SAND2015-7901C

High-Q All-Dielectric Metasurfaces

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METAMATERIALS 2015

August 7th, 2015

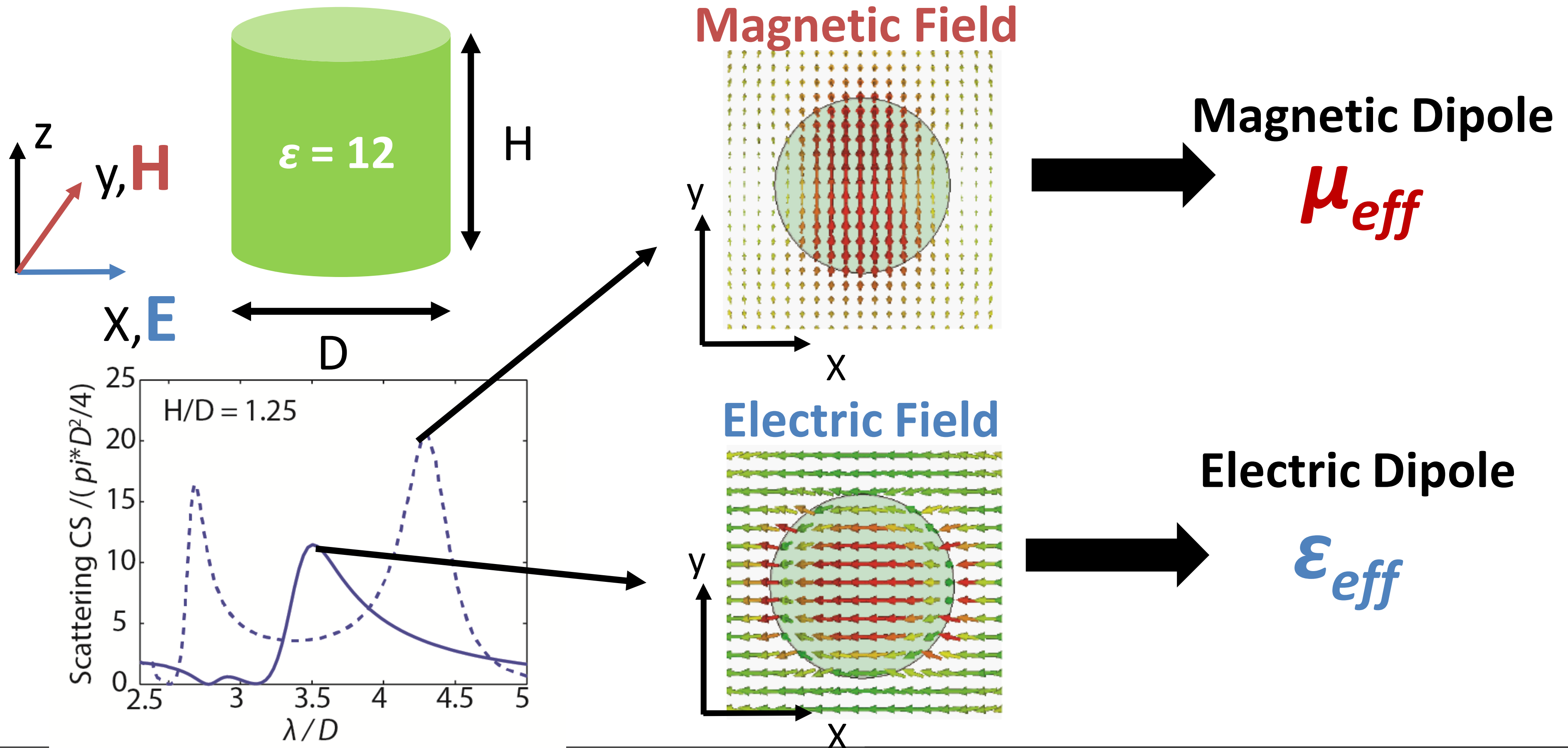
VANDERBILT UNIVERSITY

Revolutionary Research . . . Relevant Results

Center for Nanophase Materials Sciences

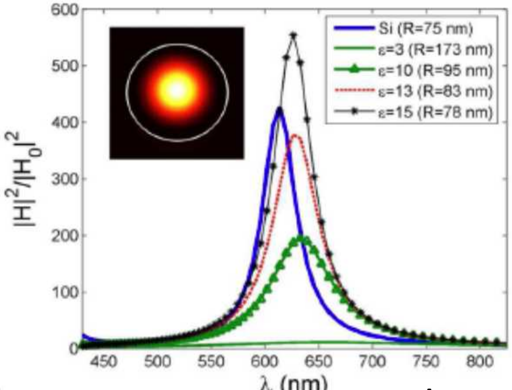
Dielectric / Semiconductor Metamaterials

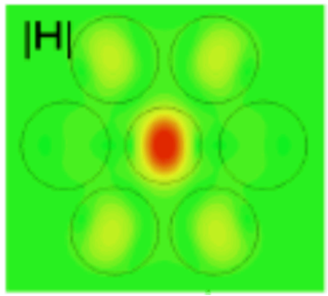
- First theorized by Lewin in 1947
  - Proc. Inst. Elec. Eng. **94** 65 (1947)
- Utilize Mie resonances in dielectric particles



Optical Dielectric Metamaterials

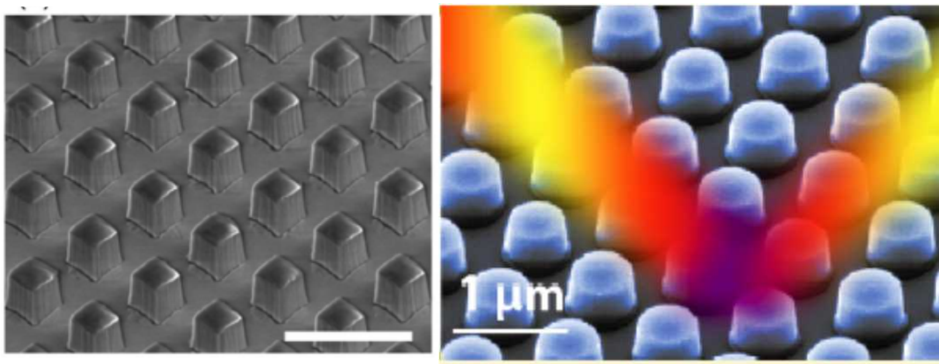
Particle Resonances





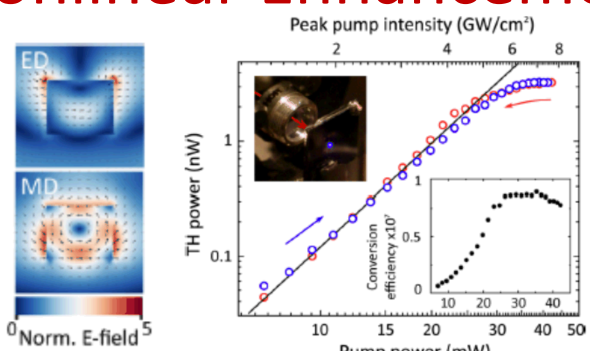
Kuznetsov et. al. Nano Lett (2012),
Evlyukhin et. al. Nano Lett (2012),
Kivshar et. al. Nano Lett (2013)

Perfect / Magnetic Reflectors



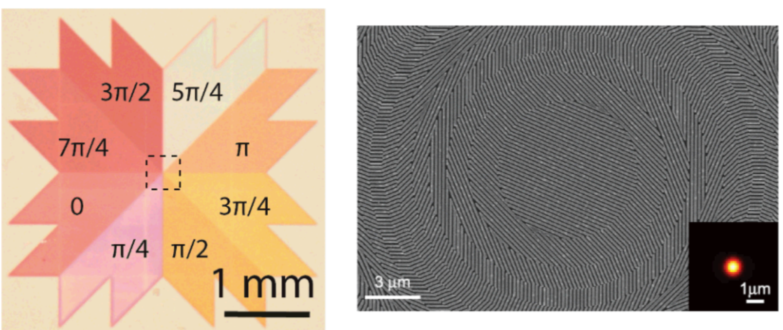
Brener et. al. Optica (2014), Valentine et. al. ACS Phot. (2015)

Nonlinear Enhancement



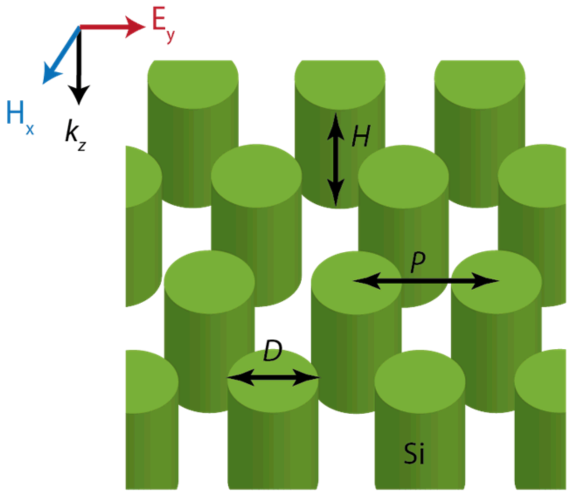
Kivshar, Neshev et. al. Nano Lett (2014), ACS Phot. (2015)

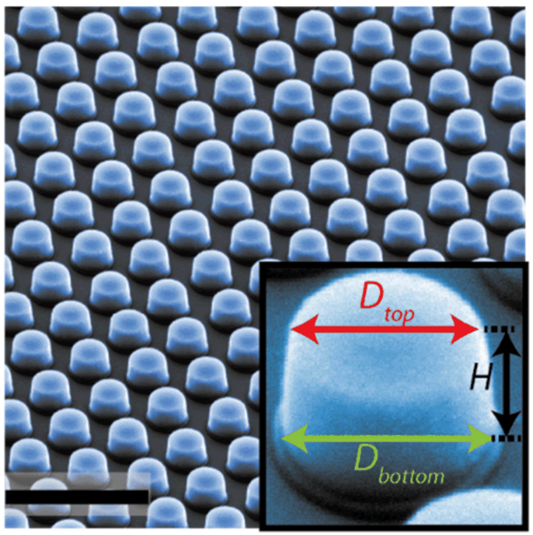
Metasurfaces

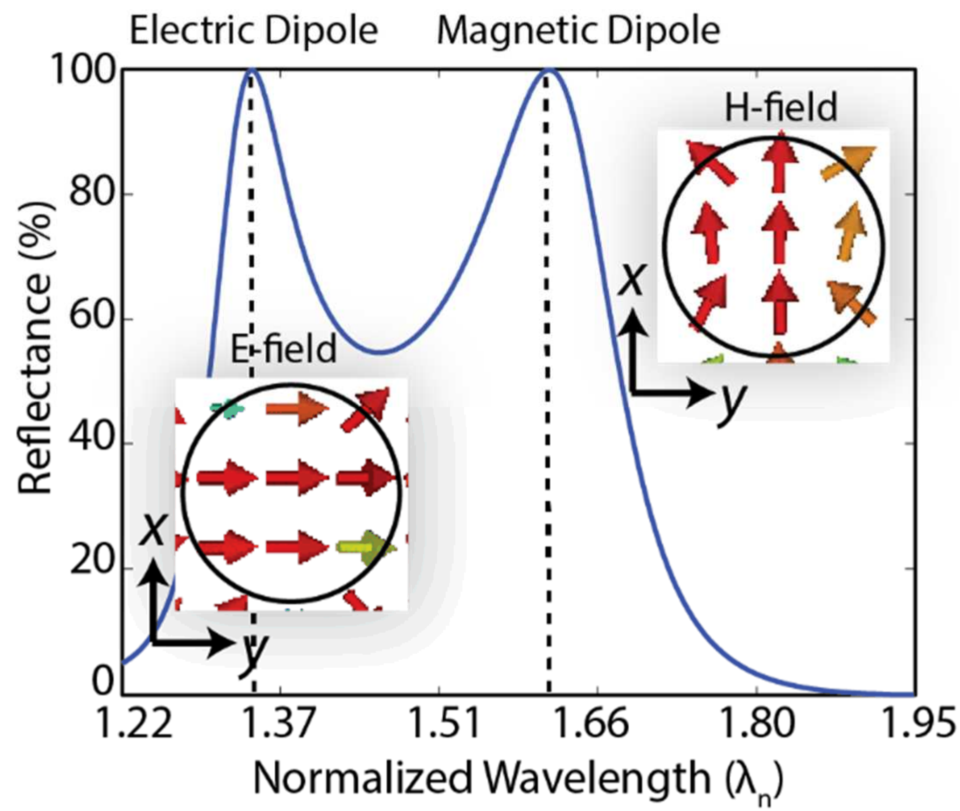


Valentine, Nano Lett (2014),
Brongersma, Science (2014)

Spectral Response







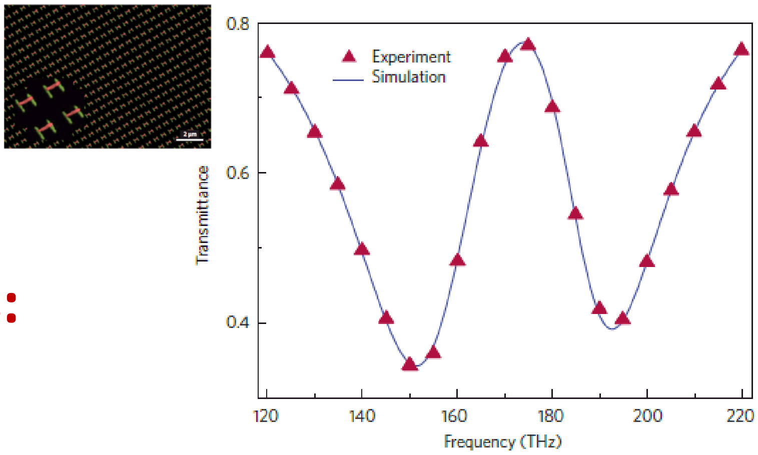
Bandwidth Limited By Radiative Damping

Moitra et. al. ACS Photonics, **2**, 692−698 (2015)

Fano-Resonant Metamaterials

High-Q Requirements

1. Minimize non-radiative damping (γ_{NR})
2. Minimize radiative damping (γ_R)



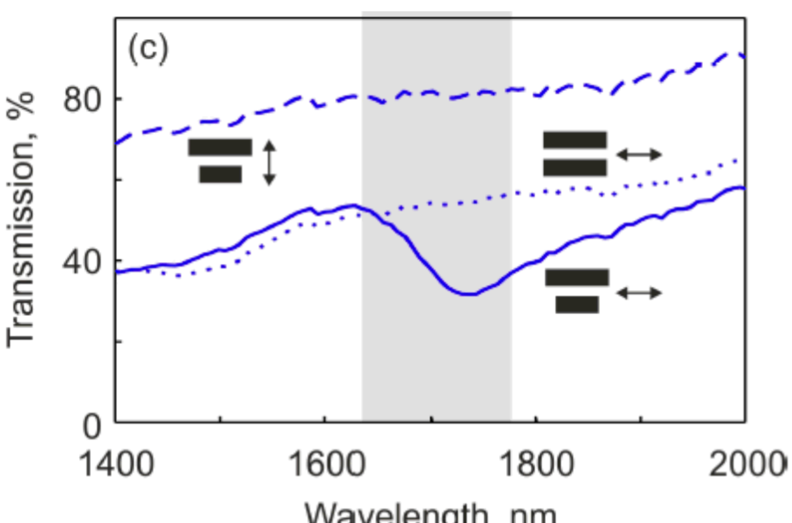
Giessen et al, Nat. Mat., 2010

Plasmonic Fano-resonant Metamaterials:

