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A New Monolithic Dielectric Resonator Metasurface Design for High Quality-Factor Fano Resonances

Sandia National Laboratories

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Metamaterials 2015

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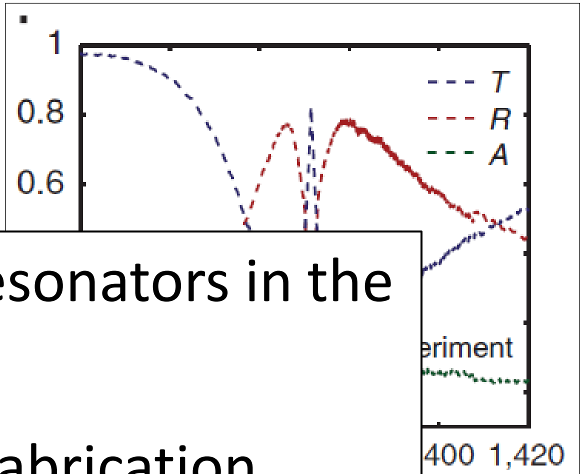
Fano resonances of dielectric resonator metasurfaces



Fano resonances:

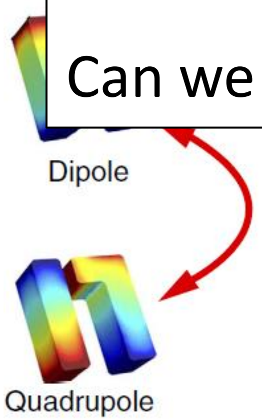
- Interference of bright and dark excitations

Techn

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

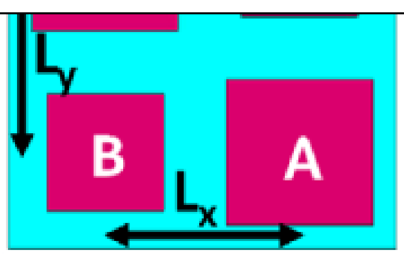
Near field coupling extremely sensitive to fabrication errors

Can we find a one-resonator design??



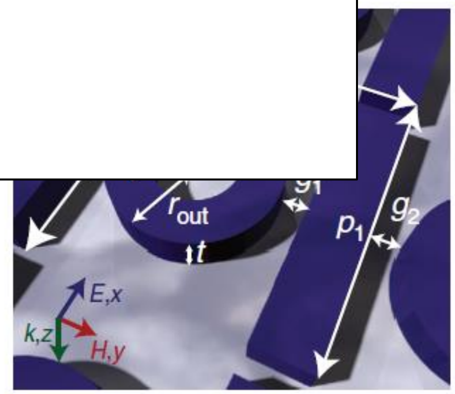
Q ~ 130 at 4 um

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



Q ~ 110 at 1.1 um

Wang, et al.
OMEX 5, 668, 2015



Q ~ 500 at 1.37 um

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

Outline

- Hi-Q monolithic design
- Theoretical underpinnings
- Experimental demonstrations:
  - SOI: measured Q-factor of ≈ 350 at 990 nm
  - GaAs: Q-factor of ≈ 600 at 975 nm

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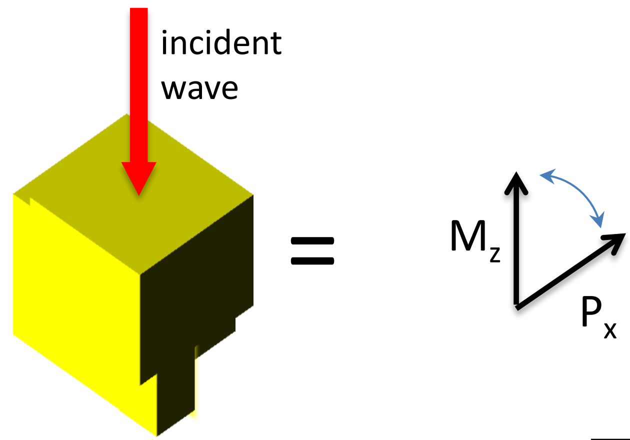
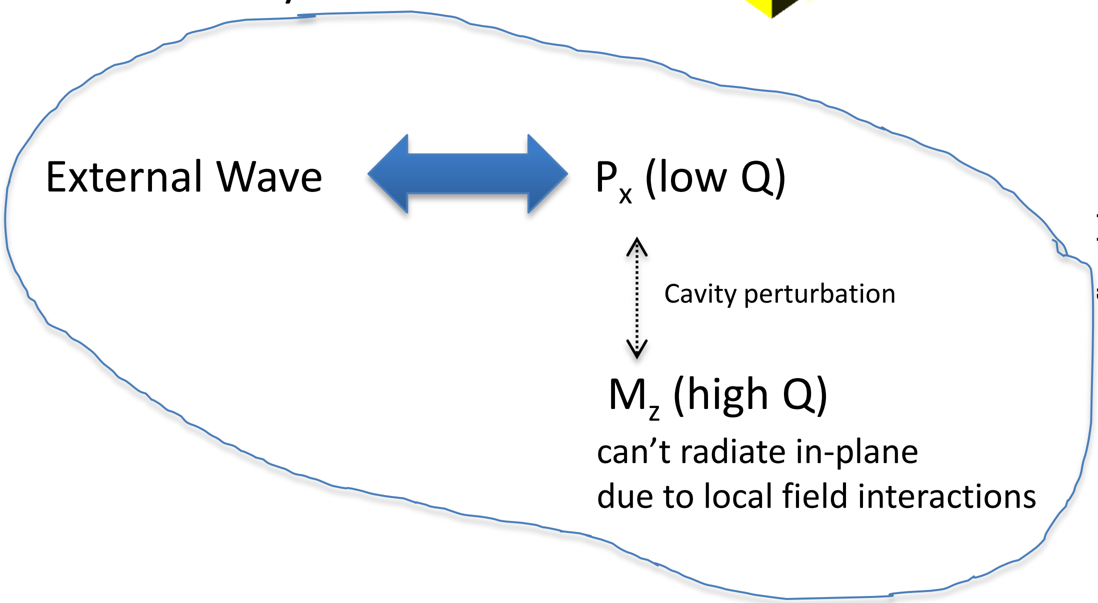
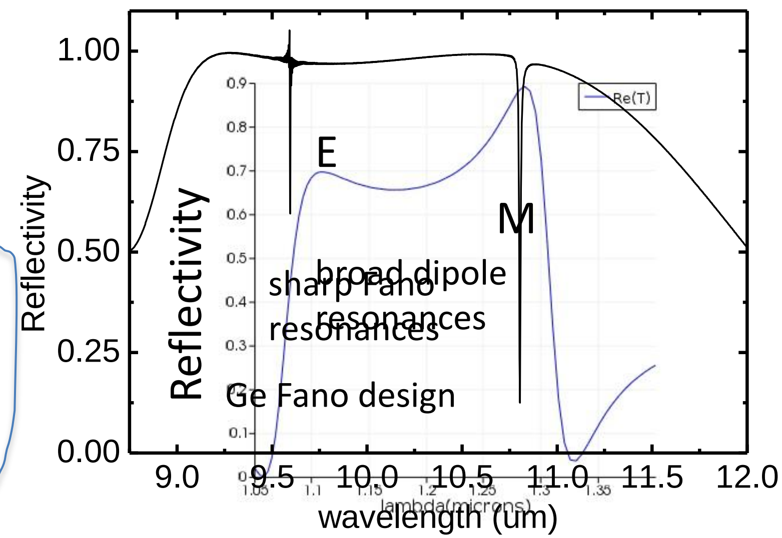
Fano resonator design: operating principles



