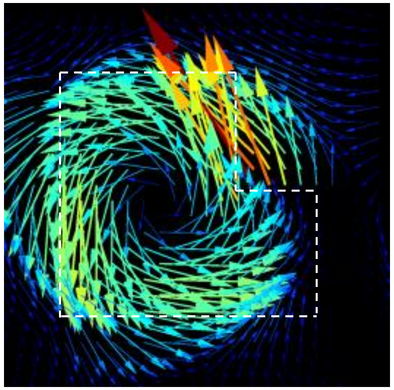
SAND2016-5933C

# High Quality Factor Fano Metasurfaces




**Michael B. Sinclair**

*Sandia National Laboratories & Center for Integrated Nanotechnologies*
*Albuquerque, NM, USA*

mbsincl@sandia.gov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# *Fano resonances of dielectric resonator metasurfaces*

**Fano resonances of metasurfaces:**

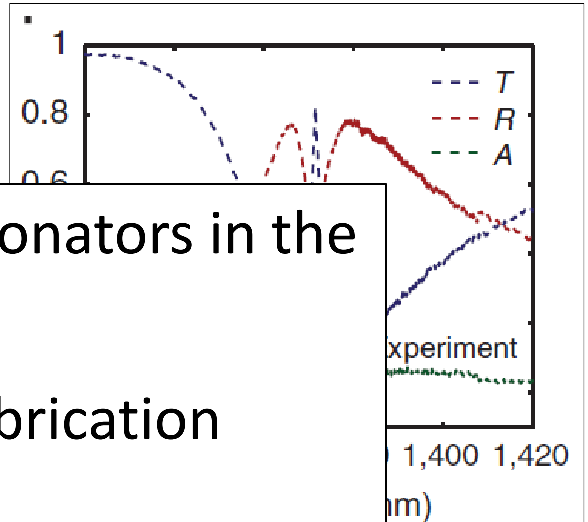
- First proposed for metal metasurfaces

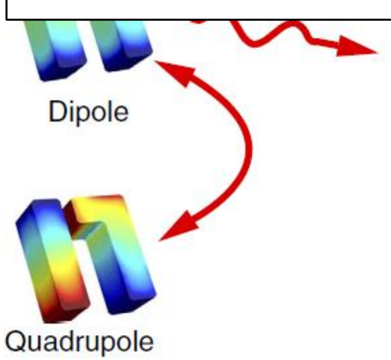
**Now**

DR Fano designs to-date rely on multiple resonators in the unit cell

Near field coupling extremely sensitive to fabrication errors

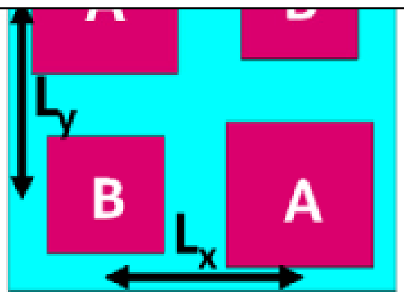
Can we find a one-resonator design??



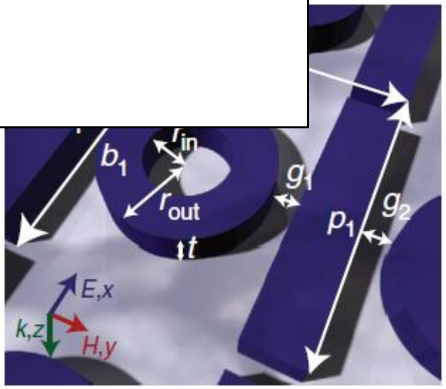

Q ~ 130 at 4 um (experimental)

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




Q ~ 110 at 1.1 um (simulation)

Wang, et al.
OMEX 5, 668, 2015



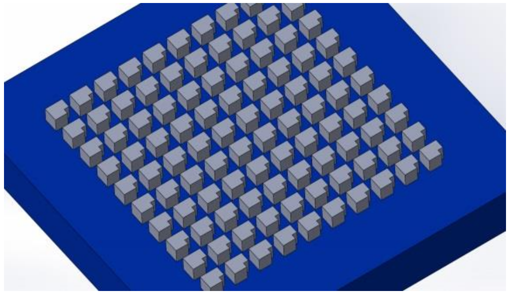

Q ~ 500 at 1.37 um (experimental)

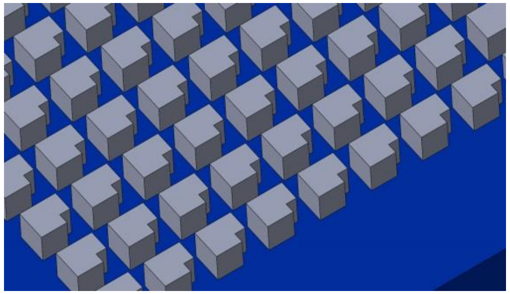
Yang, et al.
Nature Comm. 5, 5753, 2014

# A new, monolithic, Fano resonator metasurface design

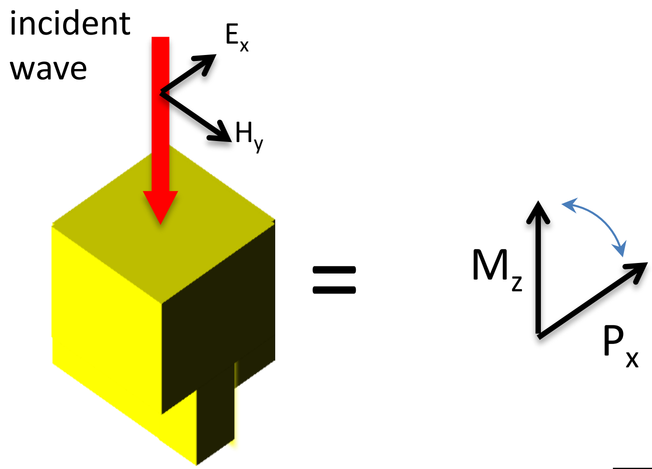
## Outline

- 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





# *Operating principles*




weakly coupled dipole modes

orthogonal dipole modes

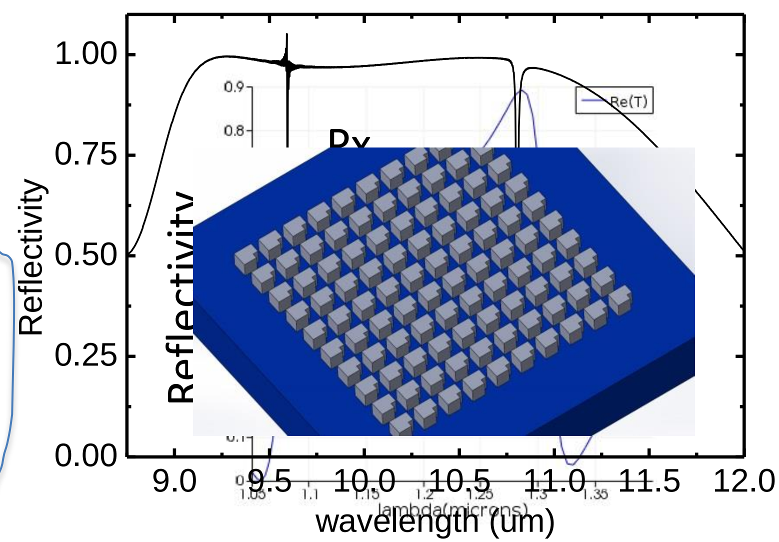
**Fano system**

External Wave ⟷ $P_x$ (low Q)

Cavity perturbation

$M_z$ (high Q)

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

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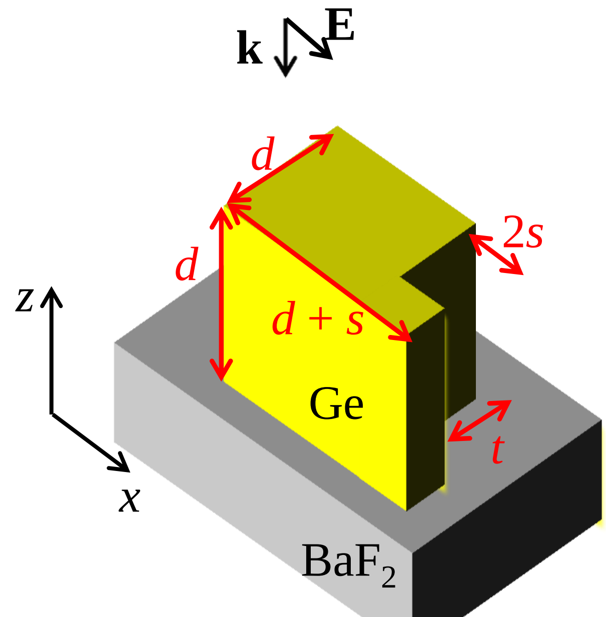
# *Ge-based Fano metasurface design*



