SAND2015-10315C

Large Third-Order Nonlinearity in a Fano-Resonant Silicon Metasurface

Yuanmu Yang[1], Wenyi Wang[1], Abdelaziz Boulesbaa[2], Ivan Kravchenko[2], Dayrl Briggs[2], Alexander Puretzky[2], David Geohegan[2], Jason Valentine[1]

[1]Vanderbilt University, United States

[2]Oak Ridge National Laboratory, United States

MRS Fall 2015

Boston, MA

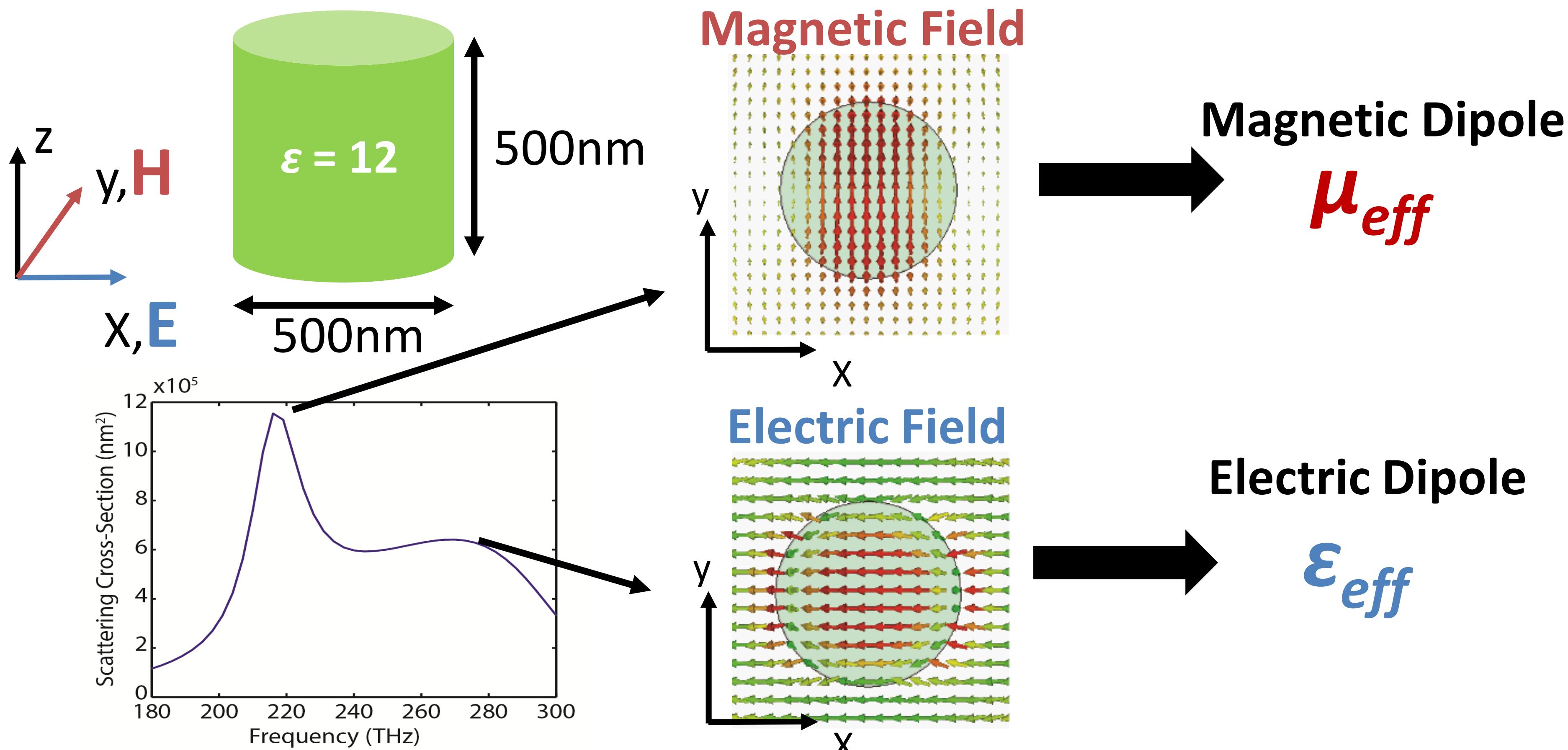
VANDERBILT UNIVERSITY

Revolutionary Research . . . Relevant Results

Center for Nanophase Materials Sciences

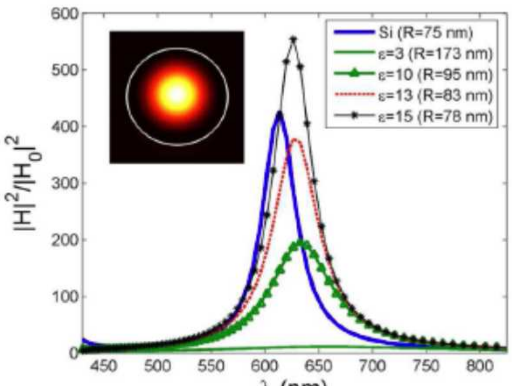
Dielectric / Semiconductor Metamaterials

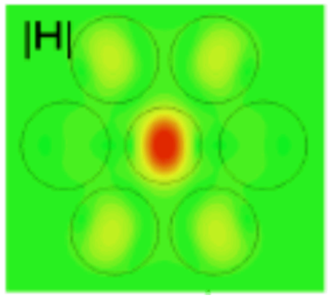
- First theorized by Lewin in 1947
  - Proc. Inst. Elec. Eng. **94** 65 (1947)
- Dielectric particles exhibit Mie resonances



Optical Dielectric Metamaterials

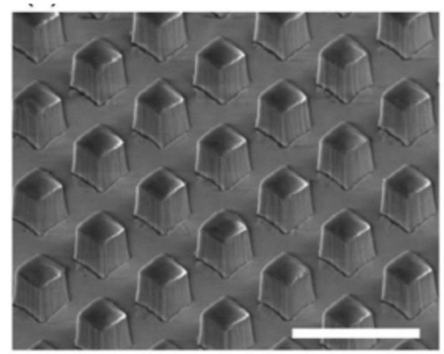
Particle Resonances

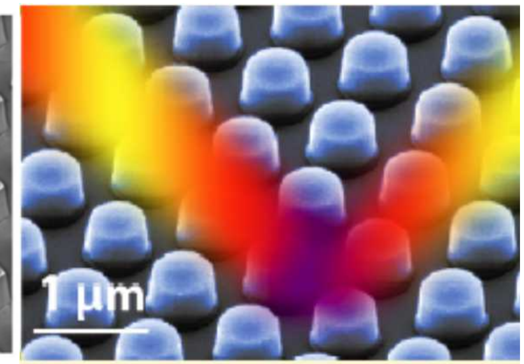




Kuznetsov et. al. Nano Lett (2012),
Evlyukhin et. al. Nano Lett (2012),
Kivshar et. al. Nano Lett (2013)

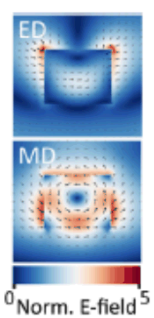
Perfect / Magnetic Reflectors

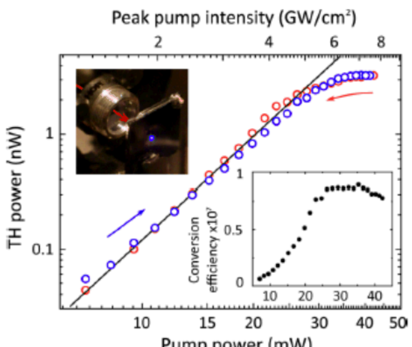




Brener et. al. Optica (2014), Moitra et. al. ACS Phot. (2015)

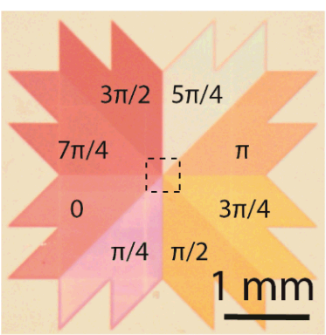
Nonlinear Enhancement

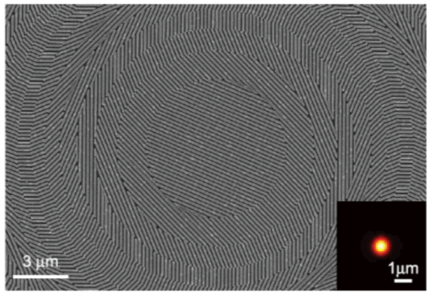




Kivshar, Neshev et. al. Nano Lett (2014), ACS Phot. (2015)

