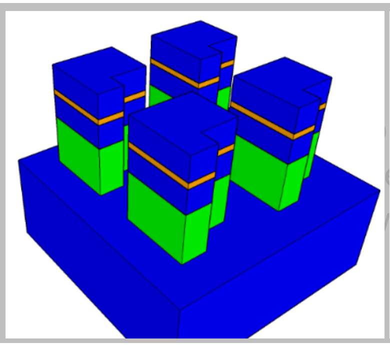
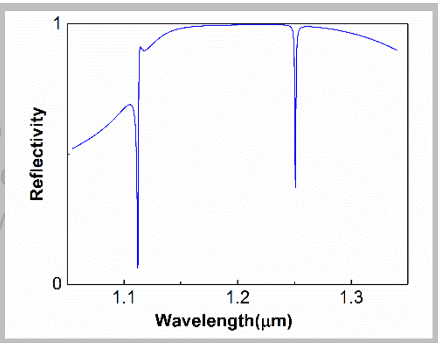
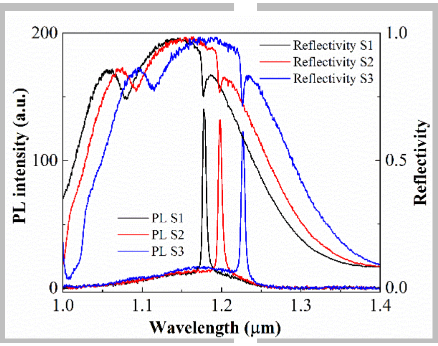
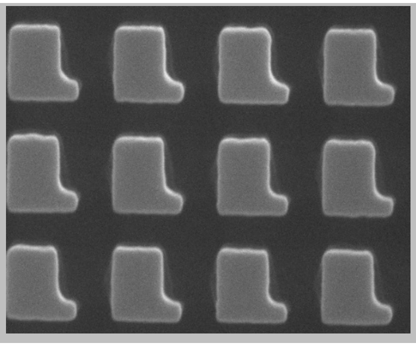
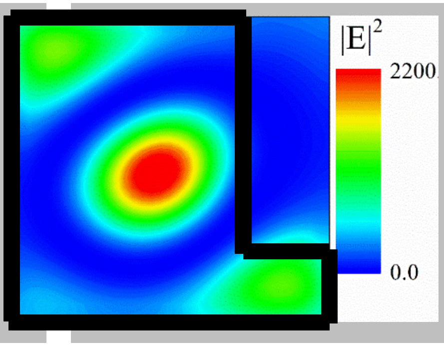
SAND2017-5524C

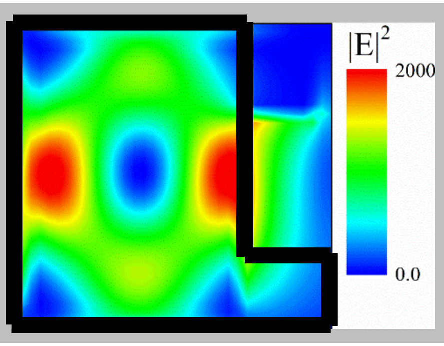












5/30/2017

Enhancing light-matter interaction with high-Q Fano dielectric metasurfaces

snliu@sandia.gov

Sheng Liu,[1] Aleksandr Vaskin,[2] Sadhvikas Addamane,[3] Xiaowei He,[4] Yuanmu Yang,[1] Gordon A. Keeler,[1] Polina Vabishchevich[1], Benjamin Leung,[1] Miao Tsai,[1] George Wang,[1] Han Htoon,[4] Steve Doorn,[4] Ganesh Balarishnan,[3] Isabelle Staude[2], Igal Brener,[1] Michael B. Sinclair,[1]

[1]Sandia National Laboratories, Albuquerque, NM 87185, USA [2]Friedrich-Schiller-Universität Jena, Max-Wien-Platz 1, 07743 Jena, Germany [3]University of New Mexico, Albuquerque, NM, USA, [4] Los Alamos National Lab, NM, USA

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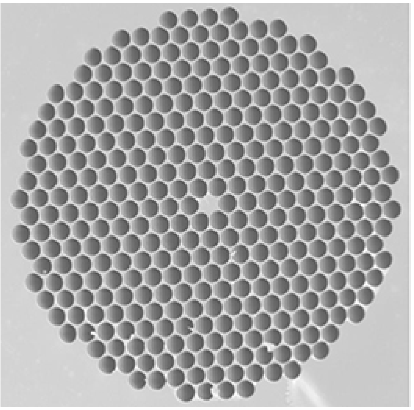
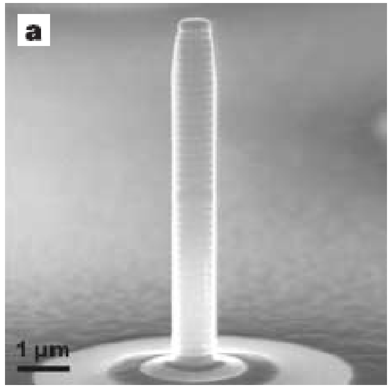
Motivation—enhanced light matter interaction

Sandia National Laboratories

- Fundamental motivation/interest for nanophotonics
- Various platforms

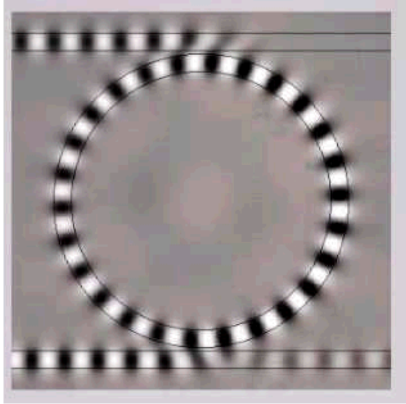


2D Photonic crystal

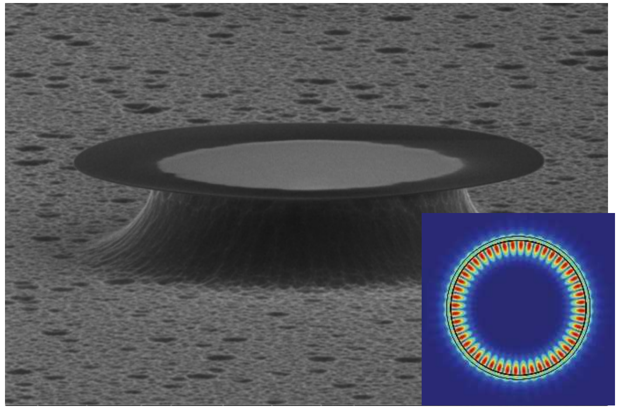


1D Distributed Bragg-reflector micro-cavity

NATURE | VOL 432 | 11 NOVEMBER 2004



On-chip microring resonators



microdisk resonators

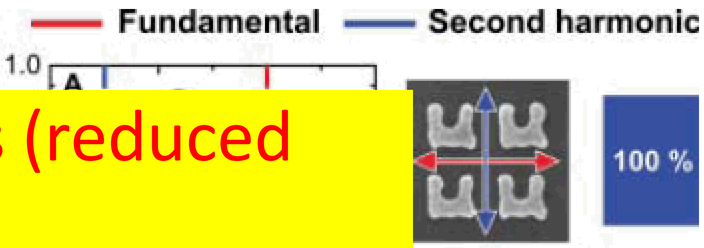
- Plasmonic nano-resonators (linear & nonlinear)

Maiken Mikkelsen (2014)

Niek F. van Hulst (2010)

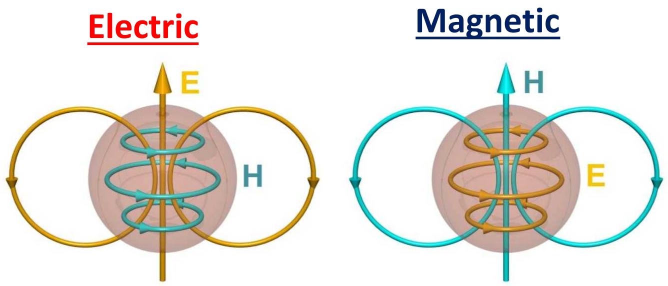
Strong metallic loss at high optical frequencies (reduced quantum efficiency).