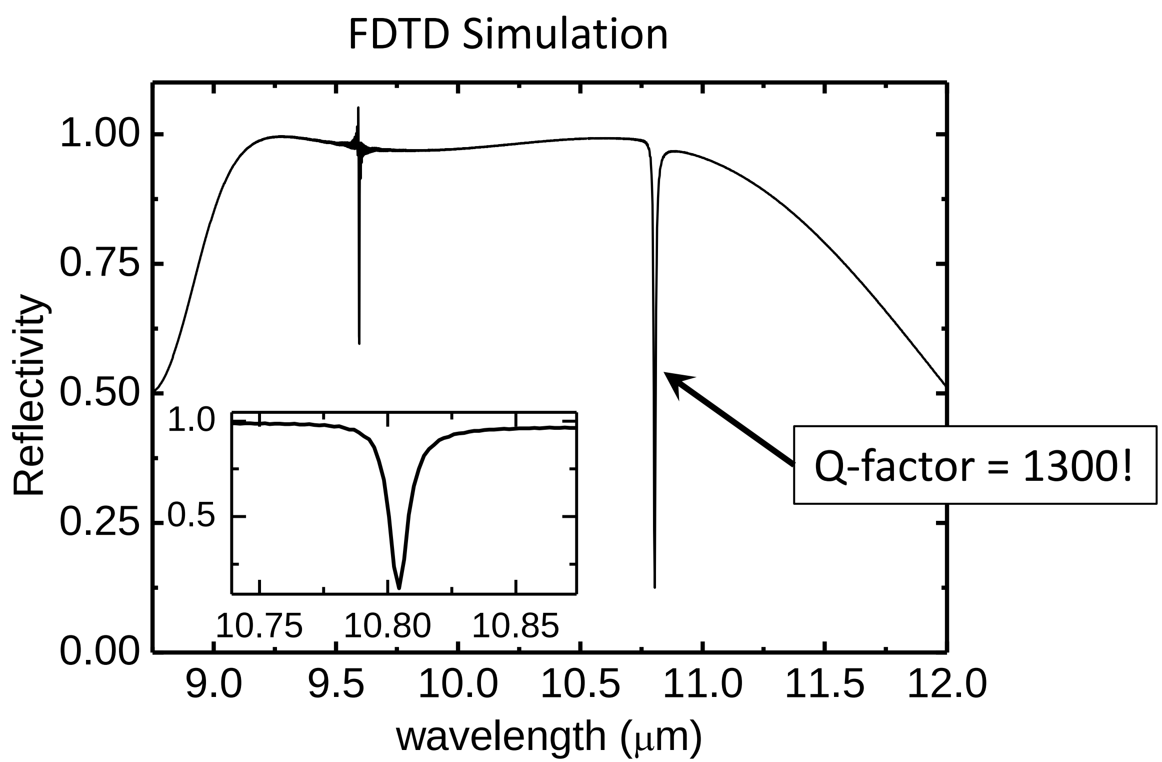

$d$ = 2.53 μm

$s = d / 5$

$t$ = 1.5 μm

Array Pitch:

$a = b$ = 4.2 μm



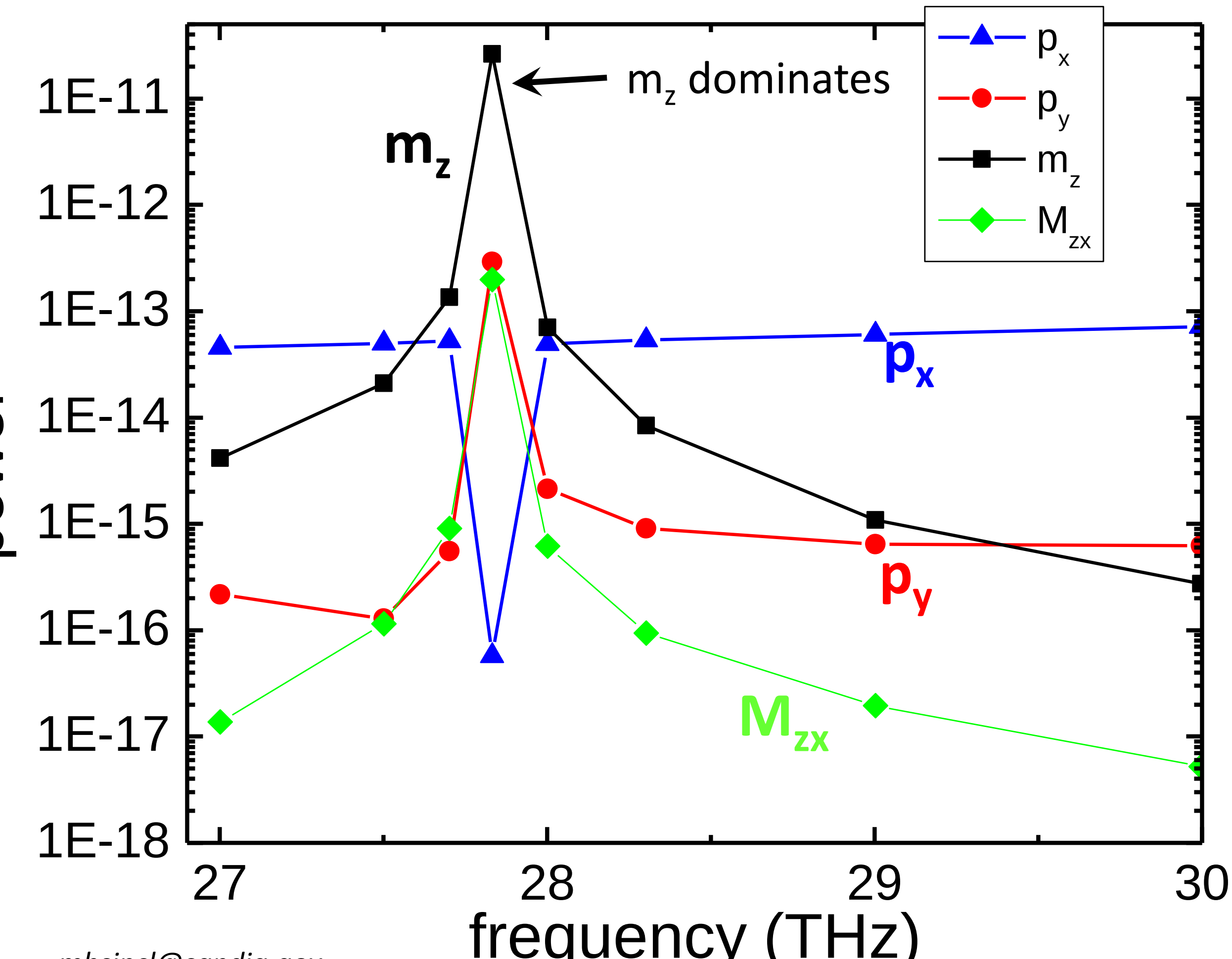

Design is scalable from NIR through RF!

