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Tailoring Dielectric Resonator Geometries for Directional Scattering, Huygens' Metasurfaces, and High Quality-Factor Fano Resonances

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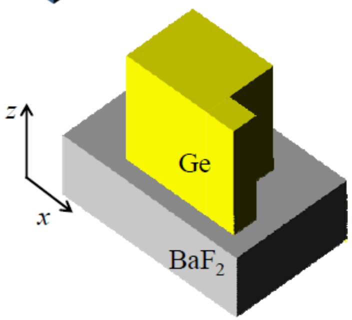
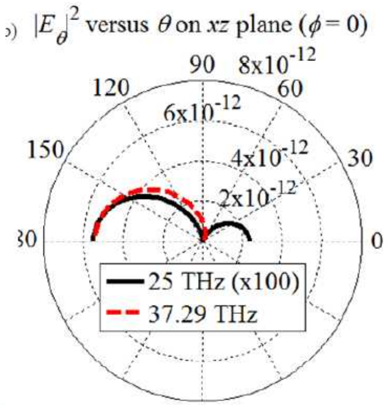
Outline of the talk

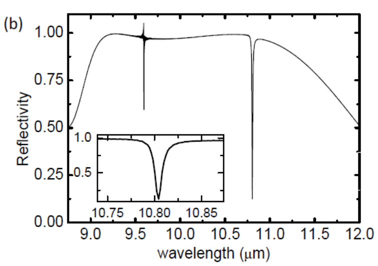
- Metamaterial dielectric resonators represent a promising path toward low-loss metamaterials at optical frequencies

  - We show that the introduction of perturbations of high symmetry geometries



  - Enables directional scattering, Huygens' metasurfaces, and high-quality factor Fano resonances

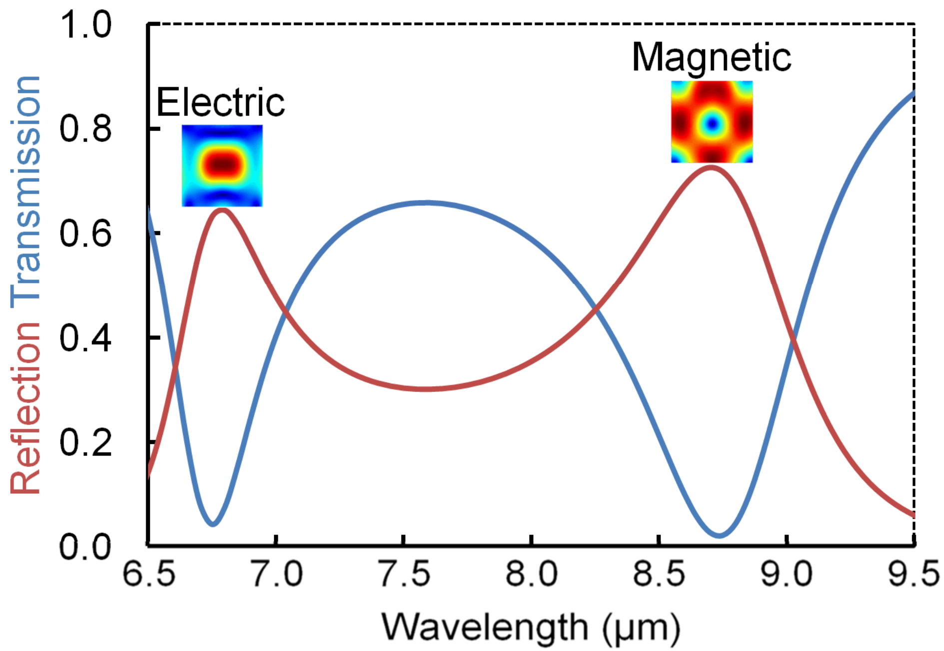




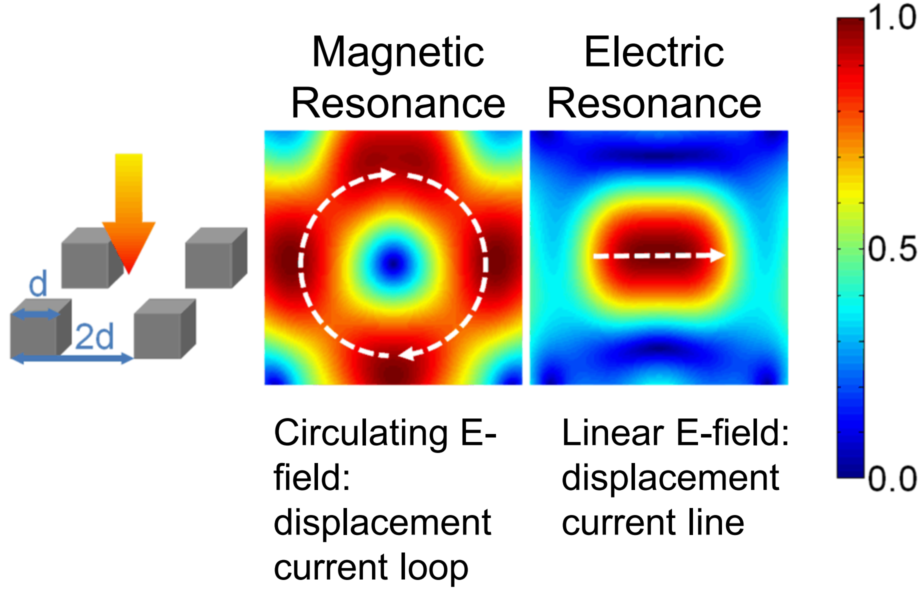
Dielectric Resonator Metamaterials

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

1.7 μm Te cube array



Electric field patterns

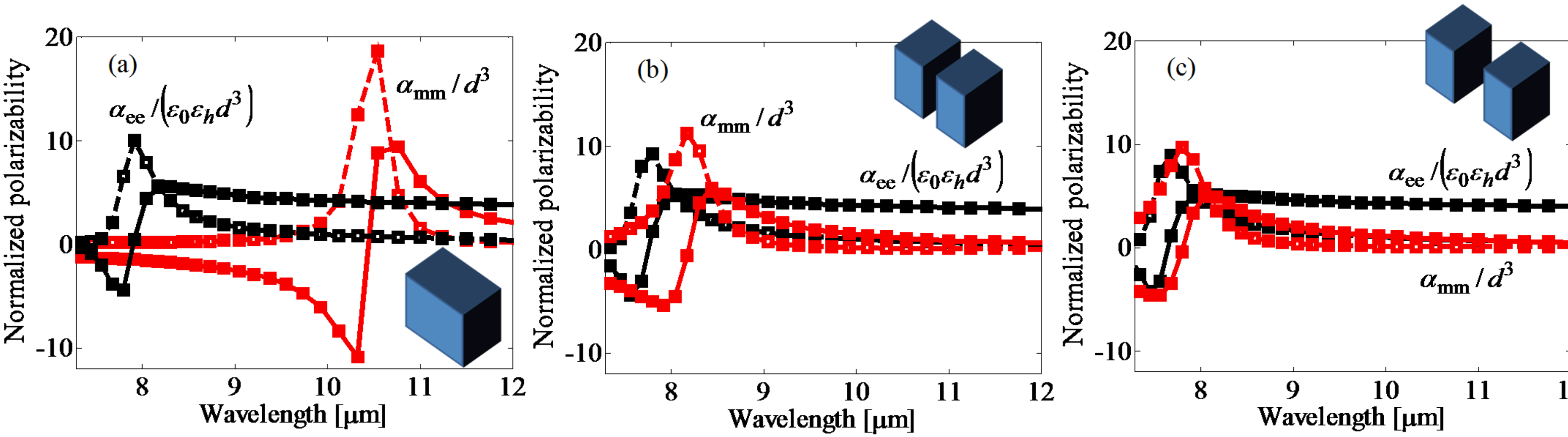


Aligning electric and magnetic resonances in single resonator

- Retrieve electric and magnetic polarizabilities of single scatterers using full-wave simulations

$$\mathbf{p} = \underline{\boldsymbol{\alpha}}_{\mathrm{ee}} \cdot \mathbf{E}_{\mathrm{loc}}; \qquad \mathbf{m} = \underline{\boldsymbol{\alpha}}_{\mathrm{mm}} \cdot \mathbf{H}_{\mathrm{loc}}$$

Basilio et al. IEEE Antennas Wireless Propag. Lett. 10, 1567 (2011); Rockstuhl et al. Phys. Rev. B 83, 245119 (2011)



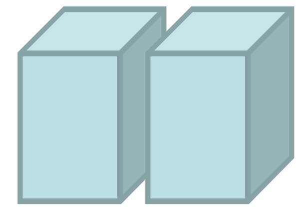
- Electric and magnetic polarizabilities can be easily engineered to overlap at a given frequency
- Quadrupole resonance is also affected and can be shifted away from the dipolar resonances

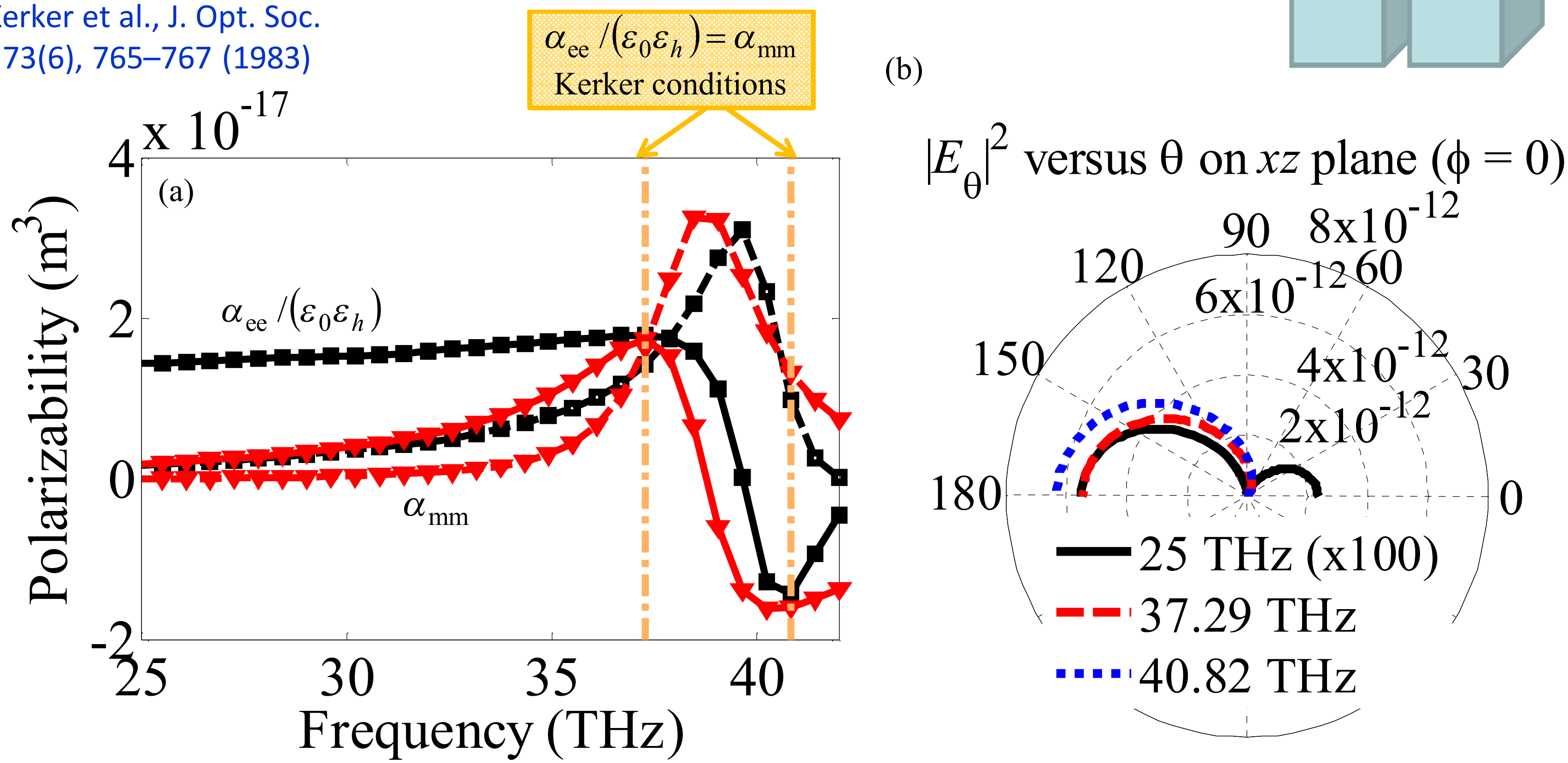
Warne et al., PIER B **44**, 1-29 (2012); IEEE Trans. Antennas Propagat. **61**, 2130-2141 (2013)
Campione et al., Opt. Express **23**, 2293-2307 (2015)

Aligning resonances leads to directional scattering

- First Kerker condition can be satisfied at two frequencies
- Forward scattering only → no back scatter

M. Kerker et al., J. Opt. Soc. Am. 73(6), 765–767 (1983)



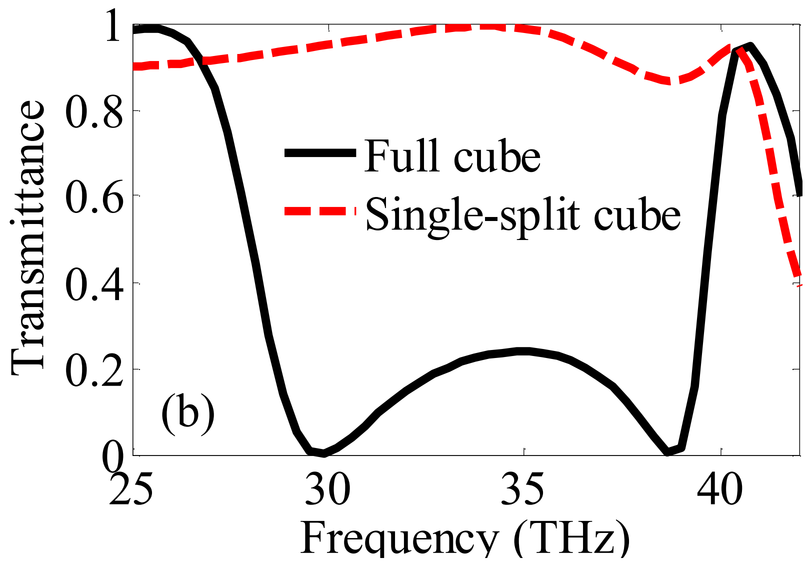


Campione et al., Opt. Express **23**, 2293-2307 (2015)