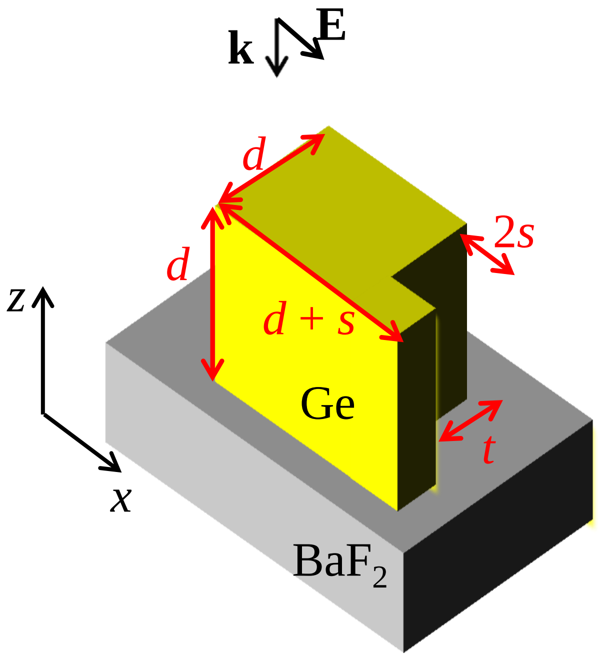
weakly coupled
orthogonal
dipole
modes

Fano system





Ge-based Fano design

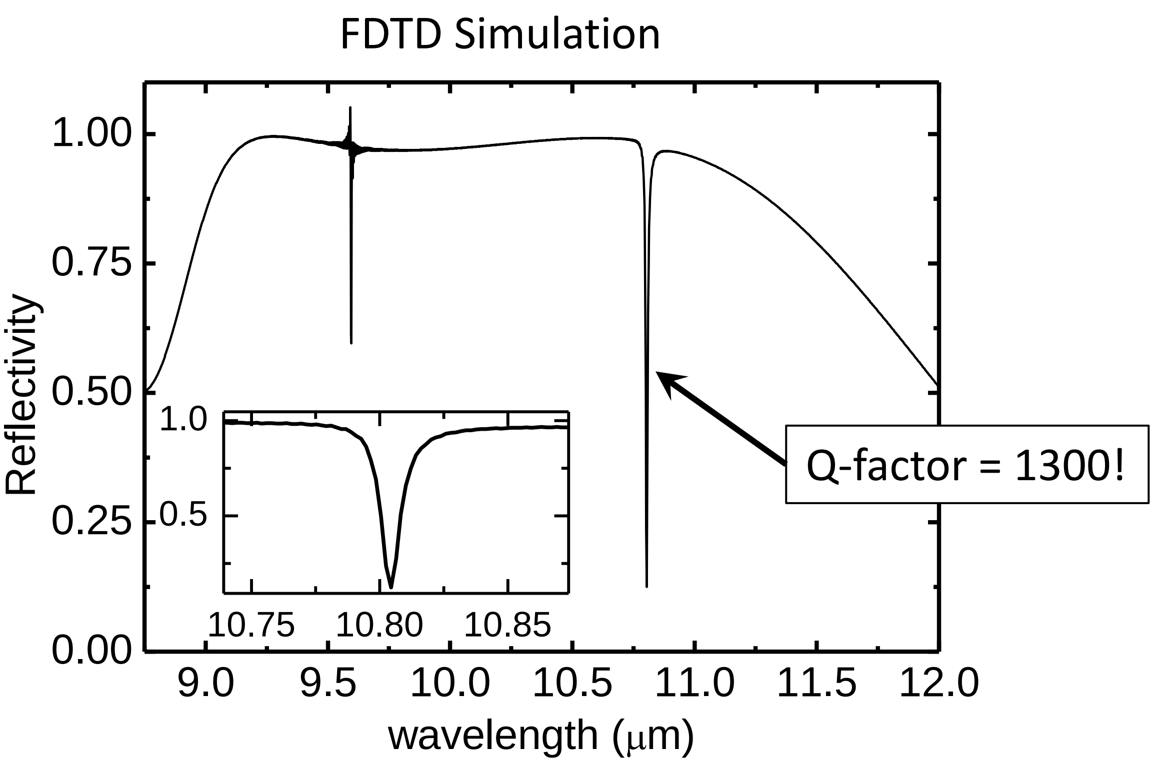


$d = 2.53$ μm

$s = d / 5$

$a = b = 4.2$ μm

$t = 1.5$ μm



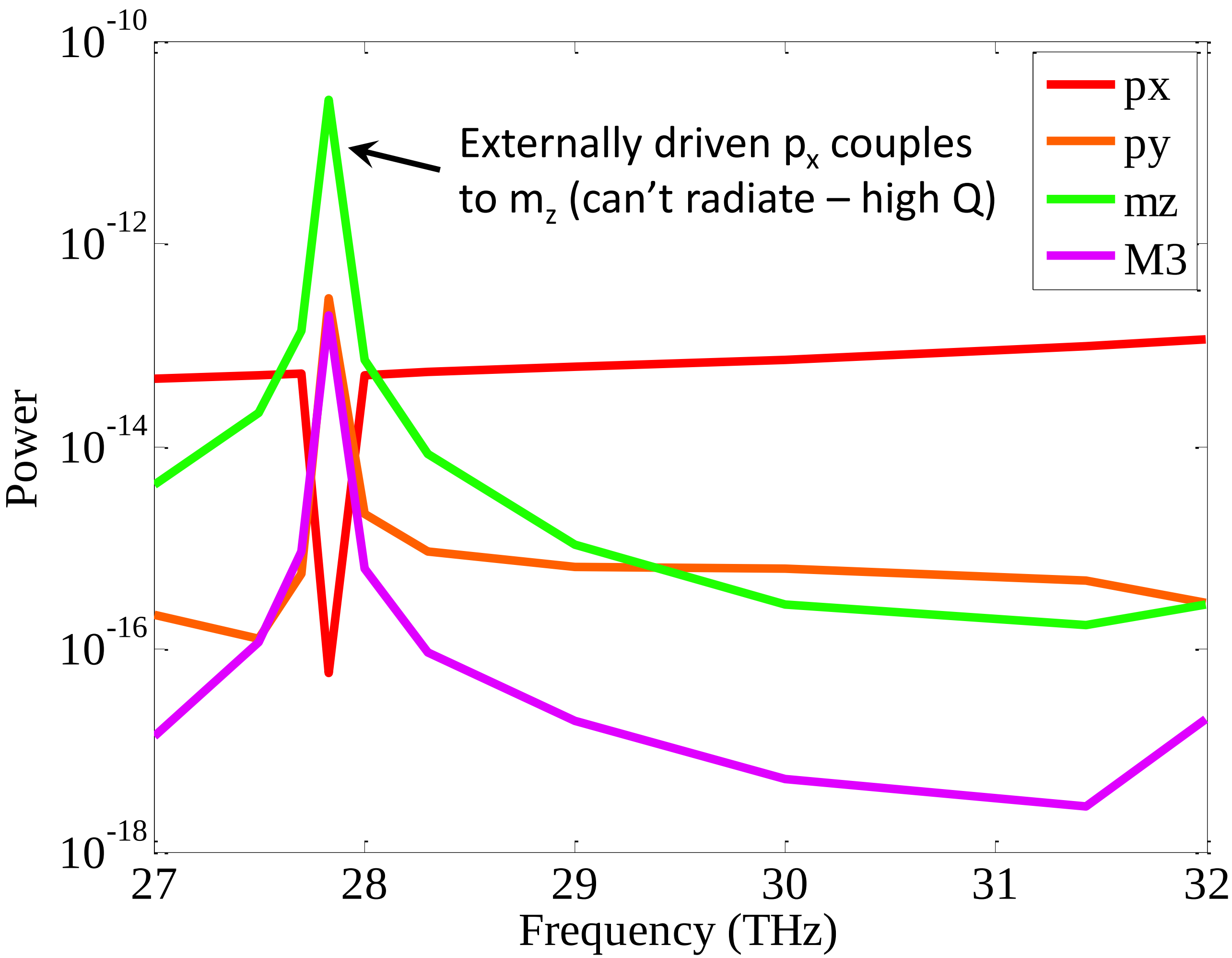
Design is scalable from NIR through RF!