# *Understanding the nature of the Fano mode*

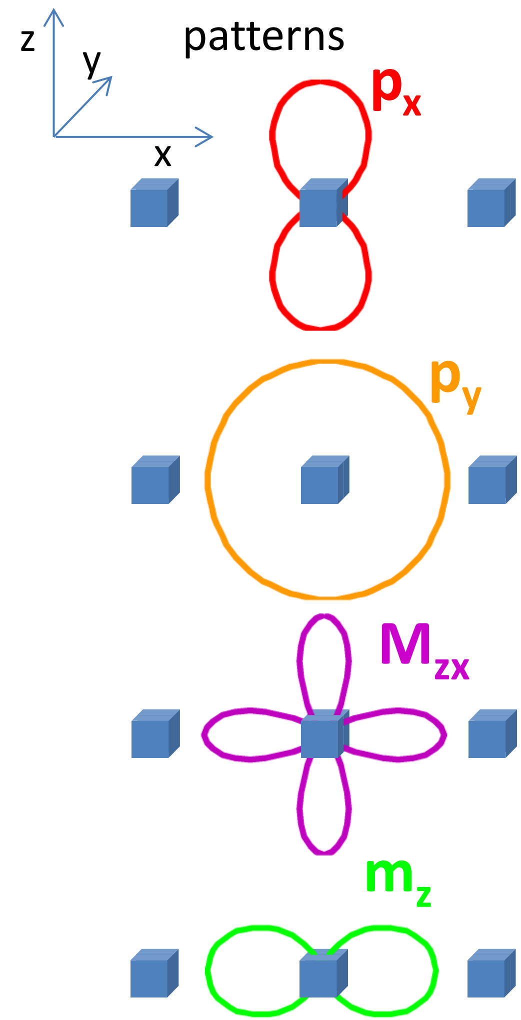
Dr. Salvatore Campione

## Multipole decomposition of resonator response

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




Far-field lobe patterns

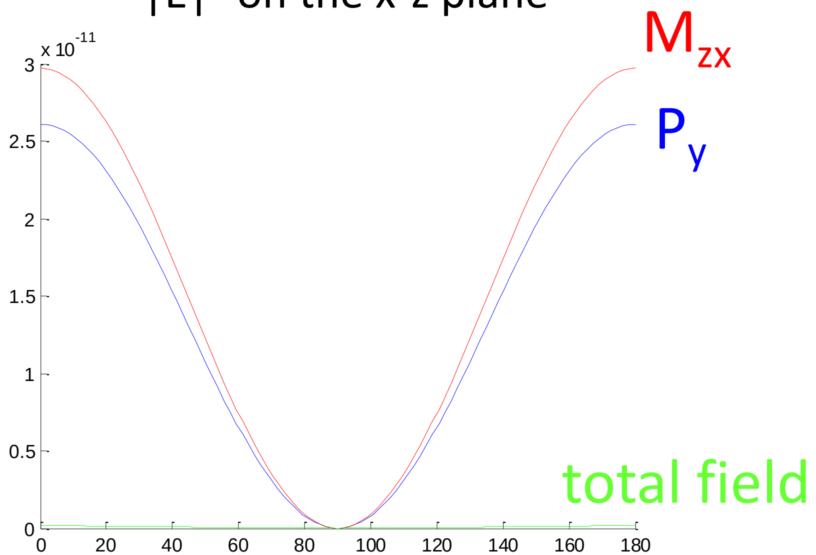


# *What about $P_y$ and $M_{zx}$?*

**At Fano resonance:**

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

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

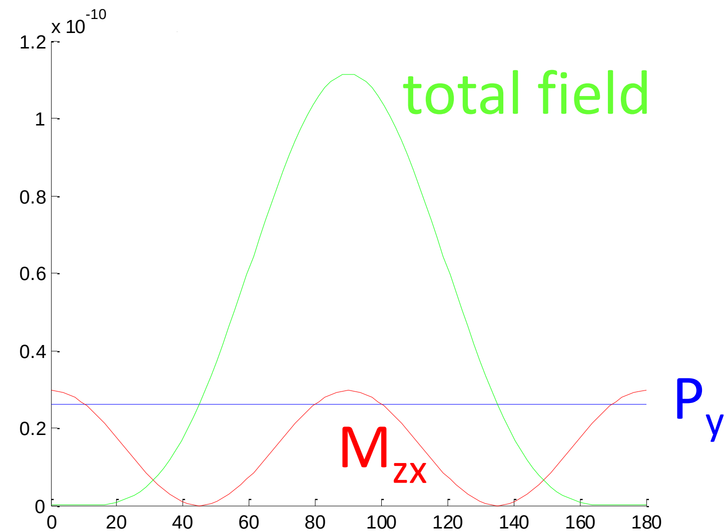



polar angle

backward scattering

forward scattering

