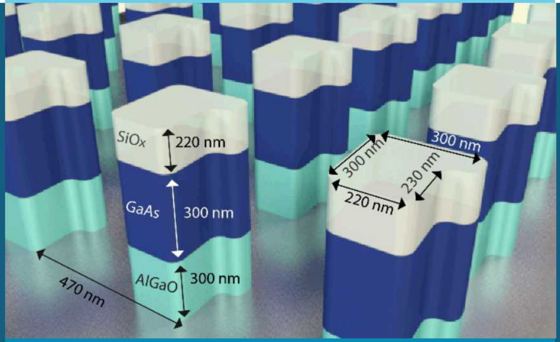
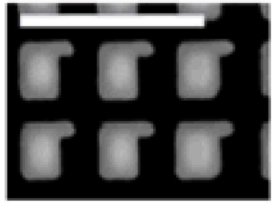
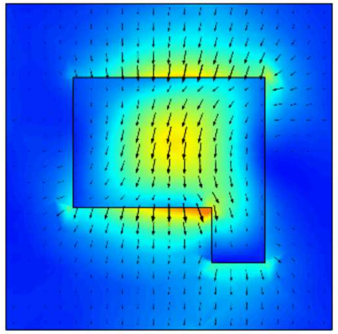
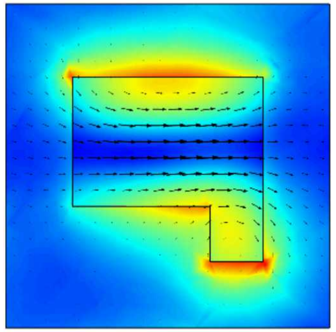
SAND2019-5191C

# All-Optical Tuning of Fano Resonances in Broken Symmetry GaAs Metasurfaces







*PRESENTED BY*

Nicholas Karl, Polina P. Vabishchevich, Sheng Liu, Michael B. Sinclair, Gordon A. Keeler, Gregory M. Peake, and Igal Brener

Sandia National Laboratories, NM, USA.
Center for Integrated Nanotechnologies, Sandia National Laboratories, NM, USA.

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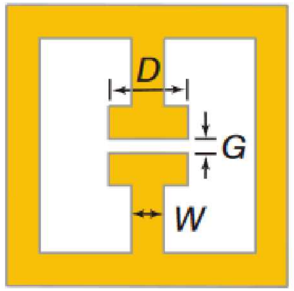
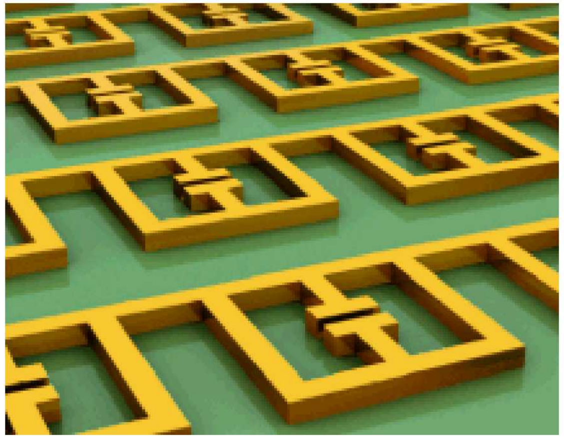
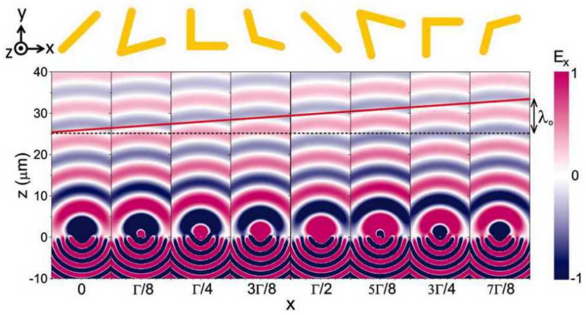
# Metasurfaces

Subwavelength ‘meta-atoms’ arranged in a planar array



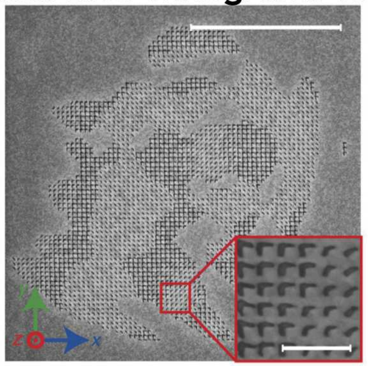



**Light Propagation with Phase Discontinuities**




Nanfang Yu *Science* 2011, 334, 6054, 333

**Metasurface holograms for visible light**




*Xingjie Ni, Nature Comm.* **4**, 2807 (2013)

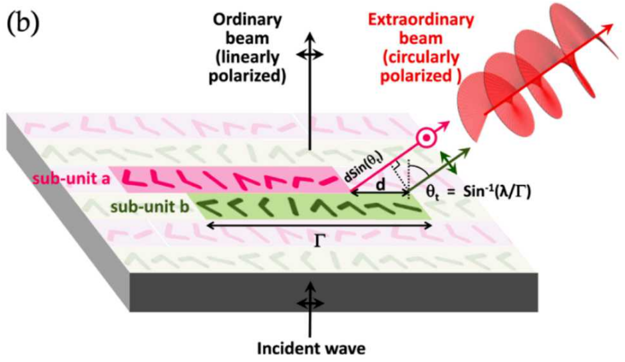
Powerful platform for control over the optical response

What about time?

↓

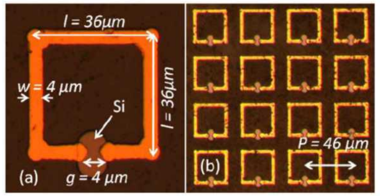
Tuning is still a challenge

**A Broadband, Background-Free Quarter-Wave Plate Based on Plasmonic Metasurfaces**




Capasso, Nano Lett. 2012, 12, 6328

Dynamically reconfigurable terahertz metamaterial through photo-doped semiconductor




Chowdhury, Appl. Phys. Lett. 99, 231101 (2011);

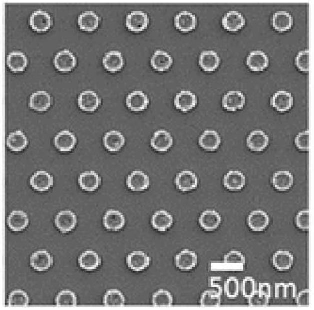
# Tunable (Real-time control)

Various Methods

- Phase Change
- Mechanical
- Liquid Crystals
- All-Optical

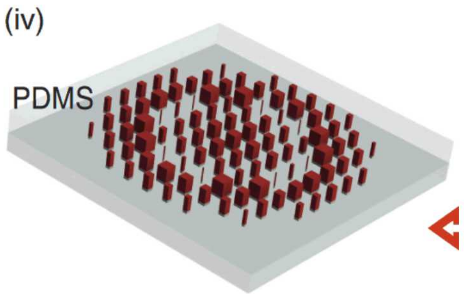
Fast & Efficient

**Solution-Processed Phase-Change $VO_2$ Metamaterials from Colloidal Vanadium Oxide ($VO_x$) Nanocrystals**



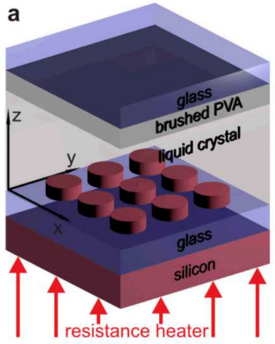

*ACS Nano*, 8 (1), pp 797–806 (2014)

Highly tunable elastic dielectric metasurface lenses



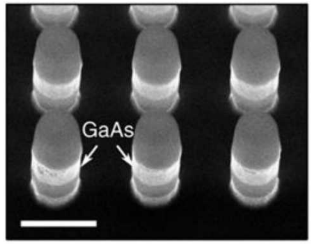

Laser & Photonics Rev. 10: 1002-1008 (2016)

**Active Tuning of All-Dielectric Metasurfaces**




ACS Nano, 2015, 9 (4), pp 4308

**Ultrafast all-optical tuning of direct-gap semiconductor metasurfaces**



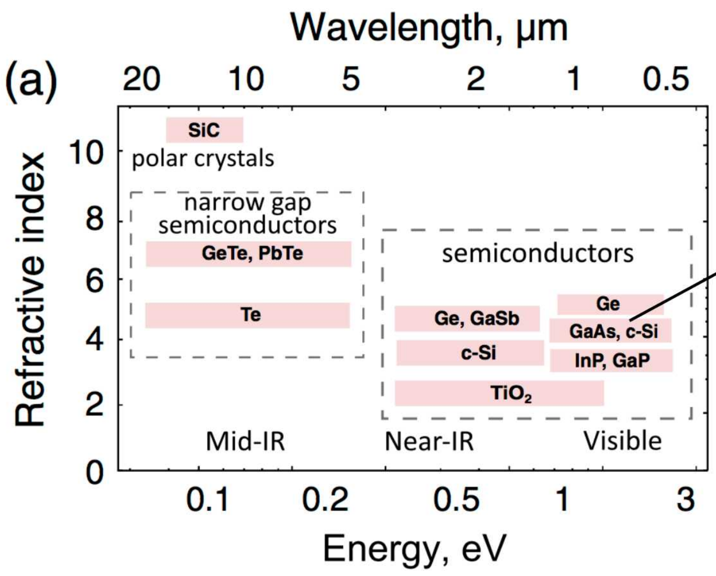

*Nature Comm.* **8**, 17 (2017)

# The all dielectric approach

## Advantages

- Low optical absorption
- High damage threshold
- Confined modes
- Free carrier injection

## Various Materials

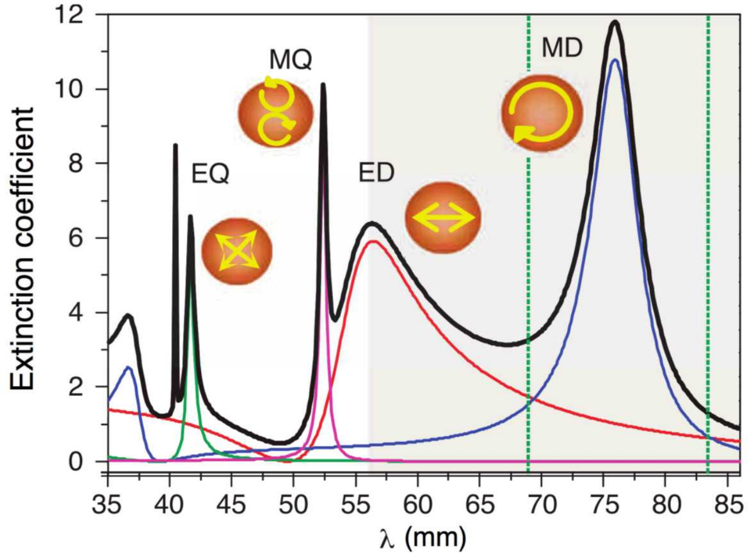



Baranov, D.G., et al. *Optica* 4.7, 814-825, **2017**

GaAs

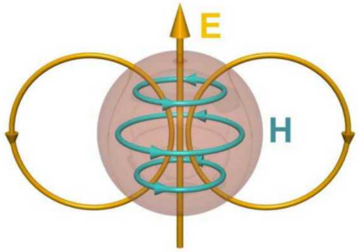
Direct Gap
Efficient generation
& recombination

