SAND2016-2869C

Nonlinear Optical Metasurfaces

--dielectric metasurfaces

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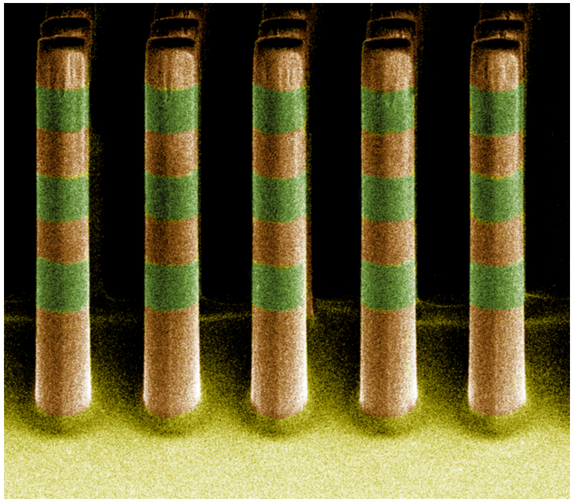
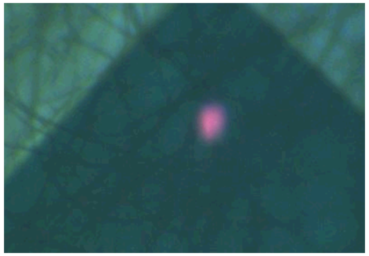
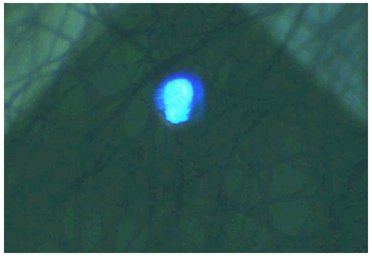


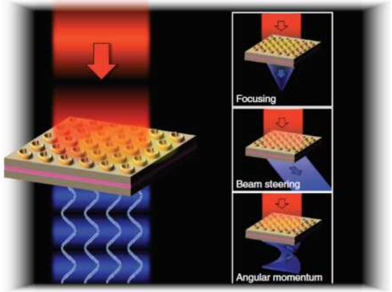




This work was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. Department of Energy, Office of Basic Energy Sciences user facility. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

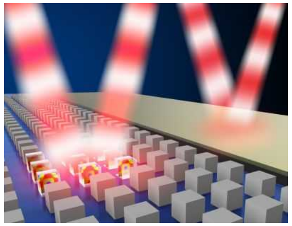
Outline

- Nonlinear optics.
- Nonlinear optical phenomena in nanostruc materials.

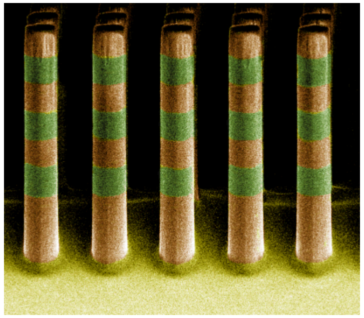


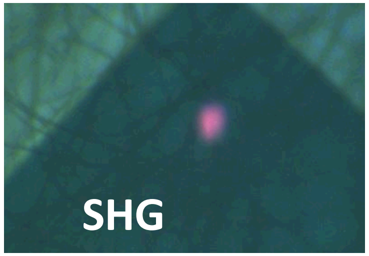
10.1038/ncomms 8667

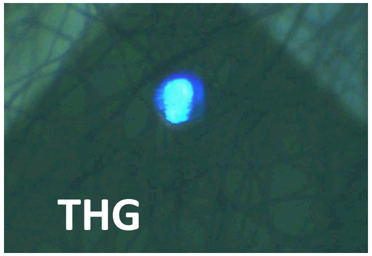
- Dielectric metasurfaces and metamaterials.
- Dielectric metasurfaces and quasi-3D metamaterials using III-V semiconductors
- SHG in GaAs all-dielectric metasurfaces
- Third-harmonic generation in GaAs all-dielectric metasurfaces
- Conclusions



Optica, 1, 250 (2014)

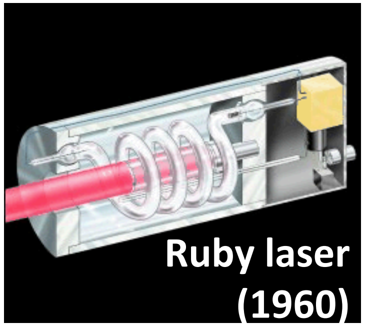


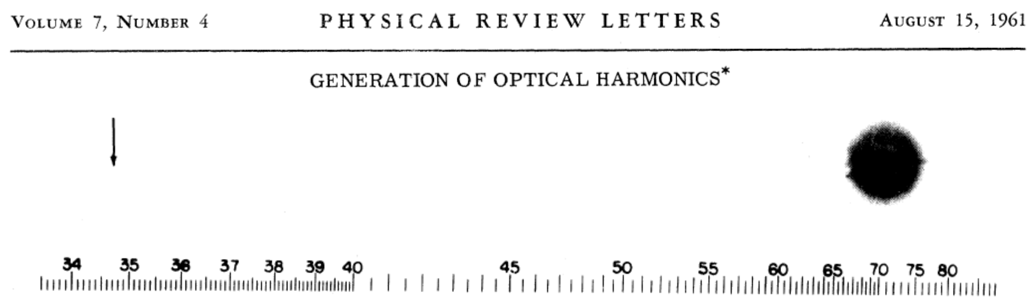




Nonlinear optics

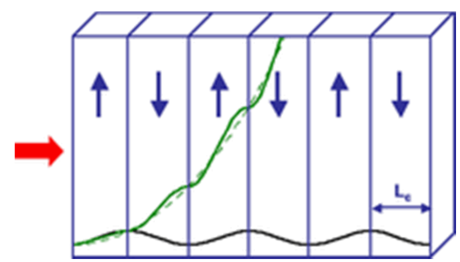
- Lasers → nonlinear optical processes





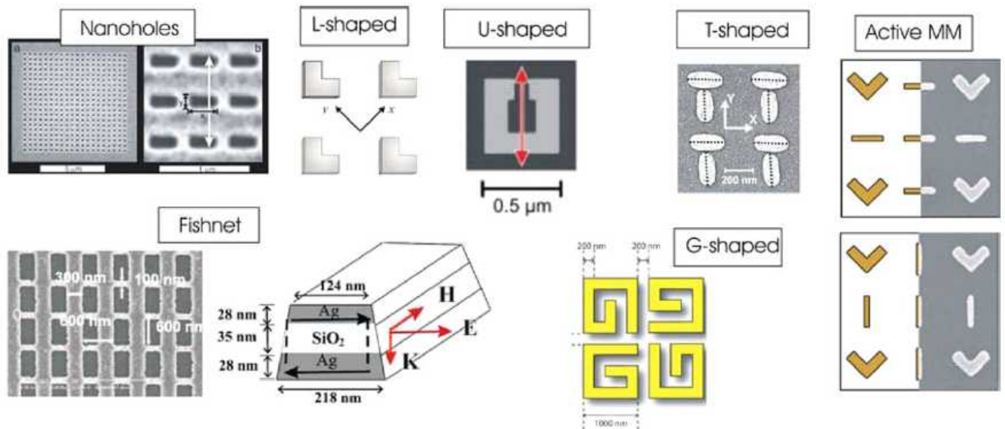
- Nonlinear optical processes → lasers (greatly broaden the spectral range we can access with lasers) (SHG, THG, parametric down conversion, four-wave mixing, Kerr effect: ultrafast pulses, supercontinuum)

- Conventional nonlinear optics: bulk nonlinear crystal—phase matching, quasi-phase matching etc.



Nonlinear optical phenomena in nanostructured materials

- Nonlinear optical properties of new materials/structures
- Nanostructured materials: plasmonic, 2D materials, etc



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

- Tight confinement
- Resonant enhancement of EM field

nature photonics

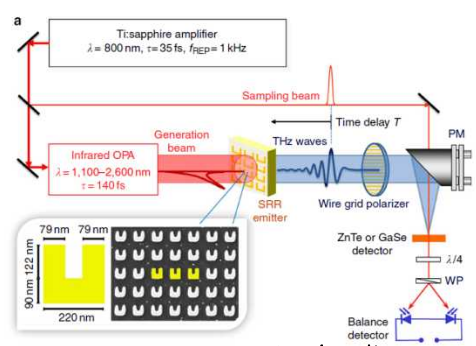
FOCUS | REVIEW ARTICLES

PUBLISHED ONLINE: 31 OCTOBER 2012 | DOI: 10.1038/NPHOTON.2012.244

Nonlinear plasmonics

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

SHG, THG, THz generation



Outline

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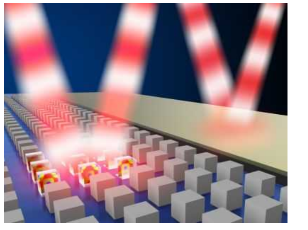
- Nonlinear optical phenomena in nanostructured materials.
- Dielectric metasurfaces and metamaterials.



Optica, 1, 250 (2014)

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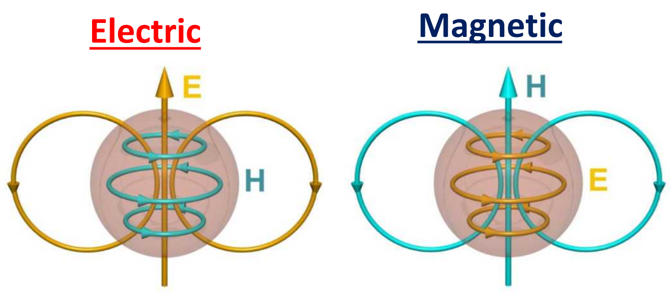
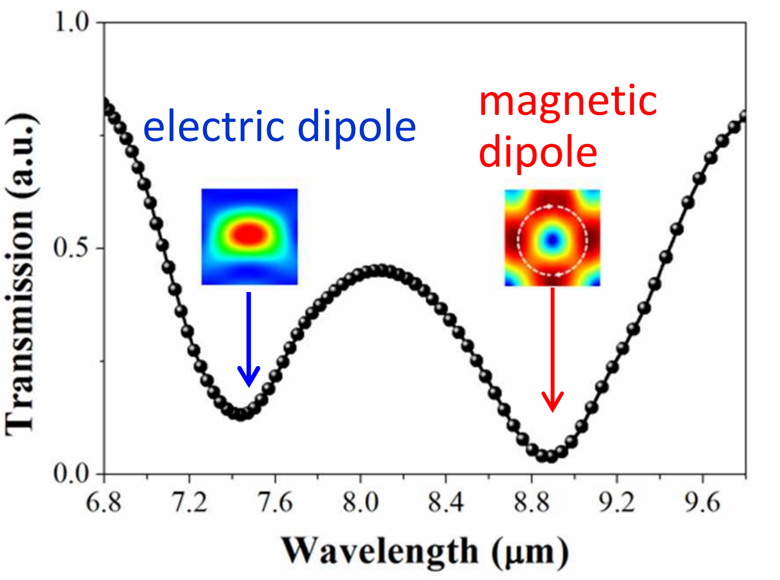
Dielectric Resonators