Understanding the nature of the Fano mode

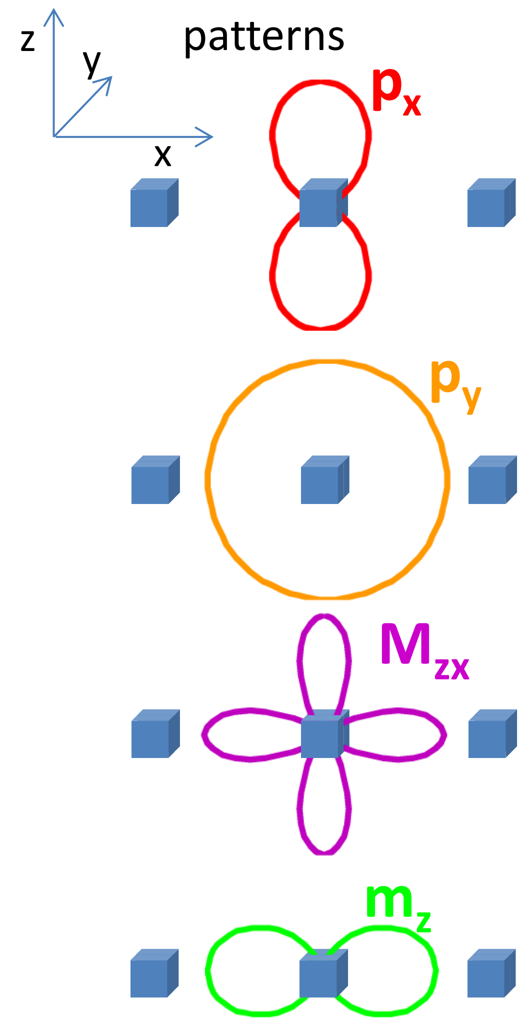
Multipole decomposition of resonator response

Dr. Salvatore Campione

- Electric field excitation for full array
- Far-field scattering for single cube

