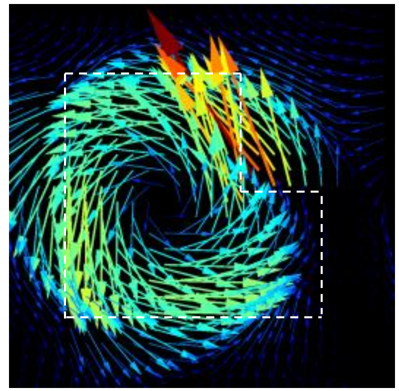
SAND2016-6965C

High Quality-Factor Fano Metasurfaces



Michael B. Sinclair

Sandia National Laboratories
Albuquerque, NM, USA

mbsincl@sandia.gov

AP-S/URSI

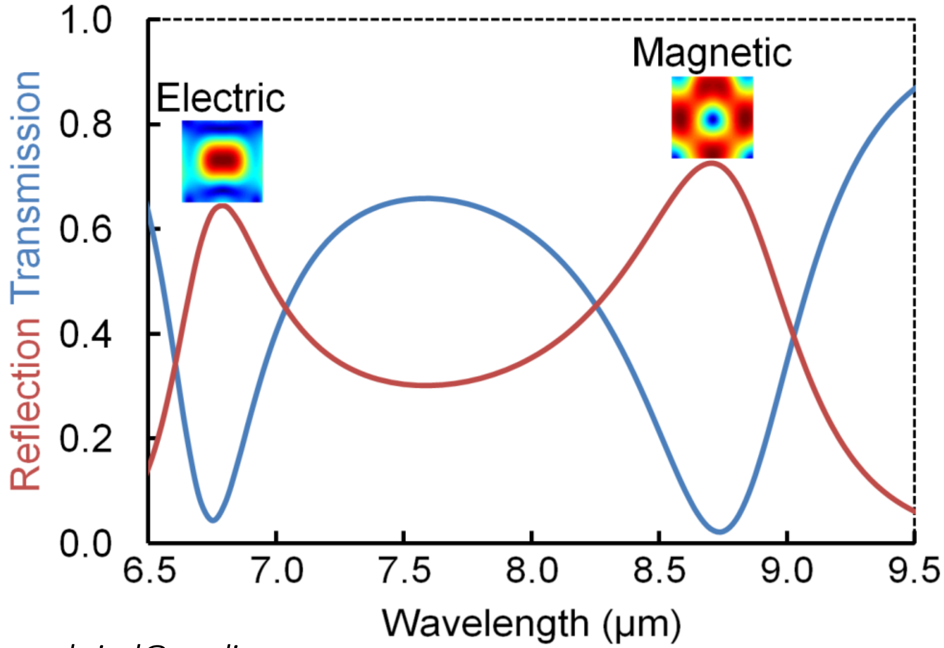
June 27, 2016

This work was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering and performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. 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.

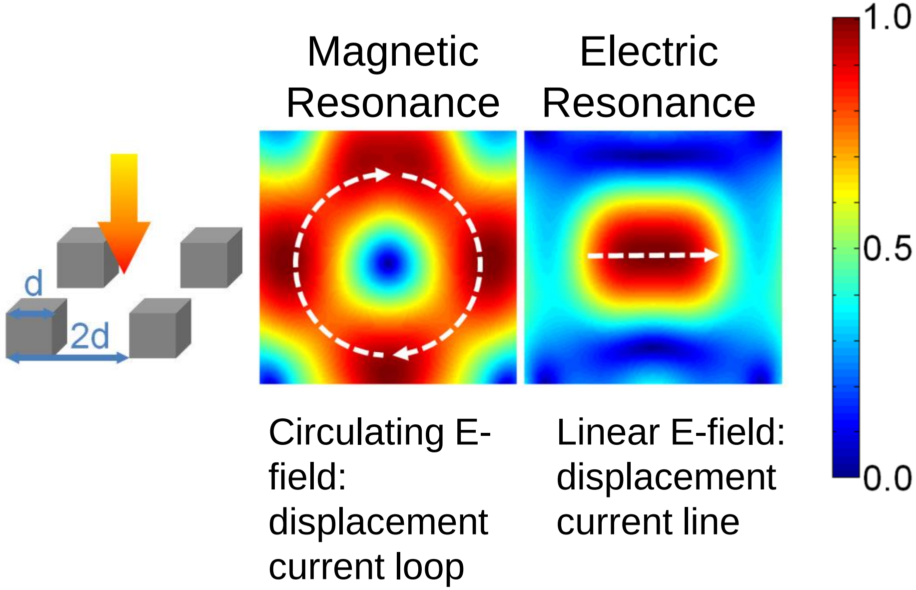
Dielectric Resonator Metamaterials

- Low loss option for IR & visible wavelengths
- Ohmic currents replaced by displacement currents
- High permittivity materials
- Starting Point: Mie theory → multipole resonances

1.7 μm Te cube array



Electric field patterns

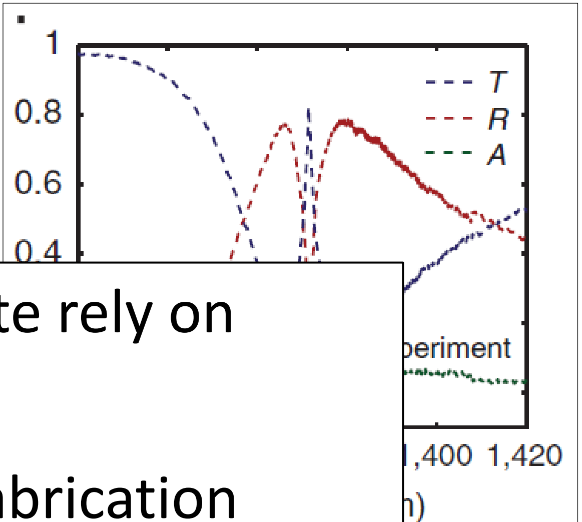


How do we achieve sharp resonances?

Fano resonances of metasurfaces:

- First proposed for metal metasurfaces
- Interference of “bright” and “dark” excitations

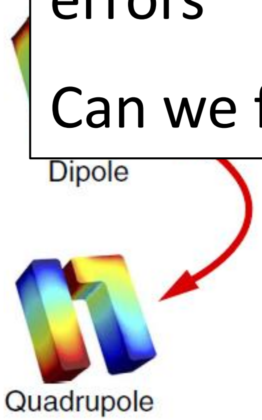
Now



The highest Q-factor DR Fano designs to-date rely on multiple resonators in the unit cell

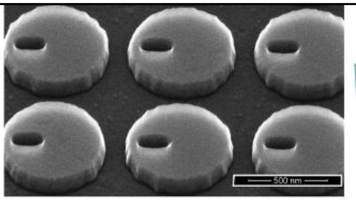
Near field coupling extremely sensitive to fabrication errors

Can we find a one-resonator design that leads to high Q??



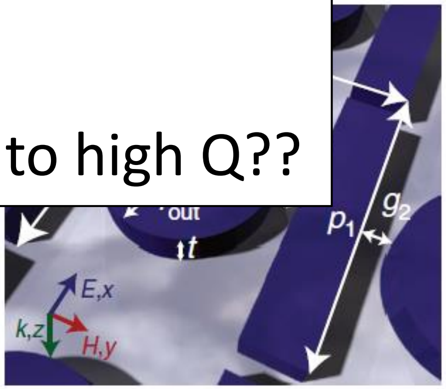
Q ~ 130 at 4 um (experimental)

Wu, et al.
Nature Comm. 5, 3892, 2014



Q ~ 100 at 1.5 um

Jain, et al.
AOM 10, 1431, 2015



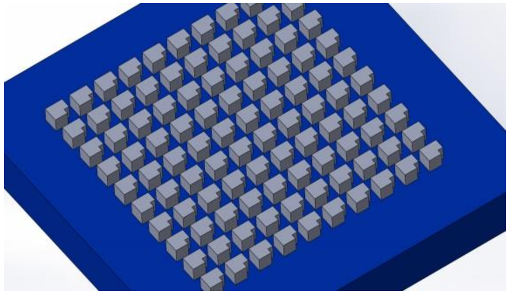
Q ~ 500 at 1.37 um (experimental)

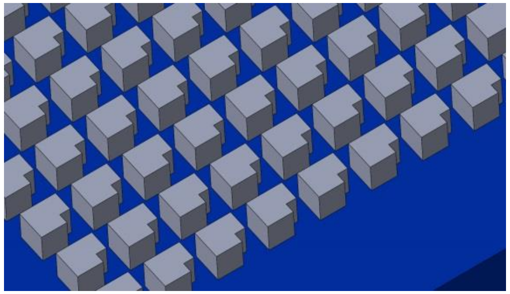
Yang, et al.
Nature Comm. 5, 5753, 2014

High Quality-Factor Fano Metasurfaces

Outline

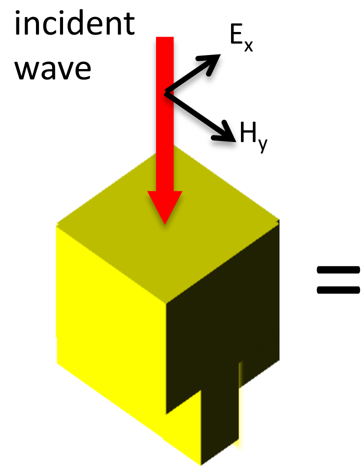
- Operating principles
- Hi-Q monolithic design
- Nature of the Fano mode
- Experimental demonstrations:
  - SOI: measured Q-factor of ≈ 350 at 990 nm
  - GaAs: Q-factor of ≈ 600 at 975 nm