Seung-Woo Kim (2008)



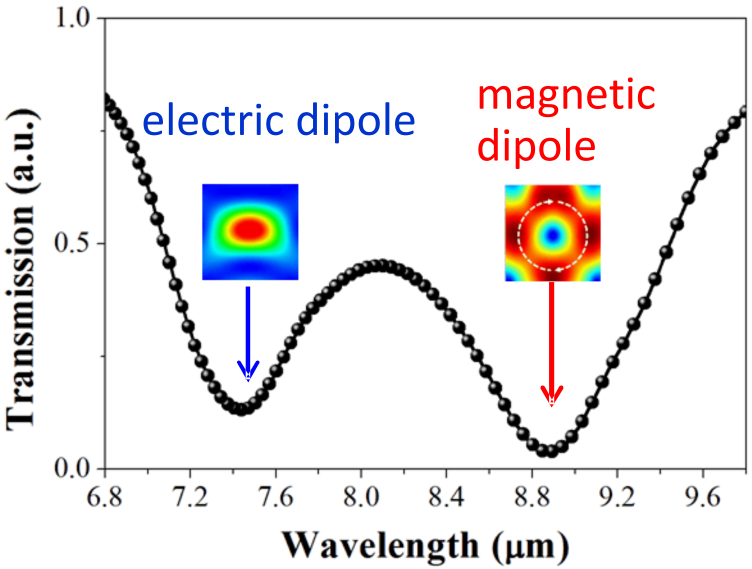
Stefan Linden (2006)

Low loss dielectric metamaterials/resonators

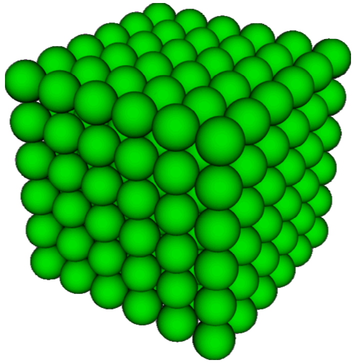


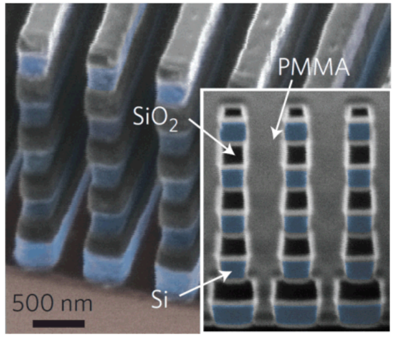
Images: A. Miroshnichenko

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



- ***Much lower loss at optical frequencies***
- ***Strong interaction with magnetic field ➔ Huygens's metasurfaces***





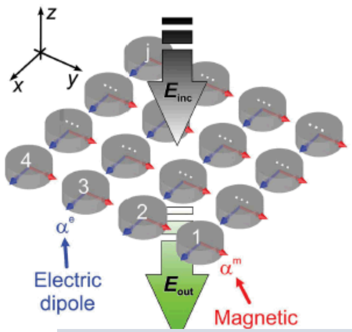
Yuanmu Yang, Jason Valentine

3D structure is possible
Isotropic response can be achieved

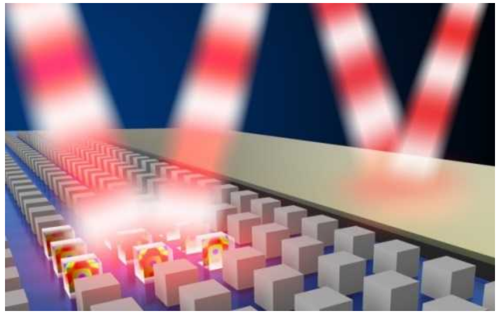
Recent progresses of dielectric metasurfaces

Sandia National Laboratories

Huygens principle:

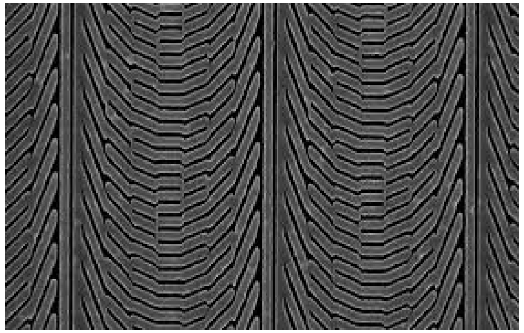


Magnetic mirror



Sheng Liu

Ultrathin gratings, lenses, axicons



Erez Hasman & Mark L. Brongersma

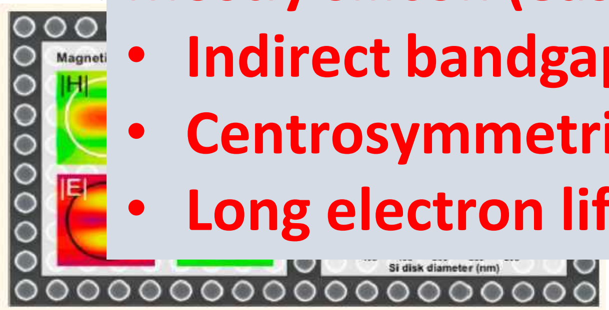
REVIEW

APPLIED OPTICS

Optically resonant dielectric nanostructures

Arseniy I. Kuznetsov,[1] Andrey E. Miroshnichenko,[2] Mark L. Brongersma,[3*] Yuri S. Kivshar,[2*] Boris Luk'yanchuk[1,4*]

Di



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**

nature nanotechnology

All-dielectric metamaterials

Saman Jahani[1] and Zubin Jacob[1,2*]

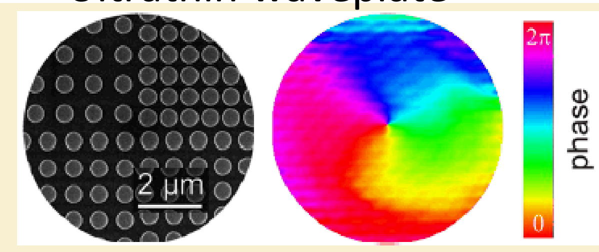
Jason Valentine

optica

Multipolar nonlinear nanophotonics

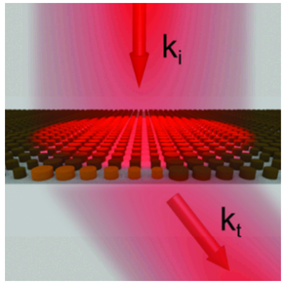
Daria Smirnova and Yuri S. Kivshar*

Ultrathin waveplate



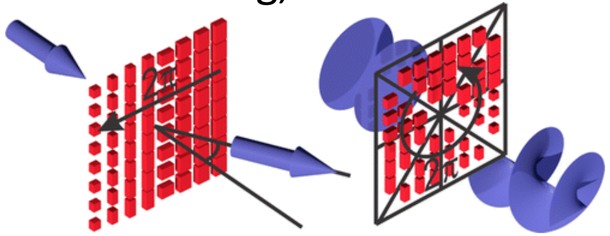
Yuri Kivshar

Beam deflection



Arseniy I. Kuznetsov

Beam steering, vortex converter



Natalia M. Litchinitser

REVIEW ARTICLE

PUBLISHED ONLINE: 28 APRIL 2017 | DOI: 10.1038/NPHOTON.2017.39

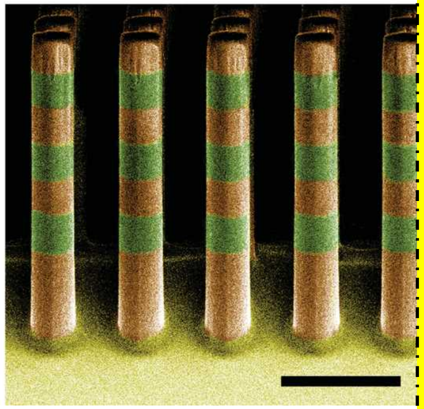
nature photonics

Metamaterial-inspired silicon nanophotonics

Isabelle Staude[1] and Jörg Schilling[2*]

