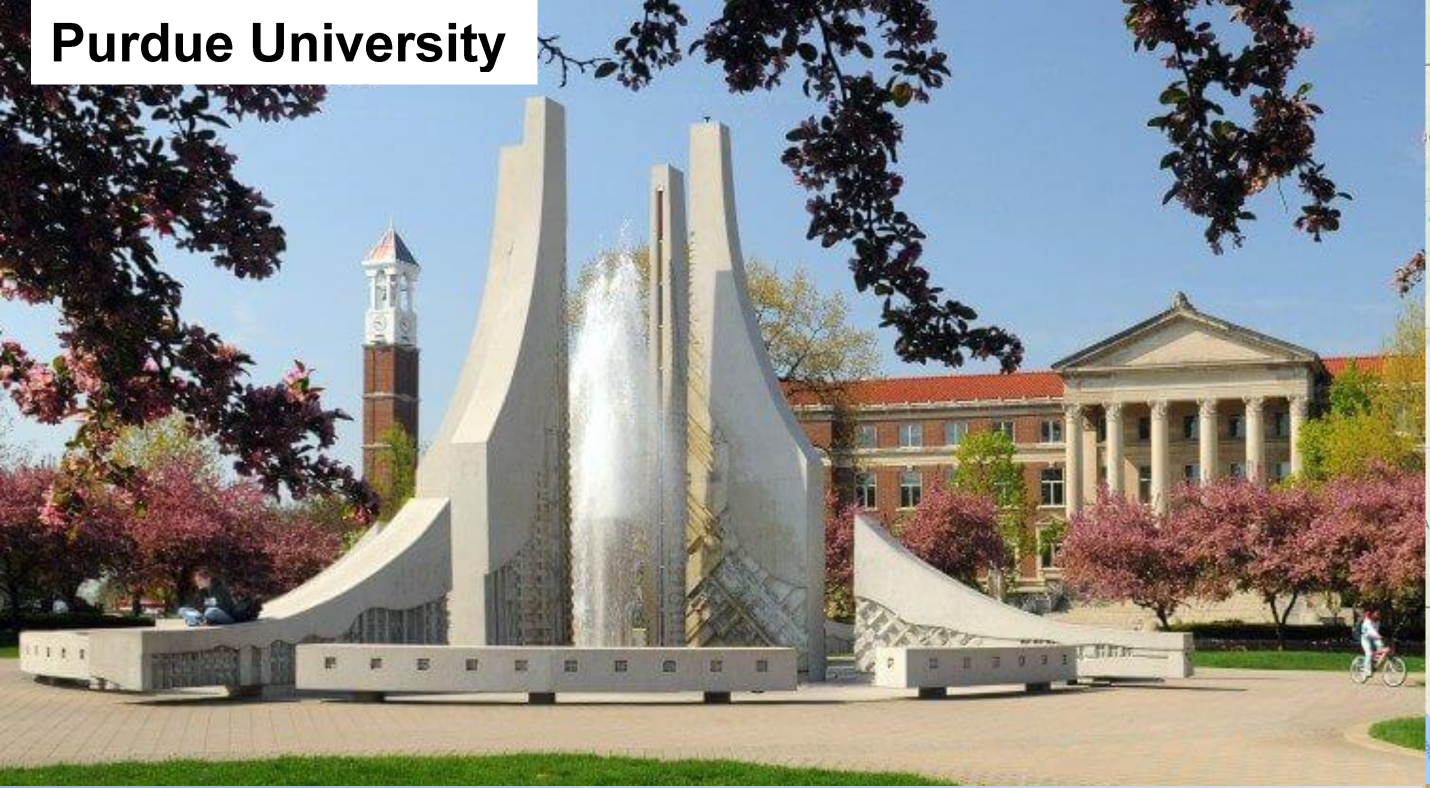
Innovations in Tunable Optical Switches: Permittivity Control in Metals, Semiconductors and Dielectrics

Soham Saha

Ph.D., Electrical Engineering,
Purdue University (2021)

PURDUE UNIVERSITY Discovery Park

Purdue University



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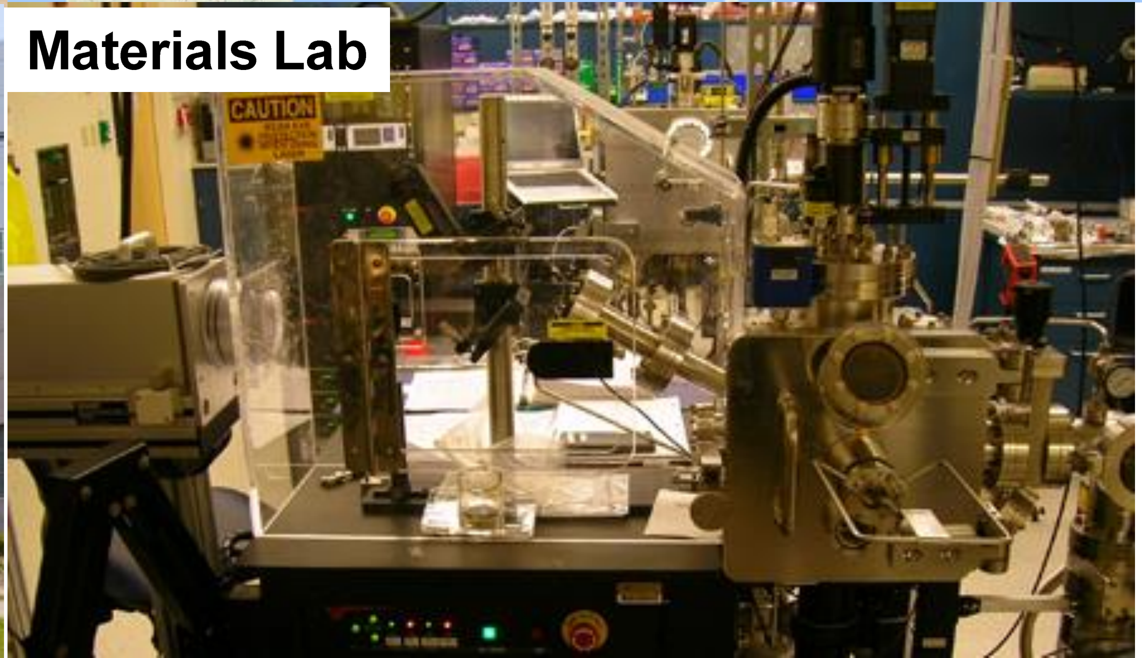
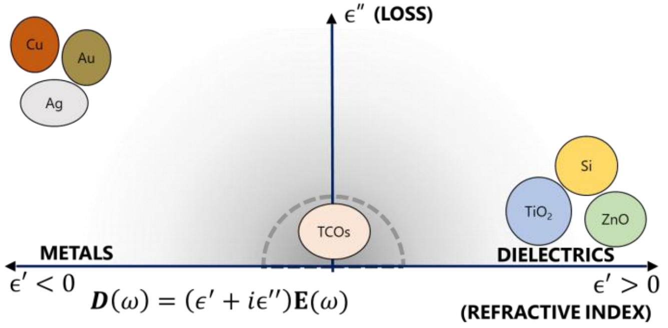
Materials Lab

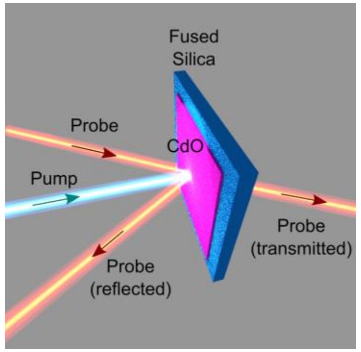


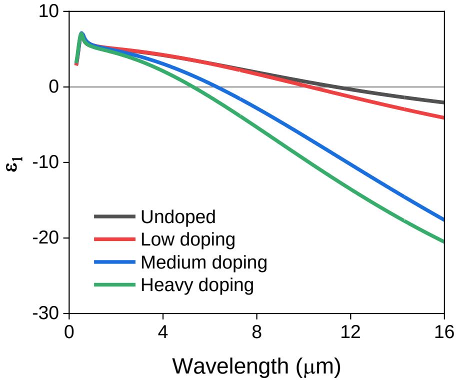
Outline



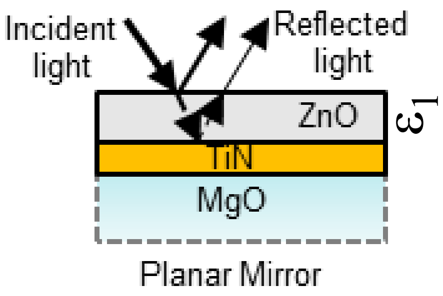
Permittivity and the Epsilon near Zero Point:

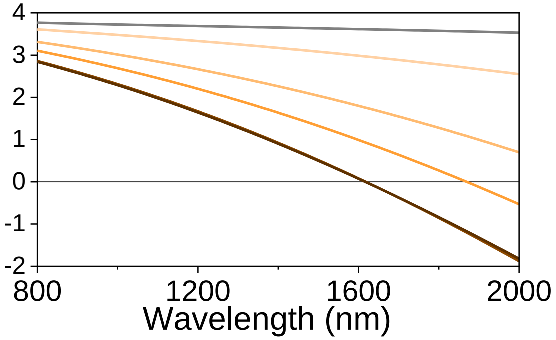
How to **tune** or **tailor** them

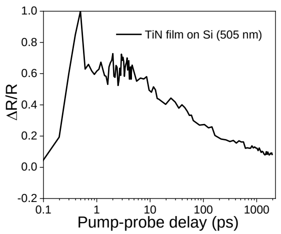




How much can we **tailor** the permittivity and relaxation-time of cadmium oxide by adding dopants?







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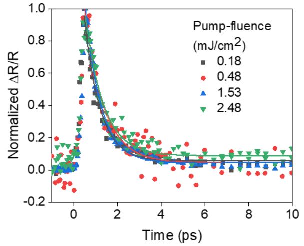

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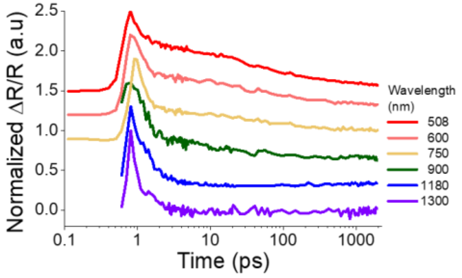


(TiN Slow) > 2 ns

AZO (Fast) < 10 ps

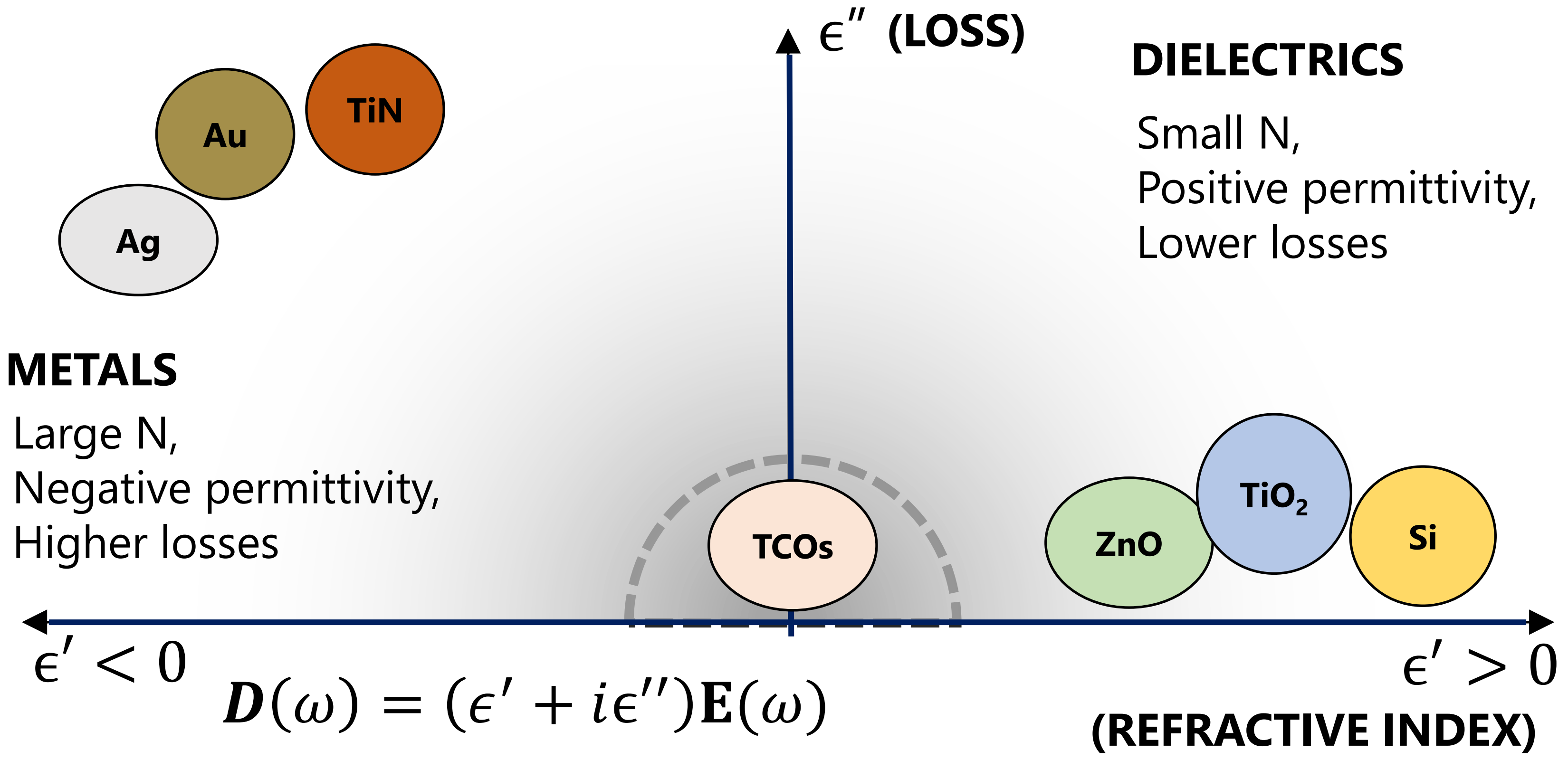
Tailorable speed

How much can we **tune** the permittivity of zinc oxide **without** adding dopants?

Can we **control** the overall **response time** of a metasurface?

Effect of Free-Electrons on Permittivity

$$\boldsymbol{D}(\omega) = (\epsilon' + i\epsilon'')\mathbf{E}(\omega)$$



Drude Lorentz Model

$$\omega_p^{\,2} = \frac{Ne^2}{\epsilon_0 m^*}$$

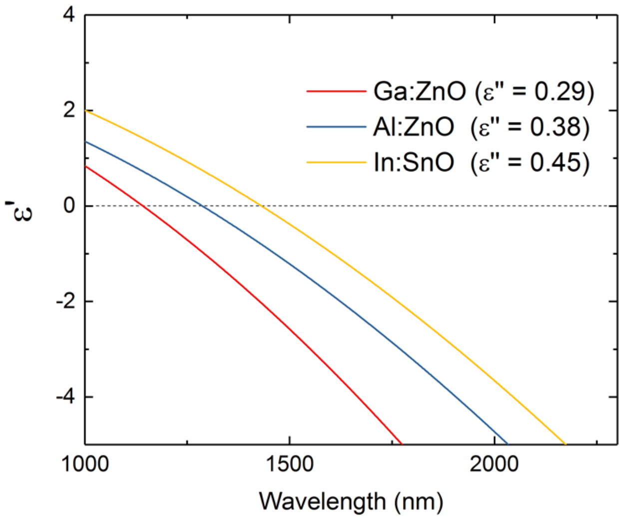
$$\epsilon' = \epsilon_B - \frac{\omega_p^{\,2}}{\omega^2 + \Gamma_d^{\,2}}$$