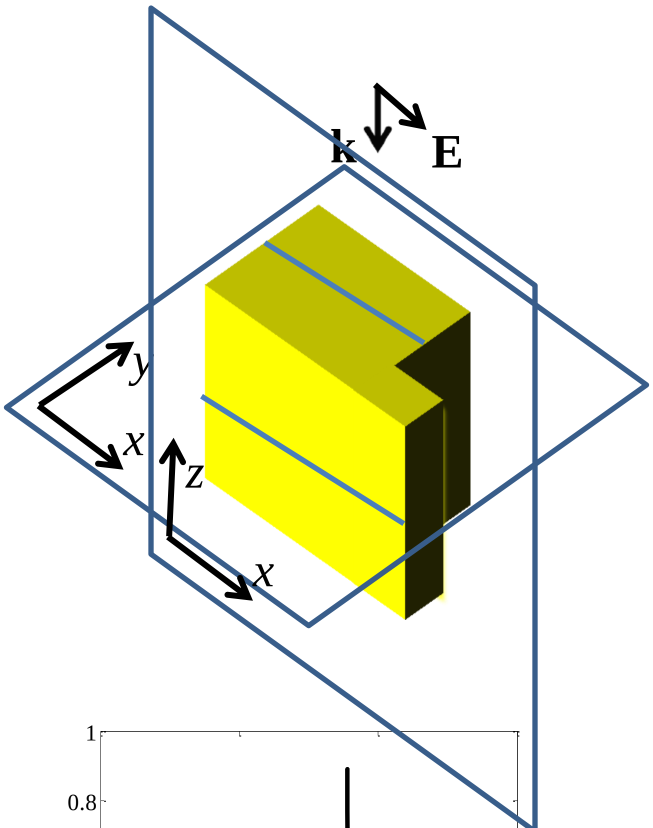


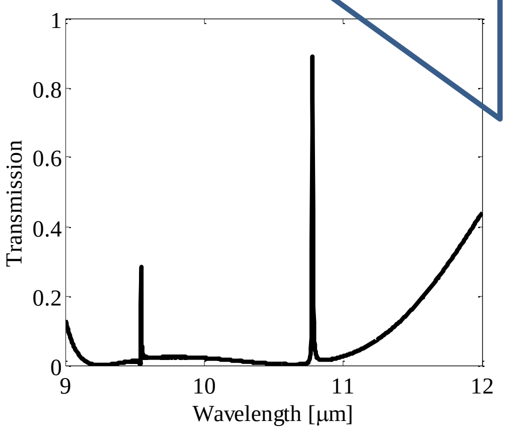
Far-field lobe patterns

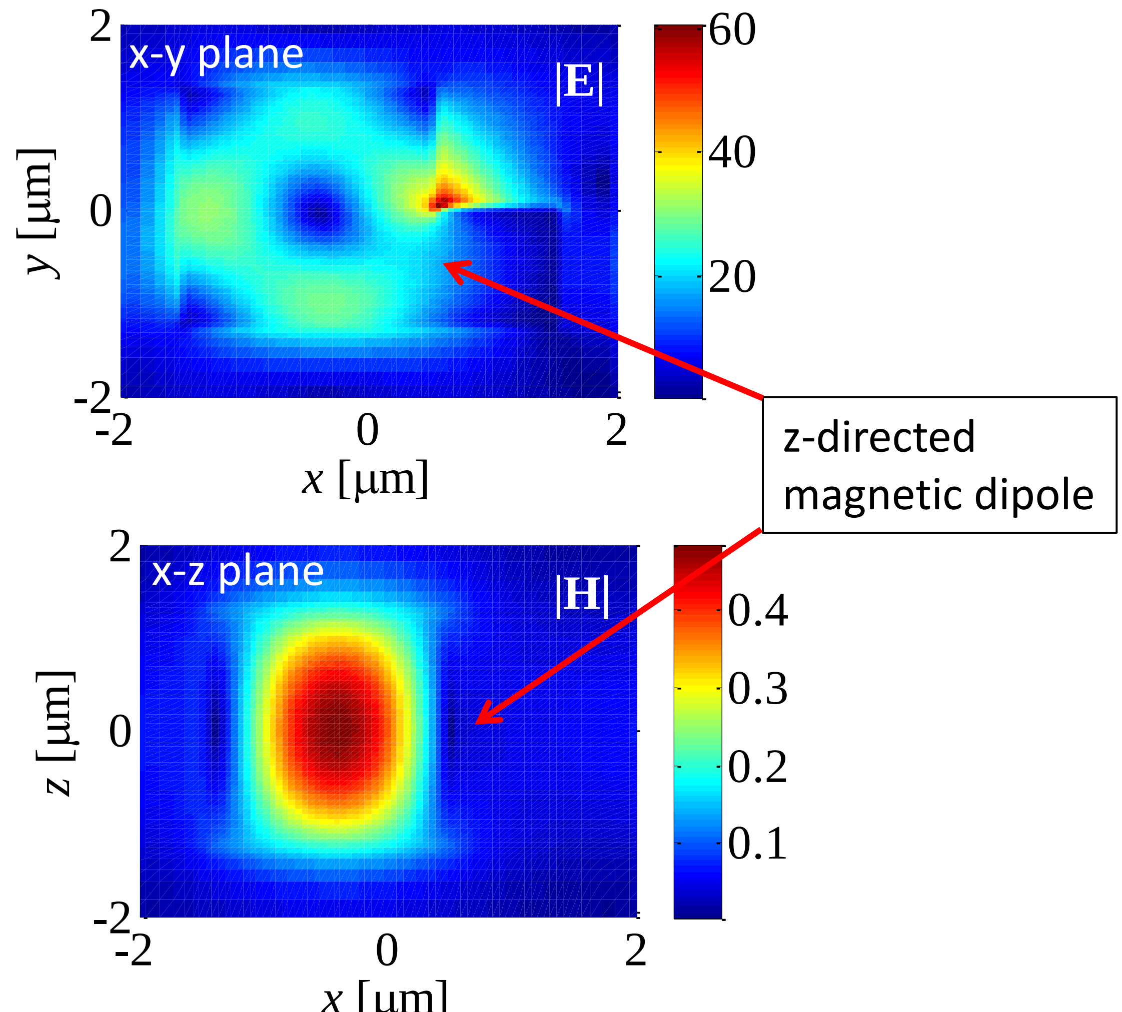


Resonant Mode Field Profiles

at the λ = 10.8 μm resonance







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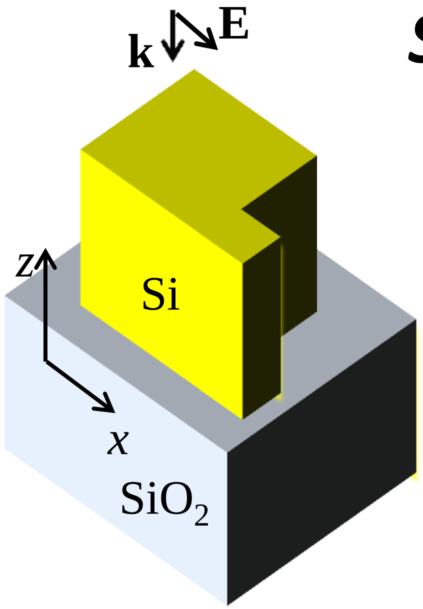
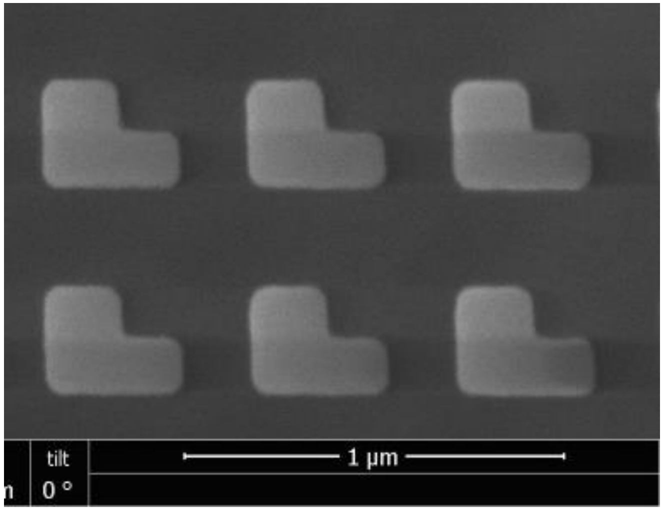
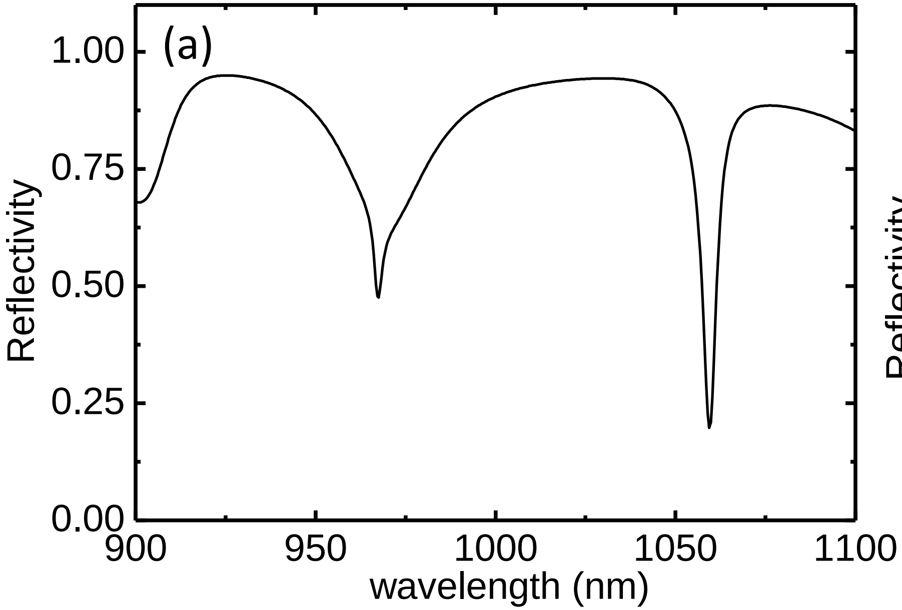
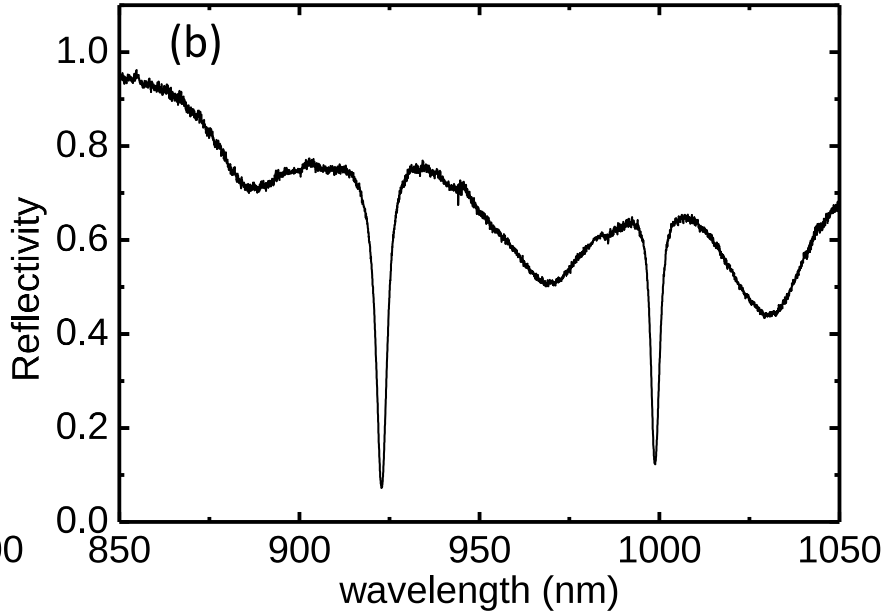
Experimental verification: SOI Fano Resonators