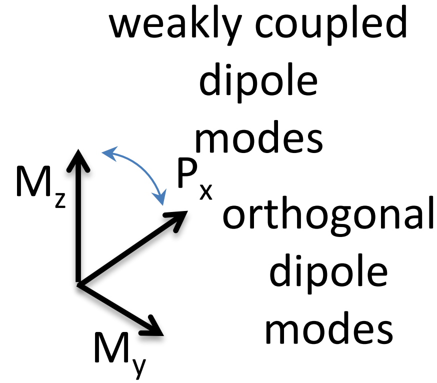




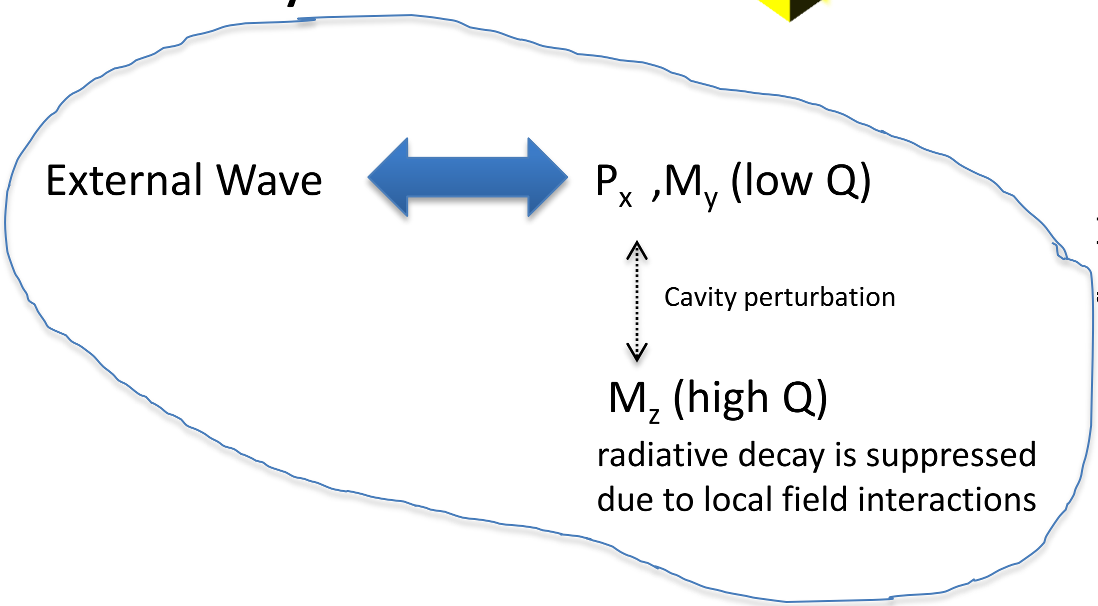
mbsincl@sandia.gov

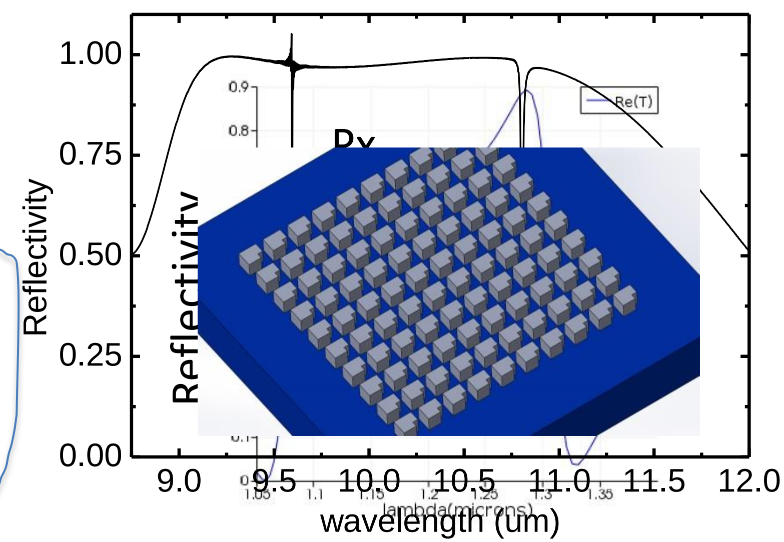
Operating principles



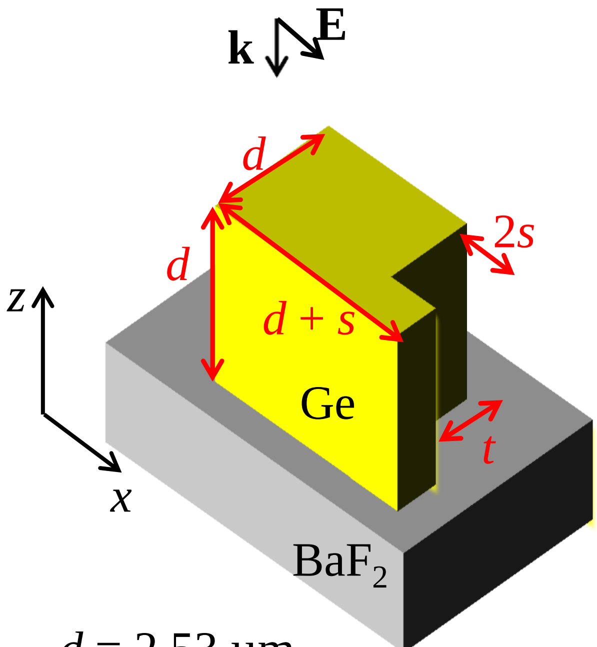


Fano system





Ge-based Fano metasurface design



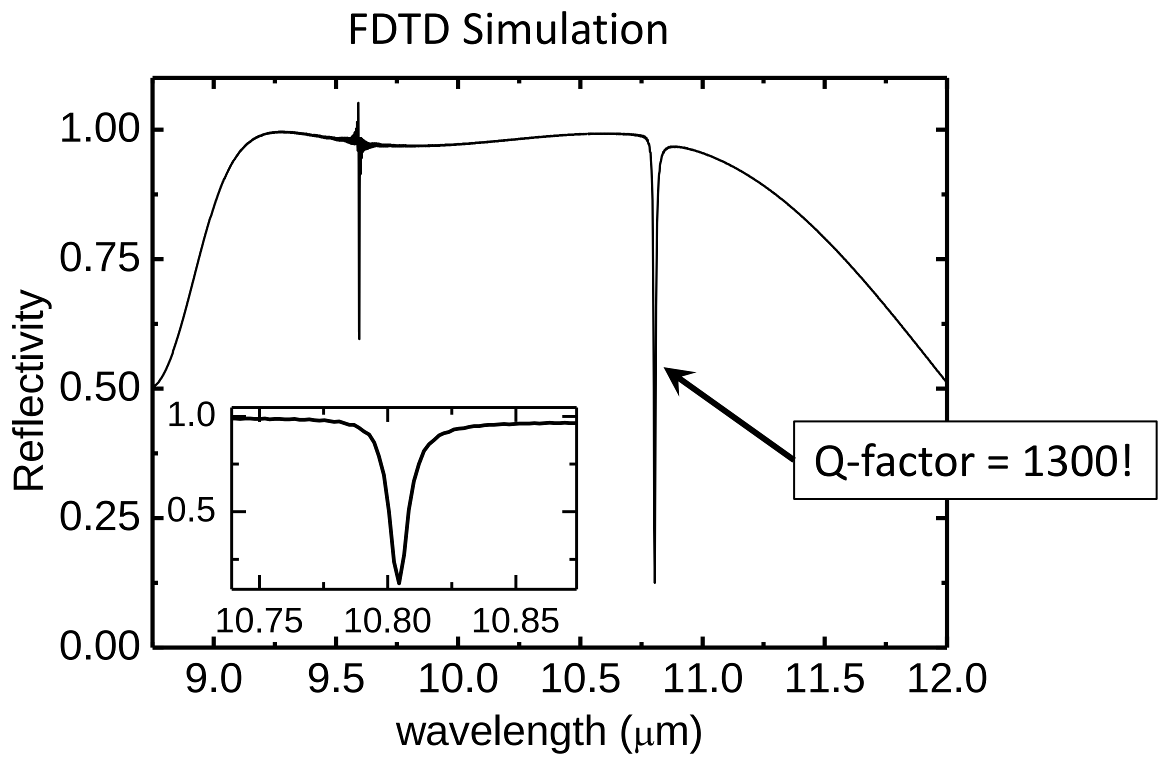
$d = 2.53$ μm

$s = d / 5$

$t = 1.5$ μm

Array Pitch:

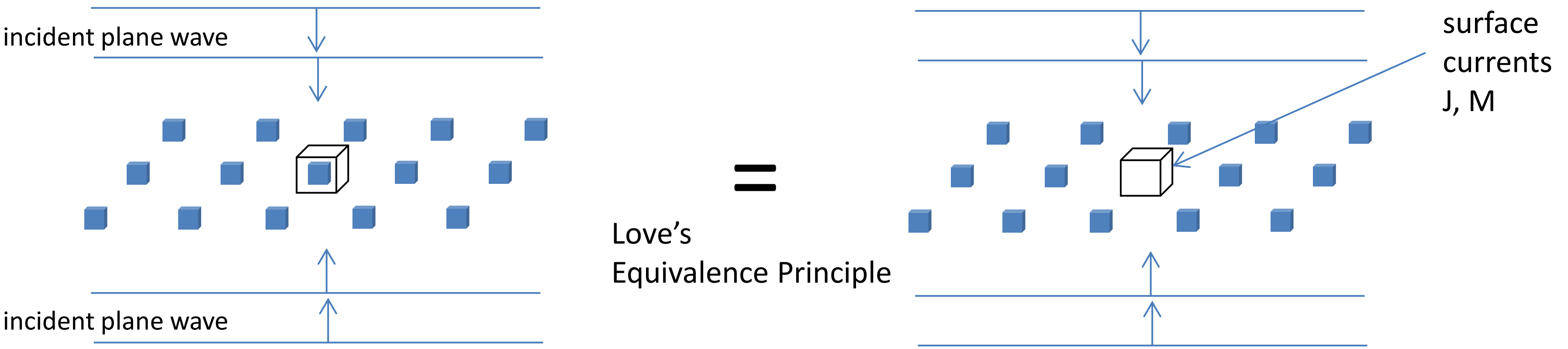
$a = b = 4.2$ μm



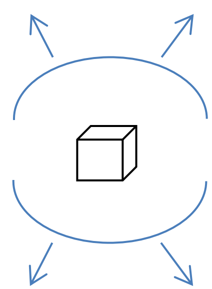
Design is scalable from NIR through RF!

Understanding the nature of the Fano mode

"Numerical Experiment": multipole decomposition of the resonator's response in the array.



1. Simulate array response
2. Collect tangential fields on fictitious box
3. Replace resonator with surface currents on box

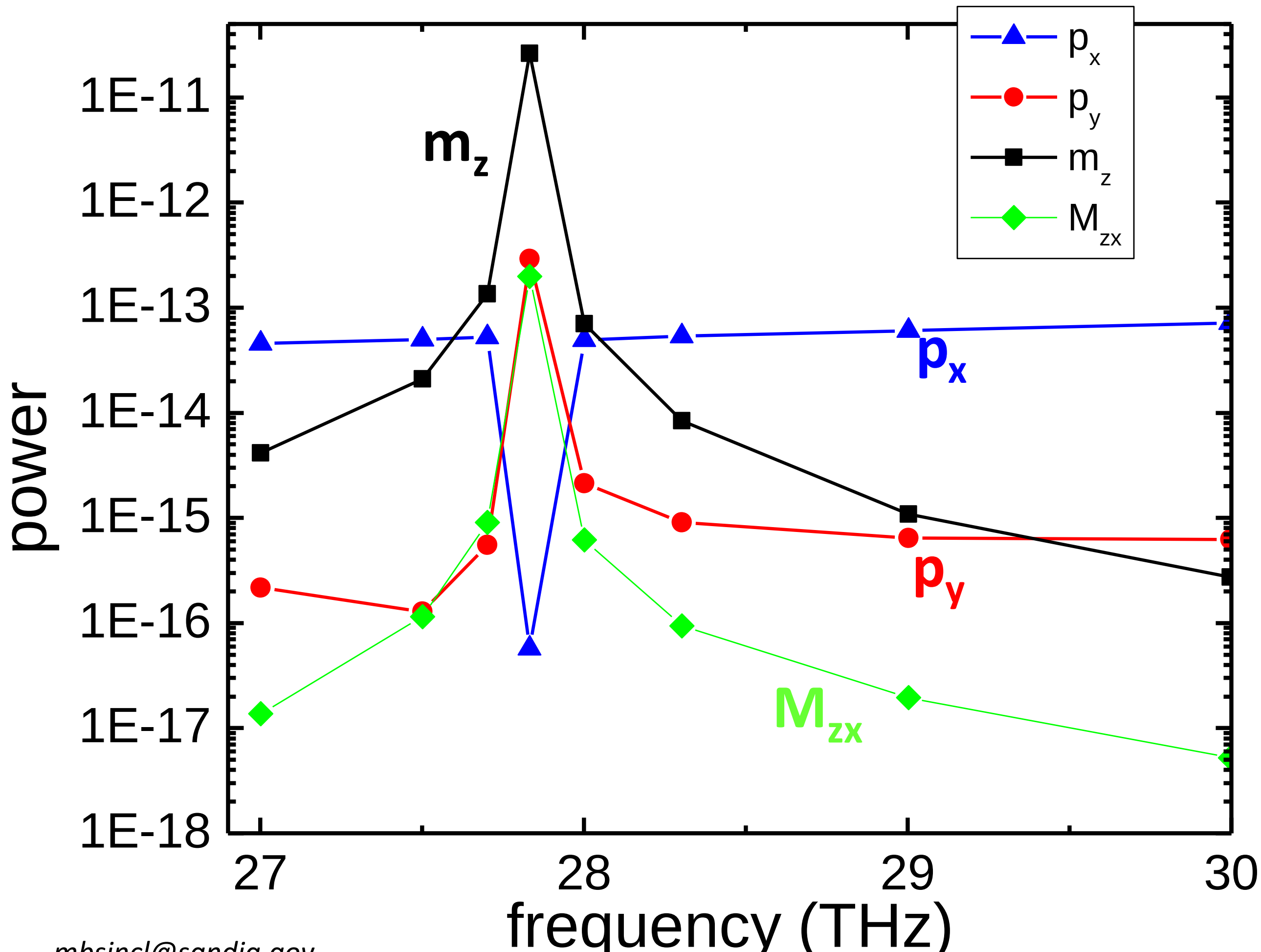


4. Calculate far-field due to surface currents on box alone
5. Fit to multipoles – all dipole and quadrupole modes

Understanding the nature of the Fano mode

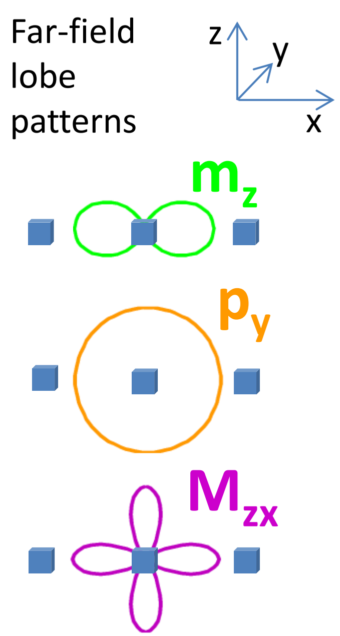
Multipole decomposition of resonator response

- x-polarized electric field excitation for full array
- Far-field scattering for single cube
- Extract multipole powers



At the Fano resonance:

- m_z dominates
- p_x is extinguished
- p_y and M_{zx} (magnetic quadrupole) are excited

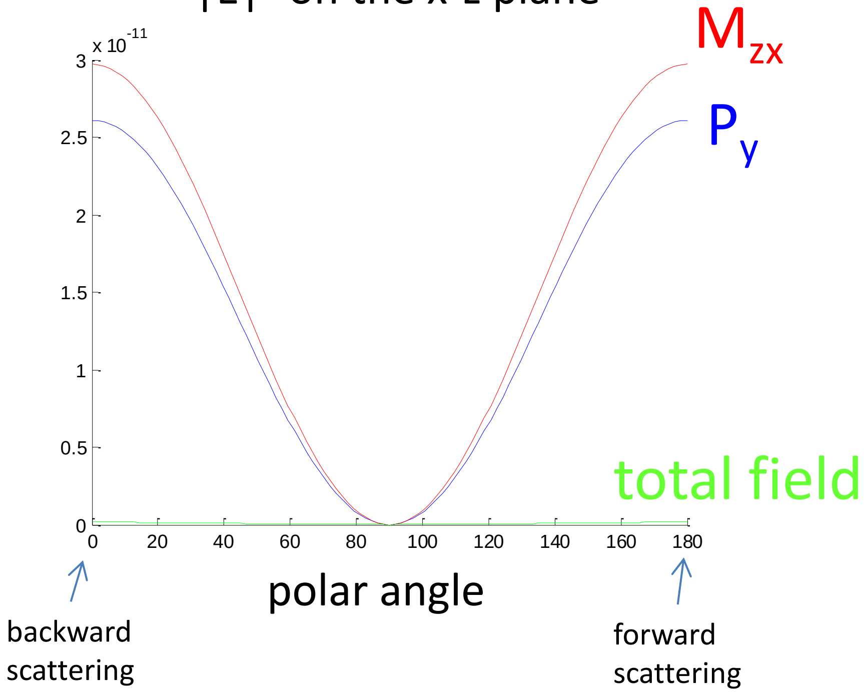


What about p_y and M_{zx}?