$$\epsilon'' = \frac{\omega_p^{\,2}\Gamma_d}{\omega^3 + \Gamma_d^{\,2}\omega}$$

Epsilon-Near-Zero (ENZ) Effects

ENZ regime is the wavelength range where the permittivity changes sign

Happens near telecom freq. in TCOs



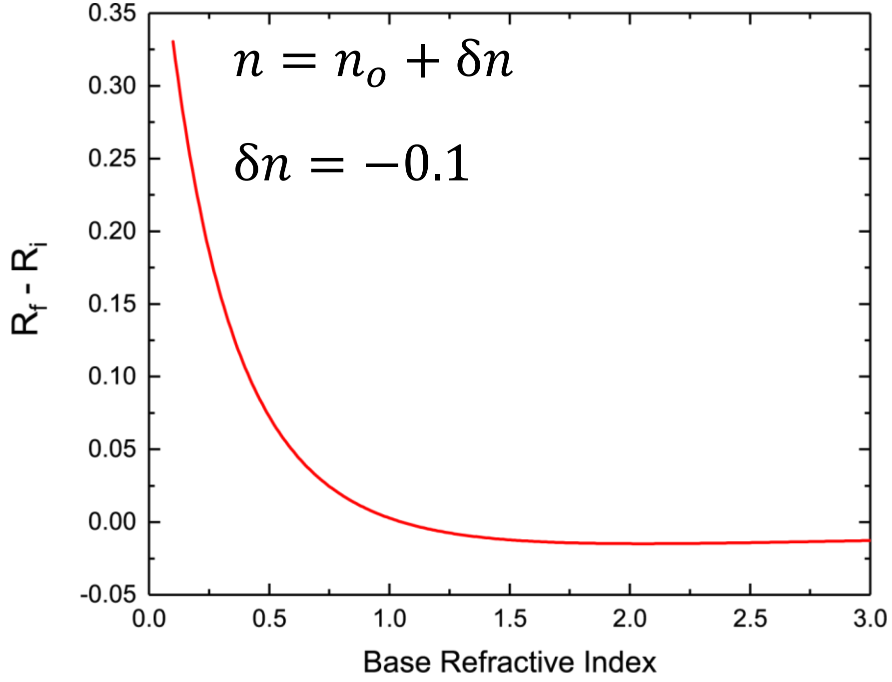
Reflectance modulation enhanced near ENZ

$$n = \sqrt{\epsilon}$$

$$\delta n = \delta\epsilon/(2\sqrt{\epsilon})$$

$$\delta \mathrm{R} = \frac{1}{2\sqrt{\epsilon}}\frac{dR}{dn}\delta\epsilon$$

$$\epsilon \to 0$$
$$\delta\mathrm{R} \to \infty$$



Kinsey et al. *Optica* (2015)

Large Field Enhancements $\boldsymbol{\varepsilon_1 E_1 = \varepsilon_2 E_2}$

Slow light effects => Enhanced light-matter interaction

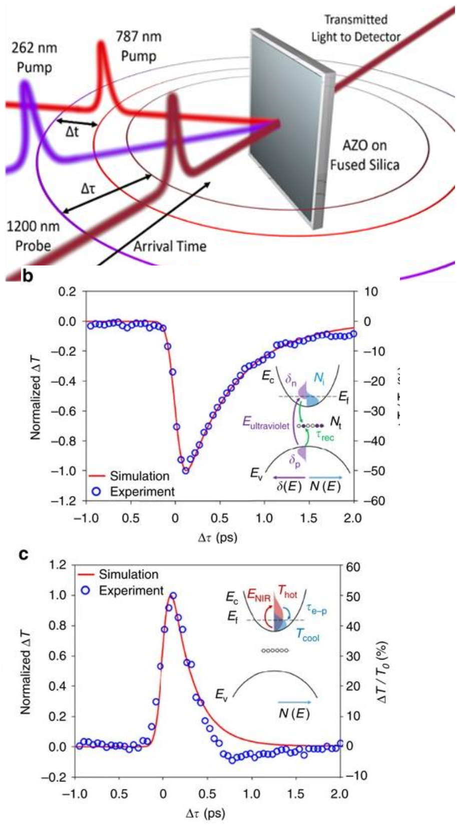
$$v_g = c\sqrt{\varepsilon'(\omega)}\left(1 + \frac{2}{\pi}\int_0^\infty \frac{\varepsilon''(\omega_1)}{(\omega_1^2 - \omega^2)^2}\omega_1^3 d\omega_1\right)^{-1}.$$

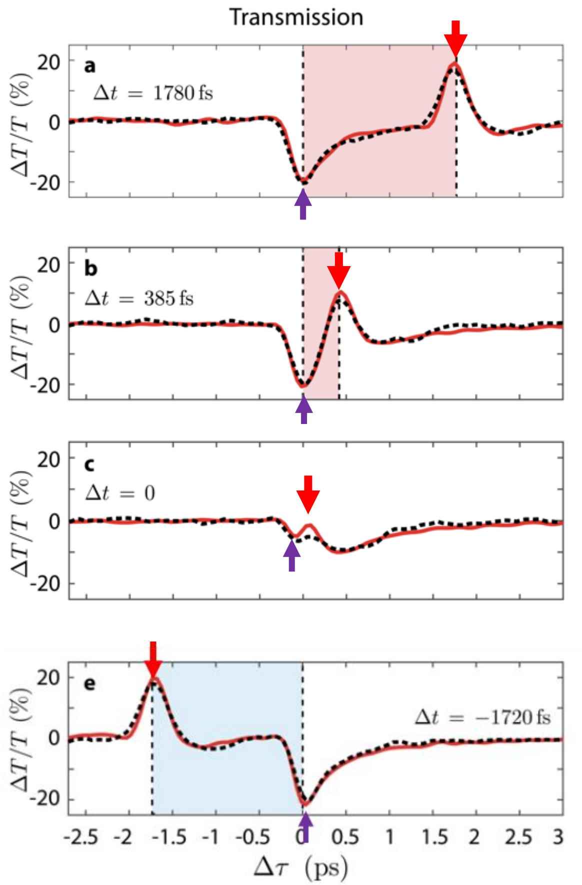
Khurgin et al. *Optica* (2020)

Notable Works: A. Boltasseva, M. Brongersma, H. Atwater, V. Sorger, E. Mazur, O. Muskens, N. Kinsey, H. Lee, R. Boyd, T. Odom

Application of Large ENZ-Enhanced Reflectance Modulation

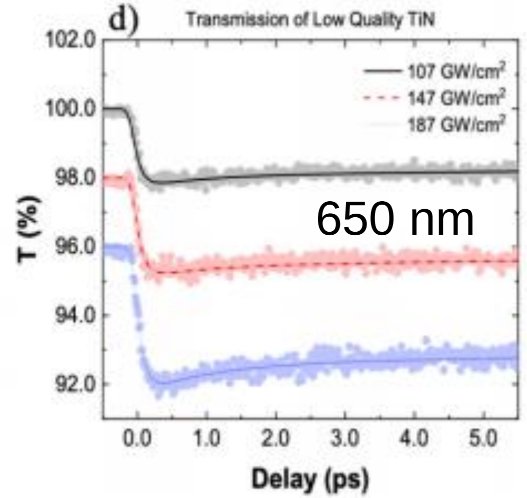
All optical addition of signals at femtosecond timescales

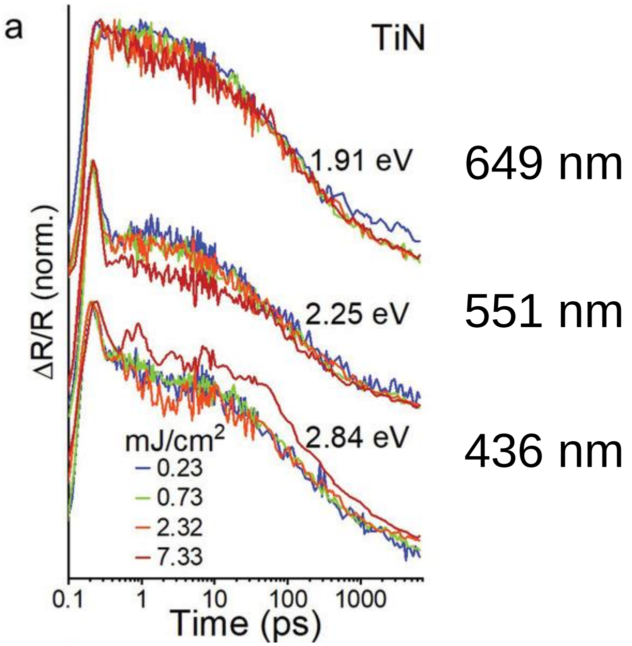




Clerici et al. *Nat. Comm.* (2016)