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



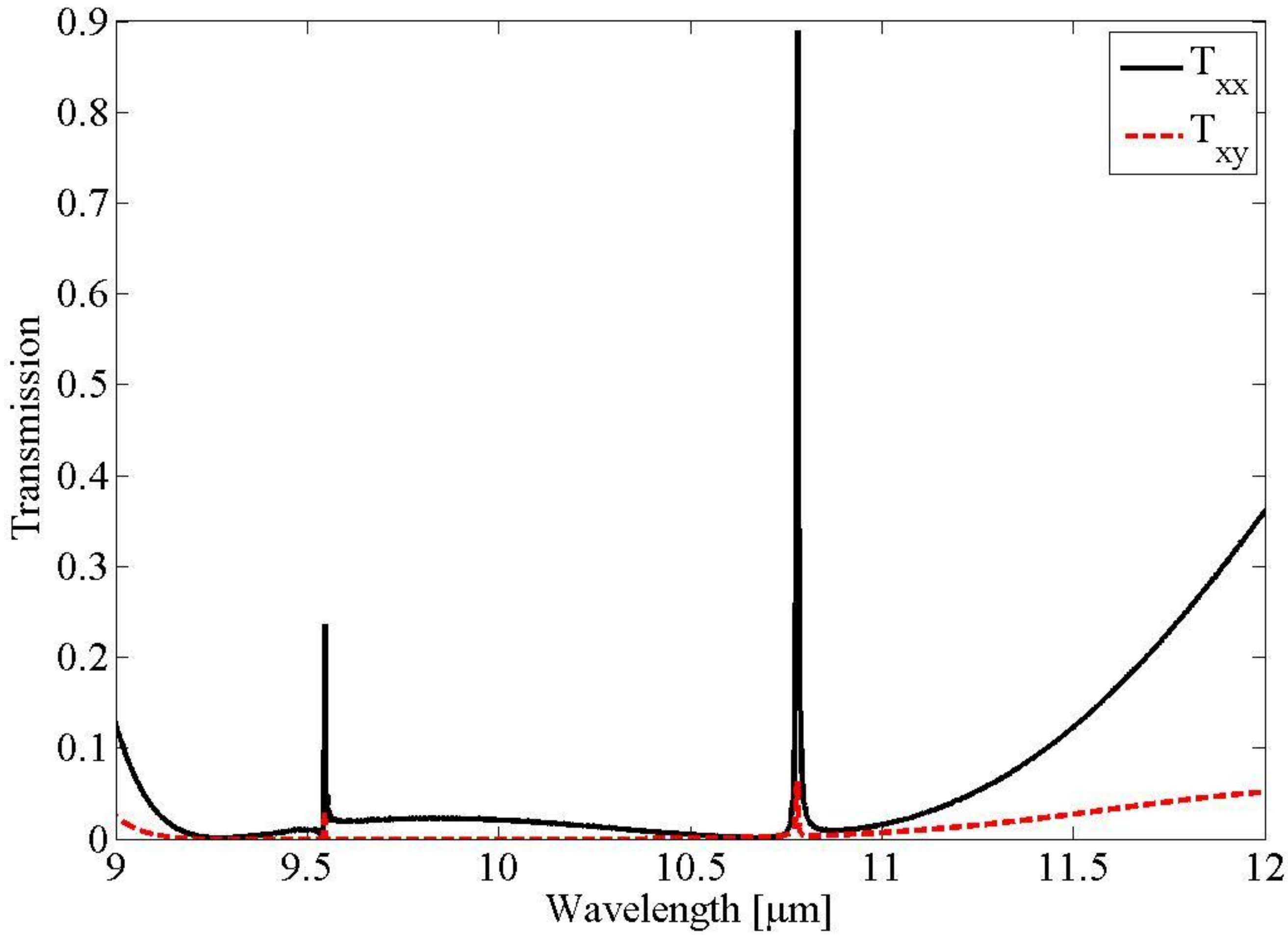

polar angle

backward scattering

forward scattering

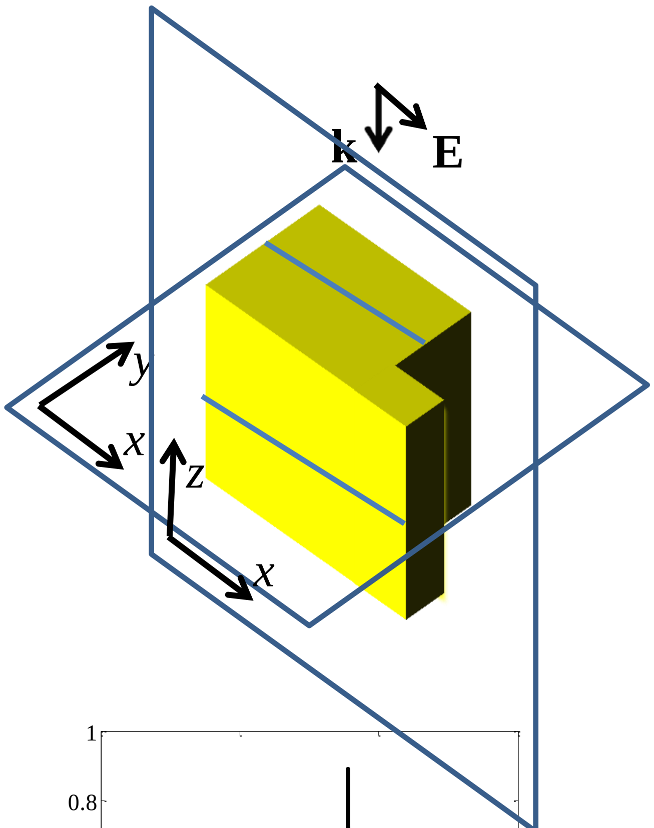
# *Small cross polarization of transmitted wave*

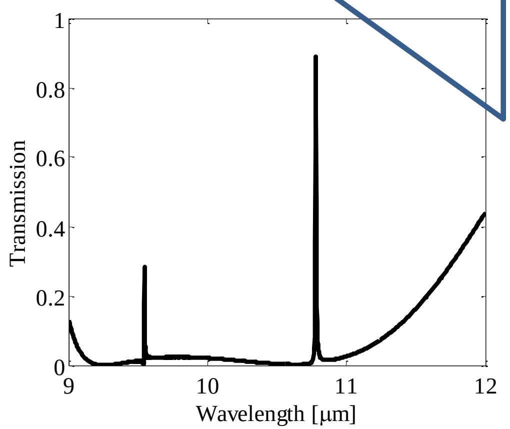
Residual scattering by $P_y$ and $M_{zx}$

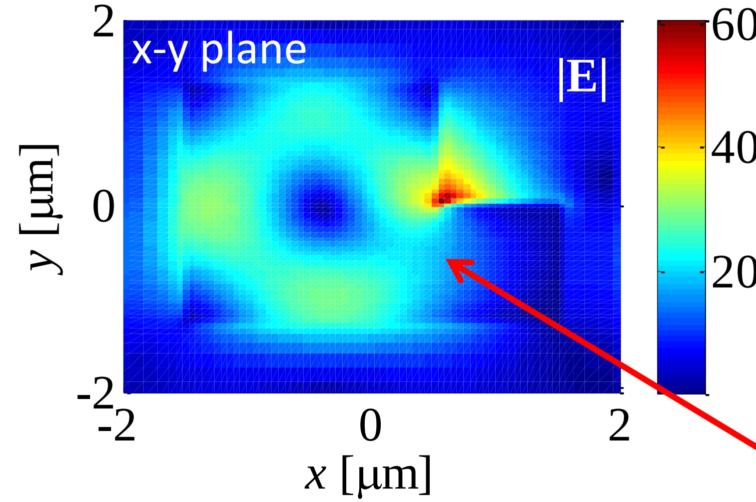


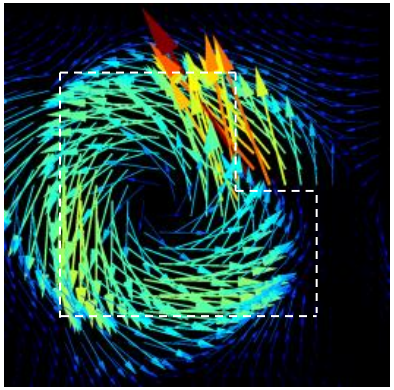
# Resonant Mode Field Profiles

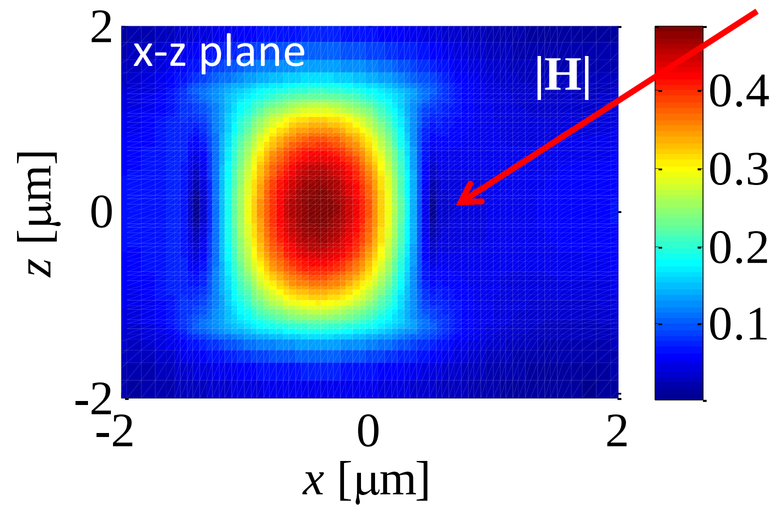
FDTD simulations at the $\lambda$ = 10.8 μm resonance