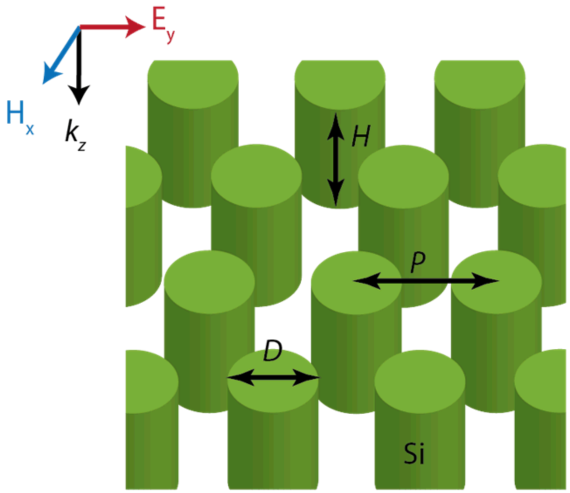
Metasurfaces

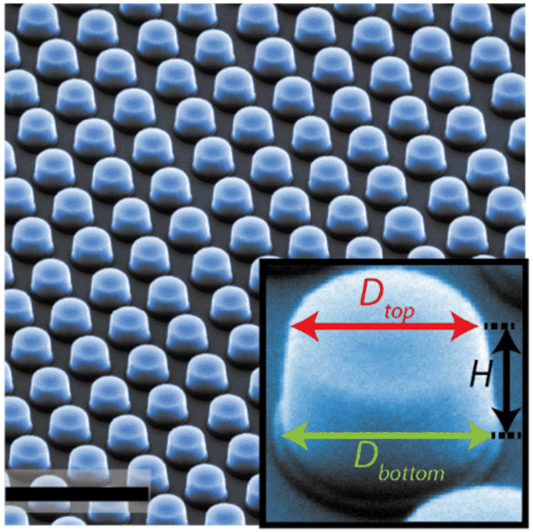


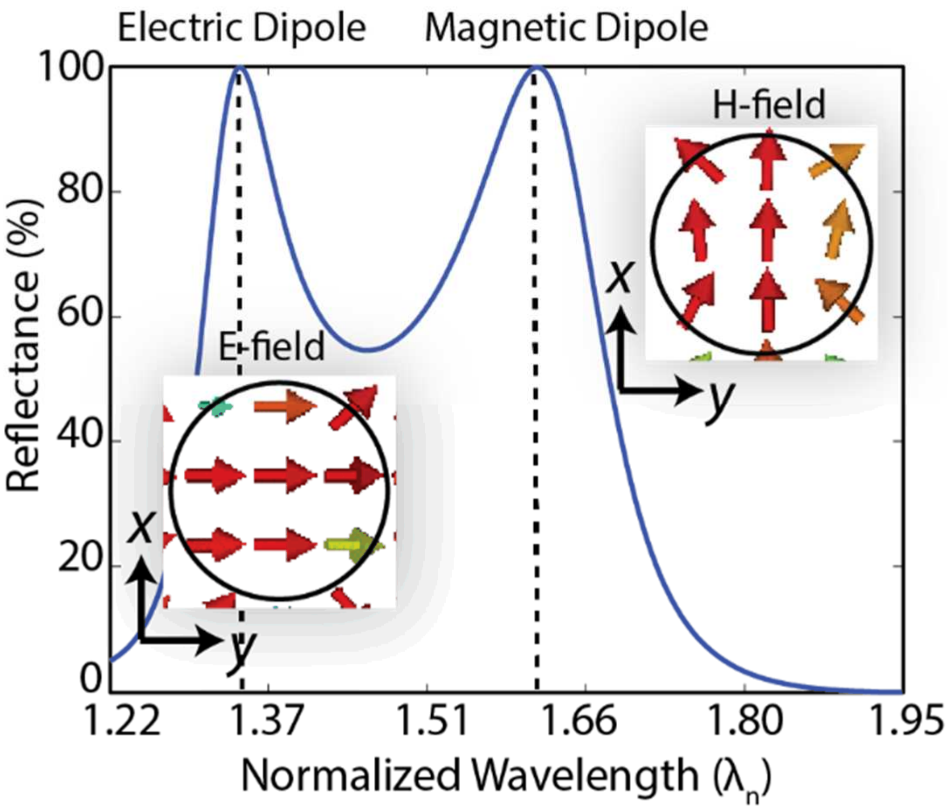


Yang et. al. Nano Lett (2014), Brongersma, et. al. Science (2014)

Spectral Response







Bandwidth Limited By Radiative Damping

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

Fano-Resonant Metamaterials

High-Q Requirements

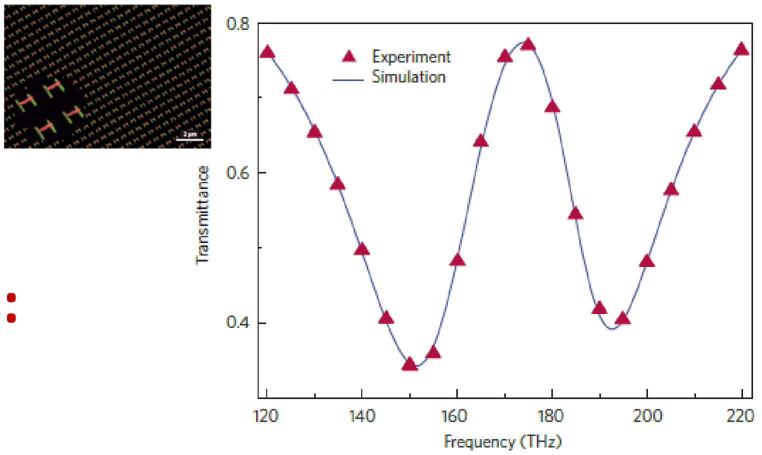
1. Minimize non-radiative damping (γ_{NR})
2. Minimize radiative damping (γ_R)

Plasmonic Fano-resonant Metamaterials:

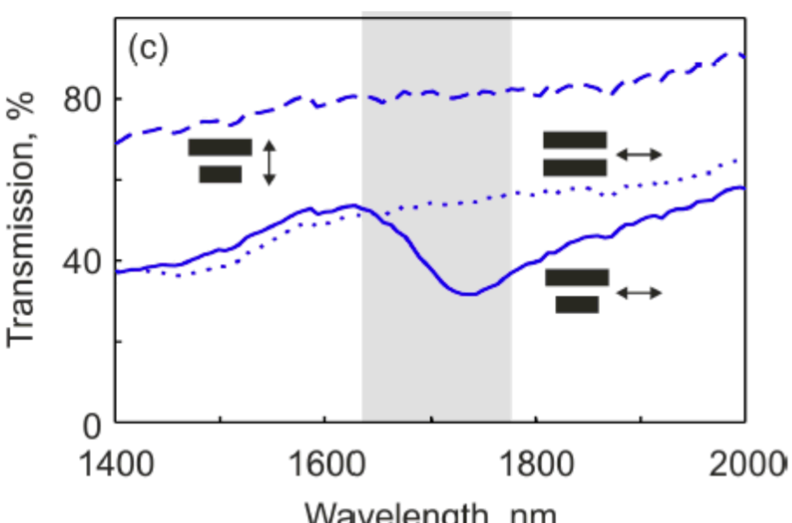
- Dominated by γ_{NR} , **Q-factors ~10**

Dielectric Fano-resonant Metamaterials:

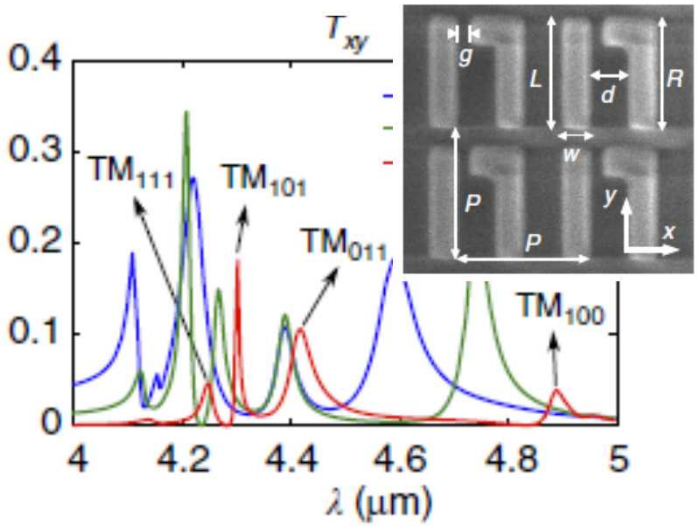
- Reduced γ_{NR} , **Q-factors ~100**



Giessen et al, Nat. Mat., 2010

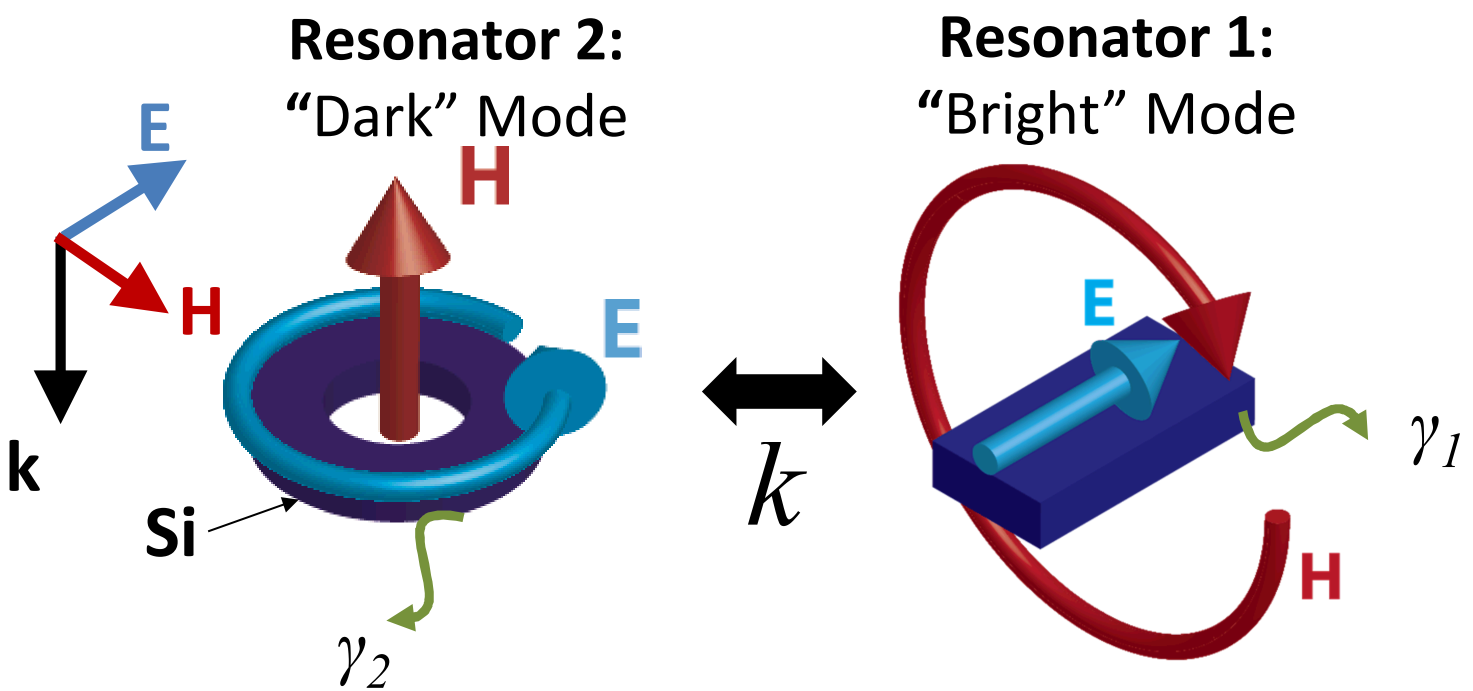


Zheludev et al, Opt. Expr., 2013



Shvets et al Nat Comm., 2014

Dark and Bright Collective Modes

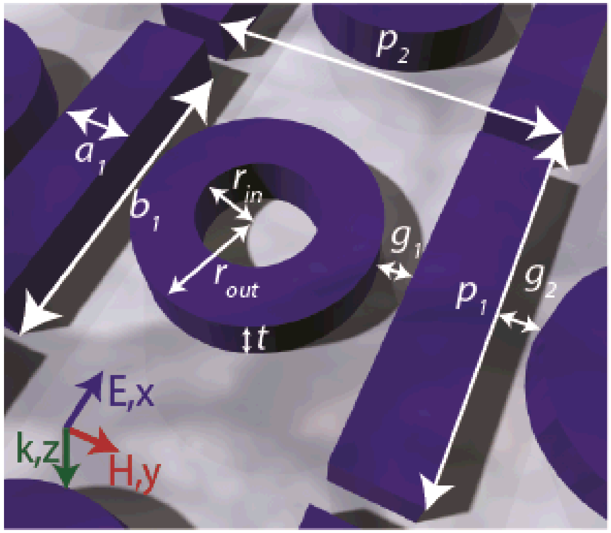


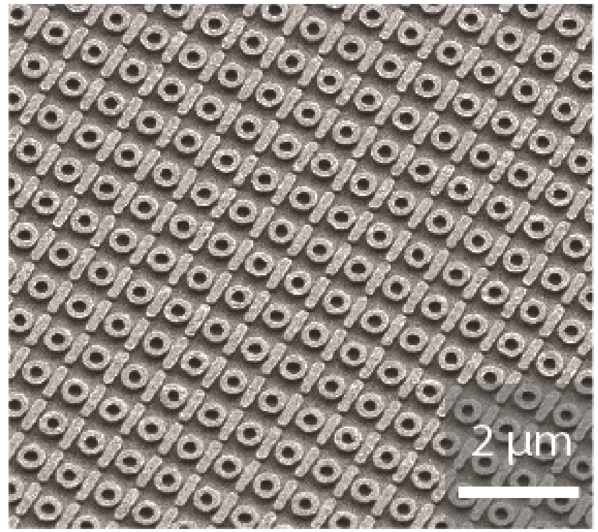
Key Points:

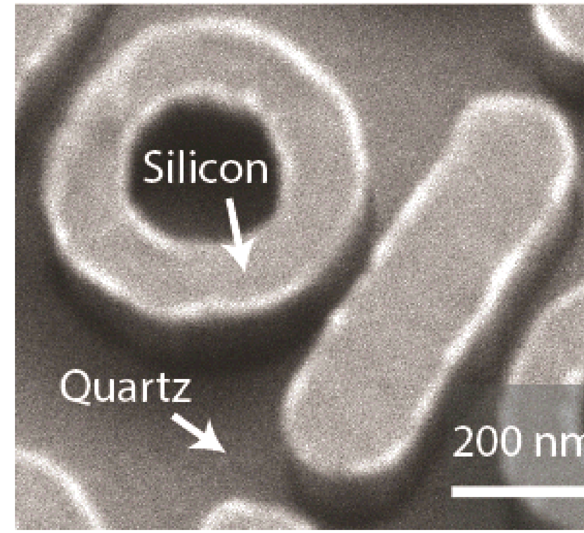
1. Reduction of γ_2 increases the Q-factor ⟶ minimize γ_2
2. In the limit of $\gamma_2 \rightarrow 0$, $dT/d\omega \propto \kappa^{-1}$ ⟶ minimize κ

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

Implementation in Silicon

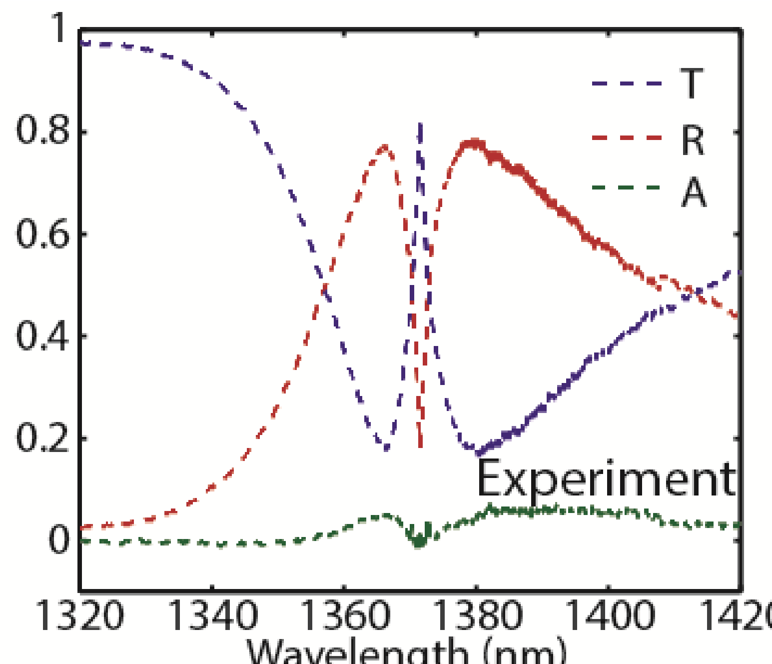




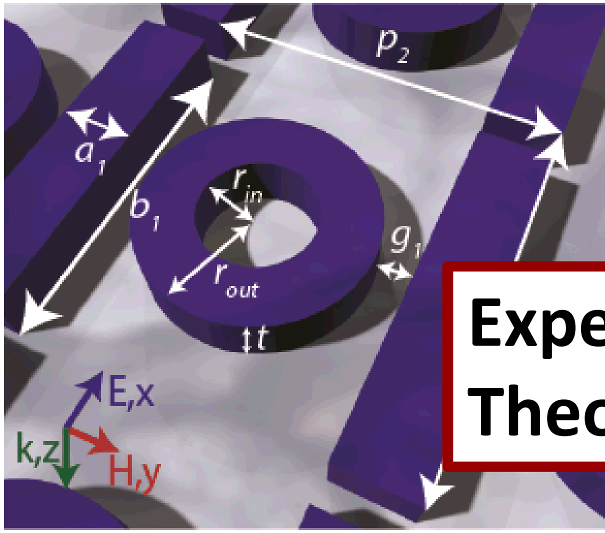


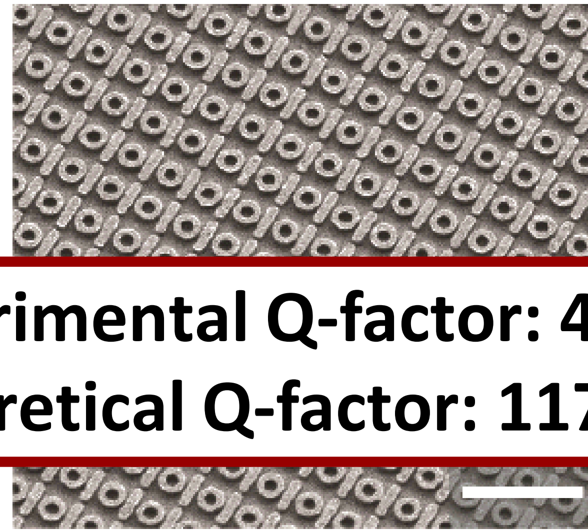
- r_{out} = 225nm
- g_1 = 70nm
- g_2 = 80nm
- t = 110nm
- p_1 = 750nm
- p_2 = 750nm

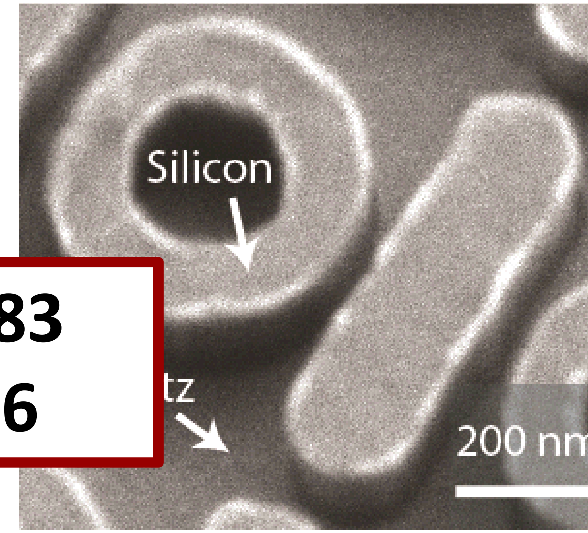
Yang, Y. et. al. *Nature Communications* 5, 5753 (2014)