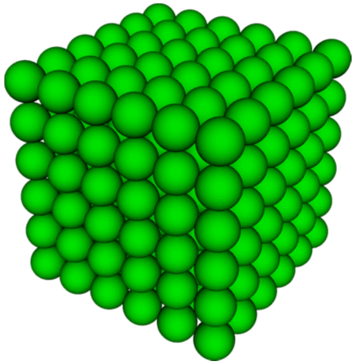


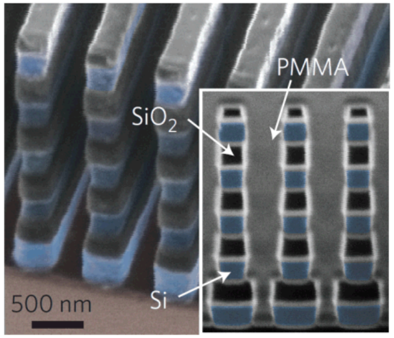
Images: A. Miroshnichenko

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

Much lower loss at optical frequencies





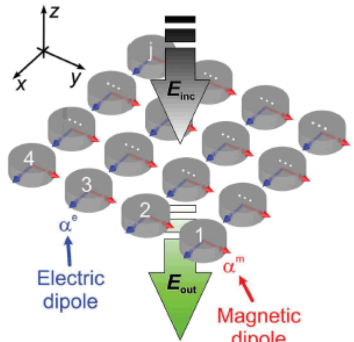


Jason Valentine

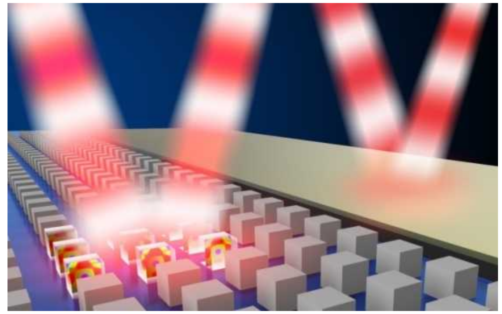
3D structure is possible
Isotropic response can be achieved

Applications of dielectric metasurfaces and metamaterials

Huygens principle:

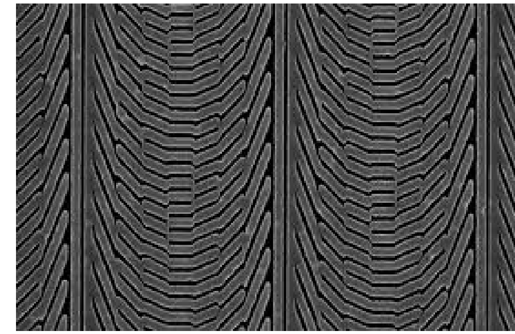


Magnetic mirror



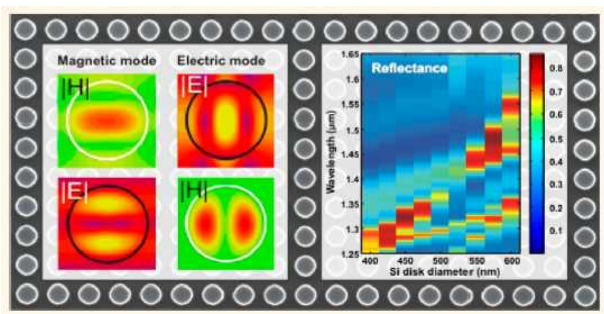
Sheng Liu

Ultrathin gratings, lenses, axicons

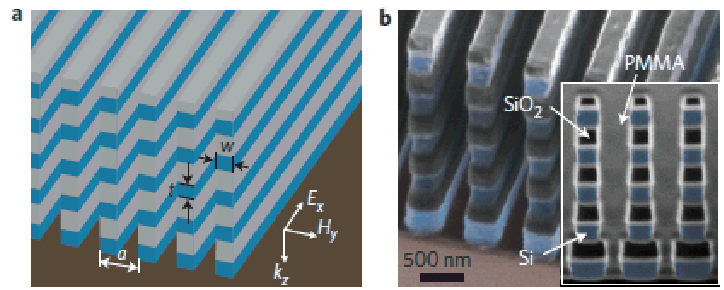


Mark L. Brongersma

Directional emission

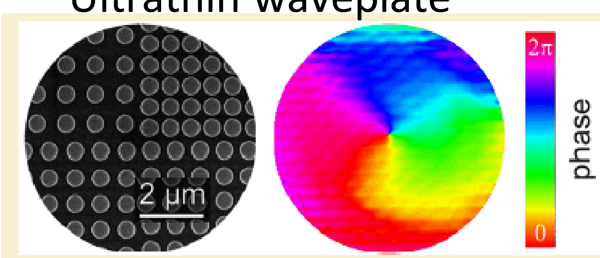


Zero index: directional emission



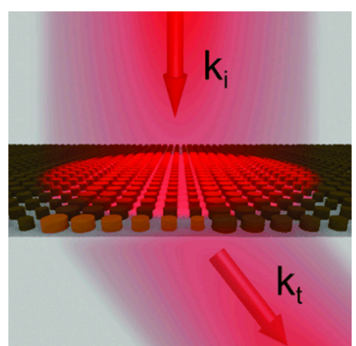
Jason Valentine

Ultrathin waveplate



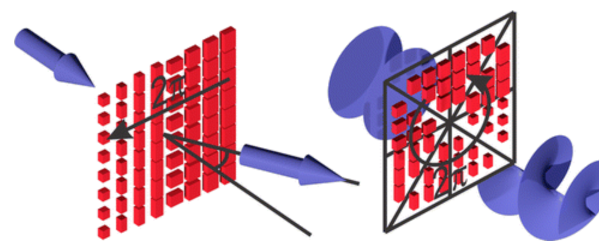
Yuri Kivshar

Beam deflection



Arseniy I. Kuznetsov

Beam steering, vortex converter



Natalia M. Litchinitser

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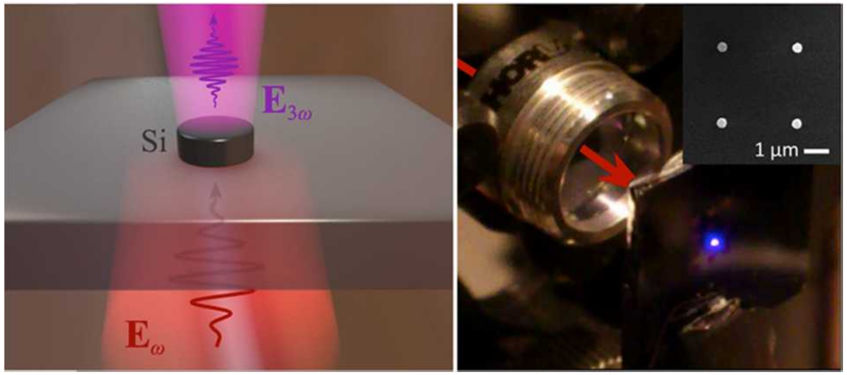
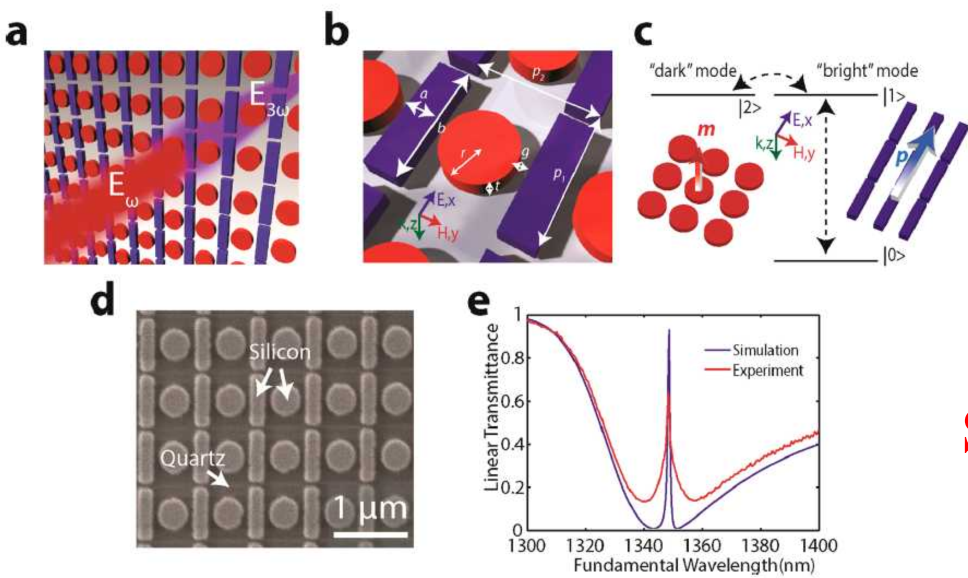
Third-harmonic generation in Si dielectric metasurfaces



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



Nano Lett., **2014**, *14* (3), pp 1394–1399

~~?? Second-order nonlinear optical processes:~~
- ~~SHG~~
- ~~sum-frequency generation~~
- ~~difference-frequency generation~~
- ~~Parametric down conversion, etc~~

Silicon: centrosymmetric

Non-centrosymmetric materials are needed

Other limitations of Si (other than centrosymmetric)

Silicon is great!!! But ……

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

nature photonics LETTERS
PUBLISHED ONLINE: 25 AUGUST 2013 | DOI: 10.1038/NPHOTON.2013.214

III-V (AlGaAs, InGaAs, GaAs) semiconductors:
- **large nonlinear susceptibilities**
- **direct bandgap (active devices)**

For active devices

- Inefficient light emission (hard to incorporate active media)

3D & No flip chip bonding?

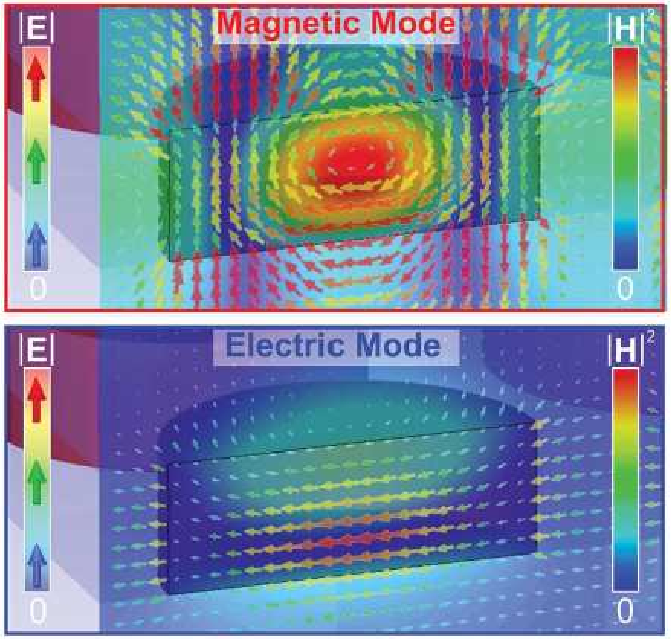
GaAs based disk resonators

Demonstration of Zero Optical Backscattering from Single Nanoparticles

Steven Person,† Manish Jain,† Zachary Lapin,‡,† Juan Jose Sáenz,§ Gary Wicks,† and Lukas Novotny*,‡,†

flip-chip bonding to fused silica

Fabrication of (Al)GaAs based dielectric MM



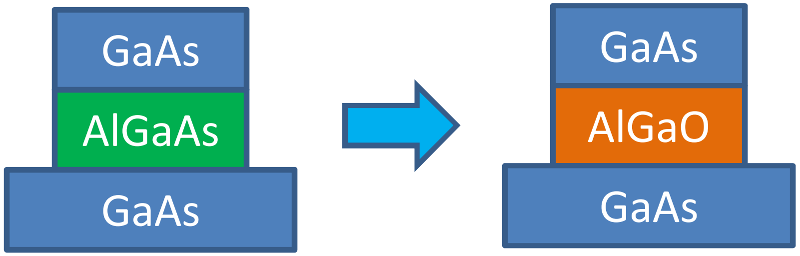
Engineering ε & μ:
high confinement of electromagnetic filed inside resonators

Low refractive index surrounding!