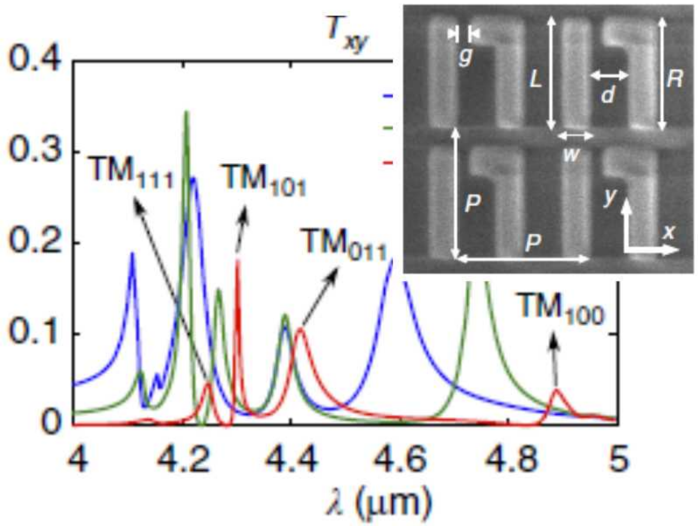
- Dominated by γ_{NR} , **Q-factors ~10**

Dielectric Fano-resonant Metamaterials:

- Reduced γ_{NR} , **Q-factors ~100**



Zheludev et al, Opt. Expr., 2013

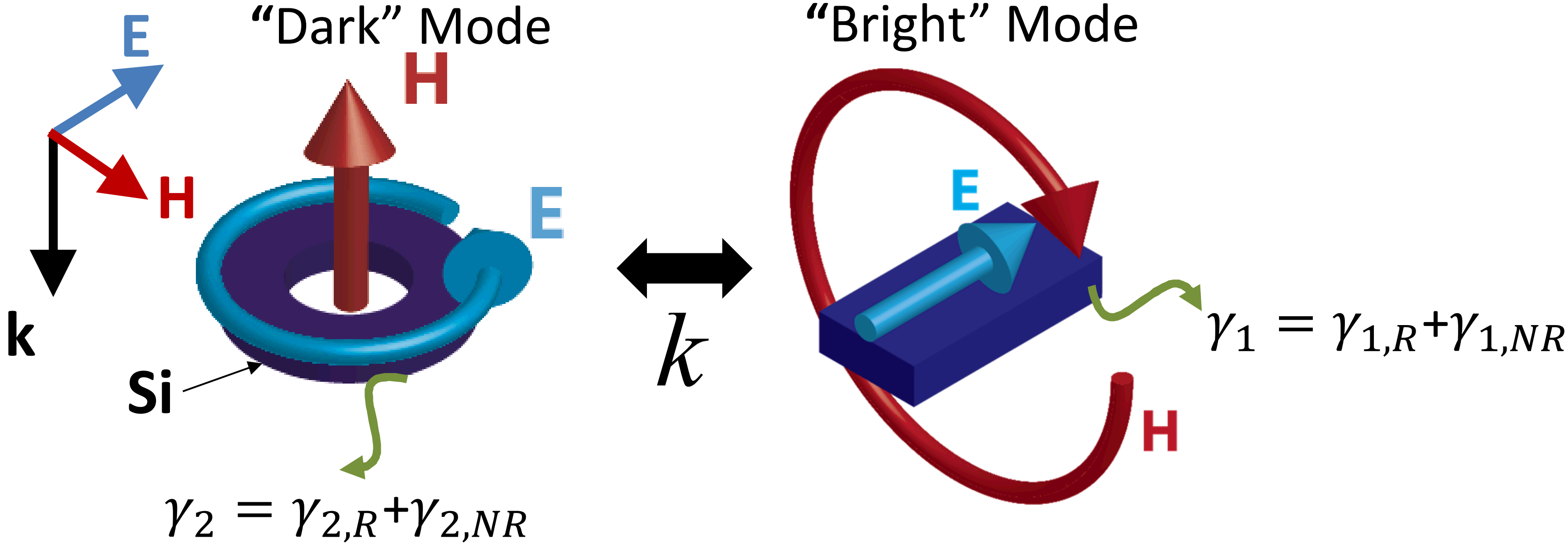


Shvets et al Nat Comm., 2014

Dark and Bright Collective Modes

Resonator 2: "Dark" Mode

Resonator 1: "Bright" Mode



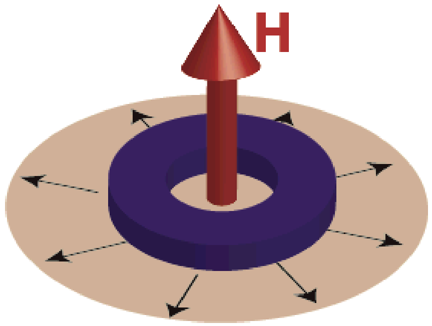
Key Points:

1. Reduction of γ_2 increases the Q-factor ⟶ minimize γ_2
2. In the limit of $\gamma_2 \rightarrow 0$, $\mathrm{d}T/\mathrm{d}\omega \;\alpha\; \kappa^{-1}$ ⟶ minimize κ

Yang, Y. et. al. *Nature Communications* 5, 5753 (2014)

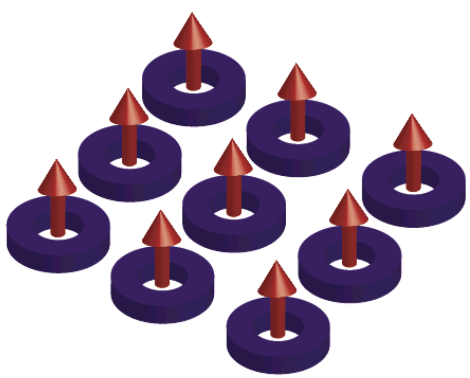
Reducing Radiative Losses

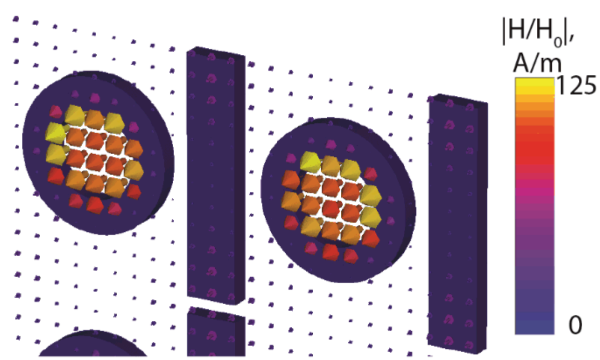
Isolated Resonator



Radiative Losses
(Large γ_R)

Interacting Resonators

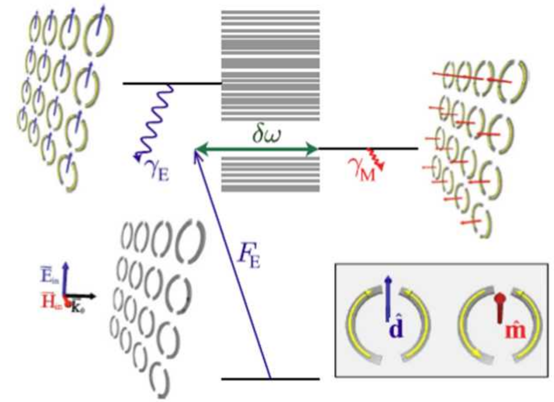


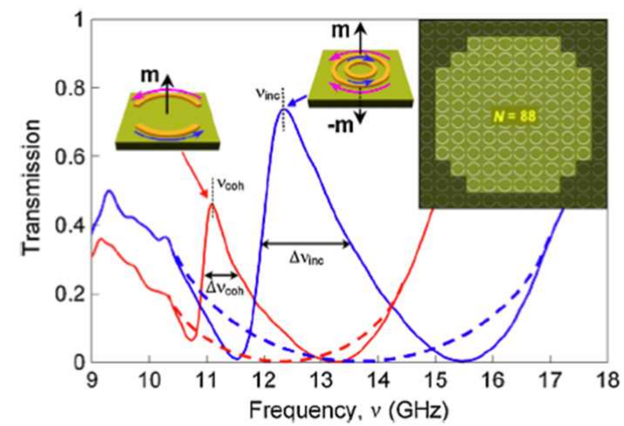


Near-field Coupling

Minimize Radiative Losses

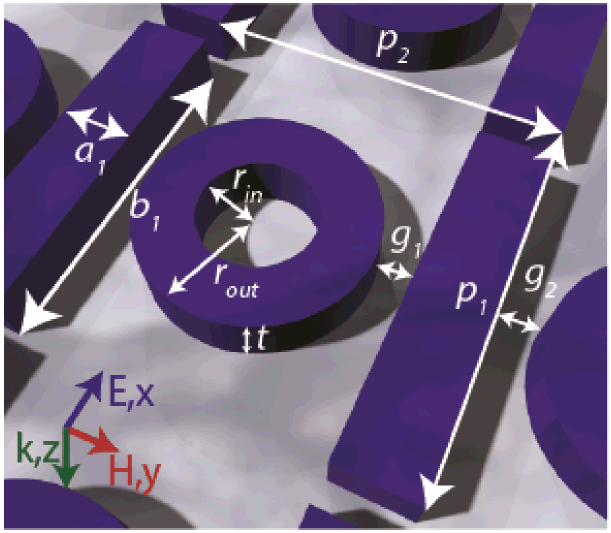
Coherent Metamaterials

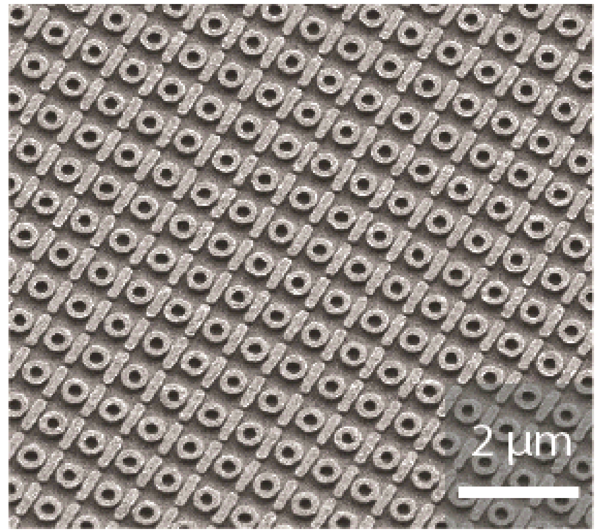


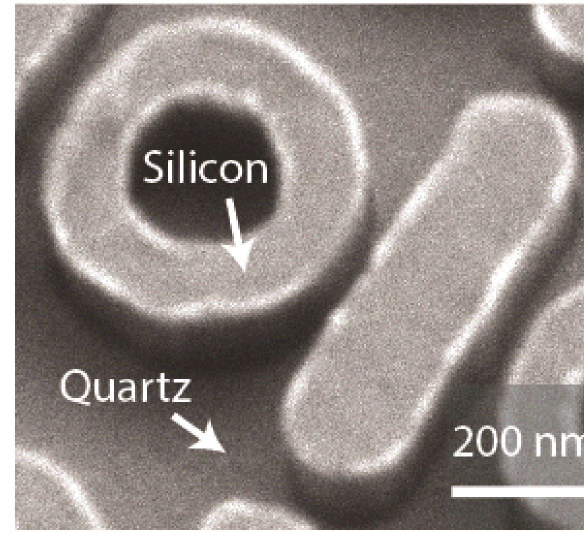


Fedotov et al, PRL (2010)
Jenkins et al, PRL (2013)

Implementation in Silicon

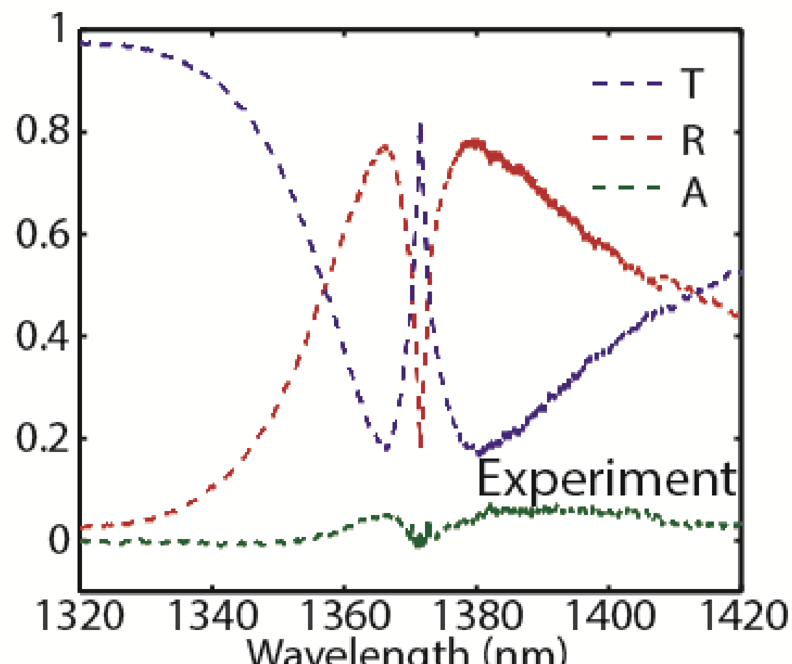




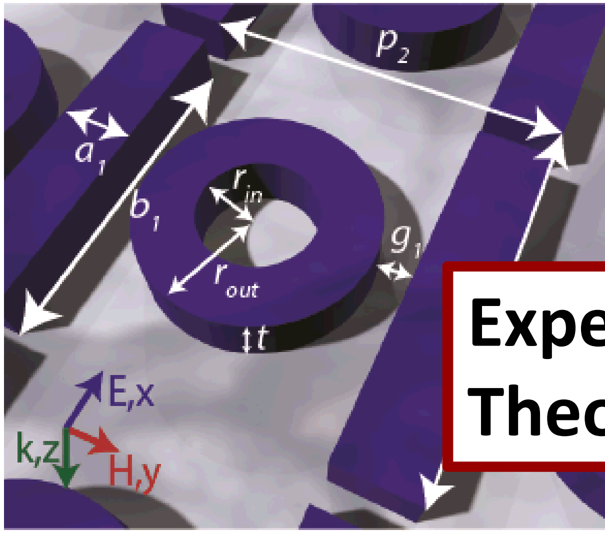


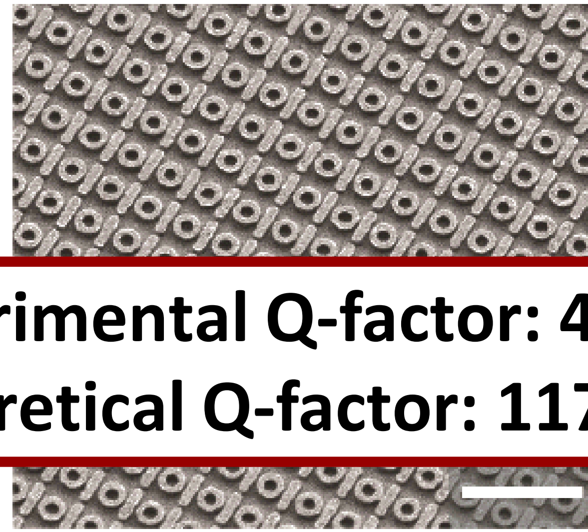
- r_{out} = 225nm
- g_1 = 70nm
- g_2 = 80nm
- t = 110nm
- p_1 = 750nm
- p_2 = 750nm

