SAND2017-5742PE

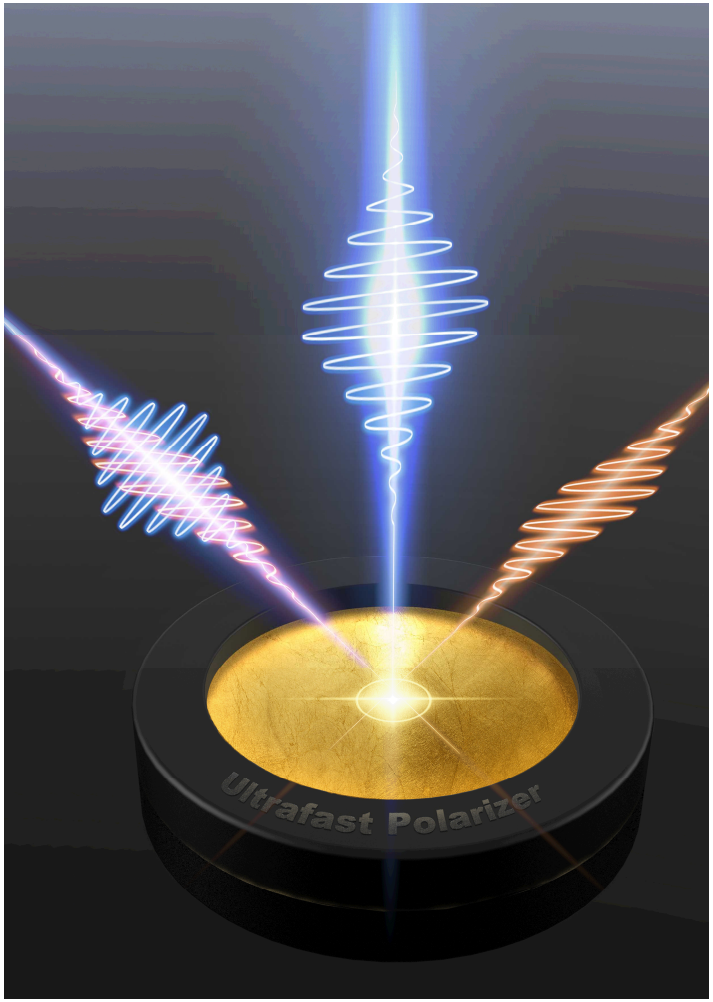
Ultrafast Plasmonics in Oxide and III-V Semiconductors

Yuanmu Yang

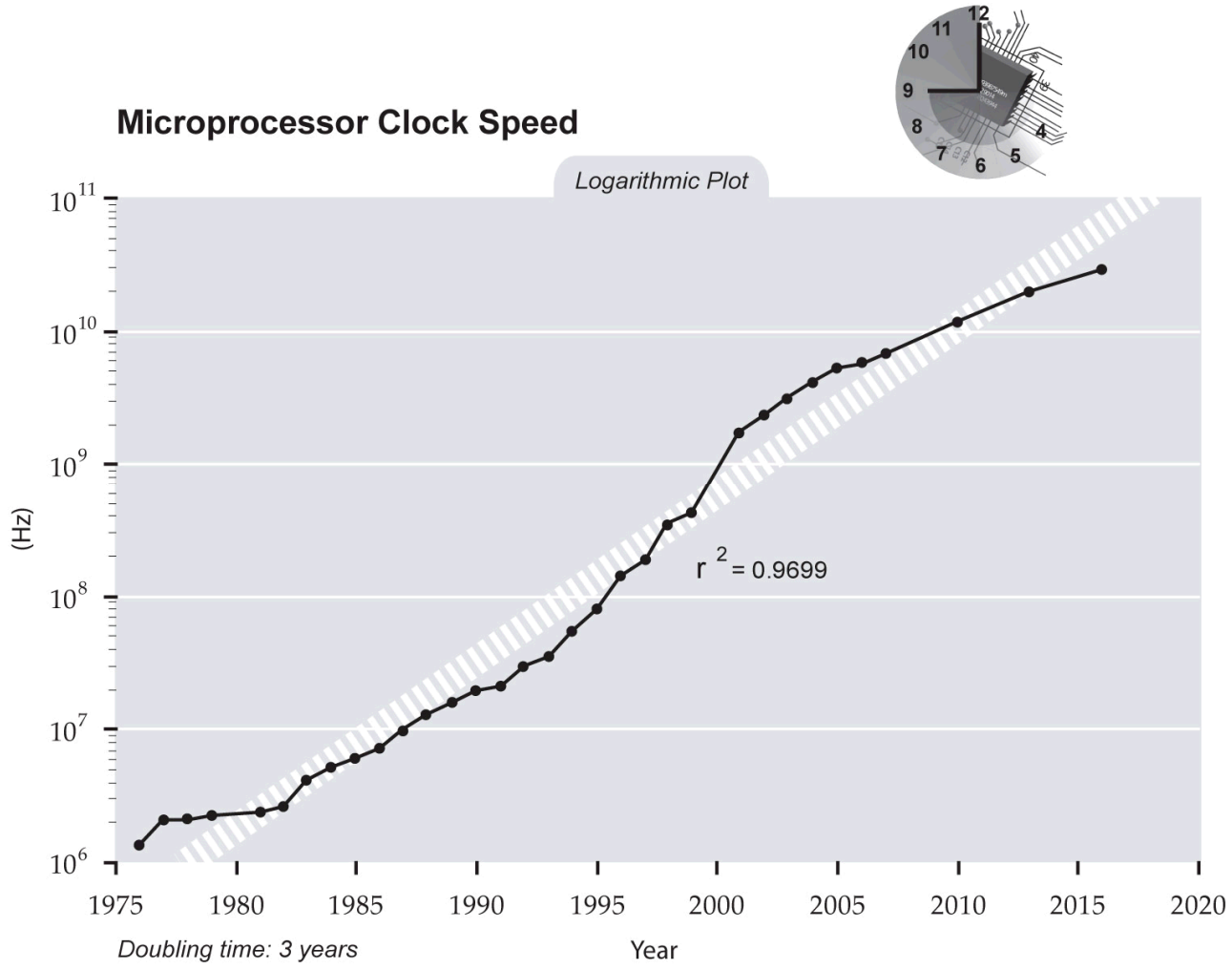
Sandia National Labs &

Center for Integrated Nanotechnologies (CINT)

yuayang@sandia.gov



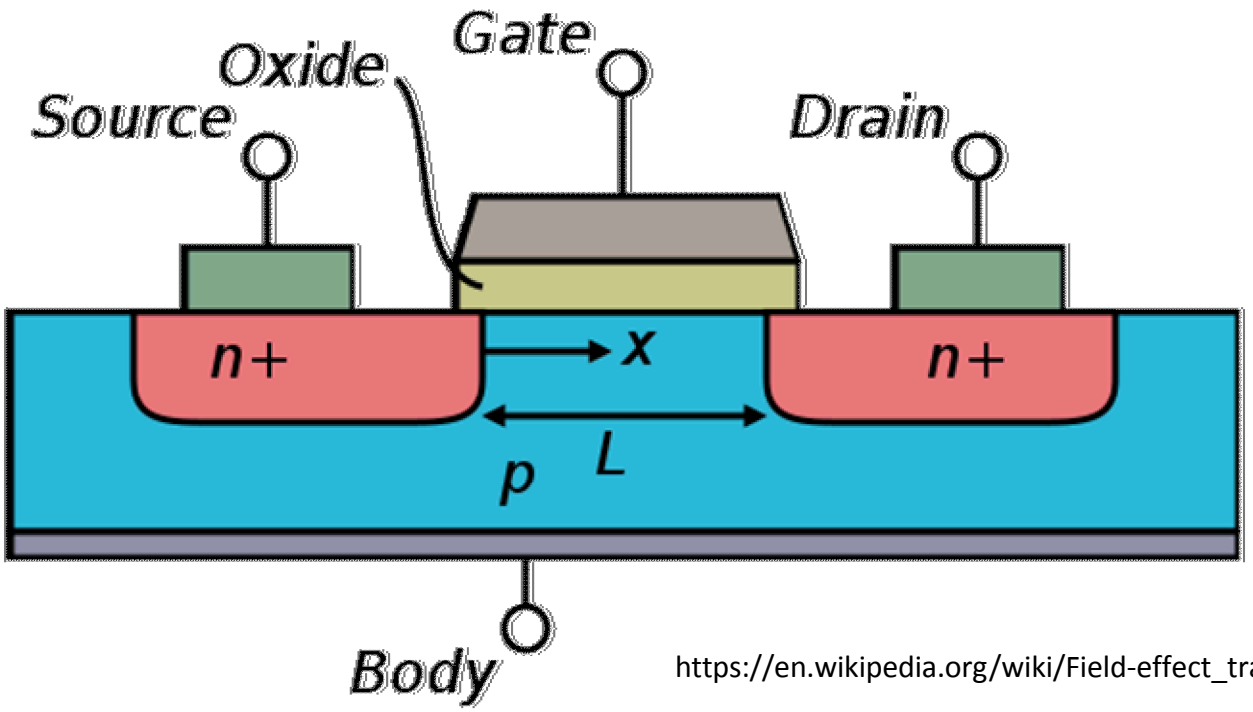
How fast can we process information?