Silicon on SiO_2
Silicon on sapphire substrate
Flip-chip process onto low n substrate

Epitaxially grown III-V semiconductors have similar n of ~3

Their native oxides have low n: ~1.5



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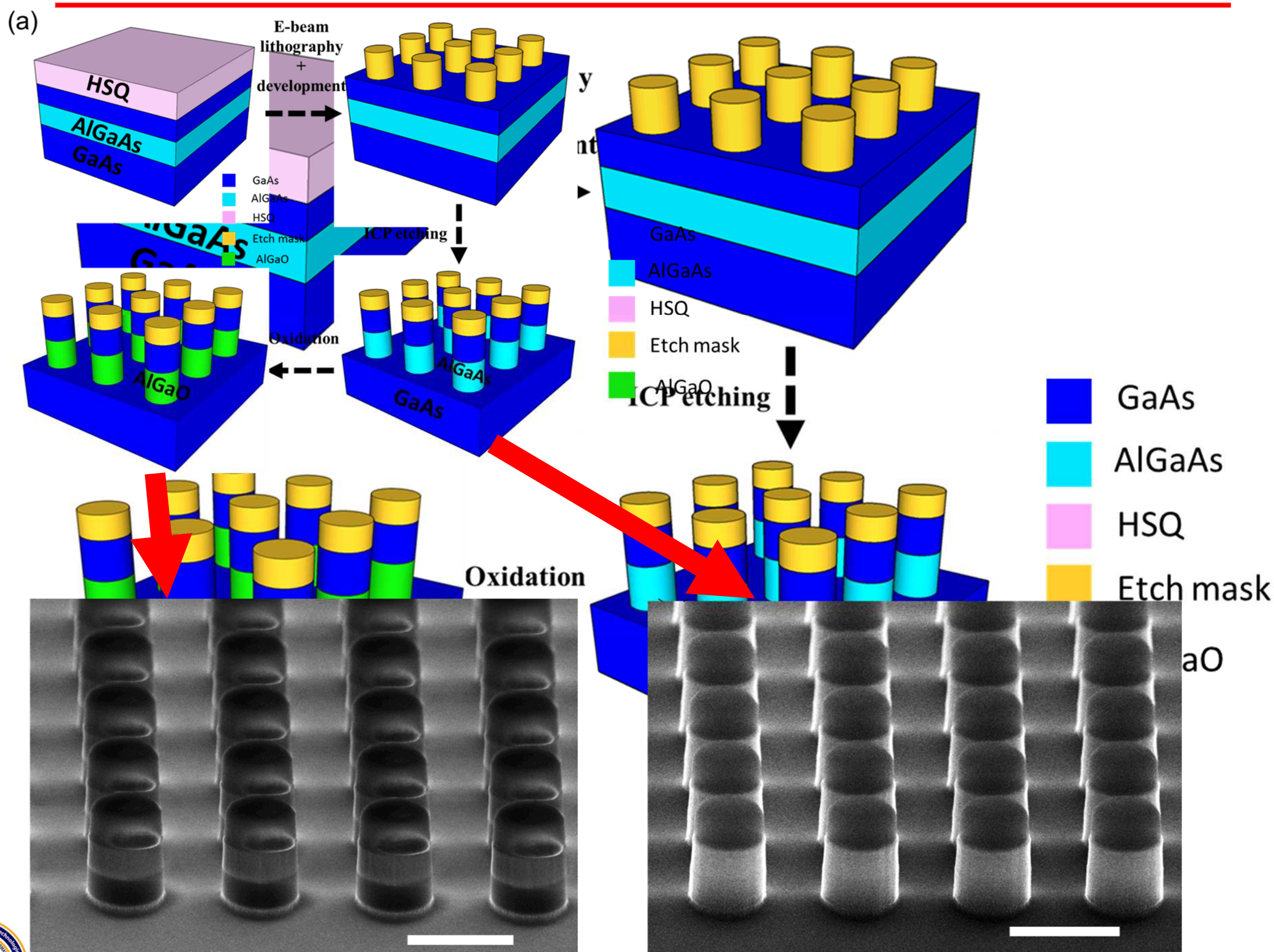
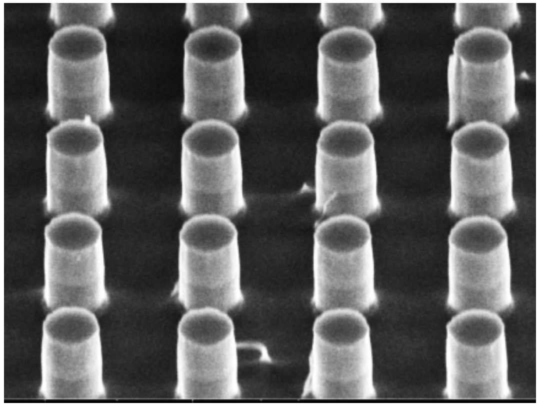


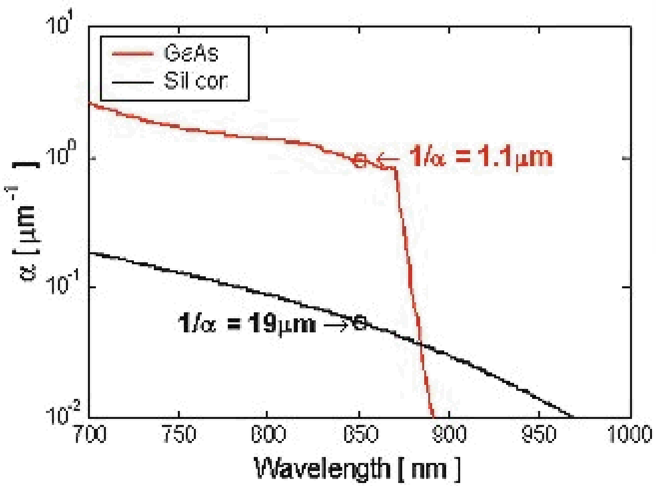
Sandia VCSEL: IEEE JSTQE, 3, 916 (1997)

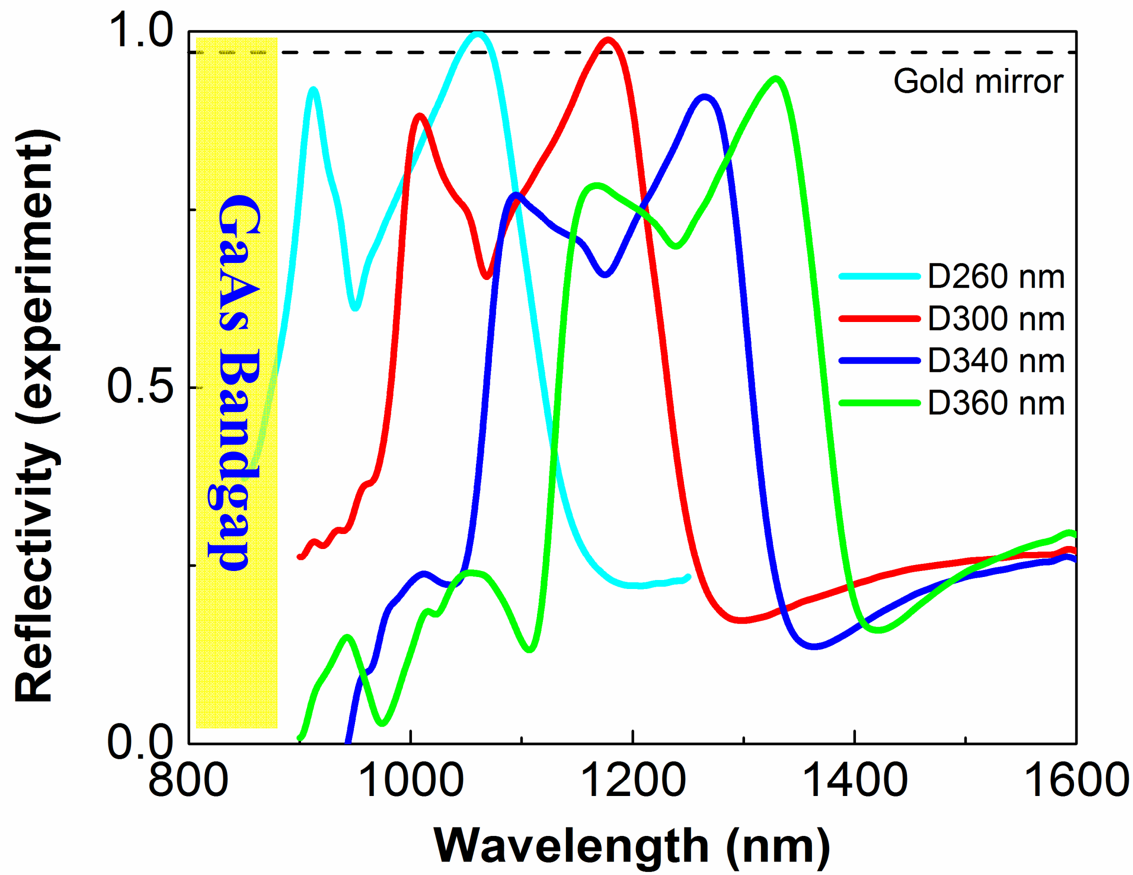
Sheng Liu, et al, submitted

Linear spectra of GaAs metasurfaces (1 layer)