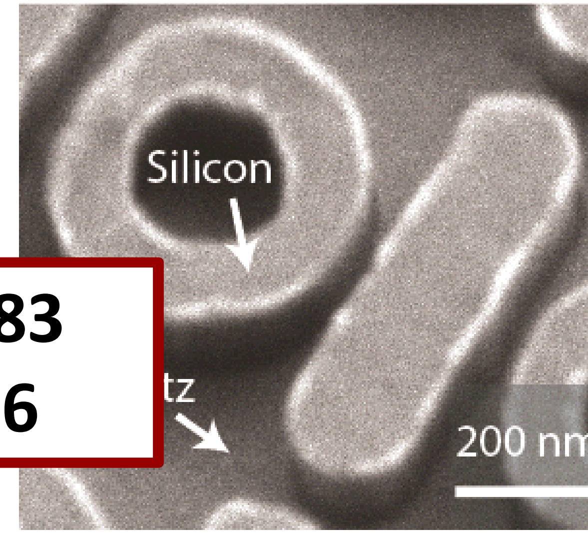
Yang, Y. et. al. *Nature Communications* 5, 5753 (2014)



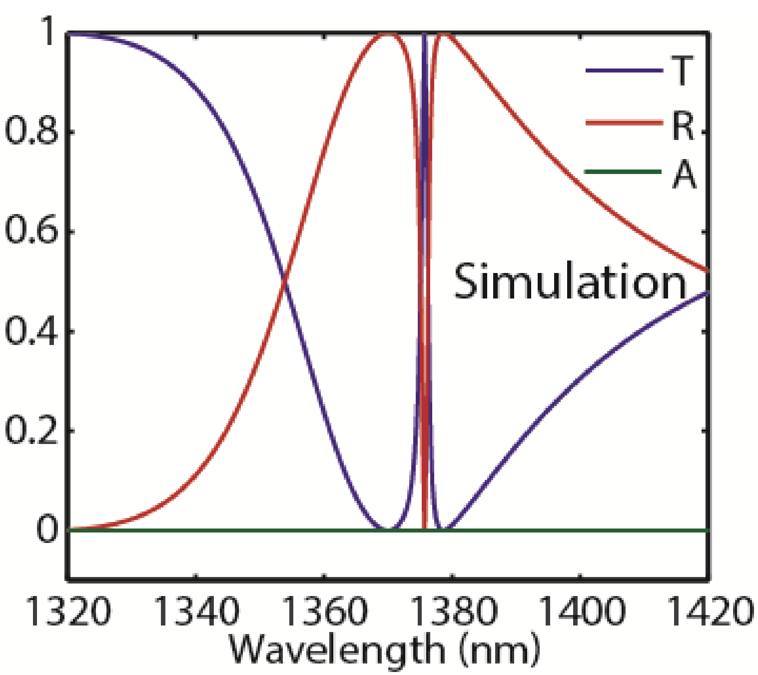
Implementation in Silicon

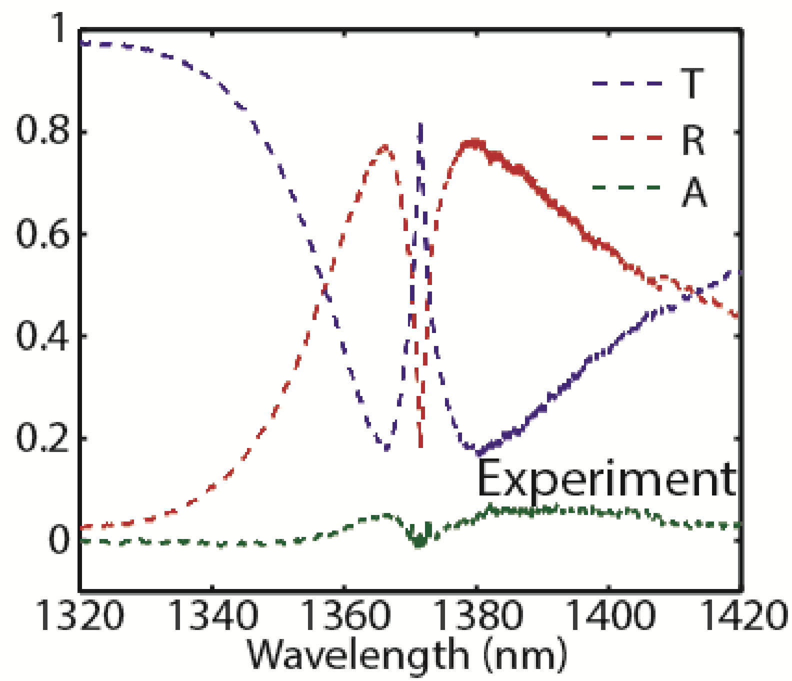




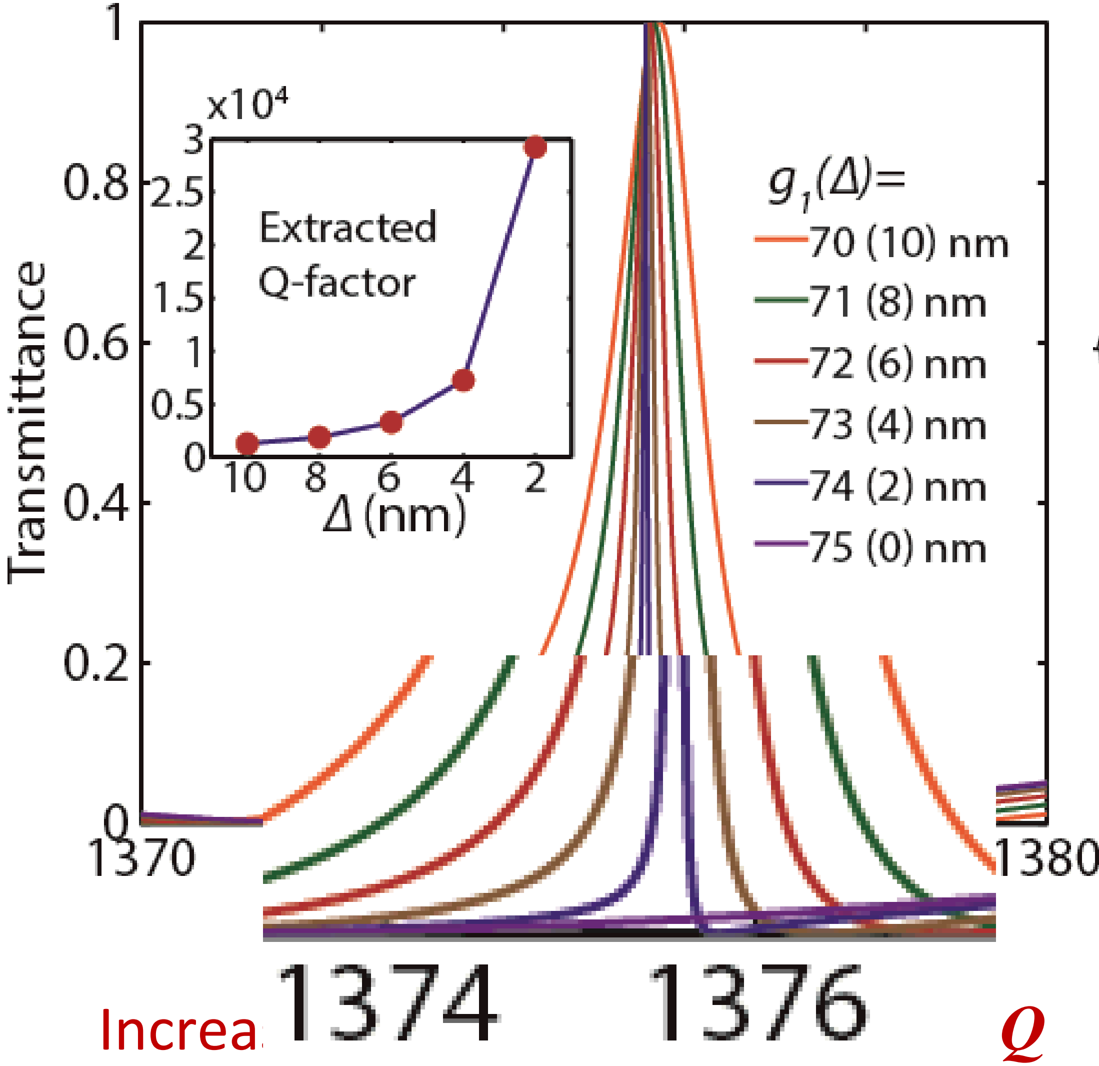


Experimental Q-factor: 483
Theoretical Q-factor: 1176

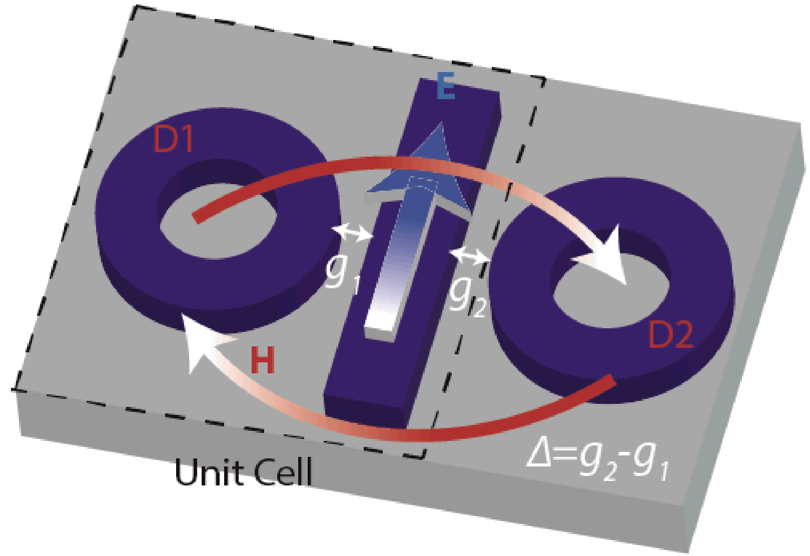




Role of Coupling Coefficient



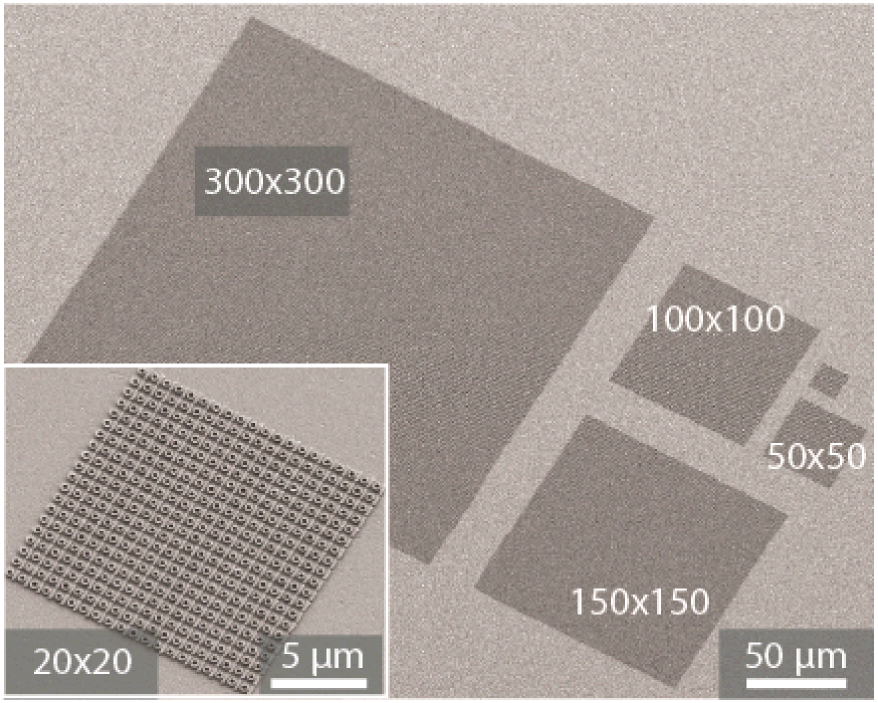
Increa *Q*

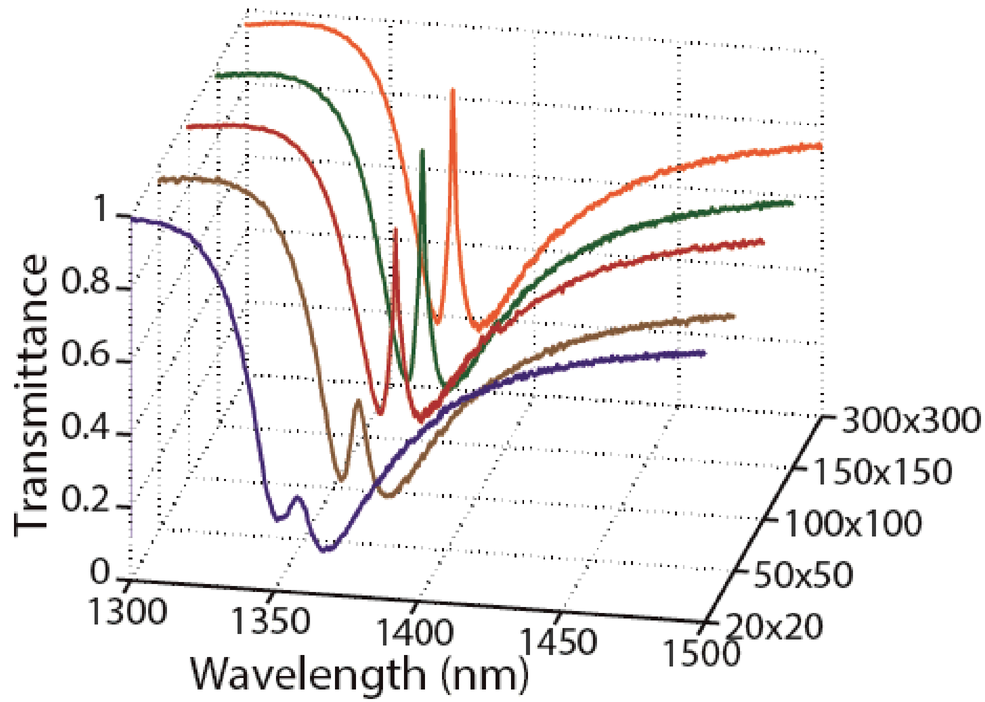


$$\Delta = g_2 - g_1$$

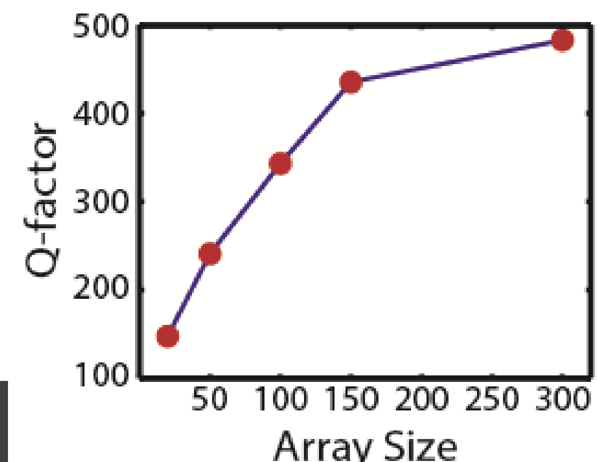
Q-factor = 30,000 @ g_1 = 74 nm (Δ = 2 nm)