http://www.singularity.com/charts/page61.html

How fast can we process information?

Field effect transistor:



https://en.wikipedia.org/wiki/Field-effect_transistor#/media/

Speed limitations:

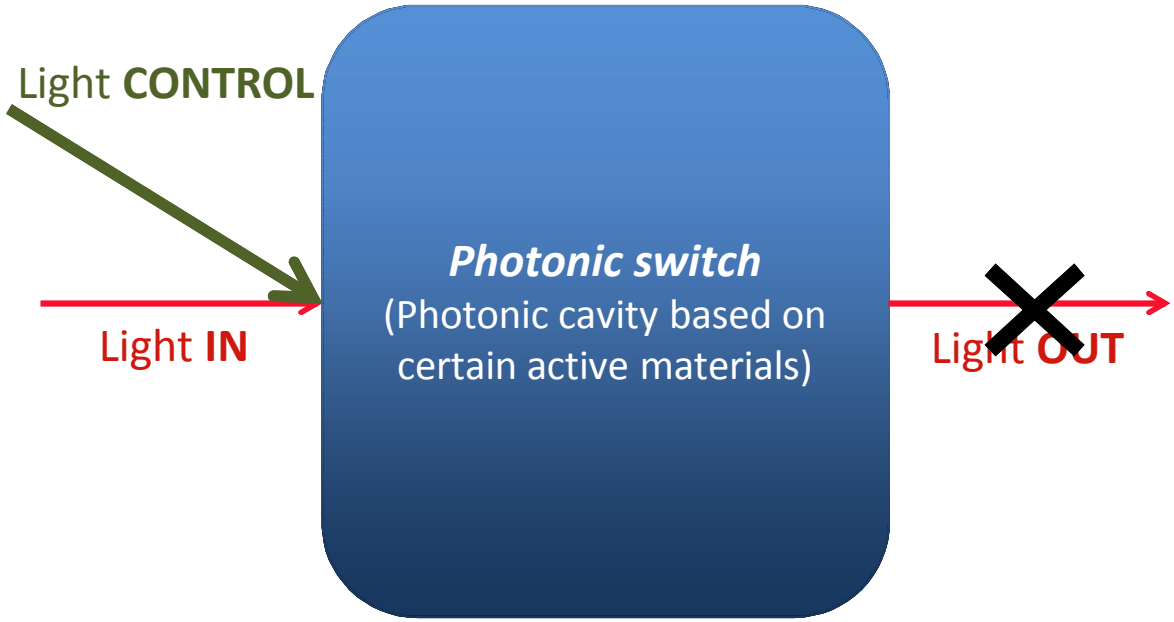
- Carrier transit time
  - It takes time for the carriers to travel
- RC constant
  - It takes time to charge up unavoidable capacitors

$$f_c = \frac{1}{2\pi RC}$$

Alternatives: All-optical information processing

All-optical information processing:

- **Photon** as an information ***switch***.
- **Photon** as an information ***carrier***.



Photon as an information switch

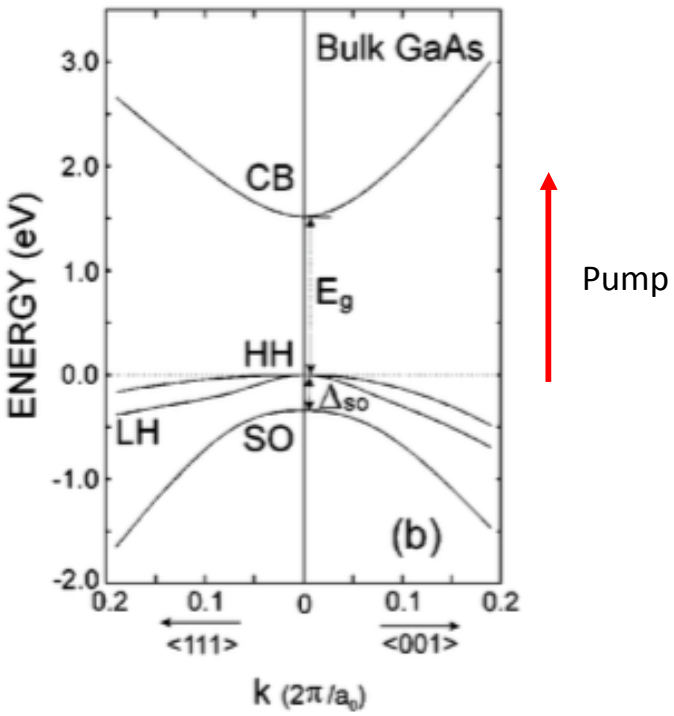
Photon-"create" electrons:

Plasma frequency:

$$\omega_p = \sqrt{ne^2/\varepsilon_0 m^*}$$

Speed limitations:

- Carrier lifetime



Vurgaftmana JAPN (2001)

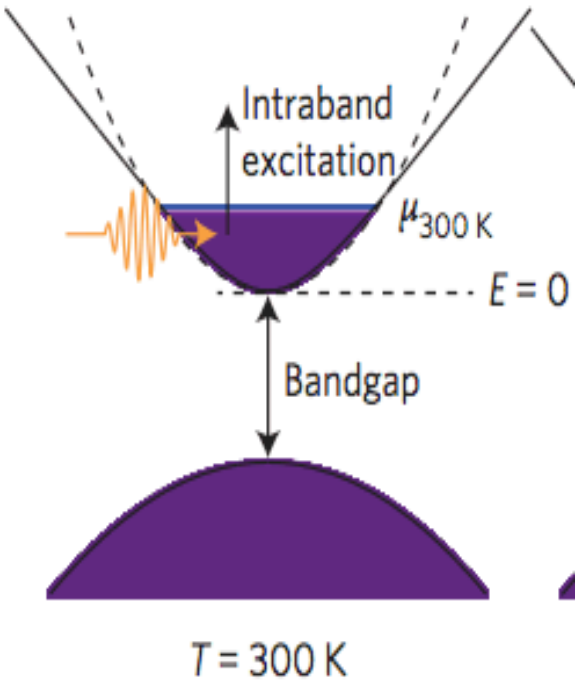
Photon as an information switch

Photon-"perturb" electrons:

Plasma frequency:

$$\omega_p = \sqrt{ne^2/\varepsilon_0 m^*}$$

Pump



$$m^* = \frac{\hbar^2}{k_{ex}} \cdot \frac{1}{\partial^2 E_n / \partial k^2}$$

Speed limitations:

- Hot Carrier lifetime

Guo et. al., Nat. Photon, (2016)