III-V dielectric metamaterials

- **Multilayer structure MBE/MOCVD fabrication**

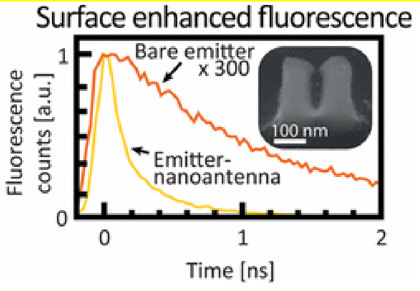


- **Direct bandgap**

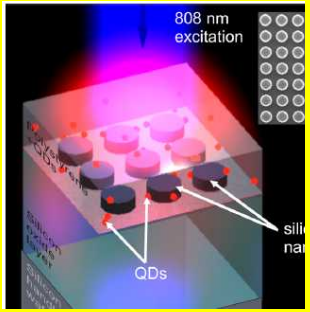
Ultrafast resonance shift ~30nm

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

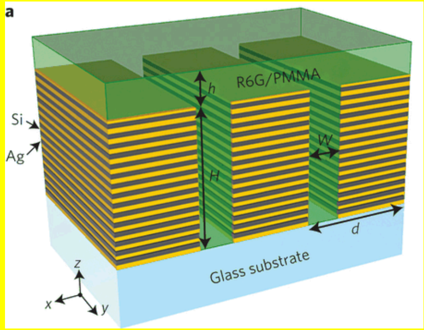
- **Enhanced light emission**



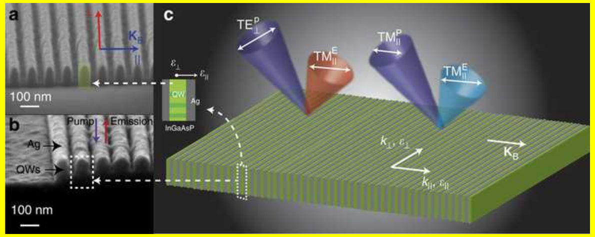
Stefan Maier (2017)



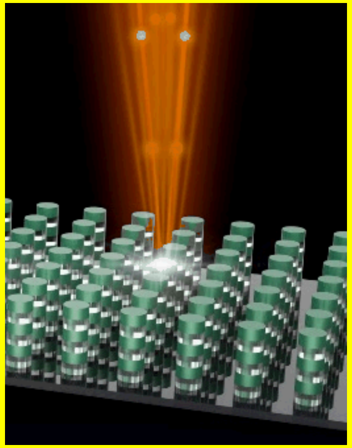
Isabelle (2014)



Zhaowei Liu (2014)



Luminescent hyperbolic metasurfaces
Joseph Smalley, UCSD



Embedding emitters inside resonators

Pump–probe delay (ps)

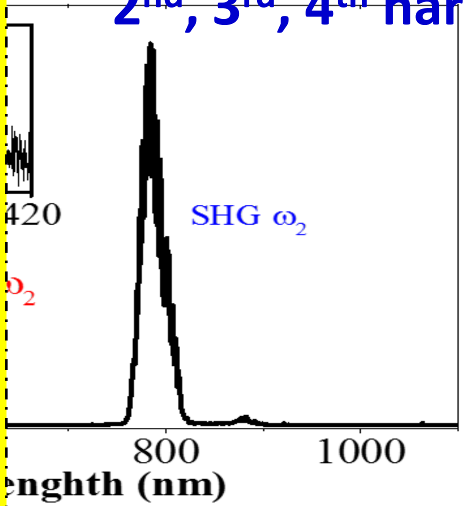
- **Resonantly enhanced second-**
on (~10^{-5})

Liu, et al, Nano Letters, **16**, 5426, (2016)

Giuseppe (2016)

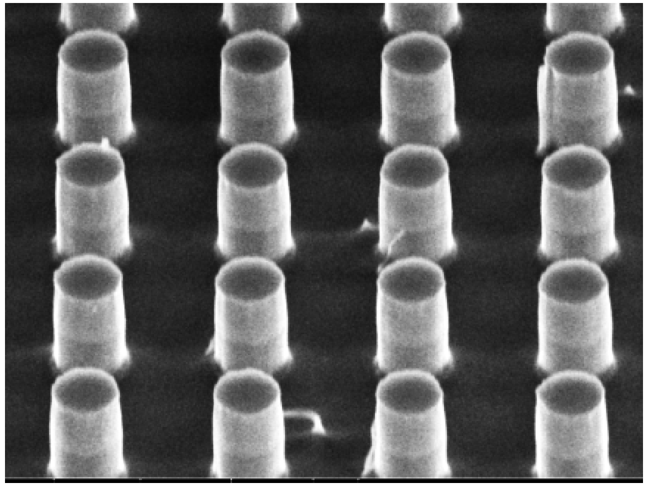
Kivshar, Dragomir Neshev,
o Letters (2016)