Mesoscale Interactions - Experimental





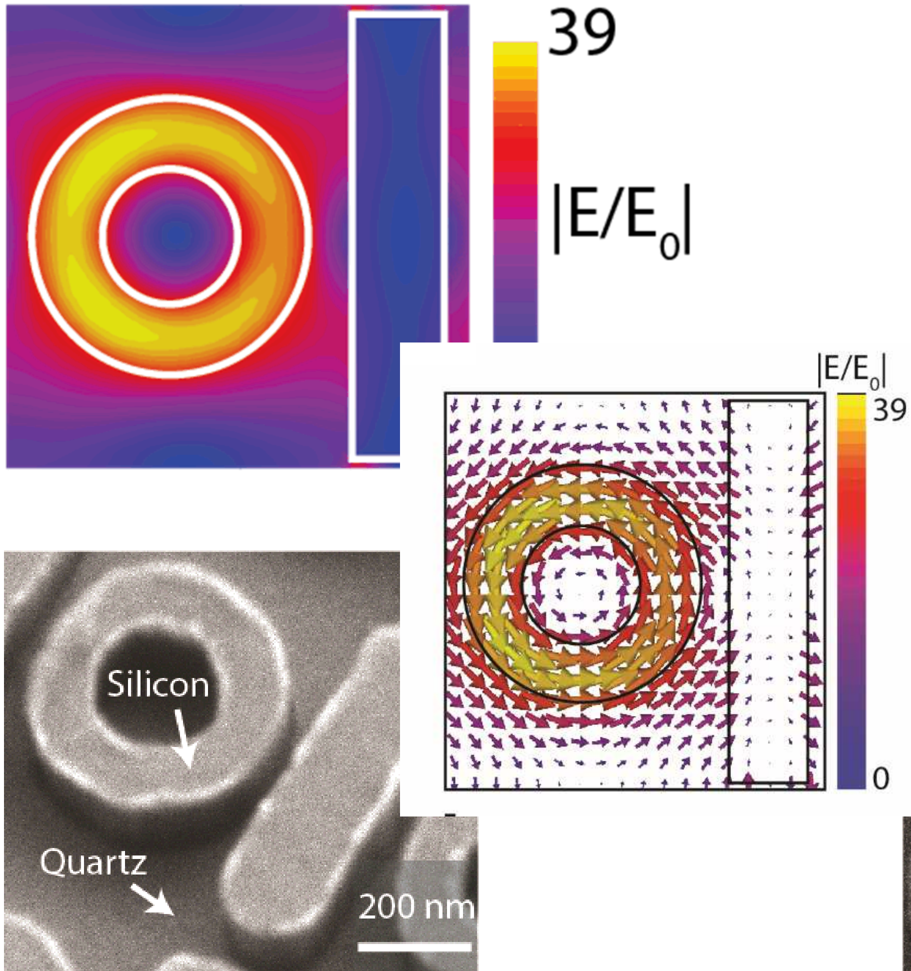
- Q-factor is strong function of # of resonators
- Q-factor remains limited by radiative and non-radiative loss



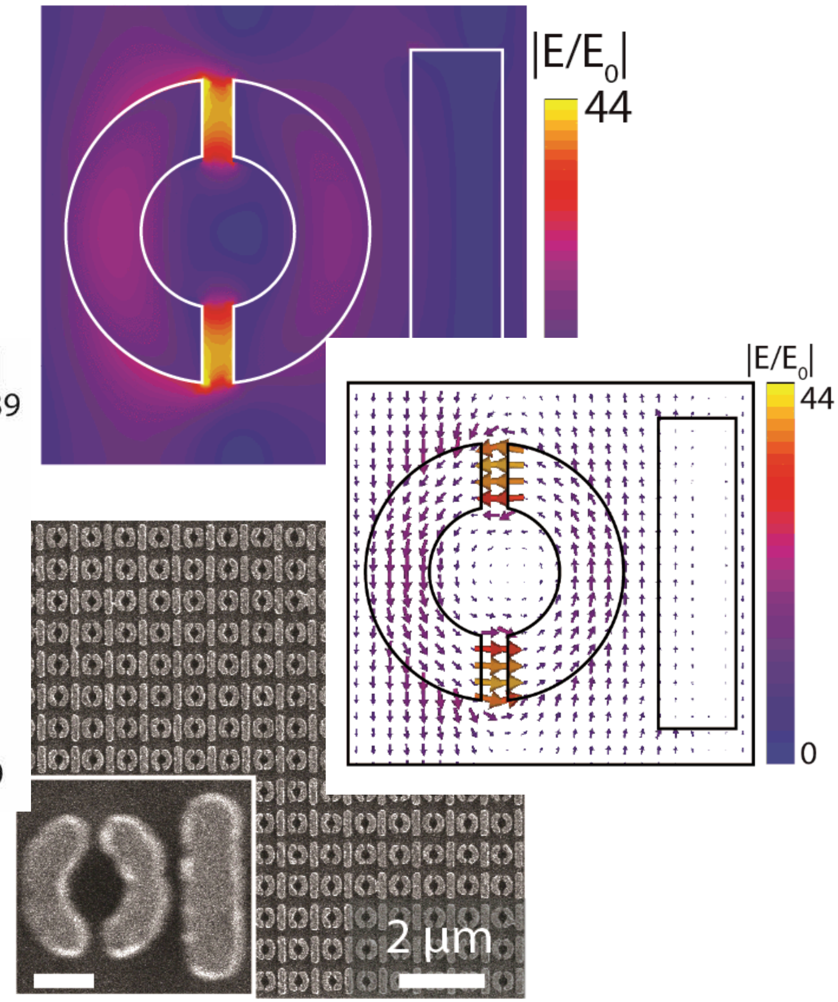
Yang, Y. et. al. *Nature Communications* 5, 5753 (2014)

Strong Field Enhancement

Ring Resonator (Q = 1176)

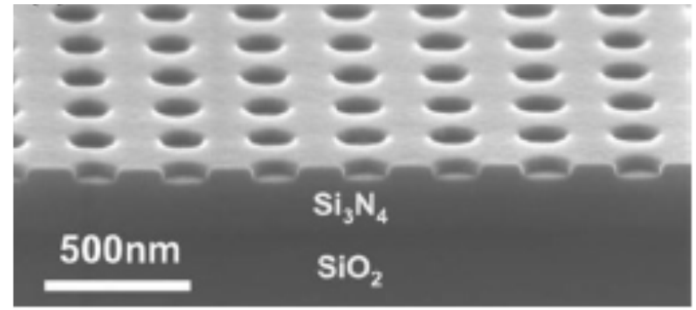


Gap Resonator (Q = 374)

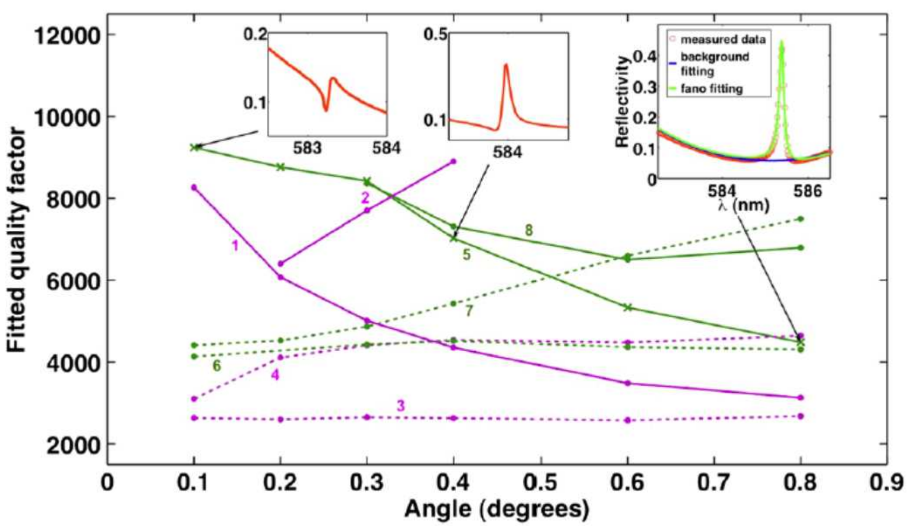


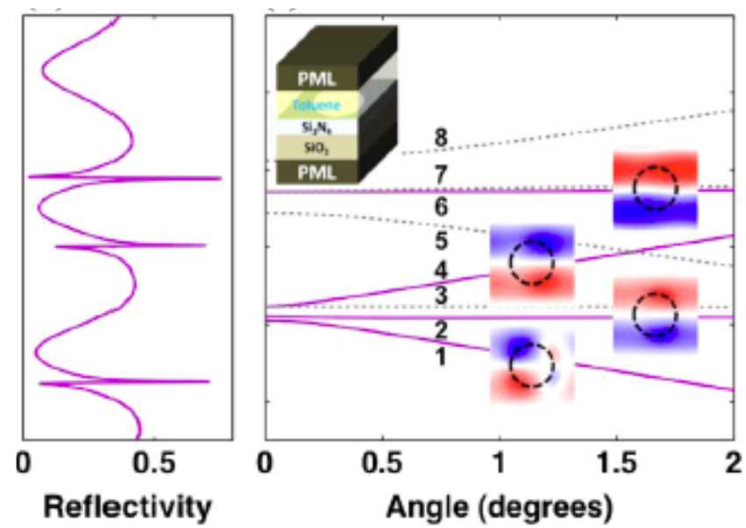
Comparison to PC Slabs

- Advantages of MM Approach
  - Ability to control Q-factor
  - **Field localization**
- Disadvantages of MM Approach
  - Complex structure = lower Q-factor



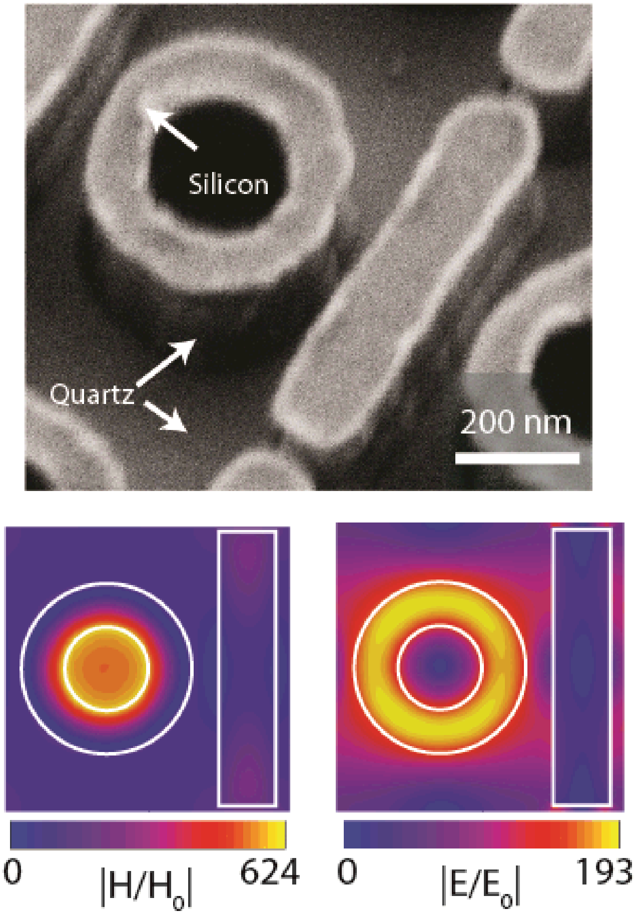
Lee et. al. PRL 109, 067401 (2012)





See also: Paddon et. al. PRB (2000), Ochiai et. al. PRB (2001), Fan et. al. PRB (2002)