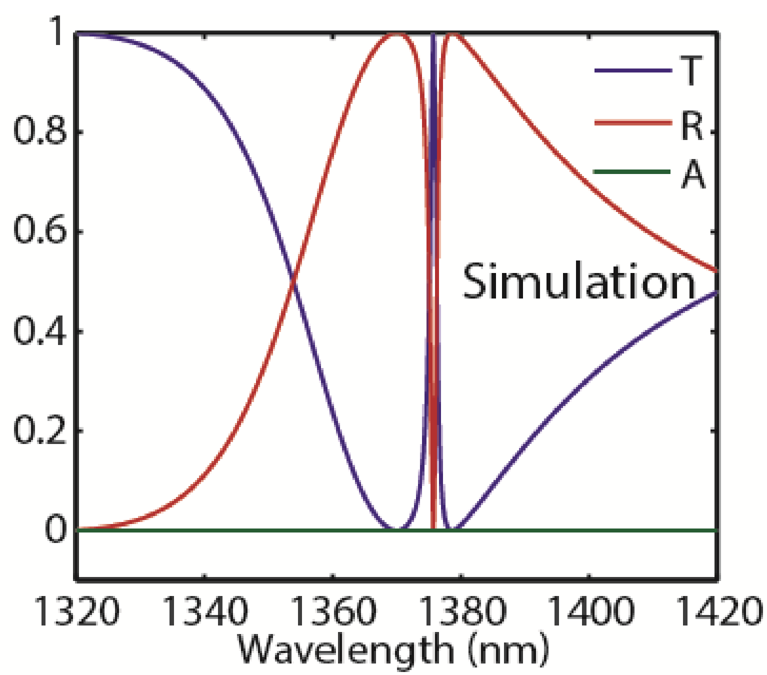
Implementation in Silicon

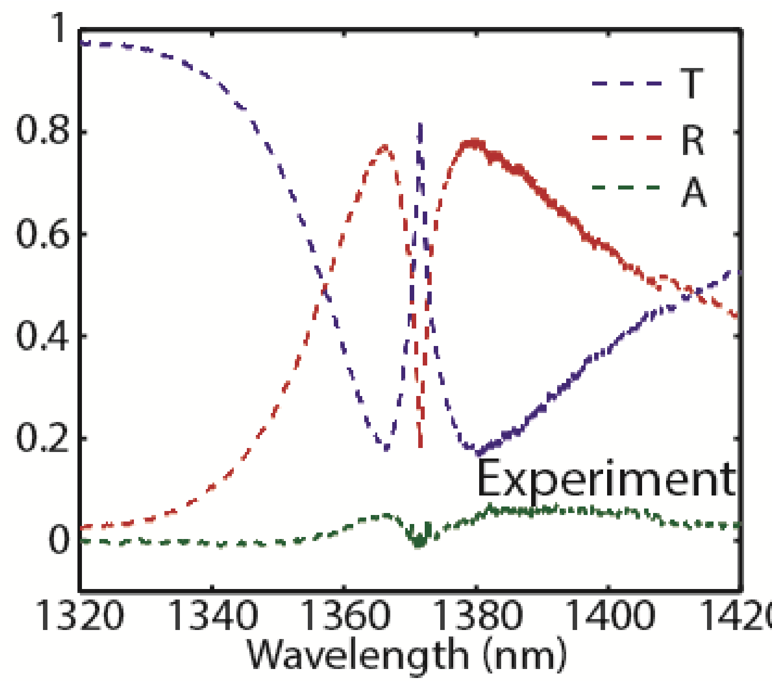




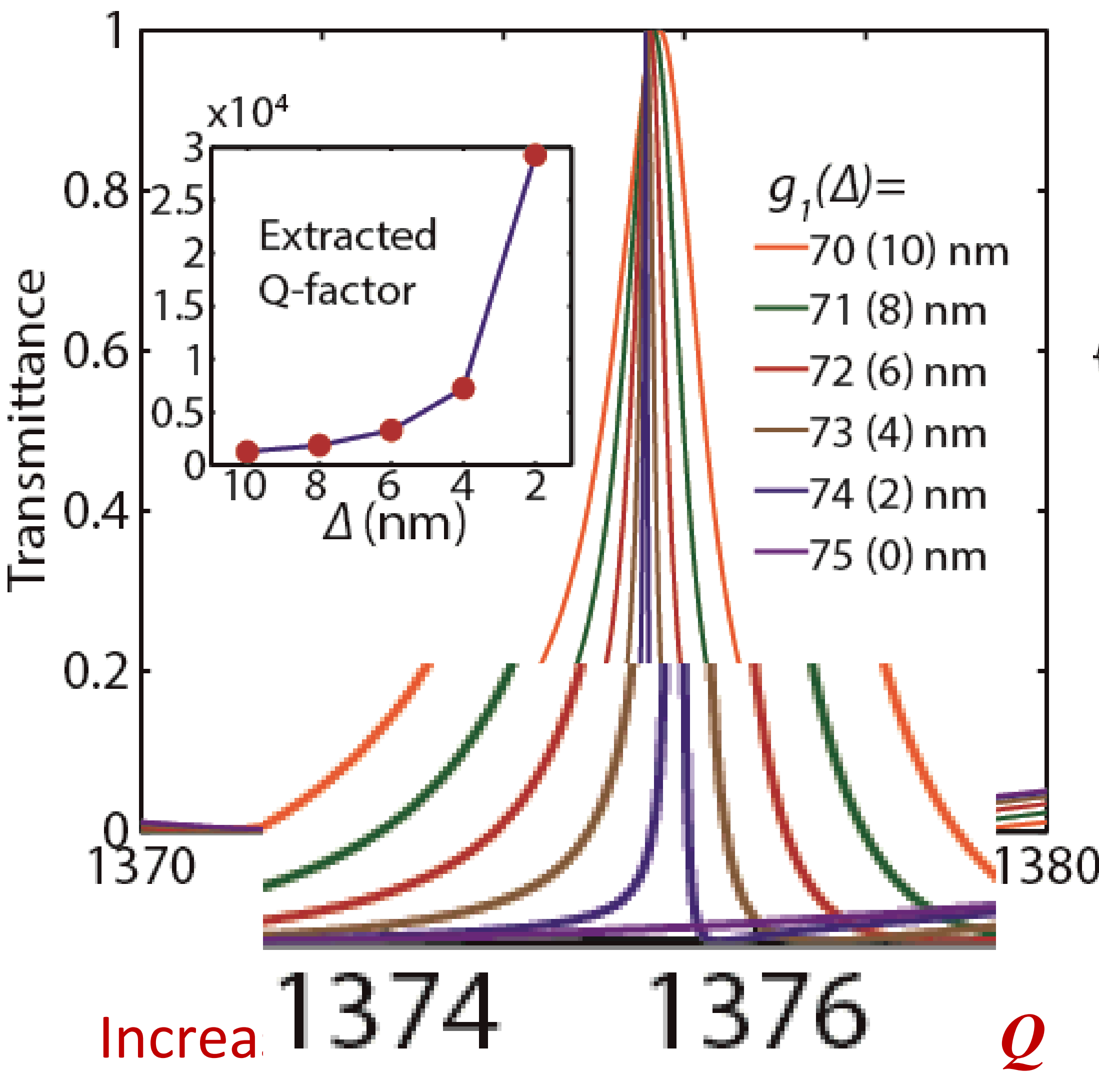


Experimental Q-factor: 483
Theoretical Q-factor: 1176

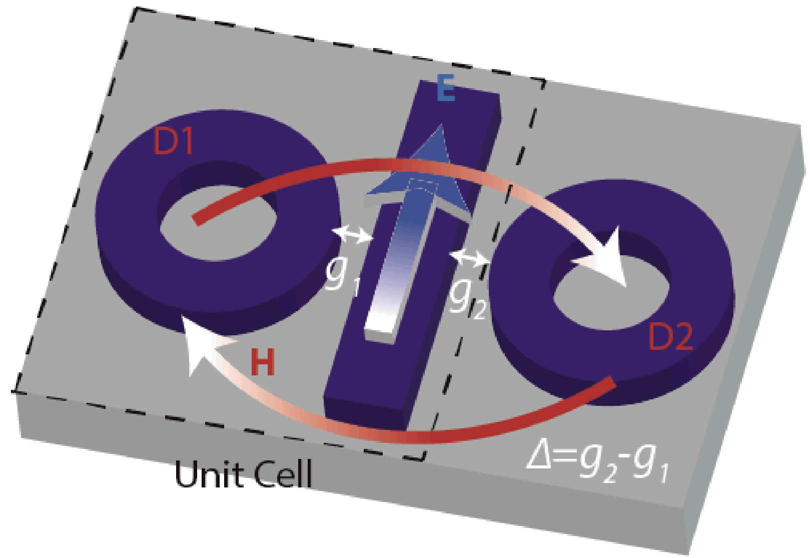




Role of Coupling Coefficient



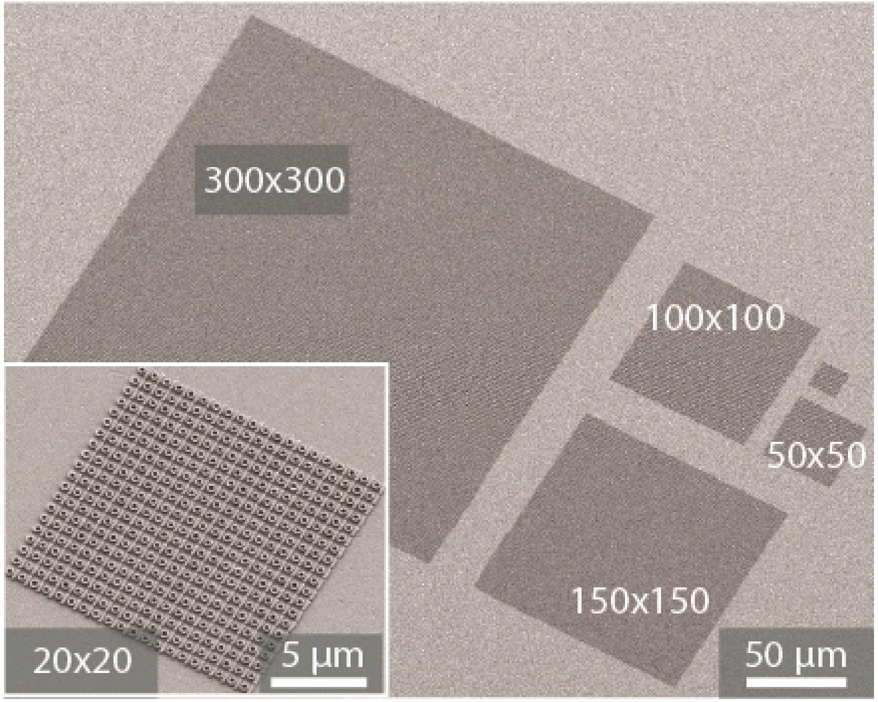
Increa *Q*

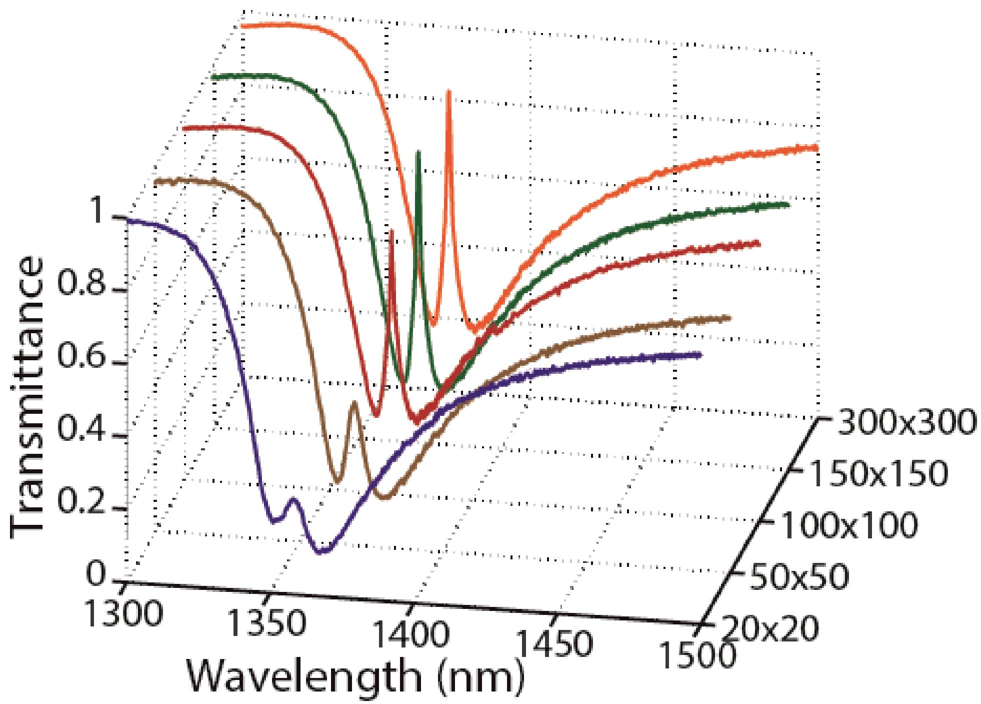


$$\Delta = g_2 - g_1$$

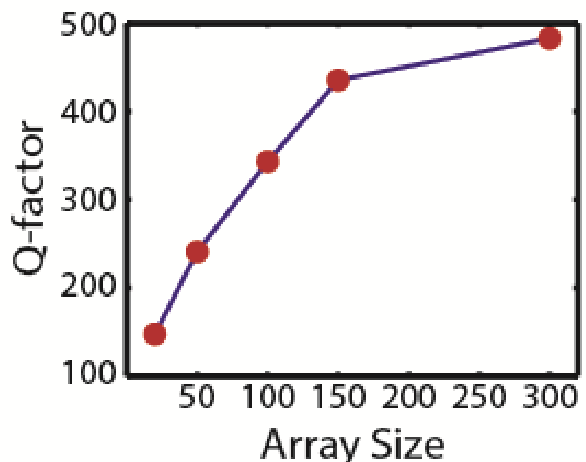
Q-factor = 30,000 @ g_1 = 74 nm (Δ = 2 nm)

