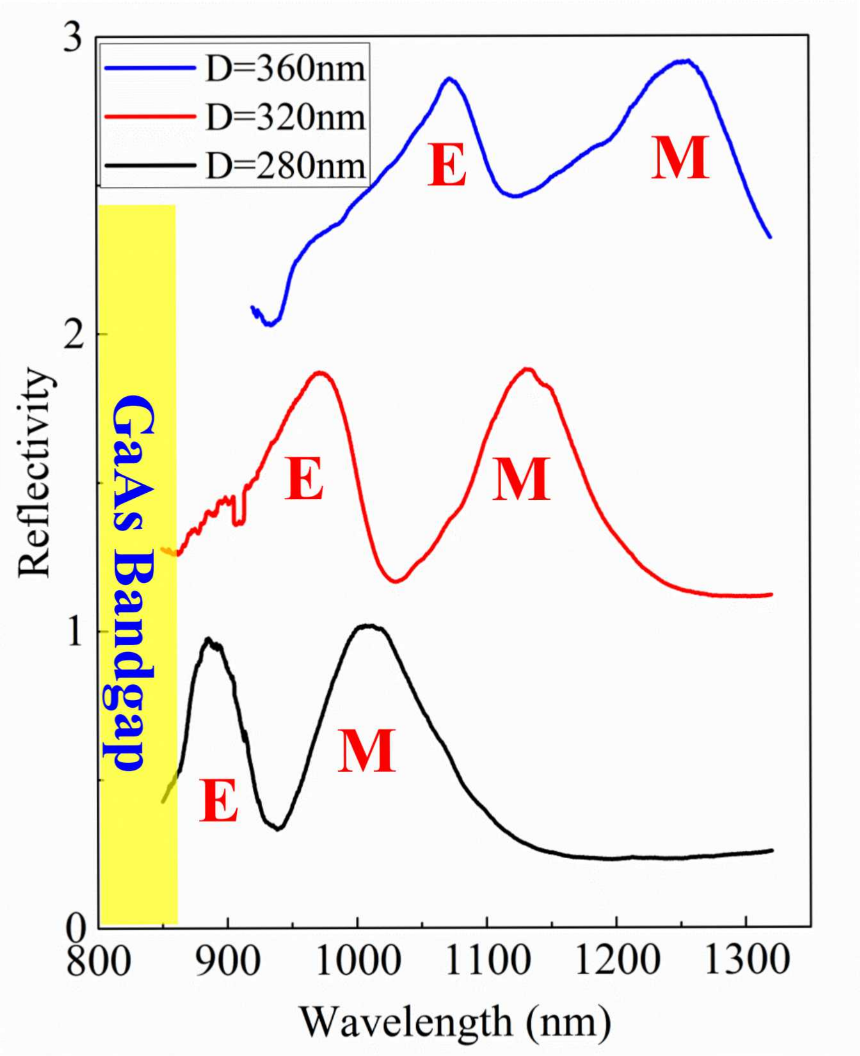
GaAs Metasurface (1 layer)

GaAs disk height ~300nm

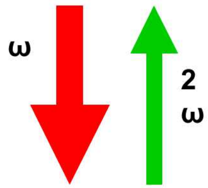
Different diameters

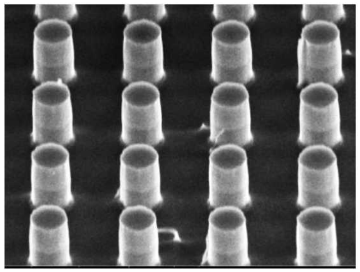


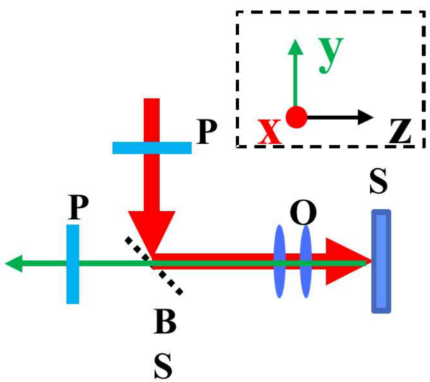
- Extremely low loss below bandgap
- Crystalline

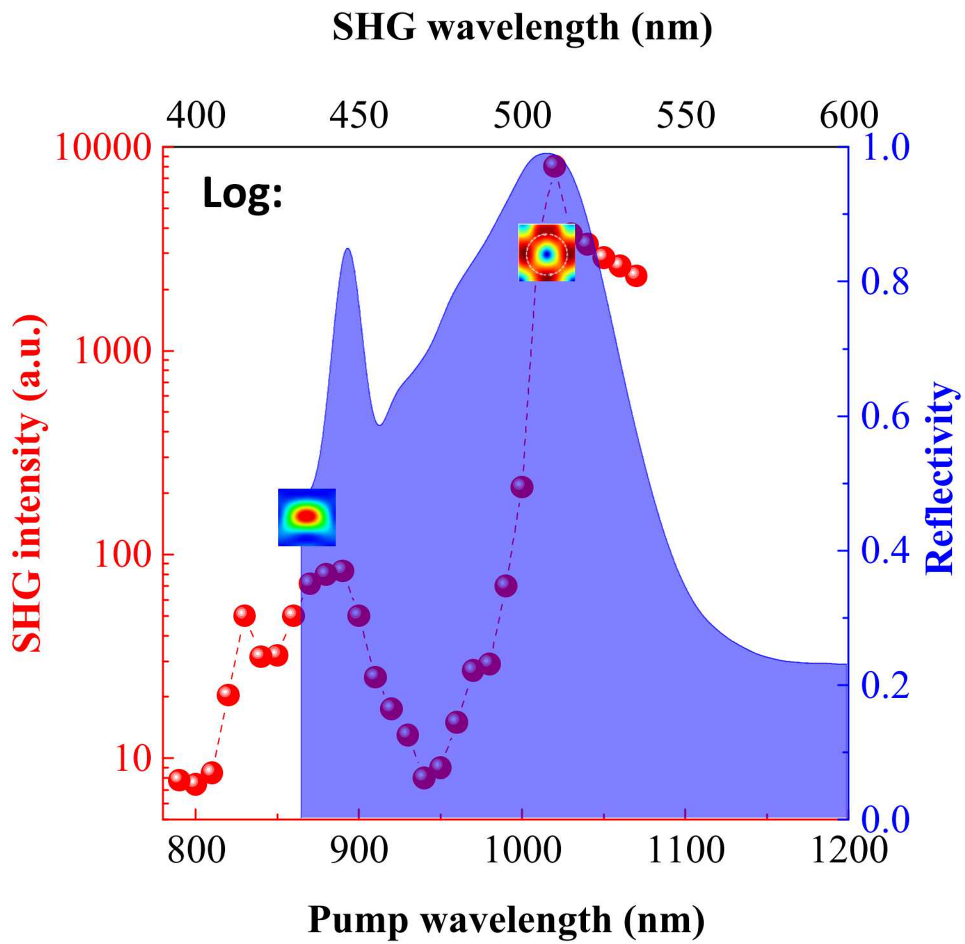


Second Harmonic Generation from GaAs Metasurfaces









Max efficiency ~10^{-5} for I ~3 GW/cm^2

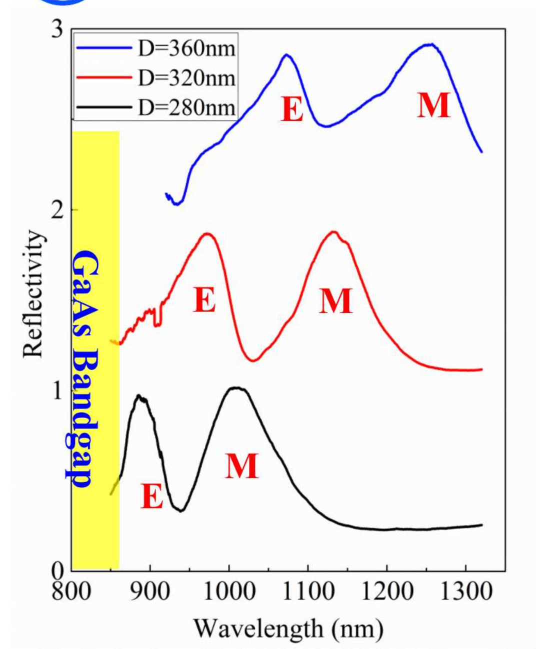
Nano Letters 2016
Also ANU, Costa (Italy)