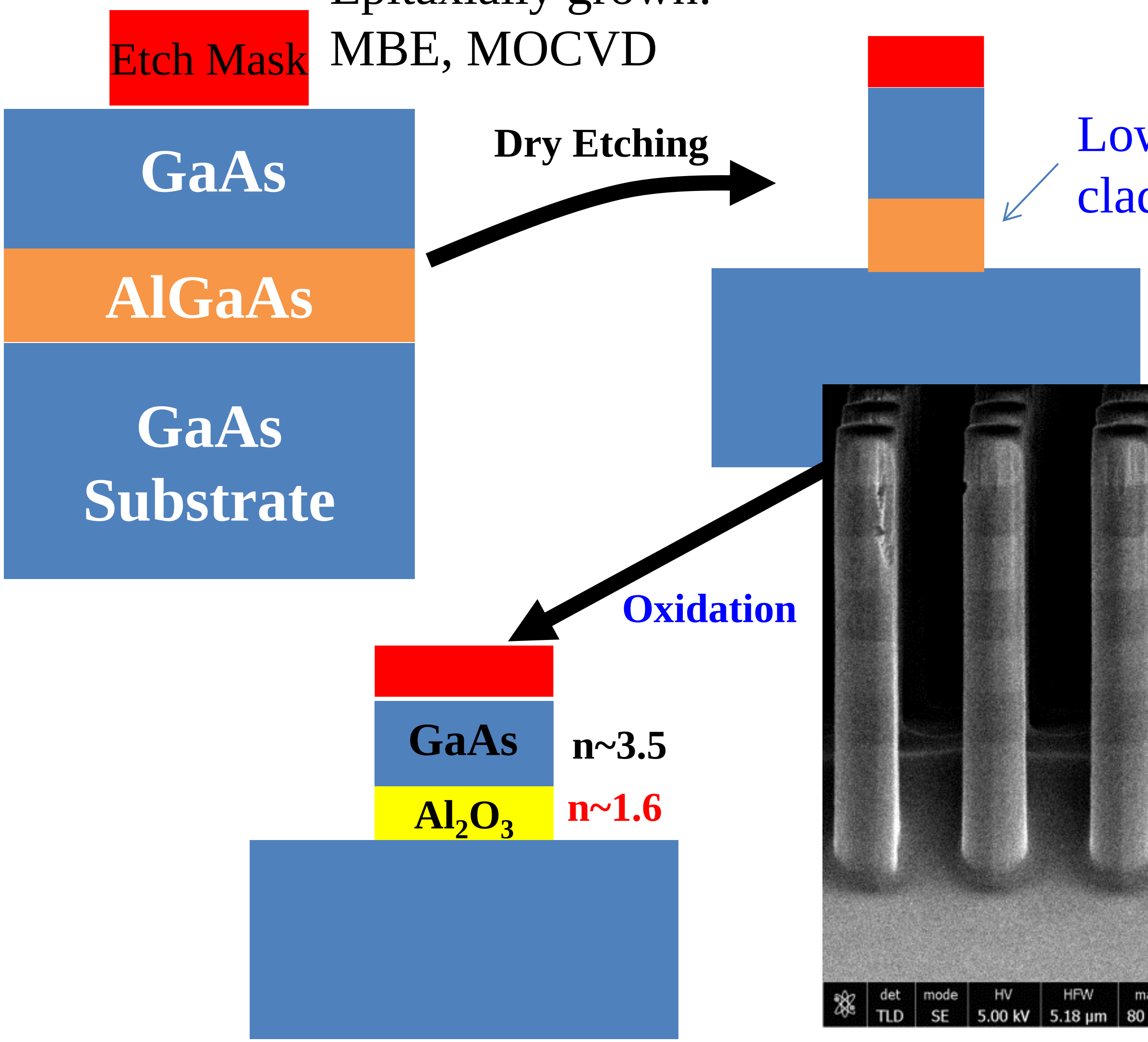


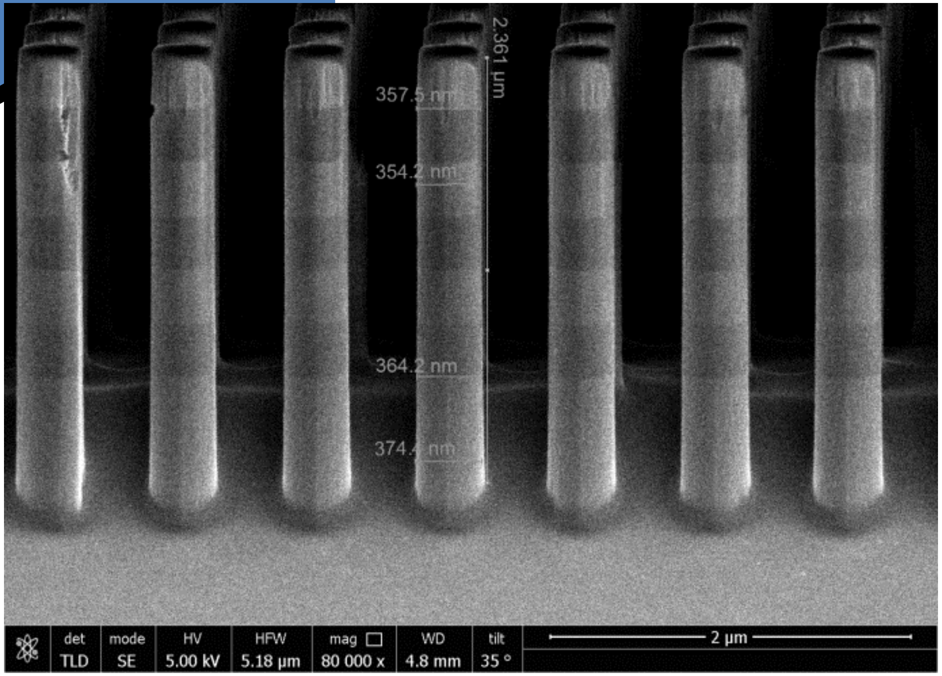


DRs are now possible in III-V semiconductors

New process for (Al)GaAs resonators

Sheng Liu





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

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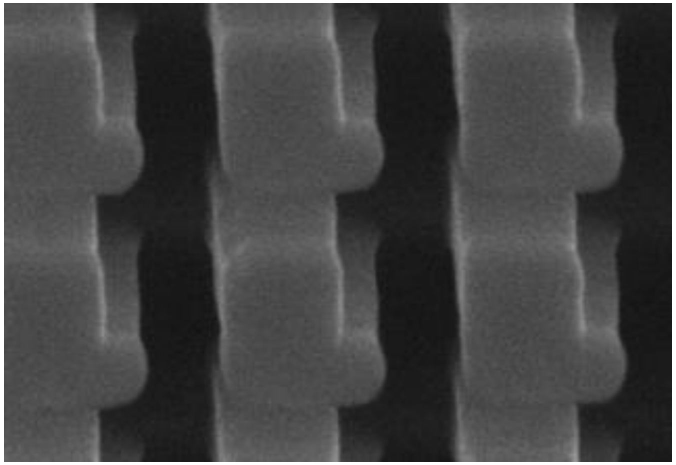
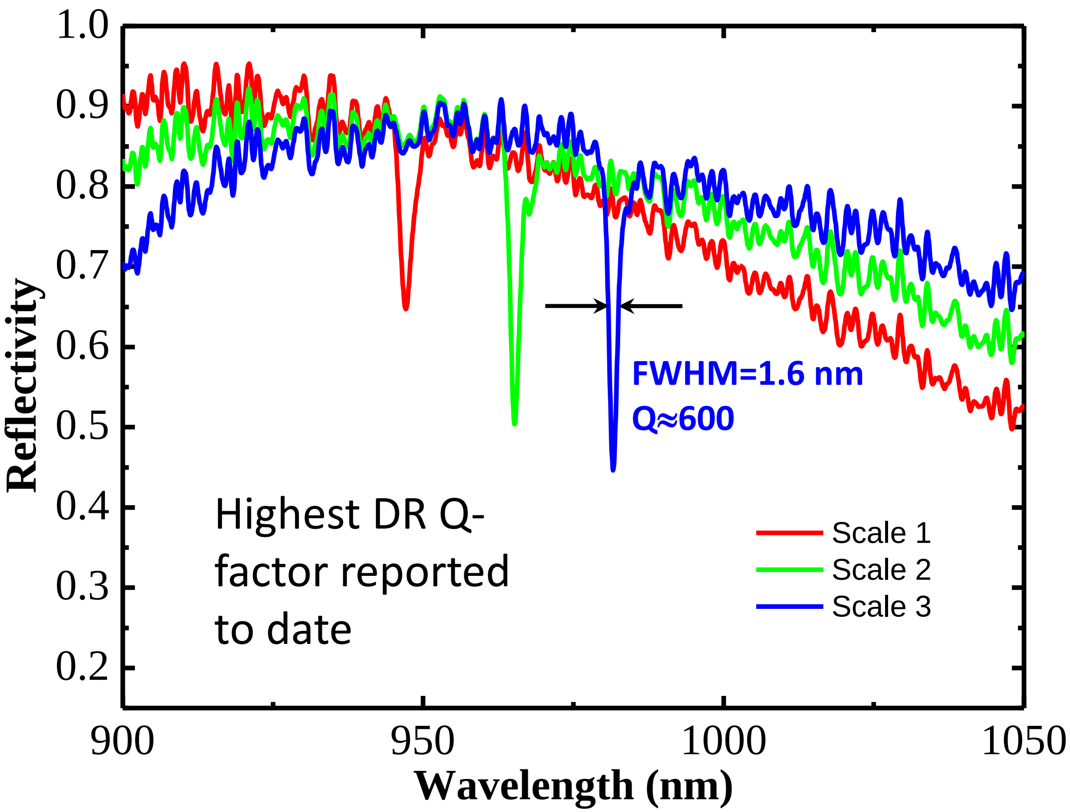
GaAs Fano Resonators: Q ≈ 600!

SEM of GaAs Fano resonators





- GaAs has a non-zero $\chi^{(2)}$ → nonlinear devices (SHG, down-conversion, etc.)
- Can incorporate InGaAs quantum wells for gain and photon detection

Conclusions

- A new, simpler design for dielectric Fano resonators
  - ➢ One resonator per unit cell
- Inter-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??

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END

Backup Slides

Multipolar expansion