Refractive Index Sensing



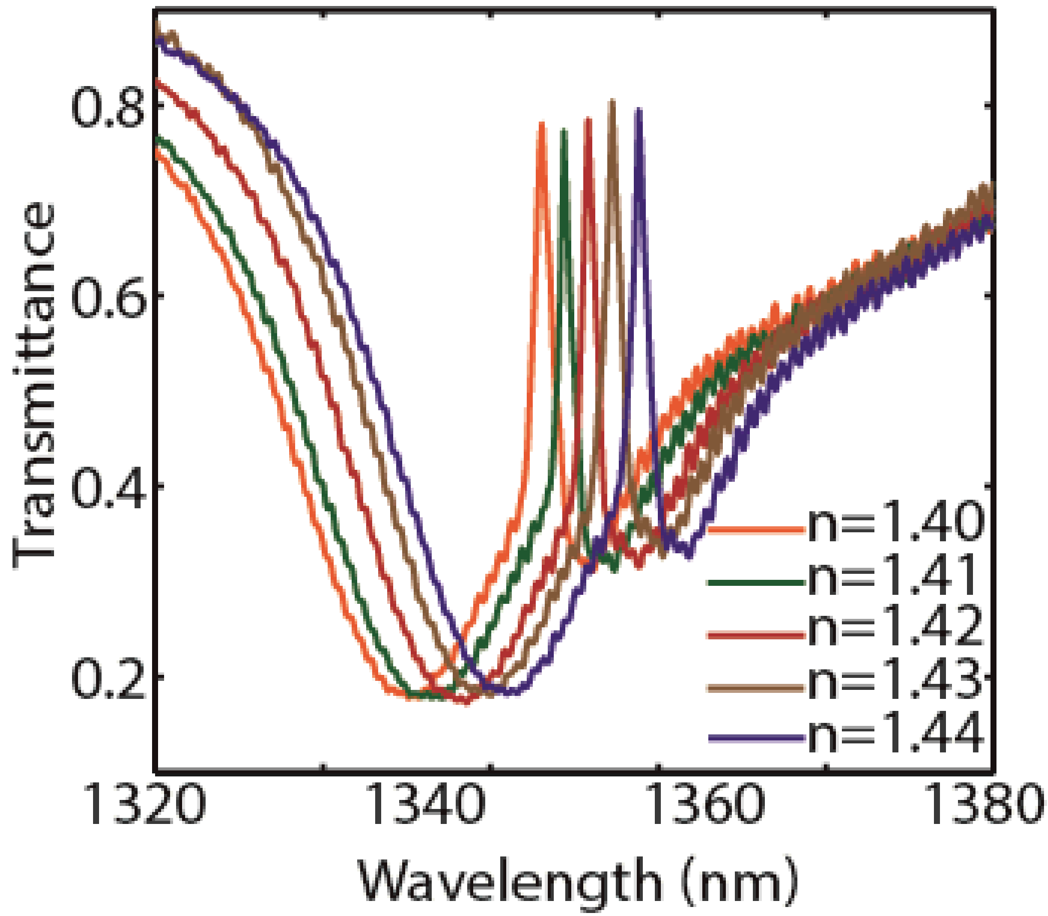
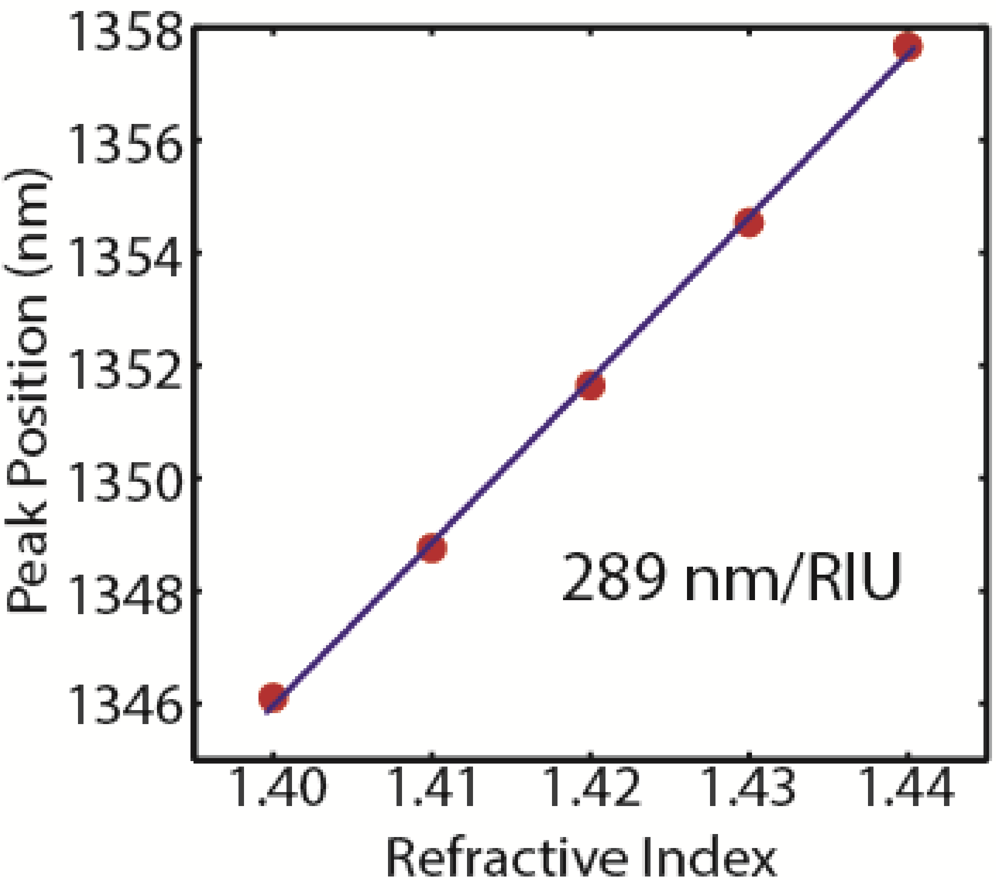


Figure of Merit

Sensitivity



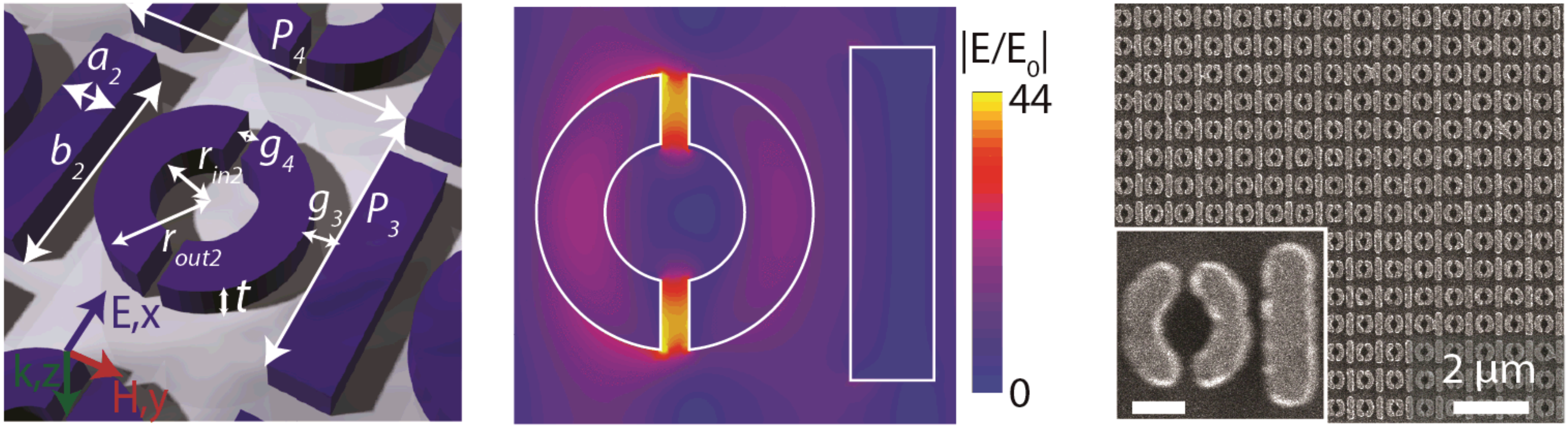
- Figure of Merit
  - FOM = S/Δλ
  - S = 289 nm / RIU
  - Δλ = 2.8 nm

FOM = 103

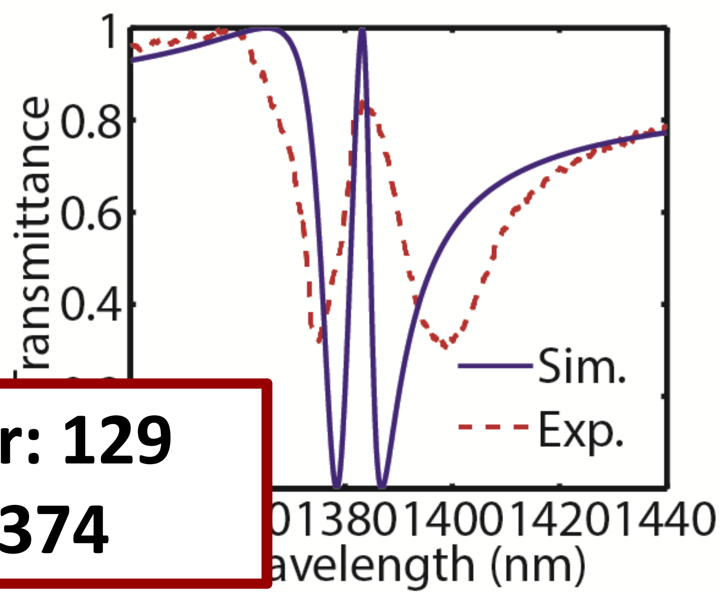
- LSPR Sensors (Fano)[1]
  - FOM up to ~20
- SPP Sensors (weak localization)[2]
  - FOM up to ~300

[1]Zhang et. al. Nano Lett (2011), [2]Kabashin et. al. Nat Mat. (2009)

Focusing the Field

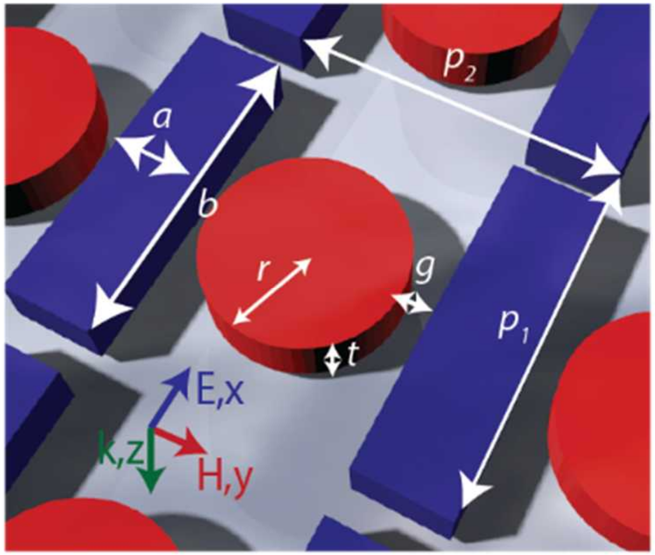


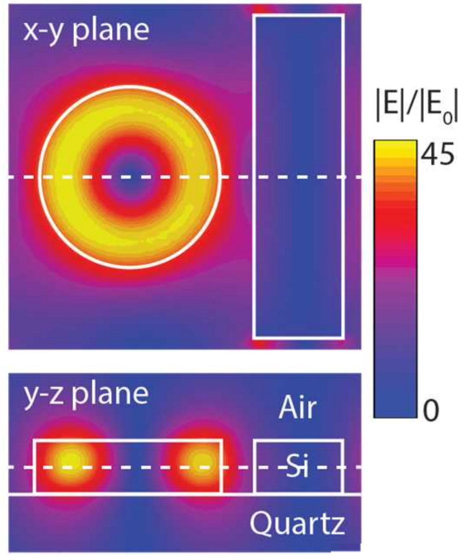
- r_{out} = 225nm
- g_3 = 70nm
- g_4 = 50nm
- t = 110nm
- p_1 = 750nm
- p_2 = 800nm

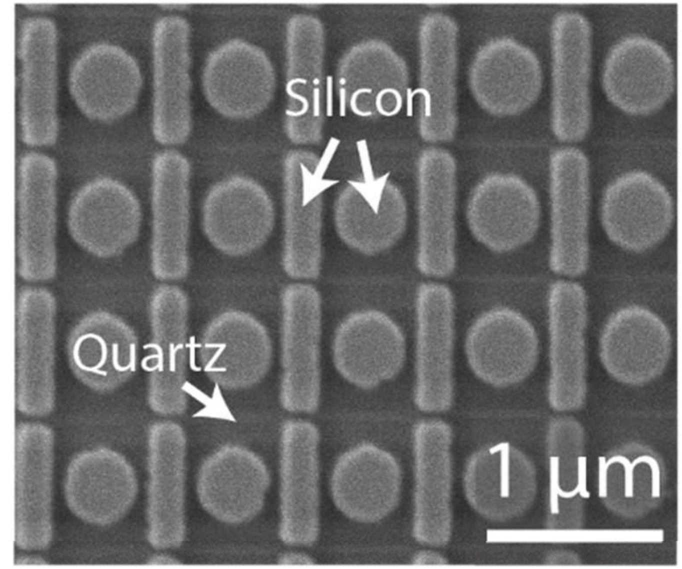


Experimental Q-factor: 129
Theoretical Q-factor: 374

Third Harmonic Configuration

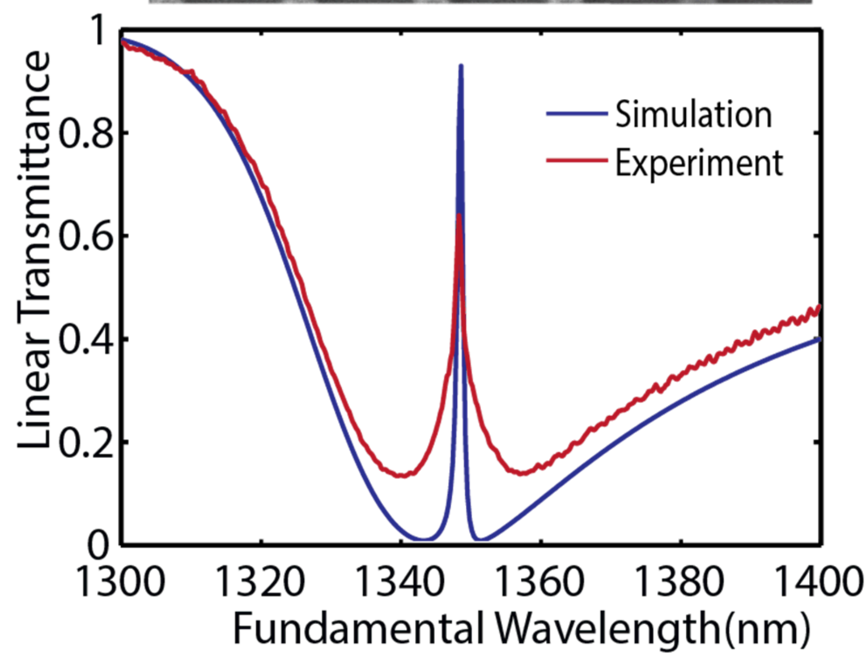




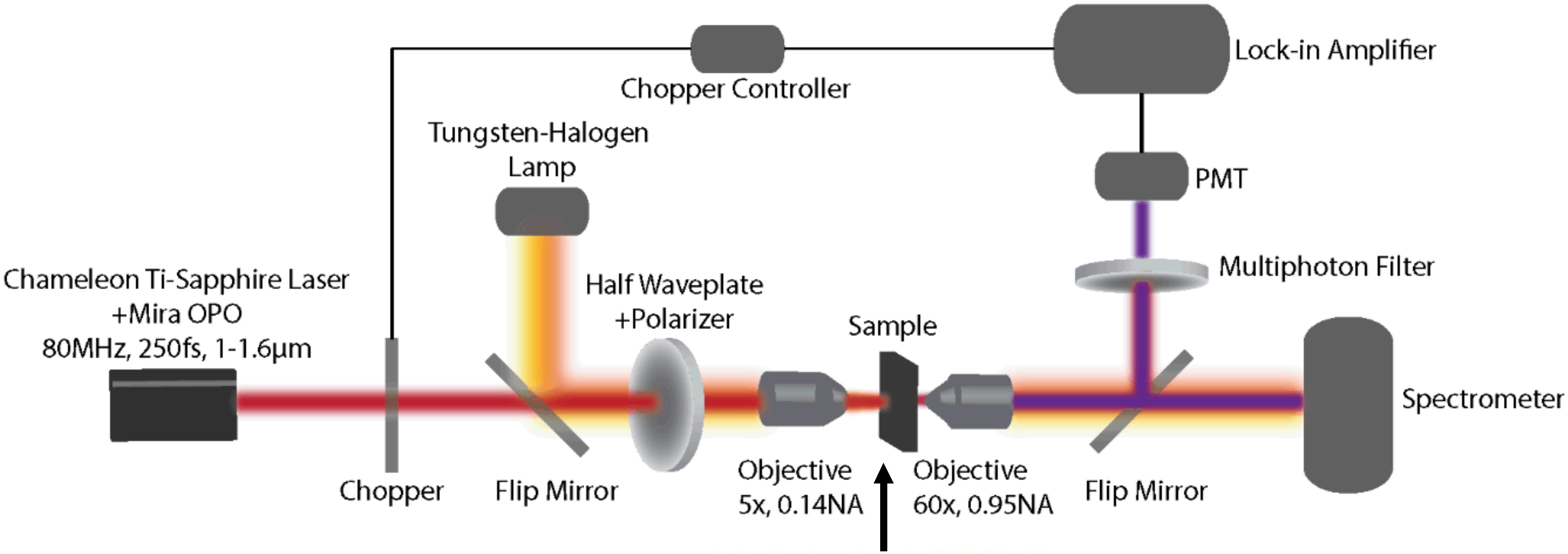


- **Polycrystalline silicon on quartz**
- $\chi^{(3)}_{Si} \sim 2.79\times 10^{-18}\,\mathrm{m^2V^{-2}}$
- r = 210nm
- g = 60nm
- t = 120nm