Extraction of hidden dynamics of hot-electrons





H. George et al. *Opt. Mat. Exp.* (2019)

B. Diroll et al. *Adv. Opt. Mat.* (2020)

Nonlinearities Enhanced by ENZ

REPORT

Large optical nonlinearity of indium tin oxide in its epsilon-near-zero region

M. Zahirul Alam[1], Israel De Leon[1,3,*], Robert W. Boyd[1,2]
+ See all authors and affiliations

Science 13 May 2016:
Vol. 352, Issue 6287, pp. 795-797
DOI: 10.1126/science.aae0330

Science
Vol 352, Issue 6287
13 May 2016

Table of Contents
Print Table of Contents
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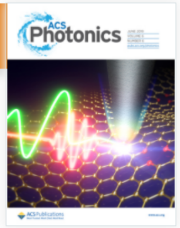
RETURN TO ISSUE | < PREV | LETTER | NEXT >

Second Harmonic Generation from Phononic Epsilon-Near-Zero Berreman Modes in Ultrathin Polar Crystal Films

Nikolai Christian Passler, I. Razdolski, D. Scott Katzer, D. F. Storm, Joshua D. Caldwell, Martin Wolf, and Alexander Paarmann*

Cite this: *ACS Photonics* 2019, 6, 6, 1365−1371
Publication Date: June 3, 2019
https://doi.org/10.1021/acsphotonics.9b00290



ACS Photonics

Article | Open Access | Published: 01 May 2020

Broadband frequency translation through time refraction in an epsilon-near-zero material

Yiyu Zhou, M. Zahirul Alam, Mohammad Karimi, Jeremy Upham, Orad Reshef, Cong Liu, Alan E. Willner & Robert W. Boyd

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Field-Effect Tunable and Broadband Epsilon-Near-Zero Perfect Absorbers with Deep Subwavelength Thickness

Aleksei Anopchenko*, Long Tao, Catherine Arndt, and Ho Wai Howard Lee*

Cite this: *ACS Photonics* 2018, 5, 7, 2631−2637
Publication Date: April 23, 2018
https://doi.org/10.1021/acsphotonics.7b01373

ACS Photonics

Negative Refraction in Time-Varying Strongly Coupled Plasmonic-Antenna–Epsilon-Near-Zero Systems

V. Bruno, C. DeVault, S. Vezzoli, Z. Kudyshev, T. Huq, S. Mignuzzi, A. Jacassi, S. Saha, Y. D. Shah, S. A. Maier, D. R. S. Cumming, A. Boltasseva, M. Ferrera, M. Clerici, D. Faccio, R. Sapienza, and V. M. Shalaev

Phys. Rev. Lett. **124**, 043902 – Published 30 January 2020

Physics See Synopsis: Plasmonic Metamaterials Bend Light Backwards

Published: 01 May 2017

Femtosecond optical polarization switching using a cadmium oxide-based perfect absorber

Yuanmu Yang, Kyle Kelley, Edward Sachet, Salvatore Campione, Ting S. Luk, Jon-Paul Maria, Michael B. Sinclair & Igal Brener

Nature Photonics **11**, 390–395(2017) | Cite this article

Letter | Published: 15 July 2019

High-harmonic generation from an epsilon-near-zero material

Yuanmu Yang, Jian Lu, Alejandro Manjavacas, Ting S. Luk, Hanzhe Liu, Kyle Kelley, Jon-Paul Maria, Evan L. Runnerstrom, Michael B. Sinclair, Shambhu Ghimire & Igal Brener

Nature Physics **15**, 1022–1026(2019) | Cite this article

Review Article | Published: 26 September 2019

Near-zero-index materials for photonics

Nathaniel Kinsey, Clayton DeVault, Alexandra Boltasseva & Vladimir M. Shalaev

Nature Reviews Materials **4**, 742–760(2019) | Cite this article

Notable Works: A. Boltasseva, M. Brongersma, H. Atwater, V. Sorger, A. Alu, O. Muskens, N. Kinsey, H. Lee, R. Boyd, N. Engheta

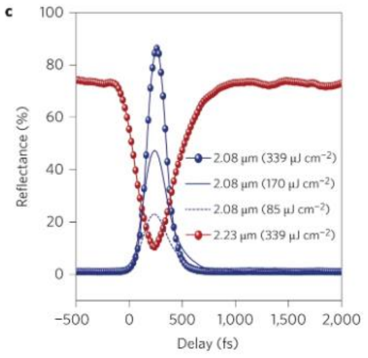
Can we **extend Epsilon Near Zero** effects to any wavelength of our choice?

How much can we **control** the permittivity in **real time**?

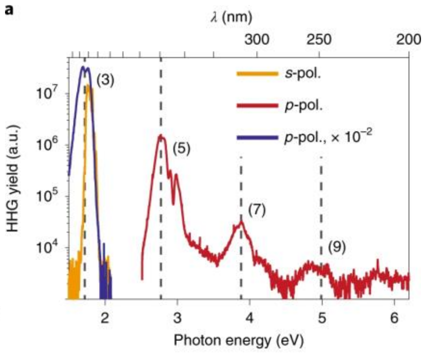
Can we **control** the **response-time** of an all-optical switch?

Materials Explored in This Work

Cadmium Oxide (CdO)



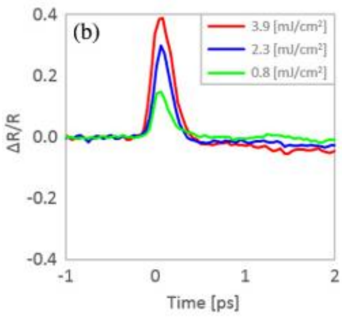
Femtosecond switching: Nat. Phot. (2017)



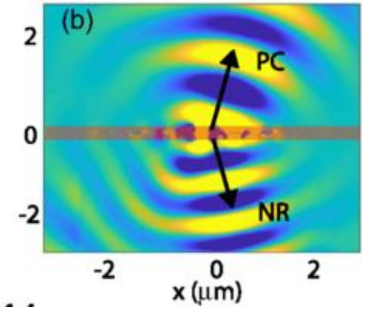
High harmonic generation: Nat. Phys (2019)

- **Low-loss metal** for MID IR Plasmonics
- **High mobility** for electroabsorption modulators
- **ENZ Applications**: ultrafast switches, high harmonic Generation

Zinc Oxide (ZnO) and Al:ZnO



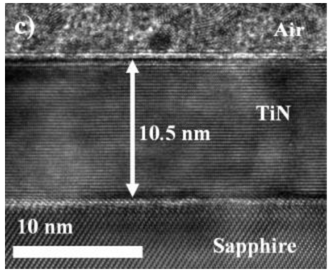
Kinsey et. al. Optica (2015)



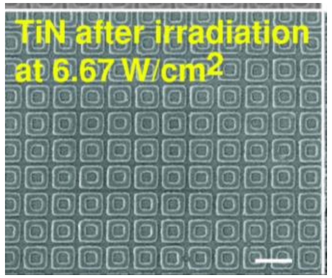
V. Bruno et. al. PRL. (2020)

- ZnO: laser tolerant, used in optoelectronic applications from **single photon emitters** to **solar cells**
- AZO Demonstrated in various ENZ applications like **reflectance enhancement**, **negative refraction**, etc.