The total far field can be decomposed to multipolar components as

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

$$\mathbf{E}_{ED} = Z_0 \frac{ck^2}{4\pi} \frac{e^{ikr}}{r} \hat{\mathbf{r}} \times \mathbf{p} \times \hat{\mathbf{r}} \qquad \mathbf{E}_{MD} = -Z_0 \frac{k^2}{4\pi} \frac{e^{ikr}}{r} \hat{\mathbf{r}} \times \mathbf{m} \qquad \mathbf{E}_{EQ} = -Z_0 \frac{ick^3}{24\pi} \frac{e^{ikr}}{r} \hat{\mathbf{r}} \times \mathbf{Q}_{EQ} \times \hat{\mathbf{r}}$$

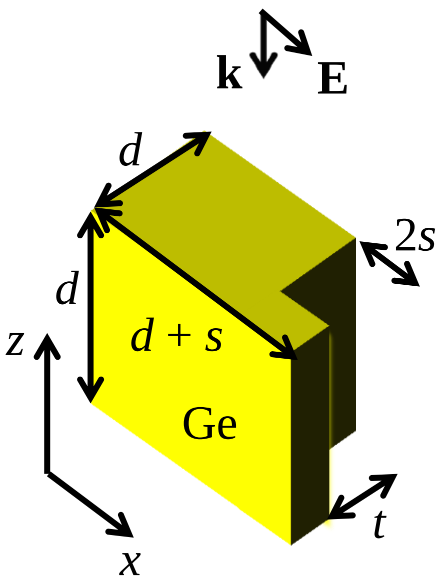
$$\mathbf{E}_{MQ} = Z_0 \frac{ik^3}{24\pi} \frac{e^{ikr}}{r} \hat{\mathbf{r}} \times \mathbf{Q}_{MQ} \qquad \mathbf{E}_{EO} = -Z_0 \frac{ck^4}{24\pi} \frac{e^{ikr}}{r} \hat{\mathbf{r}} \times \mathbf{O}_{EO} \times \hat{\mathbf{r}} \qquad \mathbf{E}_{MO} = Z_0 \frac{k^4}{24\pi} \frac{e^{ikr}}{r} \hat{\mathbf{r}} \times \mathbf{O}_{MO}$$