Mesoscale Interactions - Experimental



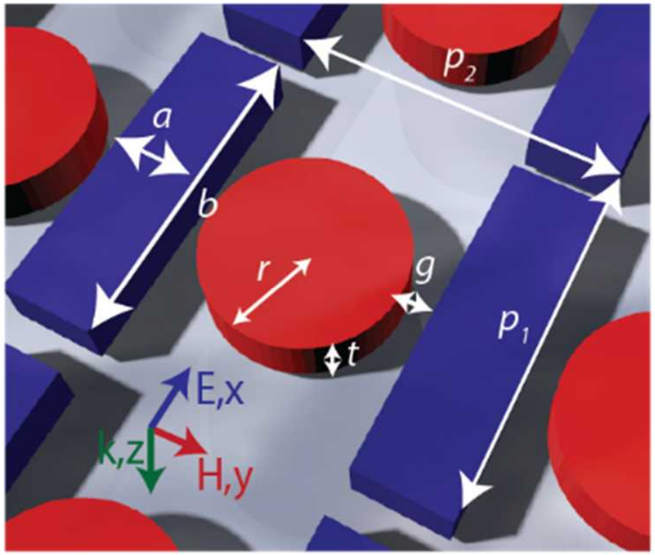


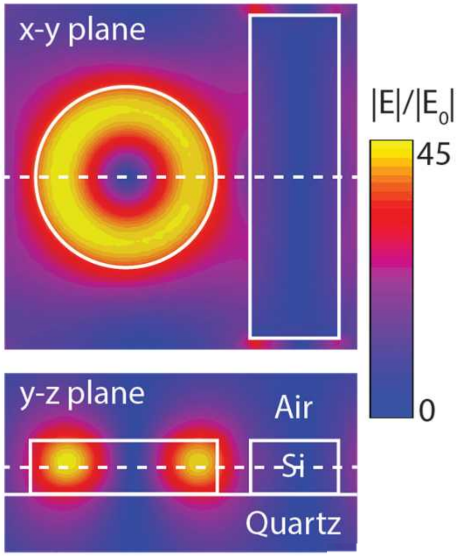
- Q-factor is strong function of # of resonators
- Q-factor remains limited by radiative and non-radiative loss

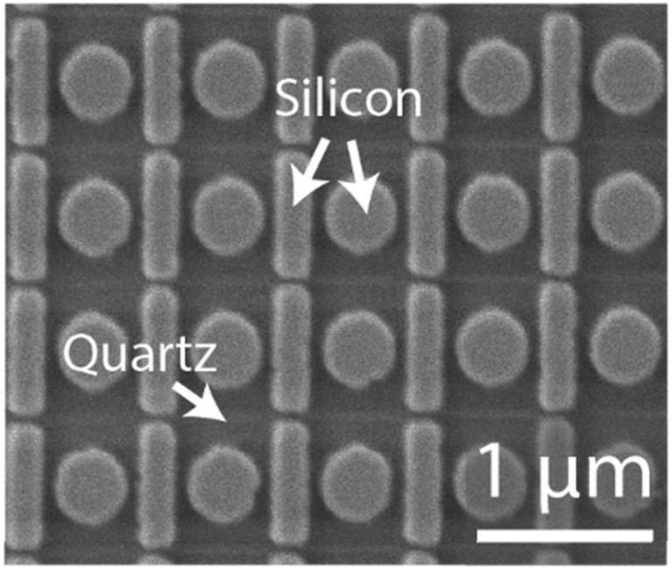


Yang, Y. et. al. *Nature Communications* 5, 5753 (2014)