Mie resonances in Dielectric spheres

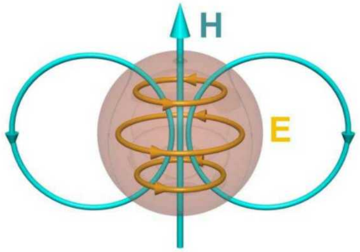



Geffrin, J.-M., et al. *Nat. Commun.* 3, 1171, **2012**

**Electric Dipole**

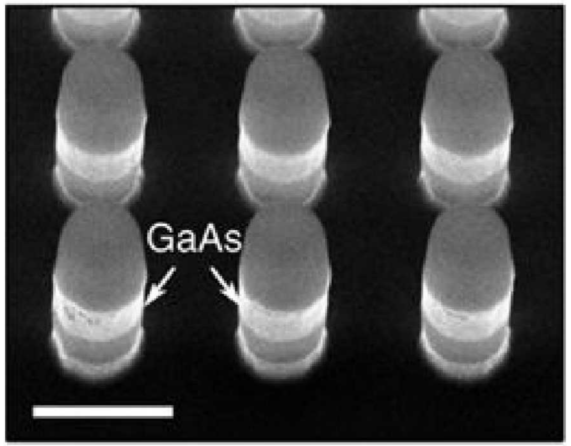


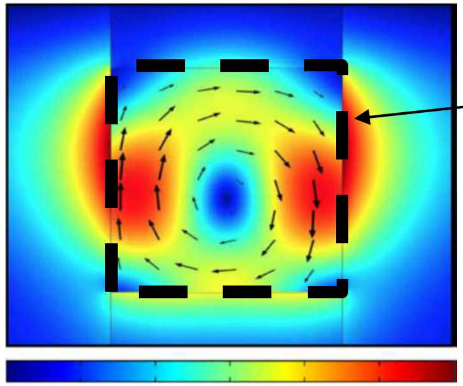

**Magnetic Dipole**



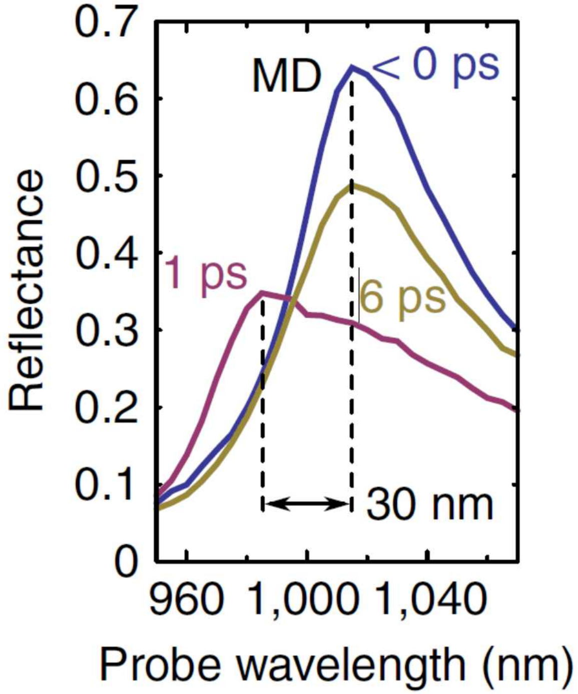

Images: A. Miroshnichenko

# Optical tuning of a magnetic dipole



GaAs Cylinder




Optical pump induces ultrafast 30 nm shift due to generation of free carriers

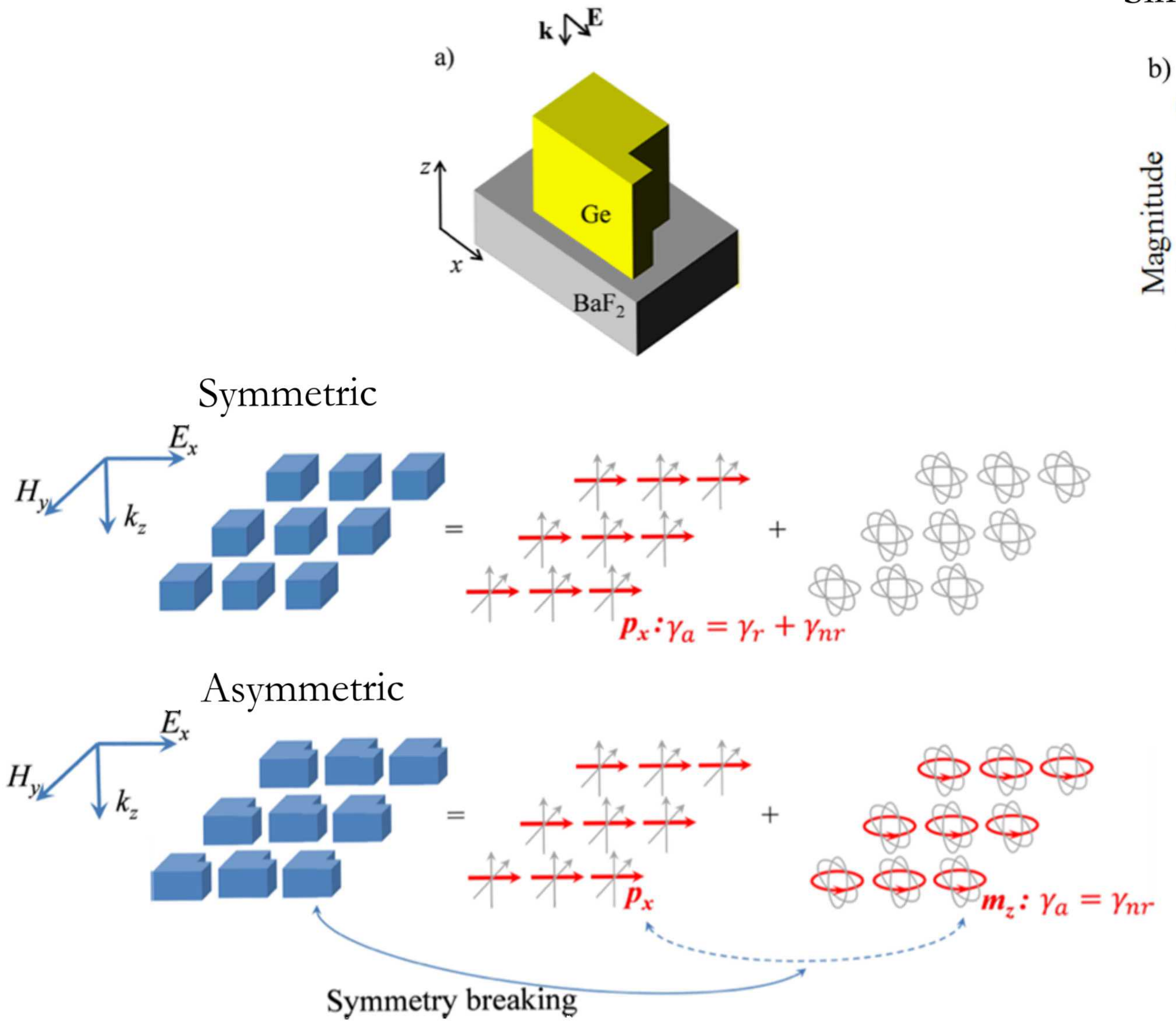
Pump fluence 310 μJ $cm^{-2}$

Magnetic Dipole Q ~ 10

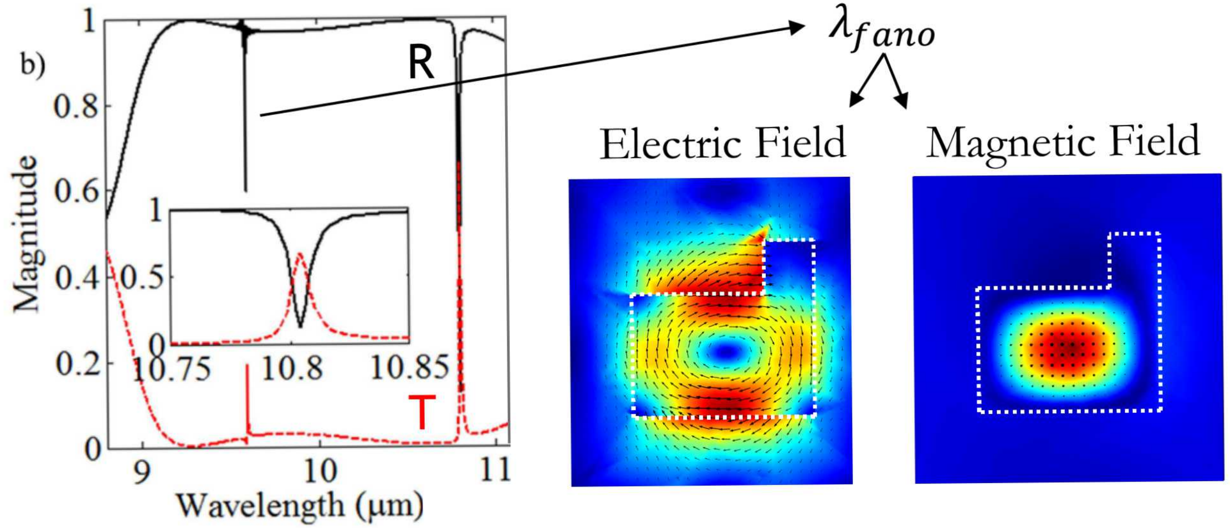
Idea: extend this method using a different resonator geometry in which the tuning will be more dramatic.