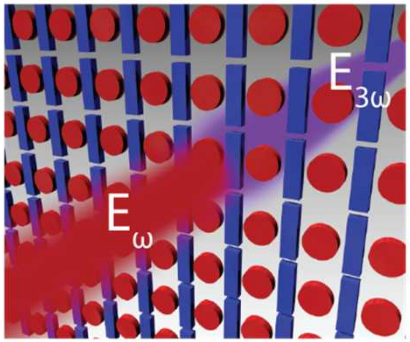
Theoretical Q-factor: 1498
Experimental Q-factor: 466



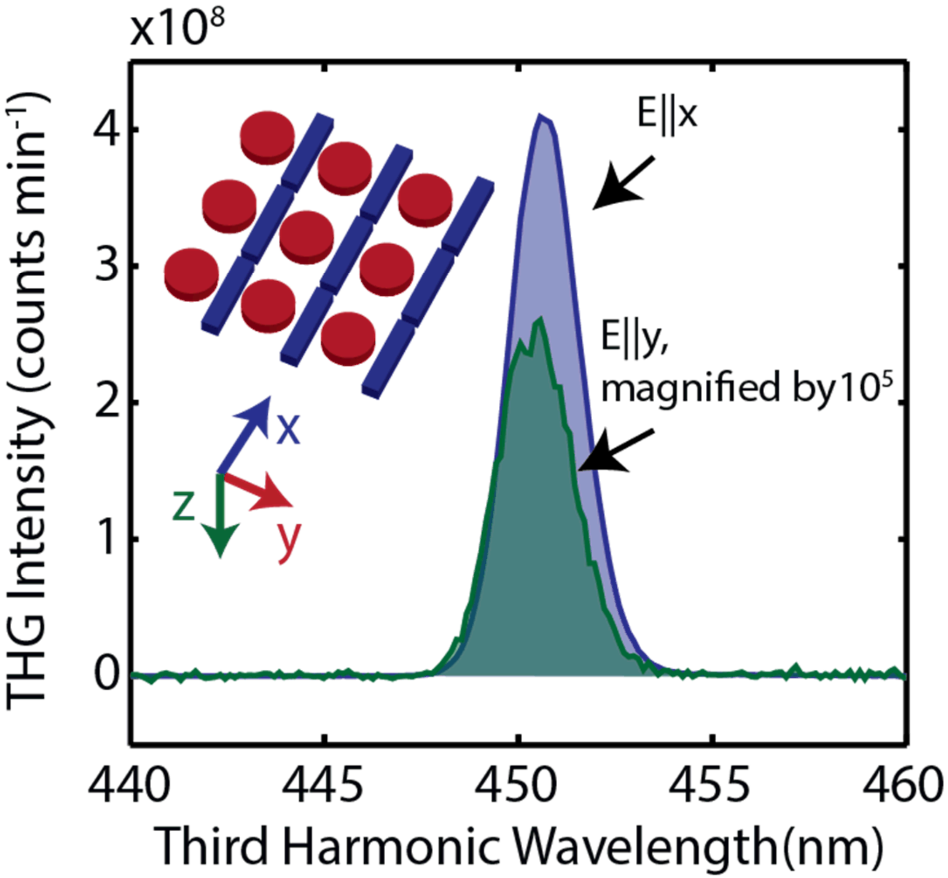
Nonlinear Measurements

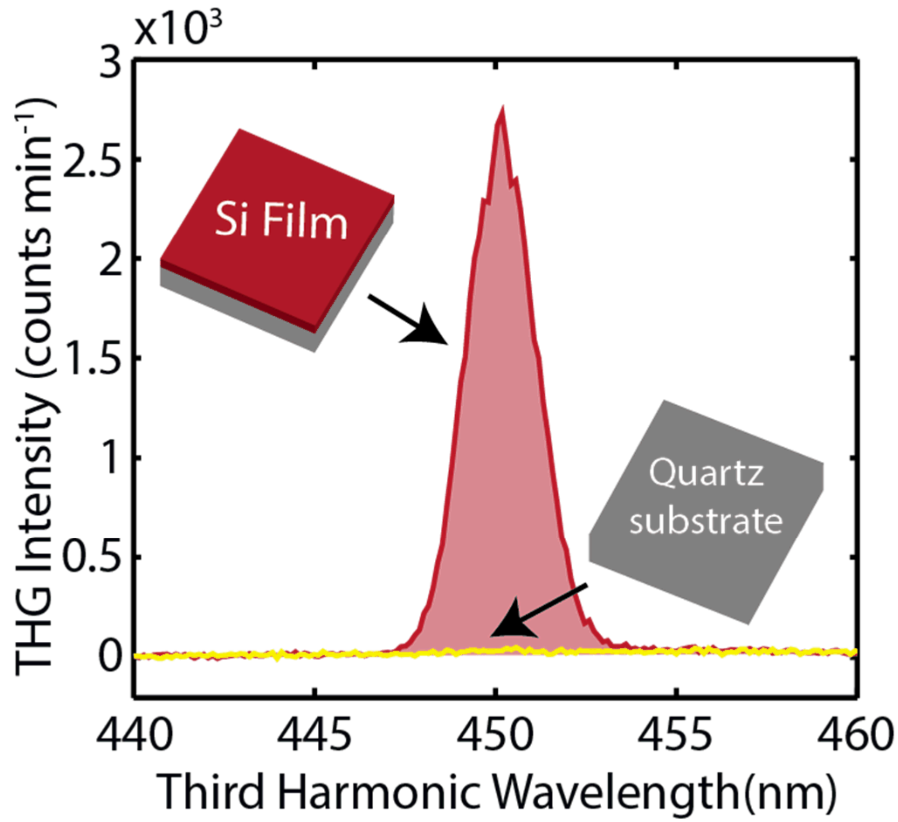


Illumination diameter: 15μm ($225\ \mu m^2$)



Third Harmonic Generation

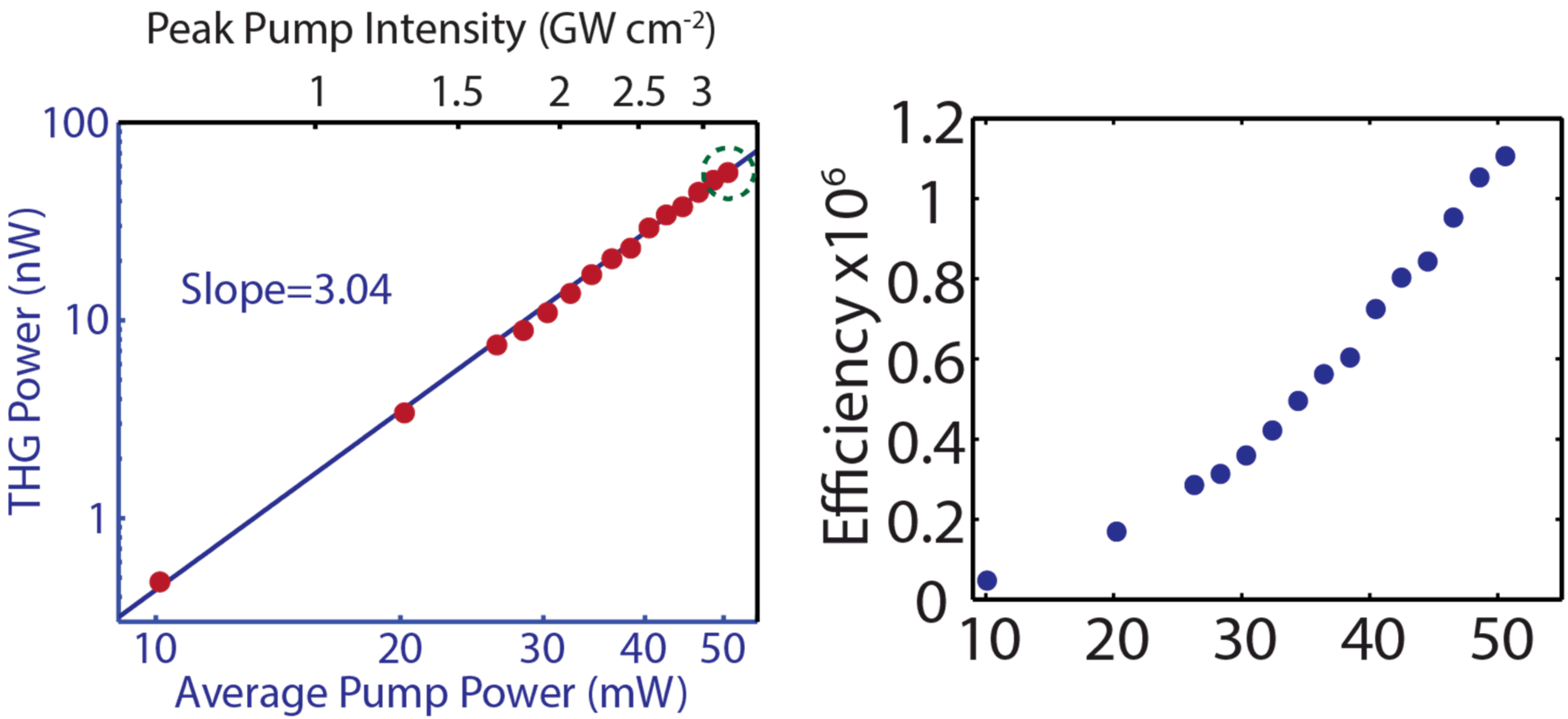




- **THG Enhancement Factor of 1.5 x 10^5**
- Pump at 1350 nm, average power: 25mW
- Peak Intensity: 1.6 GW/cm^2

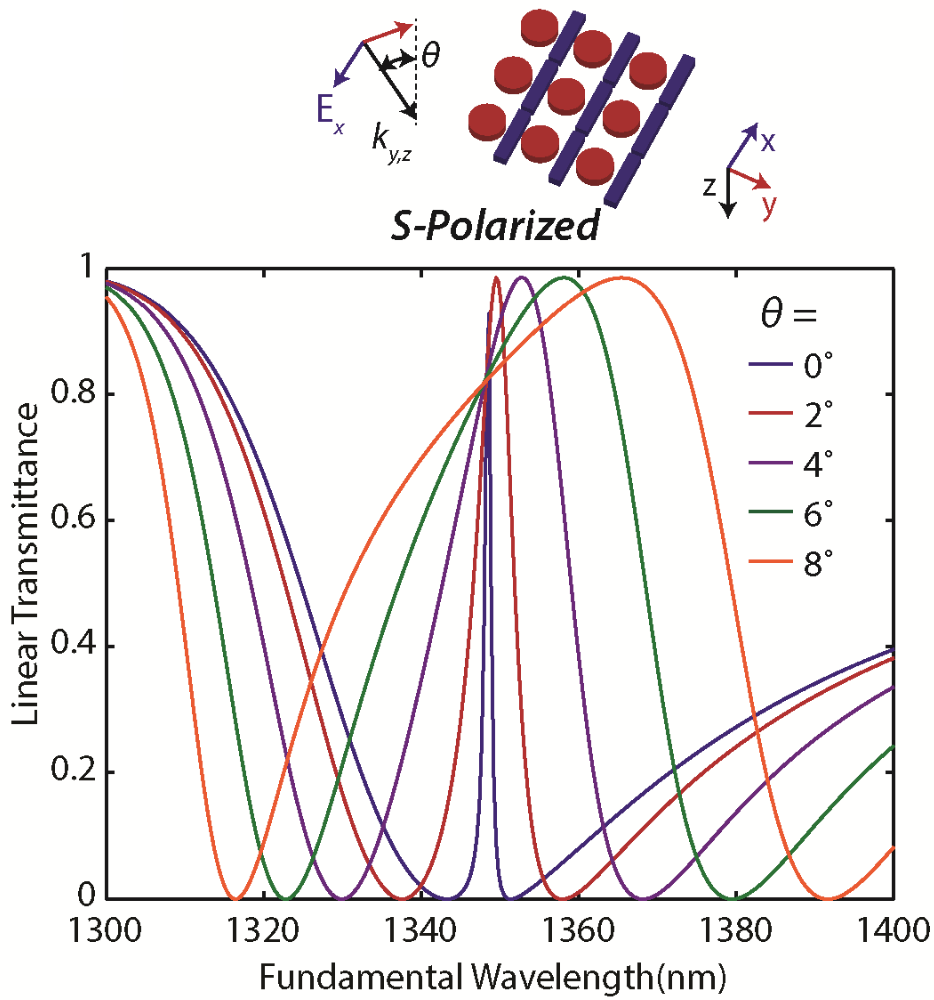
$$EF = \frac{P_{3w,MM}}{P_{3w,Si\,Film}}$$