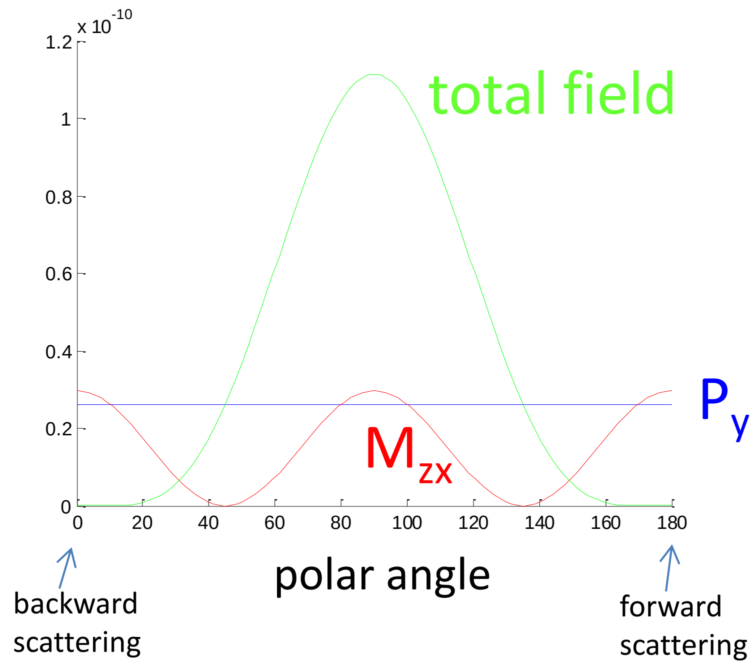
At Fano resonance:

- both multipoles are excited
- radiated fields cancel in forward and backward directions!!

$|E|^2$ on the x-z plane

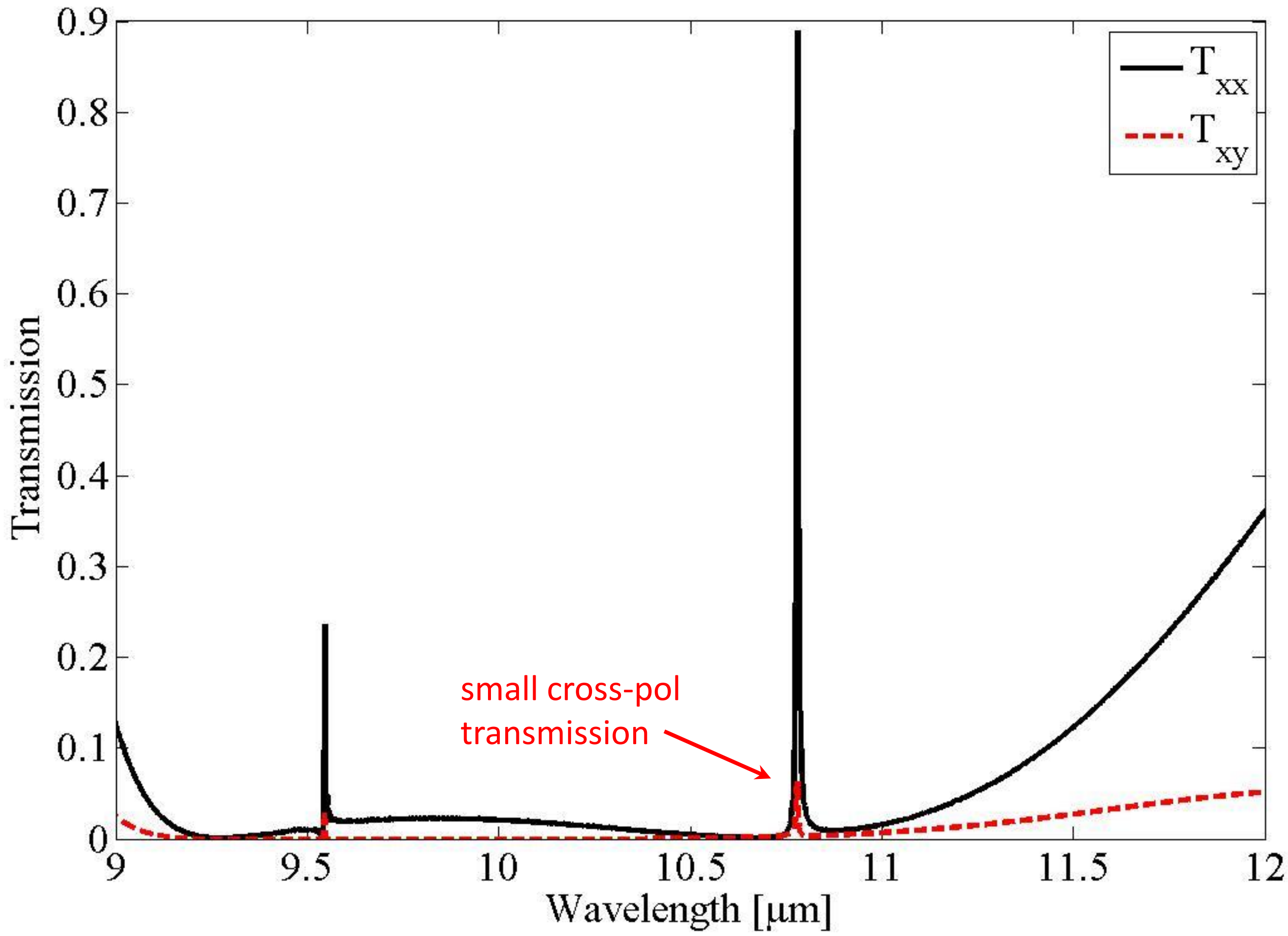


$|E|^2$ on the y-z plane



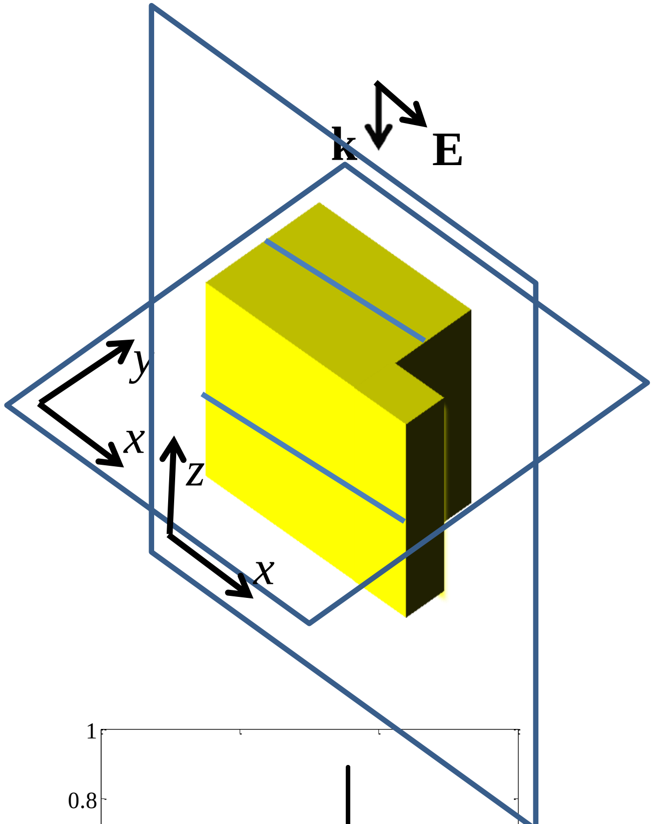
Small cross polarization of transmitted wave

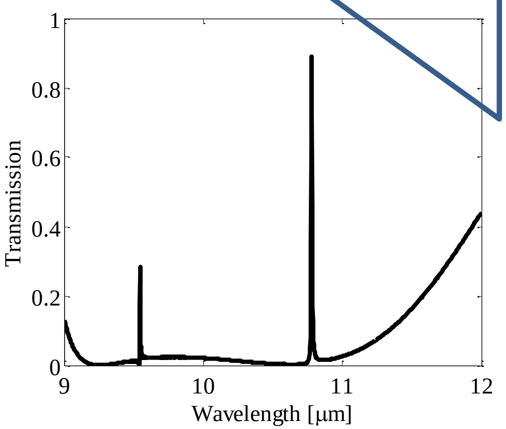
Residual imbalance of scattering by p_y and M_{zx}