Maxim R. Shcherbakov et. al., "Ultrafast all-optical tuning of direct-gap semiconductor metasurfaces" *Nature Comm.* 8, 17 (2017)

# Breaking the symmetry: high-Q resonance




Simulation: Fano Resonances




**Goal:**

Fano Q ~ 500 vs MD Q ~ 10

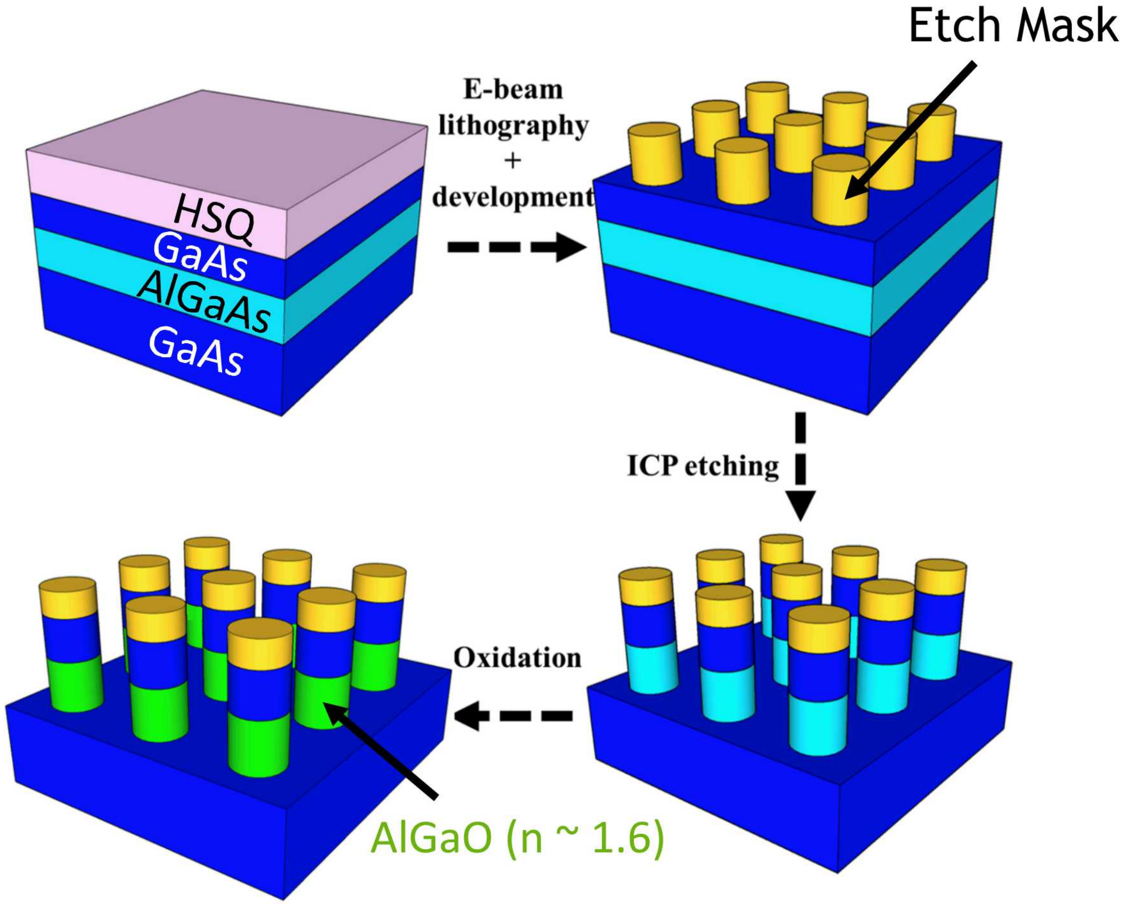
↓

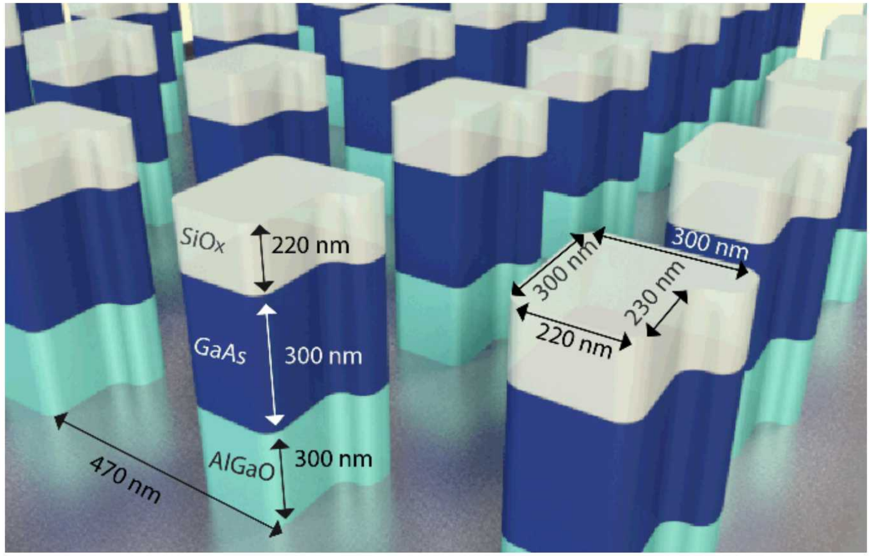
Pump the high Q Fano resonance

Campione, S. et.al. ACS Photonics 3 (12), 2362, **2016**

# Fabrication Process & Design

Process scheme:

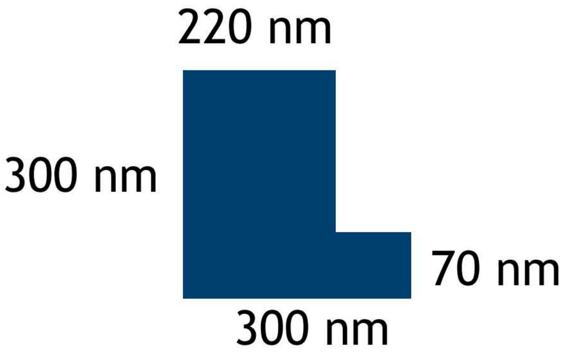


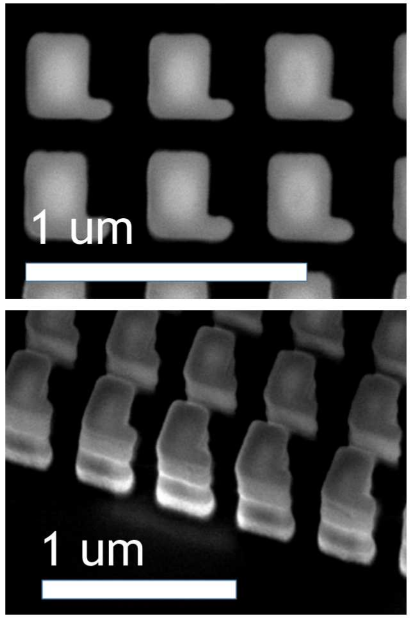

$SiO_x$ – 220 nm

**GaAs [100]- 300 nm**

$(Al_xGa_{1-x})_2O_3$ – 300 nm



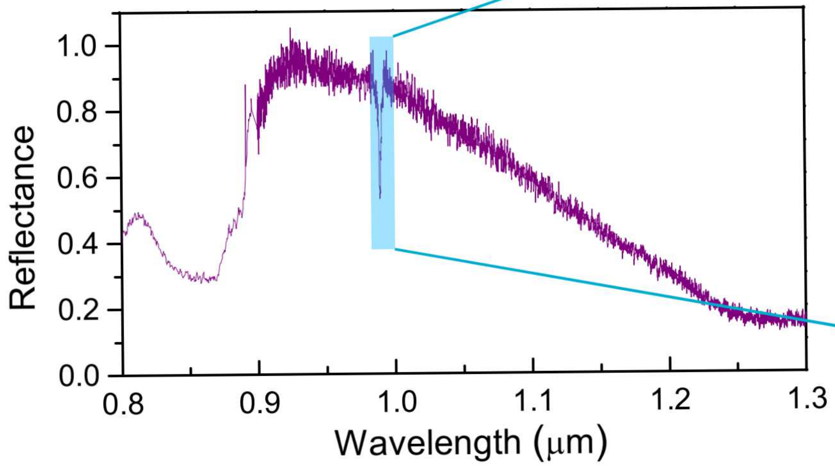

Pitch = 470 nm

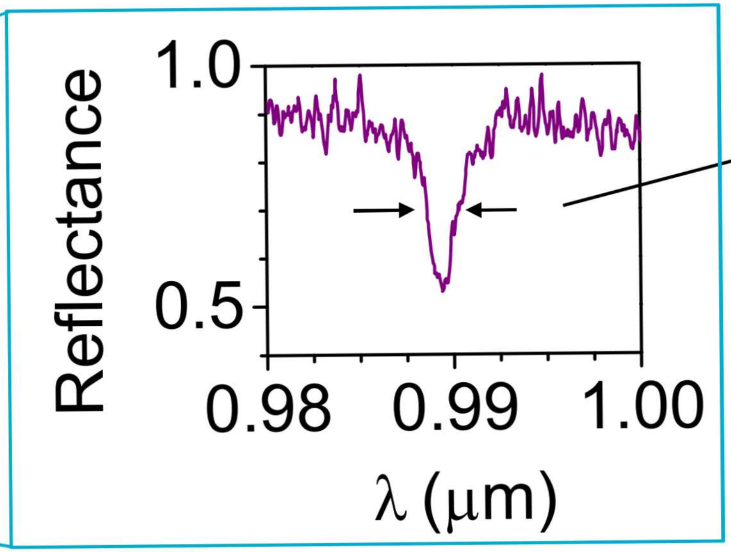



Liu, S. et. al. *Nano letters* 16.9: 5426-5432, **2016**

# Fano Resonance

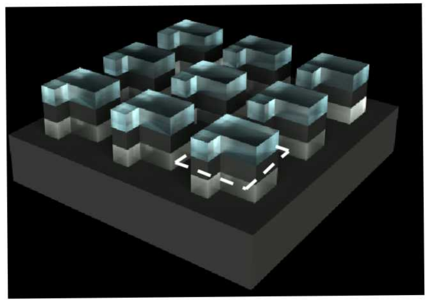
## Experimental measurements



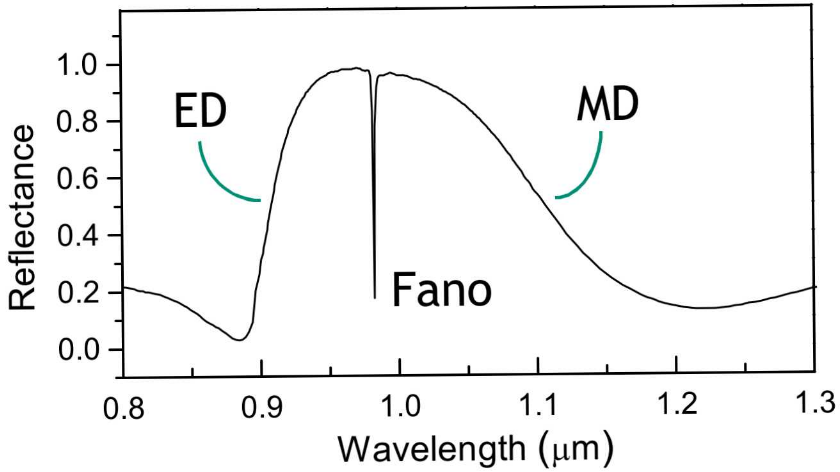

$\Delta\lambda \sim 2$ nm

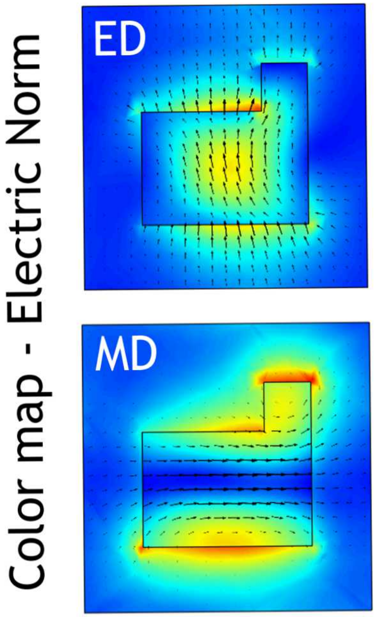
Q factor
$\lambda_F/\Delta\lambda \sim 500$