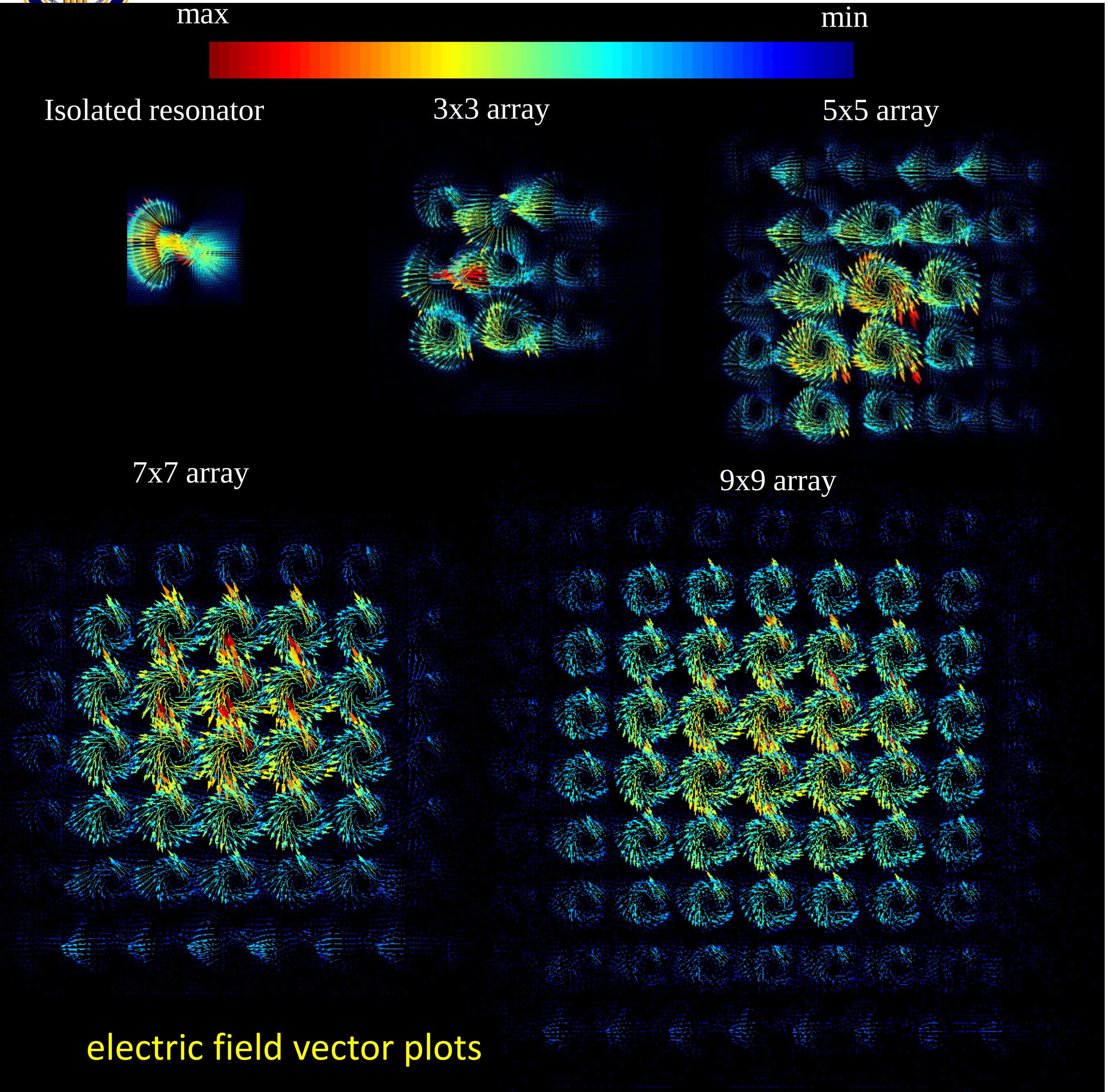






z-directed magnetic dipole

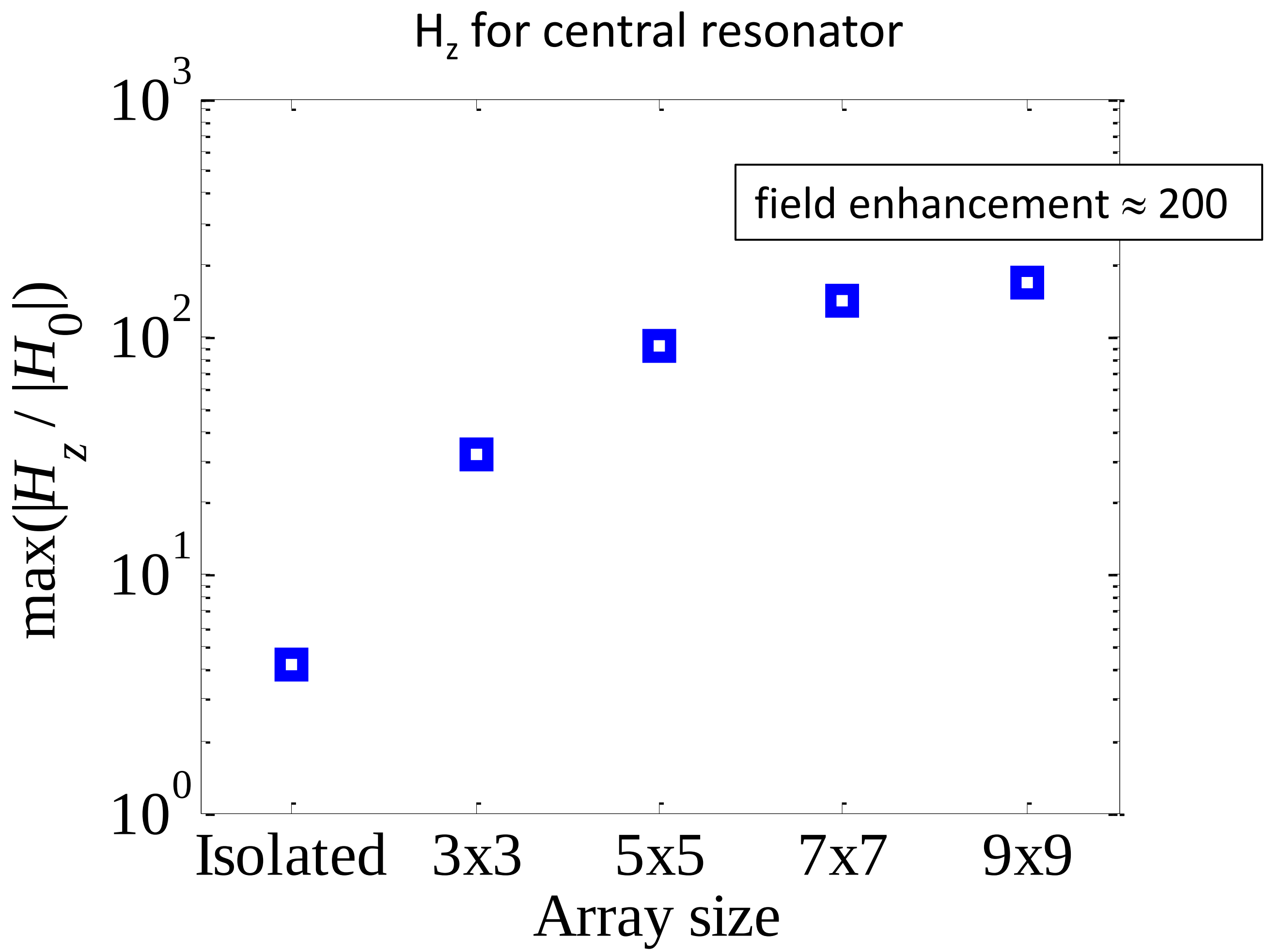
mbsincl@sandia.gov

# Array effect on the magnetic dipole




- $m_z$ can't radiate broadside
- local fields inhibit radiation
- weaker resonance at edges of array
- quality factor increases with array size