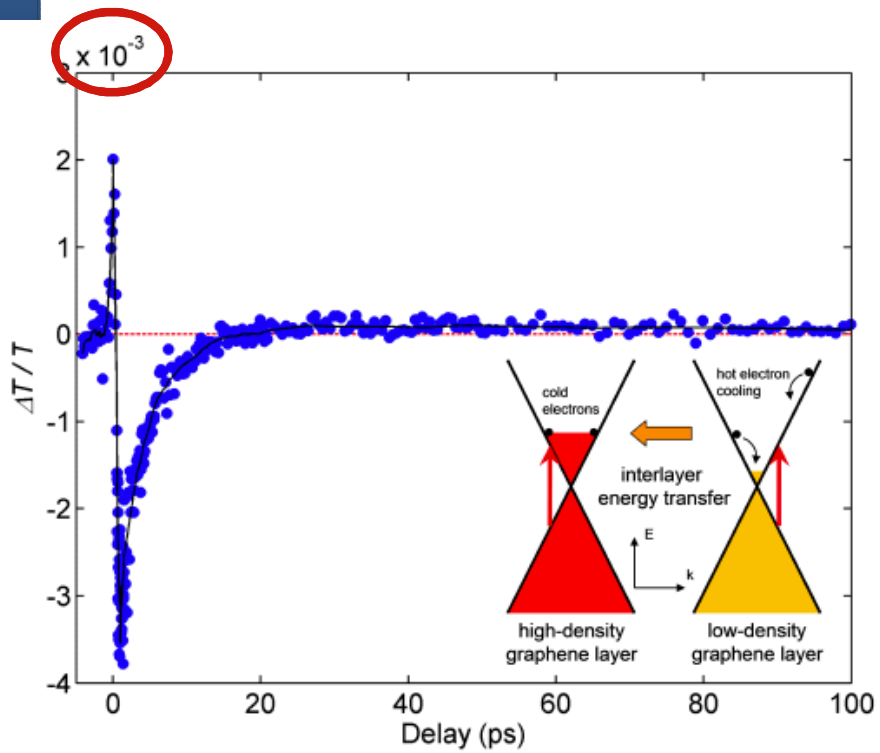
Cavity

Light **CONTROL**

Light **IN**

Photonic switch
(Photonic cavity based on certain active materials)

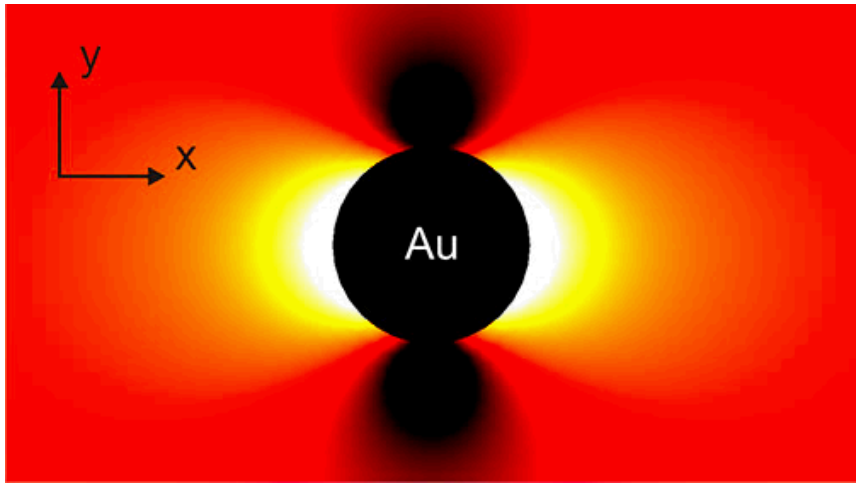
Light **OUT**

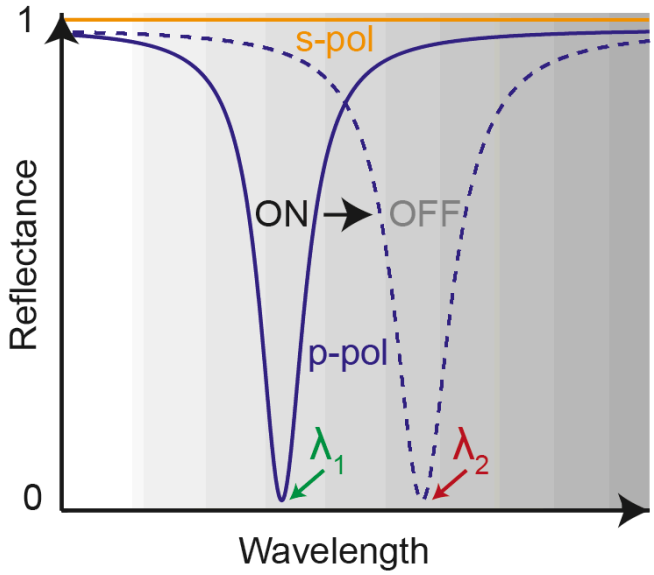


Plasmonic cavity

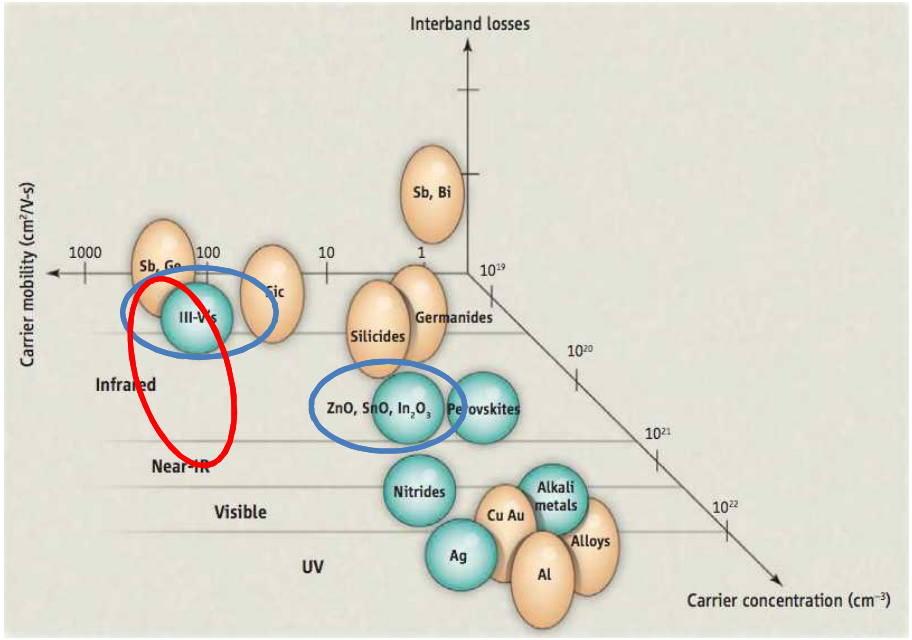
Plasmonic cavity:

- ***Enhanced*** light-matter interaction.

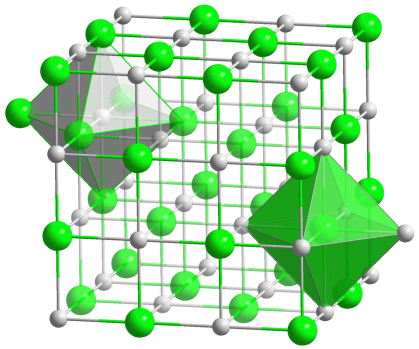




Plasmonic materials: Doped CdO



Boltasseva & Atwater, Science 331, 290 (2011)



http://chemistry.stackexchange.com/questions/23673/rock-salt-structure

- Cubic rocksalt lattice (similar to NaCl)
- n-doping (In populates the Cd sublattice with a 3^+ charge)

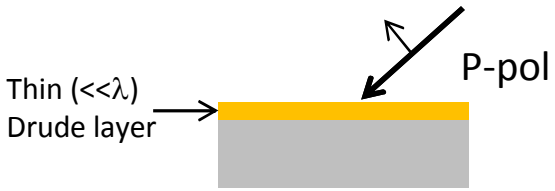
- Doping density can reach > 10^{20}cm^{-3}
- Plasma frequency tunable from near to long IR
- Mobilities in the 100's, sometimes comparable with III-V's.