$\lambda_{fano} \sim 970\ nm$

## FDTD simulations



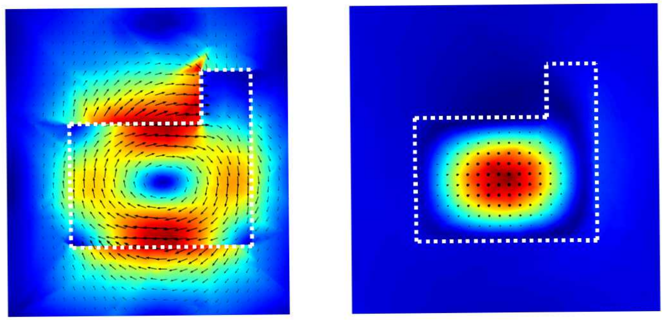




Quiver
$E_x, E_y, E_z$

Quiver
$H_x, H_y, H_z$

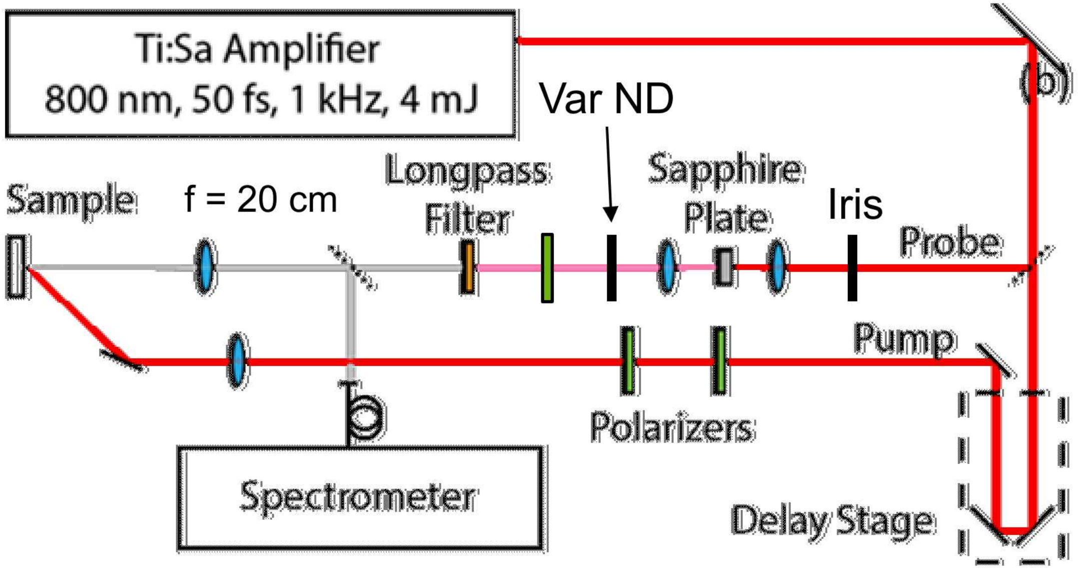
Electric Field

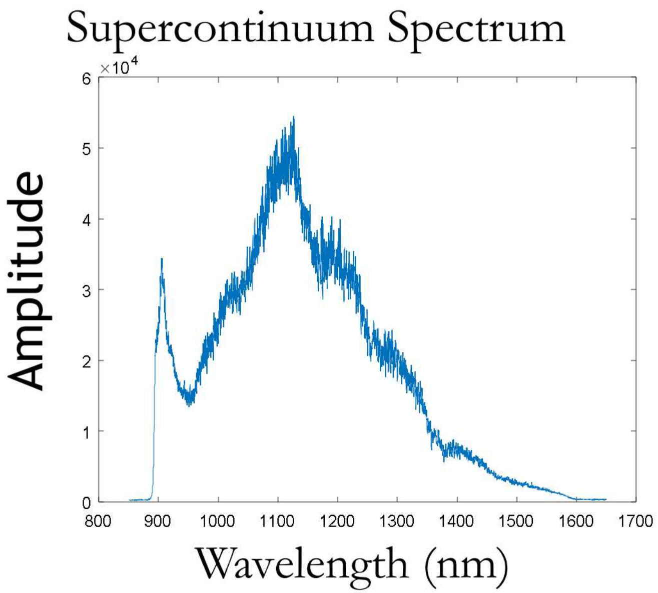
Magnetic Field

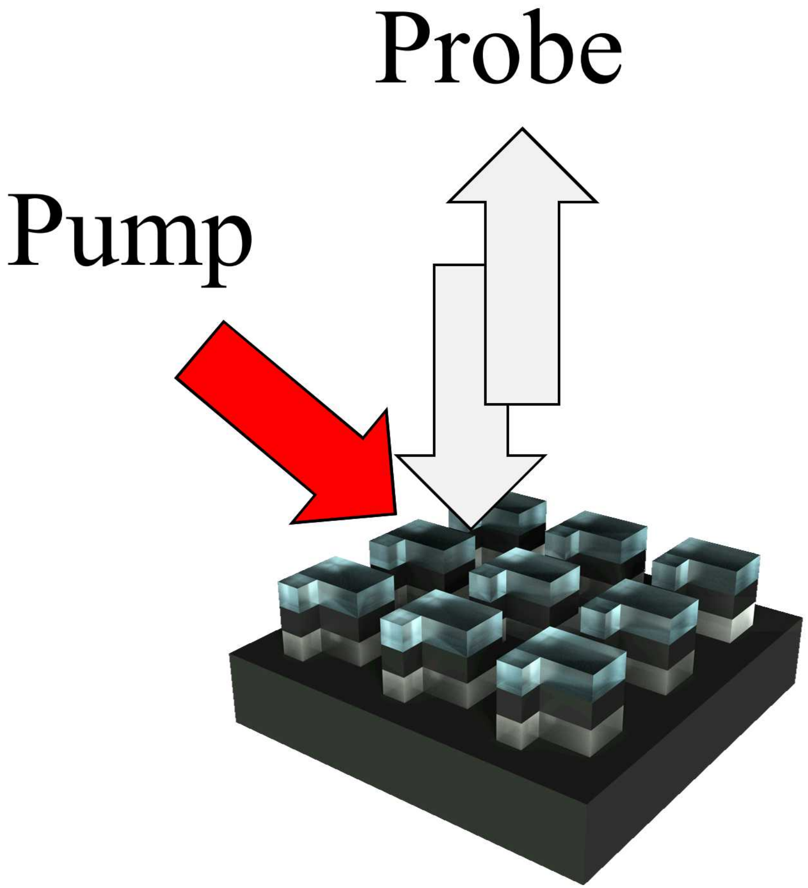


Vabishchevich, P., et al. *ACS Photonics*
DOI: 10.1021/acsphotonics.7b01478, **2018**

# Pump-probe experimental setup



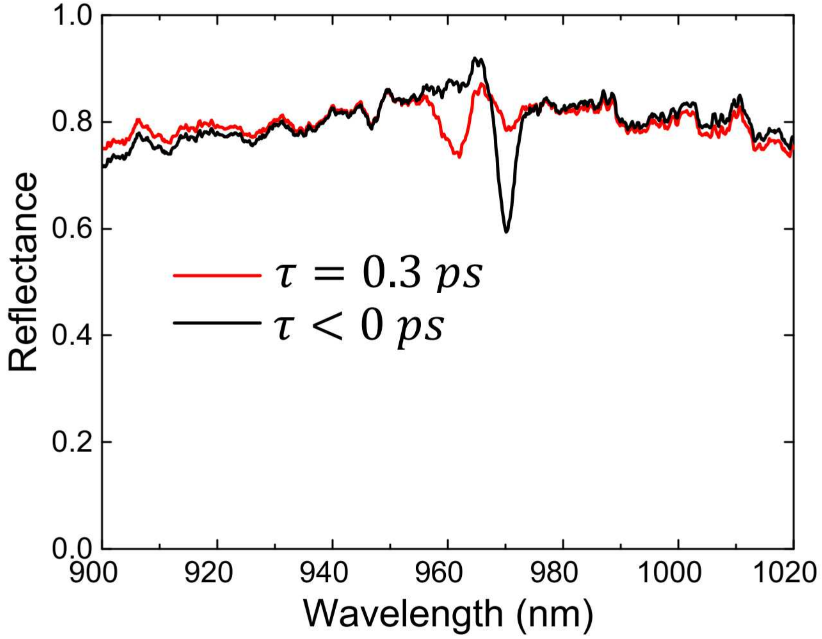




Probe beam average power is 10 uW.

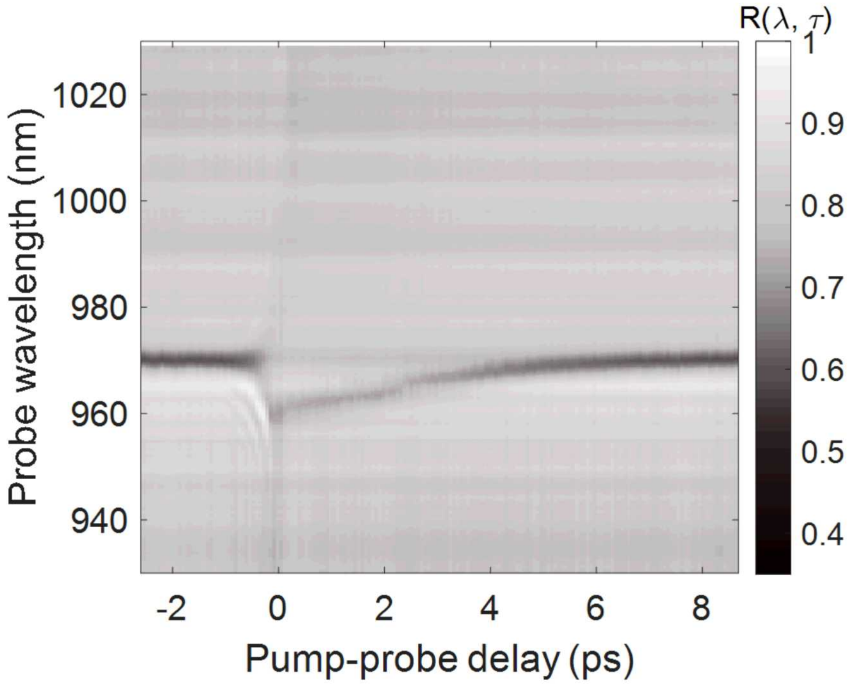
Pump -> Free Carrier Generation -> Index Shift

# Pump induced Fano shift




Pump fluence = 89 uJ / cm[2]