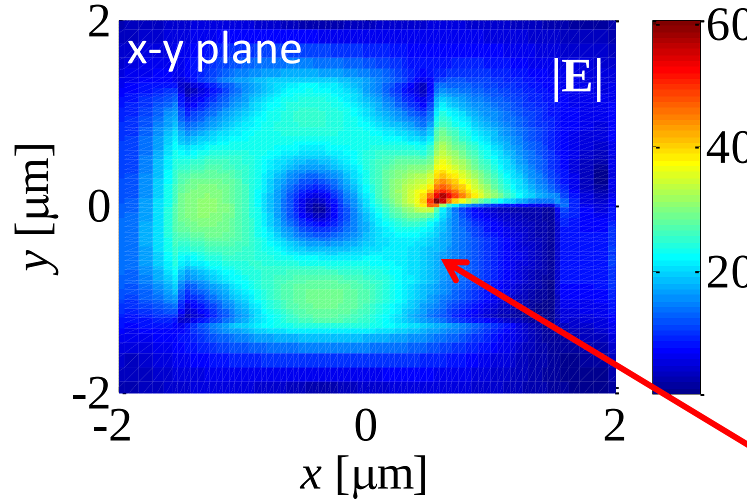


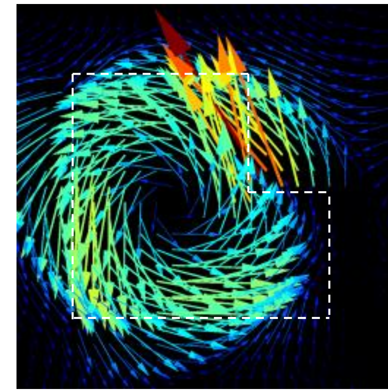
Resonant Mode Field Profiles

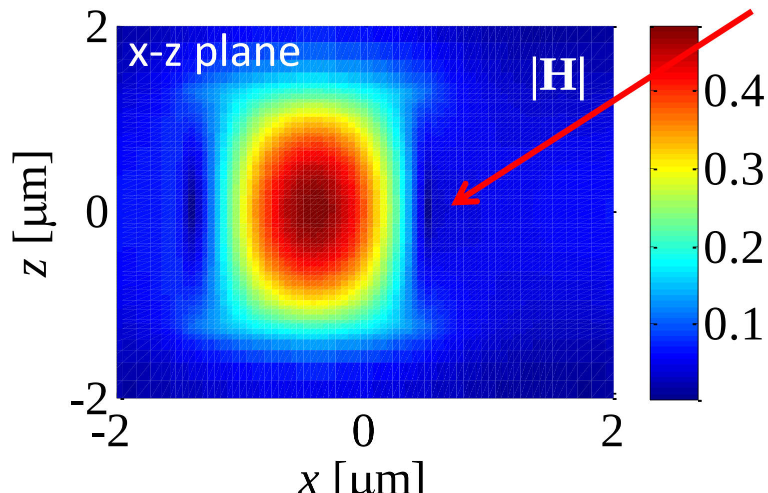
FDTD simulations at the λ = 10.8 μm resonance