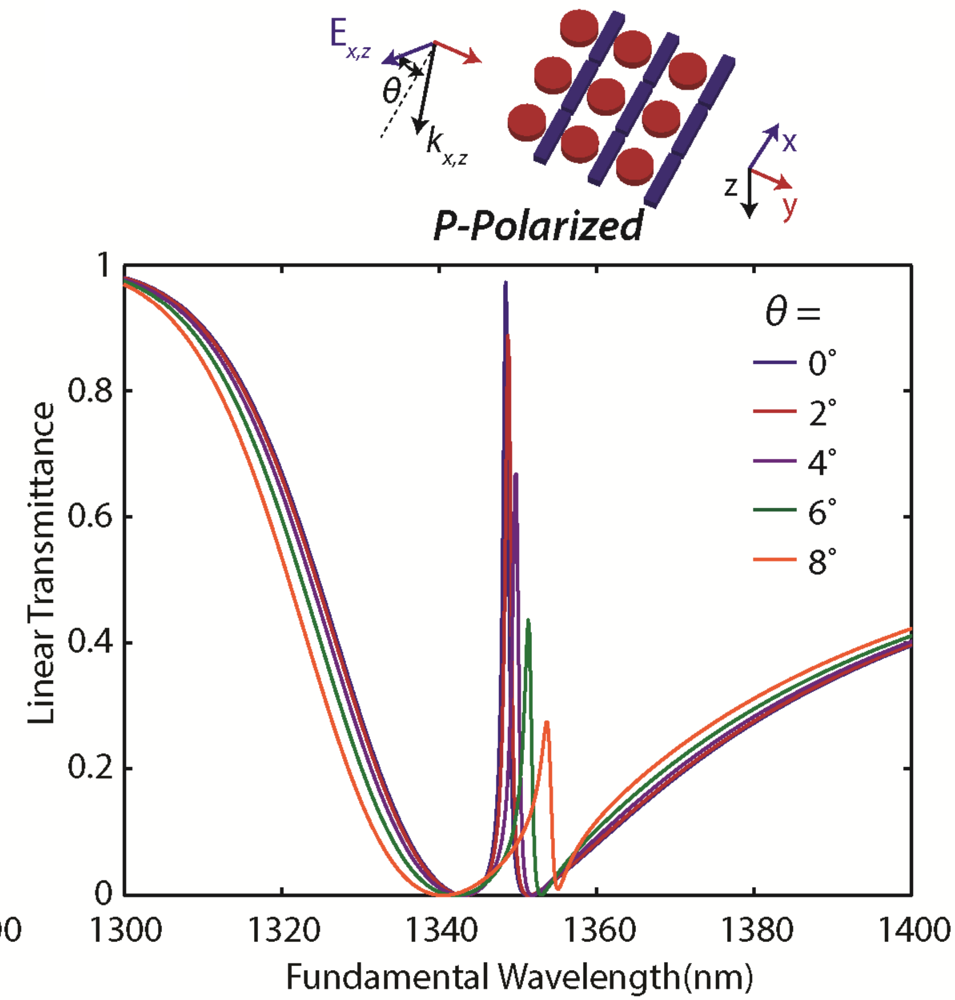
Absolute Conversion Efficiency



- **Peak efficiency = 1.2 x 10^{-6} (theory = 10^{-4})**
- Limit not yet clear (most likely TPA limited at higher power)
- Discrepancy with theory (1) lower Q-factor, (2) angle of incidence dispersion

Dispersion with Angle of Incidence

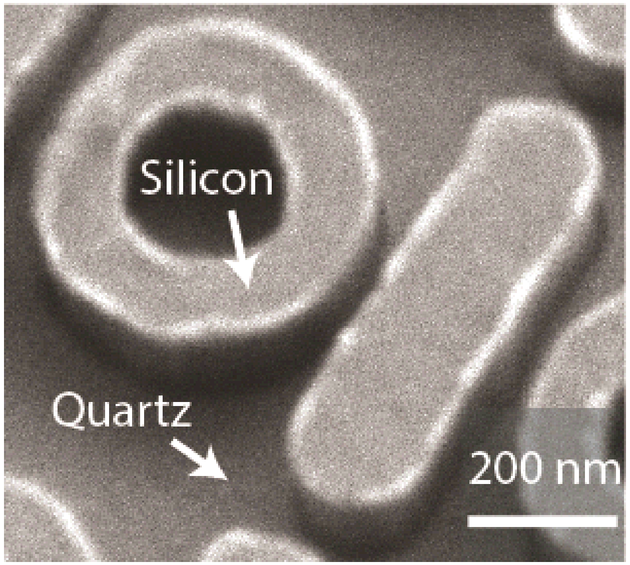


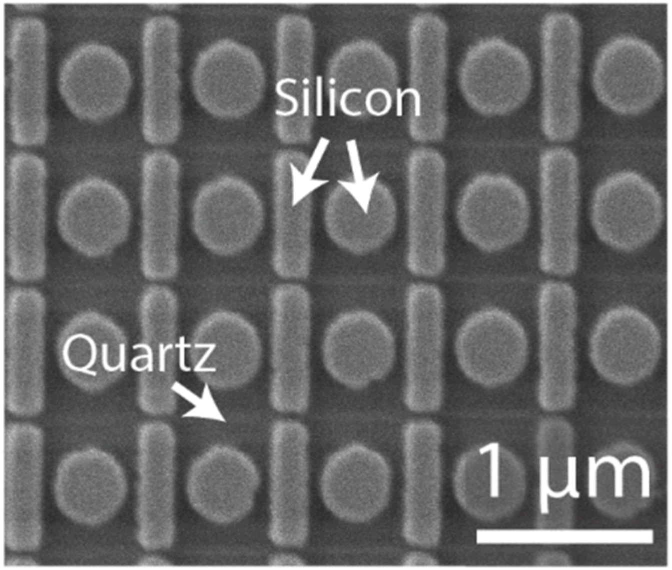


Conclusion

Si-Based Fano Metamaterials

- Low-loss, high efficiency
- Offer real advantages over metal implementations (higher Q, damage threshold)
- Potential nonlinear applications: all optical modulation and self-adjusting optics





Thanks!

- Advisor
  - Prof. Jason Valentine
- CNMS @ ORNL
  - Ivan Kravchenko
  - Abdelaziz Boulesbaa
  - Dayrl Briggs
  - Alexander Puretzky
  - David Geohegan

Revolutionary Research . . . Relevant Results

Center for Nanophase Materials Sciences

Intensity Dependent Index

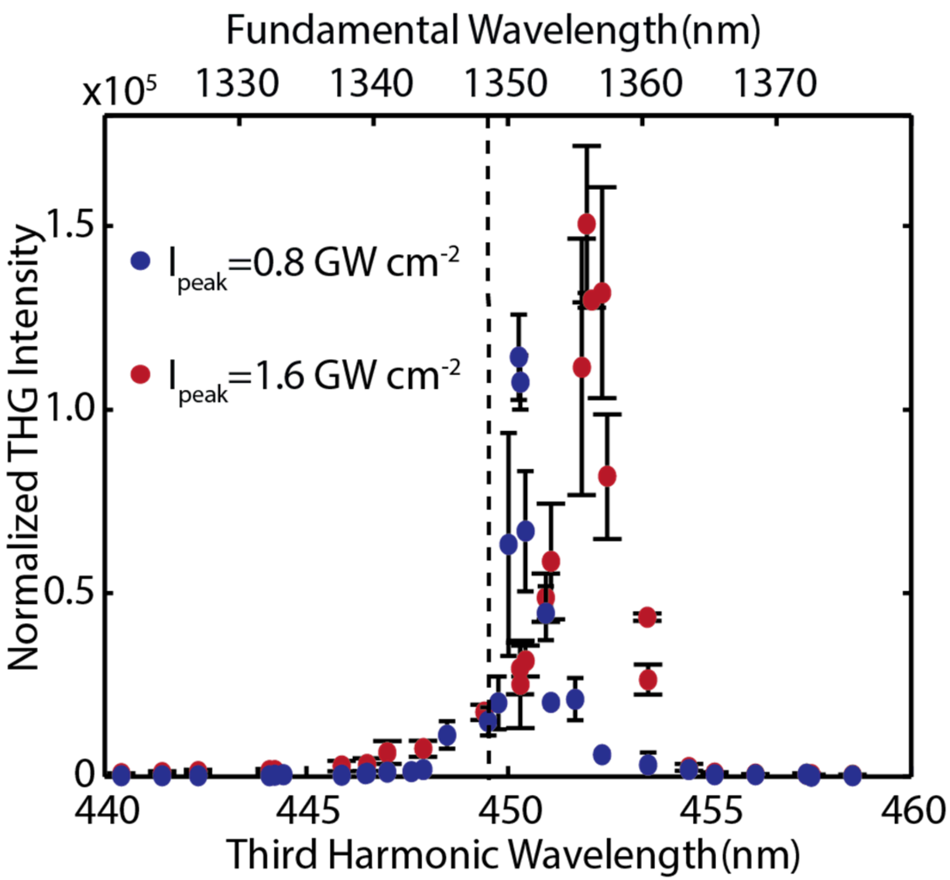
- @0.8 GW/cm^2
  - 0.93 nm shift in THG (2.79 nm at fundamental)
- 1st order approx:

$$\Delta n = n_{2(Si)} I_0 \frac{\int_{V_{Si}} |E|^2 / |E_0|^2 \, dV}{V_{Si}}$$

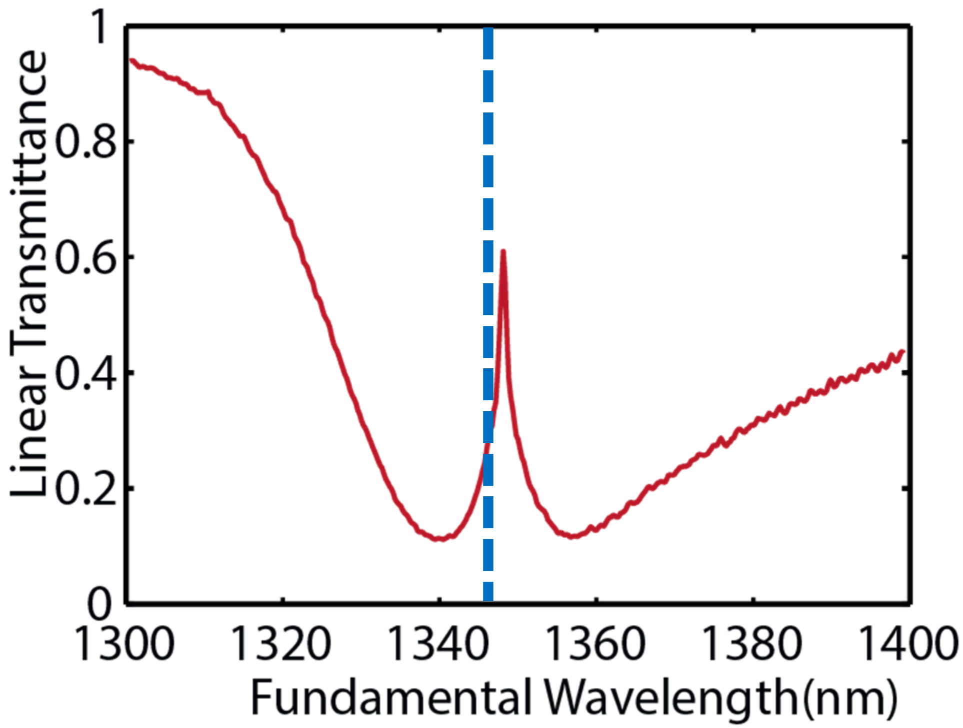
- Based on field,

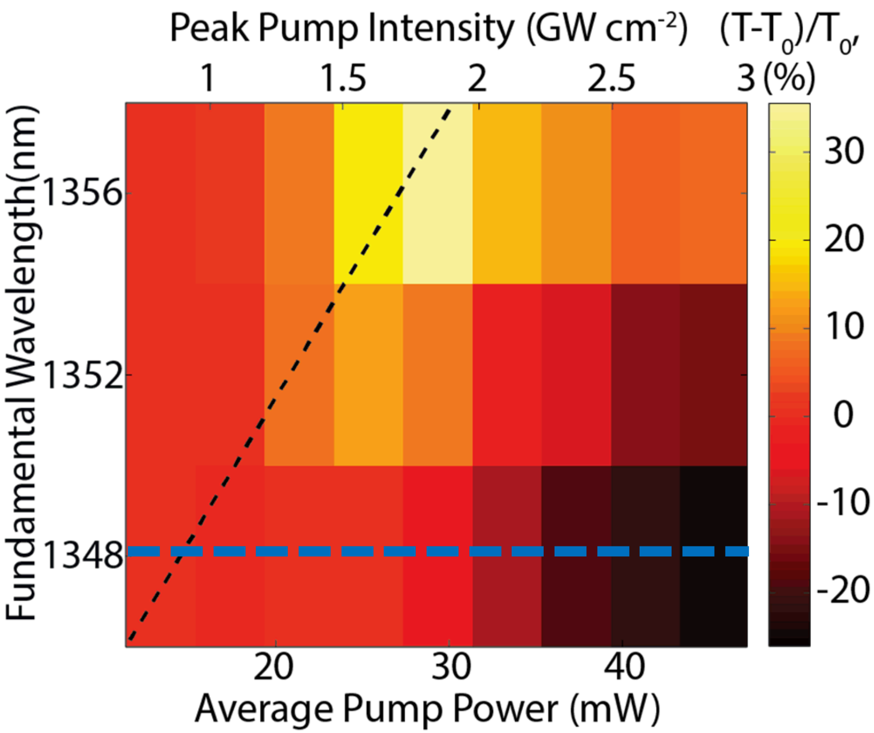
$n_2 = 2.7\text{x}10^{-18} m^2 W^{-1}$:

  - Δn ~ 0.011
  - $\Delta\lambda$ ~ 1.17nm in THG (3.5nm at fundamental)



Exploring the Kerr Effect

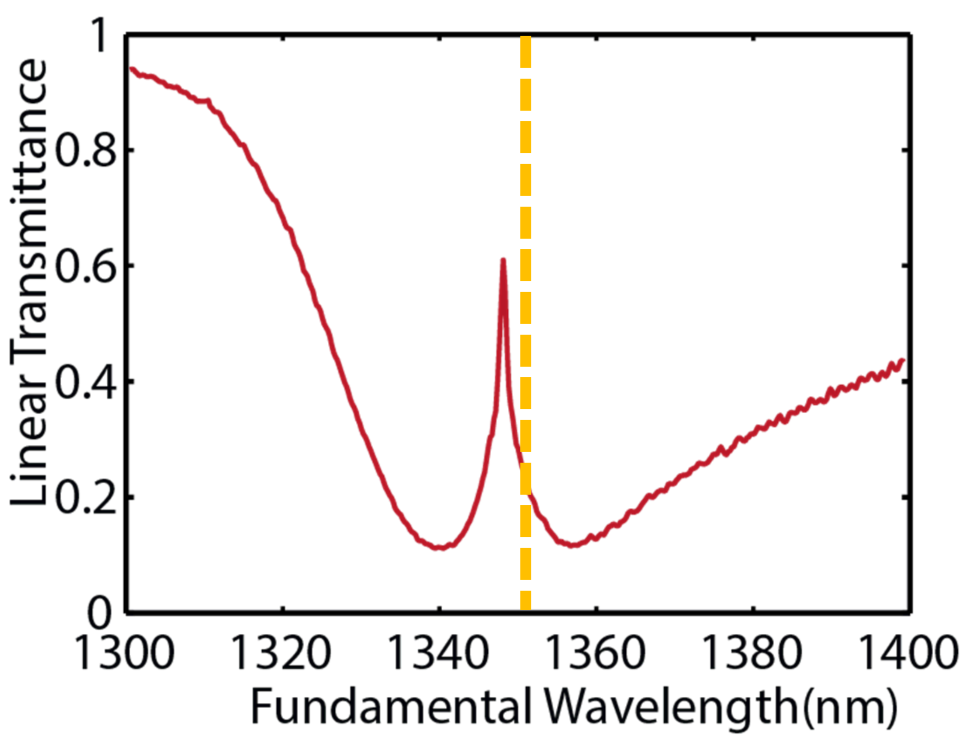


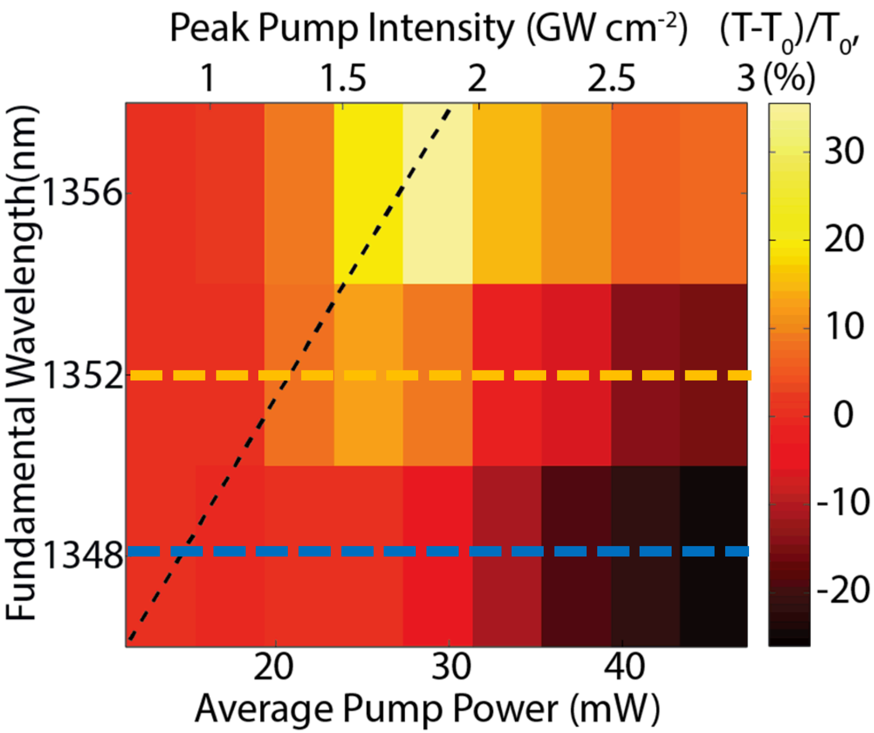


- T – transmittance @ λ
- T_0 – linear (low power) transmittance @ λ
- Max modulation depth: 36%