$\Delta\lambda = 10$ nm
blue shift




$$\Delta R = R_{\tau=0.13\ ps} - R_{\tau<0}$$

$$\frac{\Delta R}{R_{\tau<0}} = 45\%$$

$$\tau_{relax} \approx 2.45\ ps$$

# Dynamics Analysis

Dynamics of the free carrier plasma

$$\frac{dN}{dt} = -AN - BN^2 - C_{eff}N^3$$

$$\frac{1}{\Gamma} = A_{eff} + BN + C_{eff}N^2$$

Free carrier density

$$N = \frac{\frac{F_{pump}}{E_{pump}}\left(1 - e^{-\alpha d}\right)}{d \times FF}$$

$$F_{pump} = 89\ \mu J\ /\ cm^2$$

↓

$$N = 1.27 \times 10^{19}\ /\ cm^3$$

↓

$\Gamma = 300$ ps

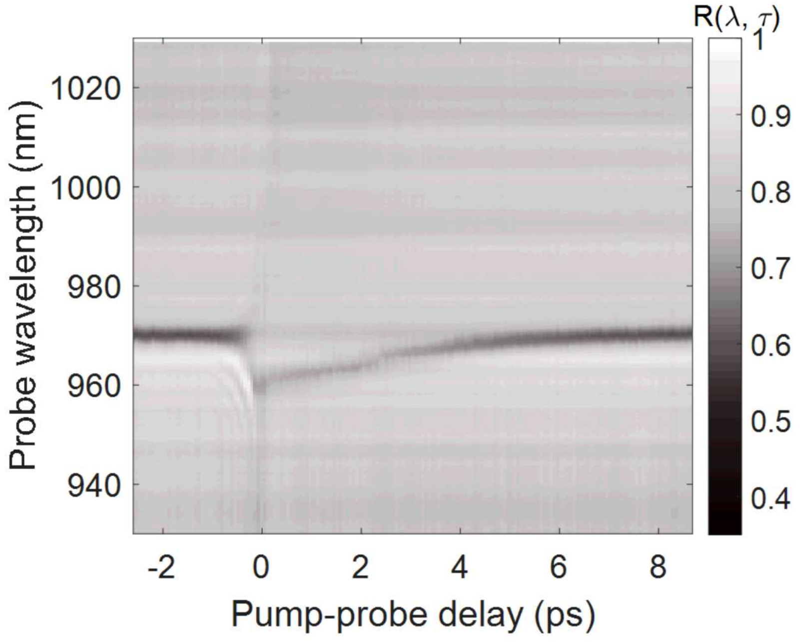
→ $\Gamma = 2.43$ ps

GaAs Relaxation Material Parameters

$A_{bulk} = 7 \times 10^{7}\ s^{-1}$

$B = 1.7 \times 10^{-10}\ cm^3 \cdot s^{-1}$

$C_{eff} = 7 \times 10^{-30}\ cm^6 \cdot s^{-1}$




$$\tau_{relax} \approx 2.45\ ps$$

$A_{eff} = 1\ /\ \tau_{relax} = 4.1 \times 10^{11}\ s^{-1}$

Recombination from surface states in nanostructures


Strauss, U., W.W. Ruhle, and K. Kohler, *Auger Recombination in Intrinsic Gaas.* Applied Physics Letters, 1993. **62**(1): p. 55-57.
Varshni, Y.P., *Band-to-Band Radiative Recombination in Groups IV, VI, and III-V Semiconductors (I)*. physica status solidi (b), 1967. **19**(2): p. 459-514.

# Free Carrier Index Shift

$$\Delta\alpha = \Delta\alpha_{BF} + \Delta\alpha_{BGS} + \Delta\alpha_D$$

$$\Delta n = \Delta n_{BF} + \Delta n_{BGS} + \Delta n_D$$

$\Delta n$ < 0
Blue shift

$$N = 1.27 \times 10^{19} \ / \ cm^3$$

$$\Delta n_{BF} = -0.061$$

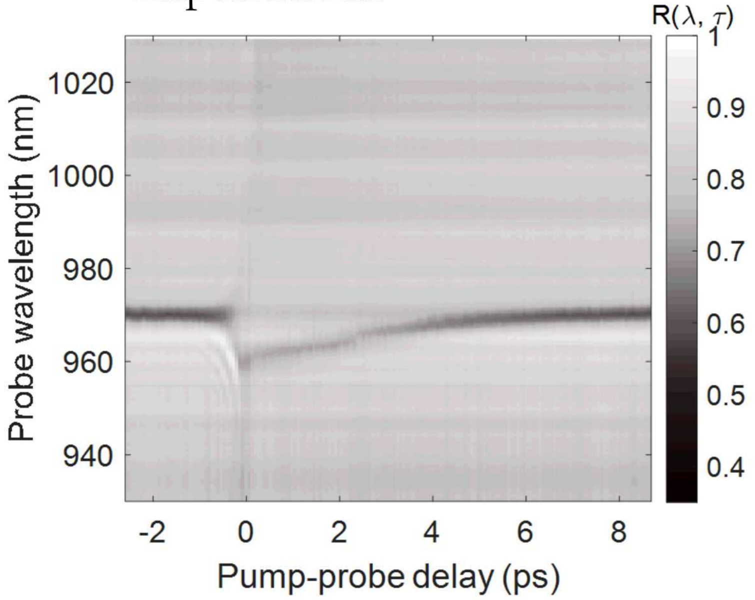
$$\Delta n_{BGS} = 0.012$$

$$\Delta n_D = -0.022$$

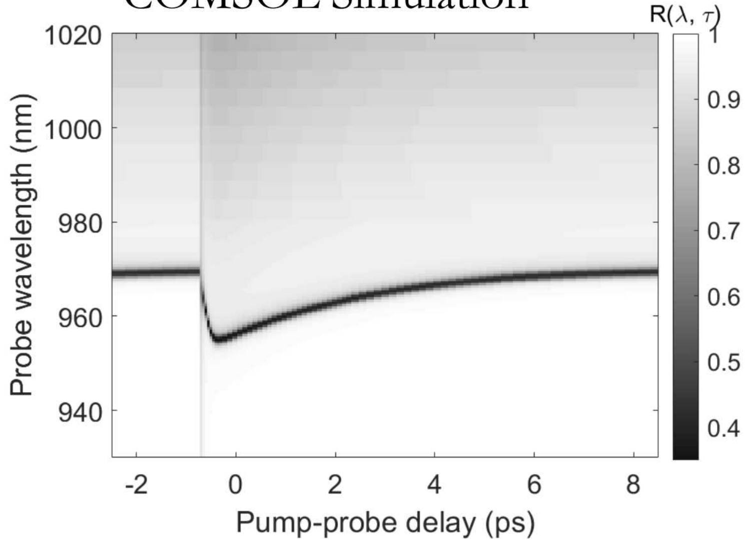
$$\Delta n = -0.061 + 0.012 \ - 0.022 = -0.071$$