Titanium Nitride (TiN)



Shah et. al. AOM. (2017)

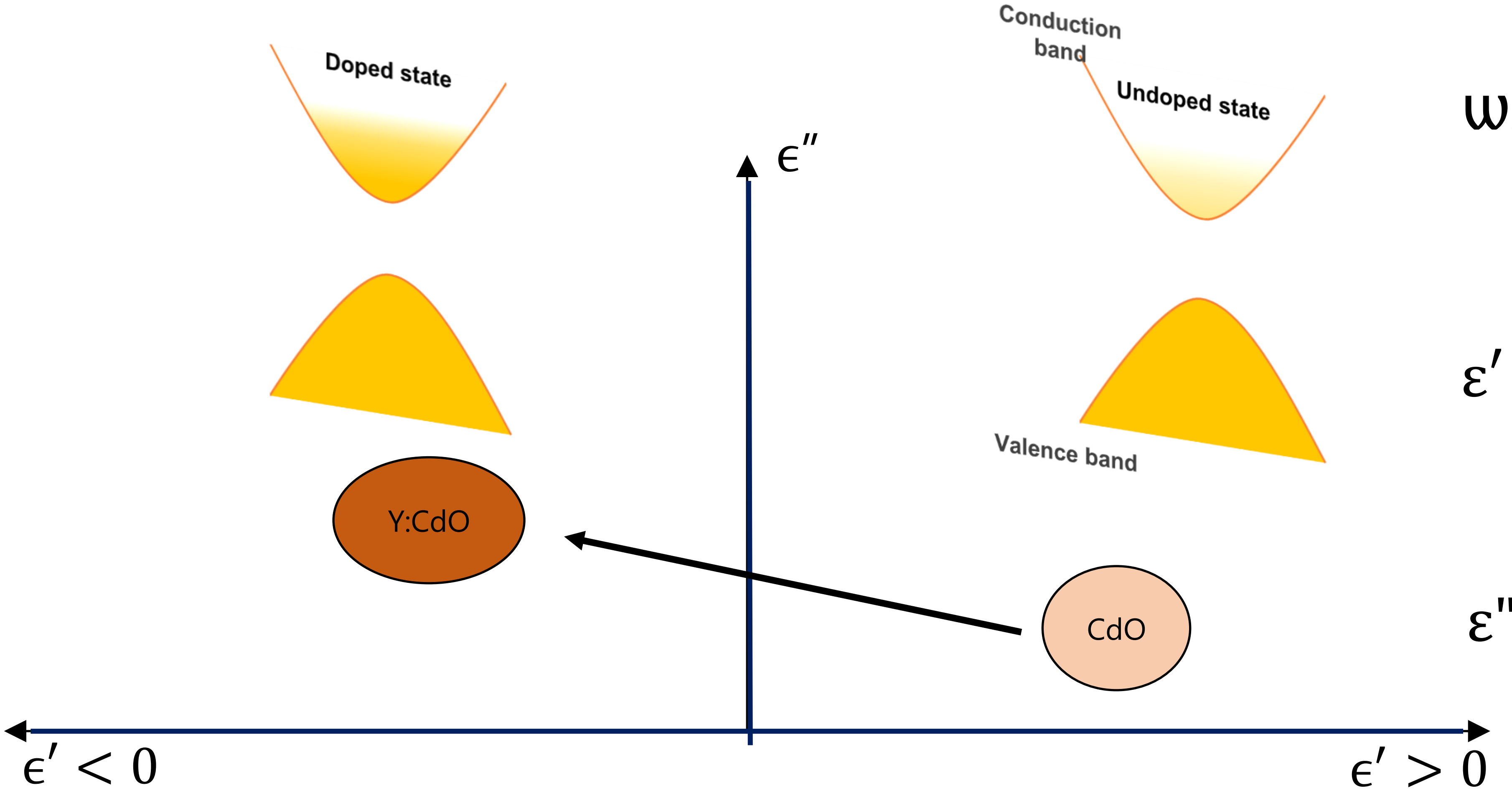


Guler et. al. Adv. Mat. (2014)

- **Gold-like** metallic properties
- Large **laser tolerance**
- Interesting dynamics with a **nanosecond** response time

How much can we tailor the **permittivity** and **relaxation time** of cadmium oxide **by adding dopants**?

How do We Tailor the Permittivity ?



$$\omega_p{}^2 = \frac{Ne^2}{\varepsilon_0 m^*}$$

$$\varepsilon' = \varepsilon_B - \frac{\omega_p{}^2}{\omega^2 + \Gamma_d{}^2}$$

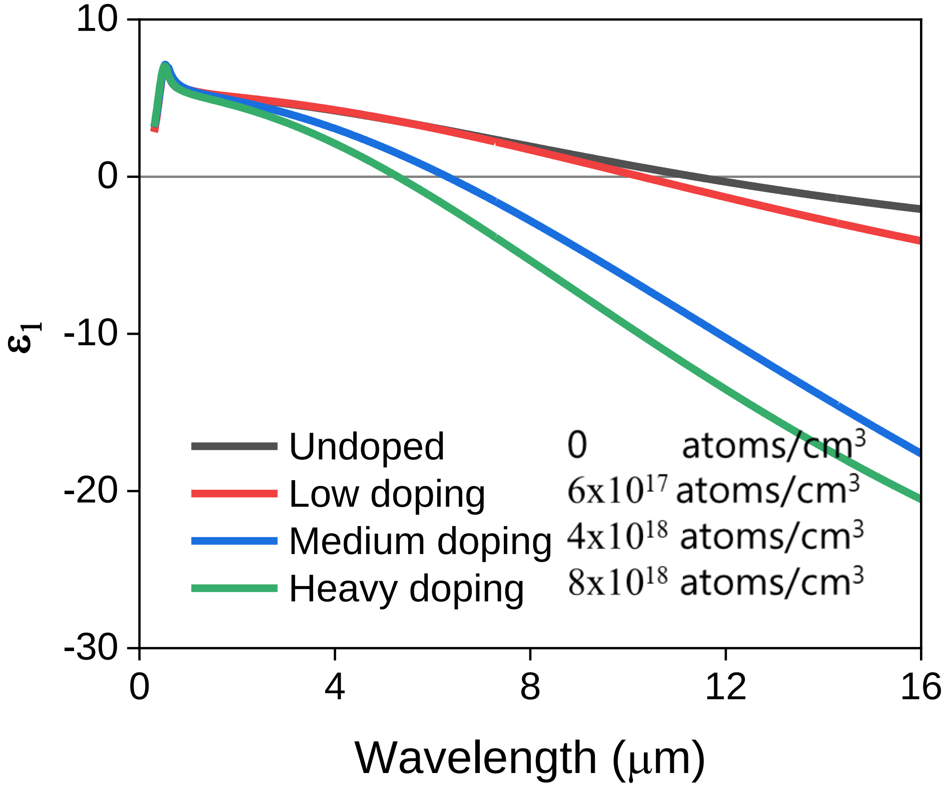
$$\varepsilon'' = \frac{\omega_p{}^2 \Gamma_d}{\omega^3 + \Gamma_d{}^2 \omega}$$

$$Y_2O_3 \xrightarrow{CdO} 2Y_{Cd}^{\bullet} + 2O_O^X + 2n + \frac{1}{2}O_2\,(g)$$

Yttrium Doping of Cadmium Oxide to Tailor the Permittivity

Material: CdO ~500 nm films grown on fused silica by co-sputtering CdO and Yttrium