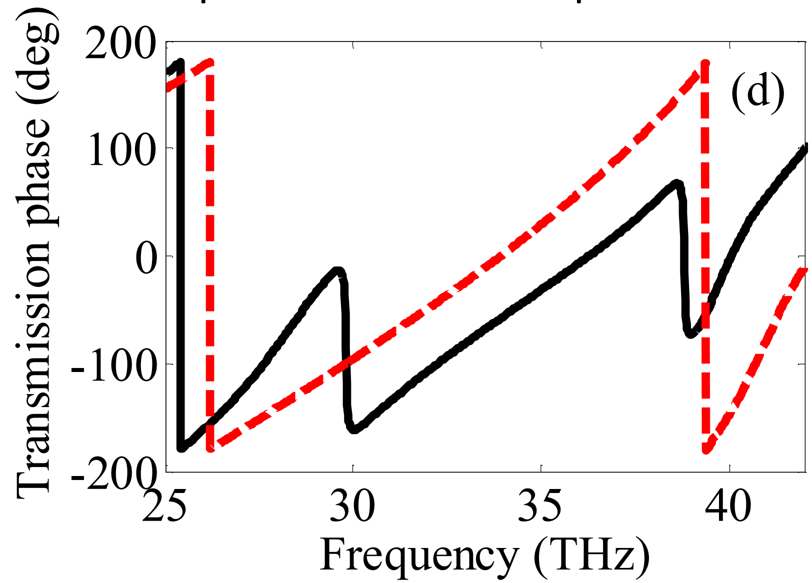
2D array of directional scatterers: Huygens’ metasurface

single particle forward scattering ➔ array high transmission

High transmission across spectral band



2π phase shift across spectral band



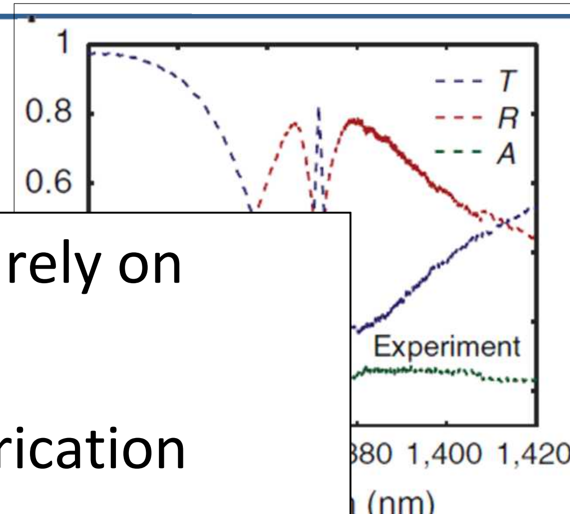
- Ultra thin optics
- Phase front manipulation

Campione et al., Opt. Express **23**, 2293-2307 (2015)

How do we achieve sharp resonances?

Fano resonances of metasurfaces:

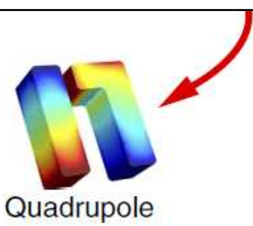
- First proposed for metal metasurfaces
- Interference of "bright" and "dark" excitations



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

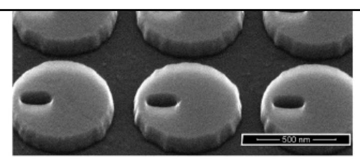
Near field coupling extremely sensitive to fabrication errors

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



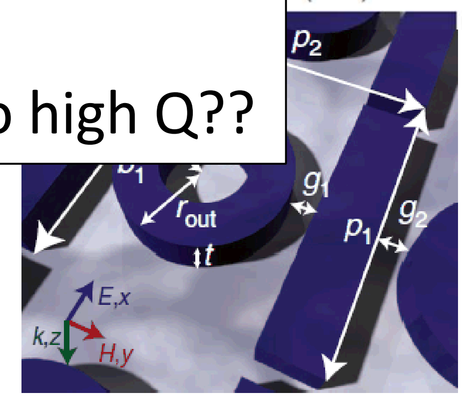
Q ~ 130 at 4 um (experimental)

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



Q ~ 100 at 1.5 um

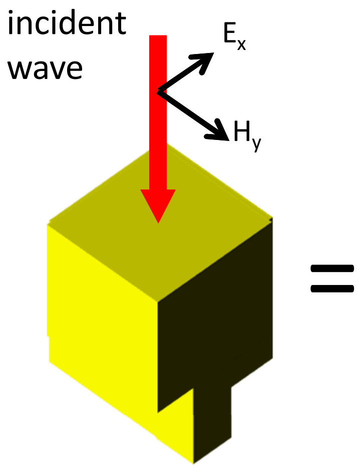
Jain, et al.
AOM 10, 1431, 2015



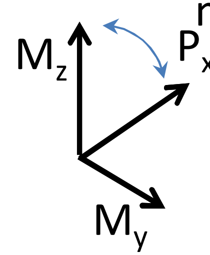
Q ~ 500 at 1.37 um (experimental)

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

Operating principles



weakly coupled dipole modes



orthogonal dipole modes

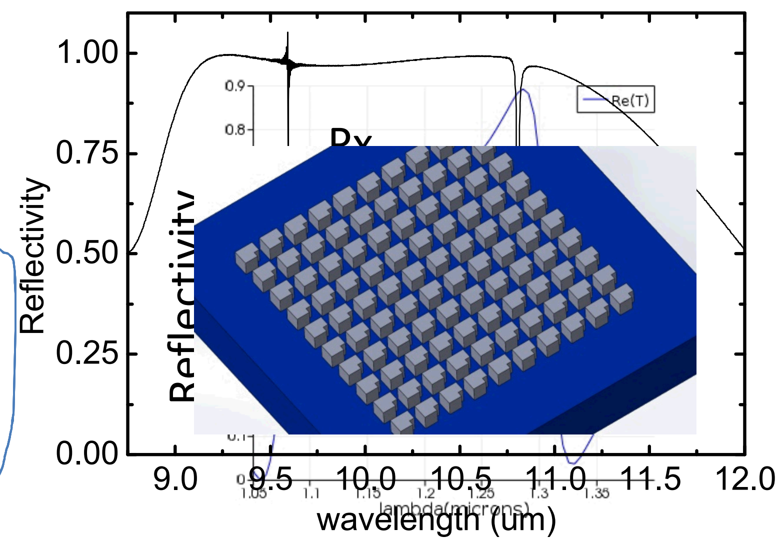
Fano system

External Wave ⟺ P_x ,M_y (low Q)

Cavity perturbation

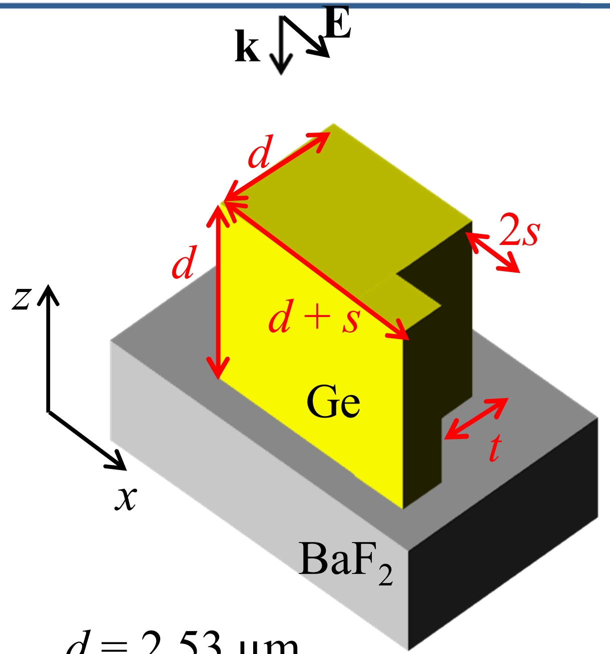
M_z (high Q)

radiative decay is suppressed due to local field interactions



Campione et al., arxiv:1607.06469 (2016)

Ge-based Fano metasurface design



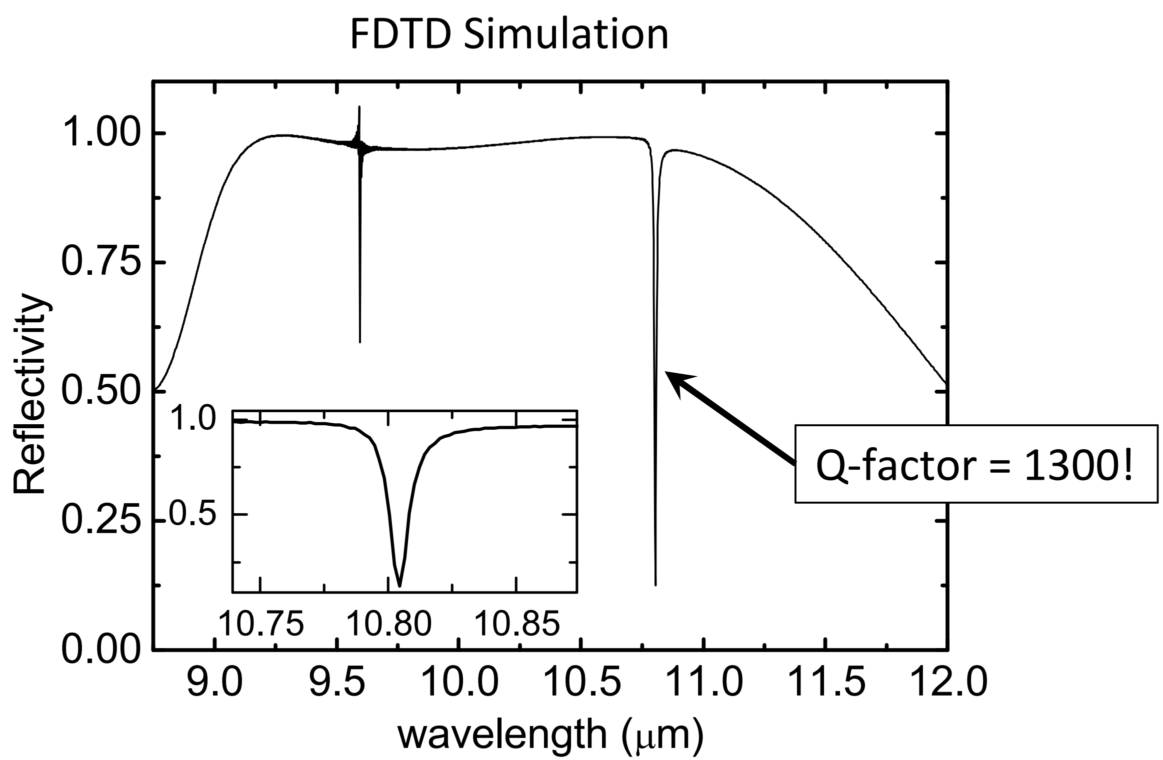
$d = 2.53\ \mu m$

$s = d / 5$

$t = 1.5\ \mu m$

Array Pitch:

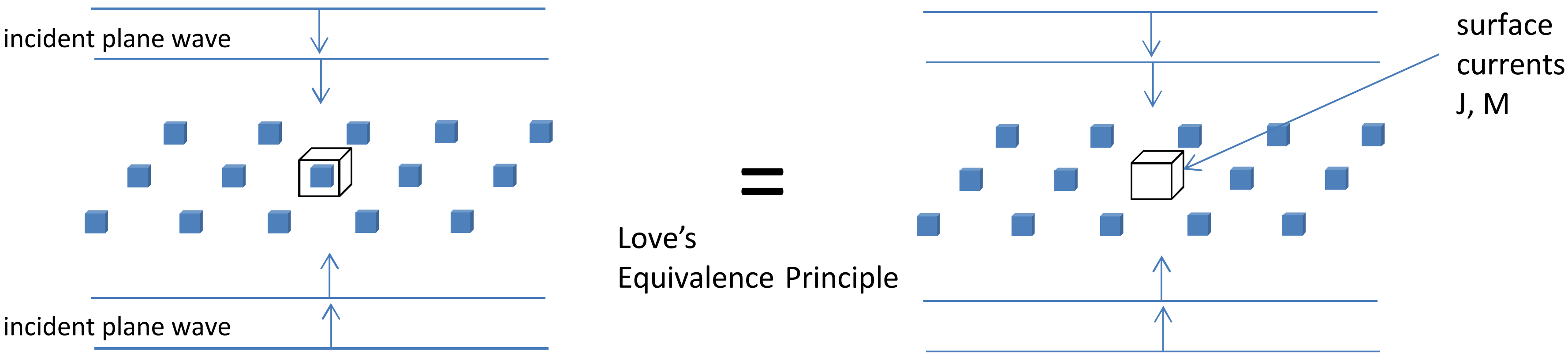
$a = b = 4.2\ \mu m$



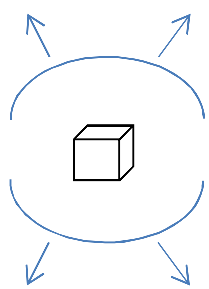
Design is scalable from NIR through RF!