$$\Delta k = -0.323 \times 10^{-3}$$

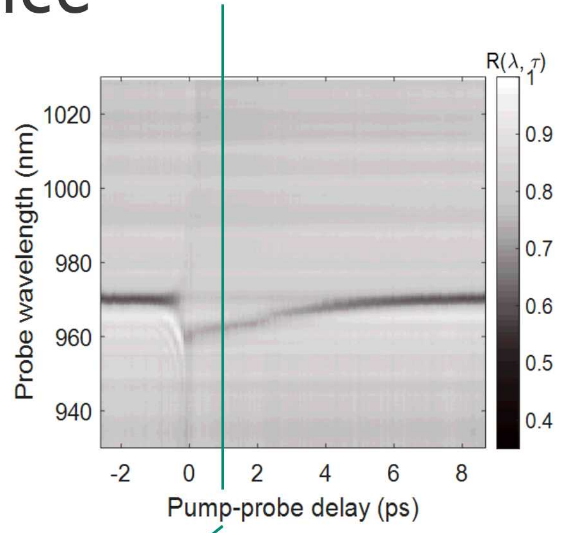
Experimental



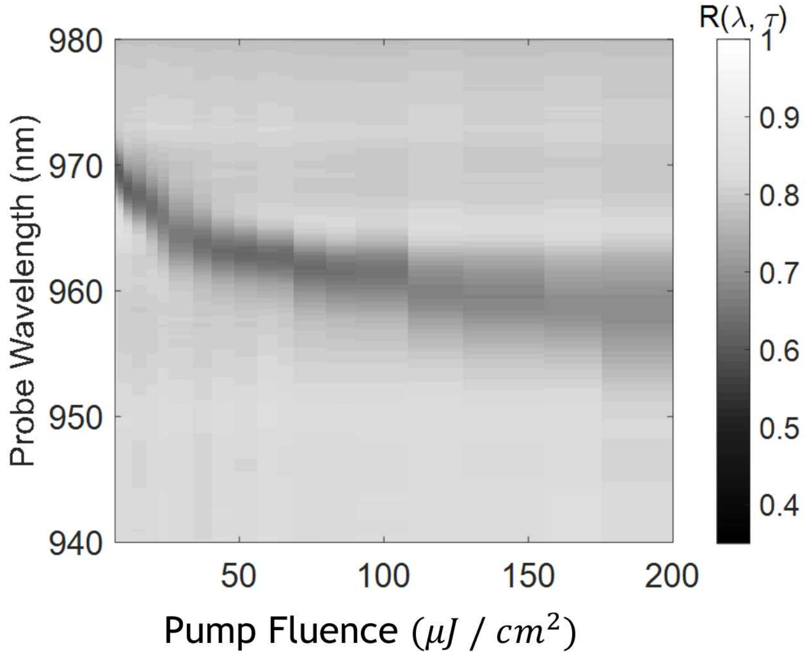

COMSOL Simulation

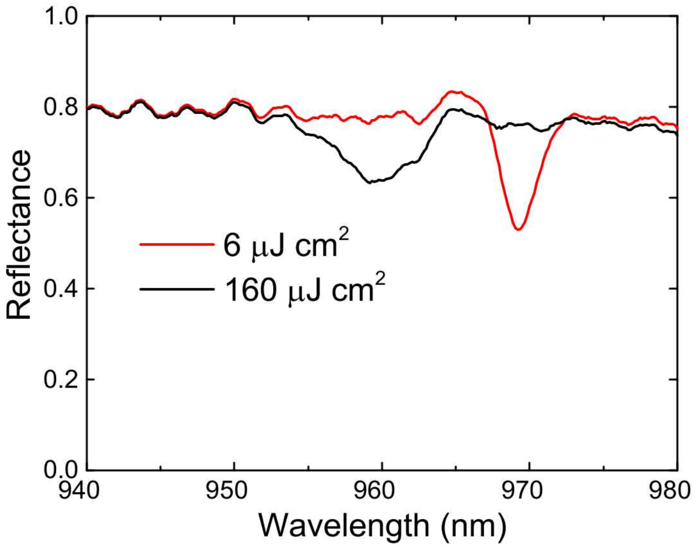


# Pump Fluence




shift at t = 1 ps



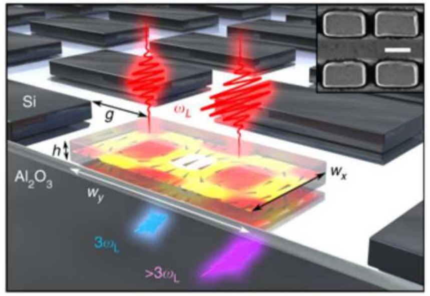



# Outlook

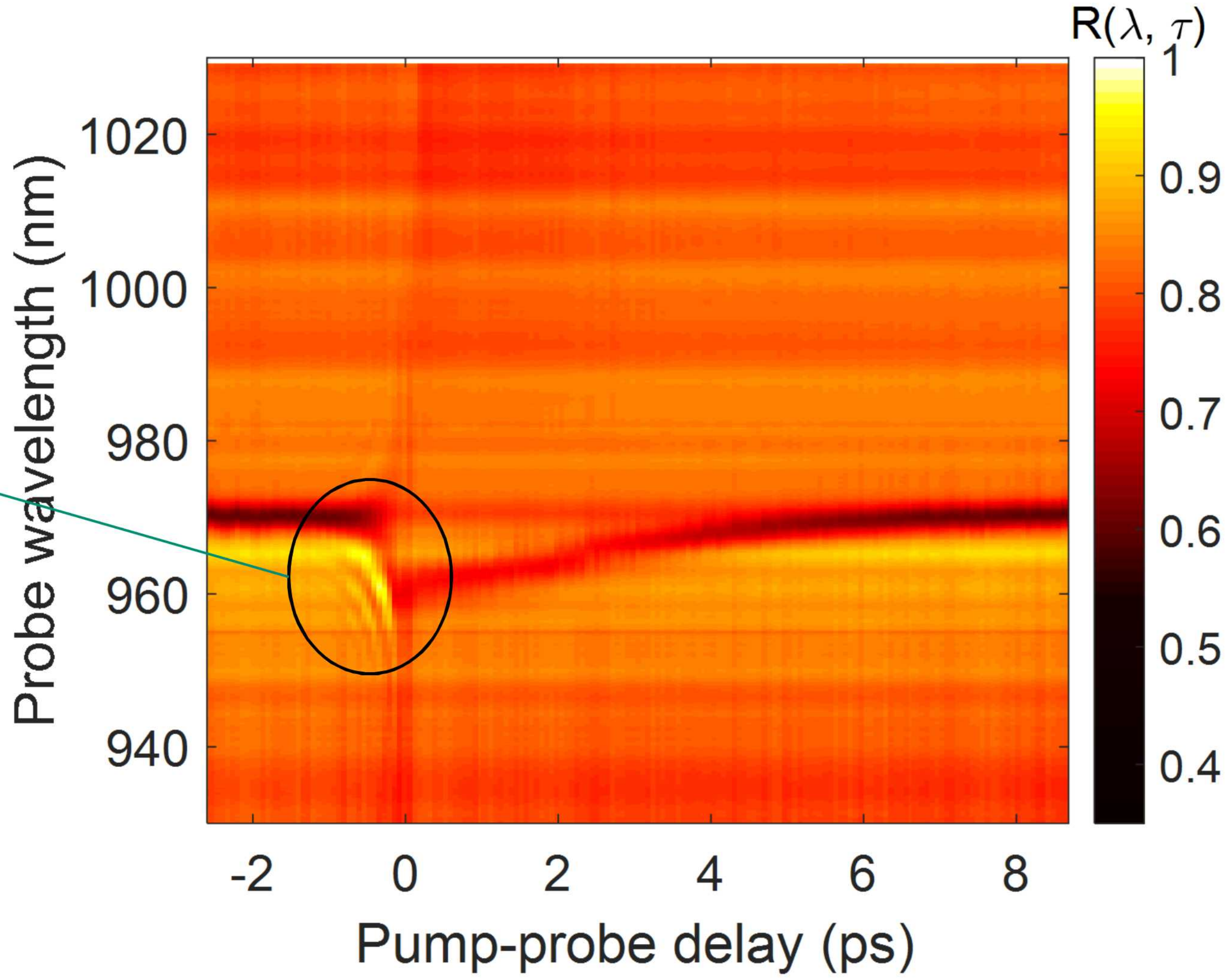
Application
- ultrafast switch,
- nearly 3dB modulation
- resonance shift of > a linewidth

Nonlinear phenomenon?
Temporal dynamics

**Photon acceleration and tunable broadband harmonics generation in nonlinear time-dependent metasurfaces**




*Nature Comm*, **10**, 1345 (2019)



# Conclusions

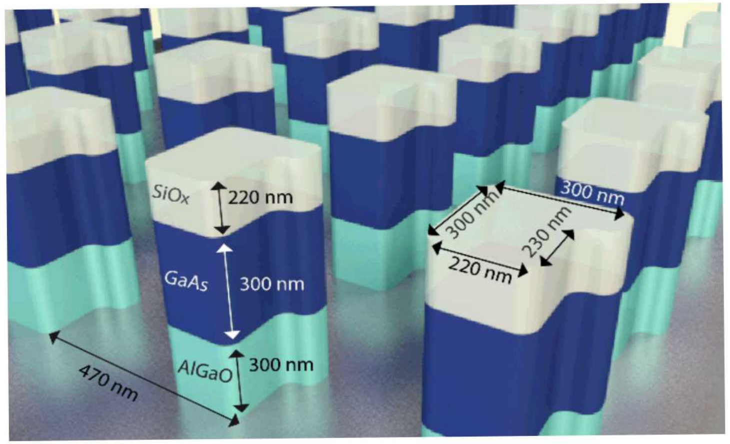
Direct gap semiconductor metasurfaces offer many advantages for ultrafast all optical modulation

- Silicon devices require larger pump fluences > 1 $mJ/cm^2$ with 30 ps relaxation for 0.2 optical modulation
- Transparent conducting oxides (AlZnO, ITO) require far higher pump fluences 1-10 $mJ/cm^2$ range

Nearly 3dB switching performance

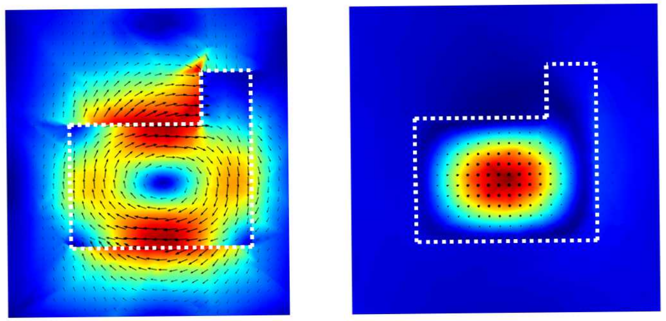
The broken symmetry dielectric metasurface studied here allows for an ultrafast, all optical modulation solution at fluences of less than 100 $uJ / cm^2$.

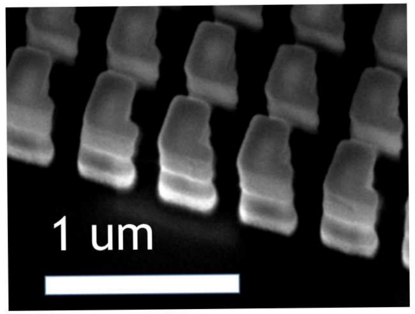
Ultrafast operation due to direct gap absorption and fast recombination assisted by surface states.




$\lambda_{fano} \sim 970\ nm$

Electric Field　　Magnetic Field





# Questions

# Carriers - Absorption

Drude:

$$\Delta n_D(N,E) = \left(\frac{N_e}{m_e} + N_h \frac{\sqrt{m_{hh}} + \sqrt{m_{lh}}}{m_{hh}^{3/2} + m_{lh}^{3/2}}\right) \frac{-\hbar^2 e^2}{2n\varepsilon_0 E^2}$$

$$\Delta\alpha_D(N,E) = \left(\frac{N_e}{m_e^2 \mu_e} + \frac{N_h}{\mu_h}\left(\frac{\sqrt{m_{hh}} + \sqrt{m_{lh}}}{m_{hh}^{3/2} + m_{lh}^{3/2}}\right)^2\right) \frac{\hbar^2 e^3}{cn\varepsilon_0 E^2}$$

Band Filling:

$$\alpha_0(E) = \frac{C}{E}\sqrt{E - E_g}$$

$$\Delta\alpha_{BF}(N,E,T) = \frac{C_h}{E}\sqrt{E - E_g}\,(f_{v,ah} - f_{c,bh} - 1) + \frac{C_l}{E}\sqrt{E - E_g}\,(f_{v,al} - f_{c,bl} - 1)$$

Bandgap Shrinkage:

$$\Delta E_g(N) = -\left(\frac{e}{2\pi\varepsilon_0\varepsilon_s}\right)\left(\frac{3N}{\pi}\right)^{1/3}$$

$$\Delta\alpha_{BGS}(N,E) = \frac{C}{E}\sqrt{E - E_g - \Delta E_g(N)} - \frac{C}{E}\sqrt{E - E_g}$$