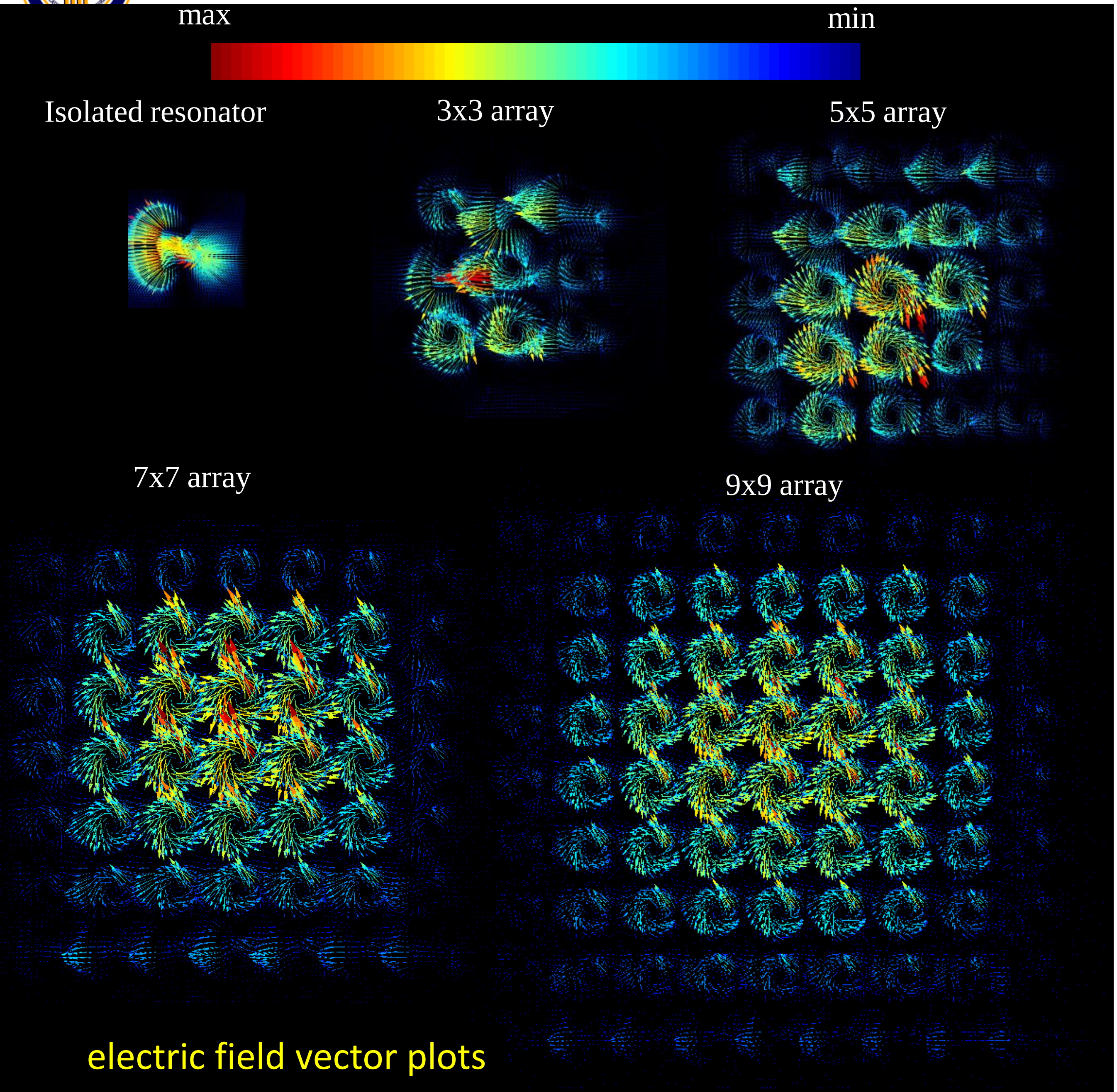






z-directed magnetic dipole

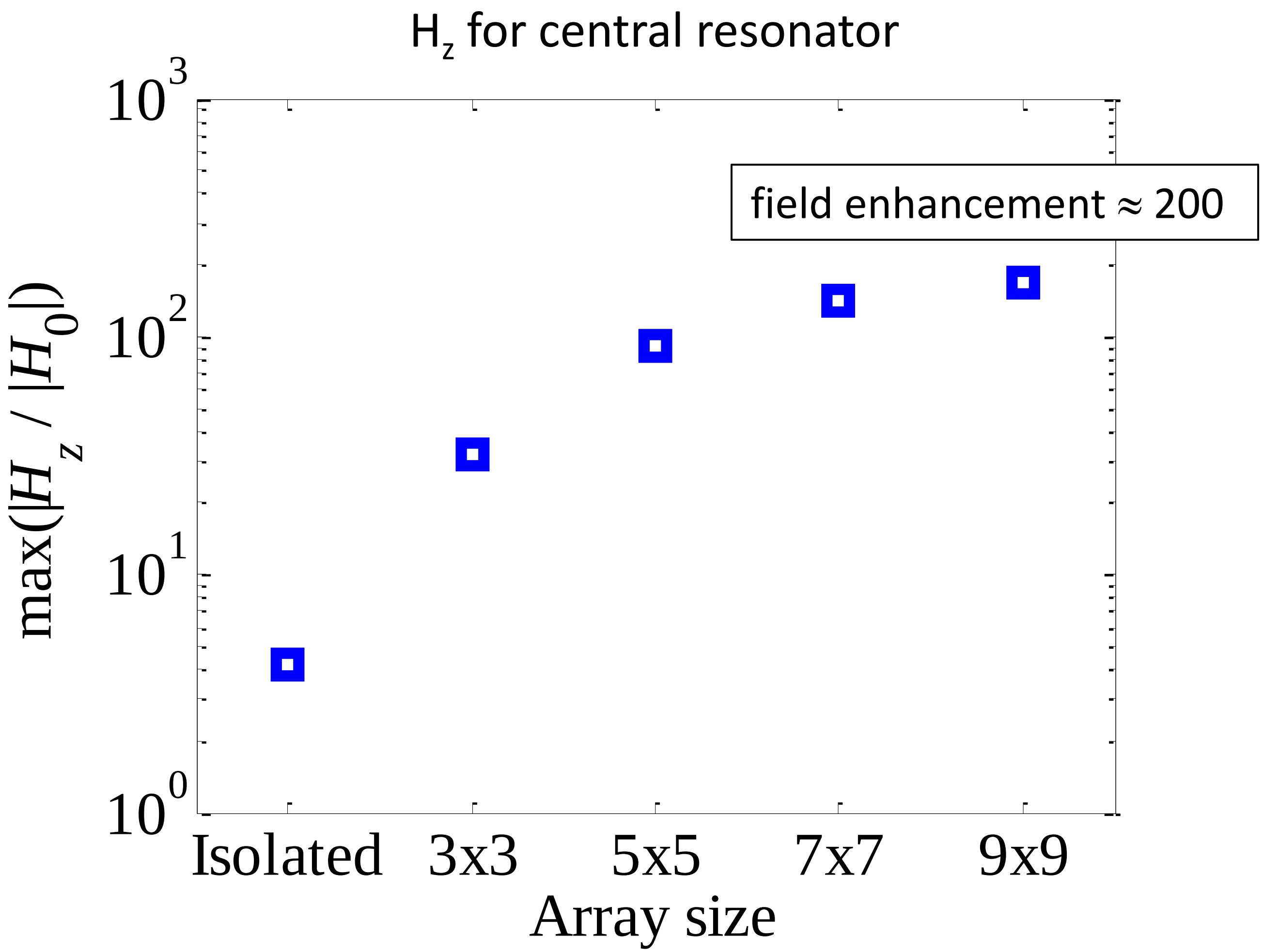
Array effect on the magnetic dipole



electric field vector plots

- m_z can't radiate broadside (no forward lobe)
- near center: local fields inhibit radiative decay of m_z
- near edges: m_z can radiate laterally
- quality factor increases towards center
- quality factor increases with array size

Field Enhancement vs. Array Size



- beginning to saturate for 9x9 array
- effect arises from nearby resonators

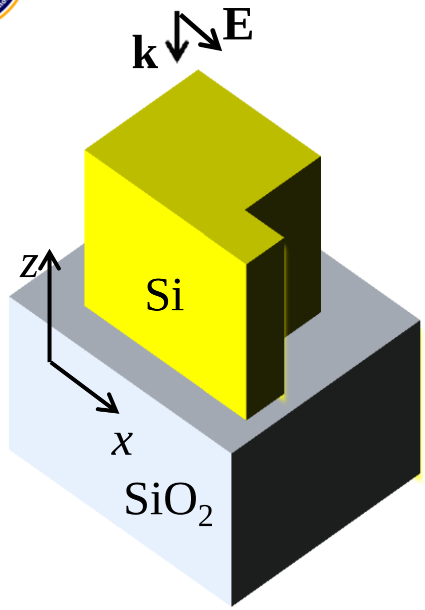
mbsincl@sandia.gov

Experimental Demonstrations of Fano Metasurfaces

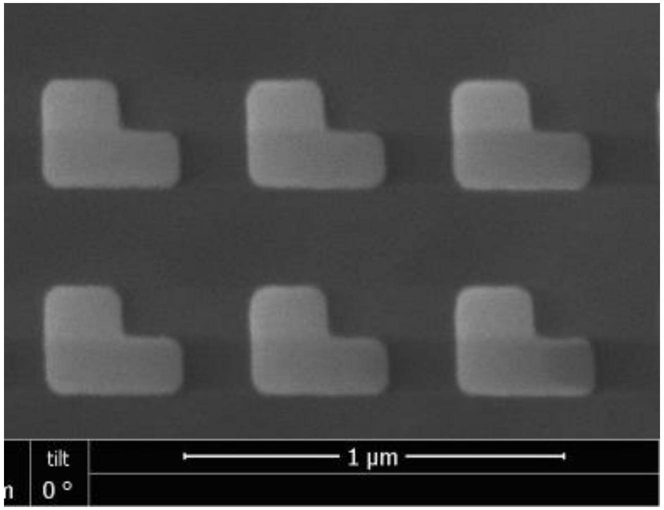
1. Silicon-on-insulator Fano arrays

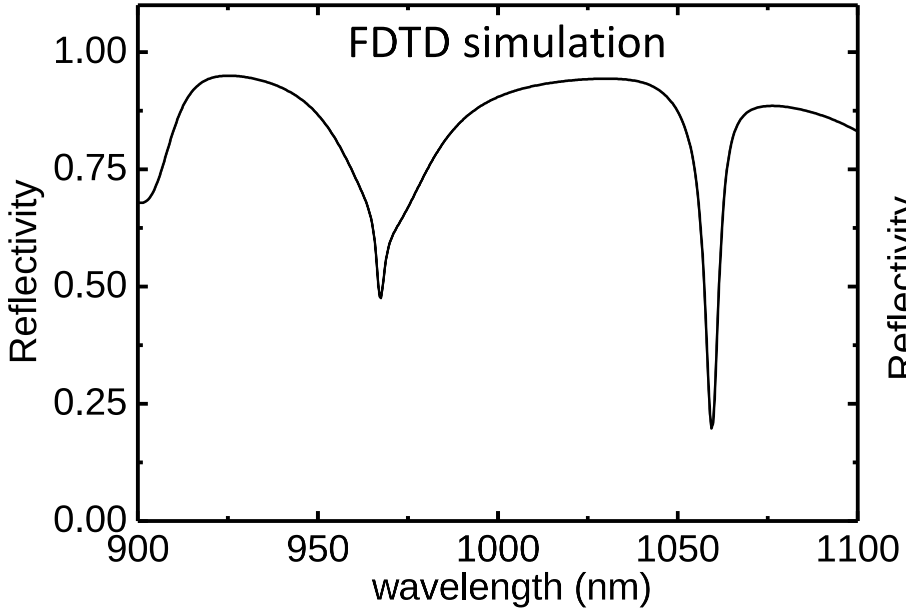
2. GaAs Fano arrays

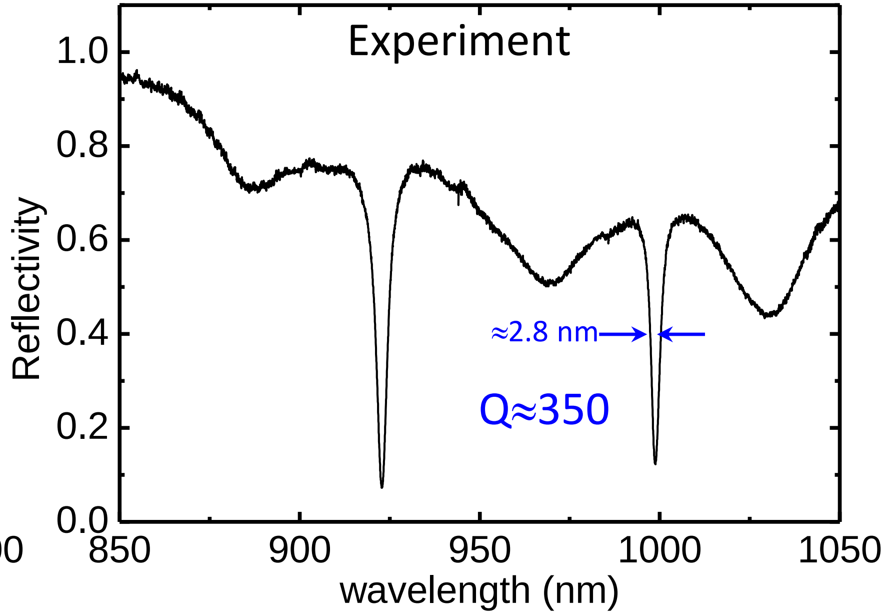
Experimental verification: SOI Fano Resonators