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

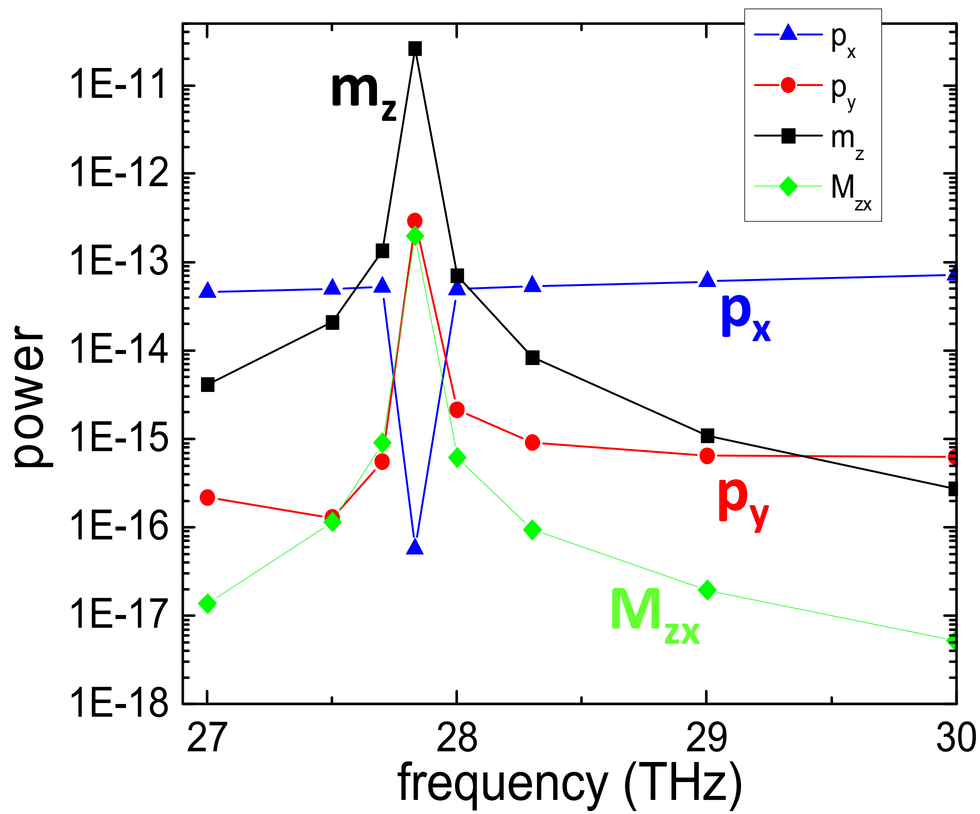


4. Calculate far-field due to surface currents on box alone
5. Fit to multipoles – all dipole and quadrupole modes

Understanding the nature of the Fano mode

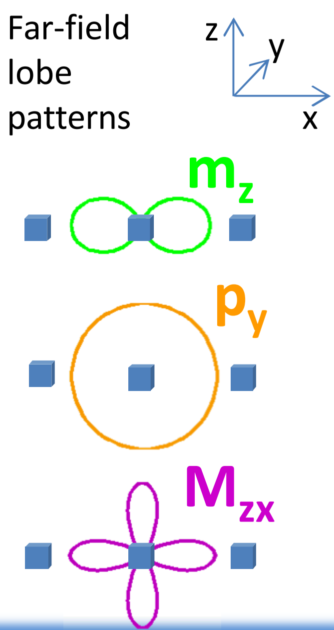
Multipole decomposition of resonator response

- 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

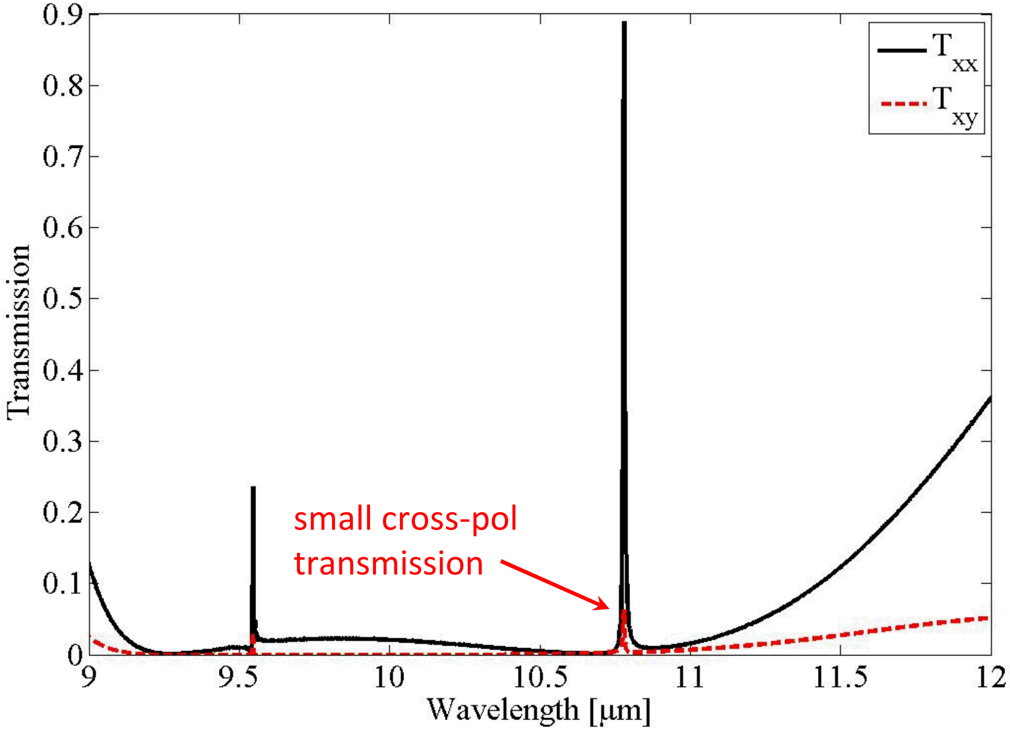


What about p_y and M_{zx}? Small cross polarization of transmitted wave

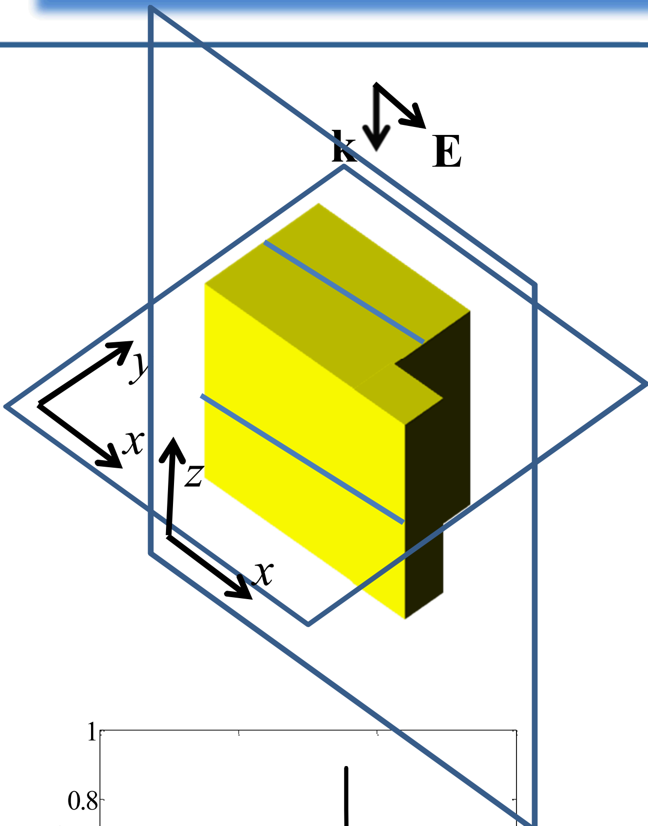
At Fano resonance:

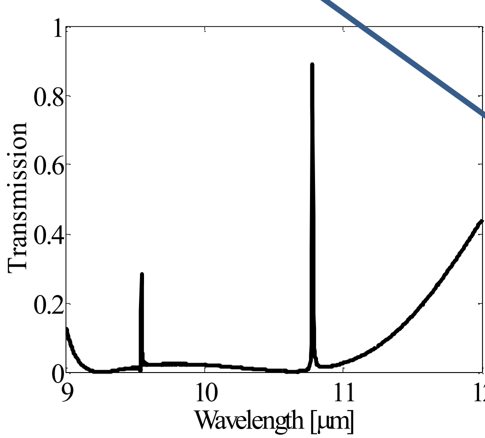
- both multipoles are excited
- radiated fields cancel in forward and backward directions!!

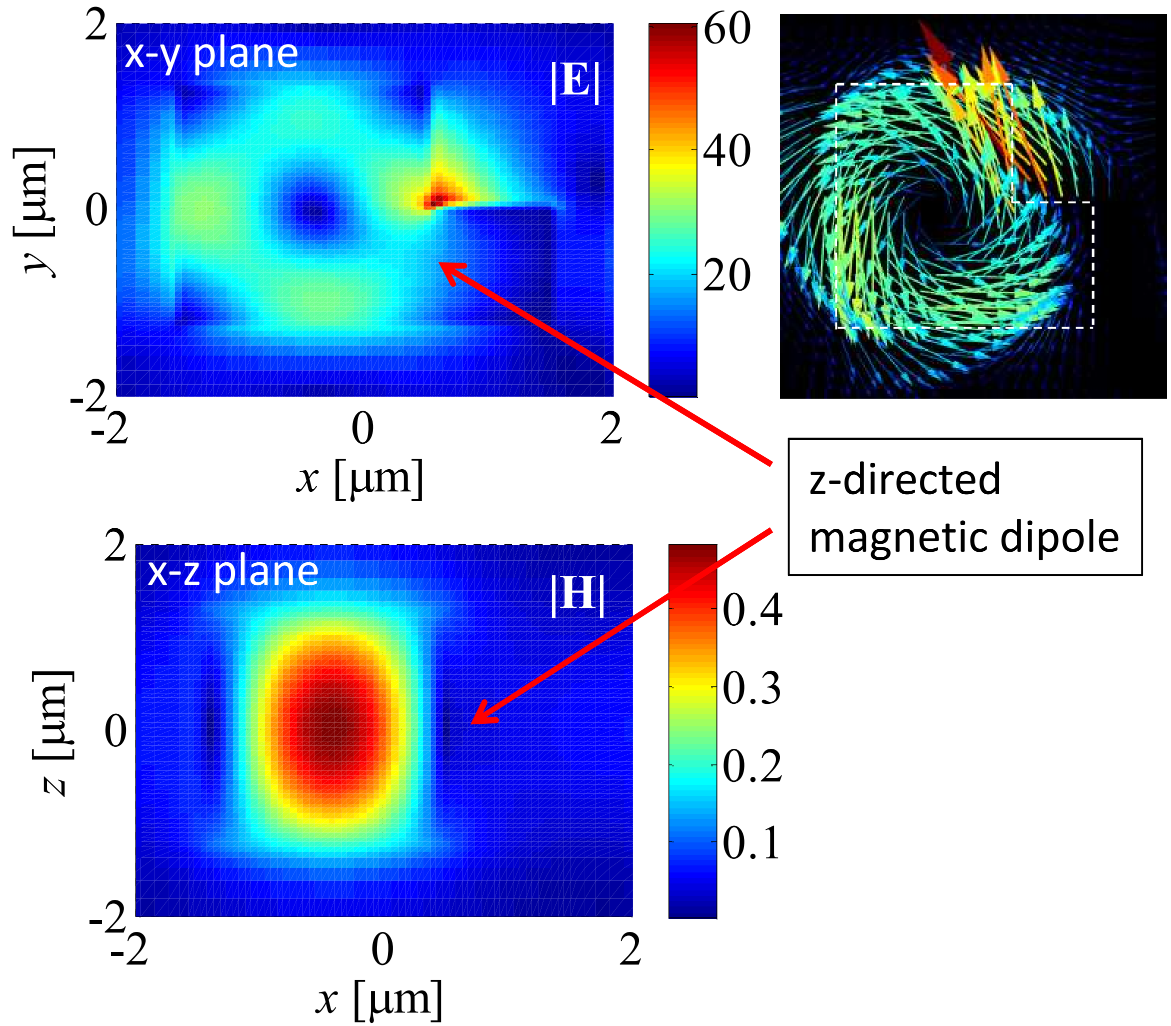
Residual imbalance of scattering by p_y and M_{zx}