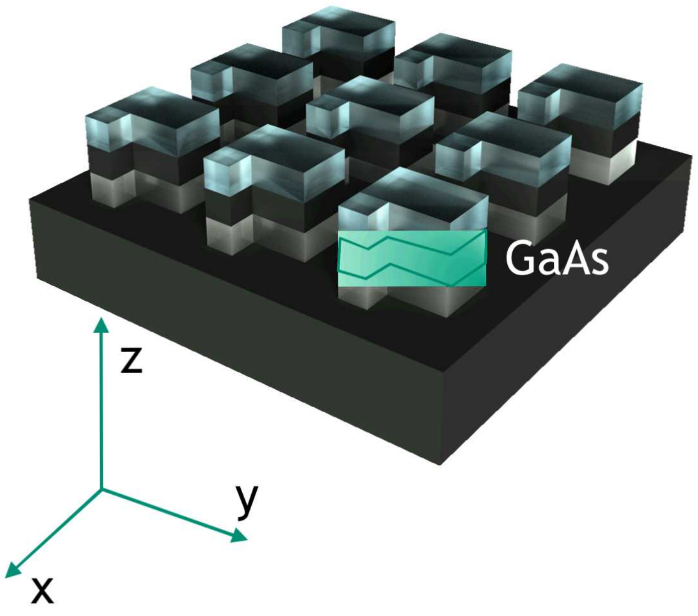
Kramers-Kronig

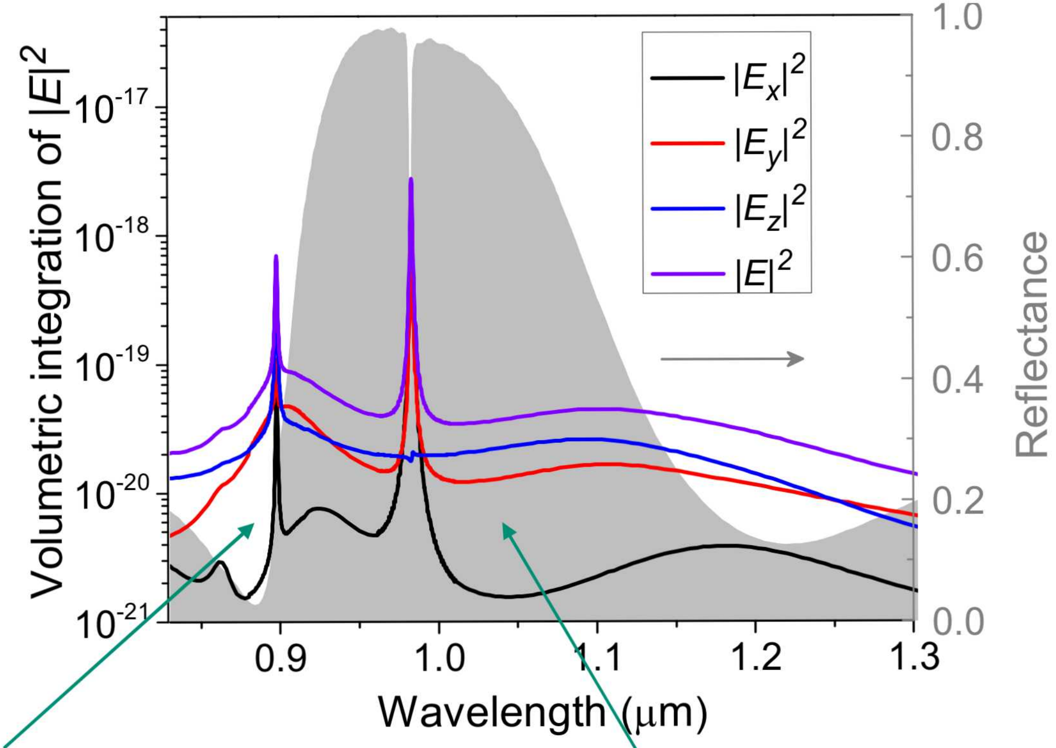
$$\Delta n_{BF}(N,E,T) = \frac{c\hbar}{\pi e^2}\, P\,V \int_0^\infty \frac{\Delta\alpha_{BF}(N,E',T)}{E'^2 - E^2} dE'$$

$$\Delta n_{BGS}(N,E) = \frac{c\hbar}{\pi e^2}\, P\,V \int_0^\infty \frac{\Delta\alpha_{BGS}(N,E')}{E'^2 - E^2} dE'$$

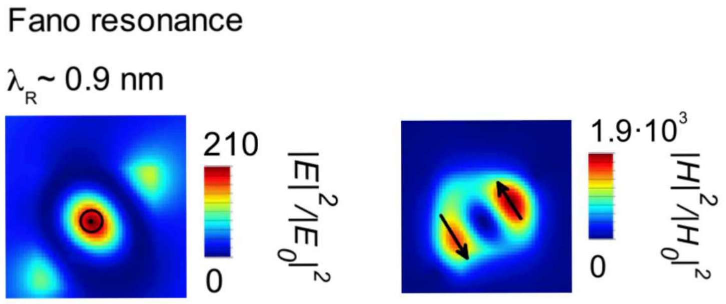
$$\Delta n = \Delta n_D + \Delta n_{BF} + \Delta n_{BGS}$$

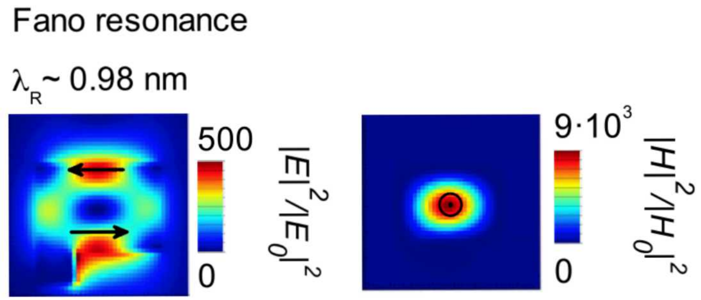
# Numerical calculations



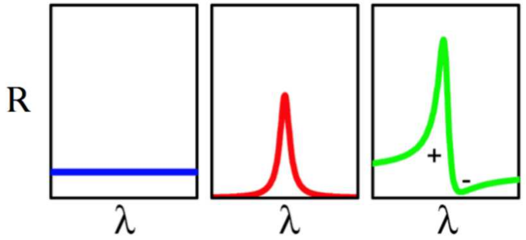

$$P_i^{(2\omega)} \propto \chi_{ijk}^{(2)} E_j^{(\omega)} E_k^{(\omega)}$$

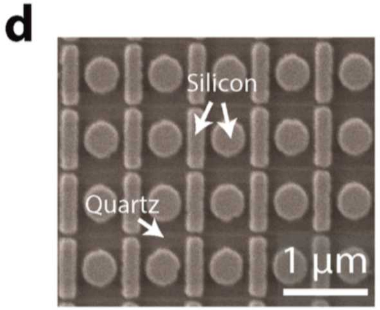


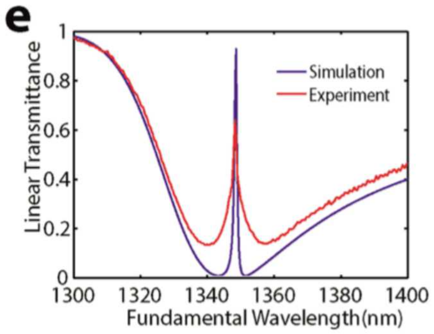



# High-Q Fano resonances in all-dielectric metasurfaces

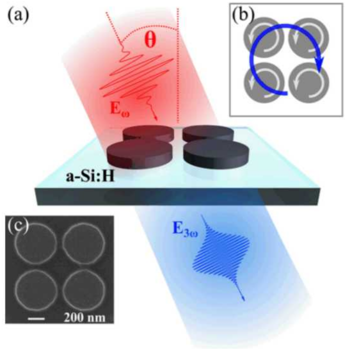
$$P = \varepsilon_0 \left[ \chi^{(1)} E + \chi^{(2)} E^2 + \chi^{(3)} E^3 + \cdots \right]$$

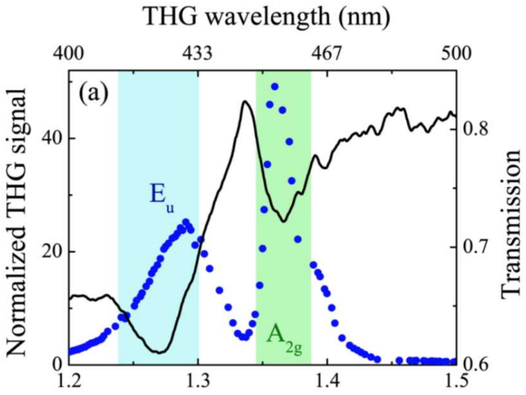



Yang, Y et. al.Nano Lett. 2015, 15 (11), 7388–7393.

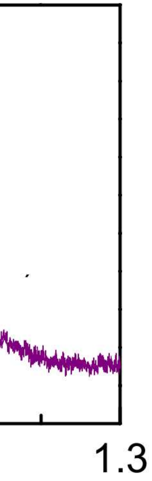


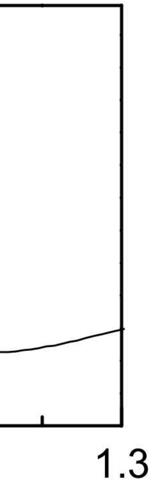




Shorokhov, A. S et al  Nano Lett. 2016, 16 (8), 4857−4861.

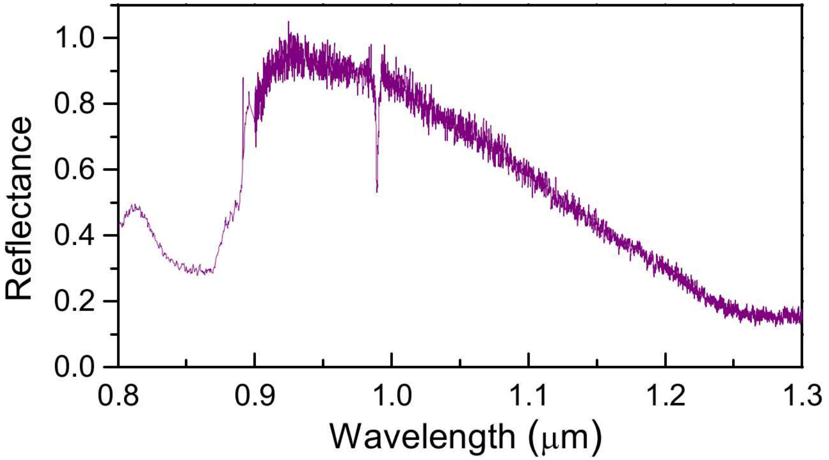
10-fold enhancement of Third-Harmonic Generation
in Si metasurfaces with Fano resonances