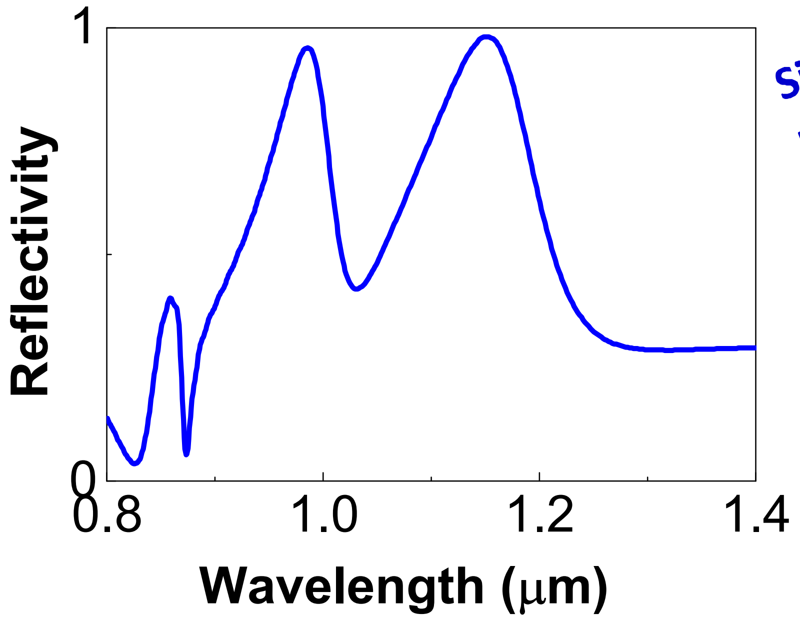
2nd, 3rd, 4th harmonic

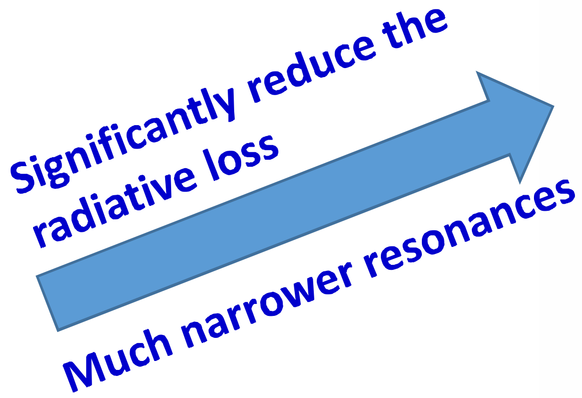


Fano metasurfaces—Broken symmetry design

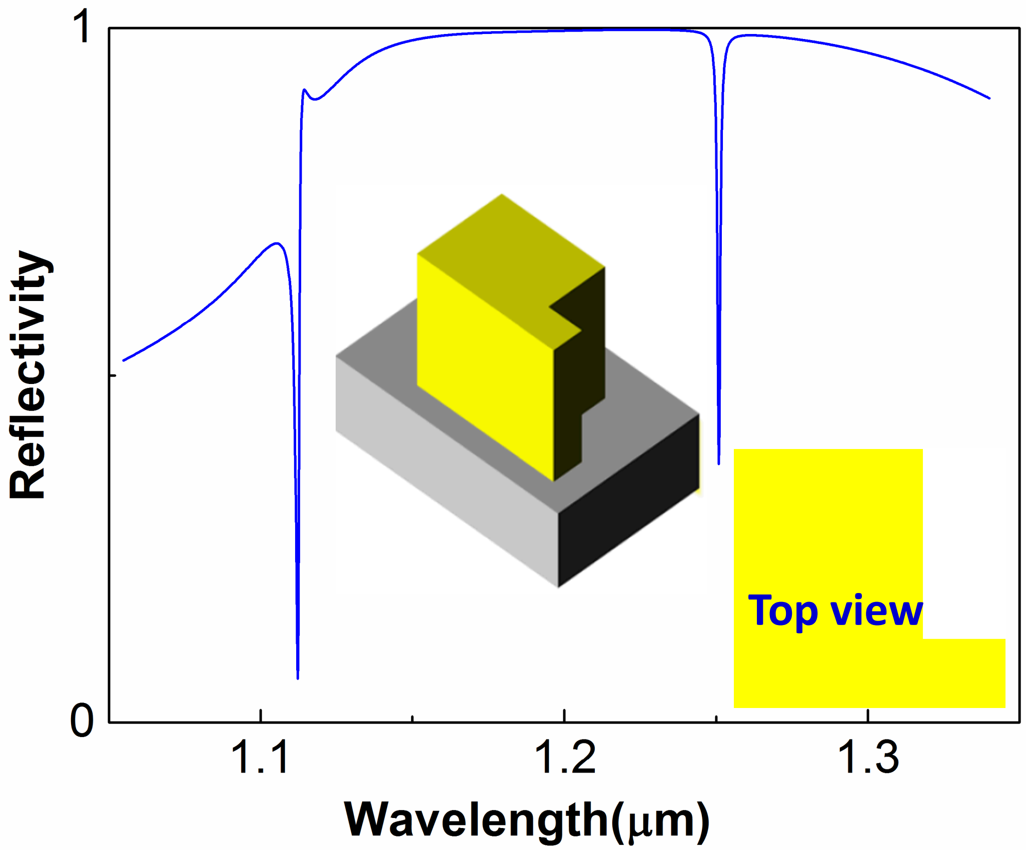
- Regular nano-cylinder resonators







- Broken symmetry design

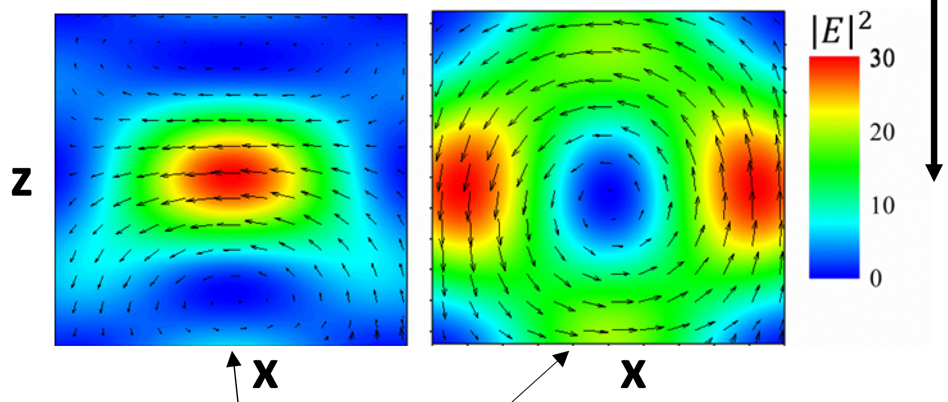


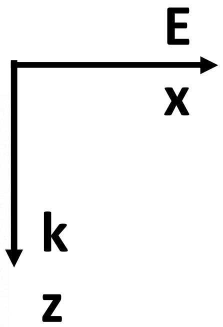
ACS Photonics 2016, 3, 2362−2367

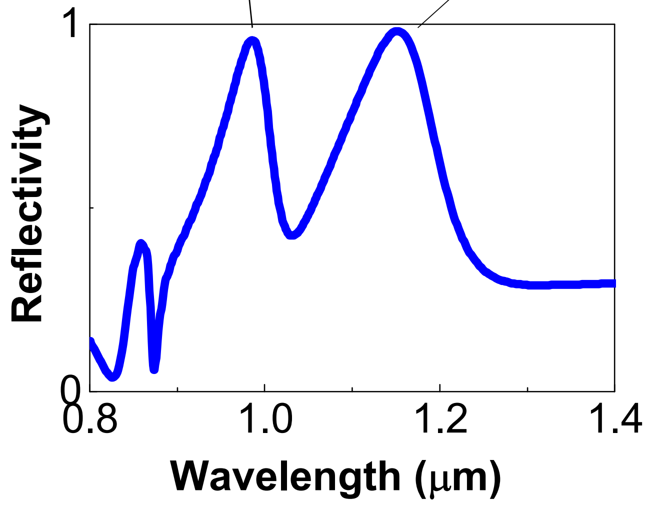