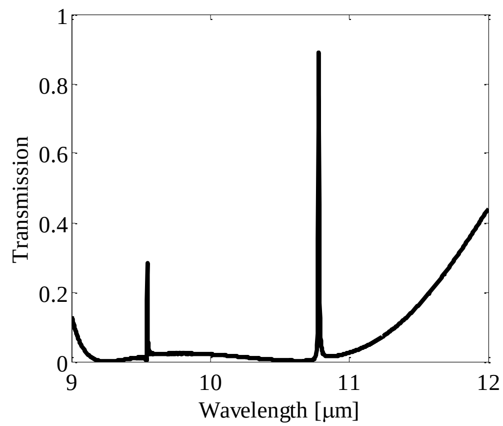
$$Weight = \frac{\int_0^{2\pi}\int_0^{\pi} \left(E_\theta^{FF} E_\theta^{multipole} + E_\phi^{FF} E_\phi^{multipole} \right) \sin\theta \, d\theta \, d\phi}{Normalization\ factor * Coefficient\ in\ front\ of\ multipole\ above}$$

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

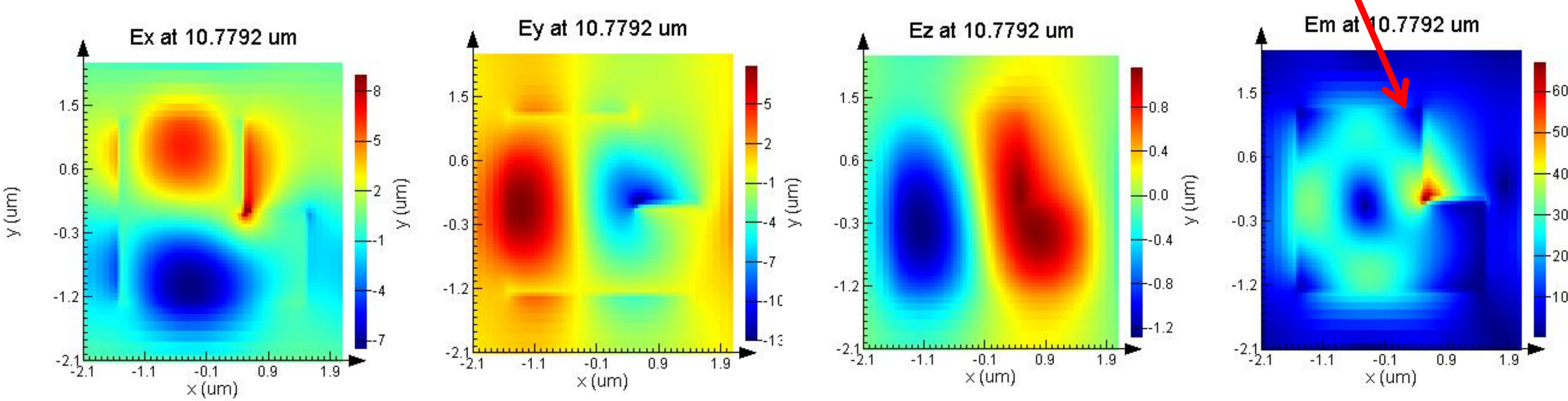
Expansion up to quadrupolar terms will be enough…

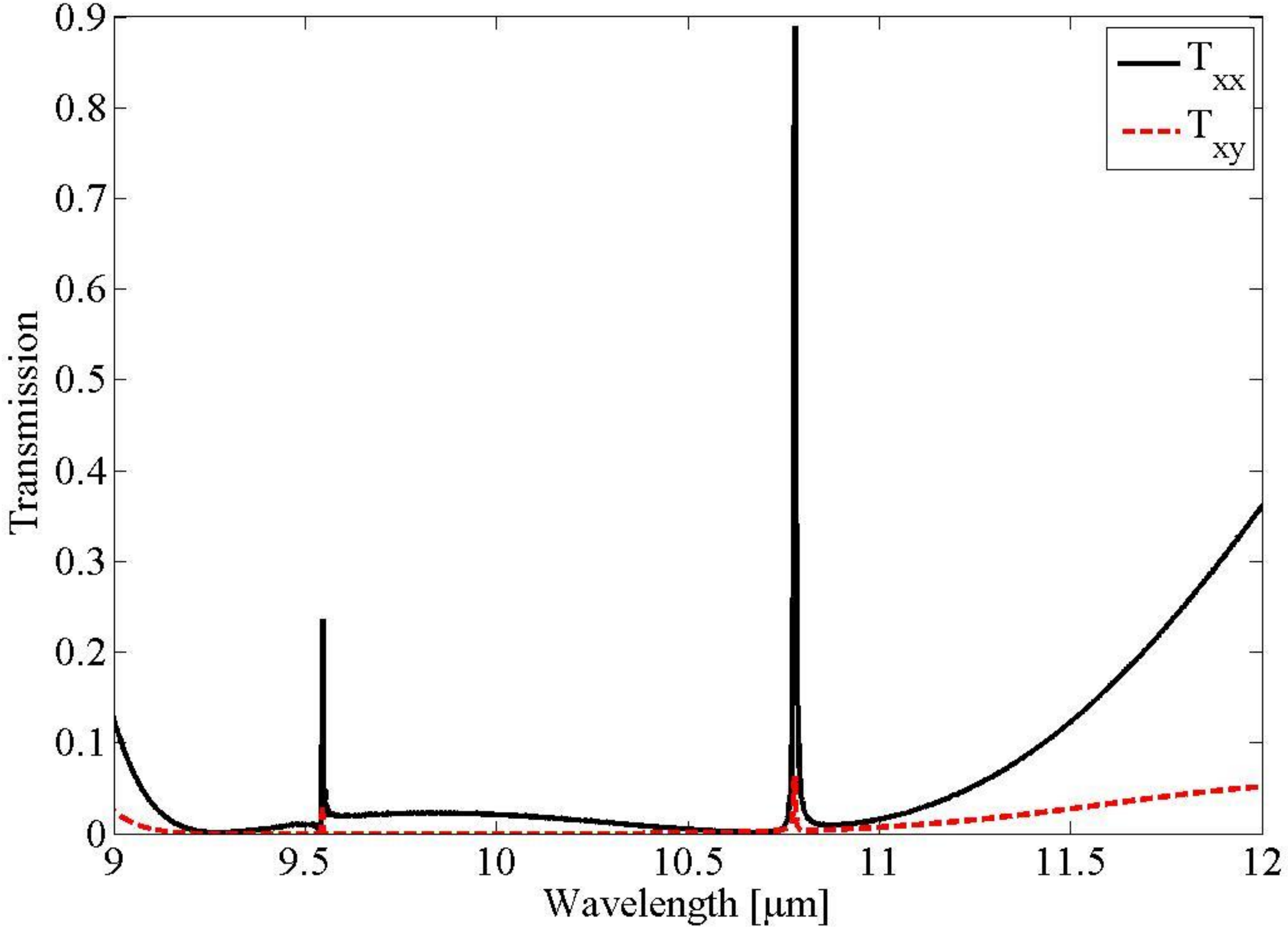
Top-L-cube – Electric field maps at Fano resonance 10.77 um x-y plane