# Fano metasurface reflectance spectrum

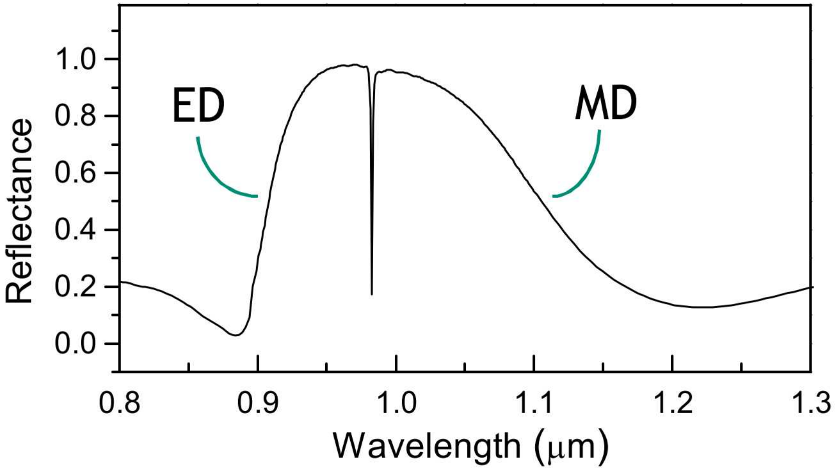


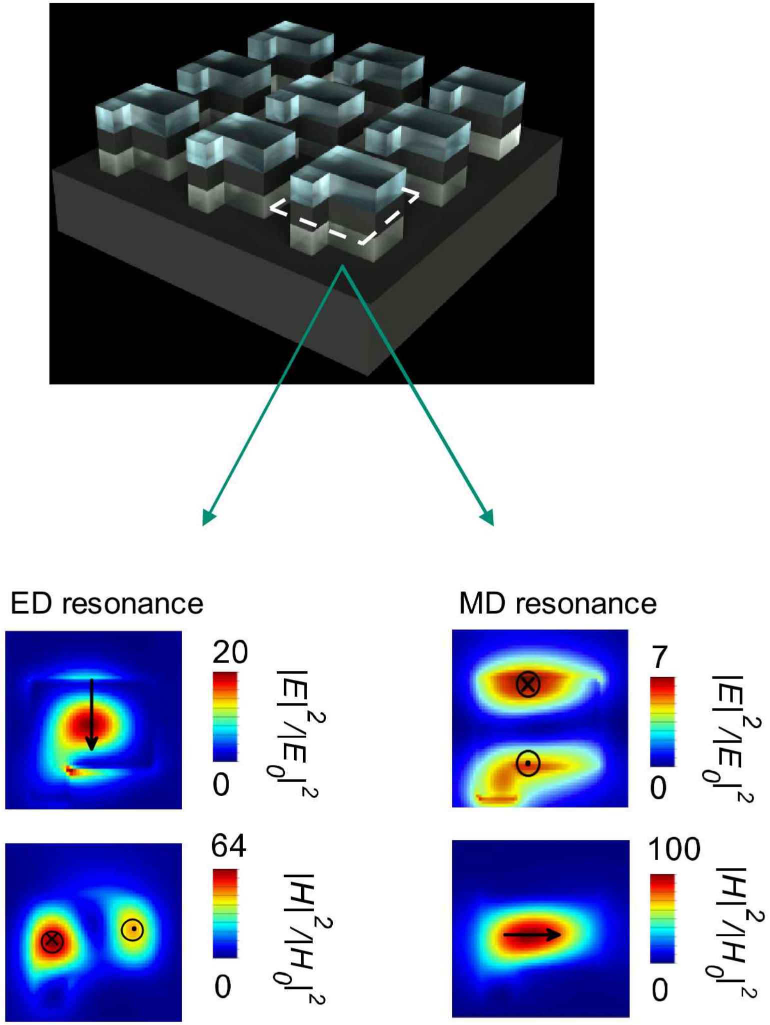



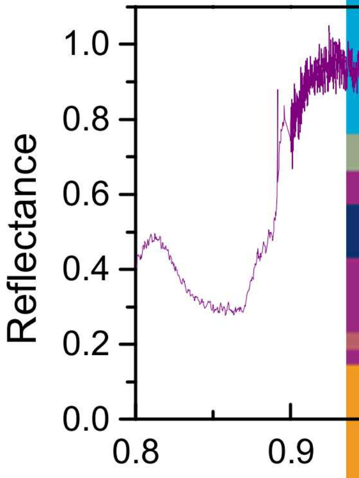

## Experimental measurements



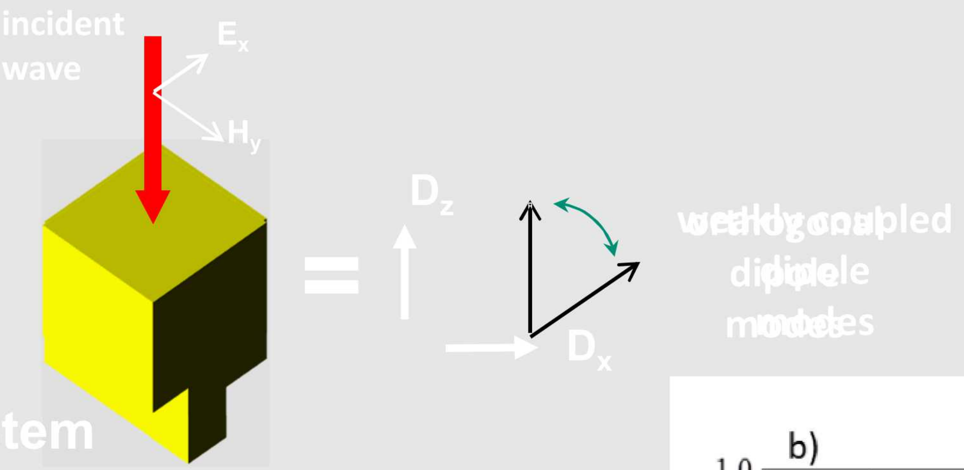

## FDTD simulations



# High Q modes Using "Broken Symmetry" Resonators



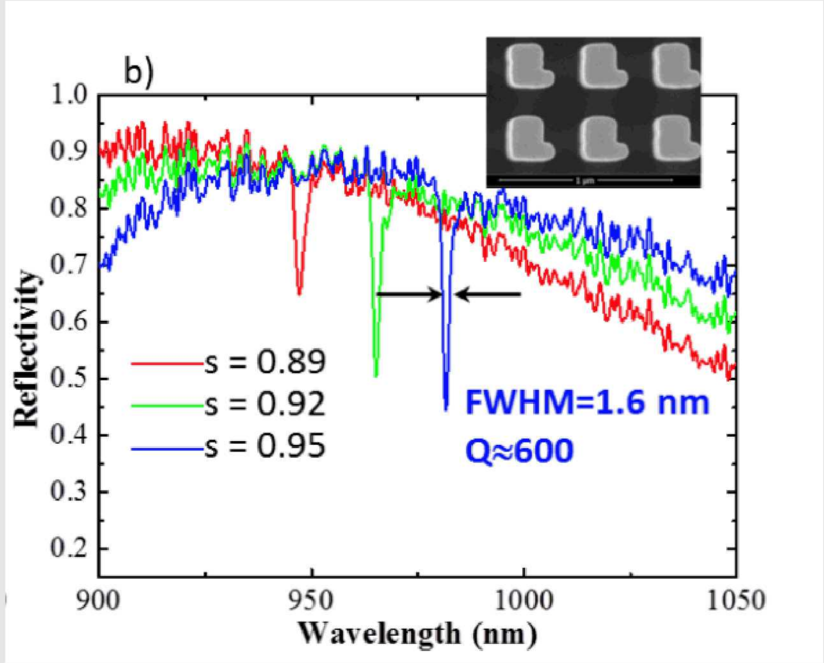

**Broken symmetry system**

**External Wave** ⟷ **$D_x$ (low Q)**

Cavity perturbation

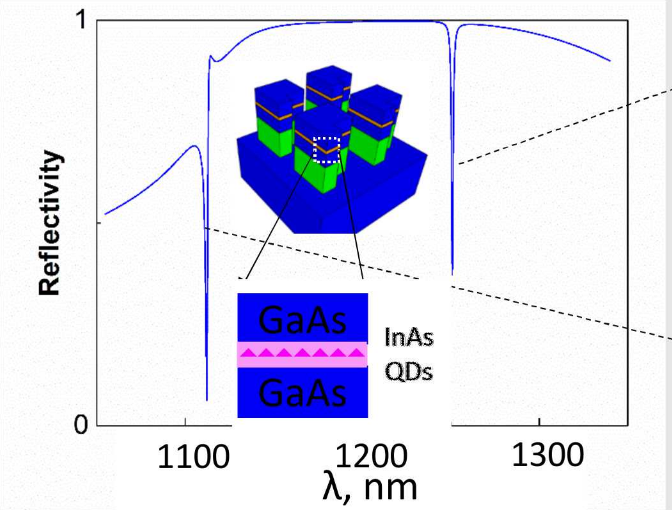
**$D_z$ (high Q)**
can't radiate in-plane
due to local field interactions

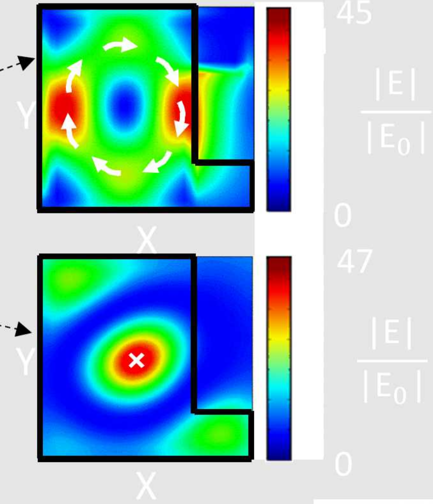
broad dipole
resonances

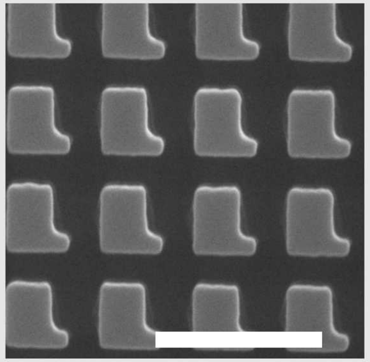


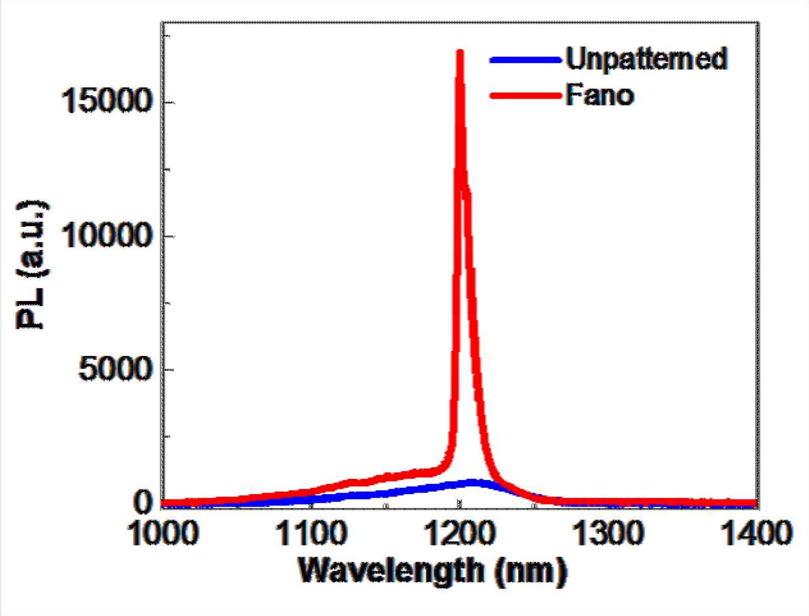

ACS Photonics 2016

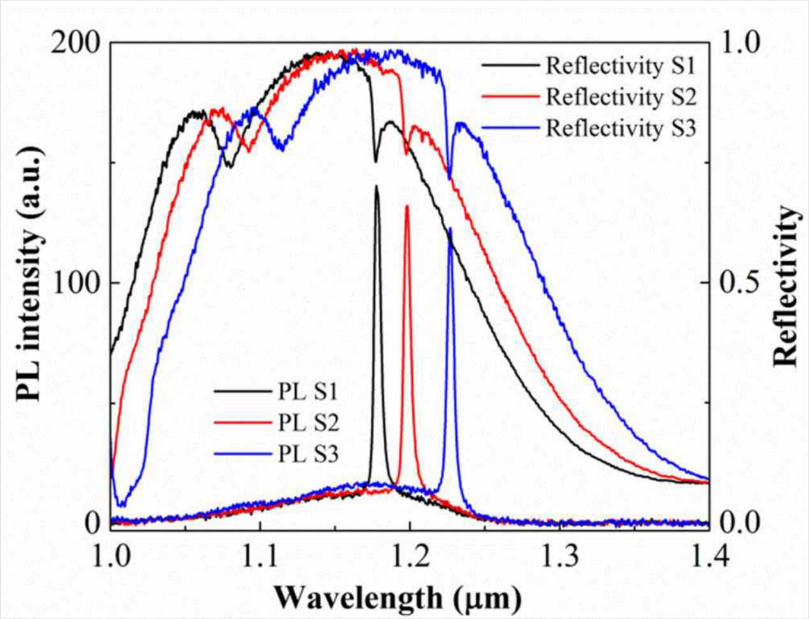
# Light Emitting Metasurfaces



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