How to Increase SHG Efficiency from all-Dielectric Metasurfaces

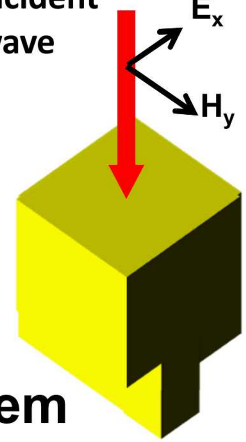
- **Find another high index material with higher $\chi^{(2)}$**
  - **GaAs already has $\chi^{(2)}$> 200pm/V**

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

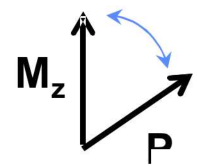
- **Increase Q of resonances ($E_{inside} \propto Q$)**



High Q modes Using "Broken Symmetry" Resonators



=



weakly coupled
orthogonal
dipole
modes

Broken symmetry system

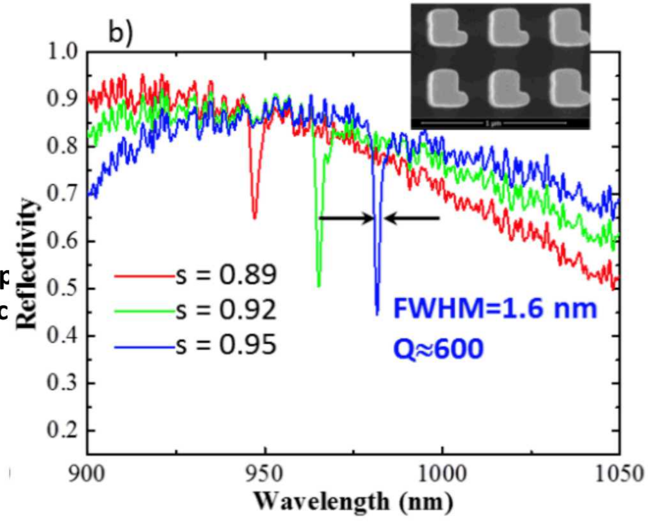
External Wave ⟷ **P_x (low Q)**

Cavity perturbation

M_z (high Q)

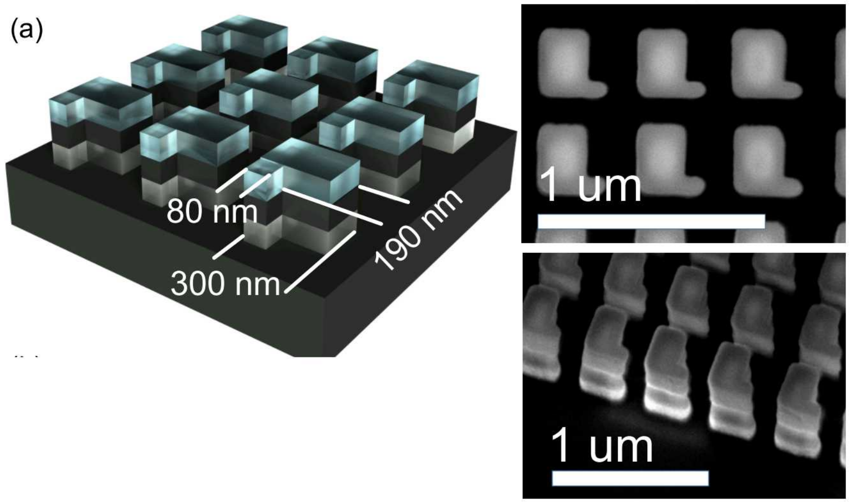
can't radiate in-plane
due to local field interactions