High Q Fano resonators

- Regular nano-cylinder resonators

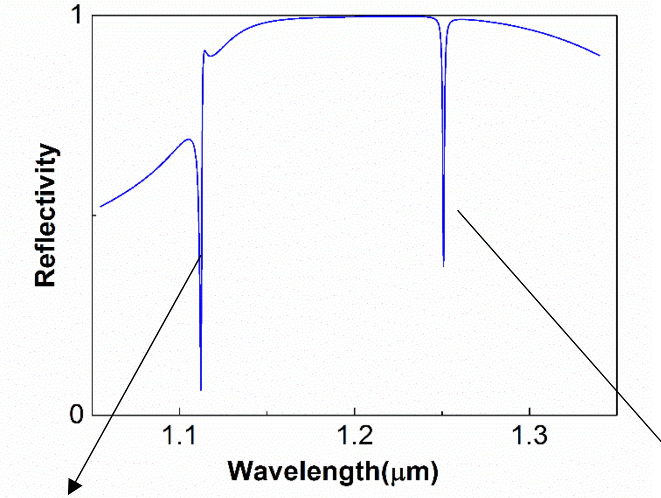
E intensity enhancement ~30





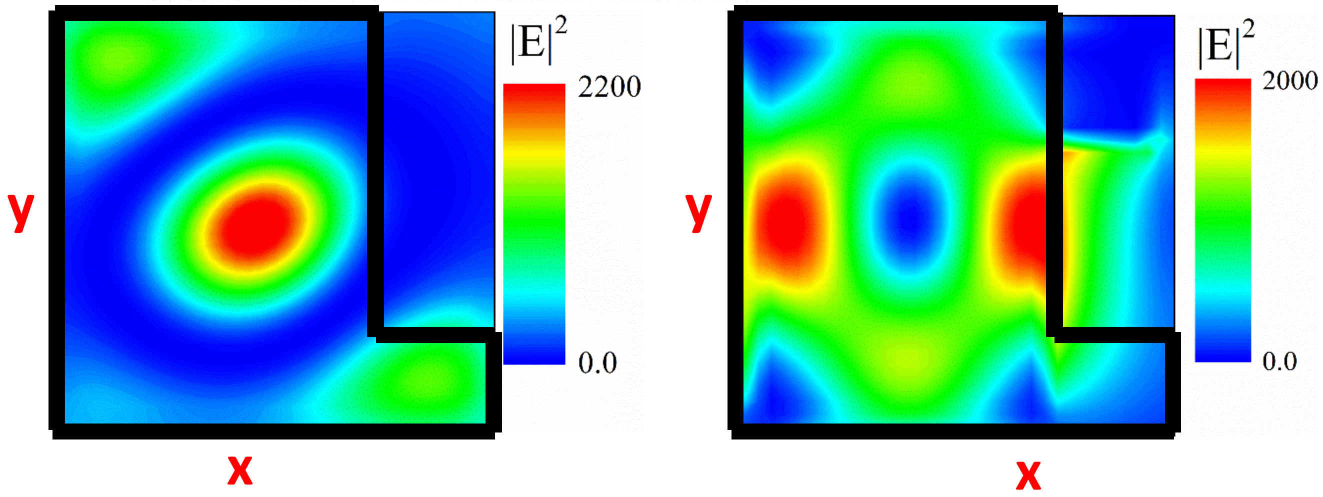


- Broken symmetry design
- Single unit cell



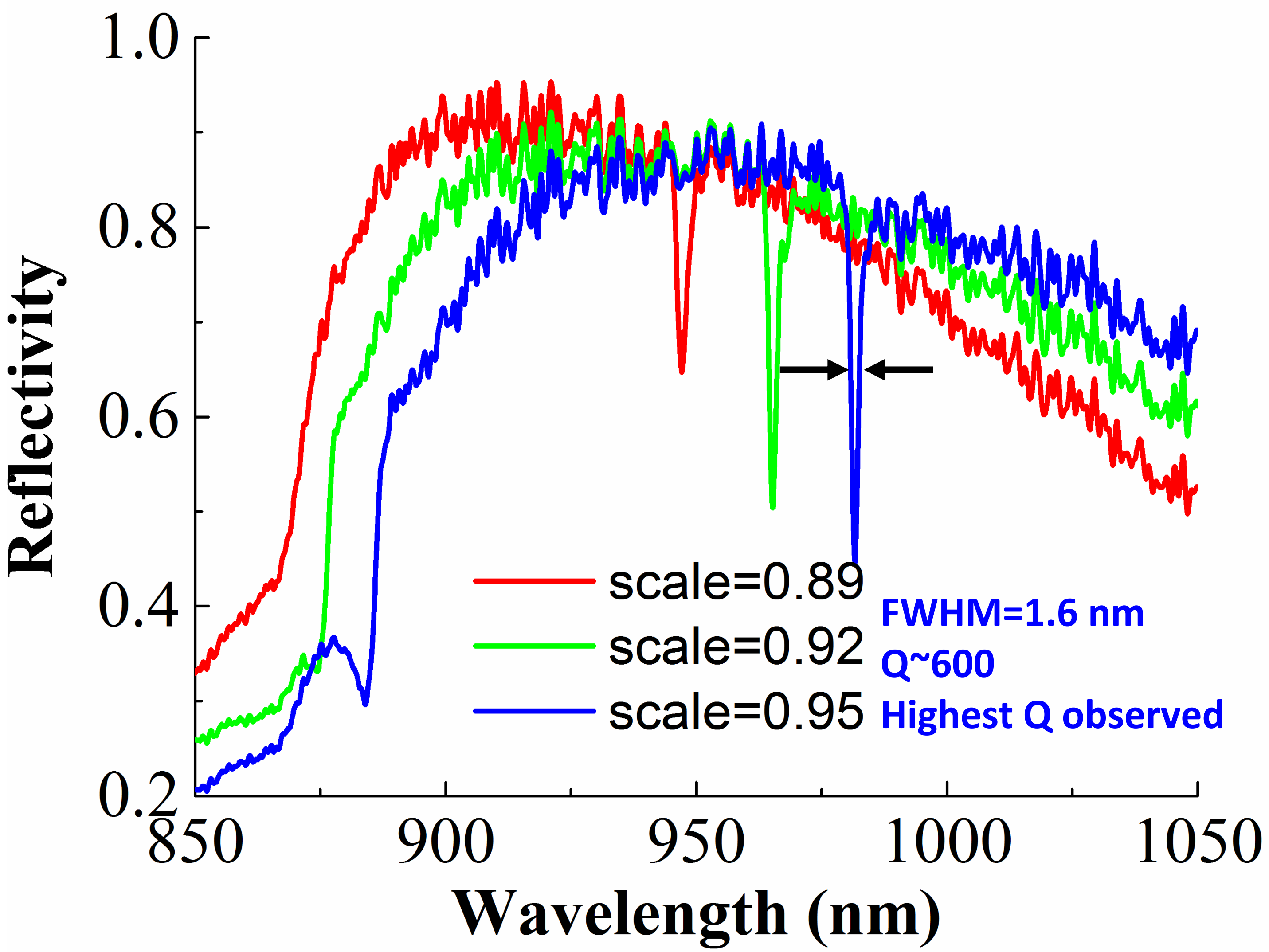
Intensity enhancement >1000

Out of plane dipoles

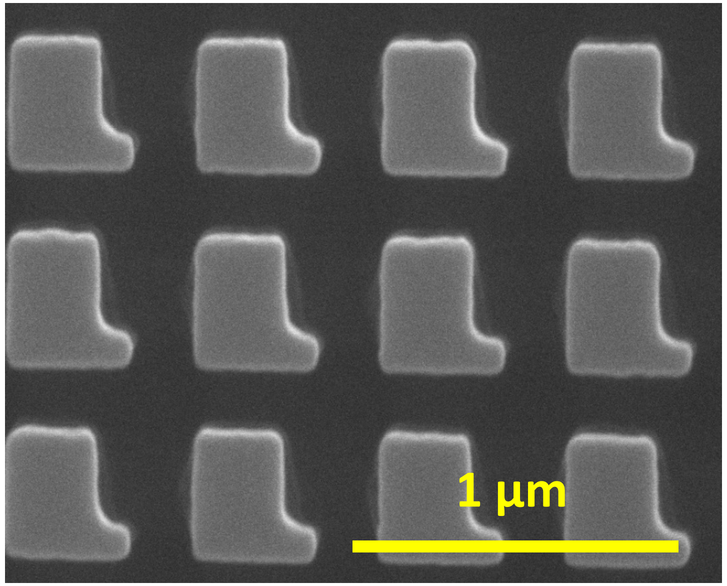


GaAs Fano metasurface samples

Sandia National Laboratories