Third Harmonic Configuration

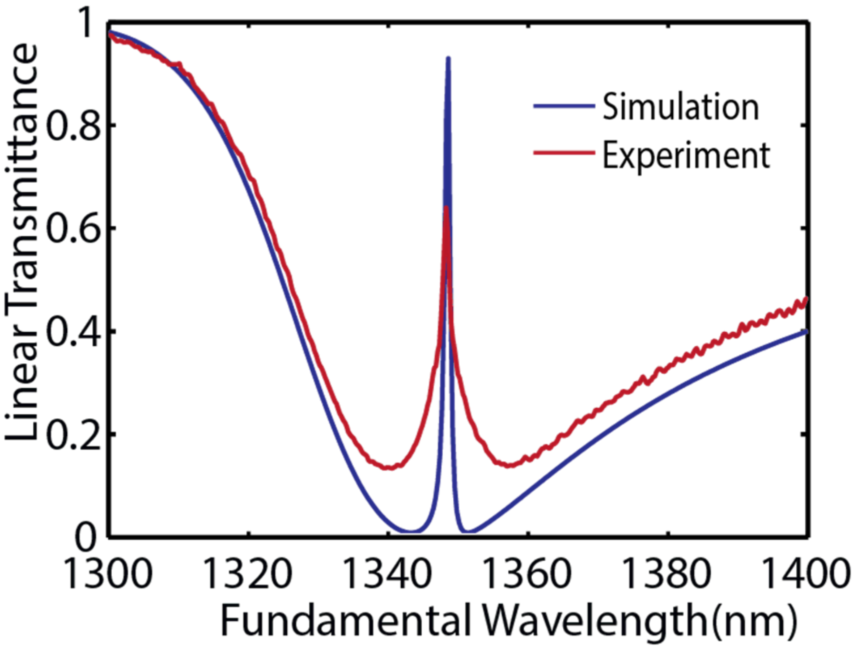




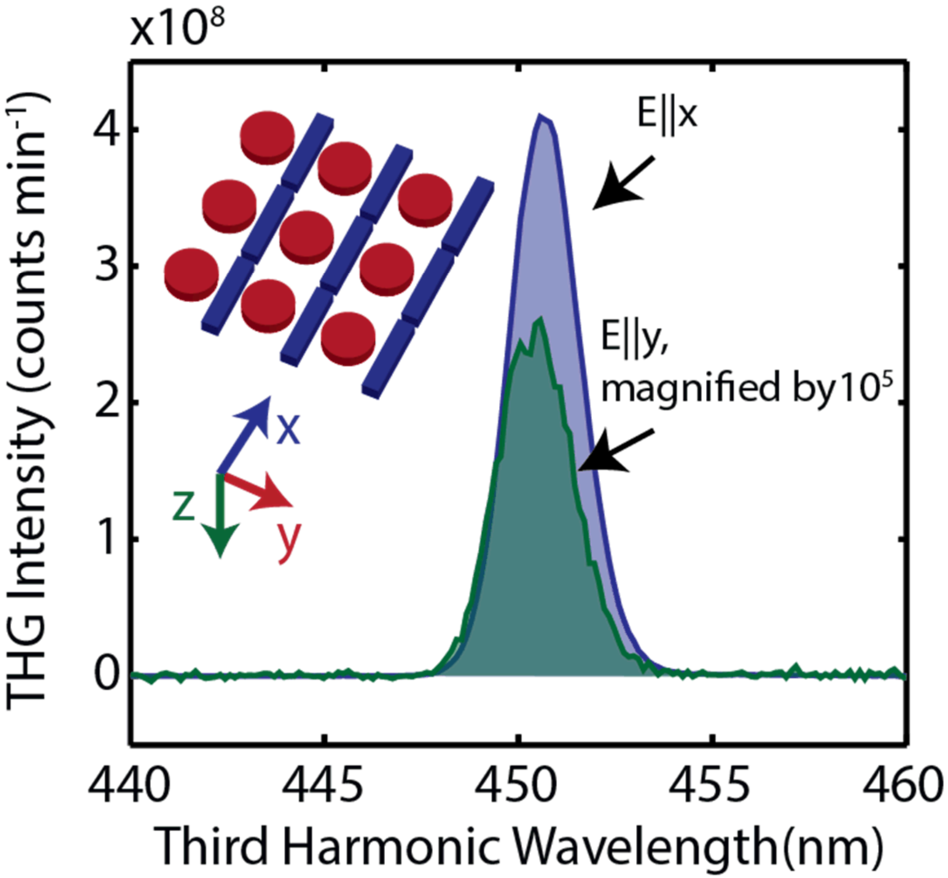


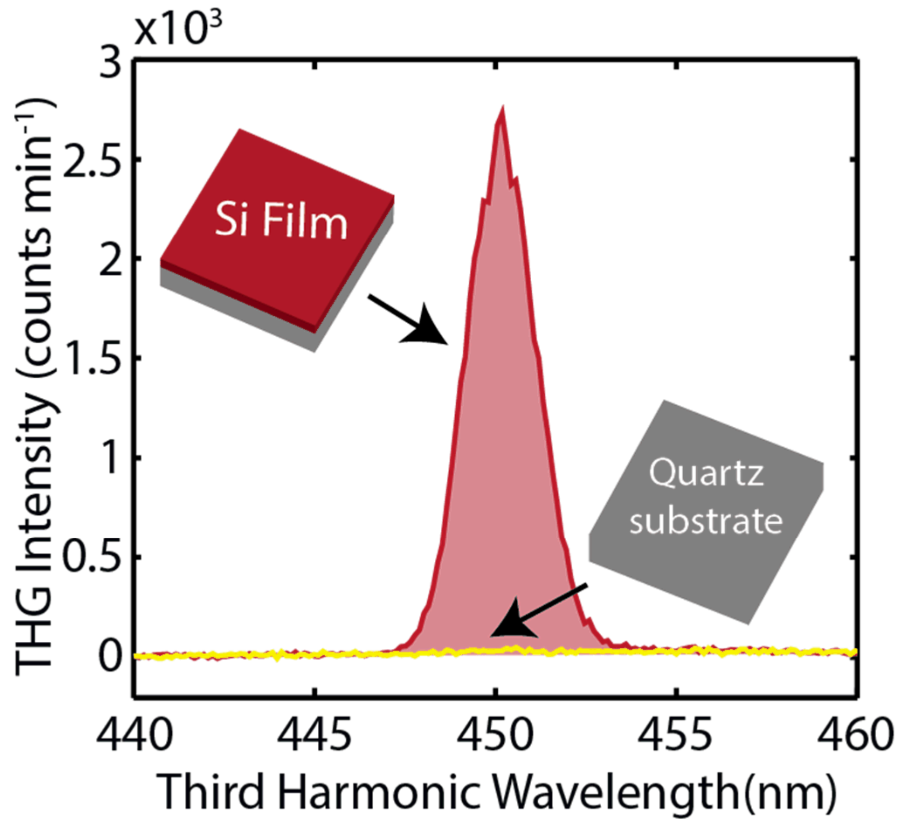
- **Polycrystalline silicon on quartz**
- $\chi_{Si}^{(3)} \sim 2.79 \times 10^{-18} \mathrm{m}^2 \mathrm{V}^{-2}$
- r = 210nm
- g = 60nm
- t = 120nm

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



Third Harmonic Generation

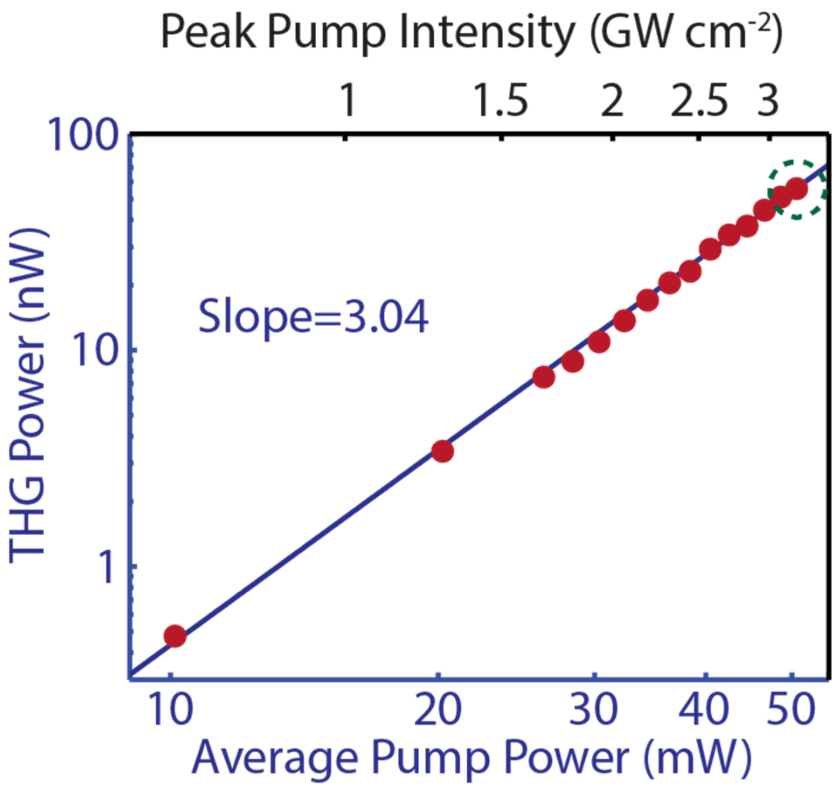


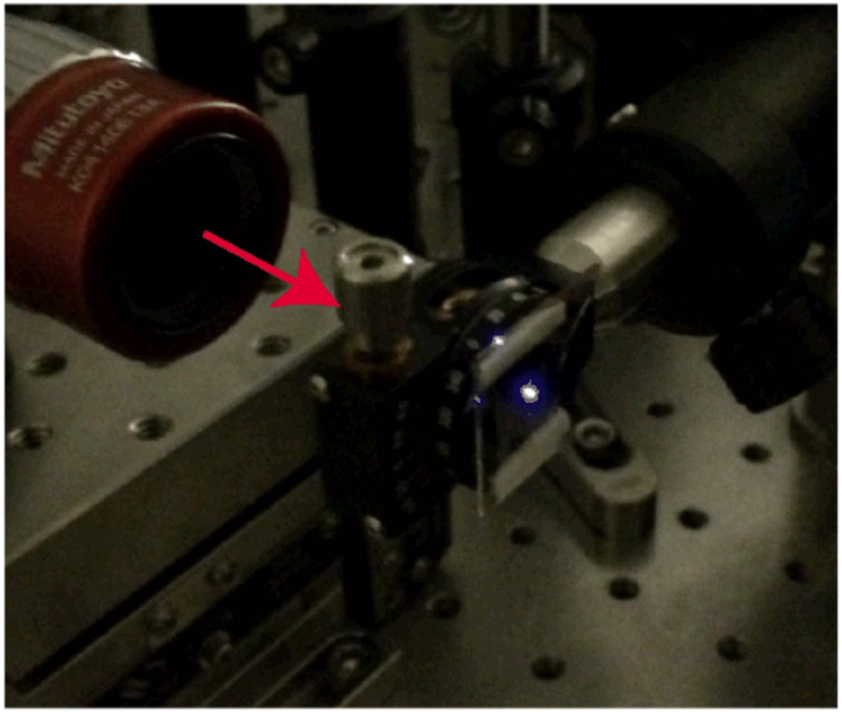


- **THG Enhancement Factor of 1.5 x 10^5**
- Pump at 1350 nm, average power: 25mW
- Peak Intensity: 1.6 GW/cm^2

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

Absolute Conversion Efficiency



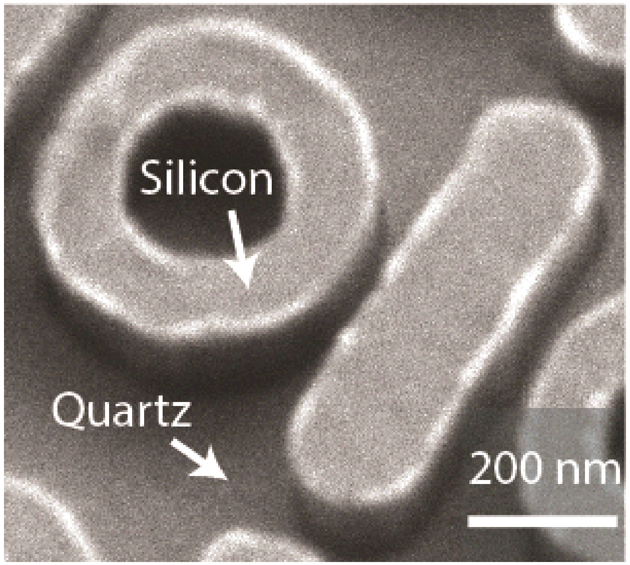


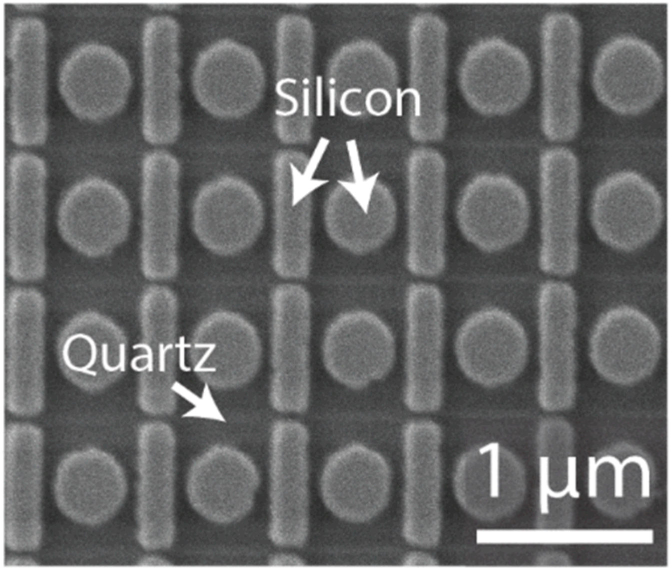
- **Peak efficiency = 1.2 x 10^{-6} (theory = 10^{-4})**
- Limit not yet clear (most likely TPA limited at higher power)
- Discrepancy with theory (1) lower Q-factor, (2) angle of incidence dispersion

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!

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

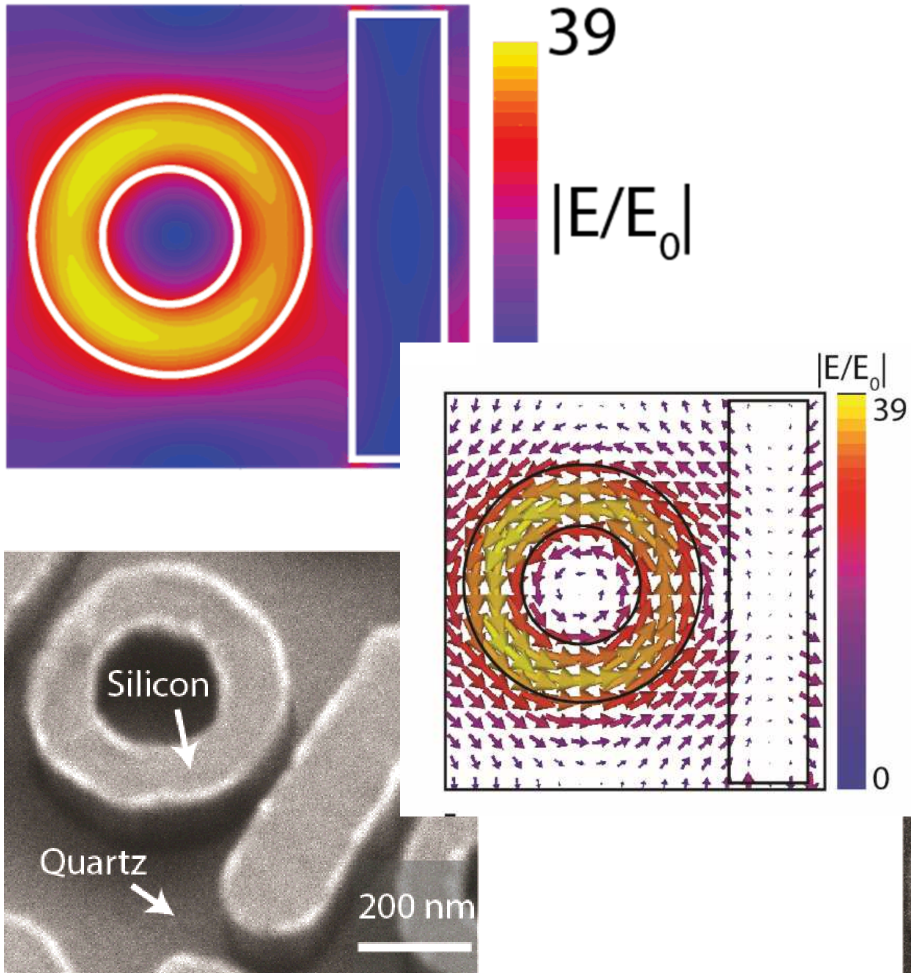
OFFICE OF NAVAL RESEARCH S&T ONR
Revolutionary Research . . . Relevant Results