- Extremely low loss below bandgap
- Crystalline





GaAs disk height ~300nm

Different diameters

Sheng Liu, et al, submitted

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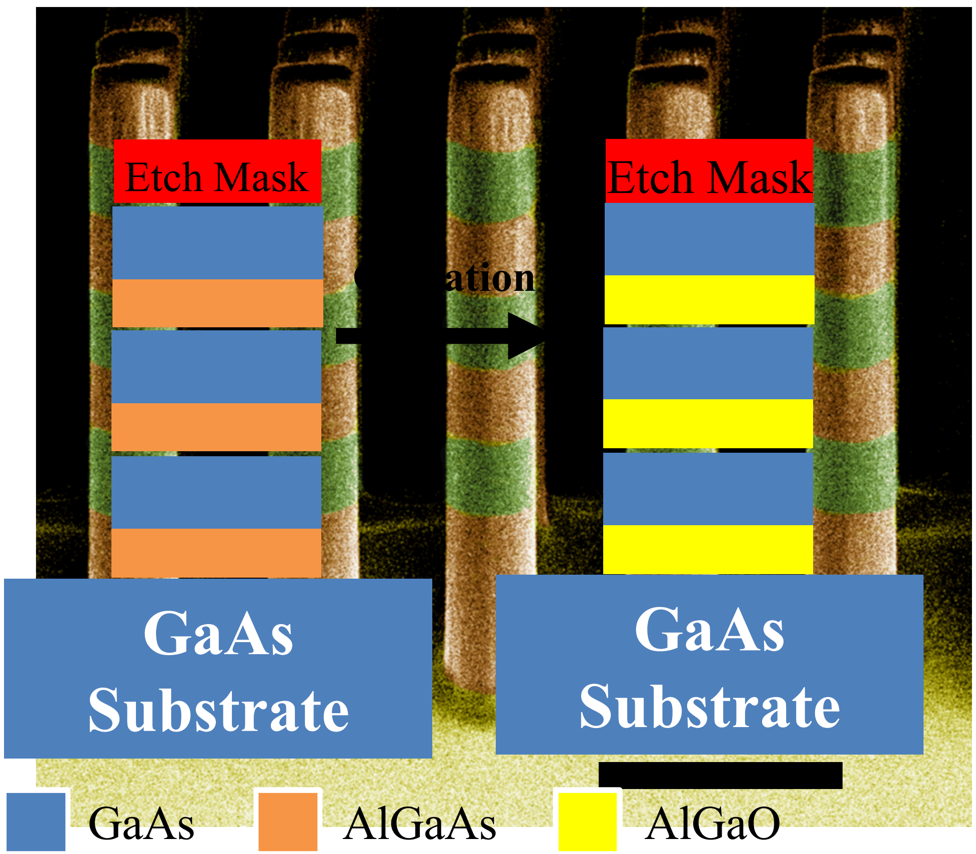
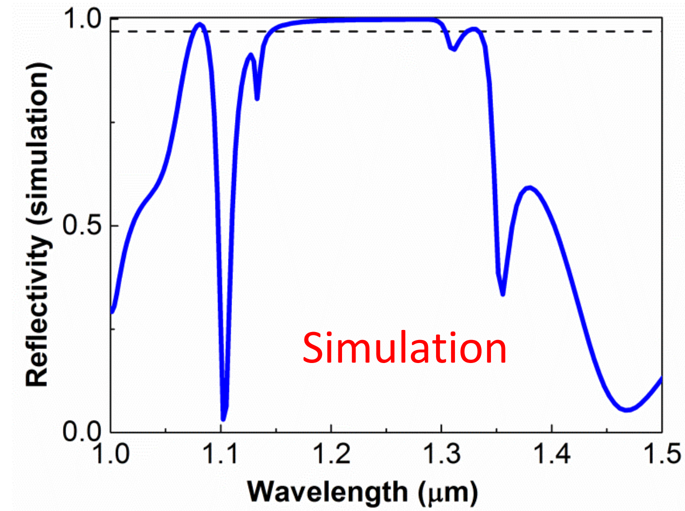
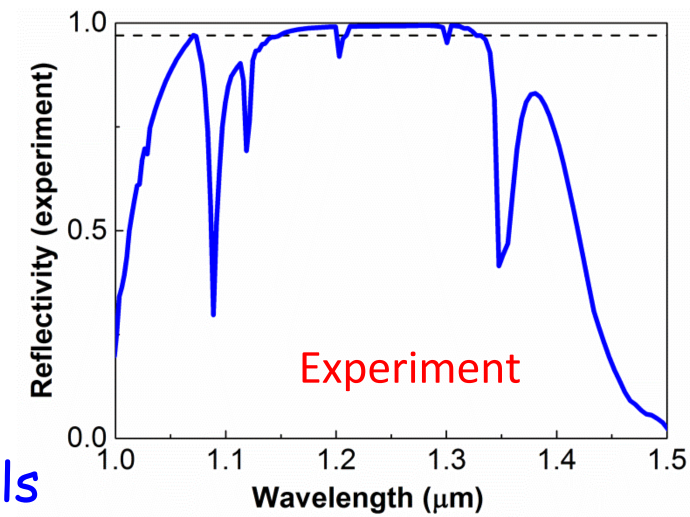
Multi-layer GaAs dielectric metasurfaces

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







➔ Lead to 3D dielectric metamaterials

Sheng Liu, et al, submitted

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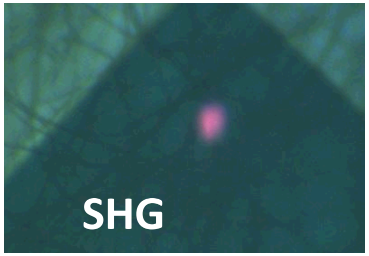
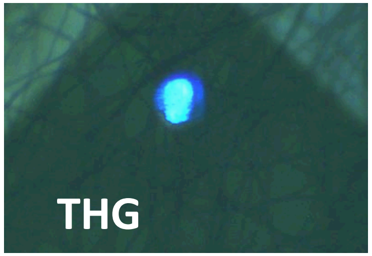
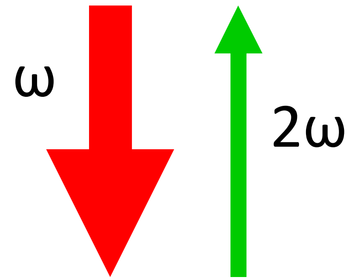
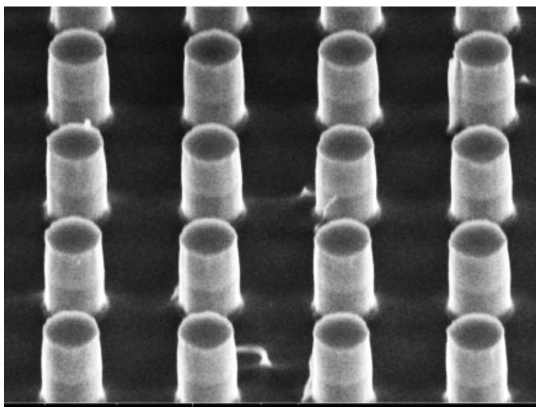


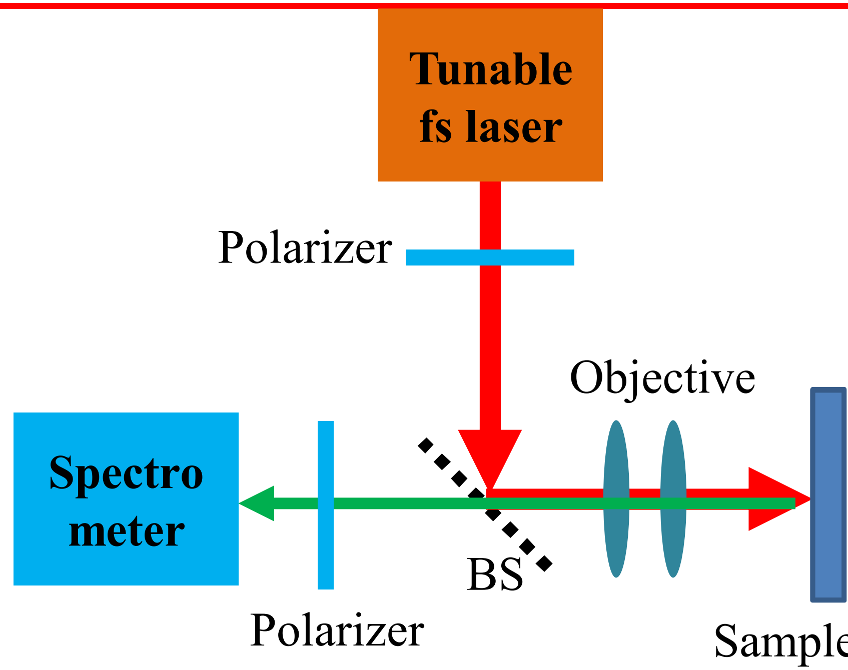


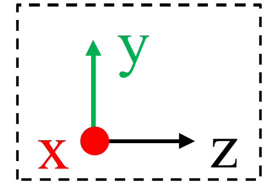
SHG using GaAs metasurfaces—setup





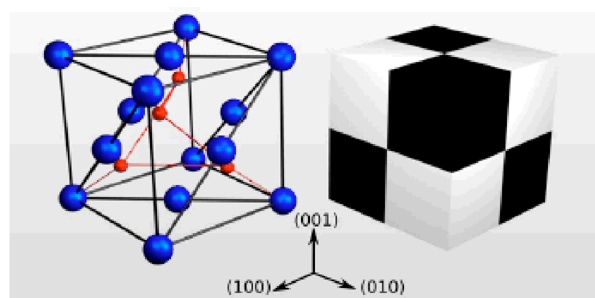
H:300nm, R: 125nm
Resonators far apart





Objective: 20X, NA=0.4
Limit the collection efficiency

GaAs:
(100)-oriented



Vol. 34, No. 13 / OPTICS LETTERS 1997

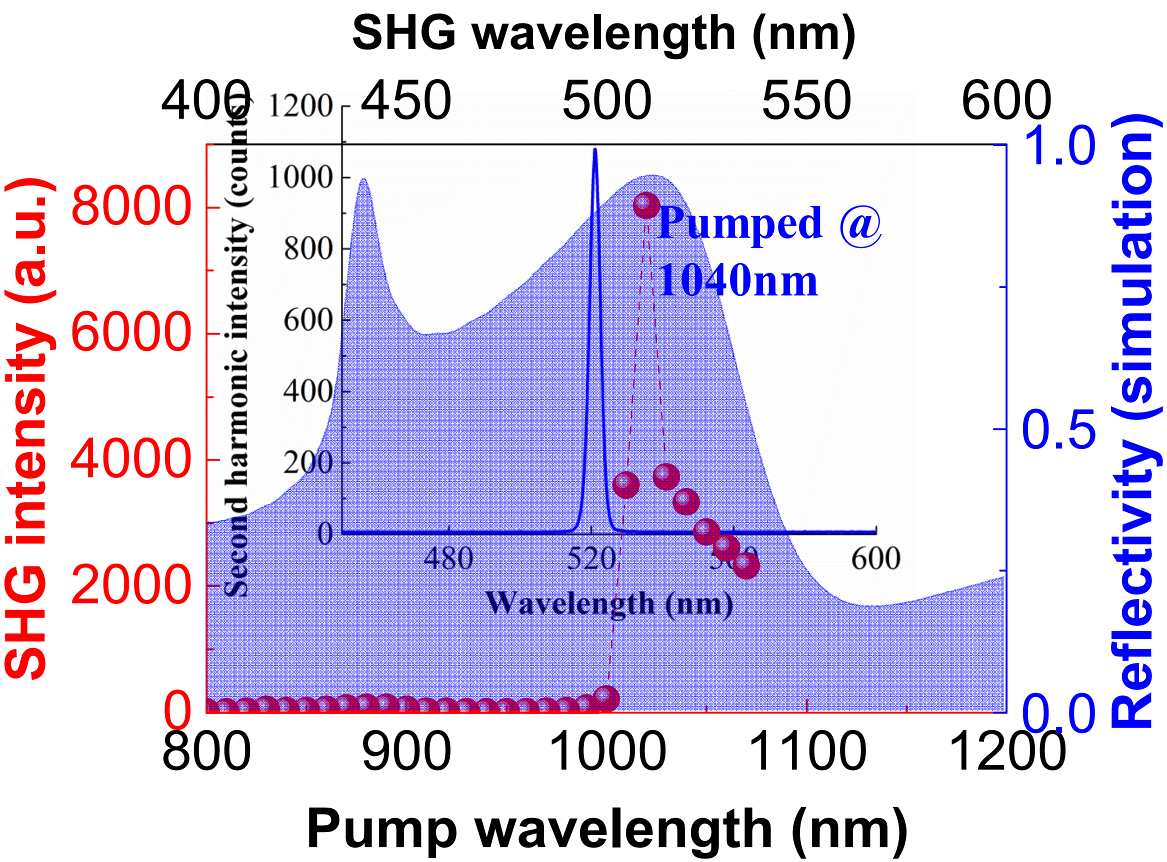
GaAs: ~200pm/V

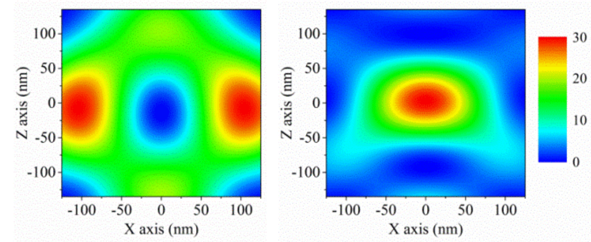
Material	deff (pm/V)
MgO:PPLN	14pm/V (typical)
KTP	3.4pm/V
BBO	2.5pm/V
LBO	0.85pm/V