Resonant mode field profiles

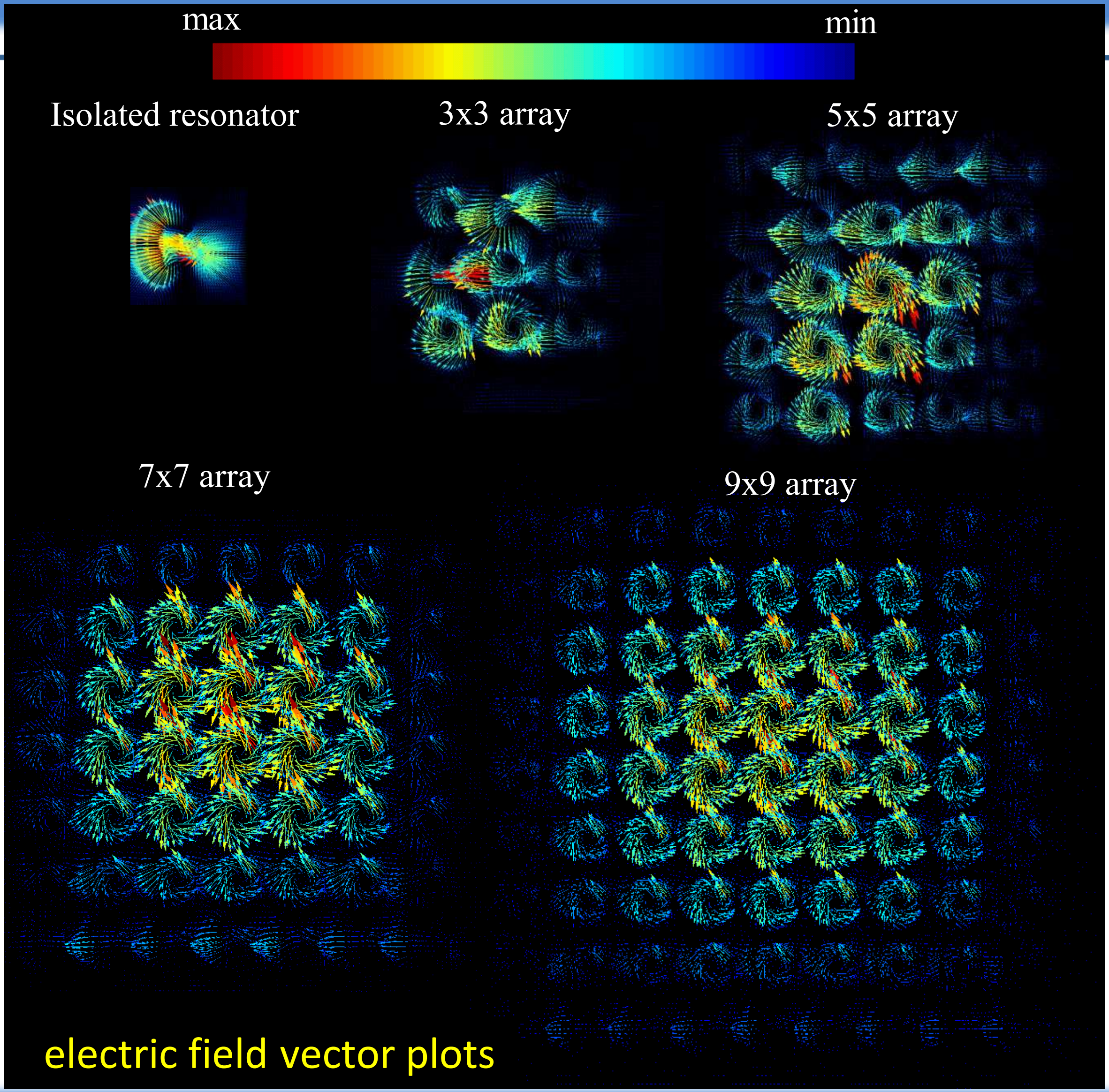






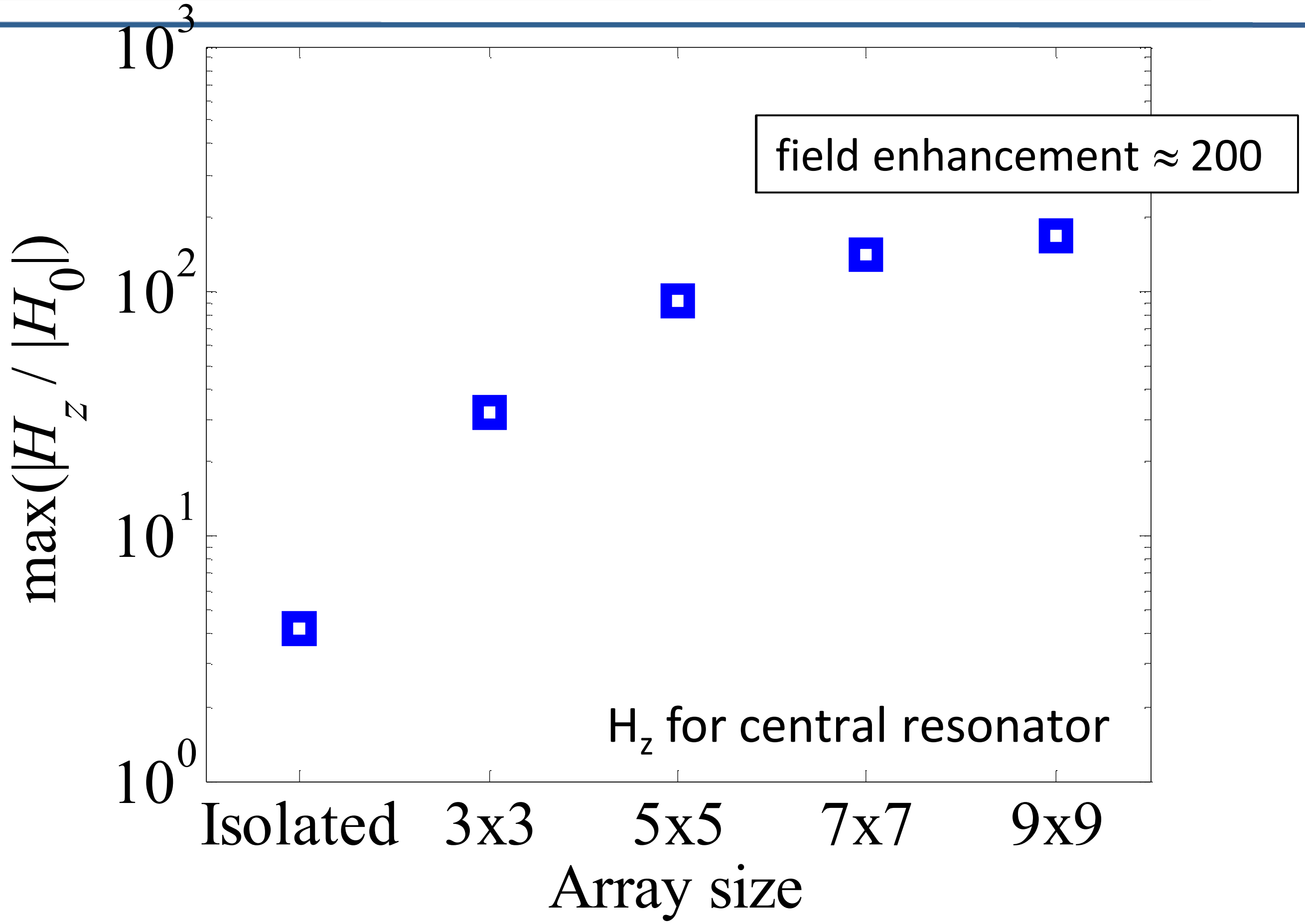
FDTD simulations at the λ = 10.8 μm resonance

Array effect on the magnetic dipole



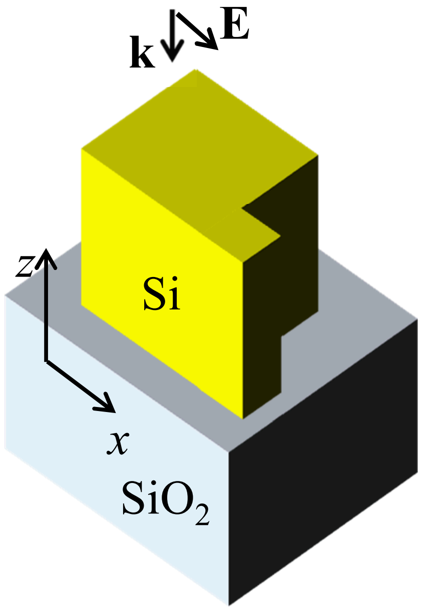
- m_z can't radiate broadside (no forward lobe)
- near center: local fields inhibit radiative decay of m_z
- near edges: m_z can radiate laterally
- quality factor increases towards center
- quality factor increases with array size

Field enhancement vs. array size

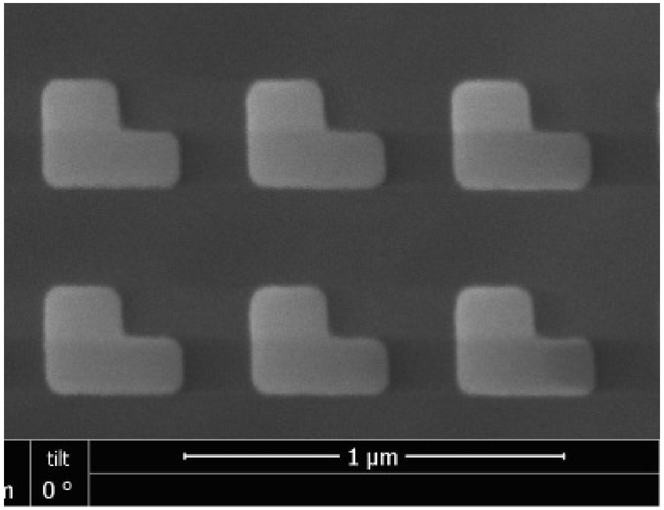


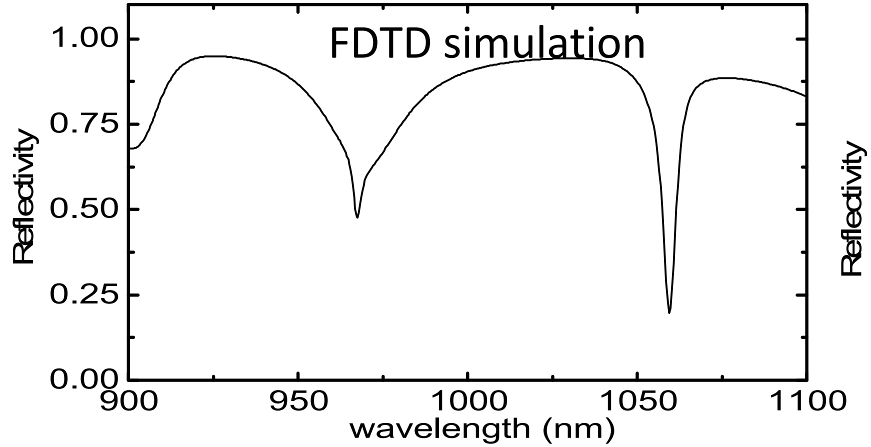
- beginning to saturate for 9x9 array
- effect arises from nearby resonators

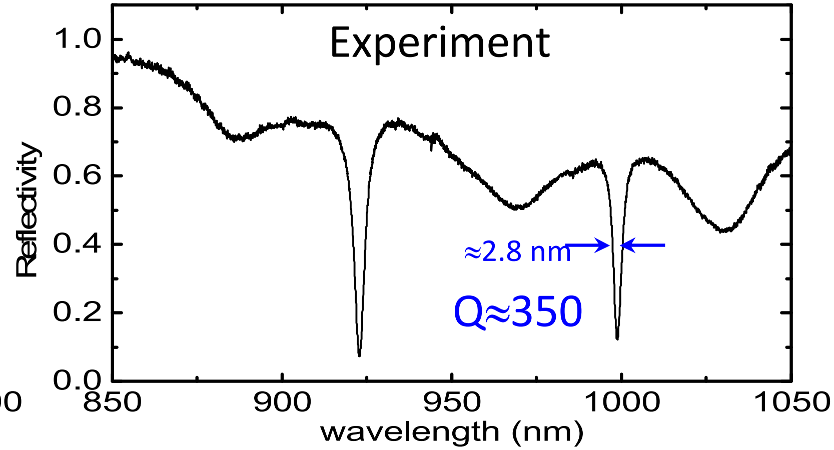
Experimental verification: Silicon-on-insulator Fano resonators



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



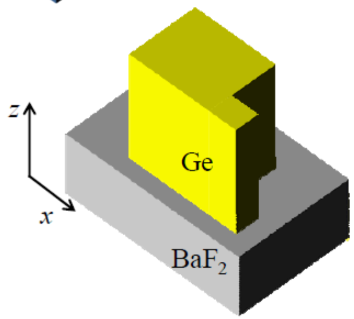




Conclusion

- The introduction of perturbations of high symmetry geometries

  Campione et al., Opt. Express **23**, 2293-2307 (2015)



- Enables directional scattering, Huygens' metasurfaces, and high-quality factor Fano resonances

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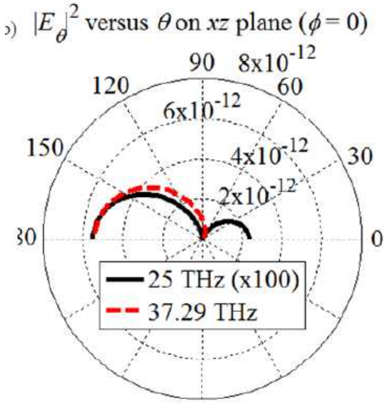
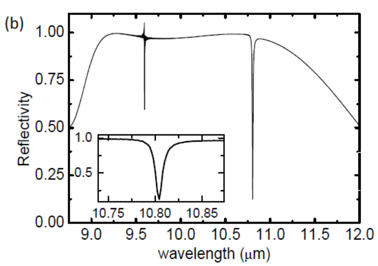
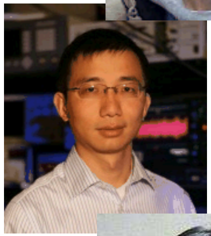
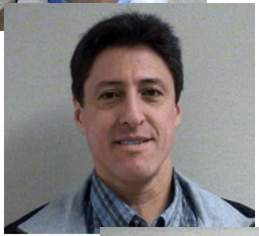


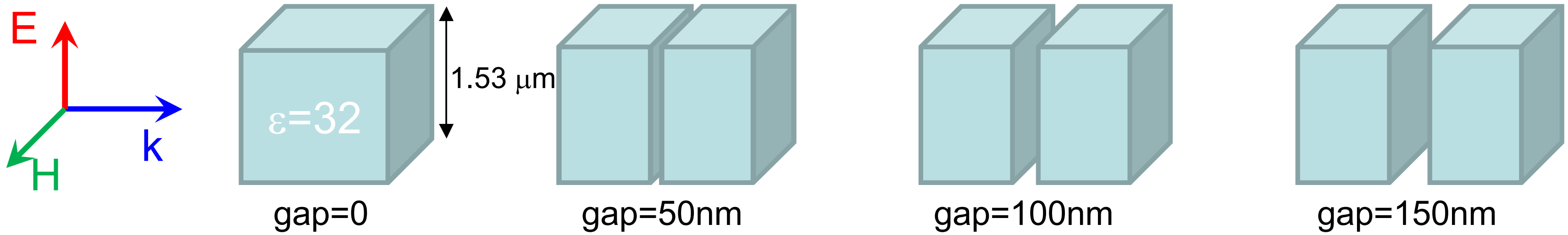


Acknowledgments

- Michael B. Sinclair 
- Sheng Liu 
- Lorena I. Basilio 
- Larry K. Warne 
- Ting S. Luk 
- Igal Brener 
- Joel R. Wendt 
- William L. Langston 

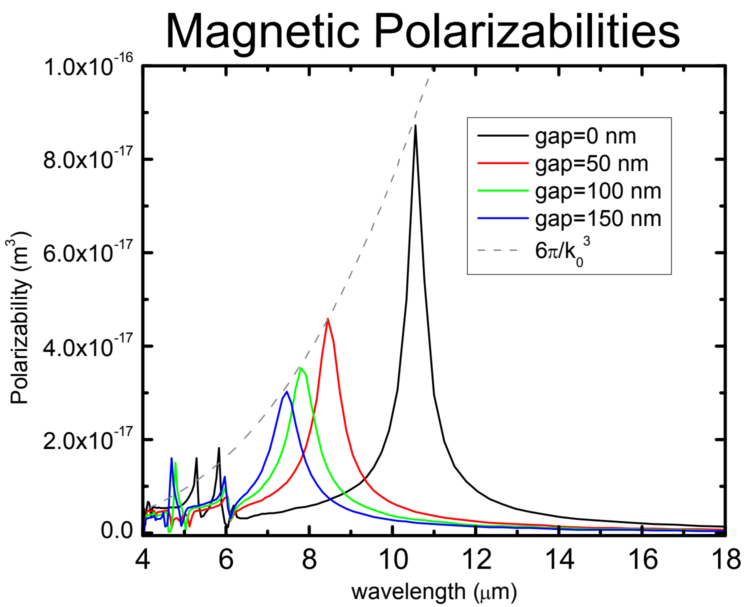
Back-up slides

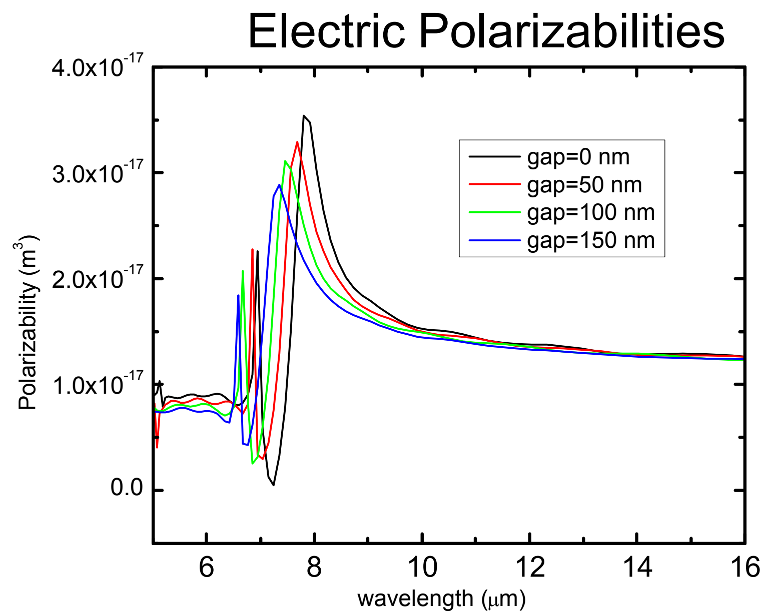
Aligning the dipole resonances: split-cubes