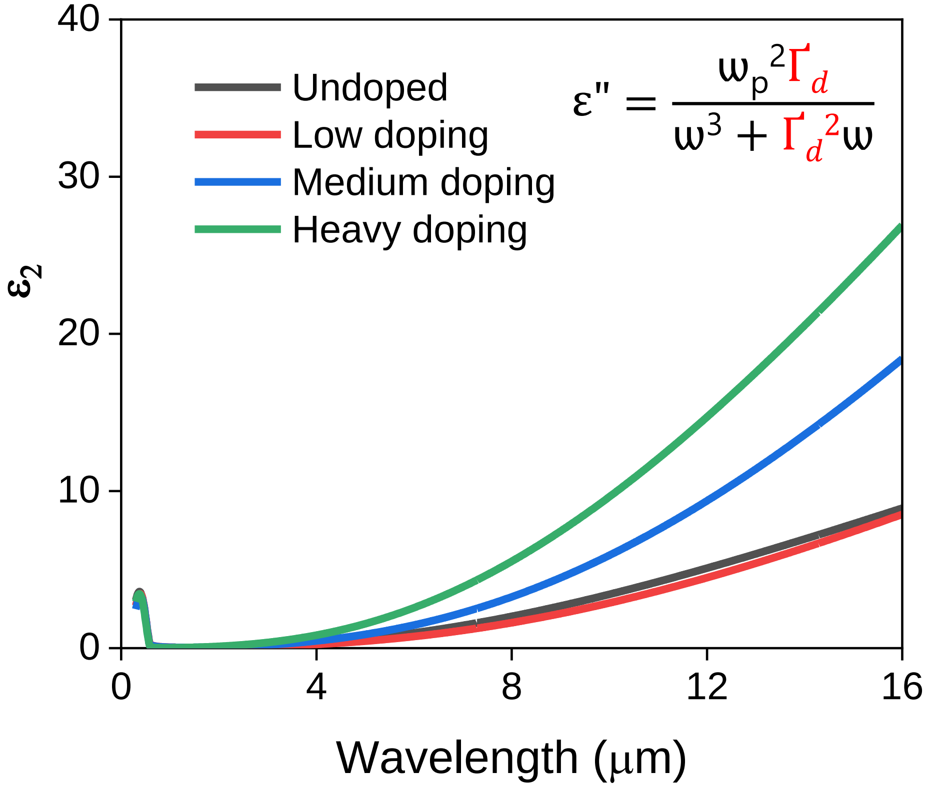
Adding more Y dopant increases electrons and blue shifts the ENZ point from 11 to 5 microns, making the films more metallic



$$\omega_p^2 = \frac{N e^2}{\varepsilon_0 m^*}$$

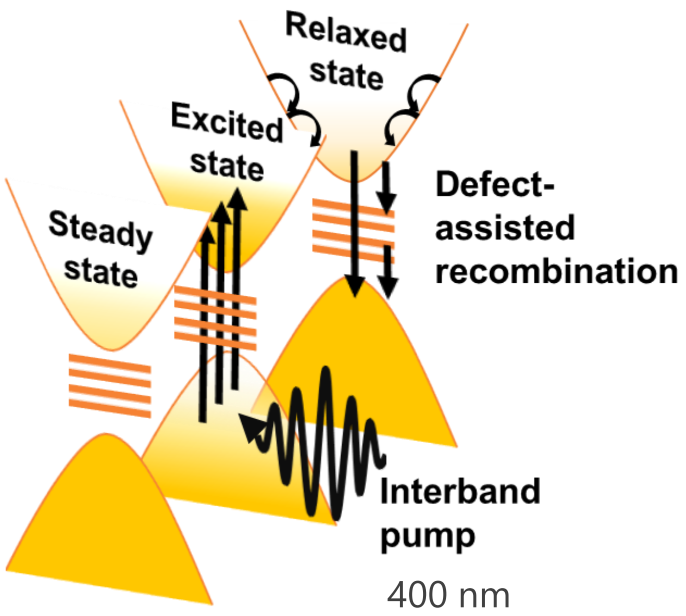
$$\varepsilon' = \varepsilon_B - \frac{\omega_p^2}{\omega^2 + \Gamma_d^2}$$

Increased electrons and defects increases the losses with doping

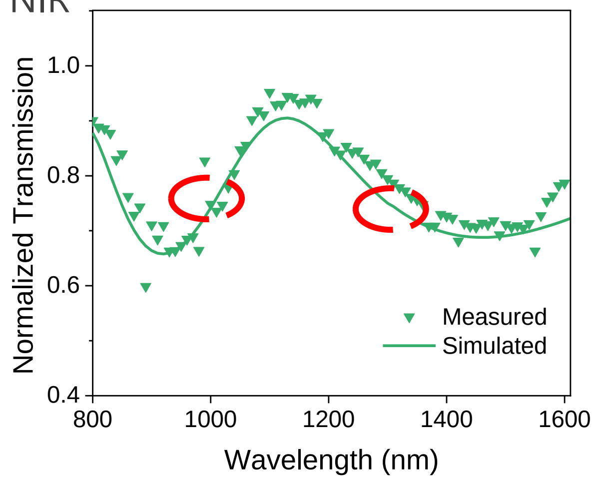


$$\varepsilon'' = \frac{\omega_p^2 \Gamma_d}{\omega^3 + \Gamma_d^2 \omega}$$

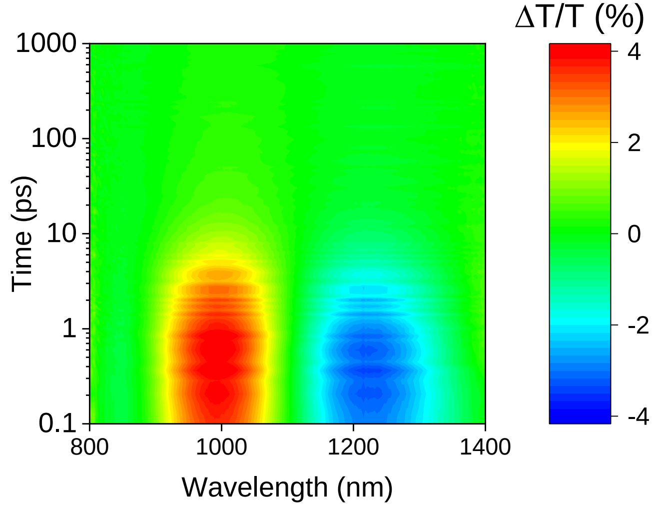
ENZ Enhanced All-optical Switching in Mid-IR



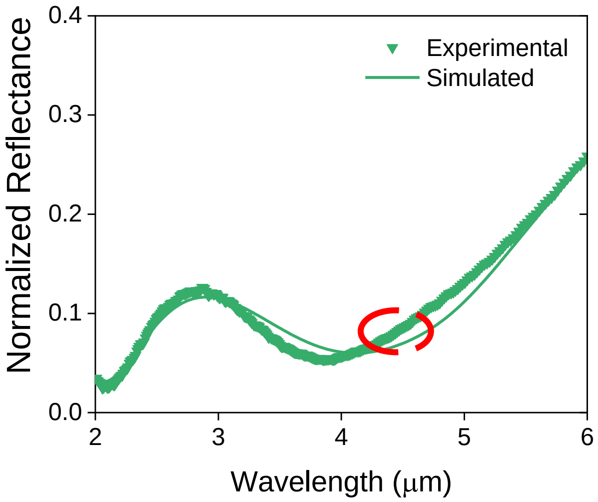
Steady state transmittance vs wavelength at NIR



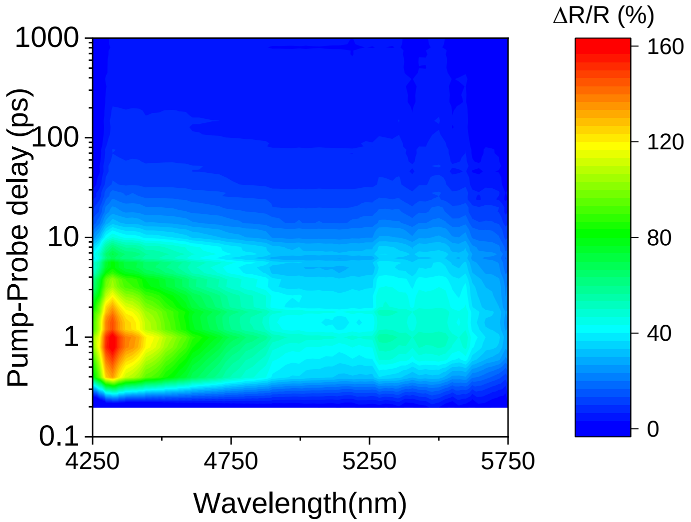
Moderate modulation near transmittance dips (4%)