Setup: reflection geometry
- X-Y plane: sample
- Z axis: pump propagation
- X axis: pump polarization

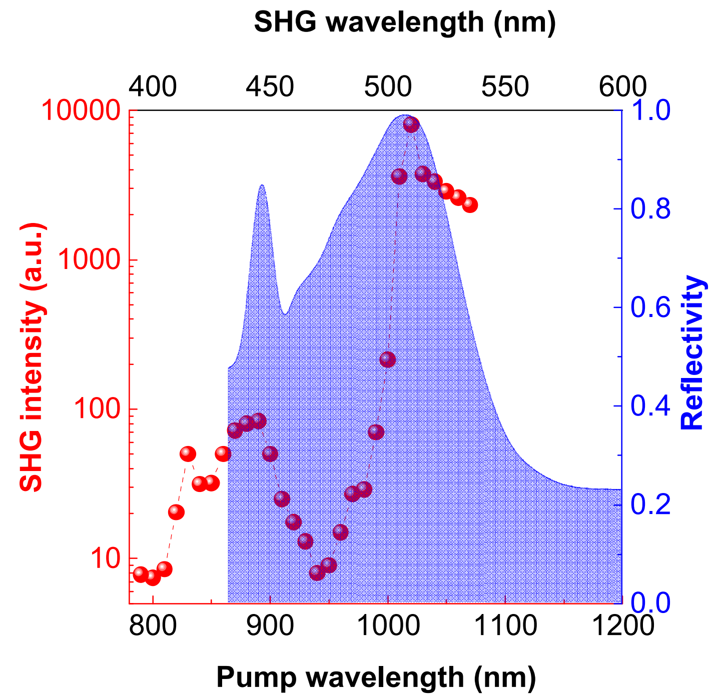
Sheng Liu, et al, in preparation

SHG - pump wavelength dependence





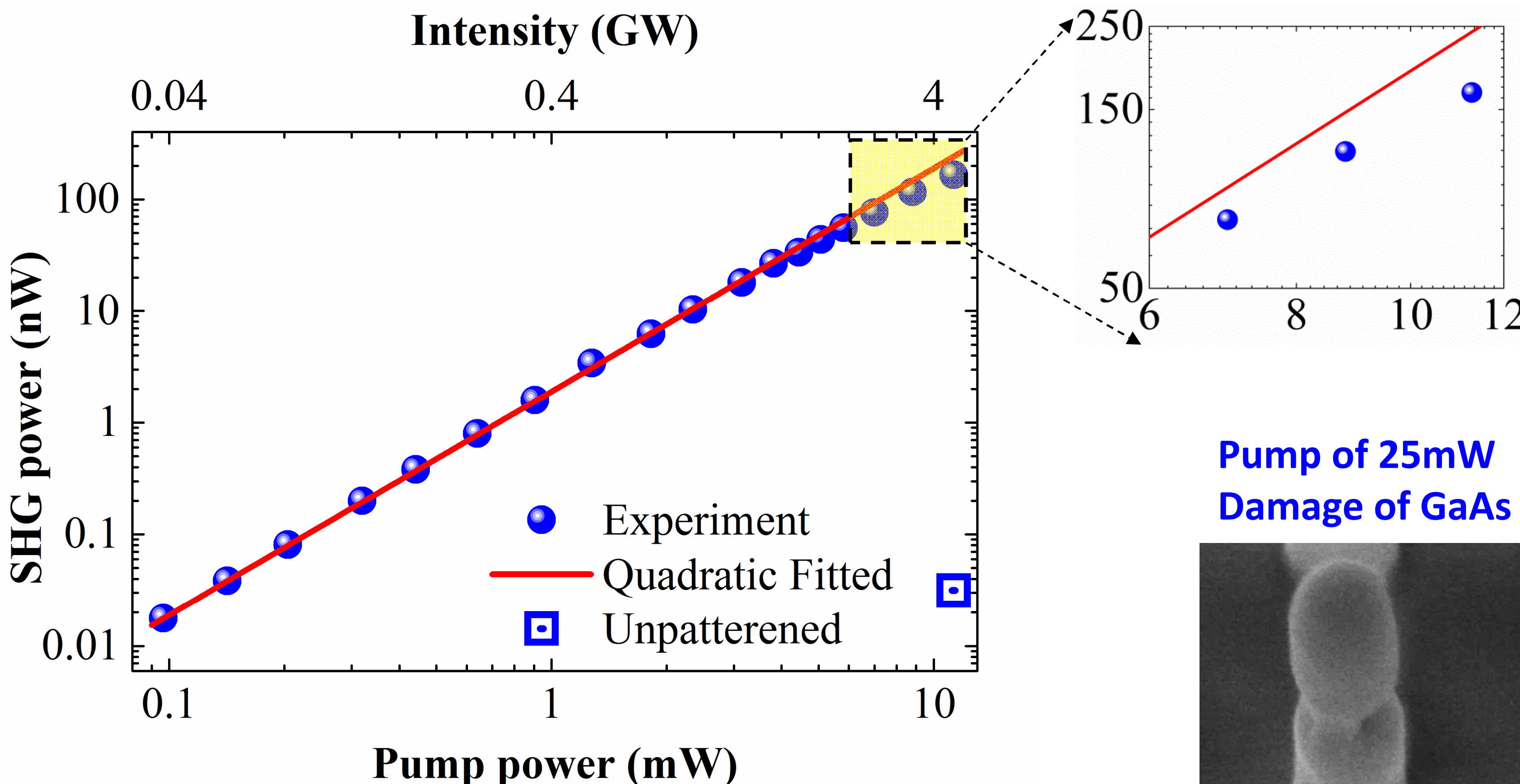
Logarithmic scale



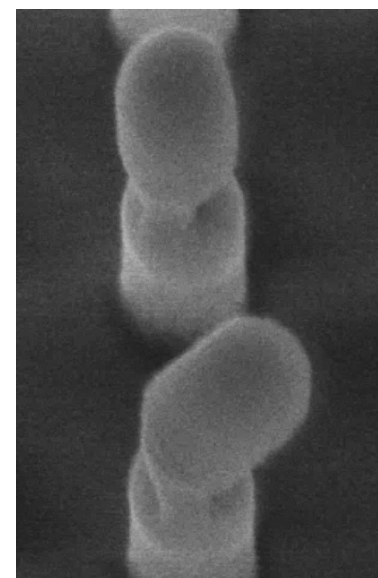
- Strong pump wavelengths dependence
- Large resonant enhancement at the magnetic and electric dipole resonances
- Phase matching free

Sheng Liu, et al, in preparation

SHG power vs pump power



Pump of 25mW
Damage of GaAs



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

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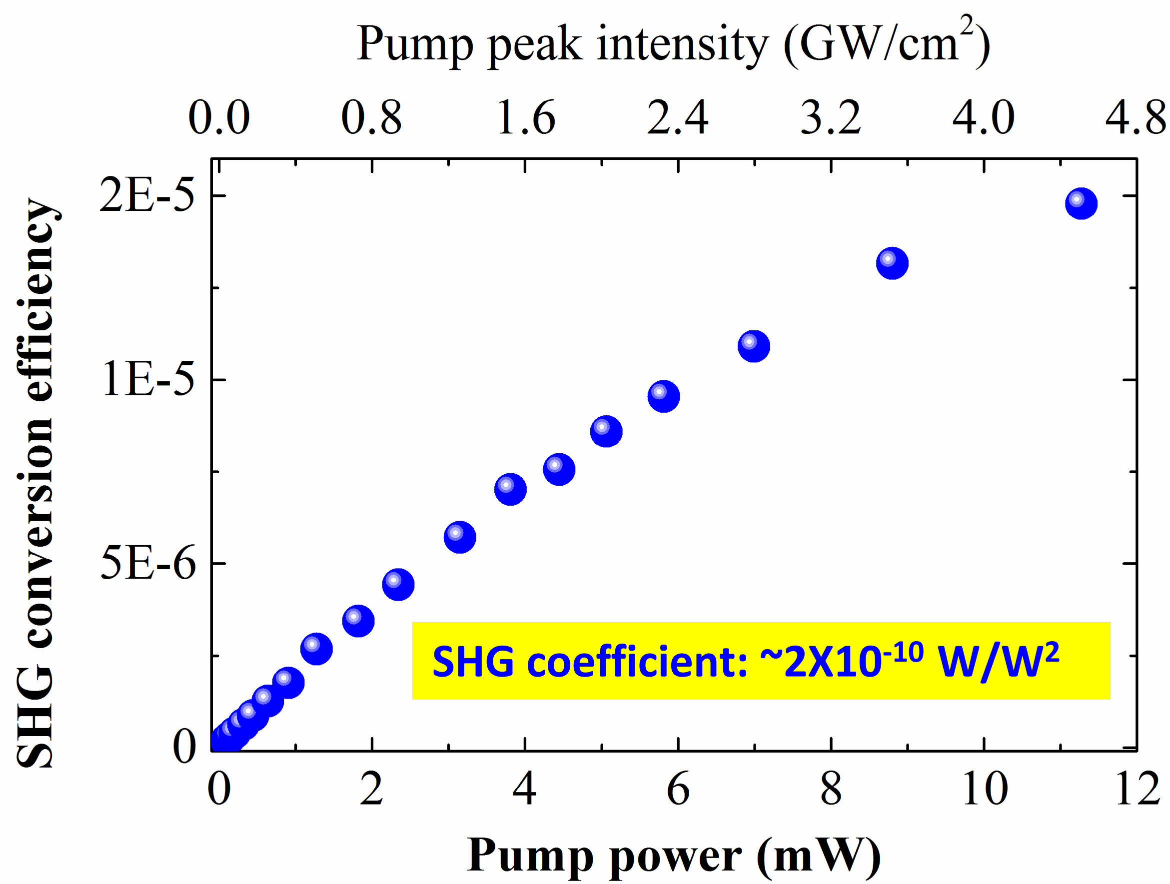
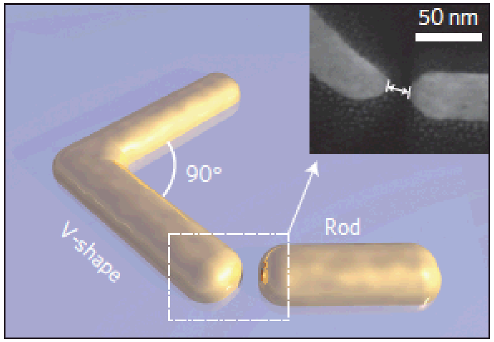
SHG - conversion efficiency



Comparable to record high SHG using plasmonic structures: ~5X10^{-10} W/W^2



Nature nano., 10, 412, 2015

Further improvement:

1. Bigger resonators with the magnetic resonant wavelength > twice of the bandgap (reduce the two-photon absorption)
2. Optimize the modal overlap between SHG and fundamental
3. Different structural designs to increase the quality factor