unpublished

Exploring the Kerr Effect

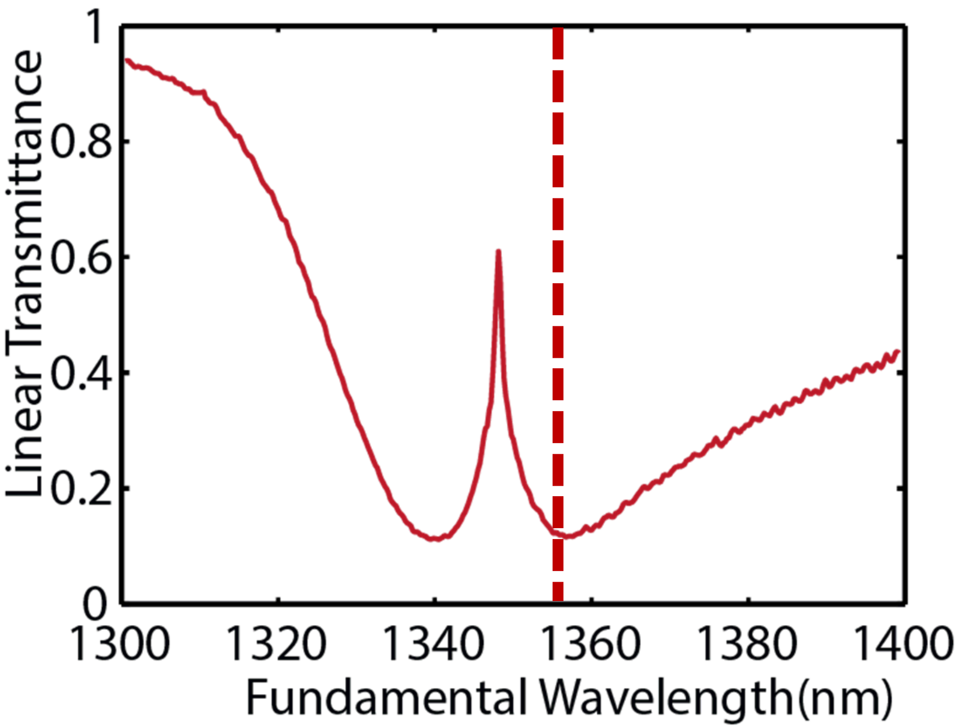


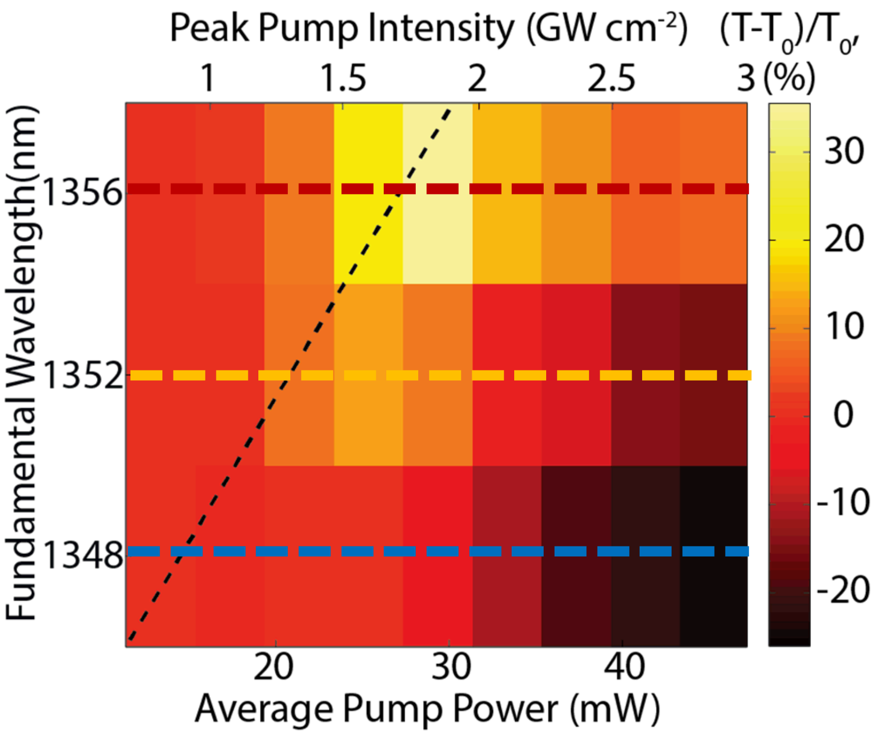


- T – transmittance @ λ
- T_0 – linear (low power) transmittance @ λ
- Max modulation depth: 36%

unpublished

Exploring the Kerr Effect





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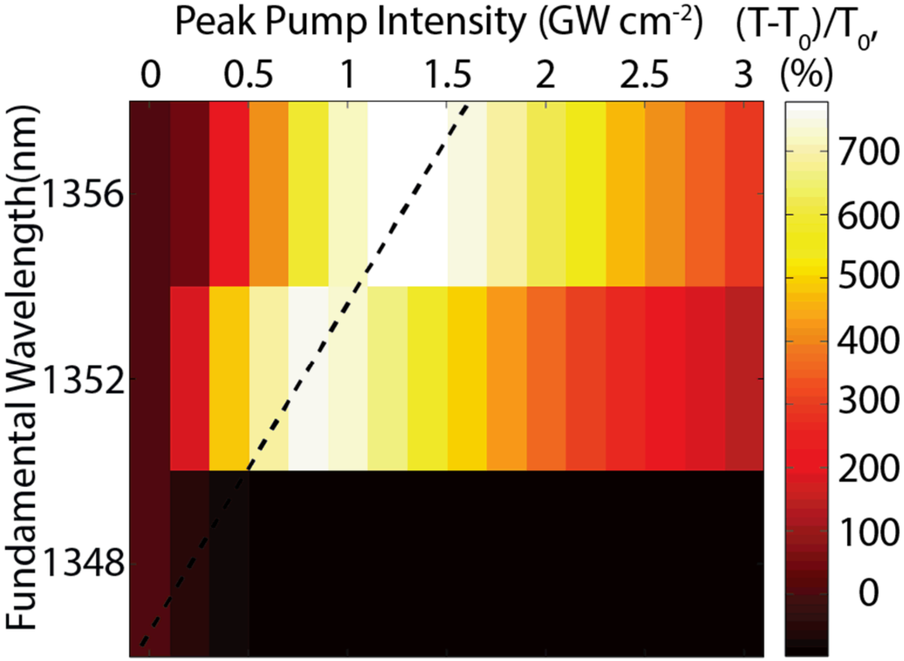
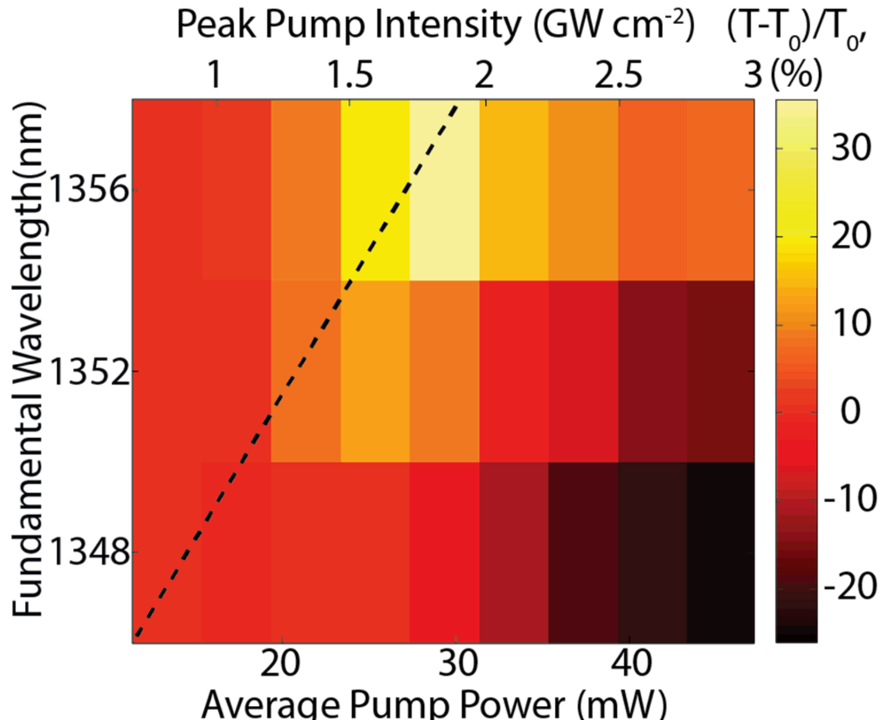
unpublished

Comparison to Theory

Simulation



Experiment

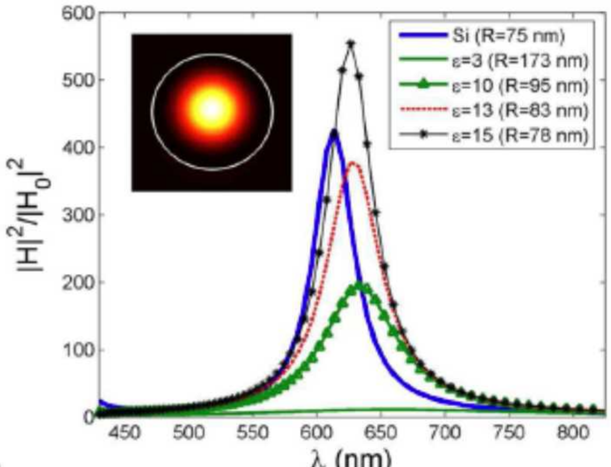


- Nonlinear simulations in Lumerical
- Silicon props: $\chi^{(3)}_{Si} = 2.79\times10^{-18}\,\mathrm{m^2V^{-2}},\ \beta = 5\times10^{-12}\,\mathrm{mW^{-1}}$
- Discrepancy: (1) Lower Q-factor, (2) finite angle of incidence, (3) free carrier absorption

unpublished

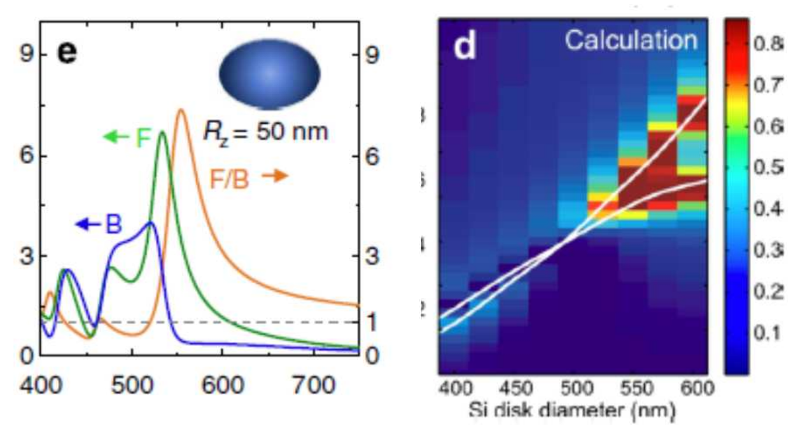
Optical Dielectric Metamaterials

Magnetic Resonances



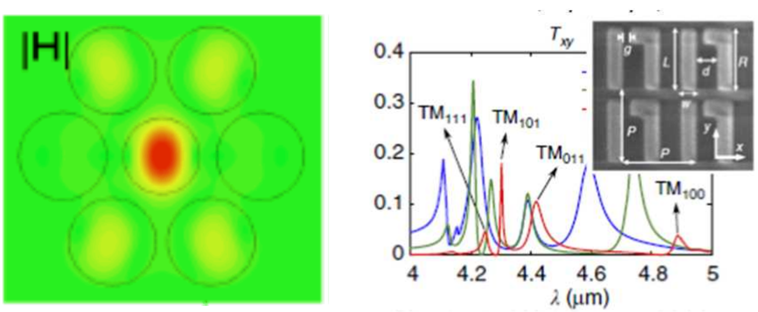
Kuznetsov et. al. Nano Lett (2012),
Evlyukhin et. al. Nano Lett (2012)

Overlapping Resonances



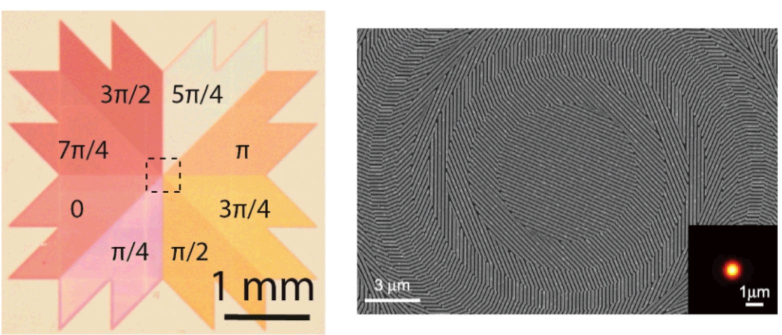
Kivshar et. al. ACS Nano (2013)
Luk'yanchuk et. al. Nat. Comm (2013)

Fano Resonances



Kivshar et. al. Nano Lett (2013), Shvets, Nat. Comm (2014)

Metasurfaces



Valentine, Nano Lett (2014),
Brongersma, Science (2014)