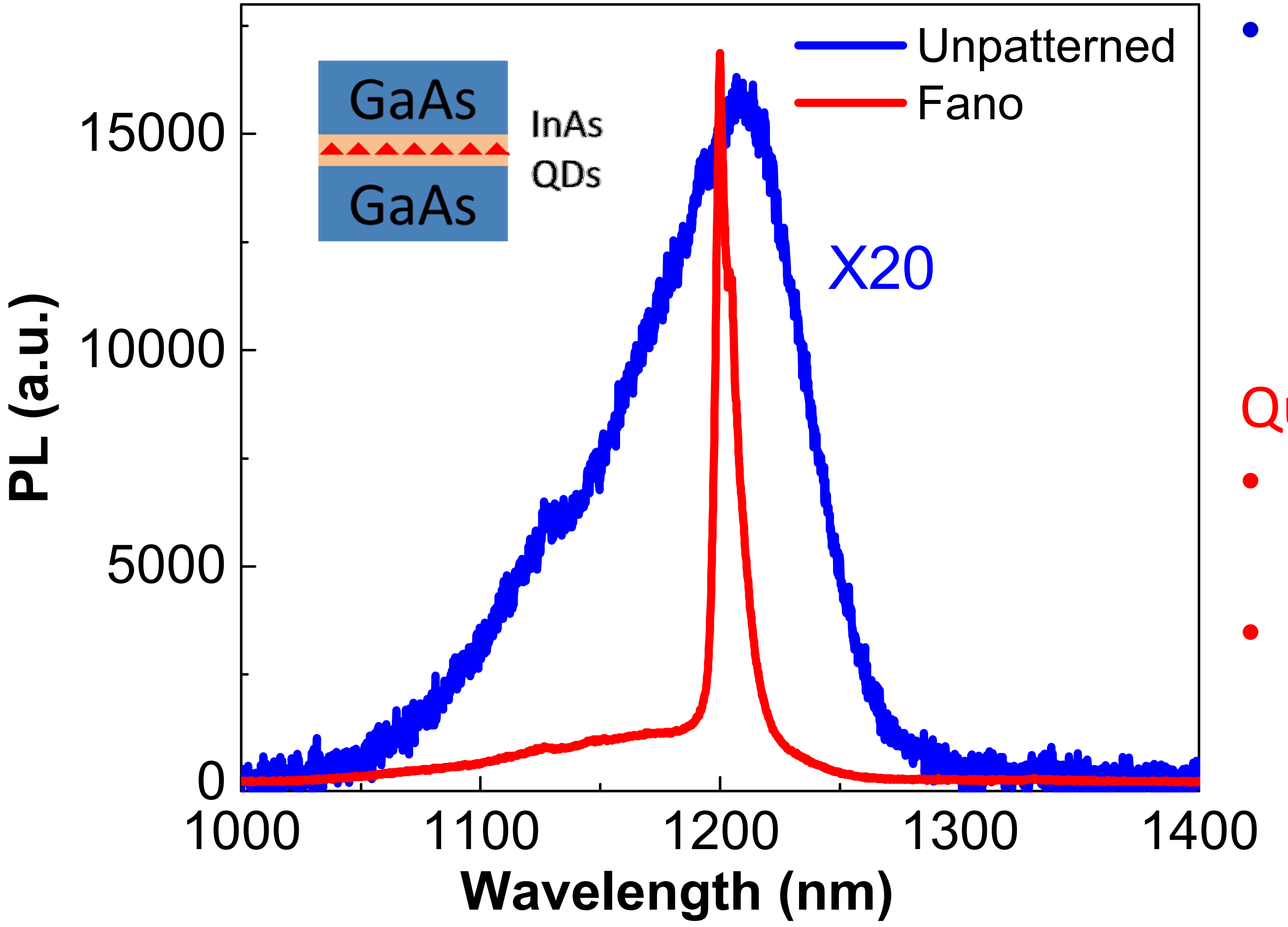


ACS Photonics 2016, 3, 2362–2367



Emitter embedded Fano metasurfaces—PL enhancement

- Femtosecond laser as pump, ~5 μW

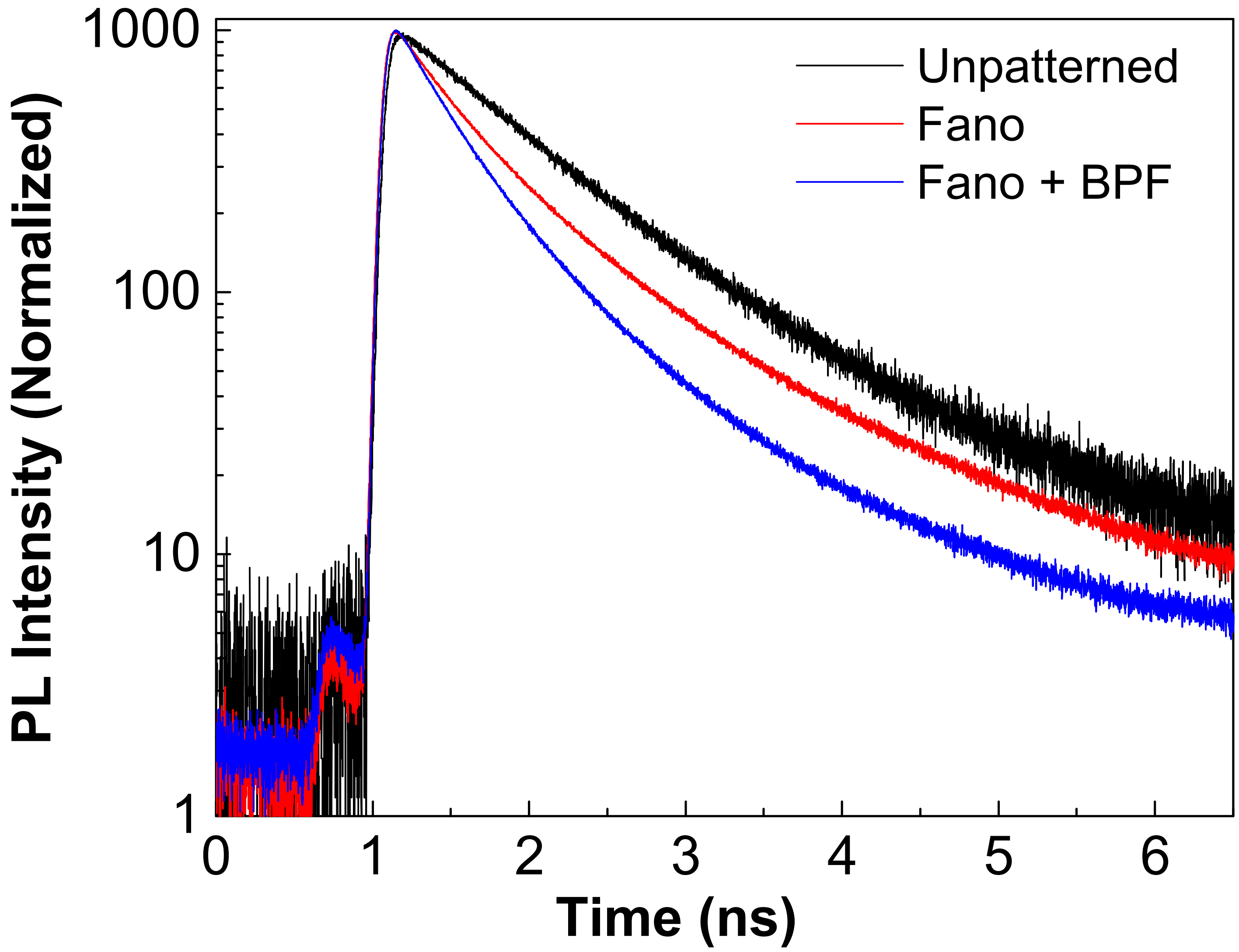


- PL linewidth narrowing
- Large enhancement of PL peak intensity

Questions:

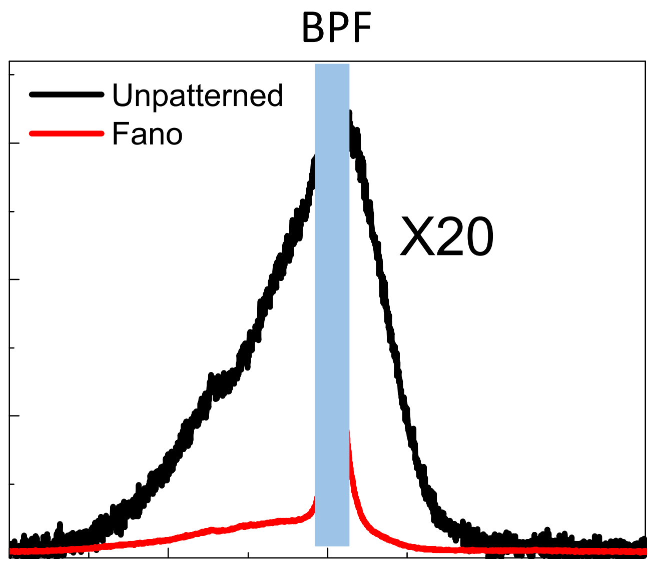
- Purcell enhancement (lifetime measurement)
- Spectral tuning + peak wavelength