$$\mathbf{m} = \underline{\alpha}_{mm} \cdot \mathbf{H}_{loc}$$

$$\mathbf{p} = \underline{\alpha}_{ee} \cdot \mathbf{E}_{loc}$$



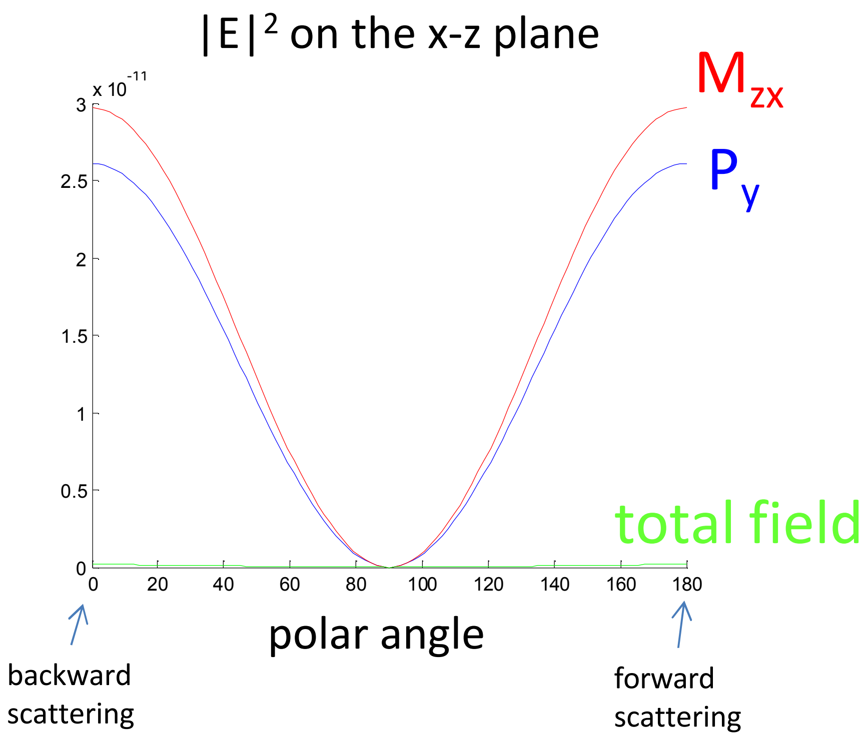


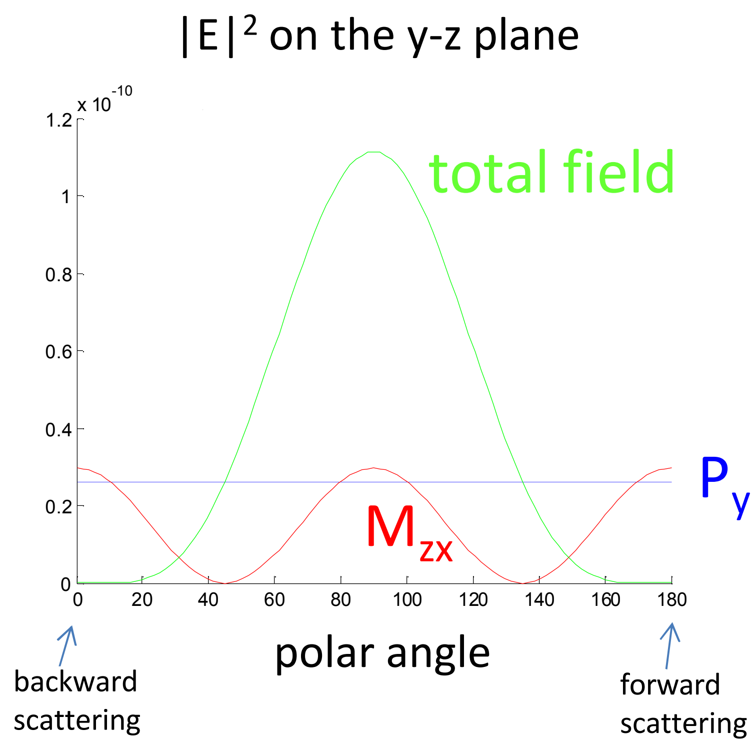
Warne et al., PIER B **44**, 1-29 (2012); IEEE Trans. Antennas Propagat. **61**, 2130-2141 (2013)
Campione et al., Opt. Express **23**, 2293-2307 (2015)

What about p_y and M_{zx}?

At Fano resonance:

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





Array suppression of scattering

$$p = \alpha E^{loc} \qquad \alpha \sim \frac{1}{\omega^2 - \omega_0^2 + i\frac{k^3}{6\pi}}$$

Radiation damping term

$$E^{loc} = E^{inc} + \beta p \qquad \beta = Re(\beta) + i\frac{k^3}{6\pi}$$

Tretyakov and Viitanen
Sipe and Van Kranendonk
Simovski

Interaction constant

$$p\left(\frac{1}{\alpha} - i\frac{k^3}{6\pi} - Re(\beta)\right) = E^{inc}$$

but

$$\frac{1}{\alpha} = Re\left(\frac{1}{\alpha}\right) + i\frac{k^3}{6\pi}$$

$$p\left(Re\left(\frac{1}{\alpha}\right) + \underbrace{\cancel{i\frac{k^3}{6\pi}}}_{\text{radiation term}} - \underbrace{\cancel{i\frac{k^3}{6\pi}}}_{\text{local field term}} - Re(\beta)\right) = E^{inc}$$

$$p = \frac{E^{inc}}{\left(\omega^2 - \omega_0^2 - Re(\beta)\right)}$$

non-radiating dipole

Multipolar expansion

The total far field can be decomposed to multipolar components as

$$\mathbf{E} = \mathbf{E}_{ED} + \mathbf{E}_{MD} + \mathbf{E}_{EQ} + \mathbf{E}_{MQ} + \mathbf{E}_{EO} + \mathbf{E}_{MO} + \ldots$$

$$\mathbf{E}_{ED} = Z_0 \frac{ck^2}{4\pi} \frac{e^{ikr}}{r} \hat{\mathbf{r}} \times \mathbf{p} \times \hat{\mathbf{r}}$$

$$\mathbf{E}_{MD} = -Z_0 \frac{k^2}{4\pi} \frac{e^{ikr}}{r} \hat{\mathbf{r}} \times \mathbf{m}$$

$$\mathbf{E}_{EQ} = -Z_0 \frac{ick^3}{24\pi} \frac{e^{ikr}}{r} \hat{\mathbf{r}} \times \mathbf{Q}_{EQ} \times \hat{\mathbf{r}}$$

$$\mathbf{E}_{MQ} = Z_0 \frac{ik^3}{24\pi} \frac{e^{ikr}}{r} \hat{\mathbf{r}} \times \mathbf{Q}_{MQ}$$

$$\mathbf{E}_{EO} = -Z_0 \frac{ck^4}{24\pi} \frac{e^{ikr}}{r} \hat{\mathbf{r}} \times \mathbf{O}_{EO} \times \hat{\mathbf{r}}$$

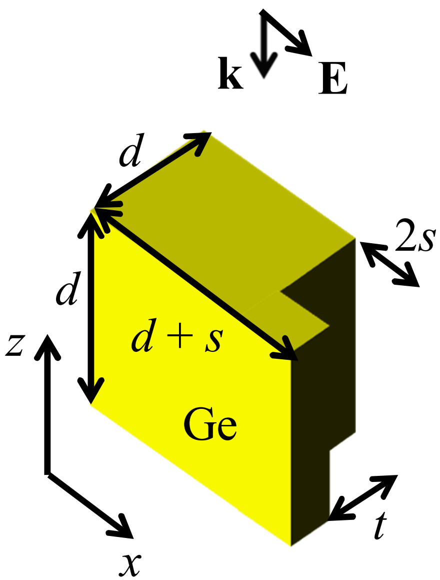
$$\mathbf{E}_{MO} = Z_0 \frac{k^4}{24\pi} \frac{e^{ikr}}{r} \hat{\mathbf{r}} \times \mathbf{O}_{MO}$$

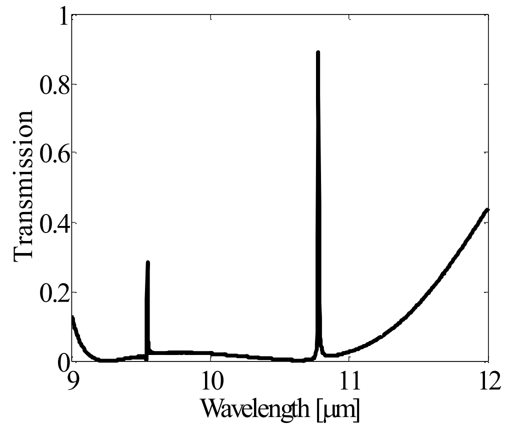
$$Weight = \frac{\int_0^{2\pi}\int_0^{\pi} \left(E_\theta^{FF} E_\theta^{multipole} + E_\phi^{FF} E_\phi^{multipole} \right) \sin\theta d\theta d\phi}{Normalization\ factor * Coefficient\ in\ front\ of\ multipole\ above}$$

$$P_i = \frac{1}{2Z_0} \left| E_i \right|^2 * Normalization\ factor$$

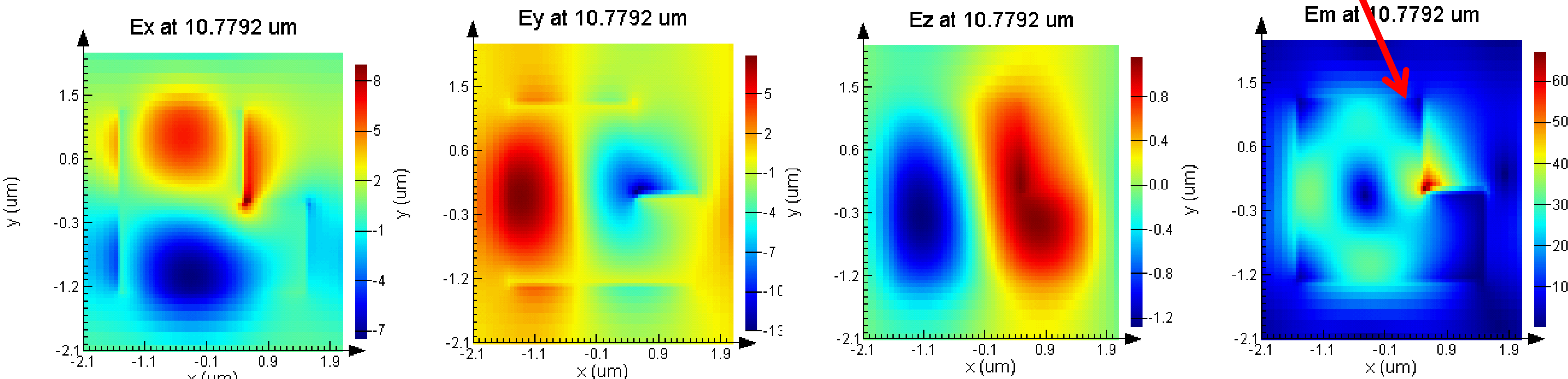
Expansion up to quadrupolar terms will be enough…