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

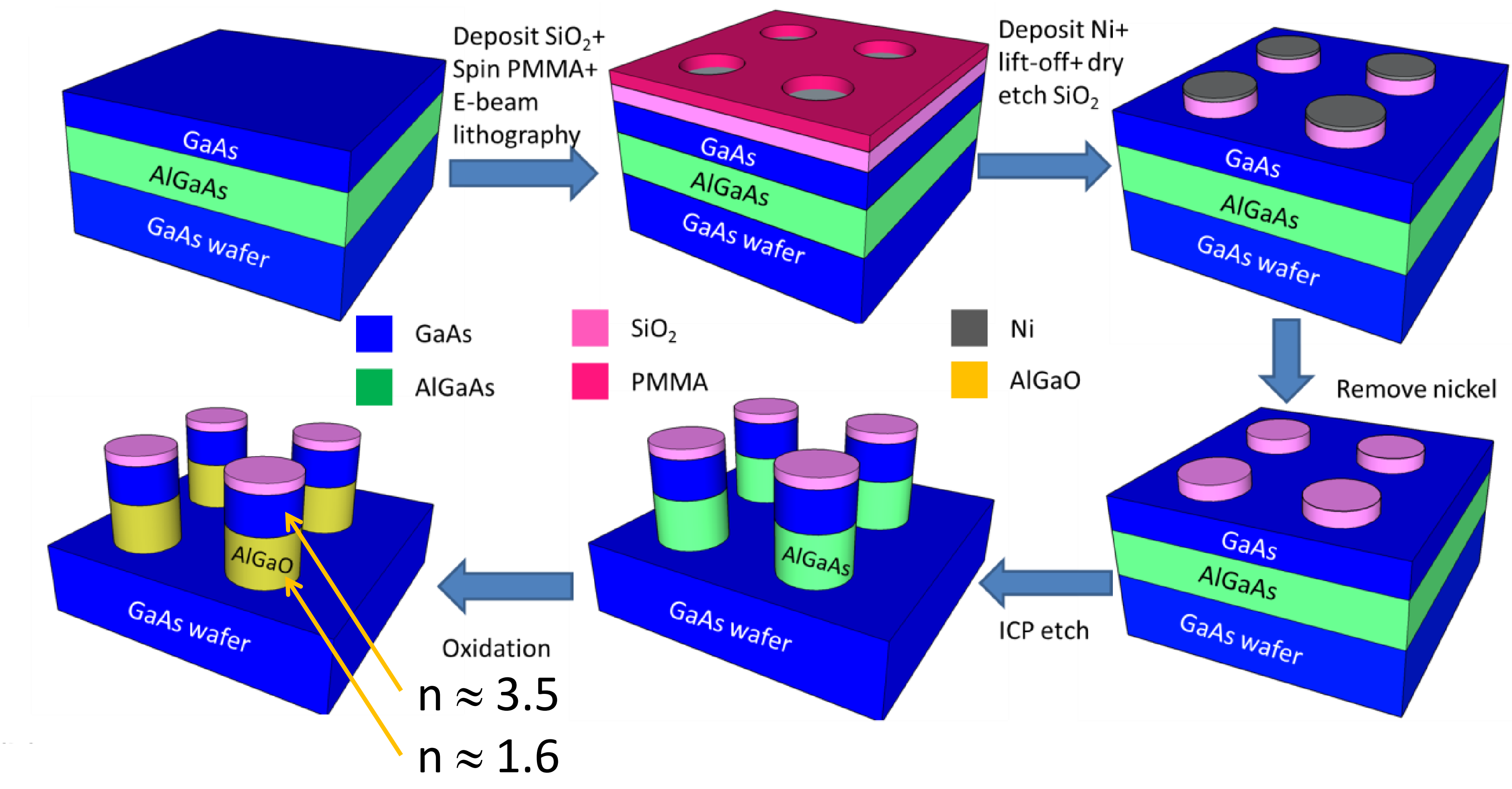






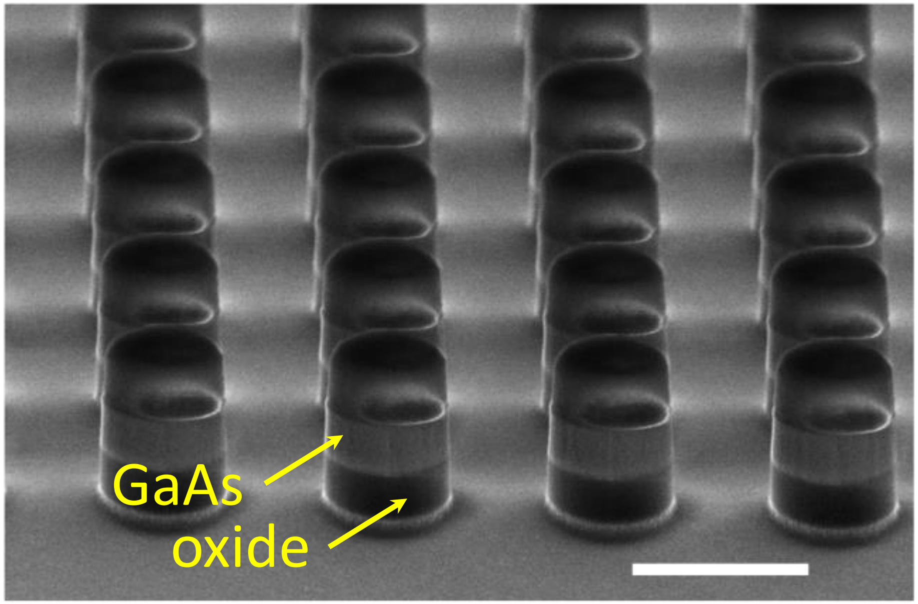
DRs are now possible in III-V semiconductors