NSF

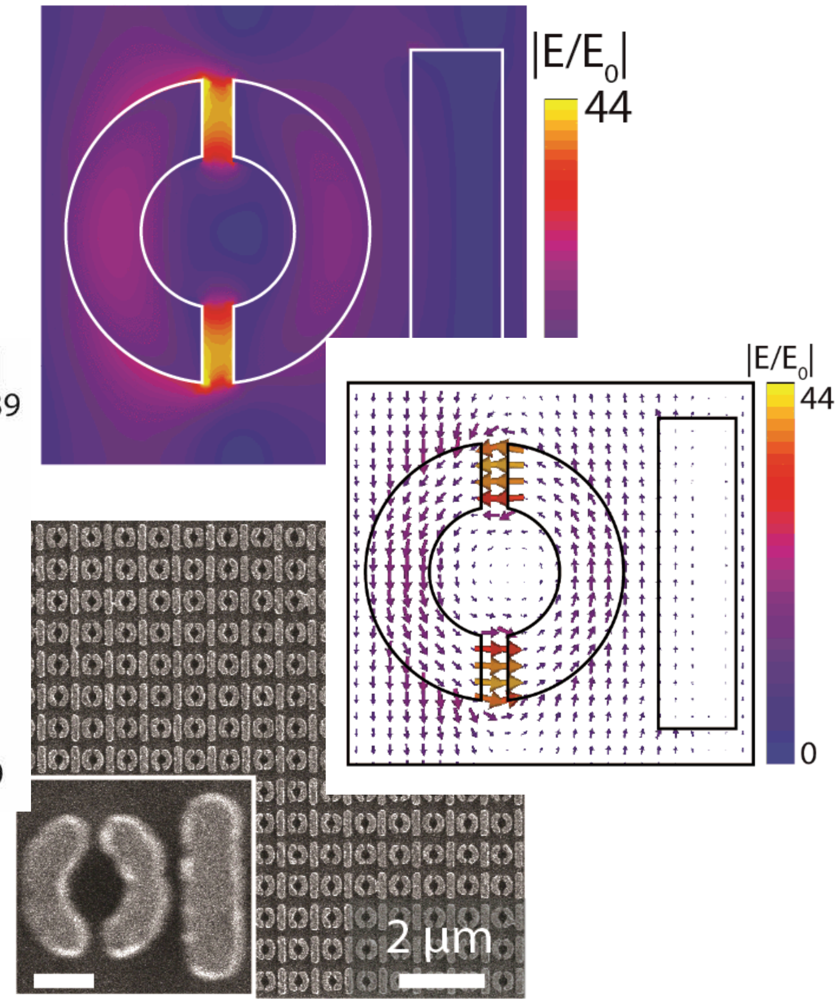
Center for Nanophase Materials Sciences

Strong Field Enhancement

Ring Resonator (Q = 1176)

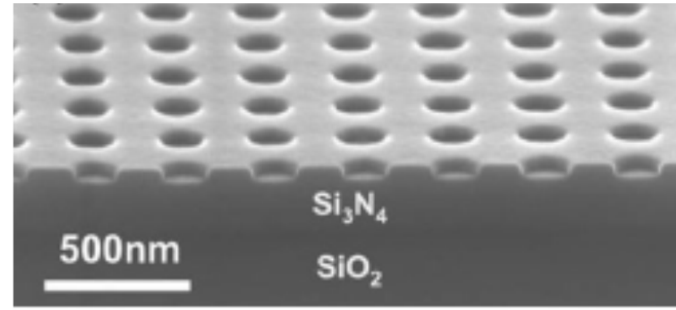


Gap Resonator (Q = 374)

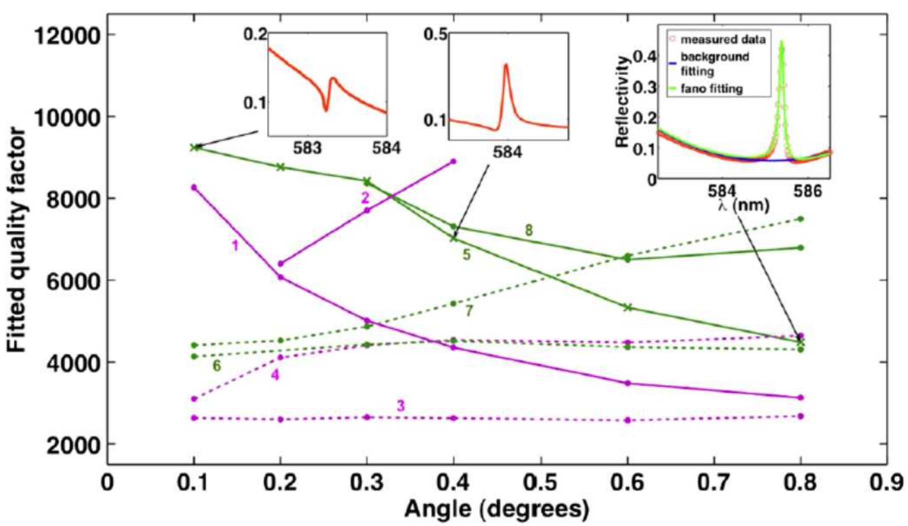


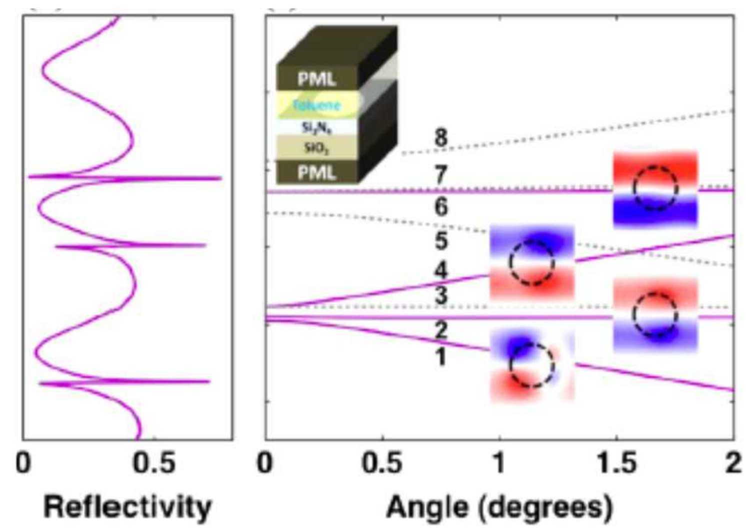
Comparison to PC Slabs

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



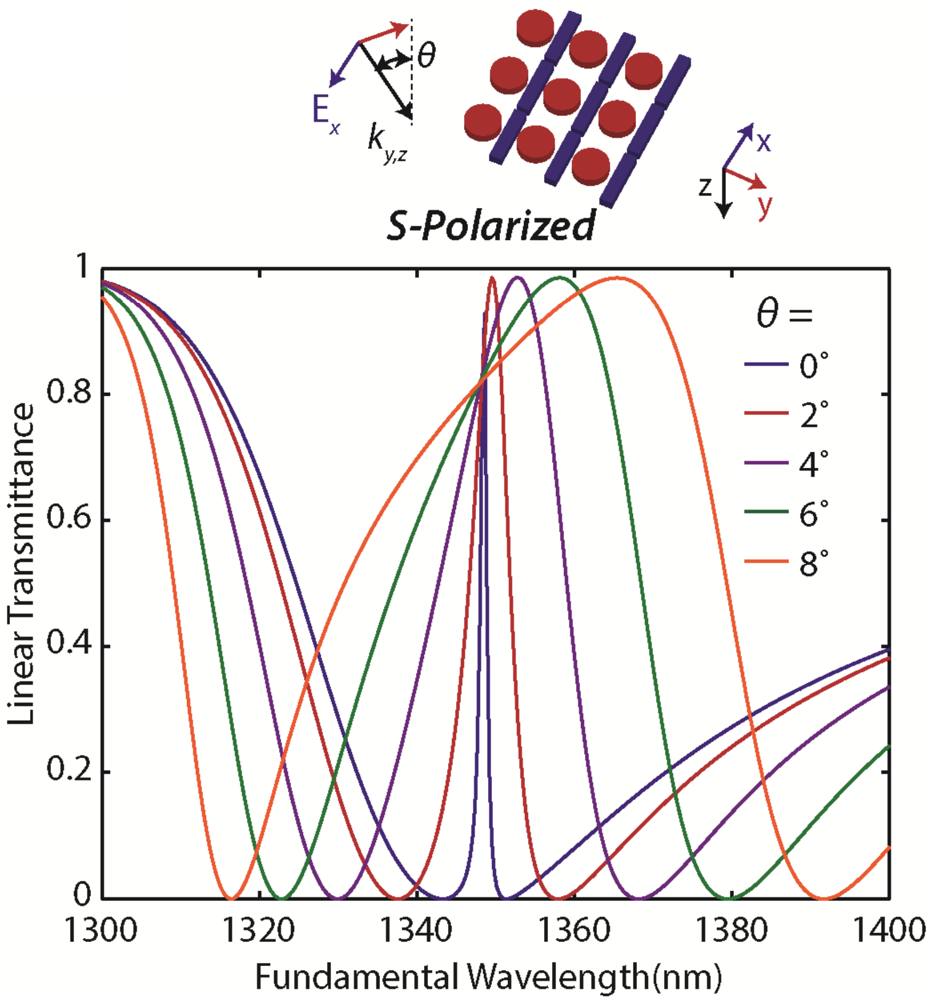
Lee et. al. PRL 109, 067401 (2012)