Top-L-cube – Electric field maps at Fano resonance 10.77 um x-y plane

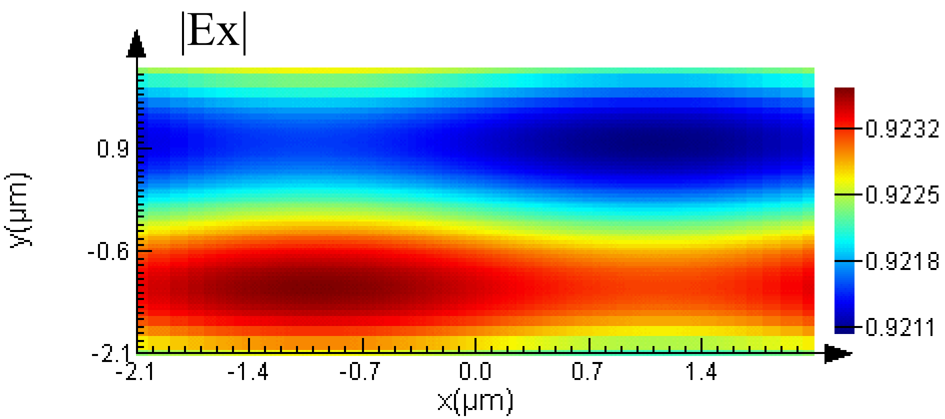


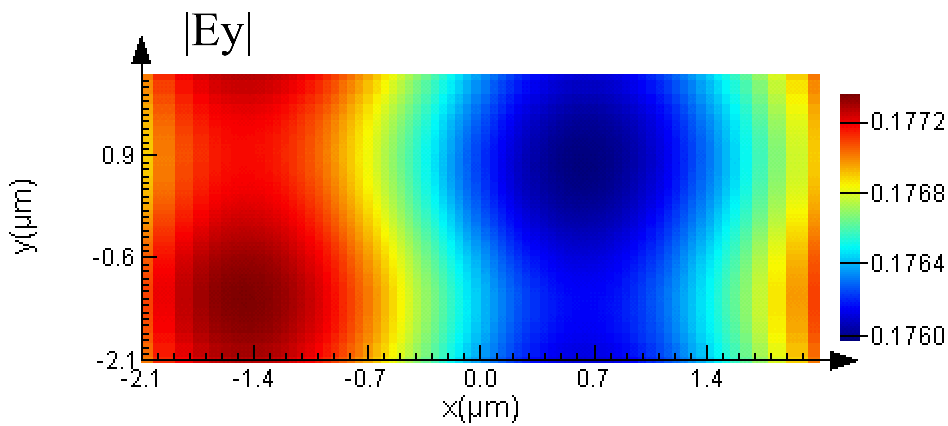


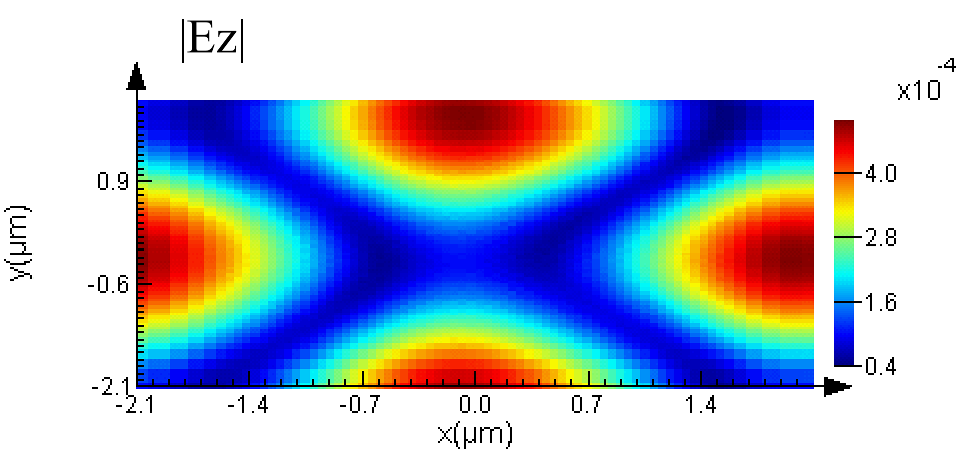
Magnetic dipole along z

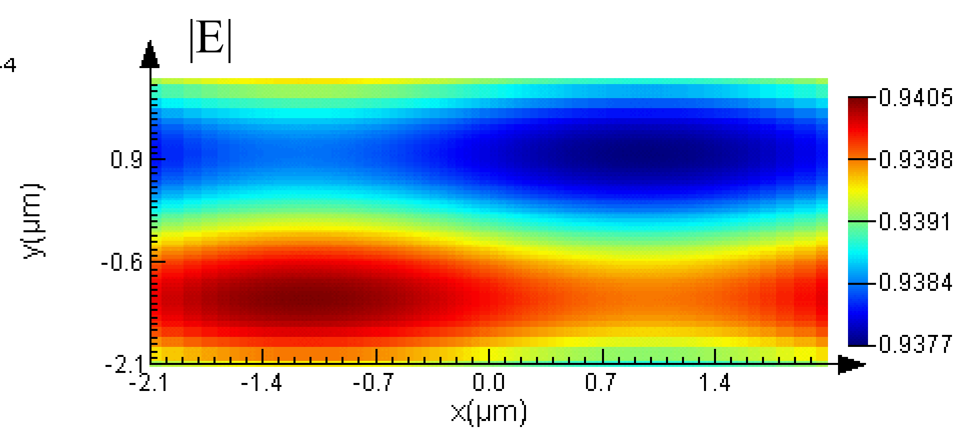


Top-L-shape – Polarization at Fano resonance – E field at T monitor at 27.8314THz



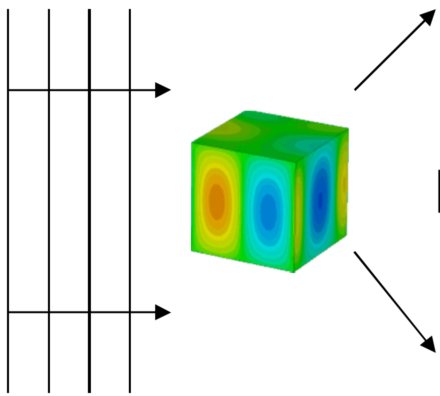




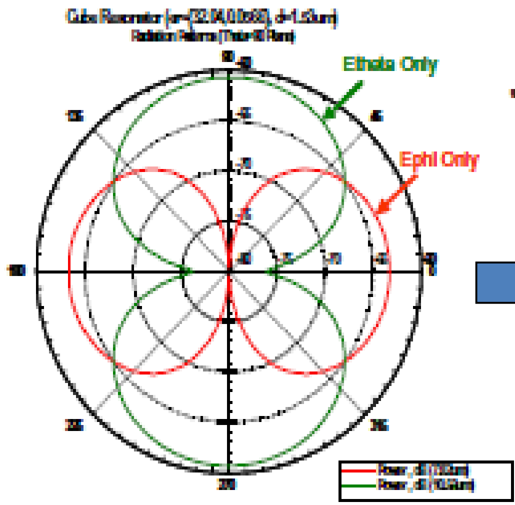


Extracting Resonator Polarizabilities: Isolated Particle Simulation and Moments (IPSaM)

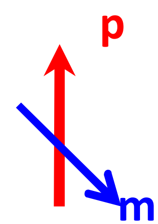
L. I. Basilio, et al., IEEE Antennas and Wireless Propagation Letters, 10, 1567, 2011
Rockstuhl, et al., PRB 83, 245119 (2011)



Simulate isolated particle scattering



Transform to far-field patterns



Extract equivalent dipoles & polarizabilities

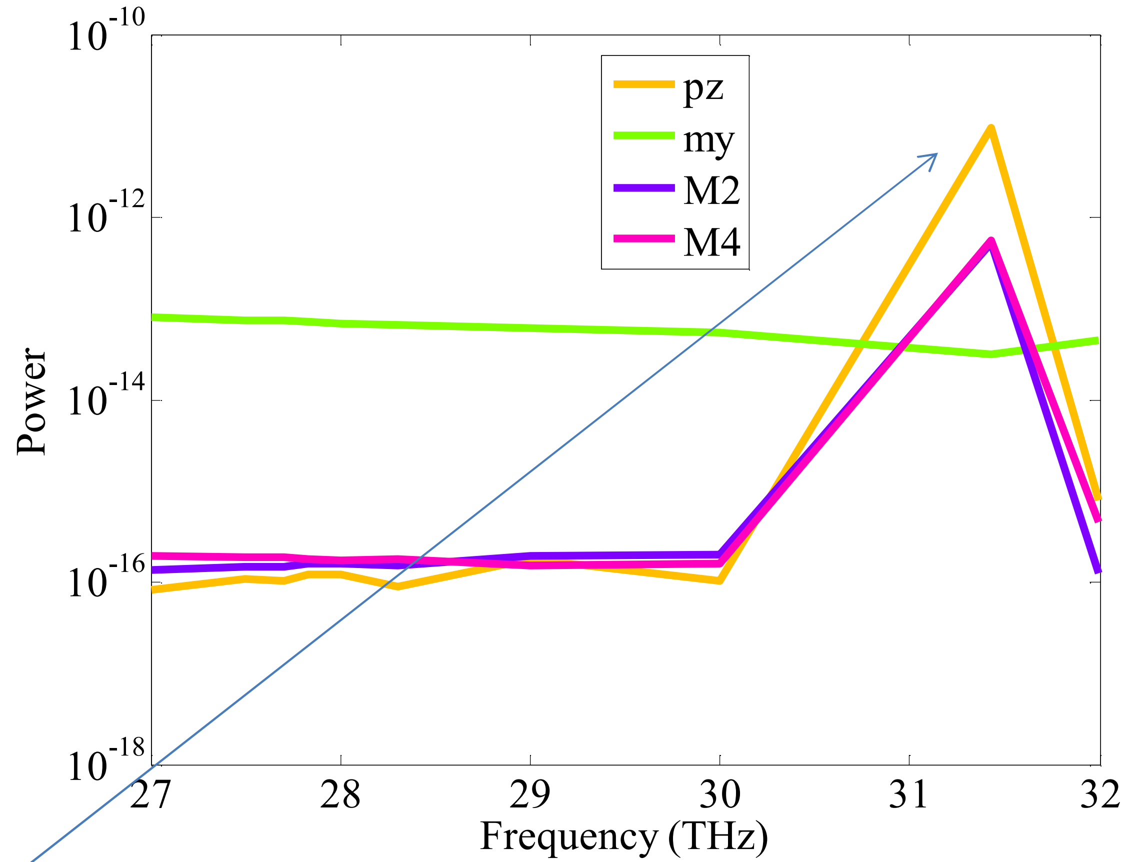
Claussius Mossotti

ε , μ

Estimate effective parameters

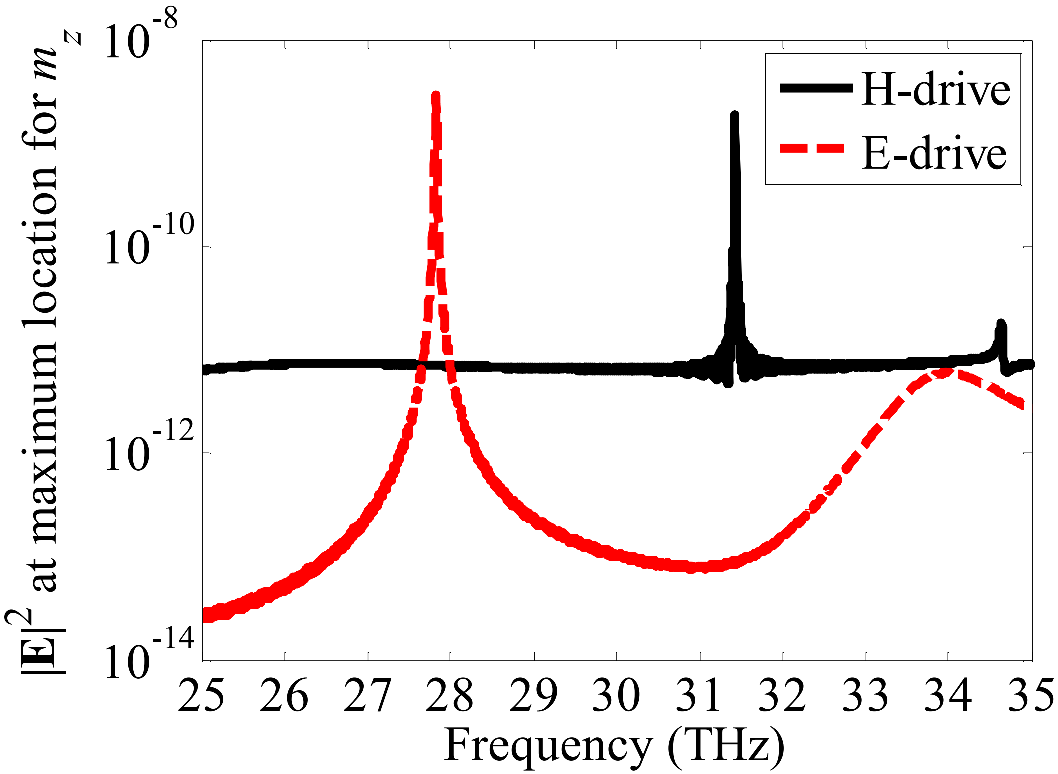
- fast, efficient, compatible with optimization
- general shapes: SRRs, dipoles, metals, DRs