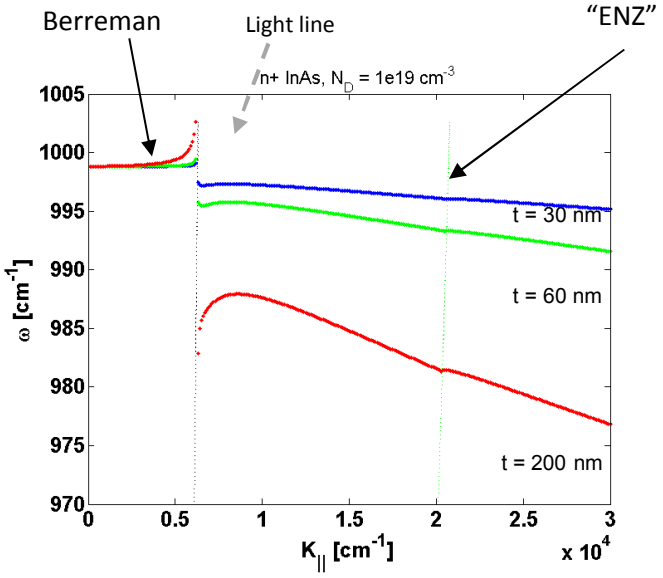
Material	Carriers [cm^{-3}]	Mobility [cm^2/V·s]	ε_1=0 [cm^{-1}]	ε_2 at ε_1=0	ε_2 at ε_1=-2
CdO:Dy	9.94x10^{19}	474	2770	0.19	0.30
CdO:Dy	3.70x10^{20}	359	5350	0.13	0.20
AZO (2 wt%)[4]	7.2x10^{20}	48	6970	0.21	0.39
ITO (10 wt%)[4]	7.7x10^{20}	36	7122	0.69	1.29

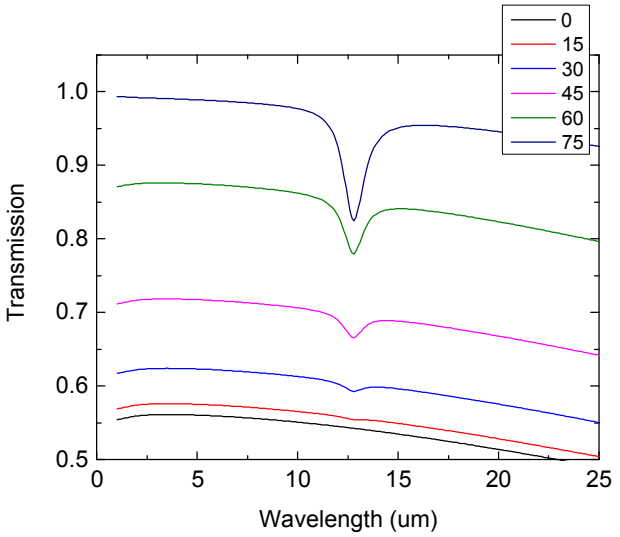
Sachet et. al., Nat. Mat (2015)

J-P Maria, NC State

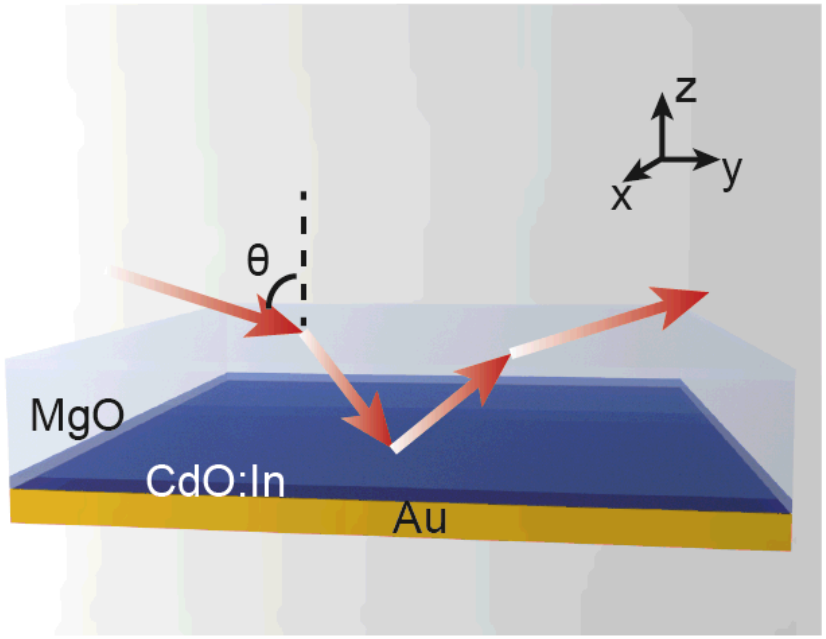
Plasmonic Cavity: “Berreman-mode”

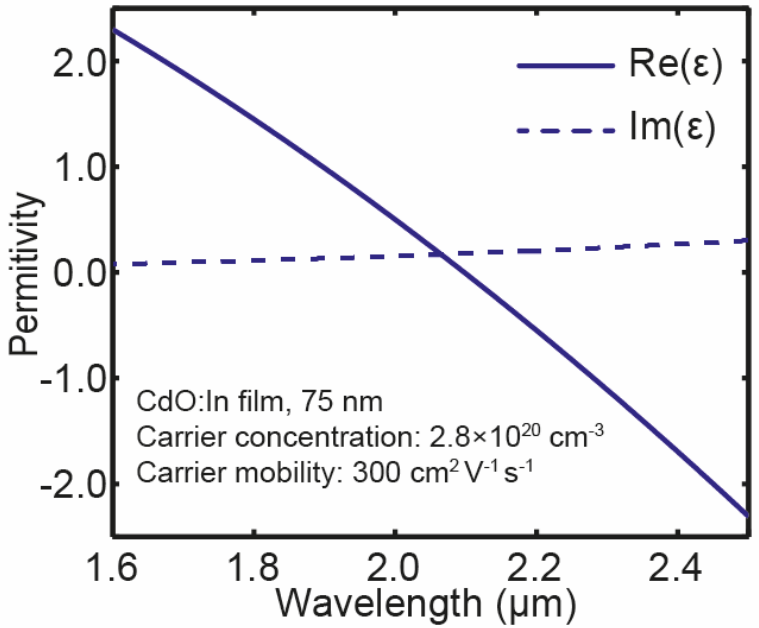






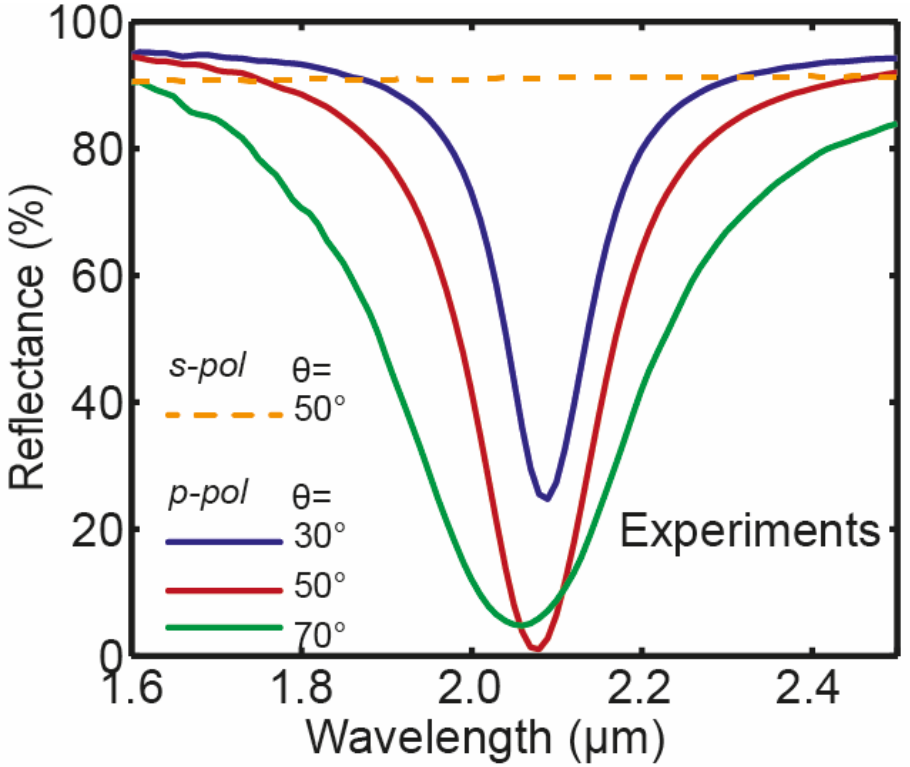
CdO-based Berreman-mode Perfect Absorber