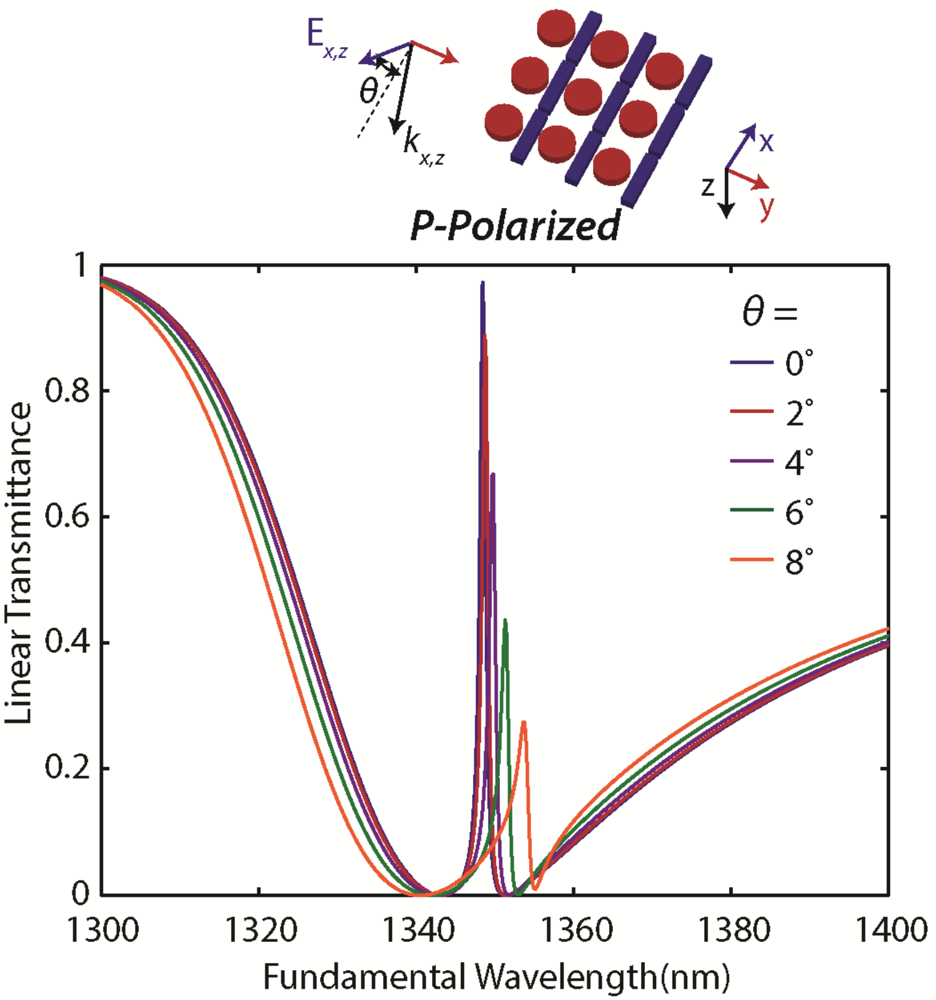




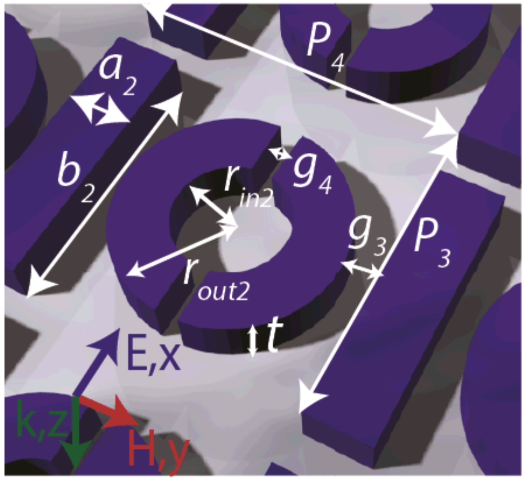
See also: Paddon et. al. PRB (2000), Ochiai et. al. PRB (2001), Fan et. al. PRB (2002)

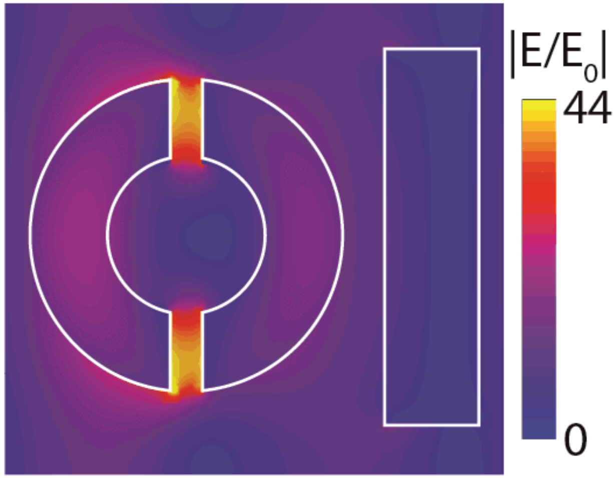
Dispersion with Angle of Incidence

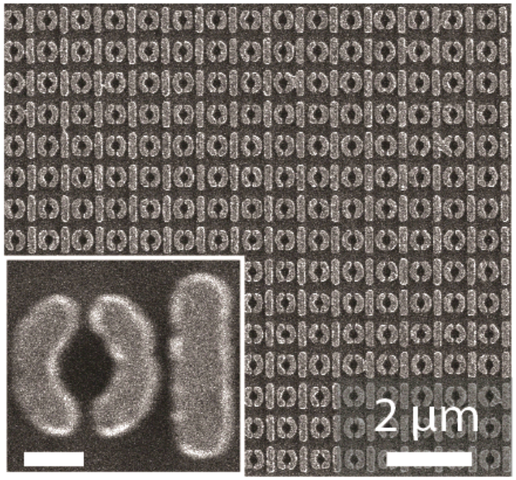




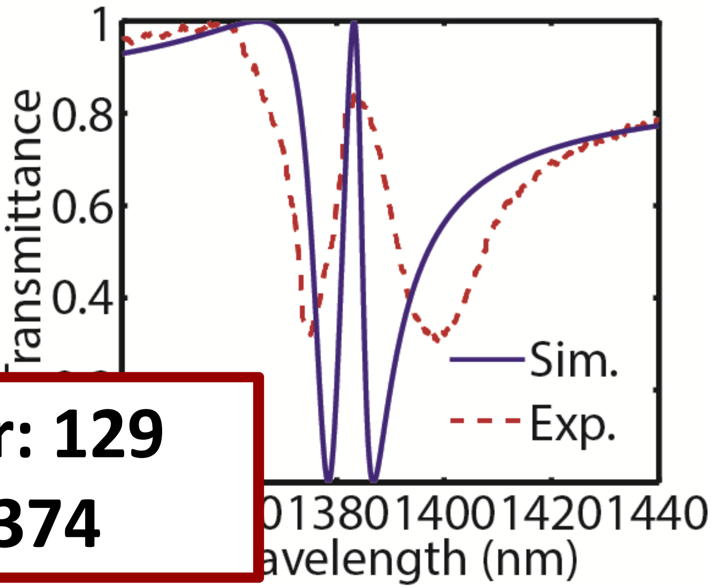
Focusing the Field





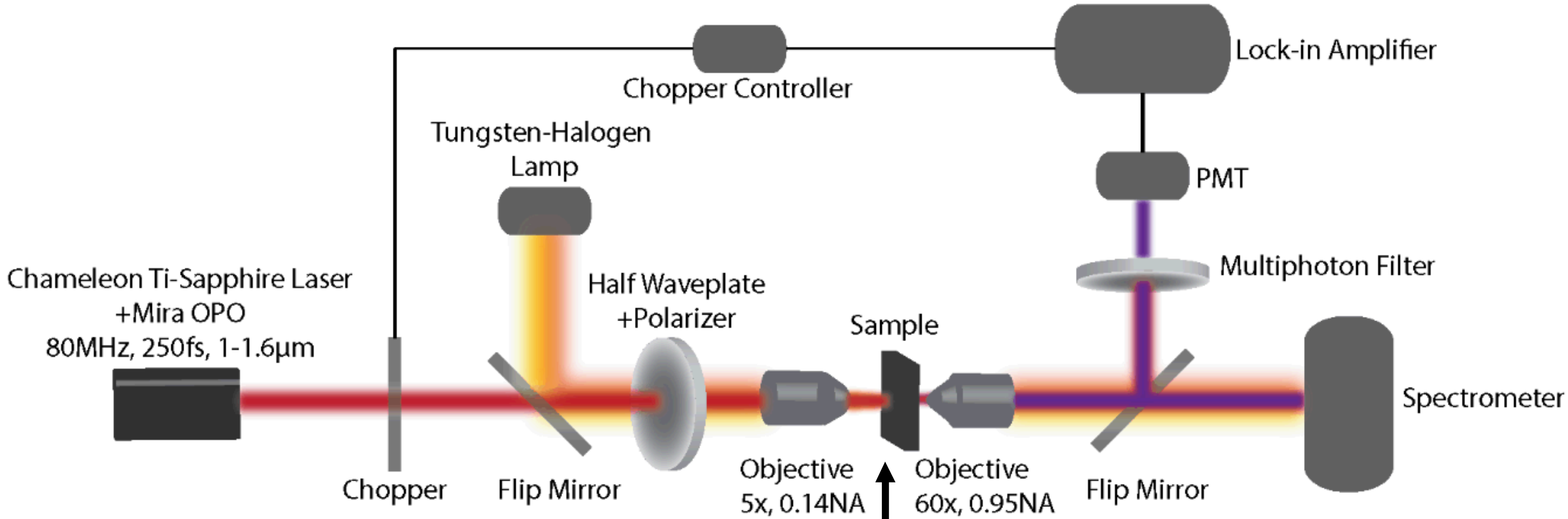


- r_{out} = 225nm
- g_3 = 70nm
- g_4 = 50nm
- t = 110nm
- p_1 = 750nm
- p_2 = 800nm



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

Nonlinear Measurements



Illumination diameter: 15µm (225 µm^2)