New process for (Al)GaAs resonators



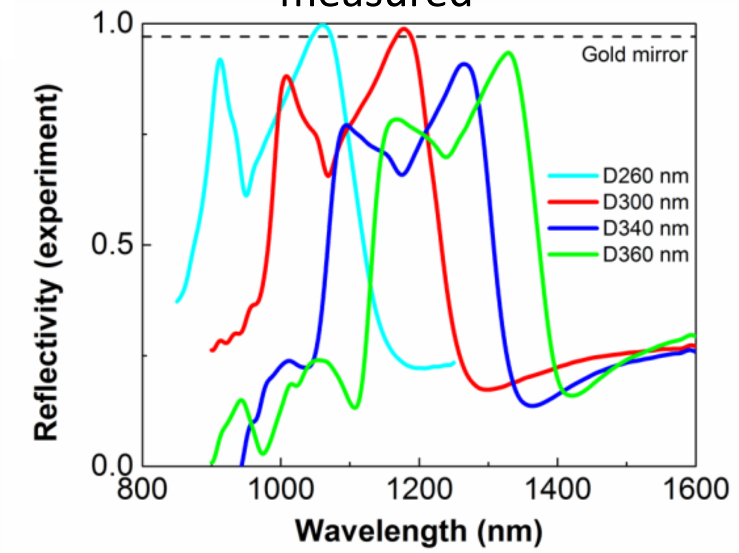
GaAs Cylindrical Resonators

- height = 300 nm
- diameter varies near 300 nm

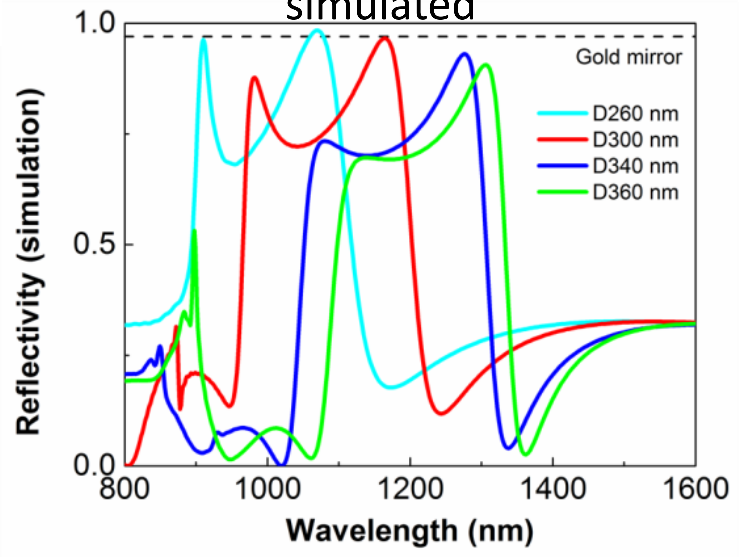


reflectivity exceeds gold at several wavelengths

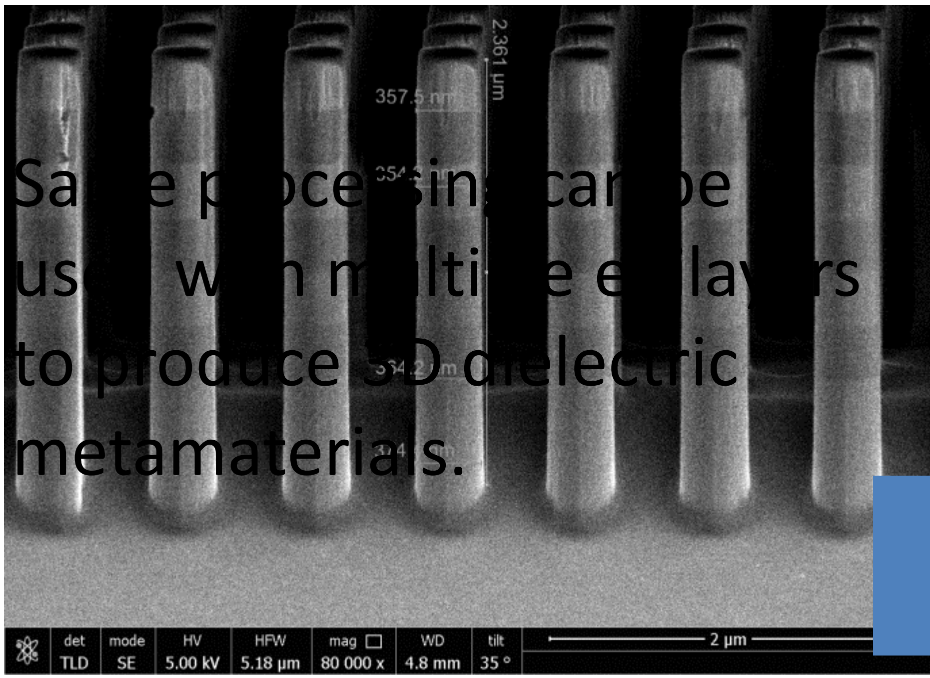
measured



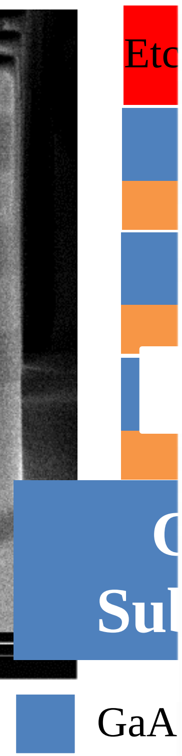
simulated

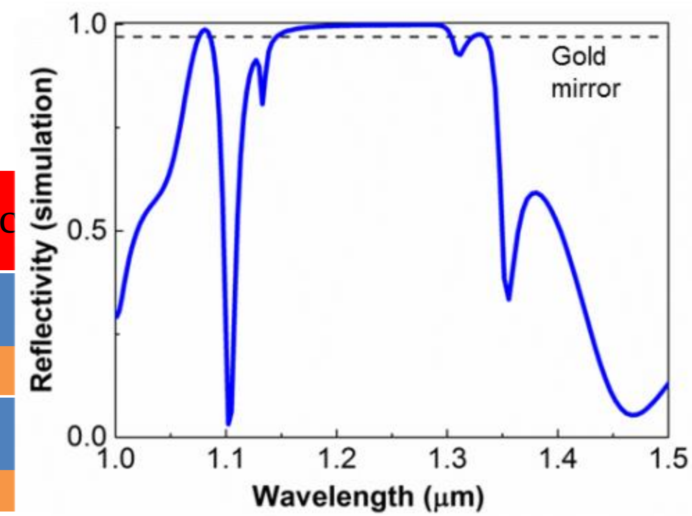


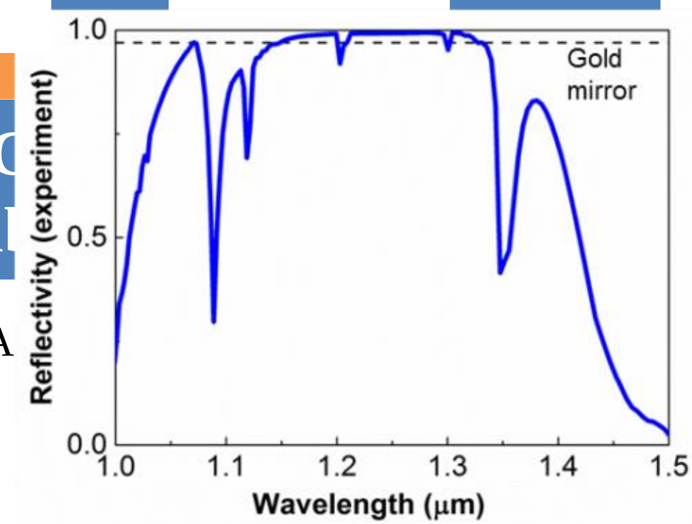
Multilayer III-V Dielectric Metamaterials



Same processing can be used with multiple epilayers to produce 3D dielectric metamaterials.



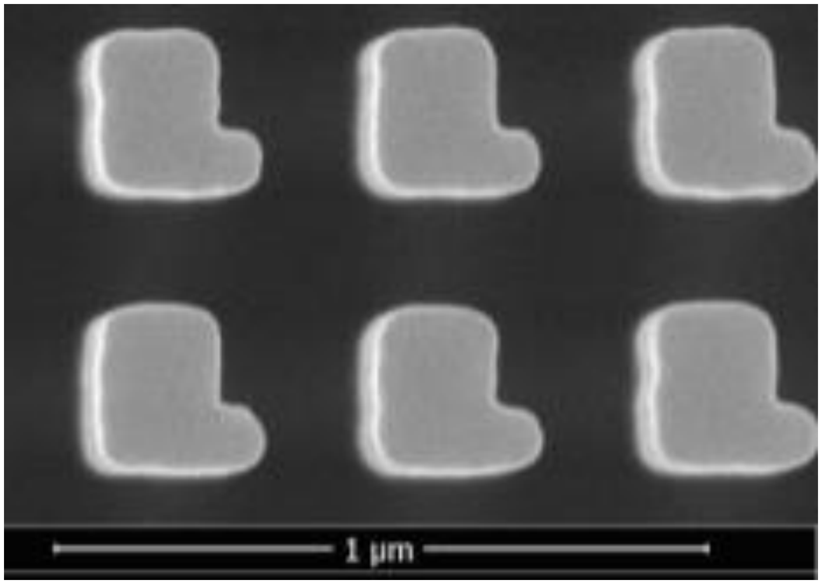


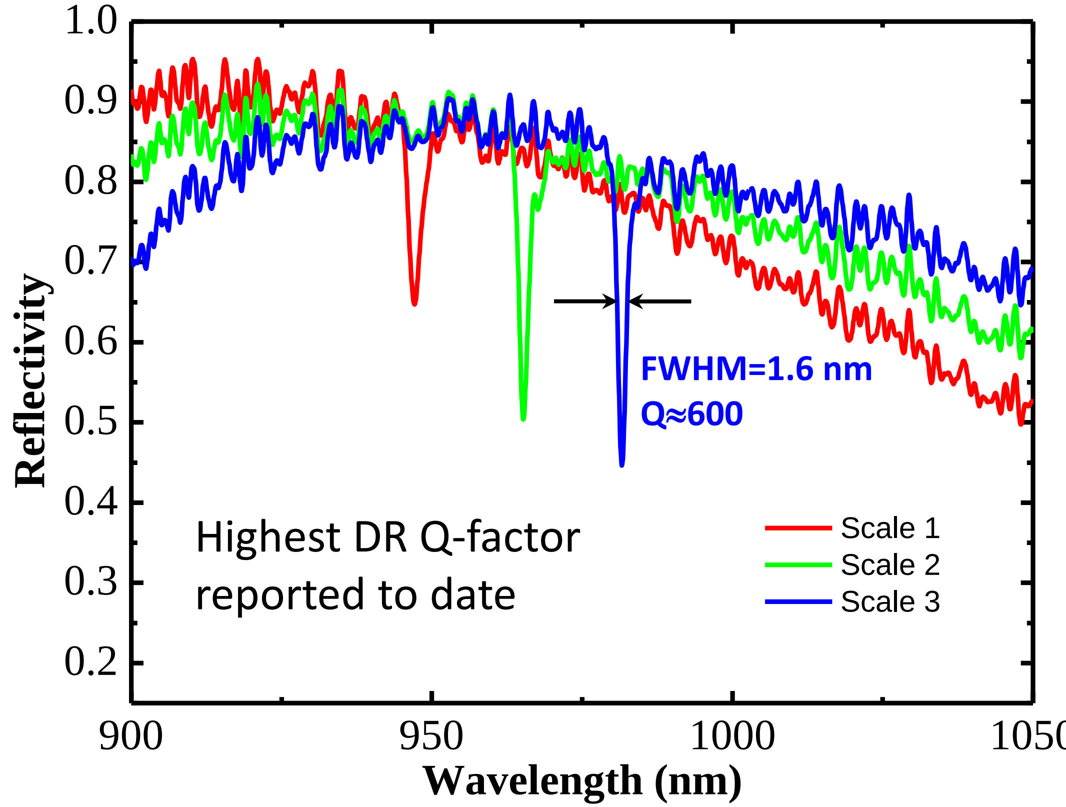


Broad spectral bands of near perfect reflectivity!

GaAs Fano Resonators: Q ≈ 600!

SEM of GaAs Fano resonators





- 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

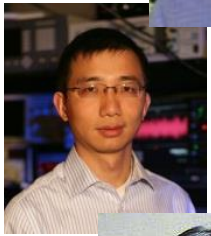
Conclusions

- A new, simpler design for dielectric Fano resonator metasurfaces
    - One resonator per unit cell
- Intra-resonator coupling between bright and dark modes
    - Bright electric dipole and dark magnetic dipole
- Approach is scalable from NIR → RF
- High Q-factors for SOI (≈350) and GaAs (≈600)
- Extension to (Al)GaAs will allow for active devices
    - Spectrally selective detectors
    - Optical modulators
    - Nonlinear devices
    - Lasers??

Acknowledgments

- Salvatore Campione

- Sheng Liu



- Lorena I. Basilio

- Larry K. Warne

- William L. Langston

- Ting S. Luk

- Igal Brener

- Joel R. Wendt

- Gordon Keeler

- John Reno