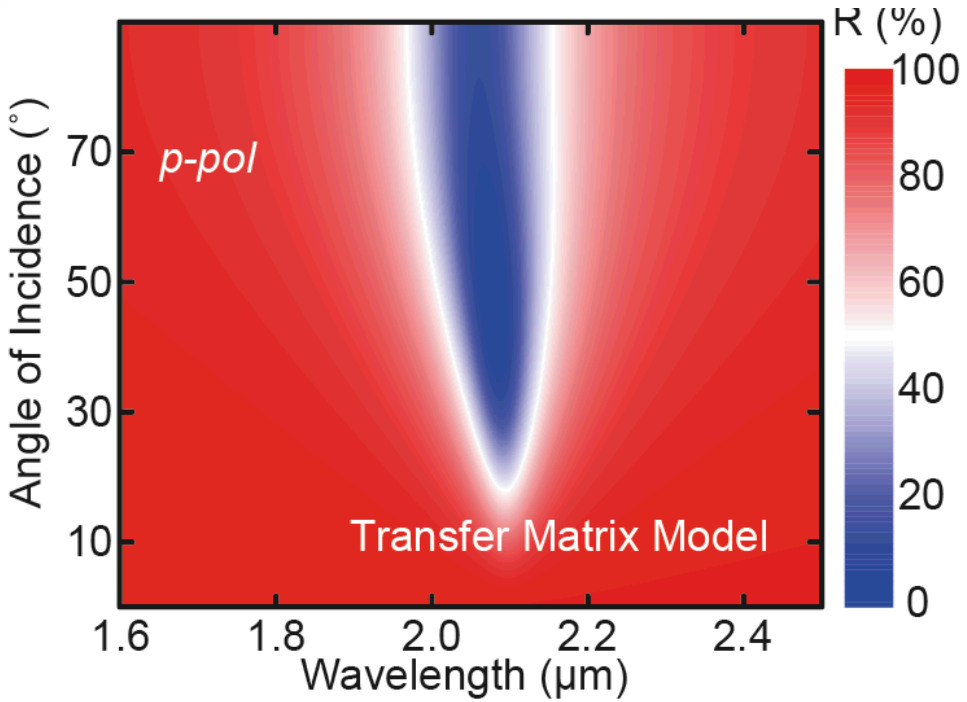




Yang et. al., Nature Photonics, accepted

CdO-based Berreman-mode Perfect Absorber

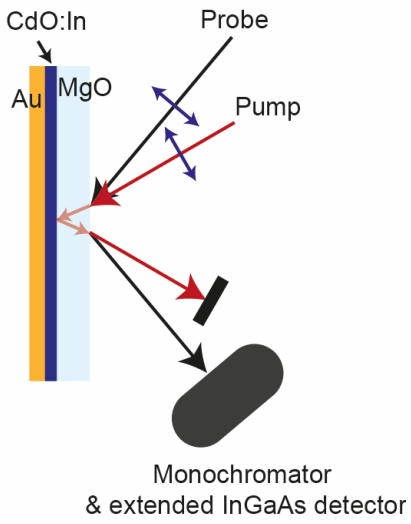


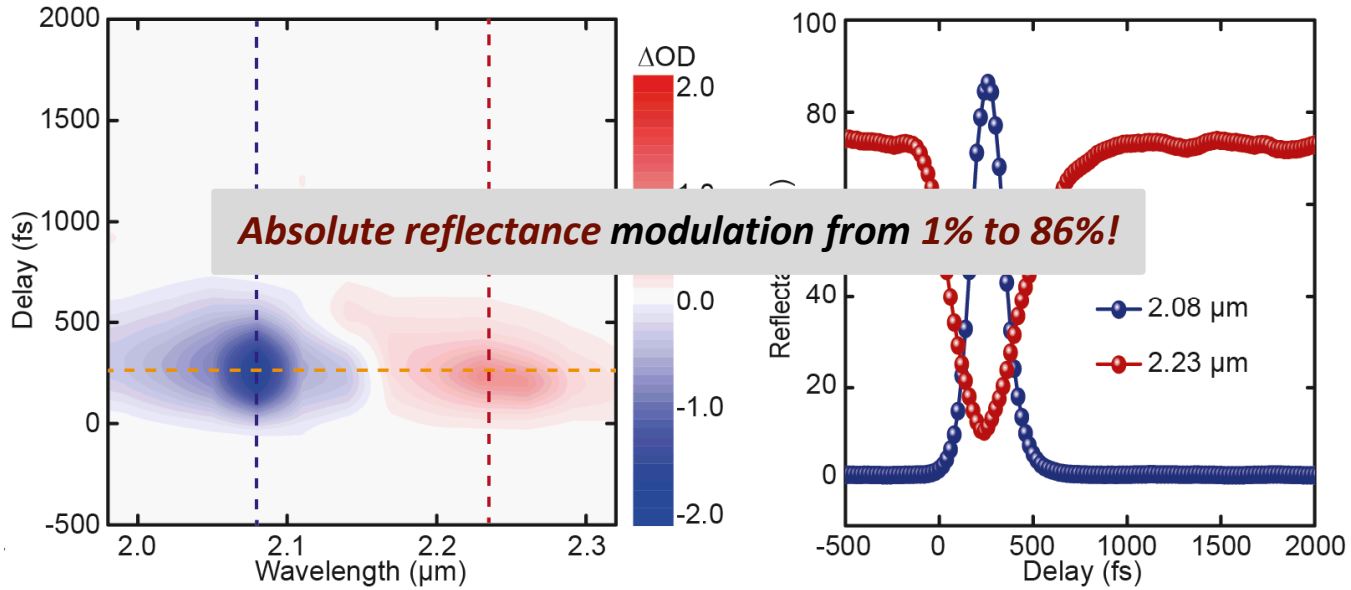


- **Berreman-type perfect absorber for p-polarized incident light at 50 degrees.**
- **>90% reflectance for s-polarized light.**

Yang et. al., Nature Photonics, accepted

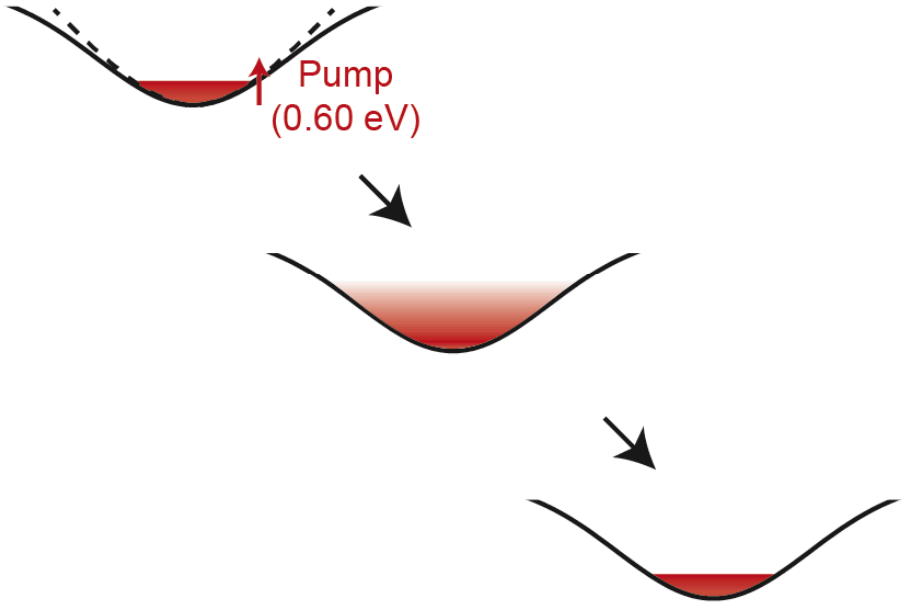
Ultrafast AMPLITUDE SWITCHING of the Perfect Absorber