# *Field Enhancement vs. Array Size*



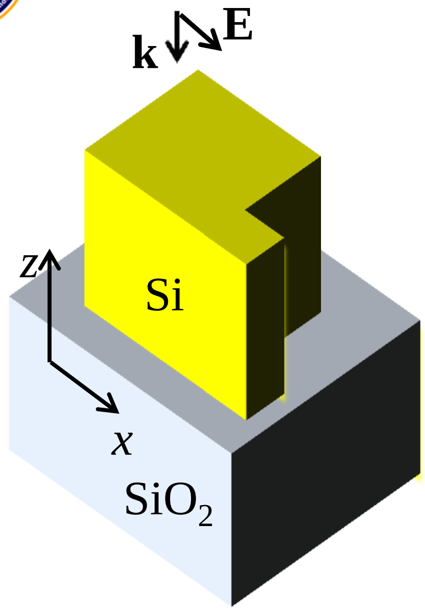

- beginning to saturate for 9x9 array
- effect arises from nearby resonators

# *Experimental Demonstrations of Fano Metasurfaces*

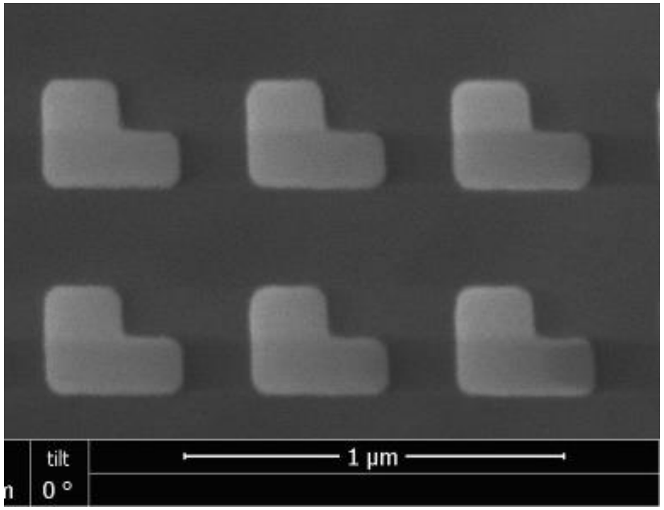
1. Silicon-on-insulator Fano arrays

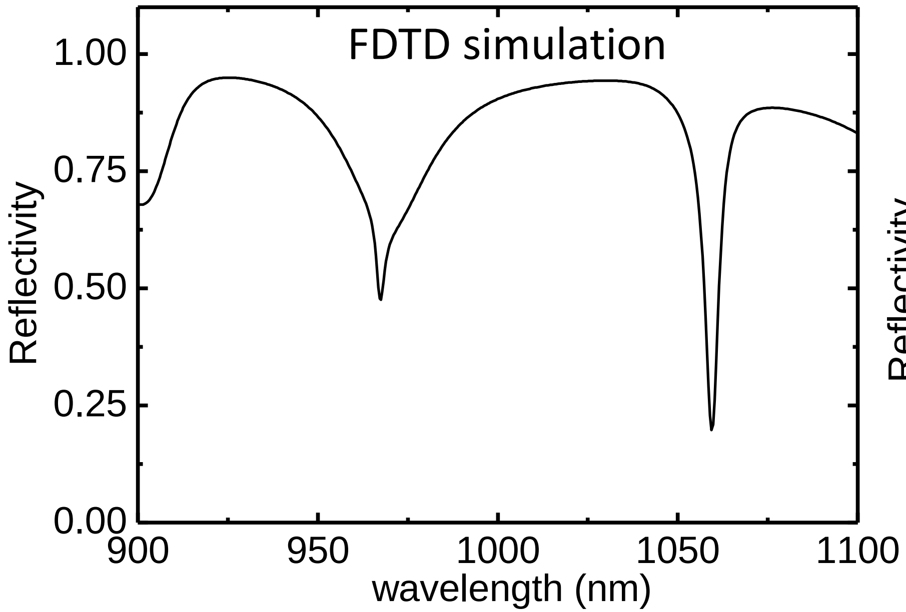
2. GaAs Fano arrays

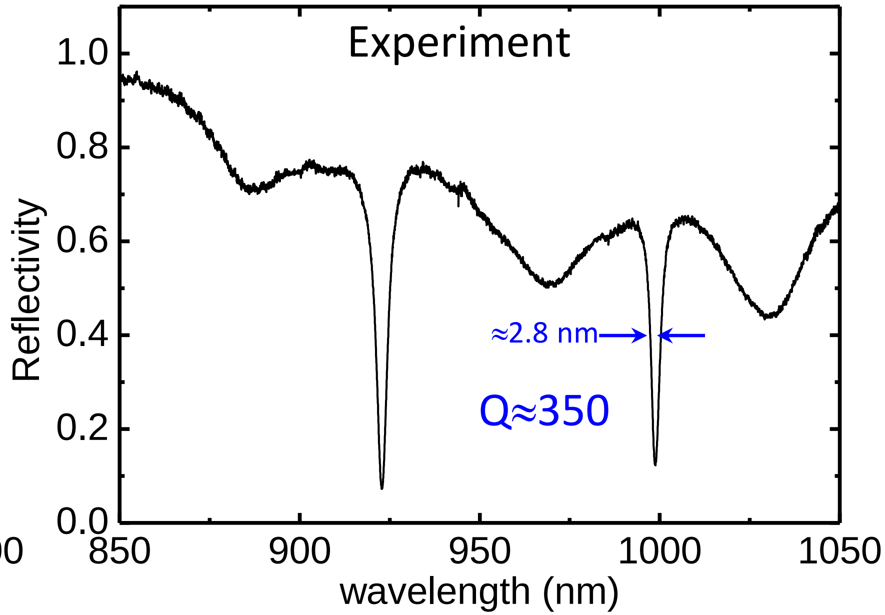
# Experimental verification: SOI Fano Resonators