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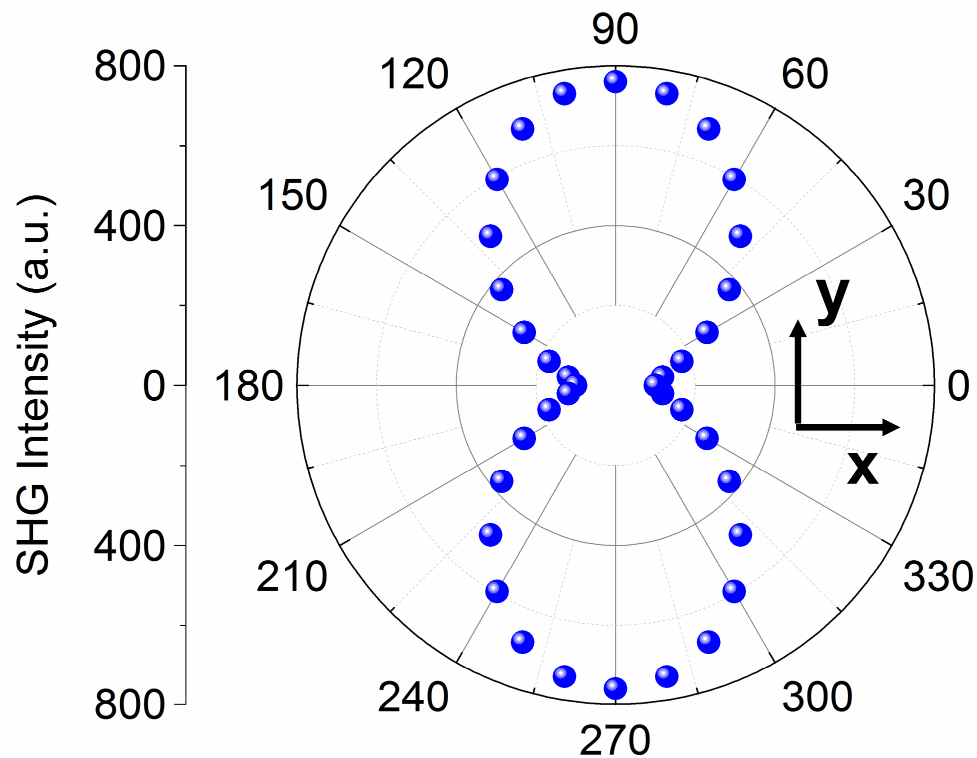
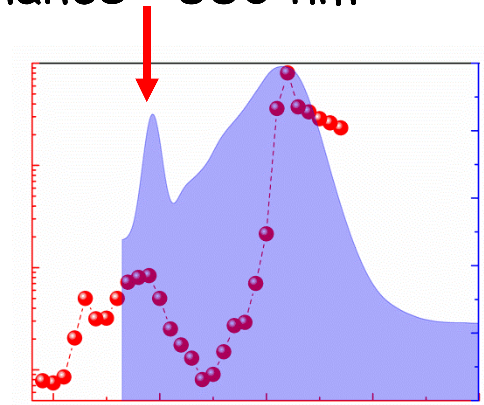
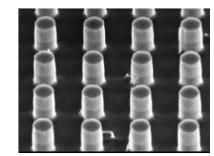
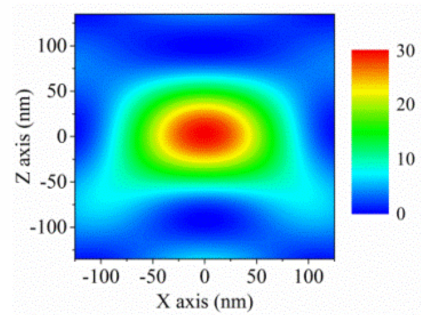
SHG - polarization (E dipole resonance)



Pump @ the electric dipole resonance ~880 nm







Sample plane: x-y

Pump prop: z axis

Pump polar: x axis

For (100)-oriented GaAs, bulk second-order susceptibility:

$\chi^{(2)}_{ijk}$ is non-zero only when $i \neq j \neq k$

Only x & z component EM filed inside resonators

$$E_y^{2\omega} = 2\chi^{(2)}_{yxz}\, E_x^{\omega}\, E_z^{\omega}$$

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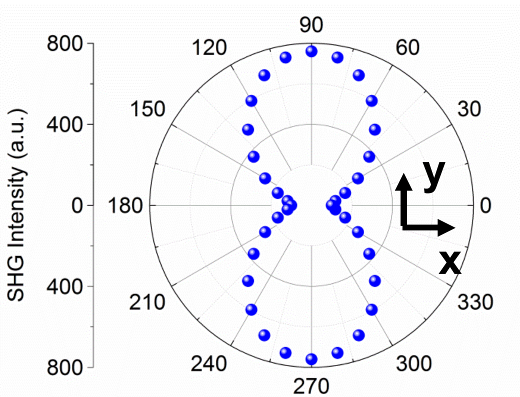
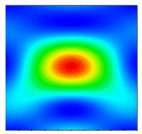
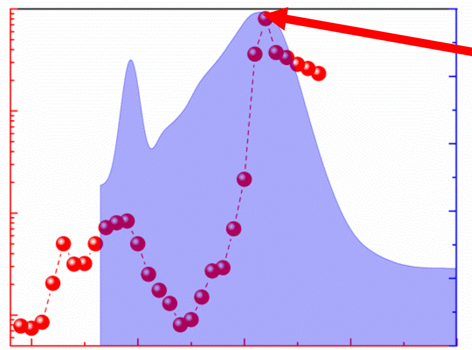
SHG - polarization (M dipole resonance)







Pump @ the magnetic dipole resonance ~1020 nm

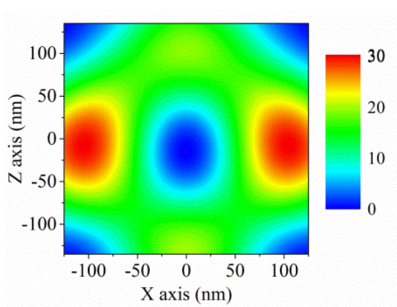
GaAs bulk nonlinearity????

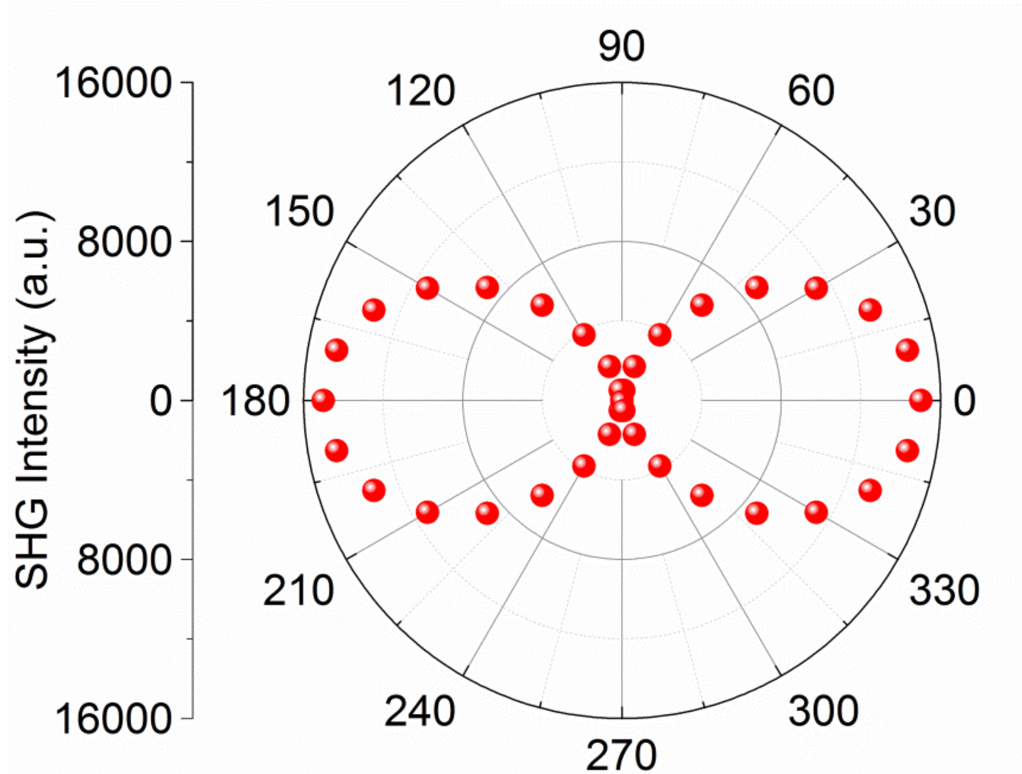
$$E_y^{2\omega} = 2\chi_{yxz}^{(2)}\, E_x^{\omega}\, E_z^{\omega}$$

GaAs surface nonlinearity

Bulk crystal symmetry $\bar{4}3m$ is broken, new symmetry for the surface is $mm2$

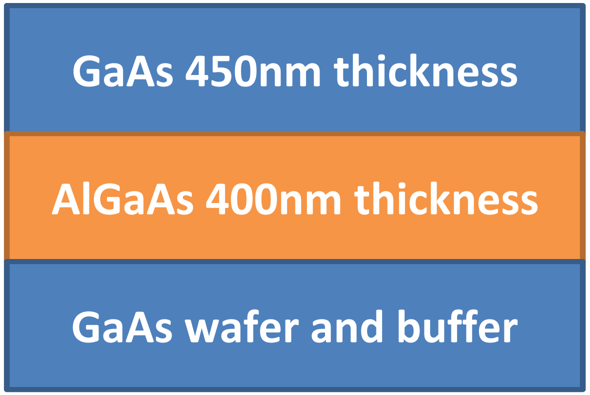
$$\boldsymbol{E_x^{2\omega} = 2\chi_{xxz}^{(2)}\, E_x^{\omega}\, E_z^{\omega}}$$