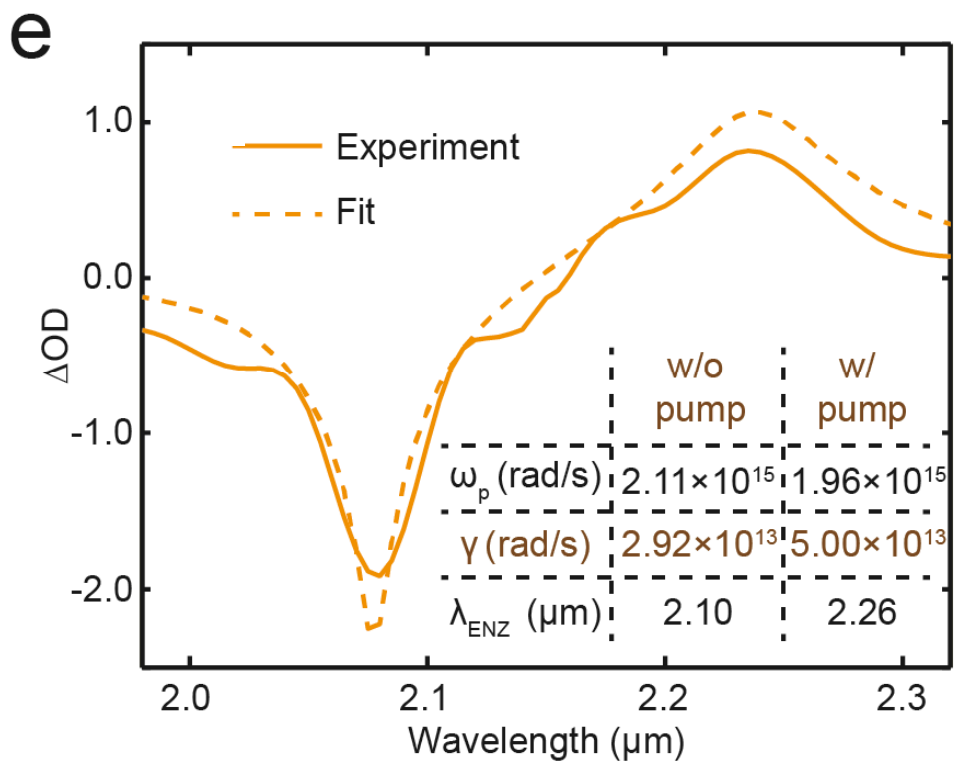




Yang et. al., Nature Photonics, accepted

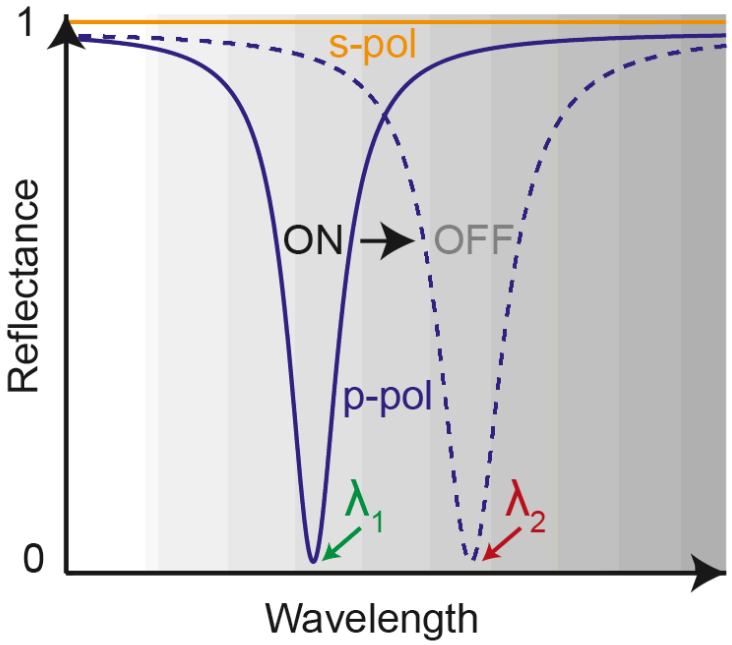
Ultrafast AMPLITUDE SWITCHING of the Perfect Absorber