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

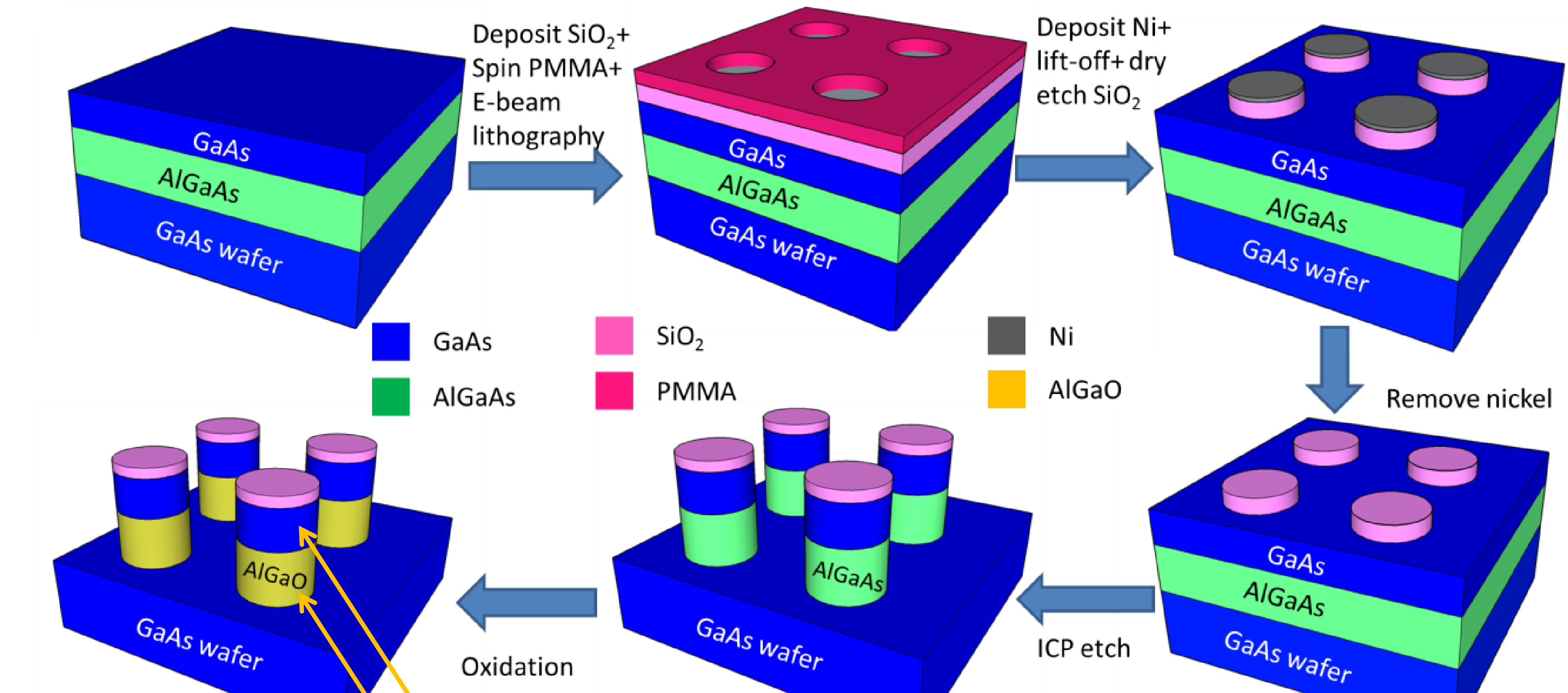


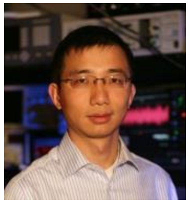



# DRs are now possible in III-V semiconductors

## New process for (Al)GaAs resonators

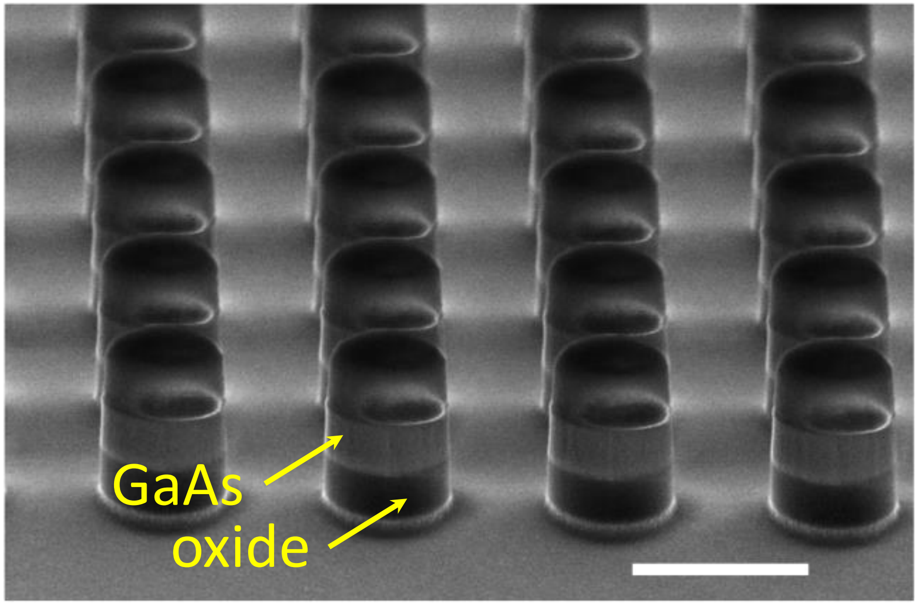


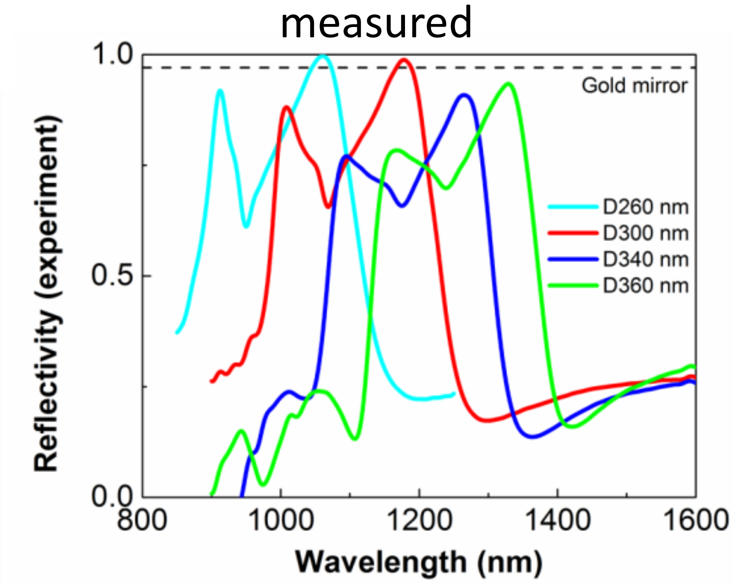



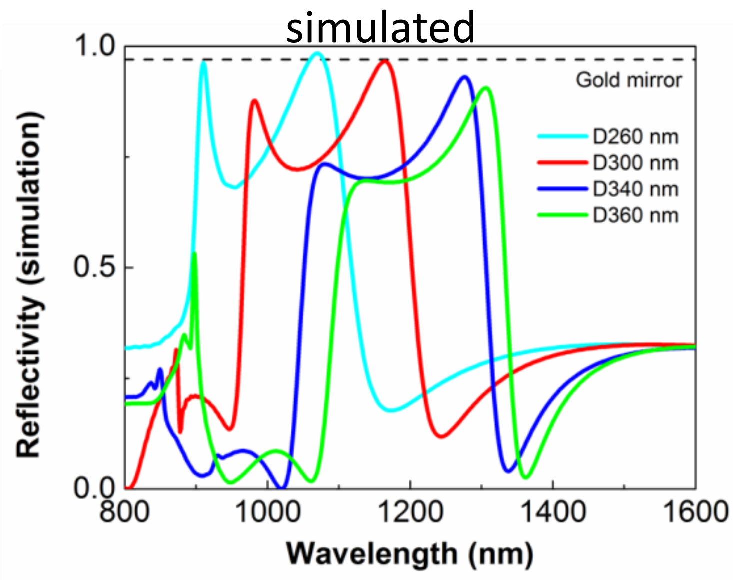
Sheng Liu

# *GaAs Cylindrical Resonators*

- height = 300 nm
- diameter varies near 300 nm

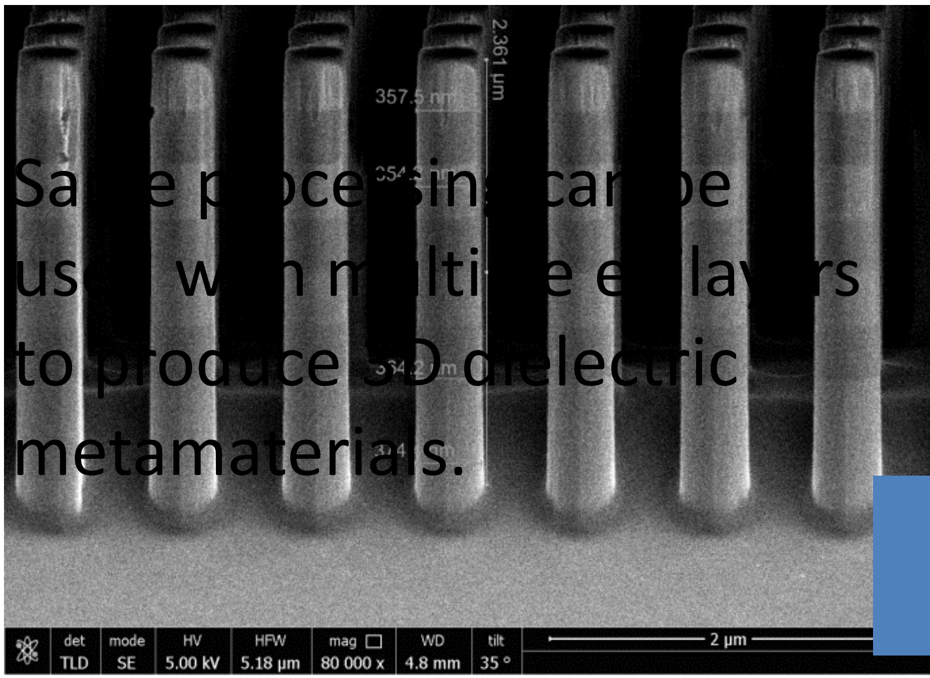



reflectivity exceeds gold at several wavelengths

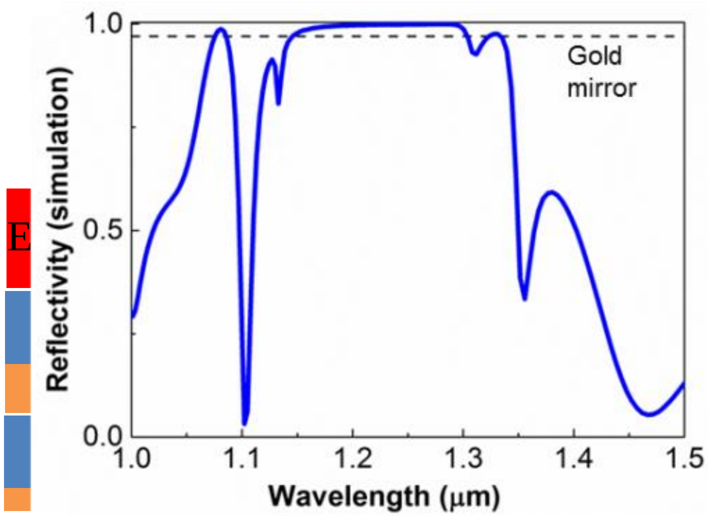
# Multilayer III-V Dielectric Metamaterials




Sa e p ocessin can be us wi h m lti e e ilay rs to produce 3D dielectric metamaterials.