Multipole decomposition H-Drive 2



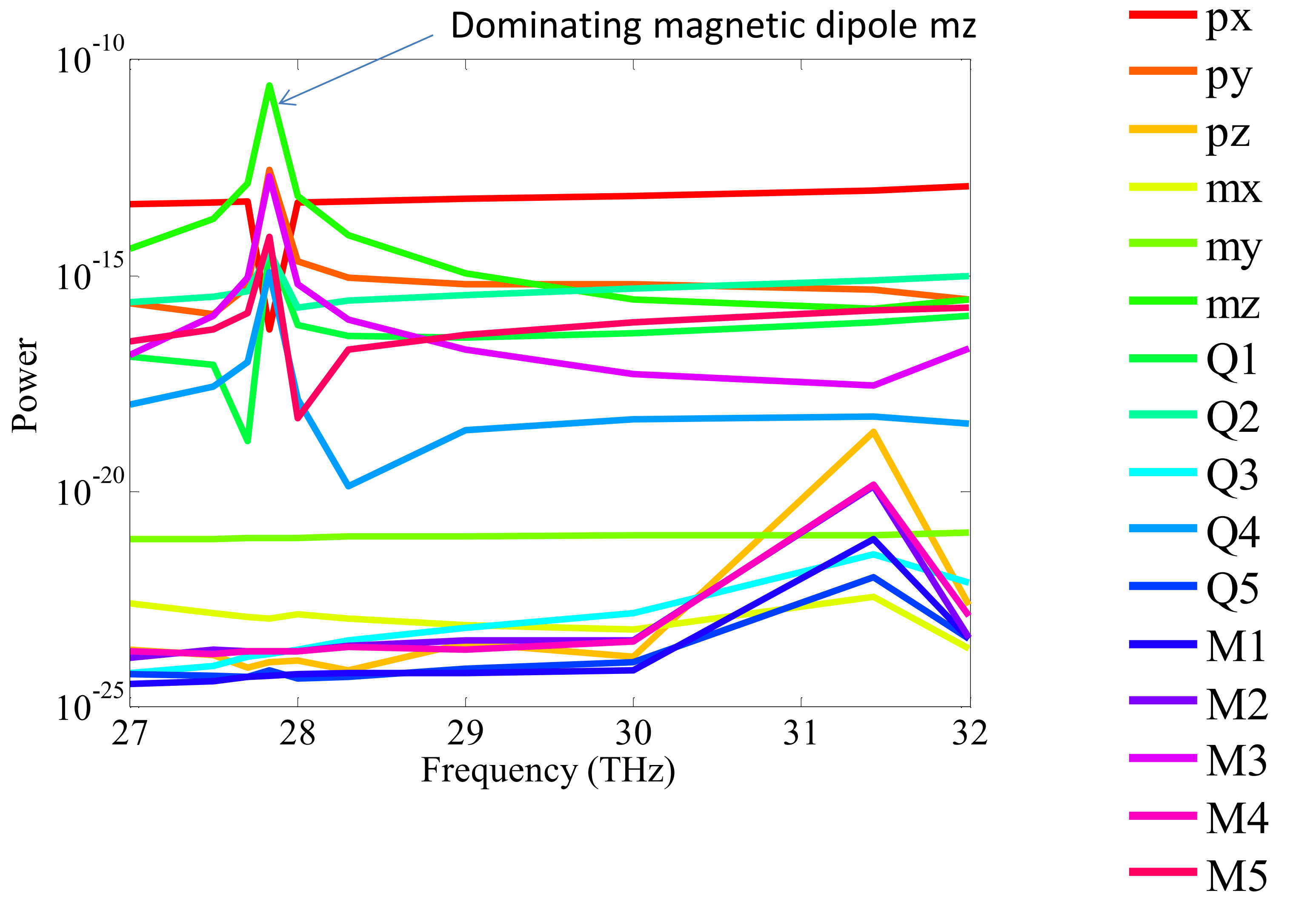
- Dominating electric dipole pz

E-Drive and H-Drive incidence



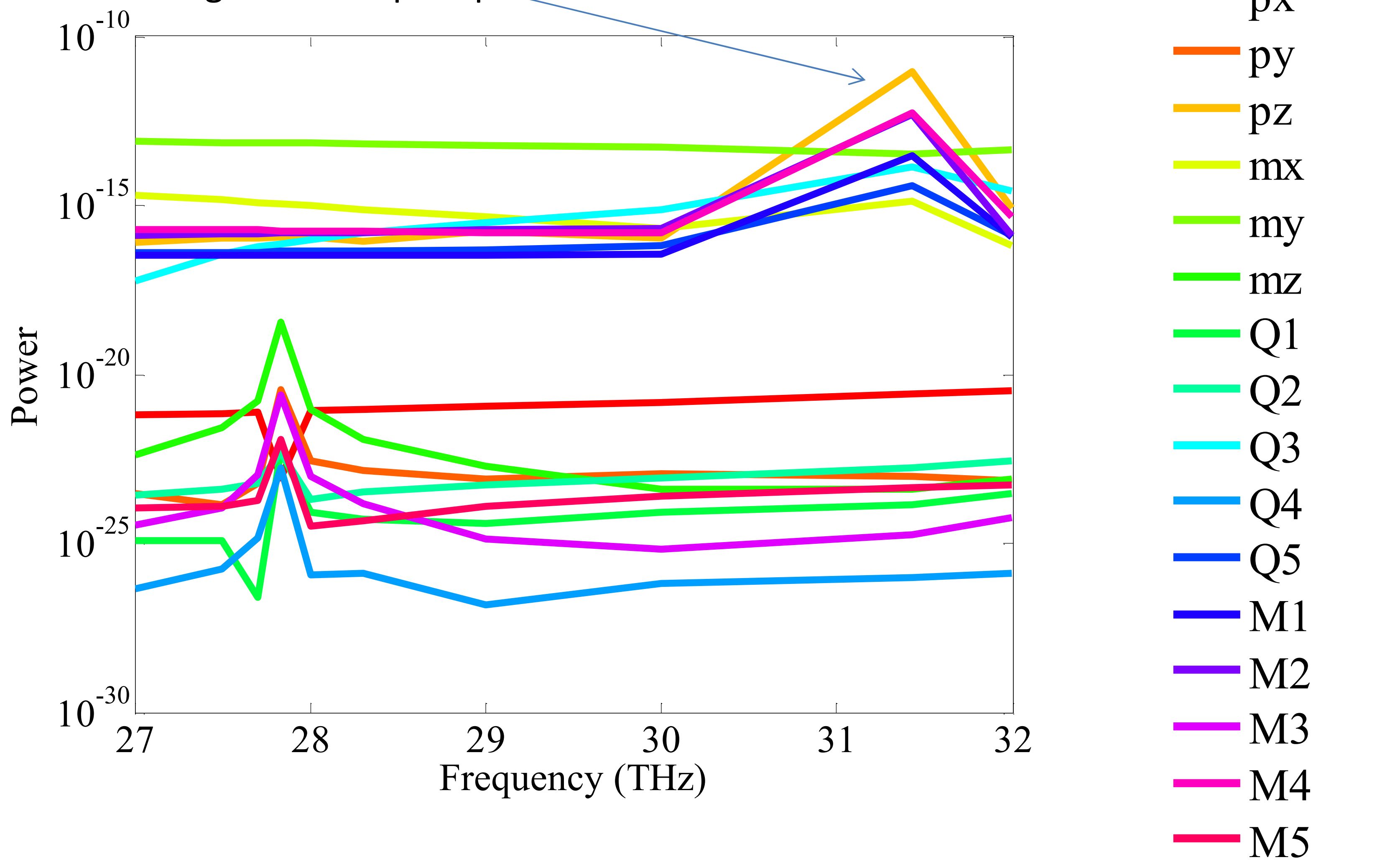
- Electric drive shows signature of the Fano resonance at 27.8314 THz only
- Magnetic drive shows signature of the Fano resonance at 31.43 THz only
- This agrees with our predictions so far

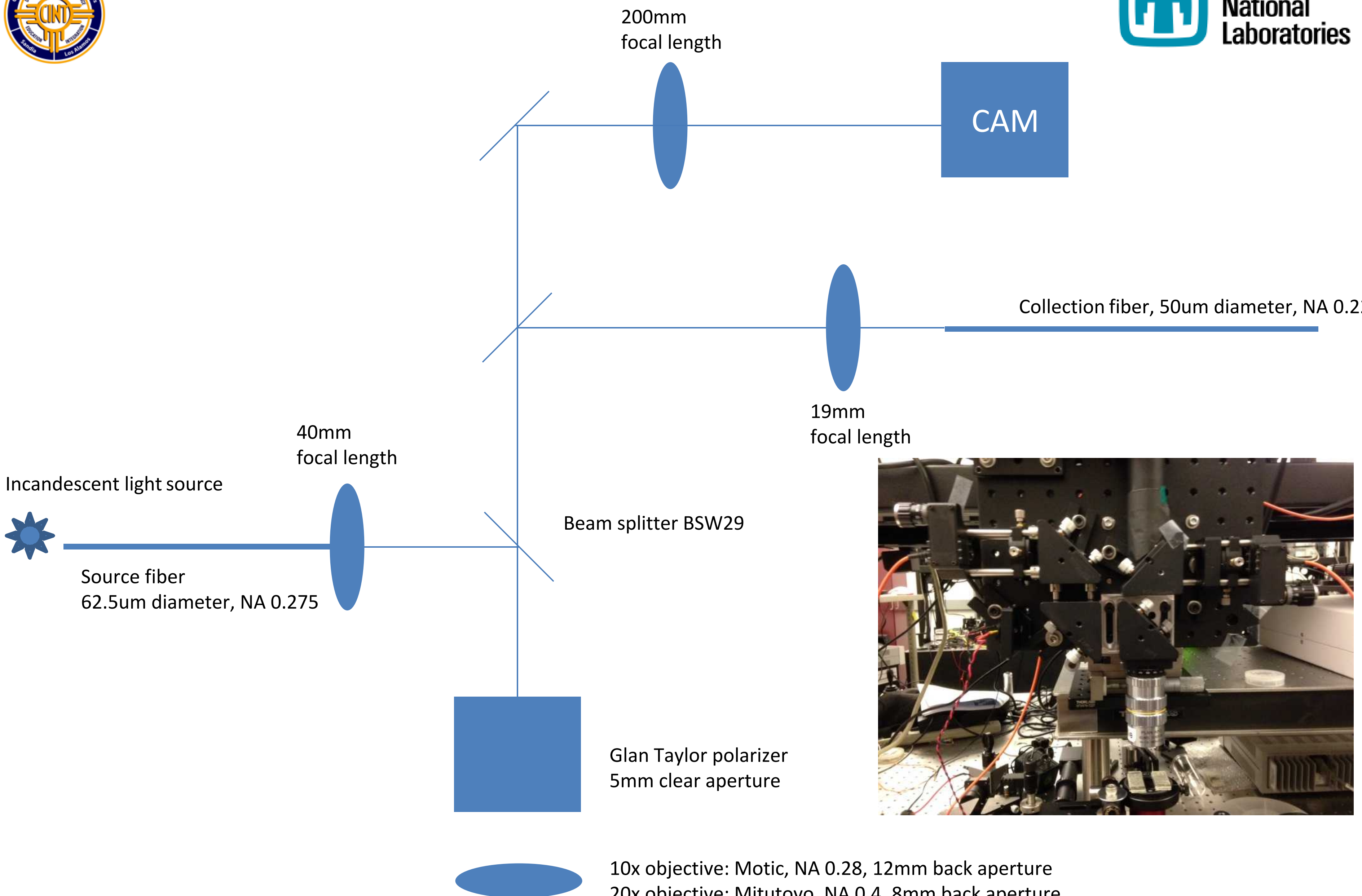
Multipole decomposition E-Drive 1



Multipole decomposition H-Drive 1

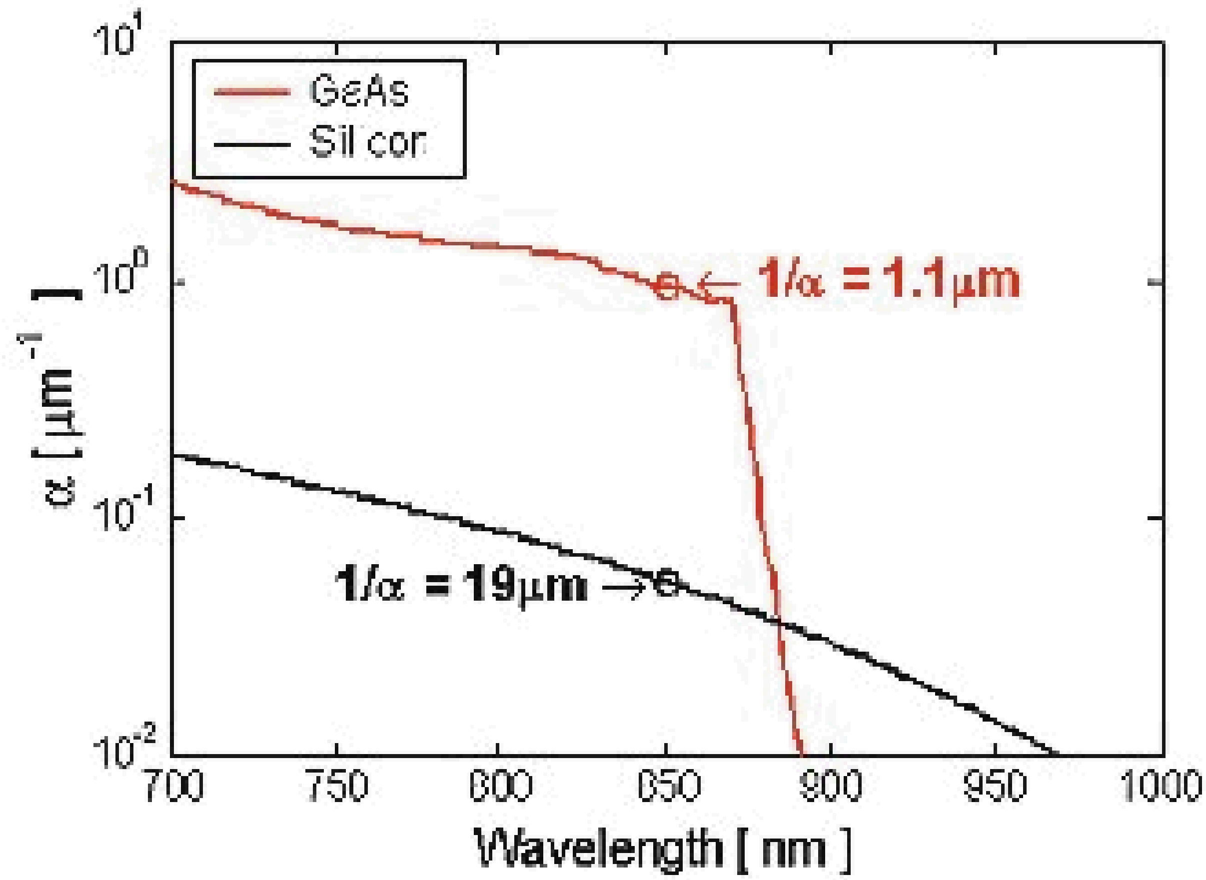
Dominating electric dipole pz




200mm
focal length
CAM
Collection fiber, 50um diameter, NA 0.22
19mm
focal length
40mm
focal length
Incandescent light source
Beam splitter BSW29
Source fiber
62.5um diameter, NA 0.275
Glan Taylor polarizer
5mm clear aperture
10x objective: Motic, NA 0.28, 12mm back aperture
20x objective: Mitutoyo, NA 0.4, 8mm back aperture