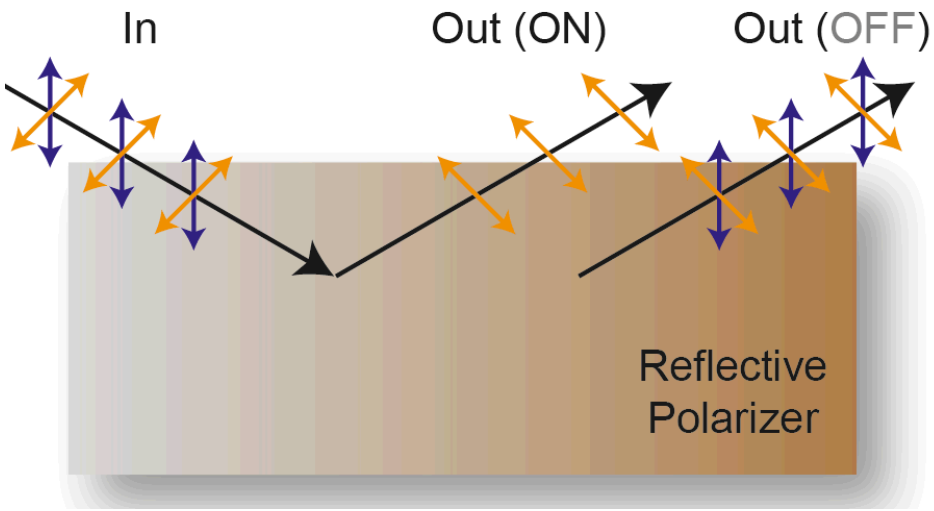




Yang et. al., Nature Photonics, accepted

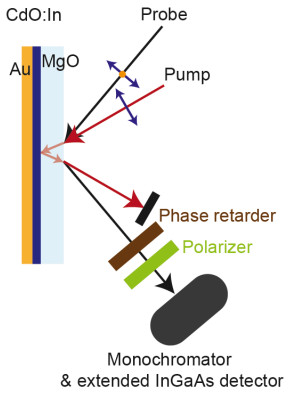
Ultrafast POLARIZATION SWITCHING



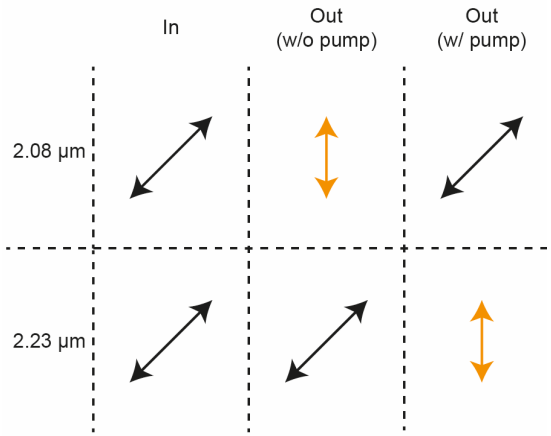


Yang et. al., Nature Photonics, accepted

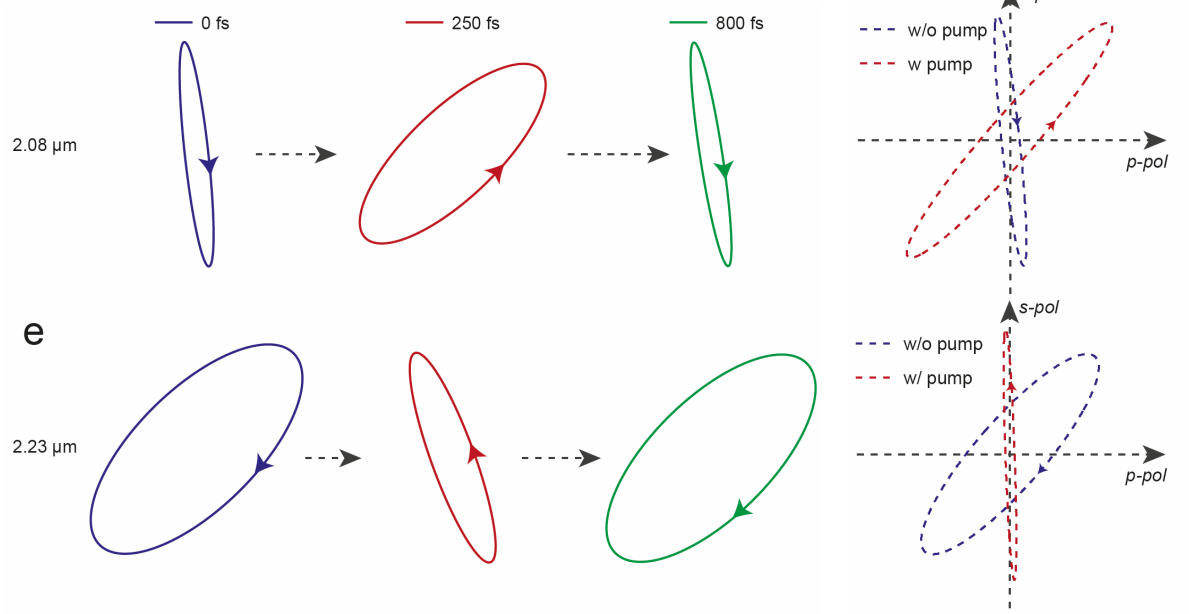
Ultrafast POLARIZATION SWITCHING



Predicted polarization input/output:

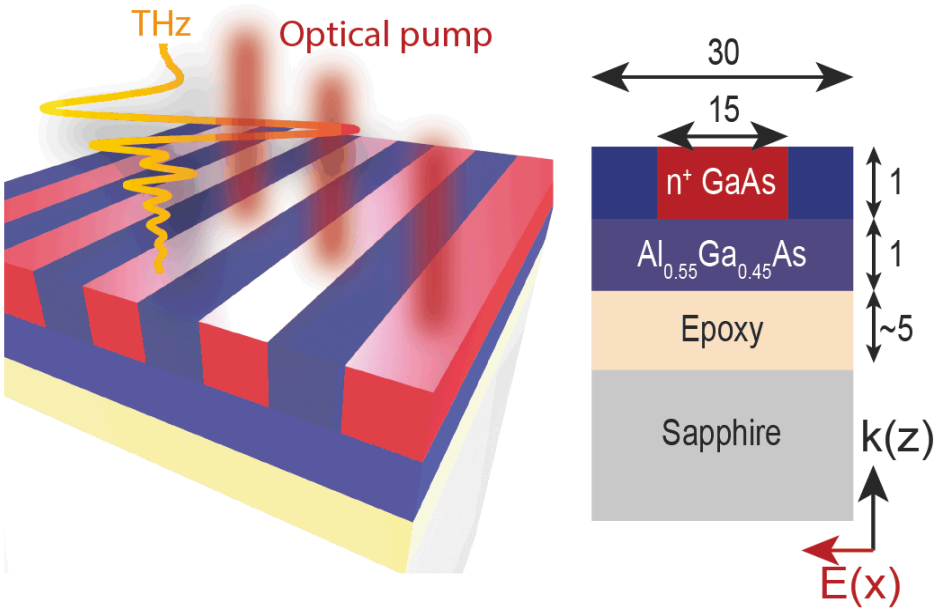


Experiments ***Simulations***

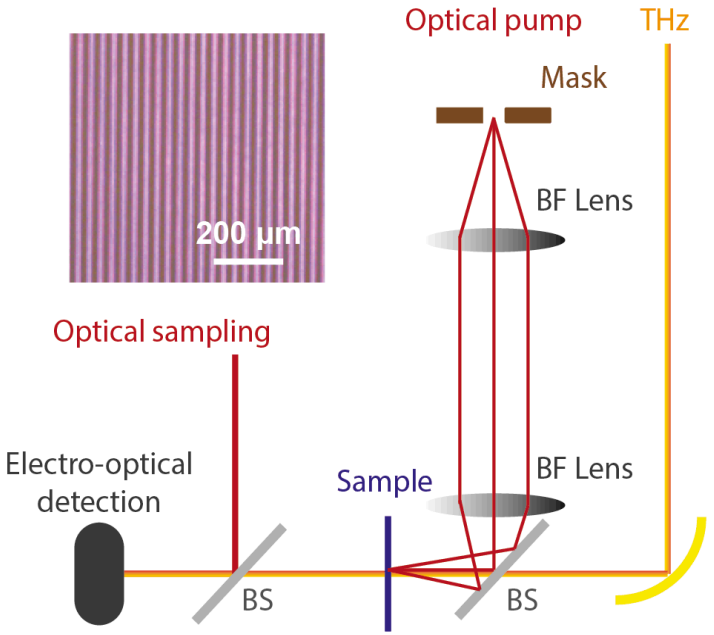


Yang et. al., Nature Photonics, accepted

TRANSIENT GaAs Plasmonic Metasurfaces

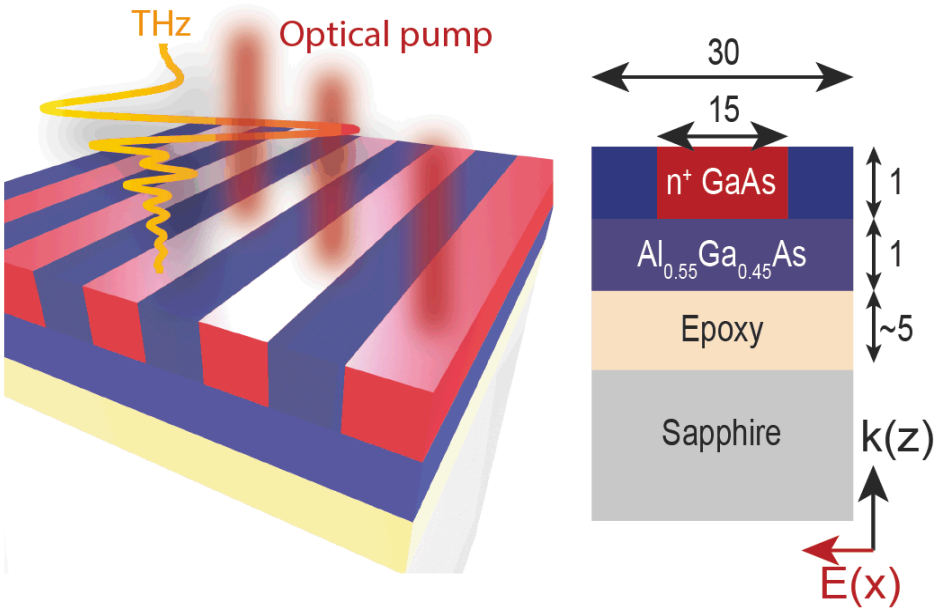


Structured-optical pump THz probe (S-OPTP):