Steady state reflectance vs wavelength at MIR

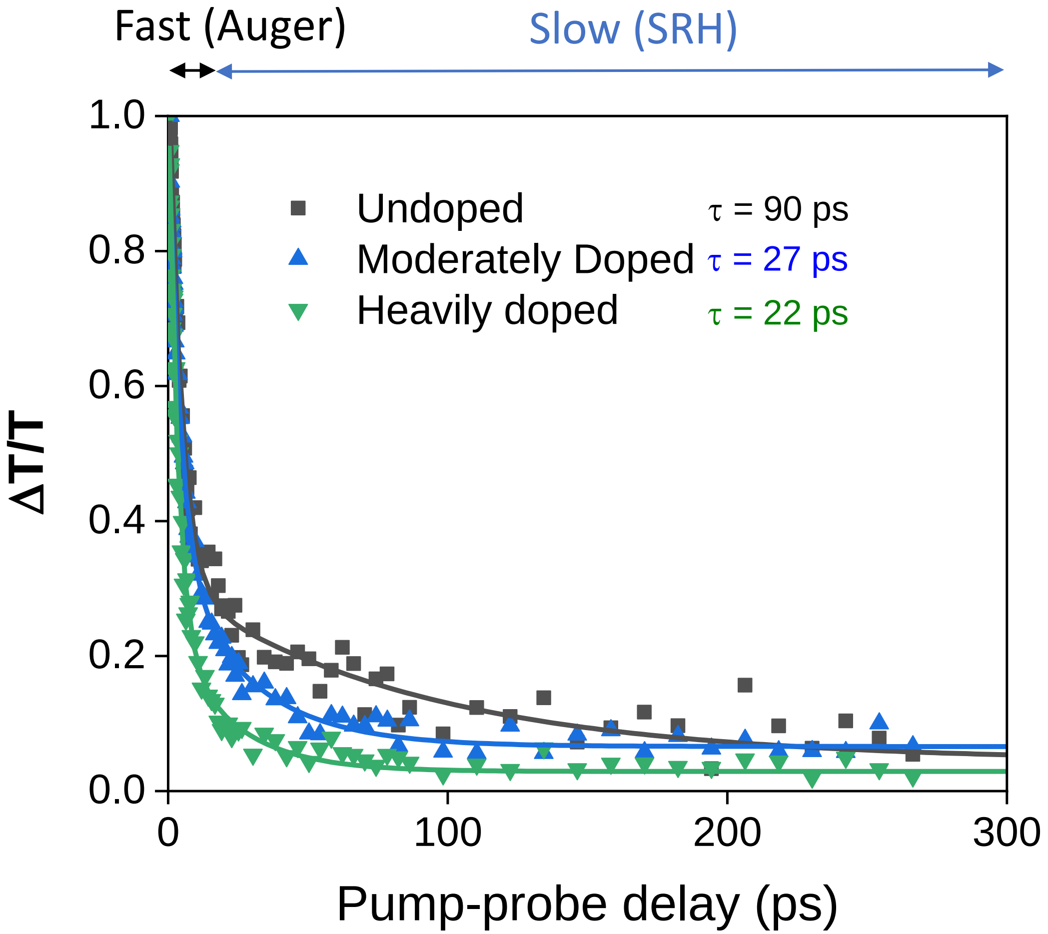


Further enhanced near the ENZ point (160%)