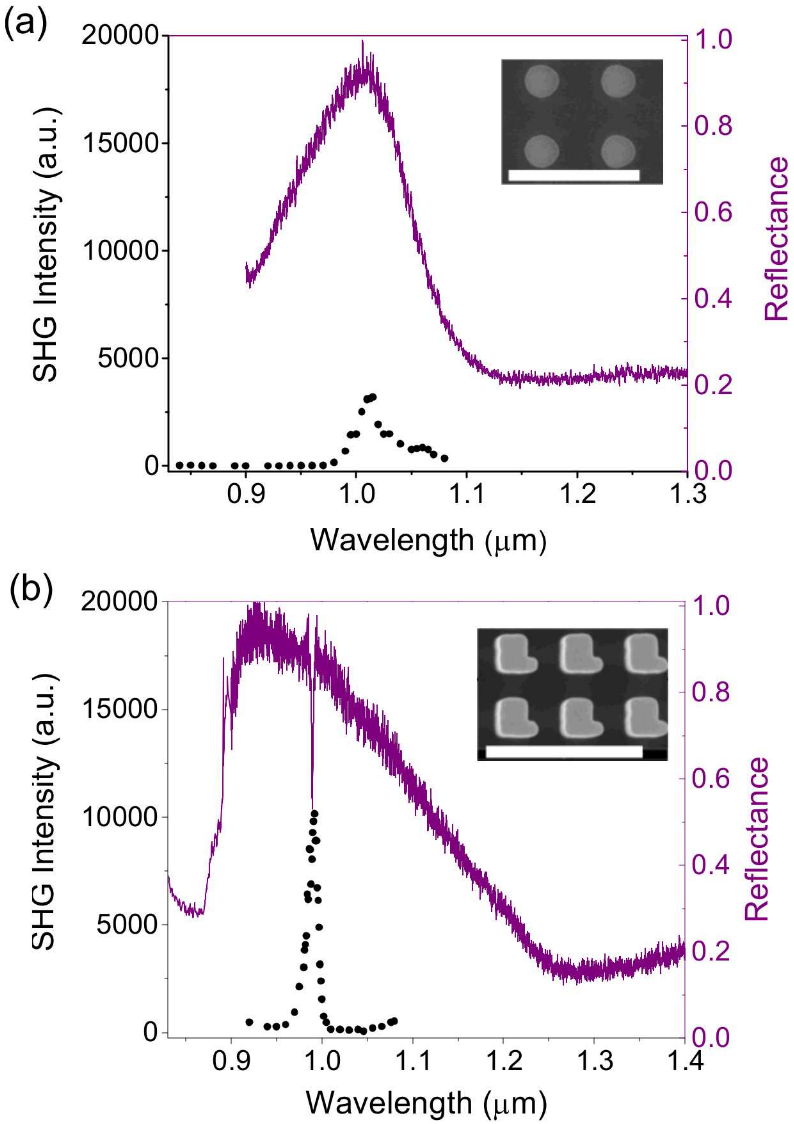
broad dip
resonanc



ACS Photonics 2016

SHG from Broken Symmetry (Fano) Metasurfaces

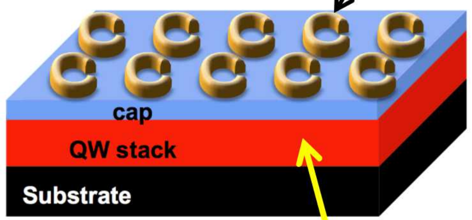


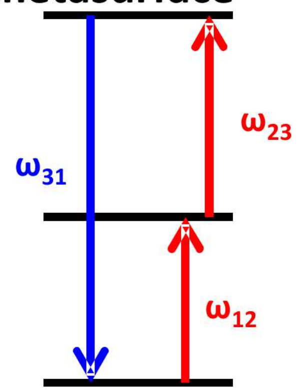


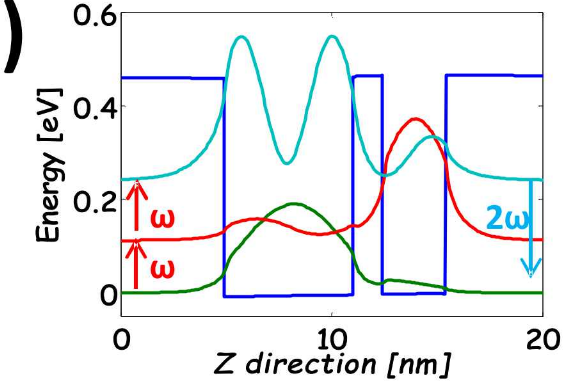
13-fold enhancement of SHG in Fano metasurface compared with the nanodisk metasurface

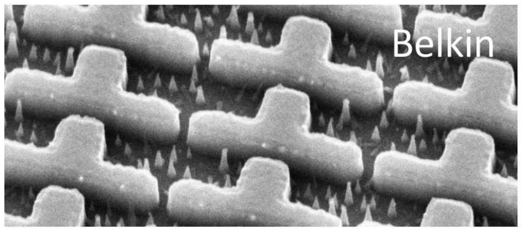
ACS Photonics 2018

Interlude: The highest nonlinearity from metasurfaces (SHG)









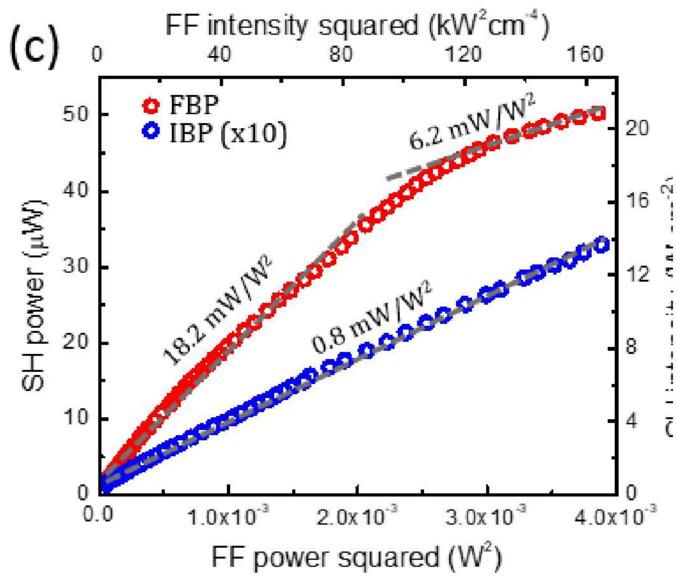
Max efficiency:

Brener (transmission): 2.3 mW/W²

Belkin (reflection, etched resonators): 17 mW/W²

Belkin & Brener 2018, 18.2 mW/W²

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



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

Nonlinear Metasurfaces: Comparison

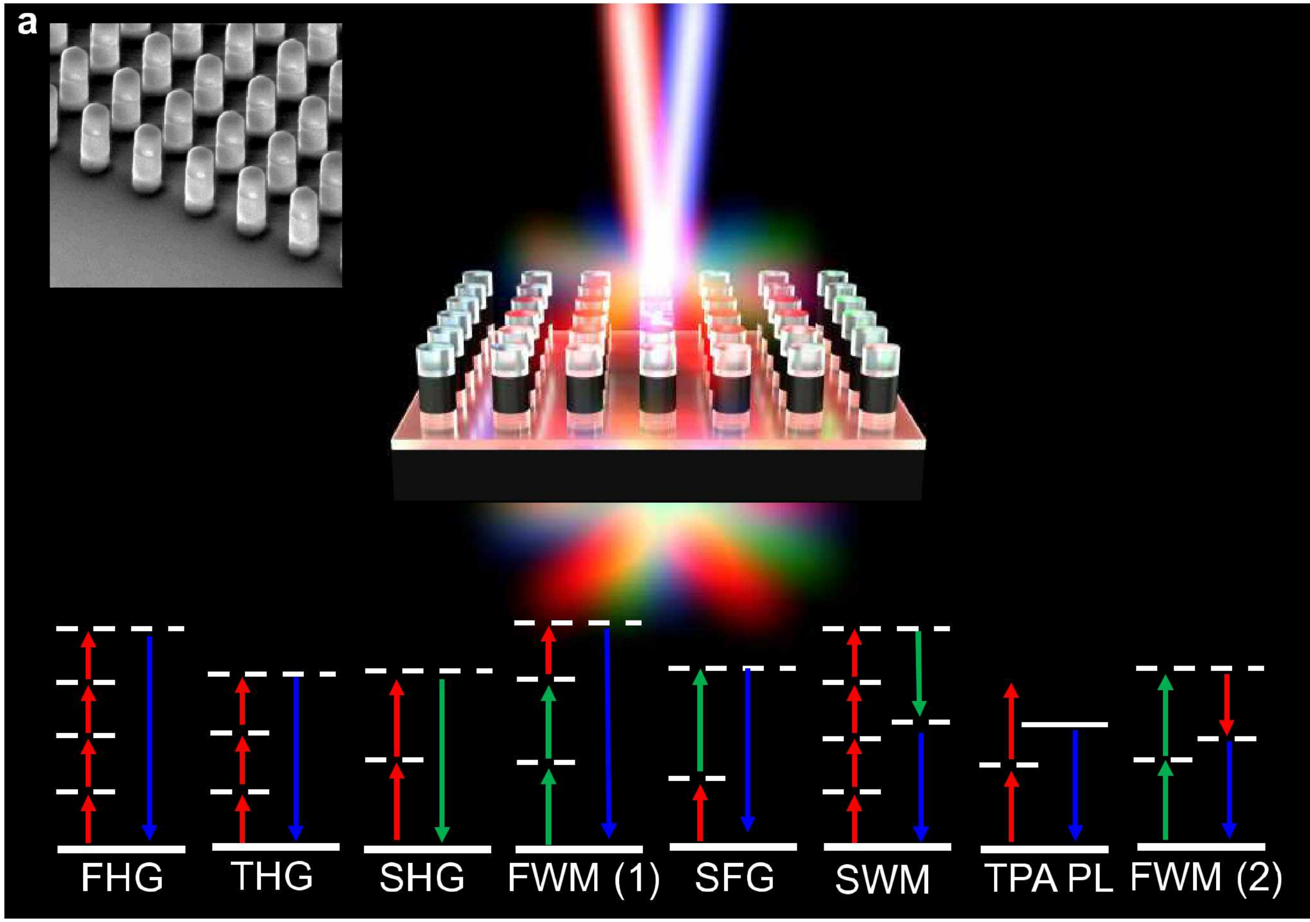
	Metallic MS + Quantum Wells	Mie Resonator MS
Reported nonlinearity	$\sim 10^{-2}$ W/W^2	$\sim 10^{-8}$ W/W^2
"Material" chi(2)	~200 nm/V	~200 pm/V
Mode Depth	$\sim\lambda/20$	$\sim\lambda/n$
Mode overlap and chi(2) utilization	**	* **(**)**
Q	~10	~10 **(1000)**
Saturation and damage threshold	Low	High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