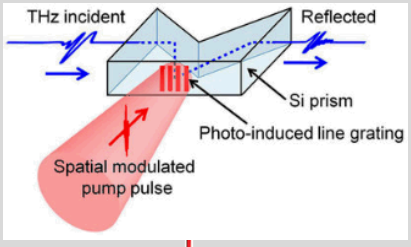


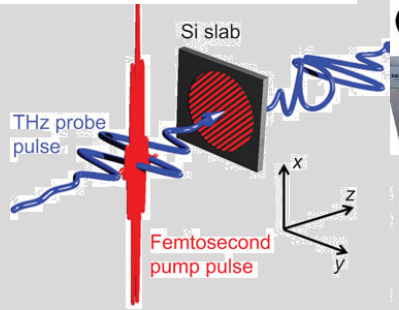
Yang et. al., ACS Photonics, 4, 15 (2017)

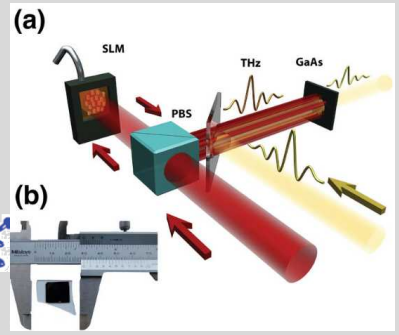
TRANSIENT GaAs Plasmonic Metasurfaces



Structured-optical pump THz probe (S-OPTP):







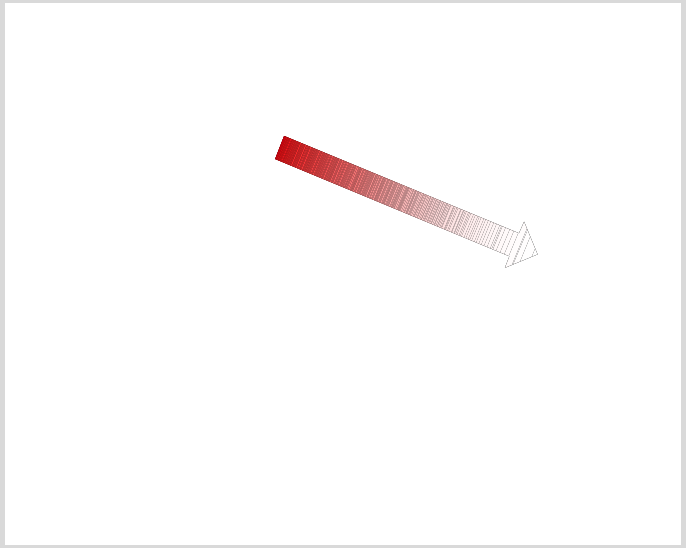
Okada et. al., Sci. Rep. (2011);
Chatzakis et. al., Appl. Phys. Lett. (2013);
Kamaraju et. al., Light Sci. App. (2014)
Georgiou et. al., Sci. Rep. (2014)

- Our **Goals**:
  - Demonstrate a **wide-bandwidth** frequency tuning;
  - Reveal the **ultrafast dynamics** of plasmon formation;

Yang et. al., ACS Photonics, 4, 15 (2017)

Dynamic Creation of THz Plasmon Resonances

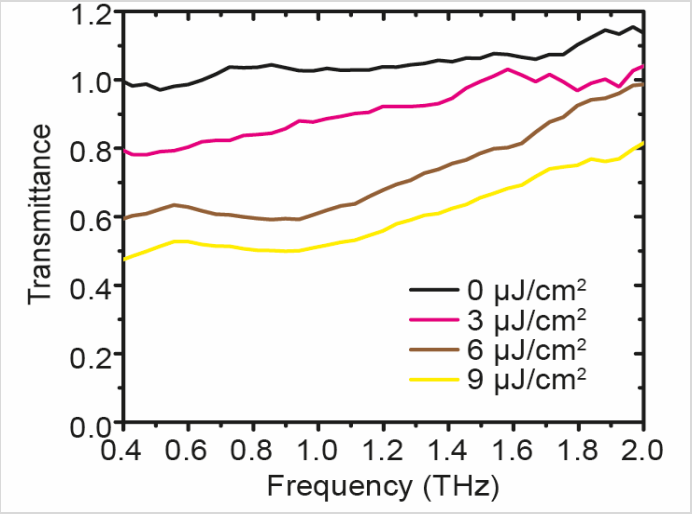
Pump fluence-dependent transmittance (Experiments-Structured Pump)



Modulation from 0.5 THz to 1.7 THz

- One of the widest dynamic modulation bandwidth demonstrated (to the best of our knowledge)

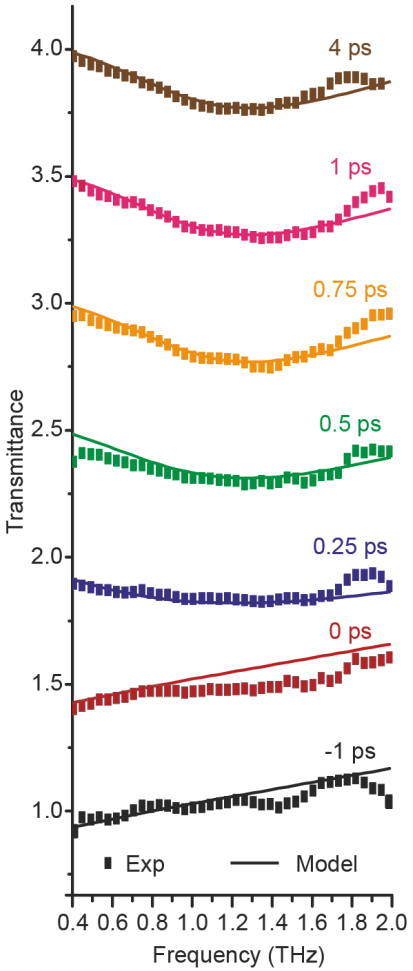
Pump fluence-dependent transmittance (Experiments-Unstructured Pump)



Only Intensity Modulation.

Yang et. al., ACS Photonics, 4, 15 (2017)

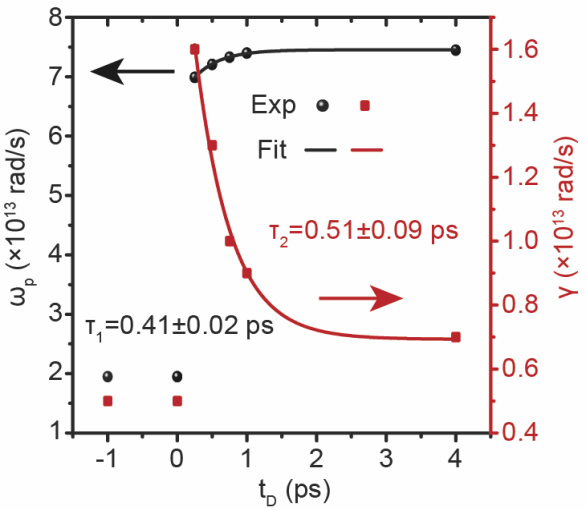
Ultrafast Dynamics of Plasmon Formation



Processes involved:

(1). Creation of non-equilibrium hot electron distribution by the optical pump;
(2). Hot electron thermalization (equilibrium within themselves & Fermi Dirac distribution); <100 fs
(3). Electron-phonon coupling. ~500 fs

$$m^* = \frac{1}{\int f(E,t)\frac{1}{\hbar^2}\frac{d^2E}{dk^2}dk}, \quad \omega_p = \sqrt{ne^2/\varepsilon_0 m^*}$$



Within the ~500 fs electron-phonon cooling process:

- Plasma frequency increases;
- Plasma damping decreases.

Yang et. al., ACS Photonics, 4, 15 (2017)

20

Conclusions & Outlook

Conclusions

- Ultrafast switches using doped CdO
  - High electron mobility oxide
  - High contrast amplitude switch
  - Femtosecond polarization switch
- Transient GaAs metasurface
  - Ultrafast dynamics of plasmon formation
  - THz modulation

Acknowledgement

- CINT (& Sandia)
  - I. Brener, M.B. Sinclair, S. Campione, S. Liu, T.S. Luk, P.Q. Liu
  - J. Reno
  - All cleanroom staff
- CINT (Los Alamos)
  - R. Prasankumar, N. Kamaraju, M.R.C. Williams
- North Carolina State
  - J-P. Maria, K. Kelley, E. Sachet