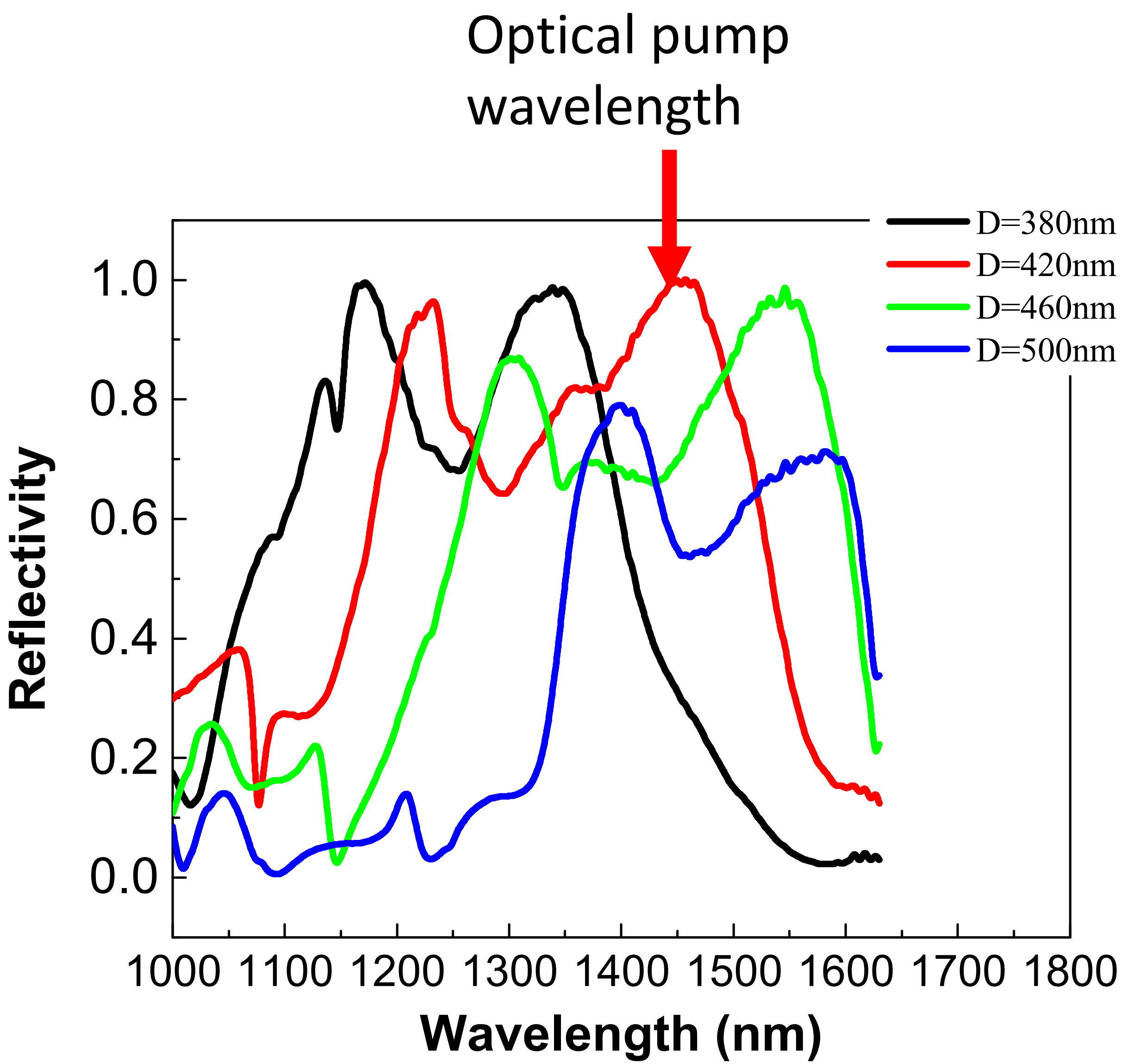




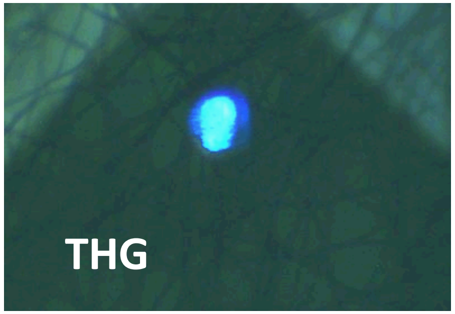
Sheng Liu, et al, in preparation

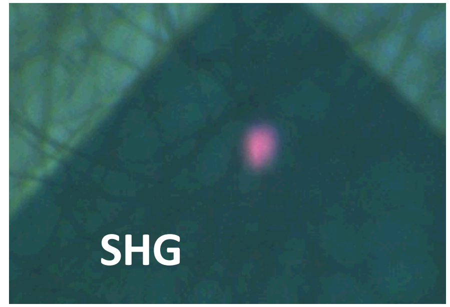
THG using GaAs dielectric metasurfaces (preliminary data)

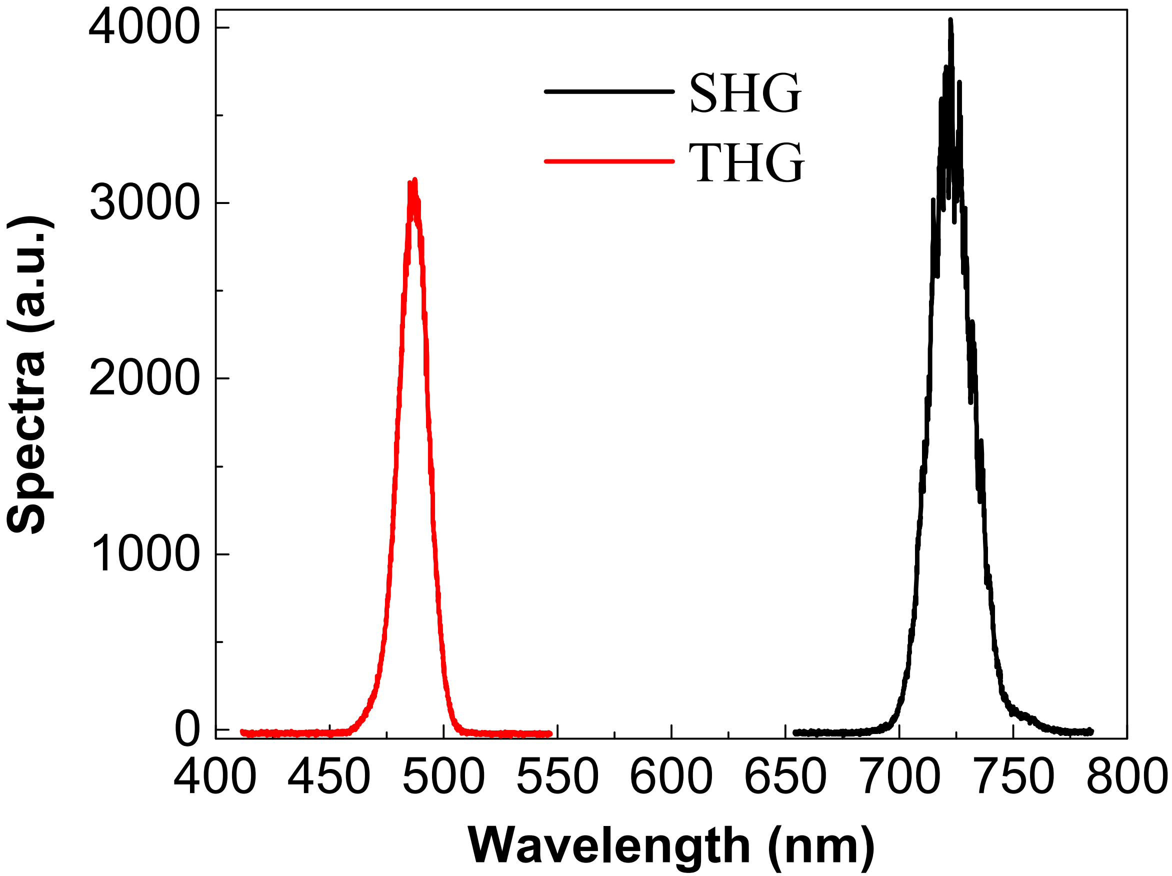




SHG & THG using GaAs dielectric metasurfaces (preliminary data)

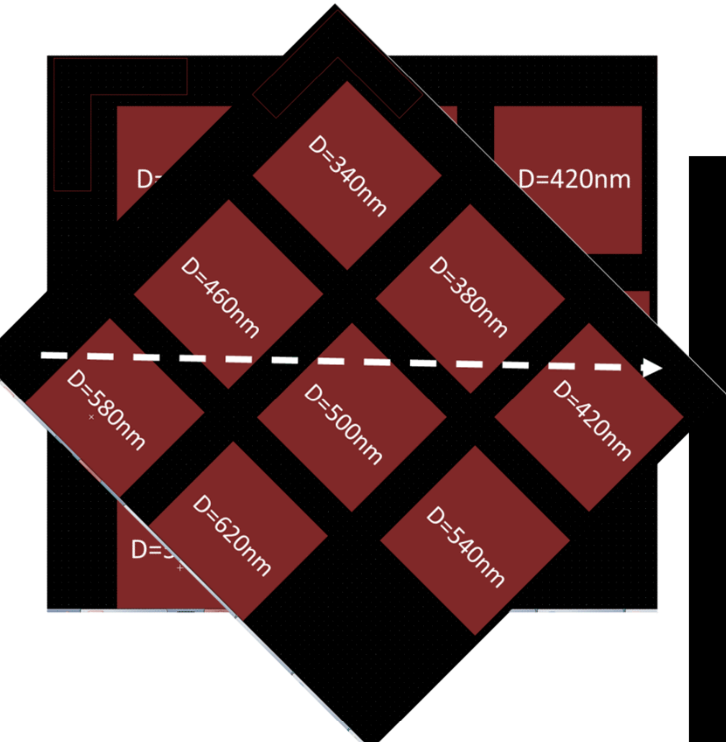






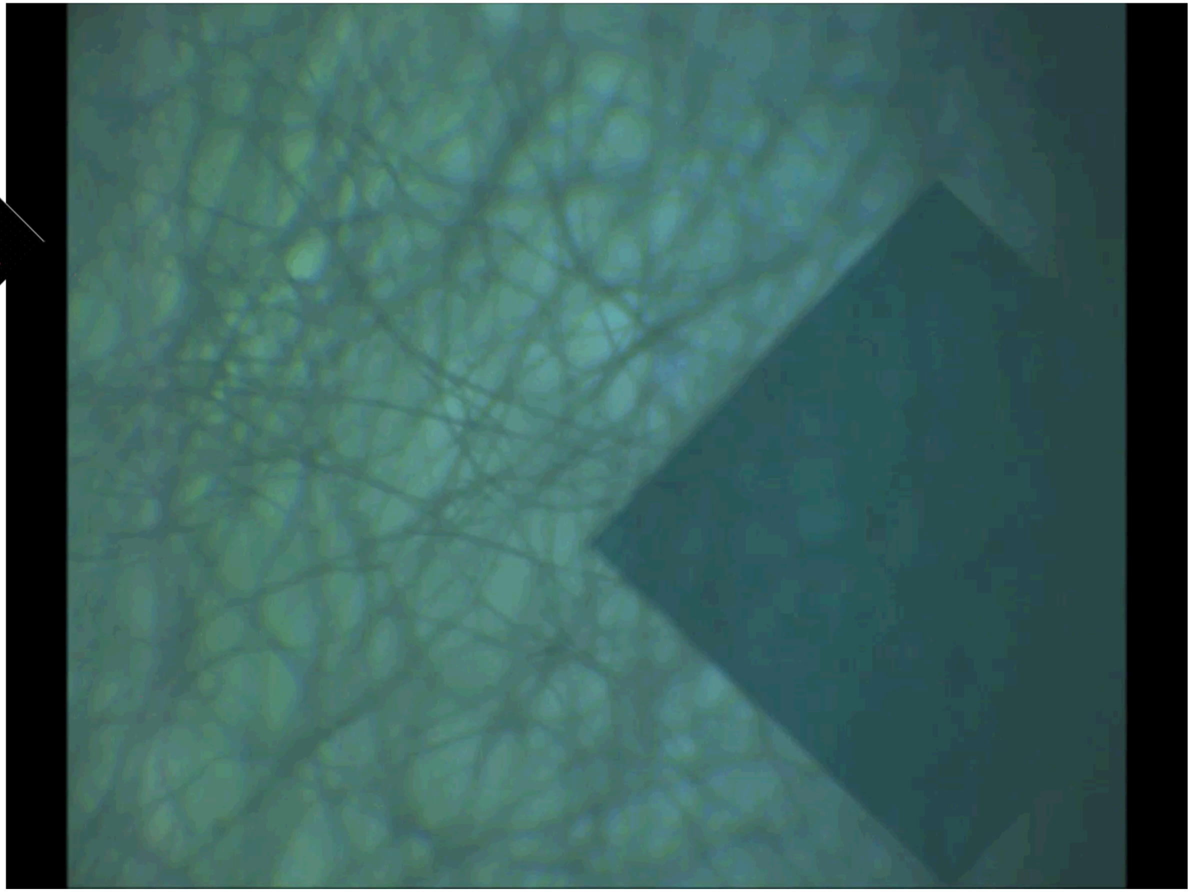
- SHG & THG simultaneously
- Resonant enhancement
- Different enhancements for SHG & THG on different GaAs metasurfaces
- **SHG and THG/SFG are horizontal polarized**