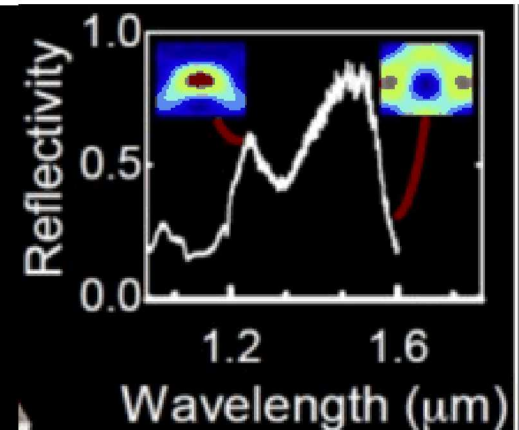
(PPLN ~ 10^{-1} -10^{-2})

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

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

Higher Harmonics:
The "Optical Metamixer"

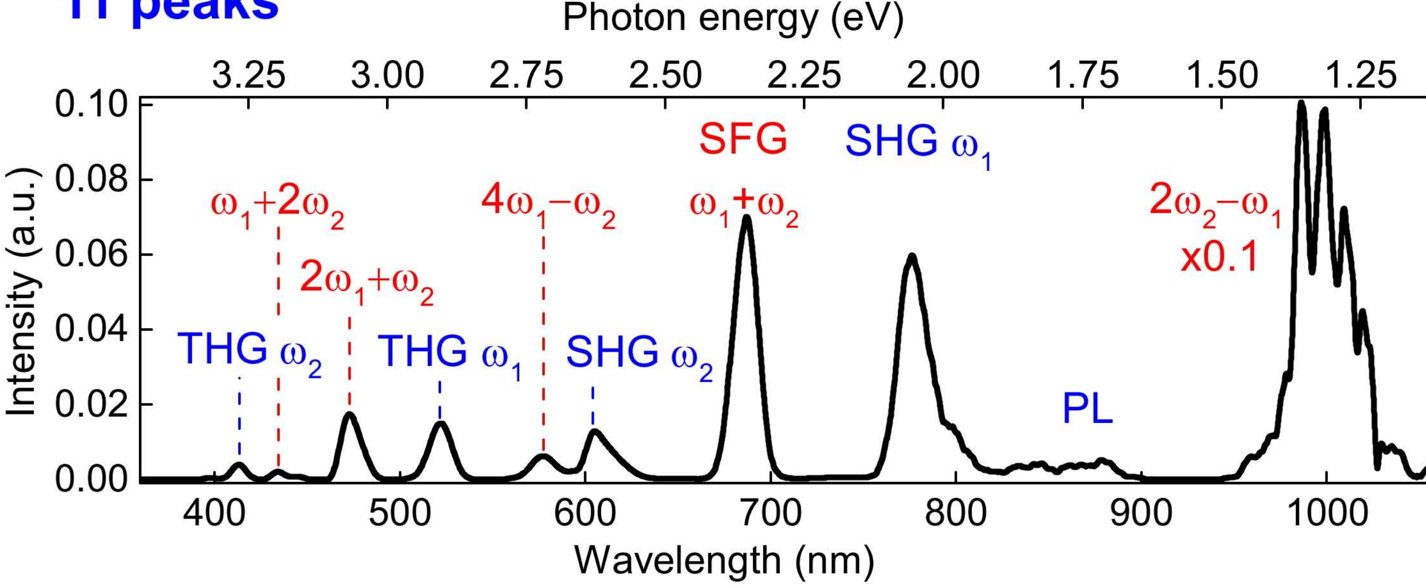


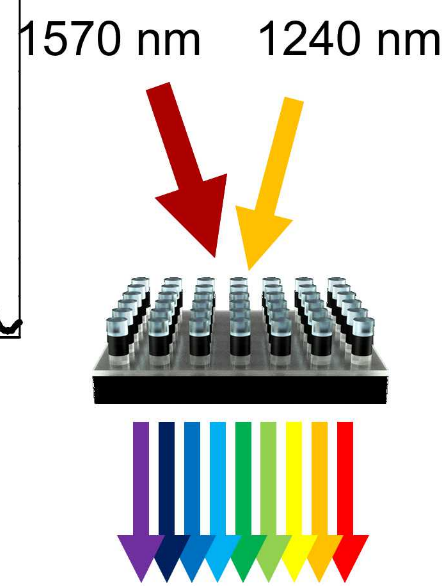


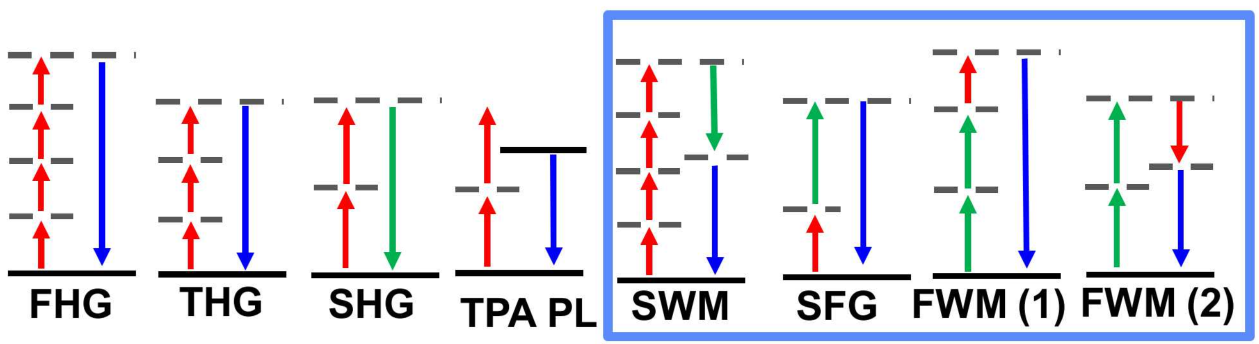
arXiv 2018
accepted Nature Comm. 2018

Frequency mixing spectra

11 peaks



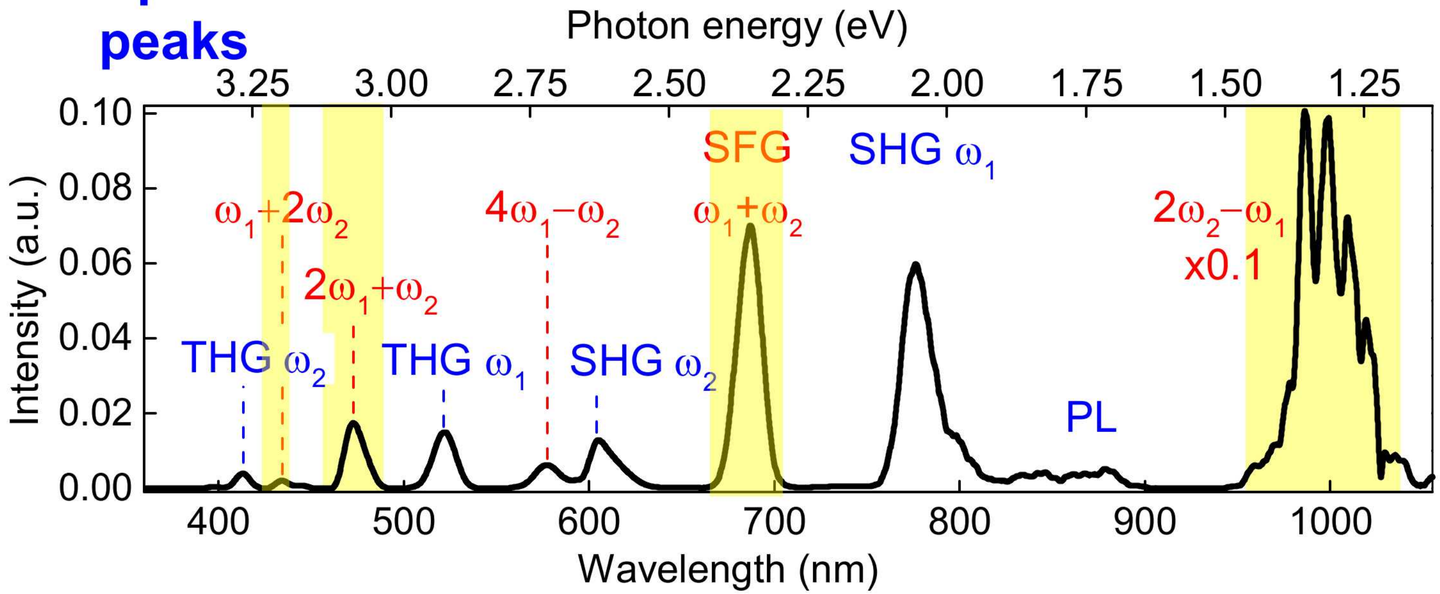


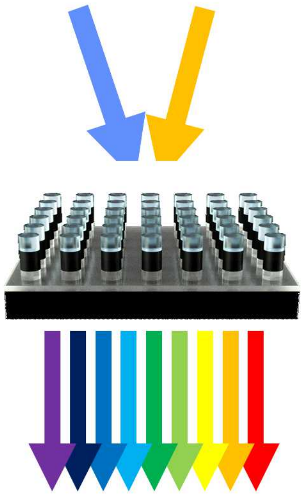


7 different nonlinear processes: 2nd, 3rd, 4th harmonics, sum frequency generation, 4 wave-mixing, six-wave mixing….