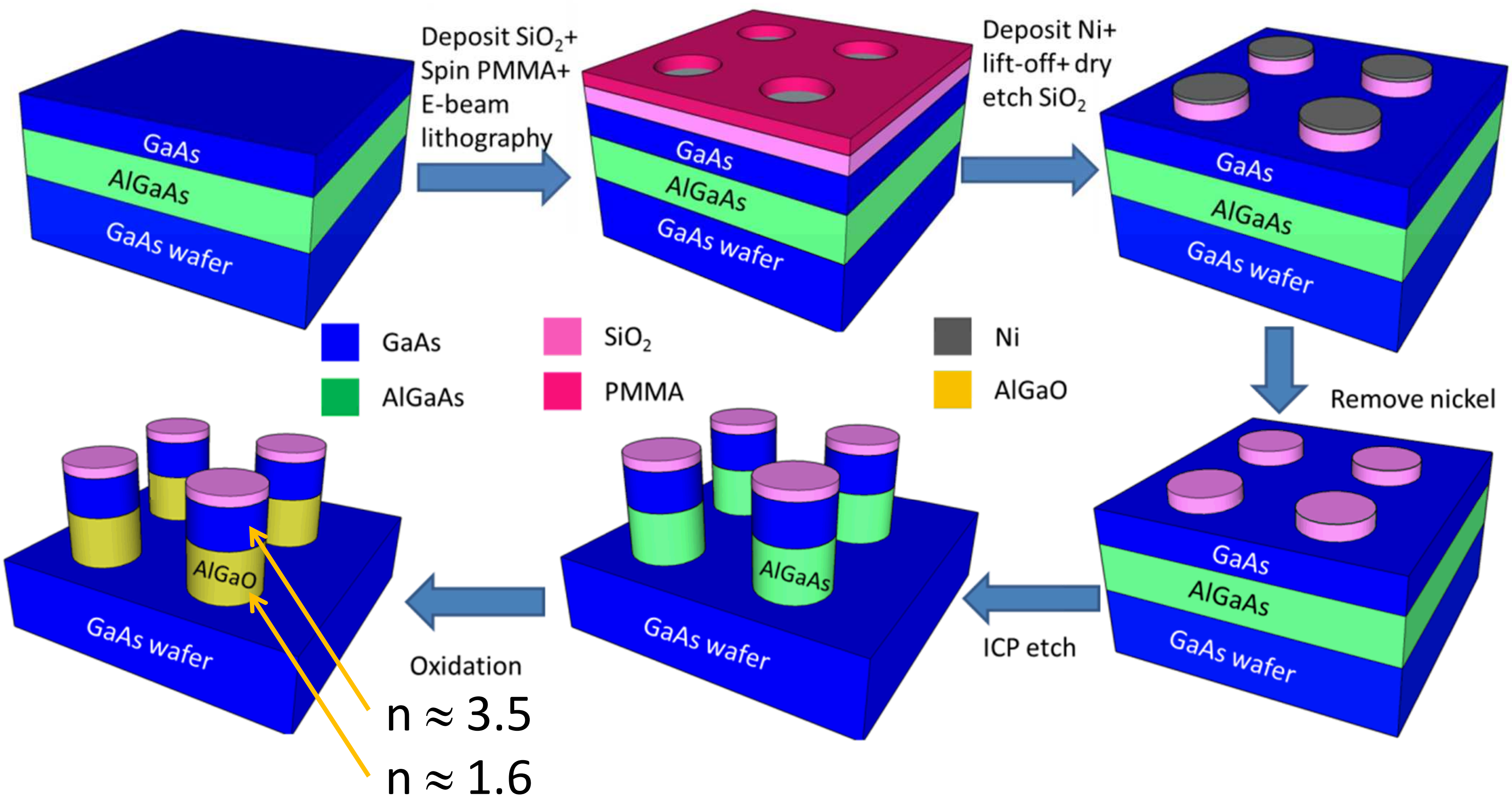
Comparison of Si and GaAs absorption

- Extremely low loss below bandgap
- Crystalline



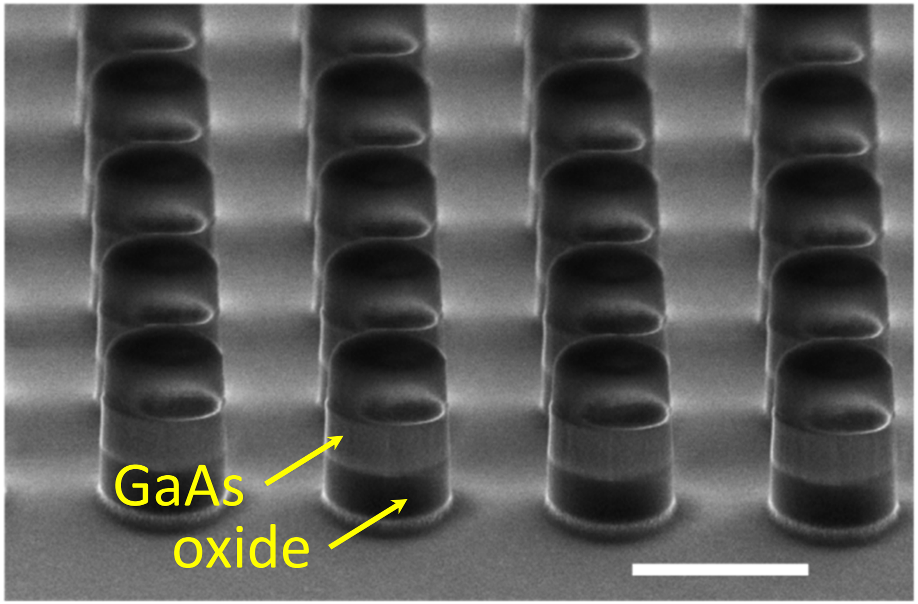
DRs are now possible in III-V semiconductors

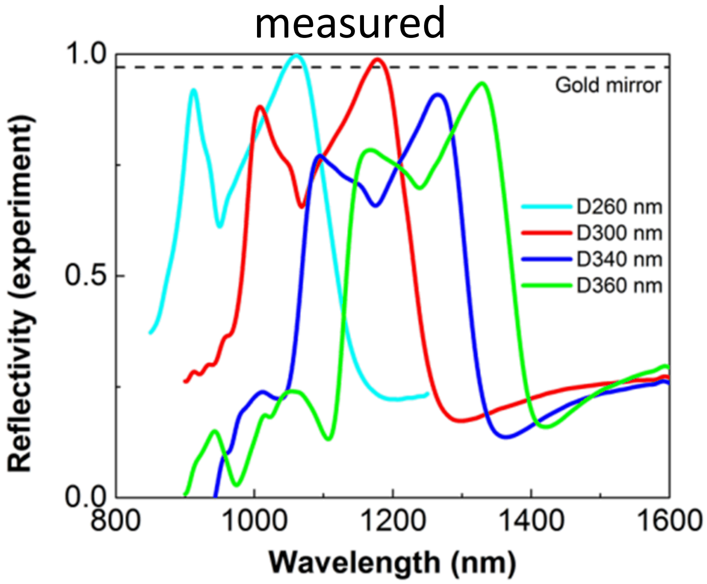
New process for (Al)GaAs resonators

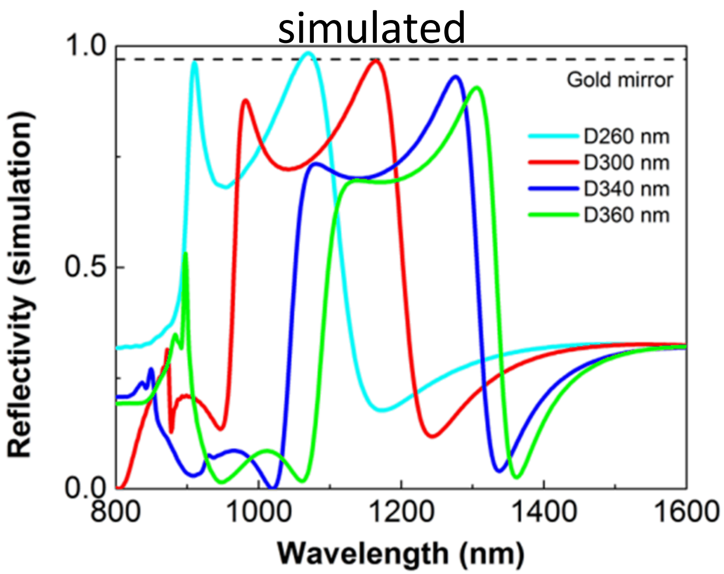


GaAs Cylindrical Resonators

- height = 300 nm
- diameter varies near 300 nm

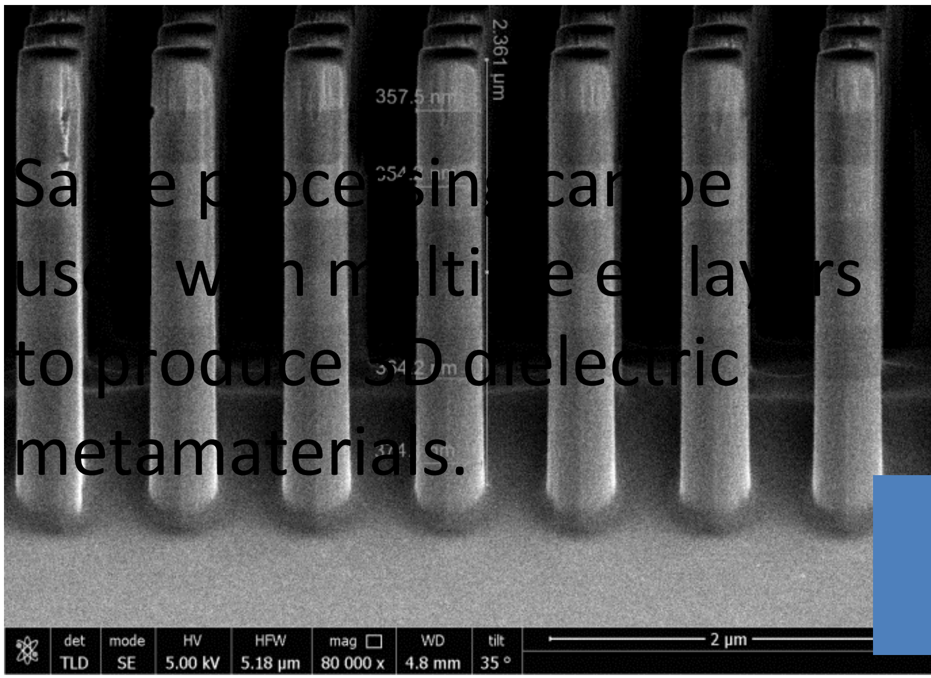




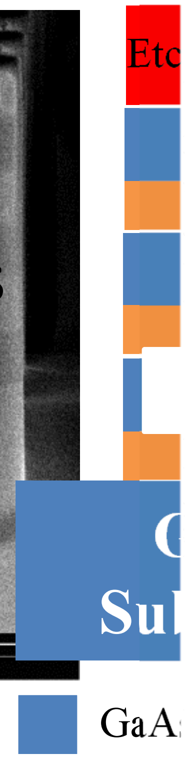


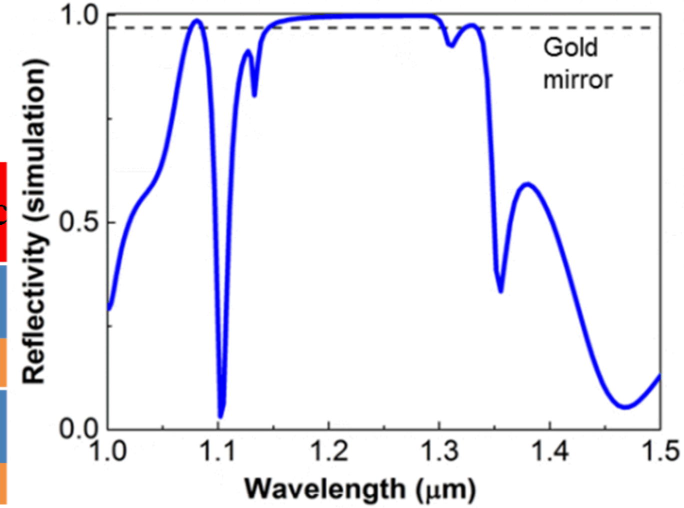
reflectivity exceeds gold at several wavelengths

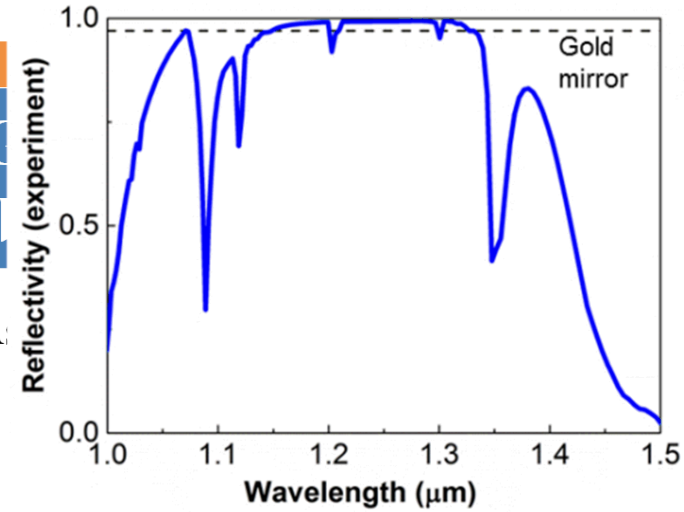
Multilayer III-V Dielectric Metamaterials



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



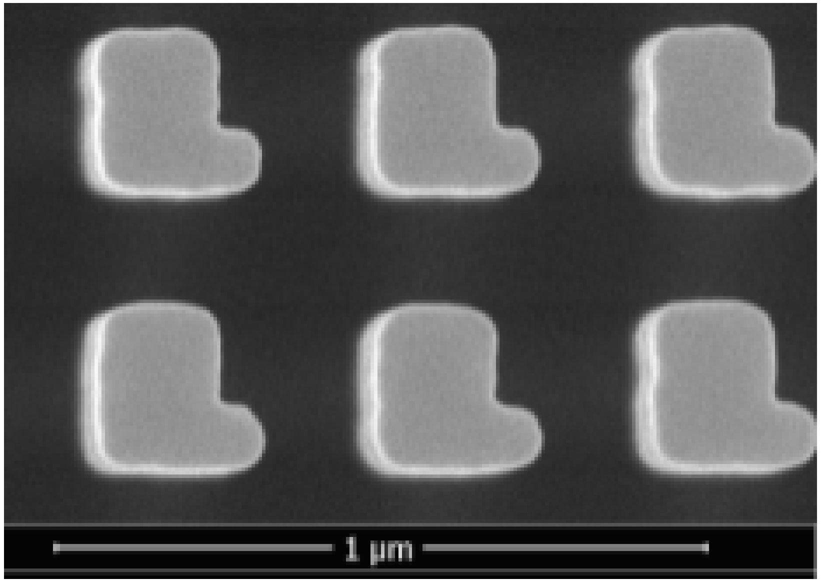


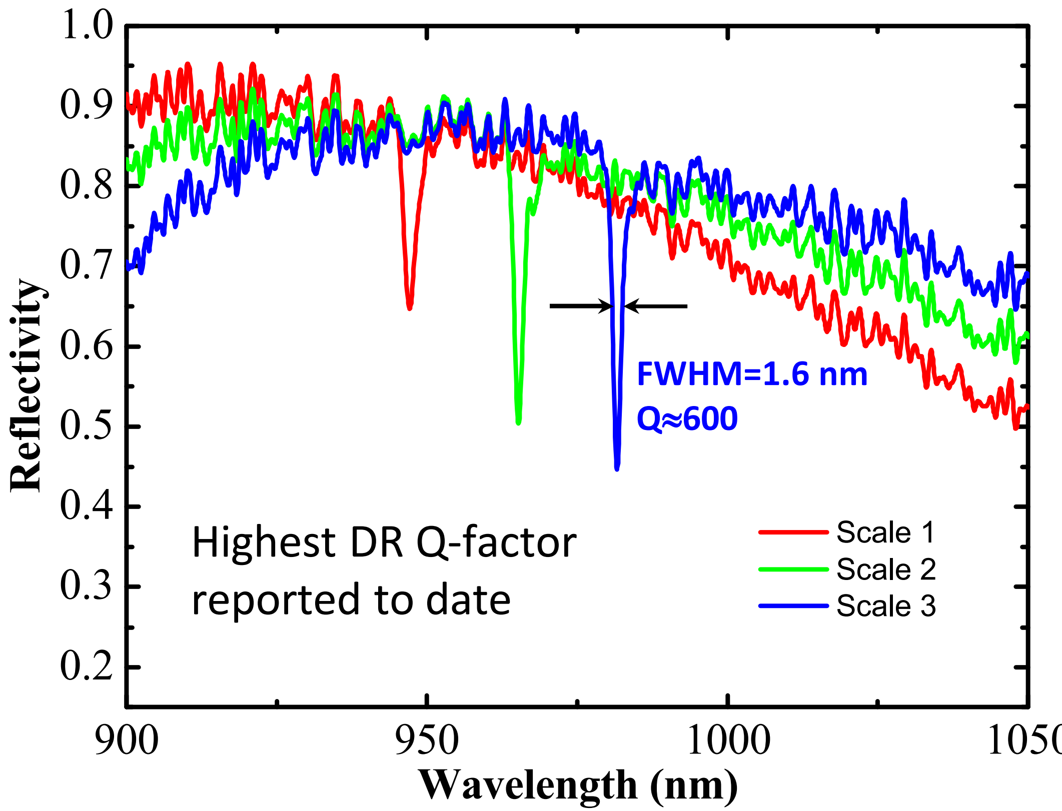


Broad spectral bands of near perfect reflectivity!

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