Purcell enhancement—lifetime reduction

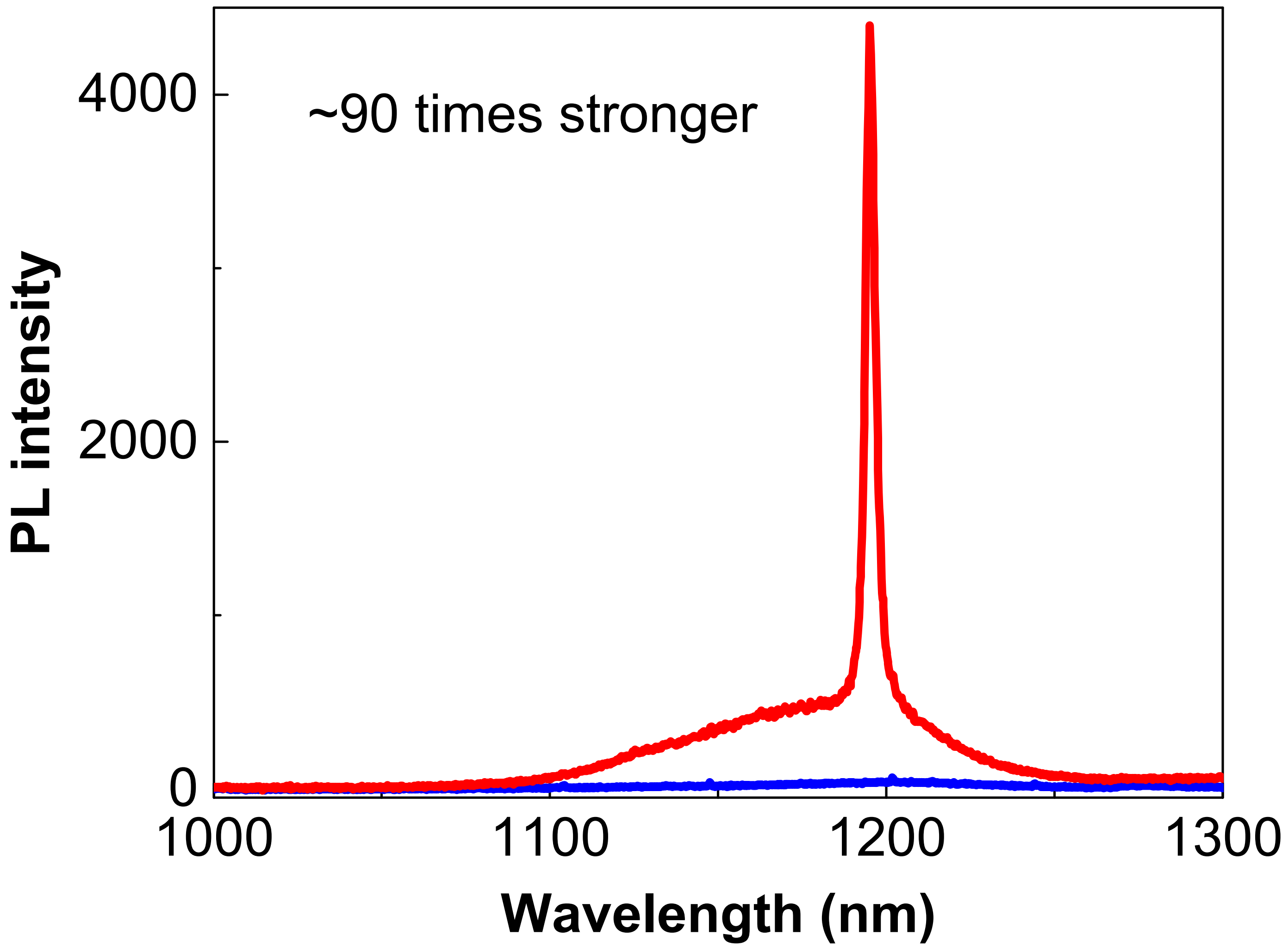


BPF: band pass filter

- Purcell enhancement (~100% quantum efficiency emitter)
- Low emission quantum efficiency from epitaxially grown InAs QDs
- Strong non-radiative decay rate (+strong surface recombination, passivation) $\tau_{PL}^{-1}=\tau_r^{-1}+\tau_{nr}^{-1}$

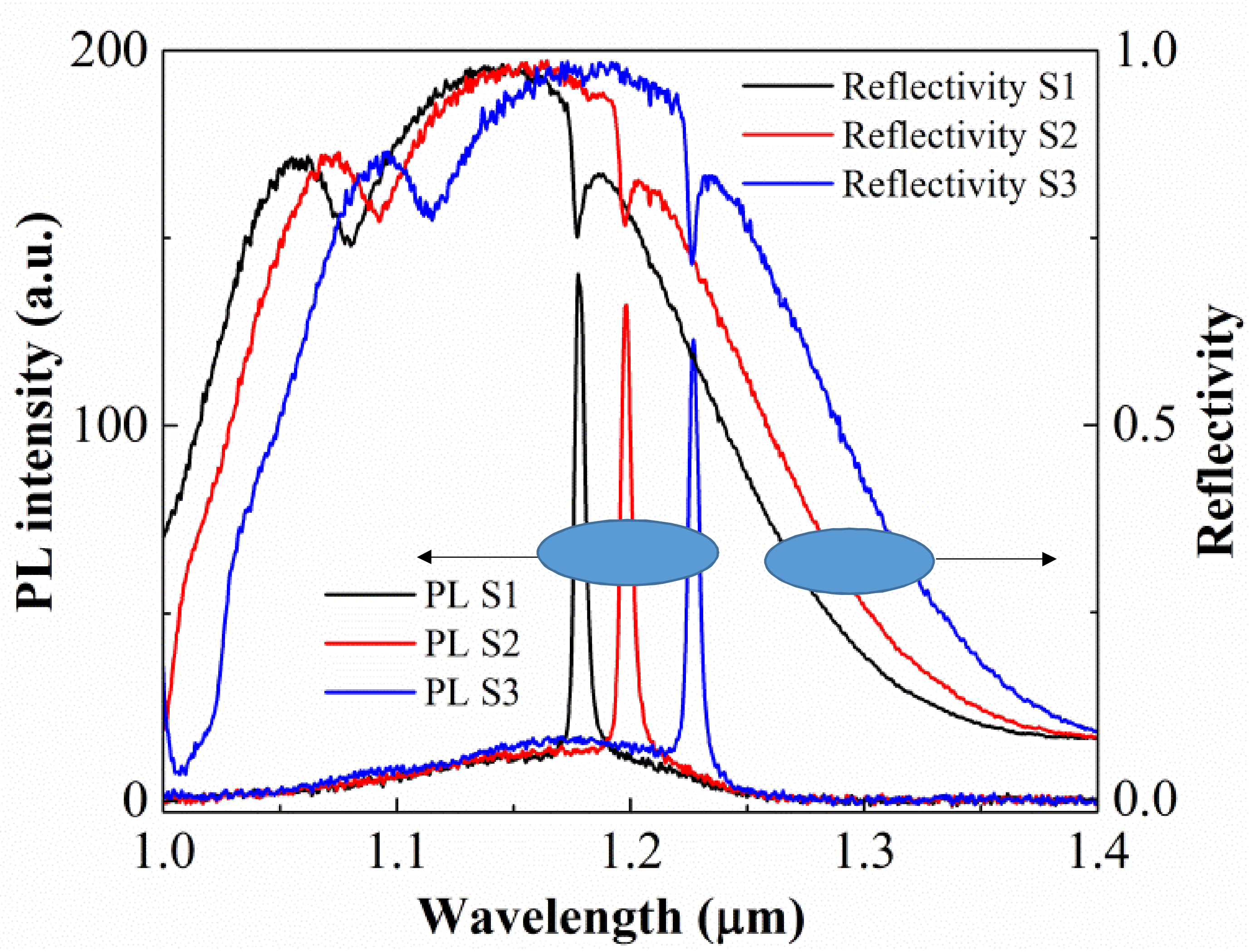


Purcell enhancement—CW pump

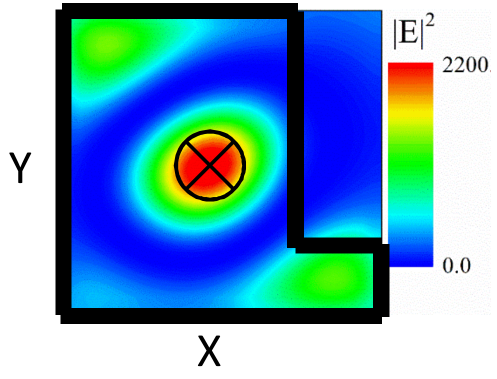


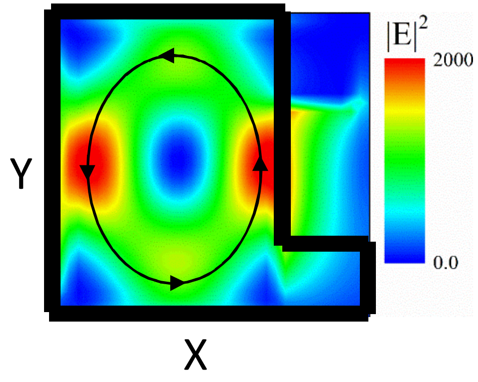
- CW light as pump
- Indirect technique to probe the PL lifetime
- 20X vs. 90X (4.5 times reduction of lifetime)