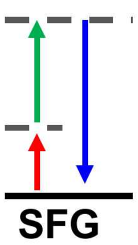
Frequency mixing spectra

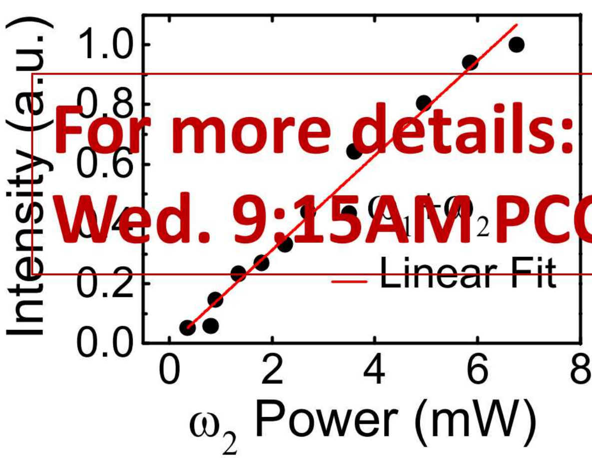
11 spectral peaks

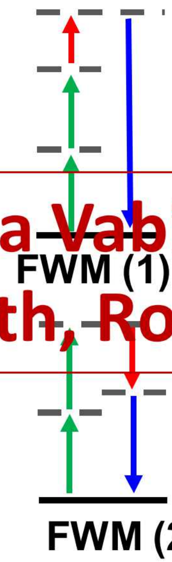




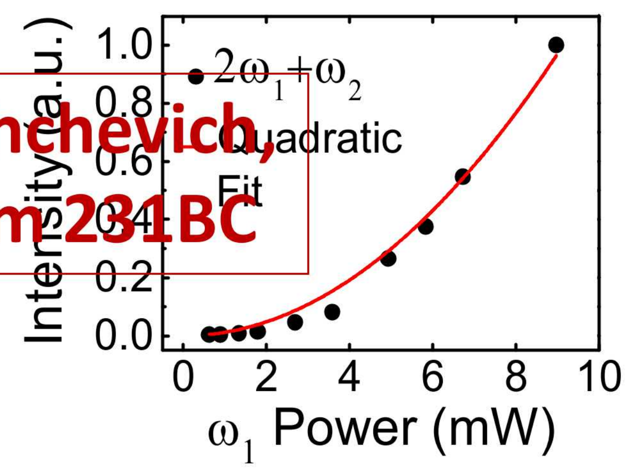
SFG power dependence





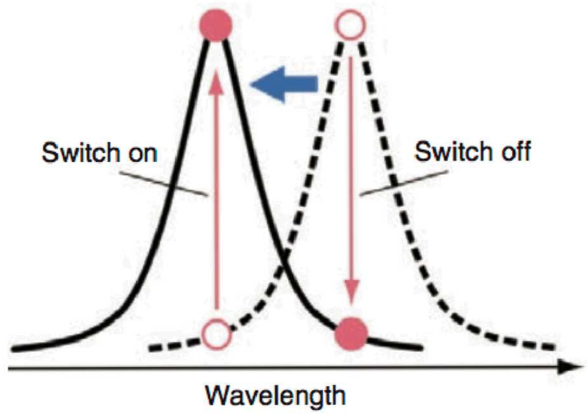


FWM power dependence



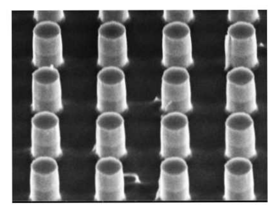
For more details: Polina Vabishchevich, Wed. 9:15AM PCC North, Room 231BC

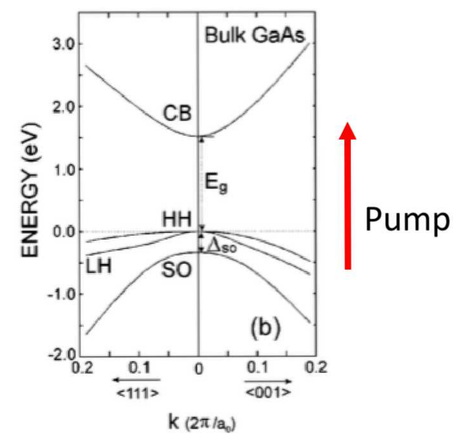
Ultrafast Switching Using Metasurfaces/Plasmonics



NTT Tech. Rev.