SHG & THG video (*preliminary data*)

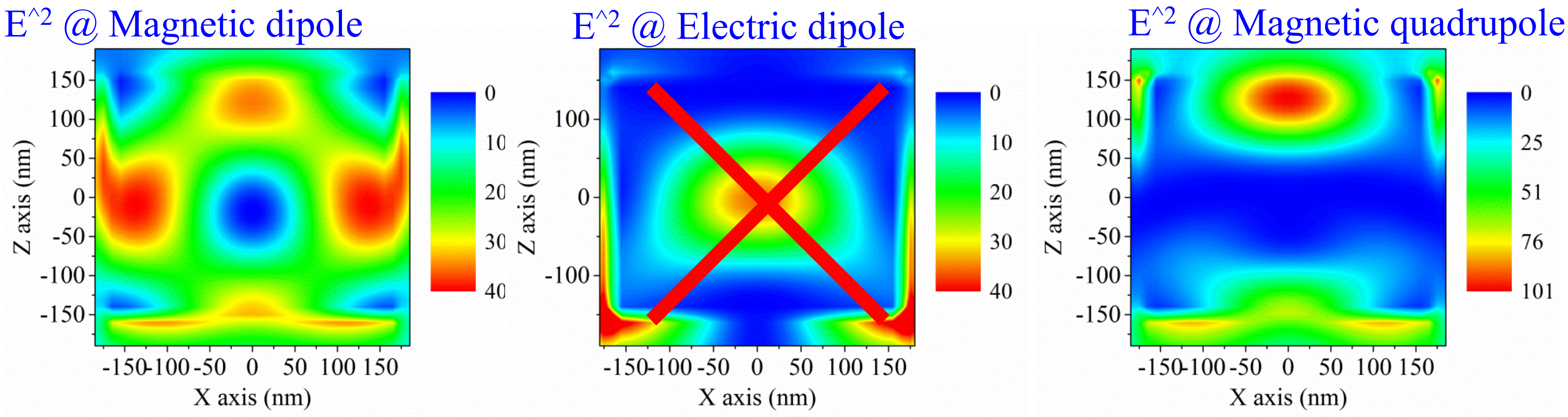


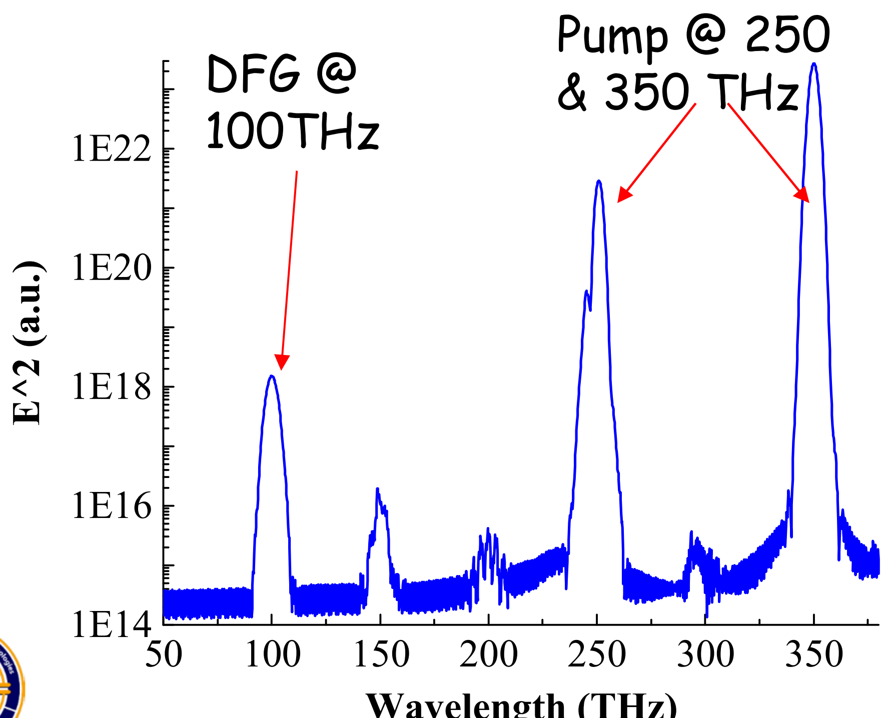
- Pure THG?
- SHG + fundamental?

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



Simulation: difference frequency generation in GaAs resonators



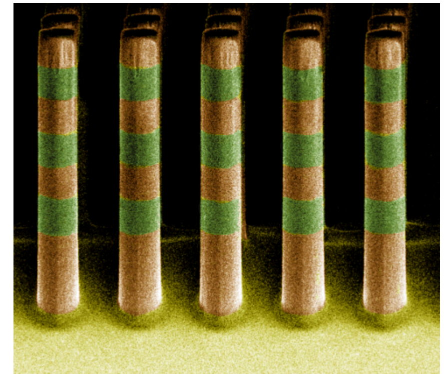


Difference frequency generation between magnetic dipole and magnetic quadrupole

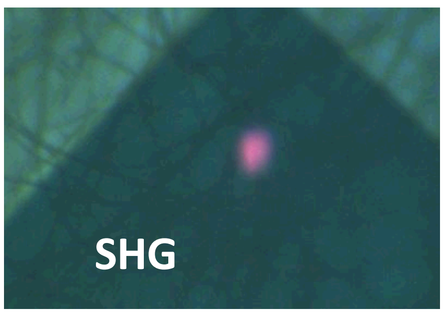
- Parametric down conversion → Entangled photon sources
- Three/Four wave mixing

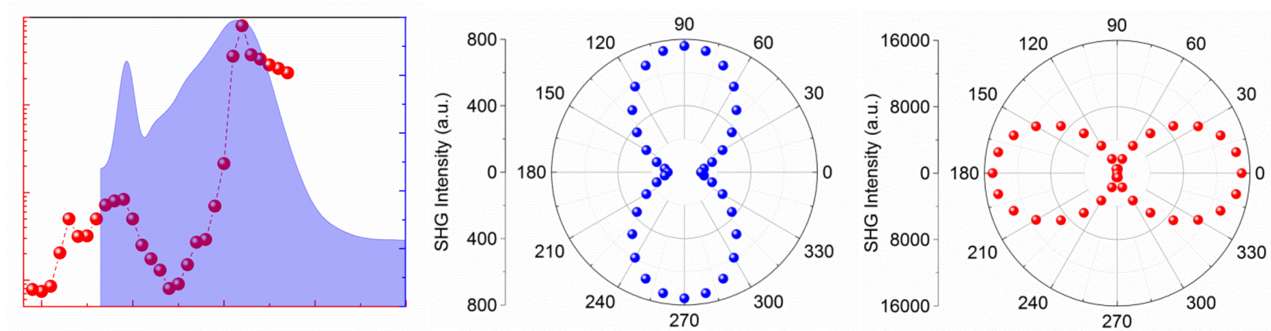
Summary

- III-V (AlGaAs/GaAs/InGaAs) based dielectric metamaterials: nonlinear optical generation, realizing 3D and active devices…

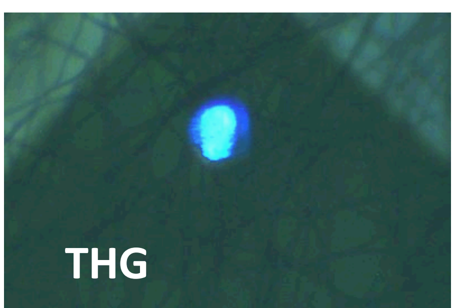


- Resonantly enhanced SHG

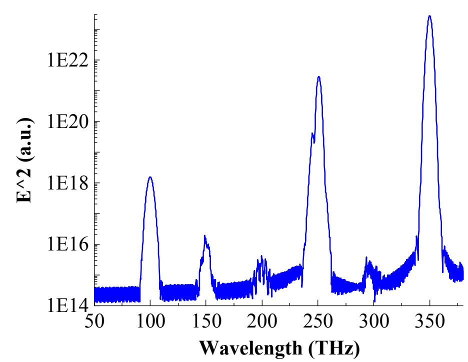




- Resonantly enhanced THG

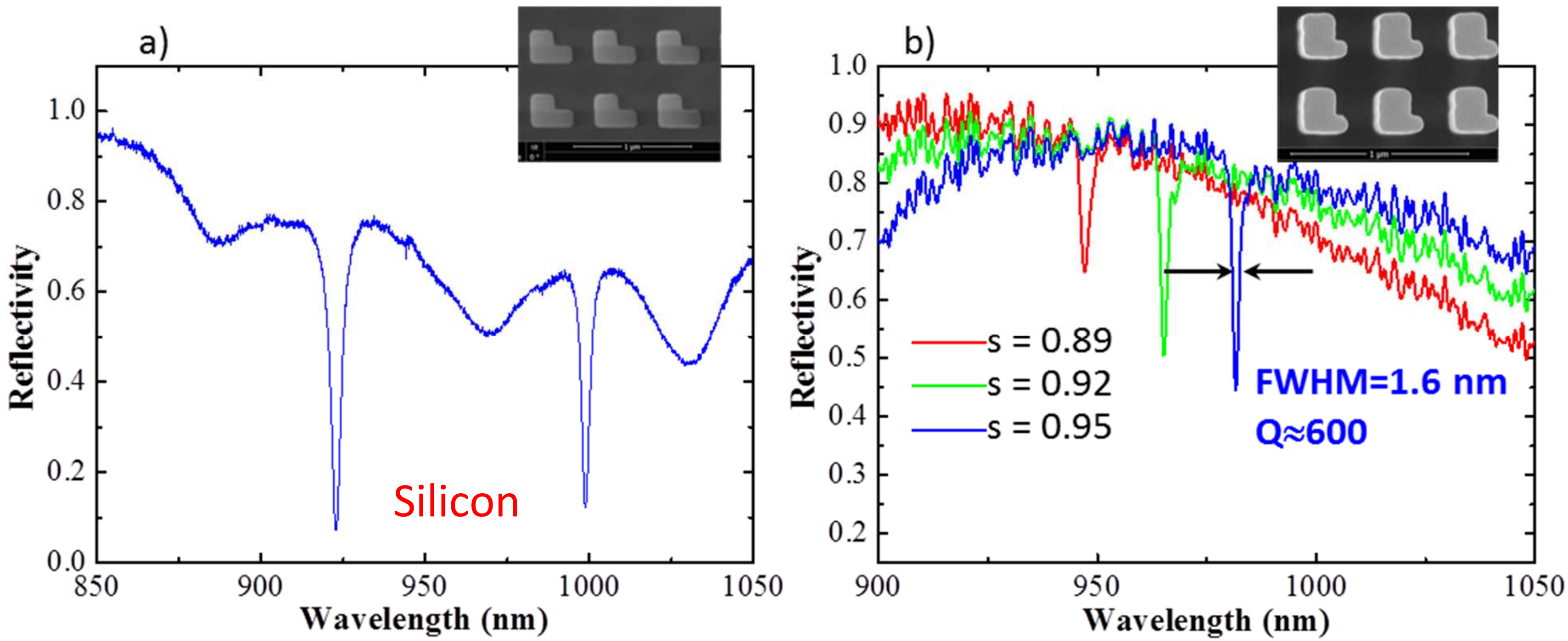


- Simulated DFG



Thank you

- Michael Sinclair "High Quality Factor Fano Metasurfaces" Thursday 9:30am **EP8.7.06**



Much higher EM field enhancement: nonlinear optics