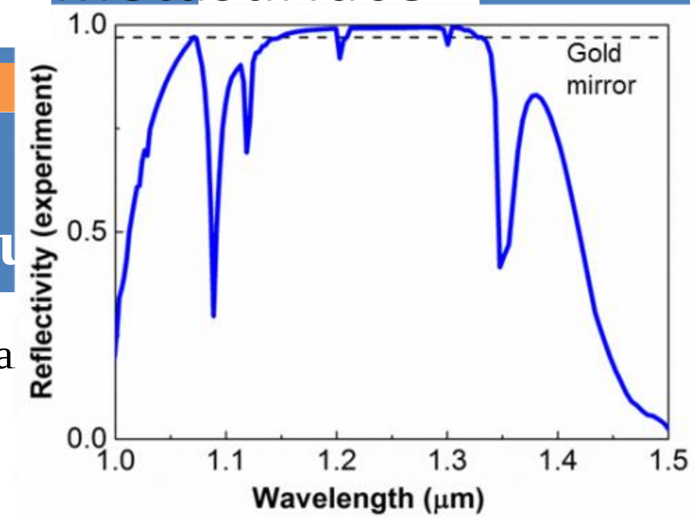
E

metasurface




Su e

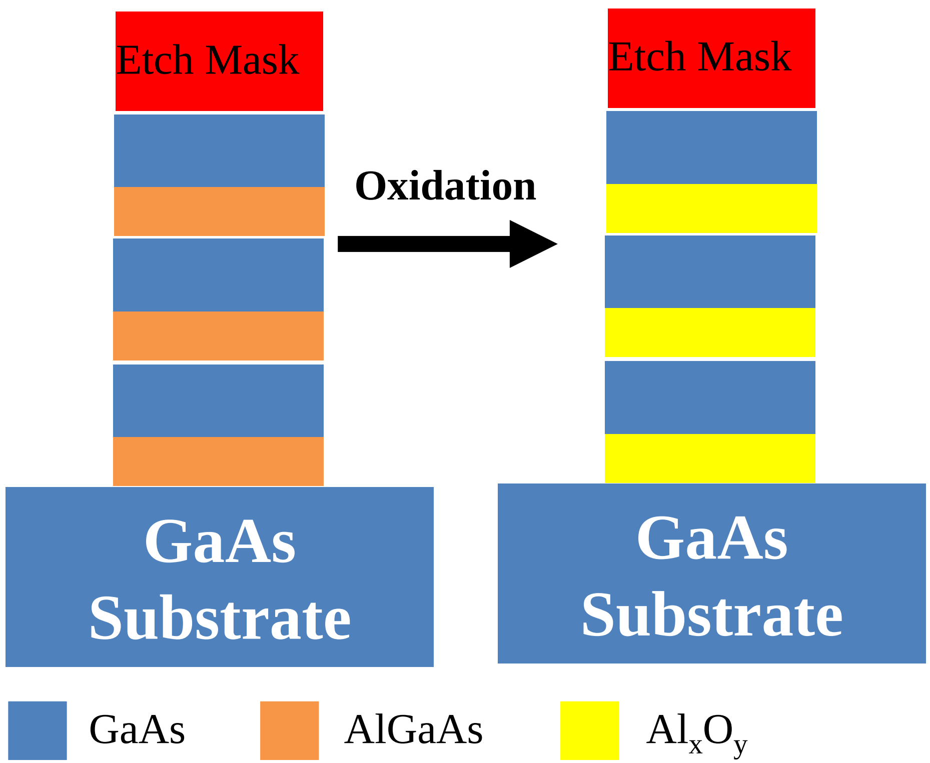
Ga

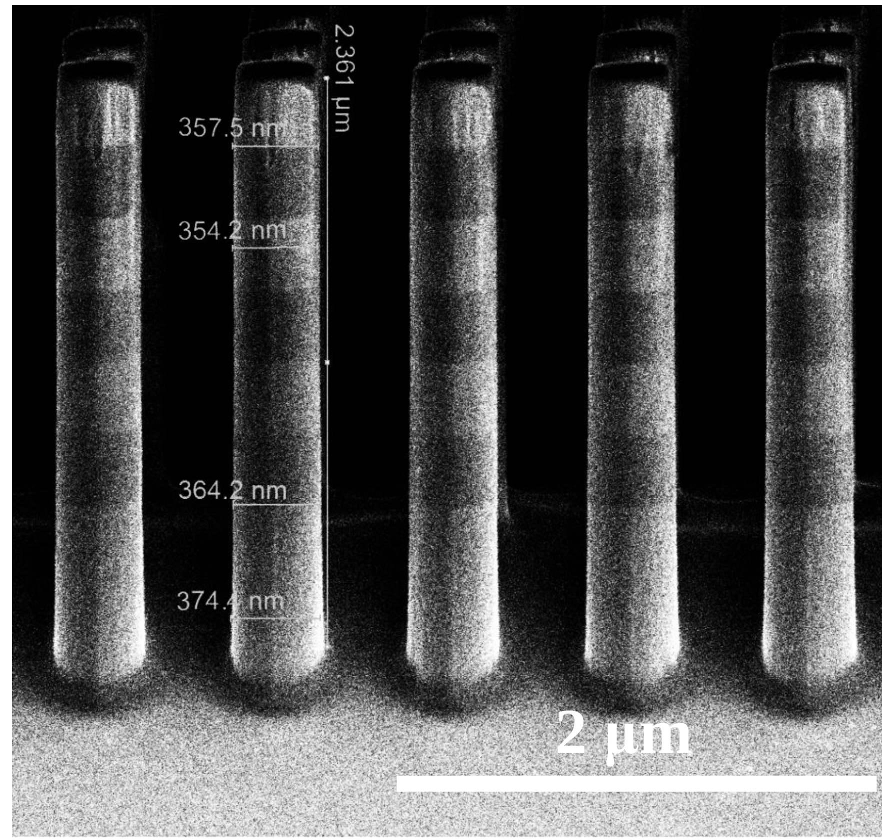



Broad spectral bands of near perfect reflectivity!

# Multilayer III-V Dielectric Metamaterials

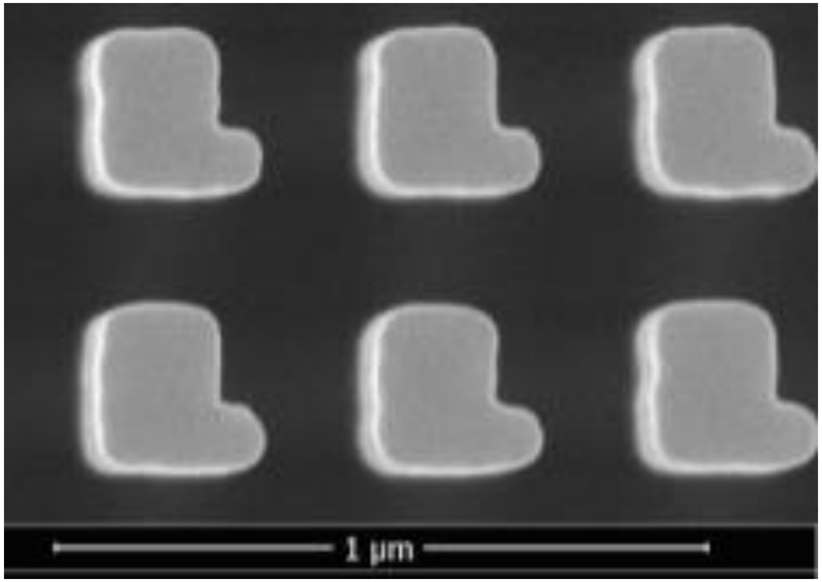
**Epitaxially grown multi-layer GaAs/AlGaAs**

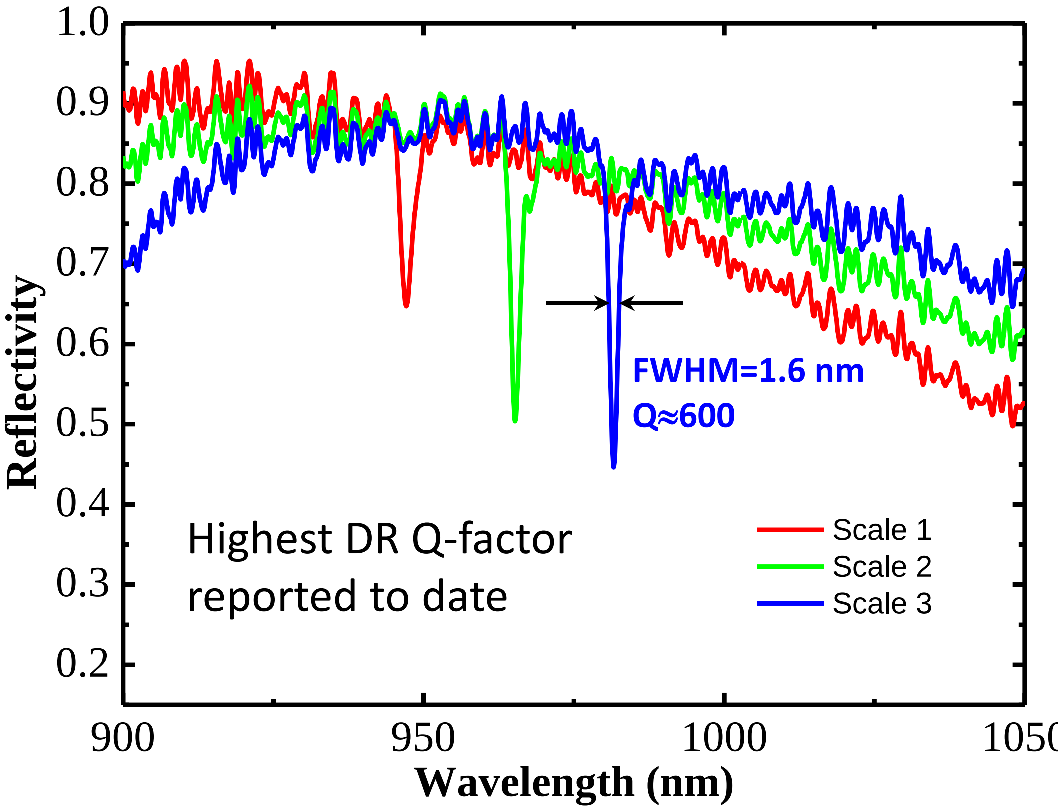


# GaAs Fano Resonators: Q ≈ 600!

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
- <u>Intra</u>-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

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- John Reno
- Igal Brener

*END*