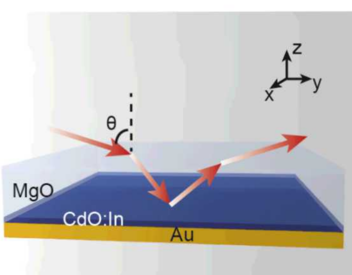
- **Dielectric Metasurfaces**

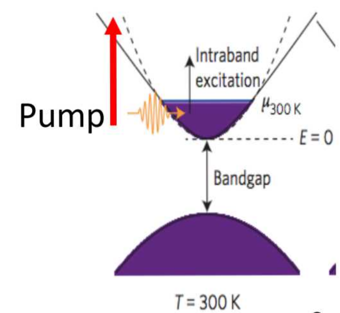




Vurgaftmana
JAPN (2001)

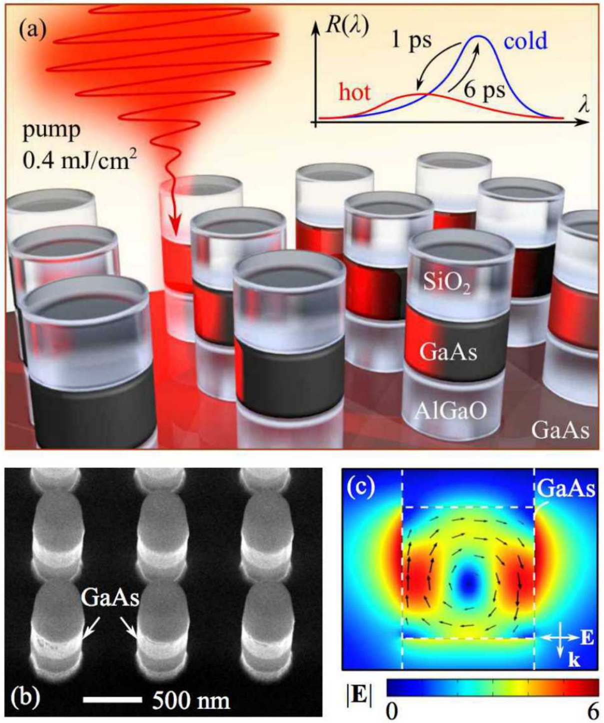
- **Perfect Plasmonic Absorber**



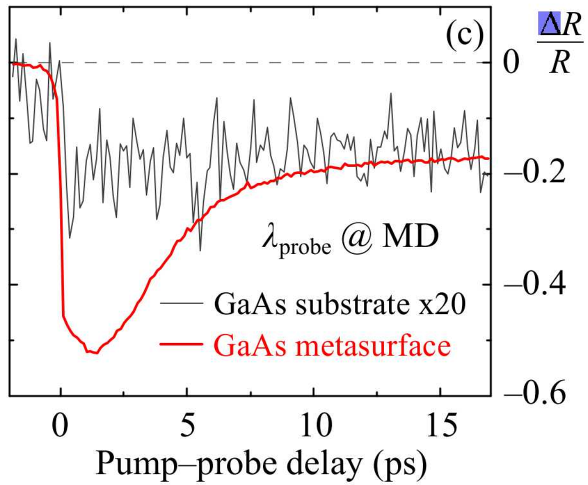


Guo et. al., Nat. Photon, (2016)

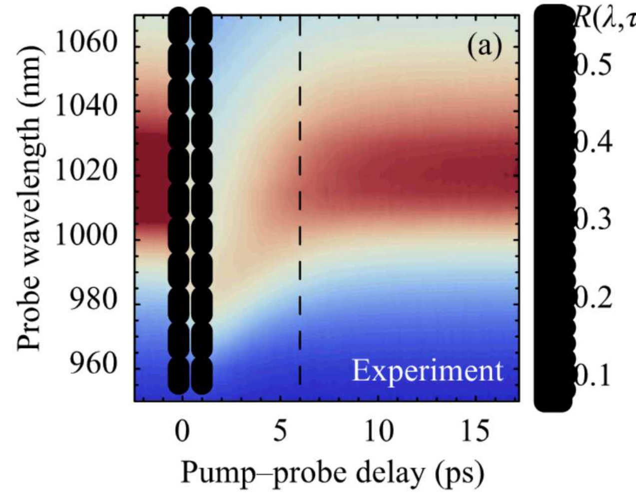
Dielectric Metasurface: Ultrafast Tuning of Magnetic Dipole Mode

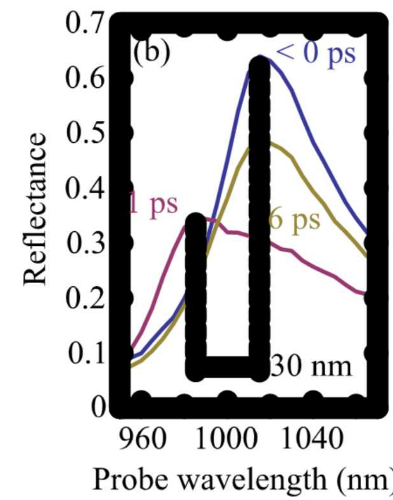


Modulation 50x of substrate



Resonance tuning by 30 nm

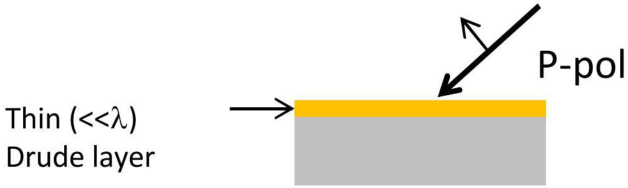


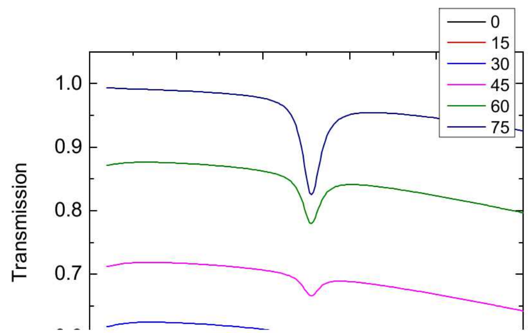


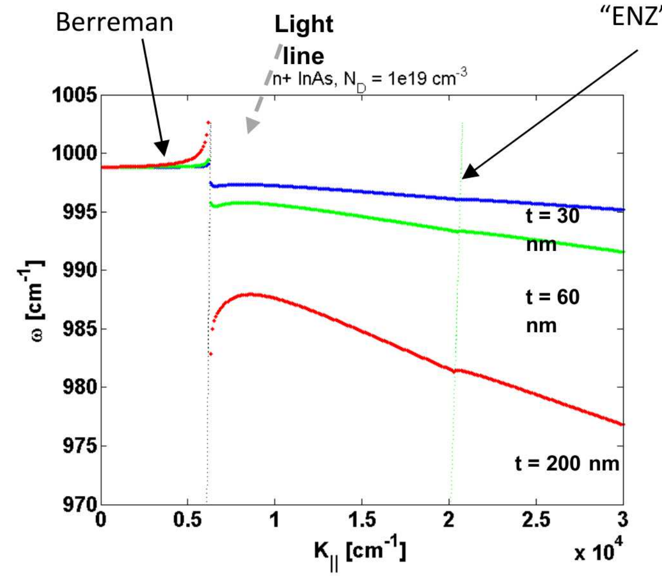
- **Fast recovery due to surface recombination (~2.5 ps from low power expts)**
- **Maximum index modulation is –0.14 due to Drude dispersion and band filling effects**