PL spectral tuning



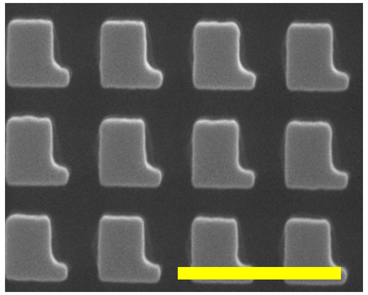
- Spectral tuning of the Fano resonances by changing the sizes
- PL peaks agree well with the reflectivity dips
- PL enhancement only occurs at one of the two resonances
  - ➢ Higher Q (fabrication, absorption)
  - ➢ Out of plane emission vs in-plane emission (NA)

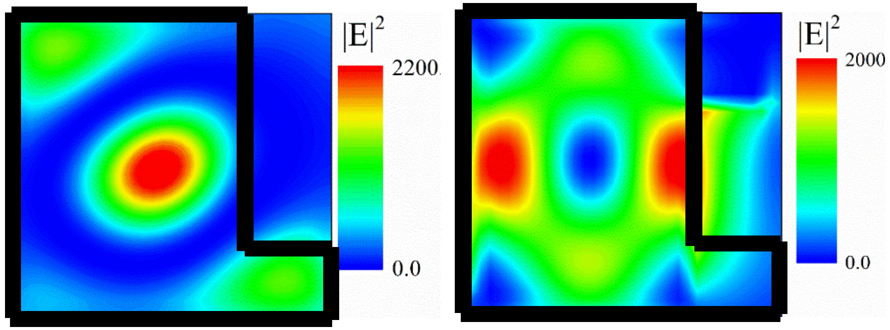




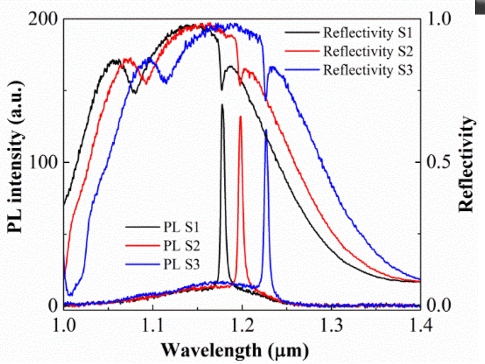
Thank you

- First metasurface with emission media epitaxially grown inside

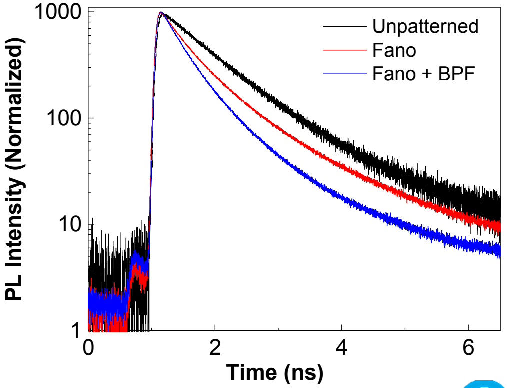




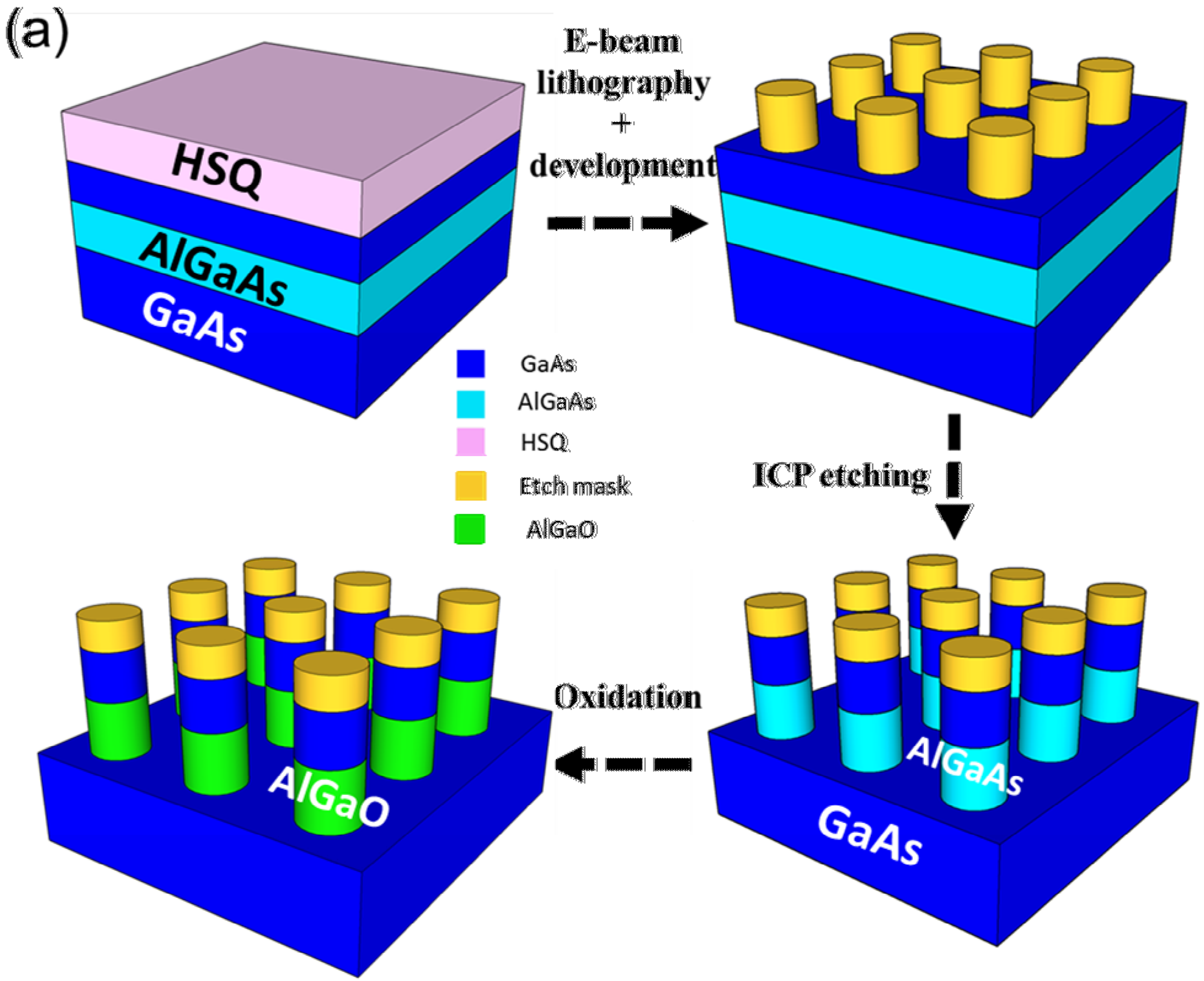
- Spectral tuning



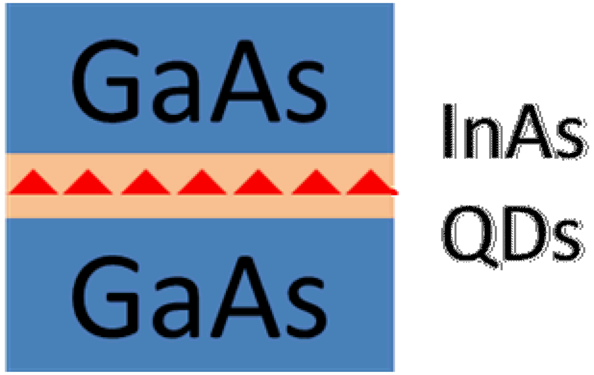
- Large Purcell enhancement



Fabrication active dielectric resonators



IEEE JSTQE, 3, 916 (1997)



- GaAs
- AlGaAs
- HSQ
- Etch mask
- $Al_xGa_yO_z$

Exploring dark modes in nano-cylinder resonators