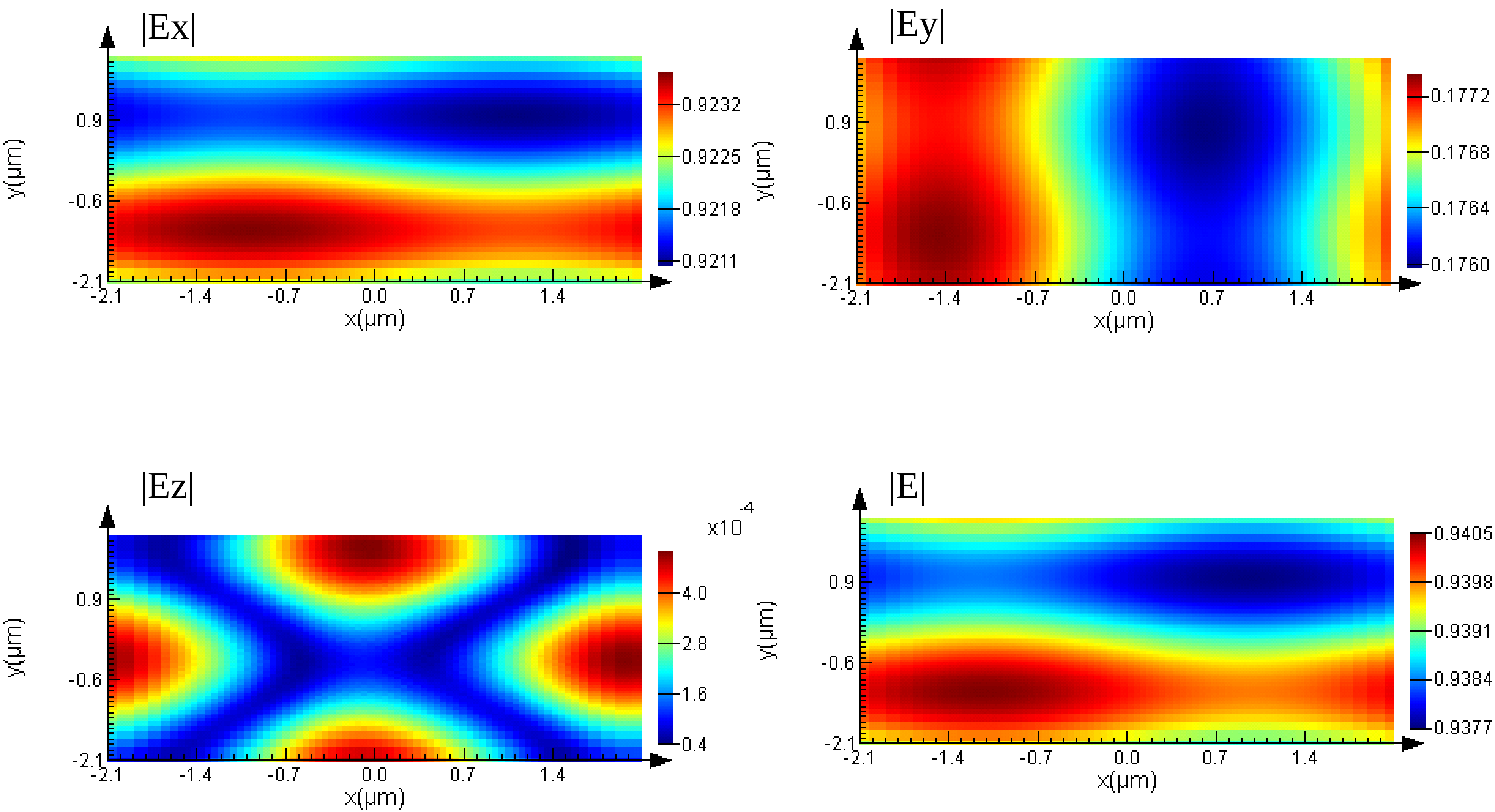


Magnetic dipole along z



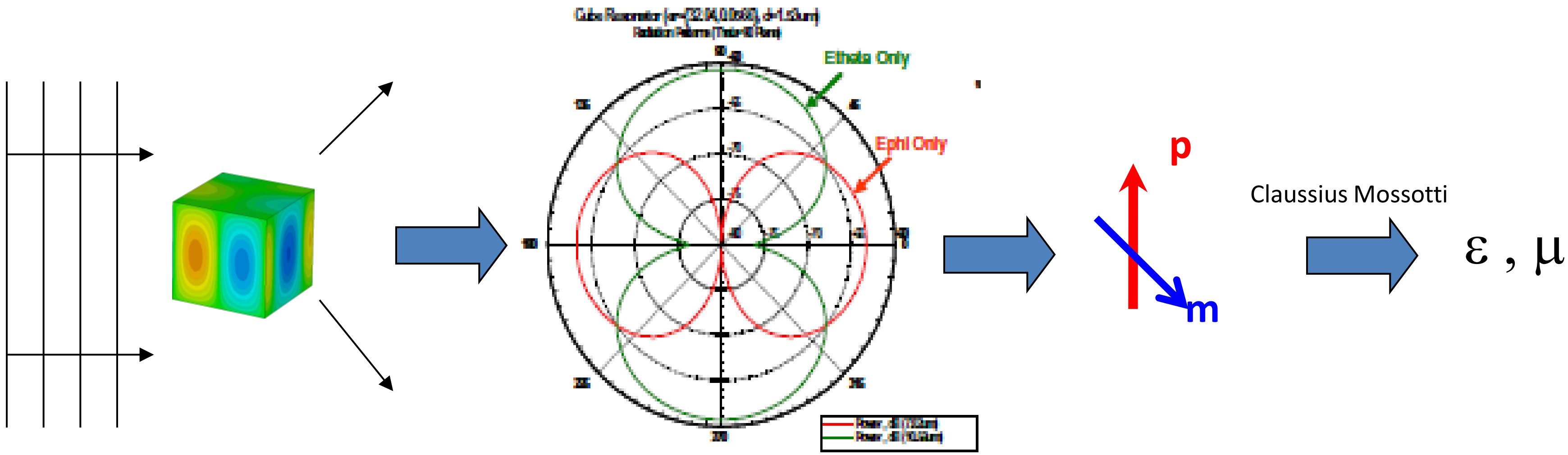

Transmission
Wavelength [μm]
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
9
9.5
10
10.5
11
11.5
12
T_{xx}
T_{xy}

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

Estimate effective parameters

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