Nat. Comm. 2017

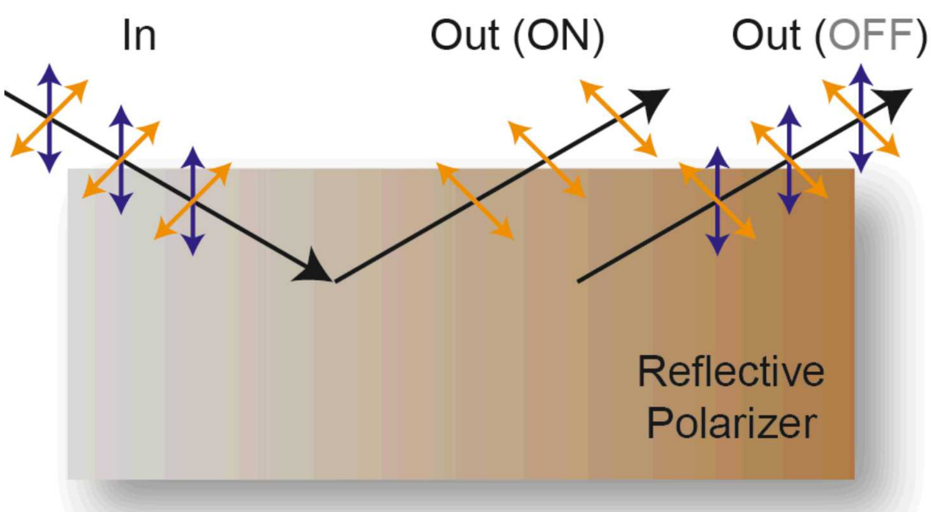
Plasmonic Perfect Absorber: Ultrafast Switching

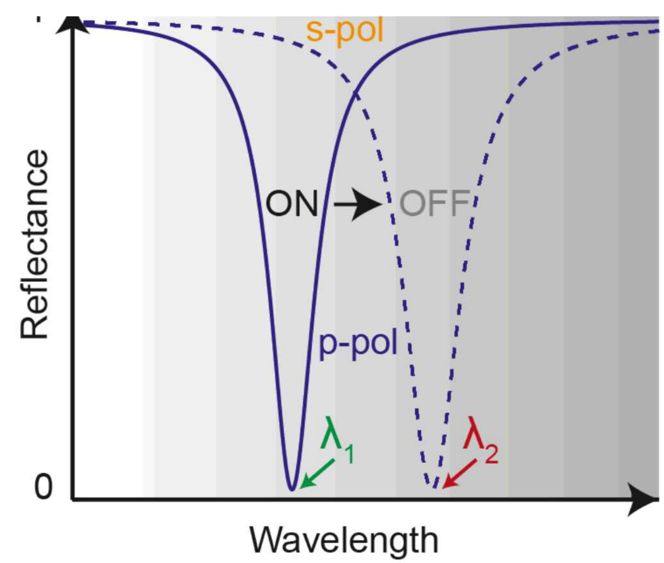






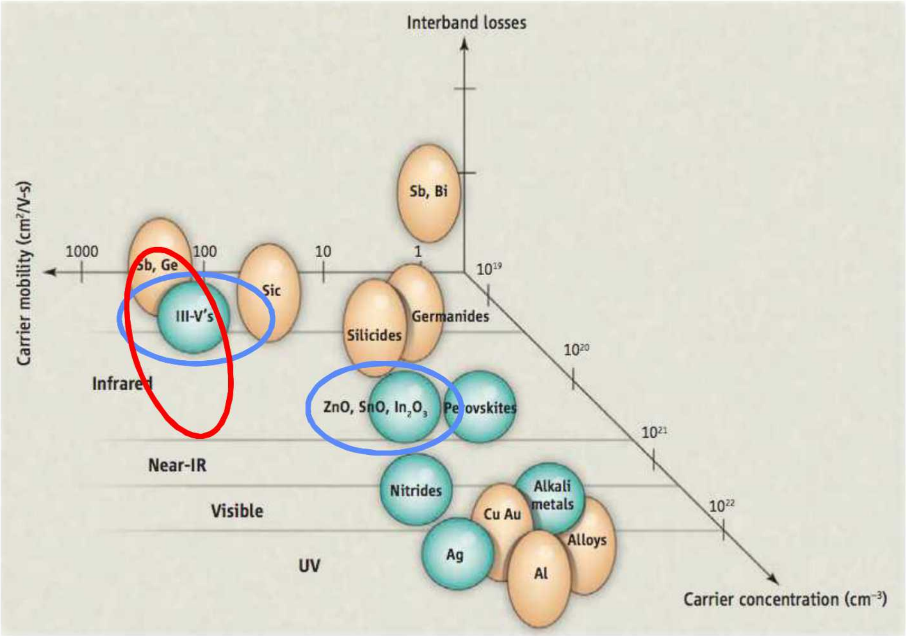
Concept of a switchable reflective polarizer:



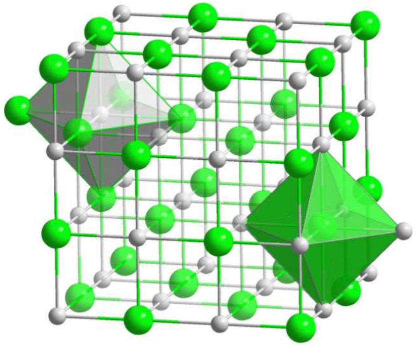


Nat. Phot. 2017

Doped CdO
An Amazing Plasmonic Material!



Boltasseva & Atwater, Science 331, 290 (2011)



http://chemistry.stackexchange.com/questions/23673/rock-salt-structure

- **Cubic rocksalt lattice (similar to NaCl)**
- **n-doping (In populates the Cd sublattice with a 3^+ charge)**

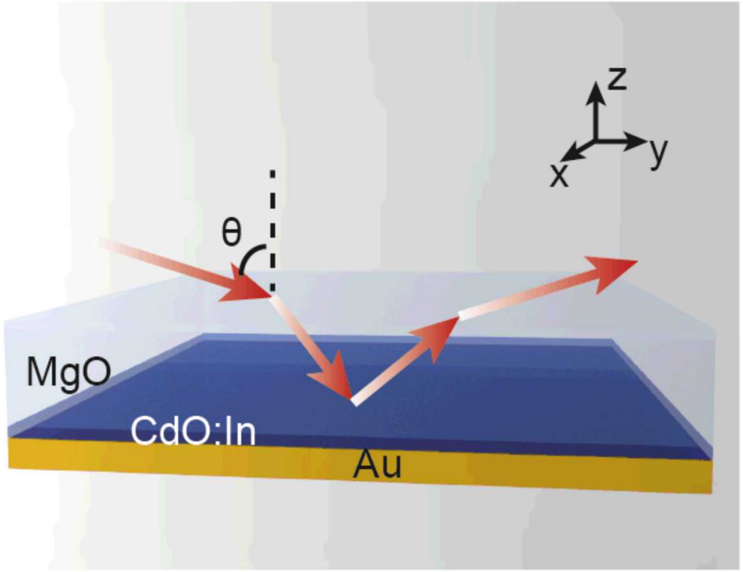
- Doping density can reach > 10^{20}cm^{-3}
- Plasma frequency tunable from near to long IR
- Mobilities in the 100's, sometimes comparable with III-V's.

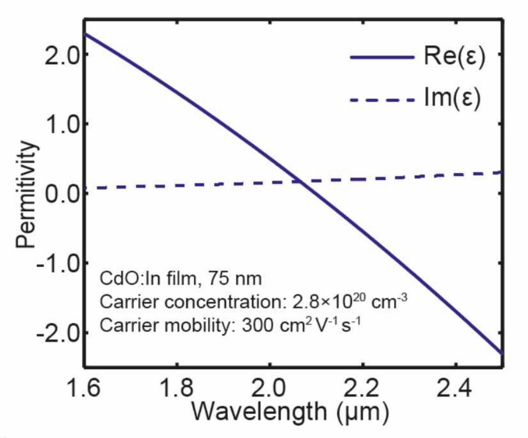
Material	Carriers [cm^{-3}]	Mobility [cm^2/V·s]	ε_1=0 [cm^{-1}]	ε_2 at ε_1=0	ε_2 at ε_1=-2
CdO:Dy	9.94×10^{19}	474	2770	0.19	0.30
CdO:Dy	3.70×10^{20}	359	5350	0.13	0.20
AZO (2 wt%)[4]	7.2×10^{20}	48	6970	0.21	0.39
ITO (10 wt%)[4]	7.7×10^{20}	36	7122	0.69	1.29

J-P Maria, NC State

Sachet et. al., Nat. Mat (2015)

CdO-based Perfect Absorber

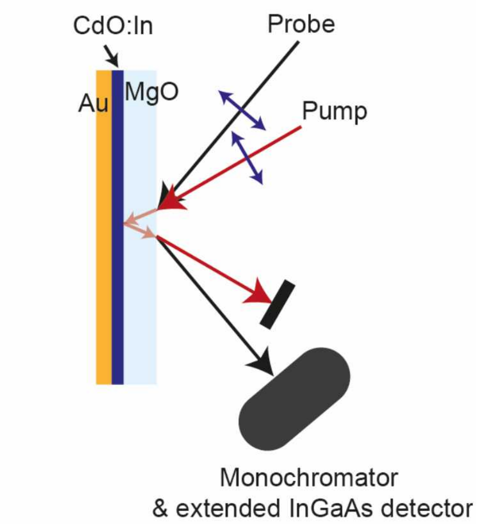


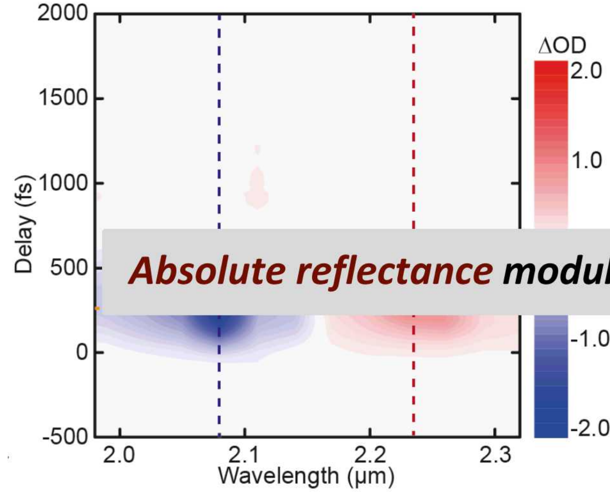


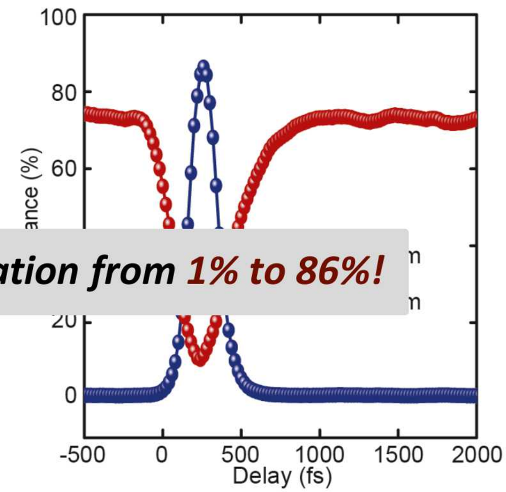
Sachet et. al., Nat. Mat (2016)

- **Berreman-type perfect absorber for p-polarized incident light at 50 degrees.**
- **>90% reflectance for s-polarized light.**

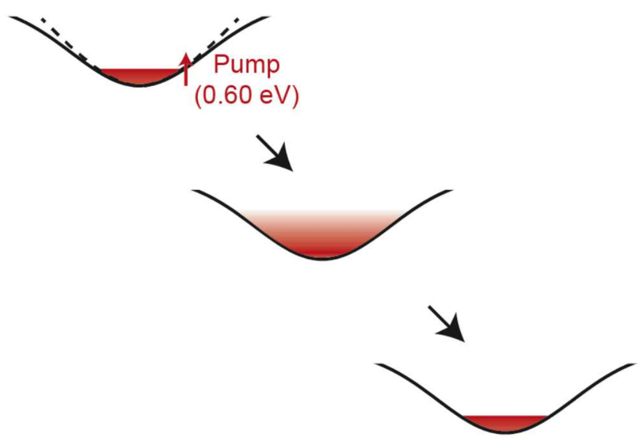
Ultrafast **Amplitude Switching** of the **Perfect Absorber**

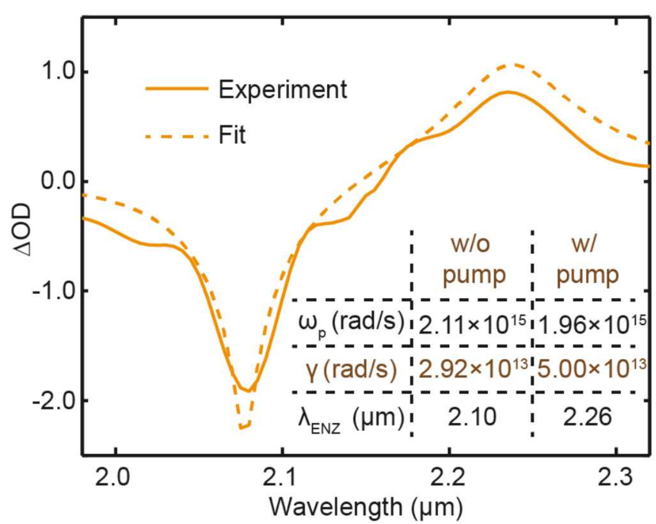






Absolute reflectance** modulation from **1% to 86%!





Nat. Phot. 2017

Acknowledgments

Departed postdocs: Omri Wolf , Yuanmu Yang
Current postdocs: Polina Vabishchevich, Raktim Sarma

CINT + Sandia: Salvo Campione, Sheng Liu (*), John Reno, Greg Peake, Mike Sinclair, Gordon Keeler (*),…

ANU: Yuri Kivshar, Dragomir Neshev, Andrey Miroshnichenko, Isabelle Staude, Katie Chong, Manuel Decker, ….

Jena: Isabelle Staude, Aleks Vaskin, Sinca Saravi

Moscow State: Maxim Shcherbakov, Andrey Fedyanin

NC State/Penn State: JP Maria

U.S. DEPARTMENT OF ENERGY | Office of Science