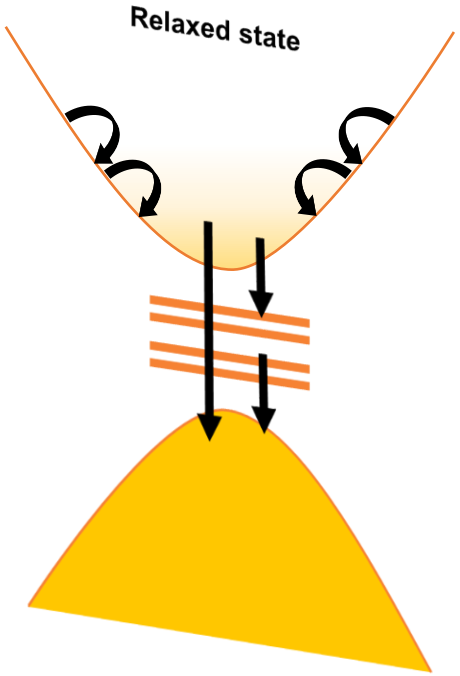


S. Saha et al., Adv. Func. Mat. (2019)

The Overall Response Time can be Engineered by Doping



Defect-assisted recombination

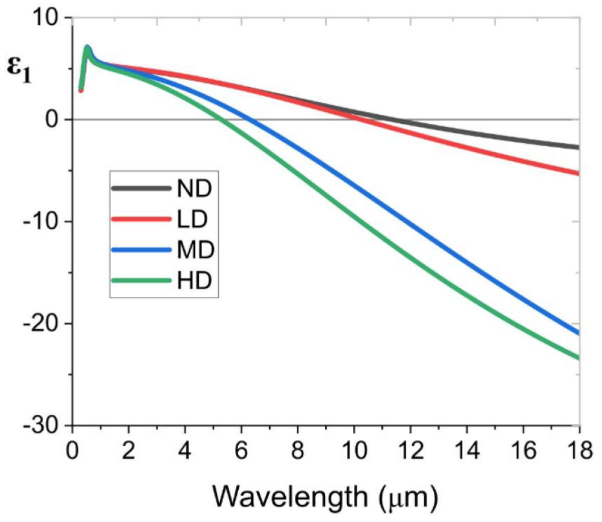


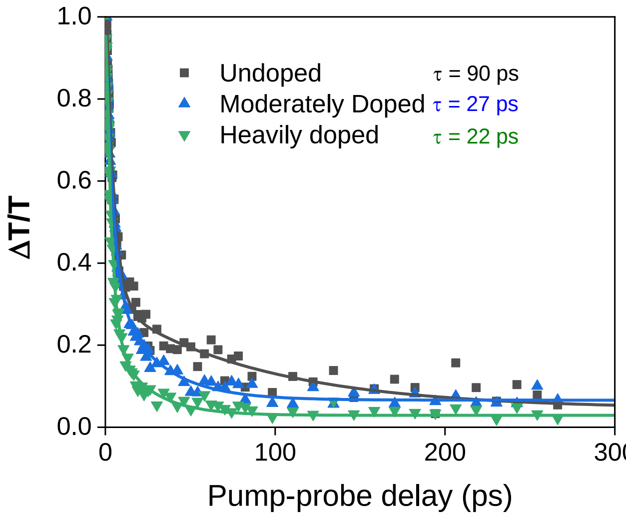
More defects, faster recombination

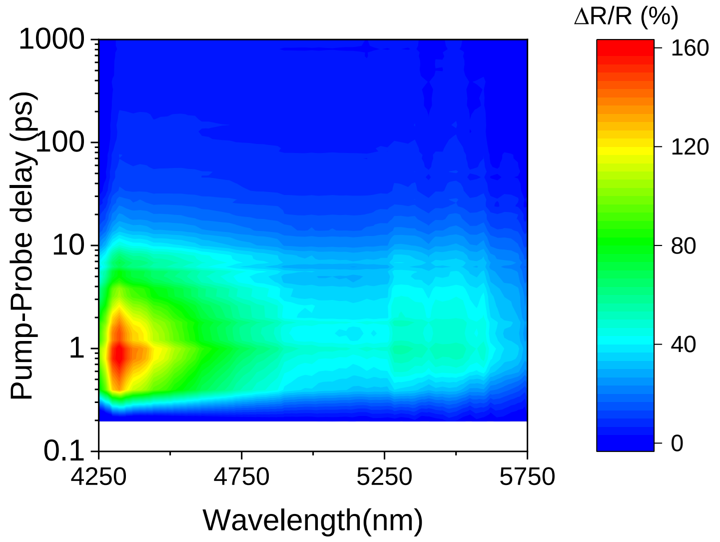
Summary

Application: All optical switching in the MIR for satellite communications

Application 2: ENZ enhanced phenomena across a broad MIR range







ENZ can be tailored from 5 to 11 microns by adding dopants

Doping reduces the relaxation time

Modulation of 160% near ENZ at 1.3 mJ/cm^2 pump power with 50ps relaxation time

Doping introduces losses in the oxide

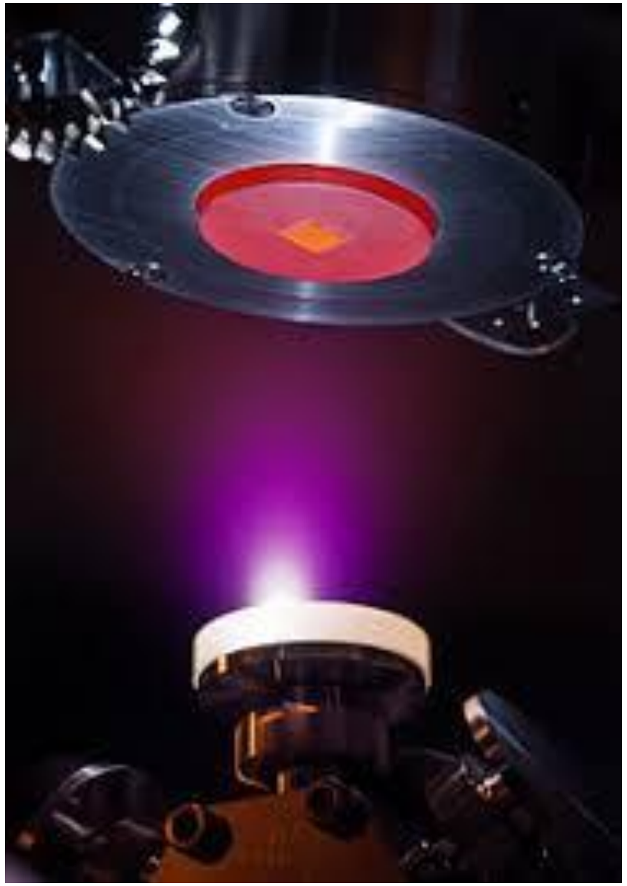
Large on-state losses

The process is irreversible

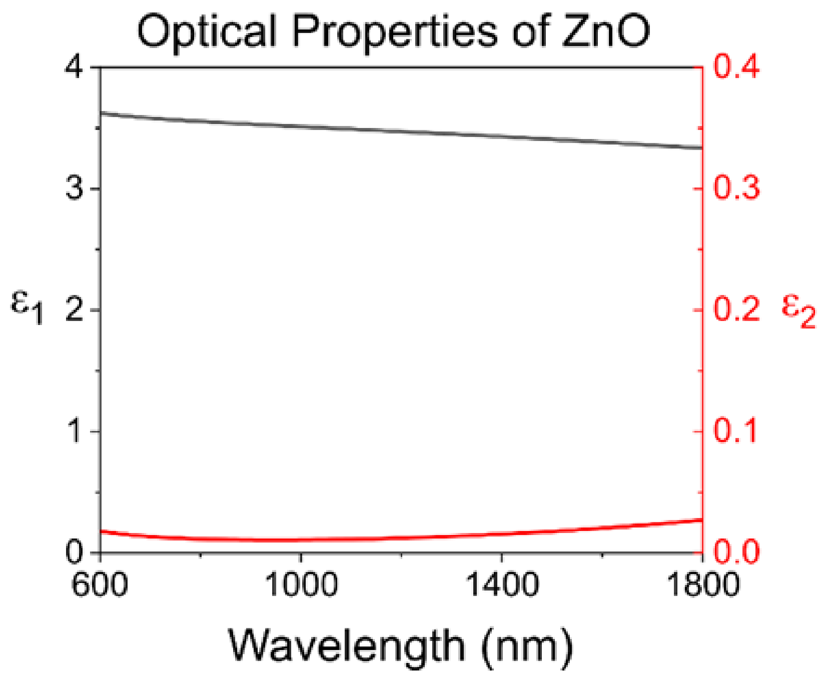
How much can we tune the **permittivity** of zinc oxide **in real time, without** adding dopants?

Material of Choice: Zinc Oxide (Undoped)

ZnO films grown by
Pulsed Laser Deposition

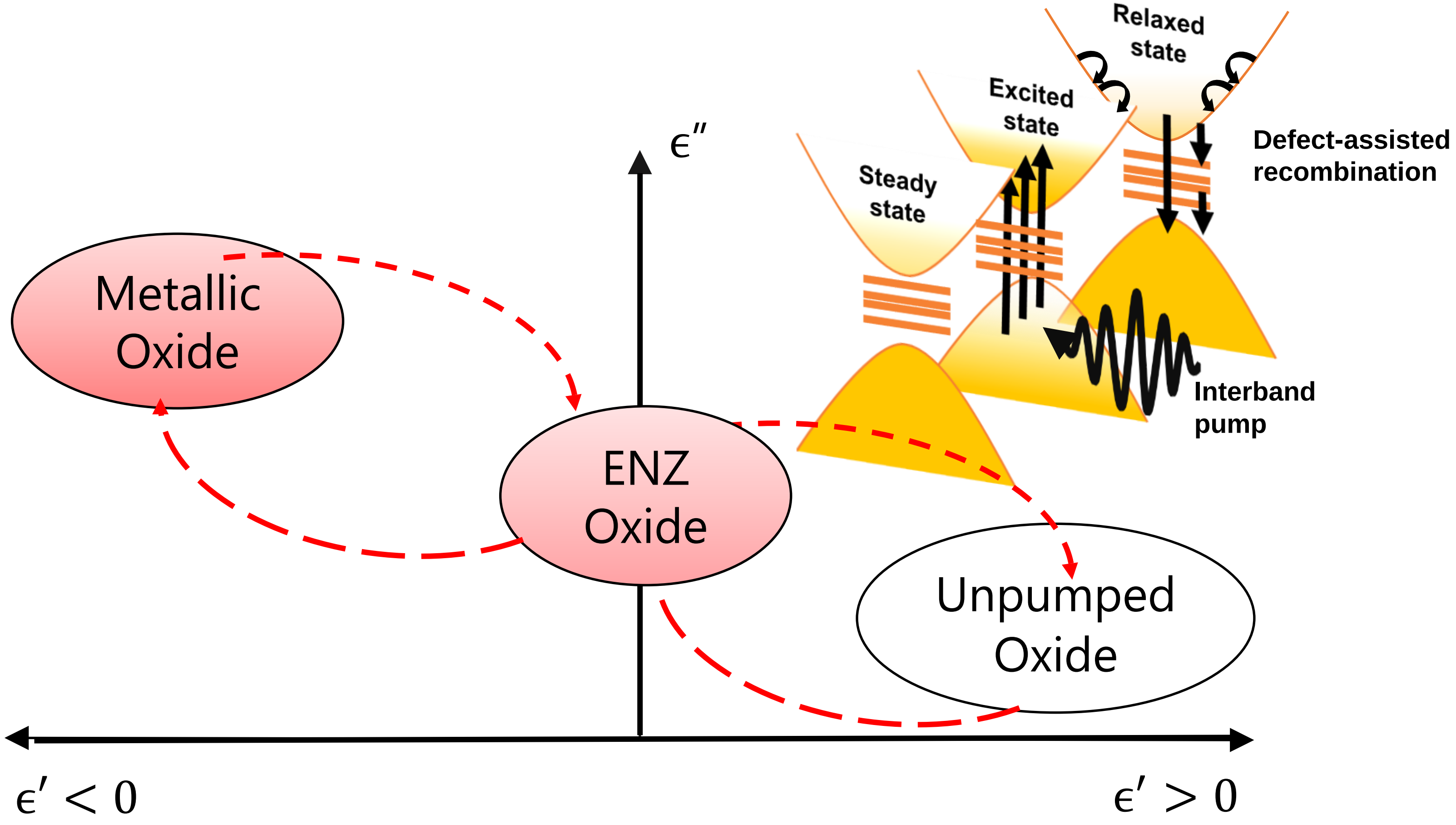


Dielectric with low optical losses



$$\varepsilon = \varepsilon_\infty + \frac{A_1}{E_1^2 - (\hbar\omega)^2 - iB_1\hbar\omega} - \frac{A_0}{(\hbar\omega)^2 + iB_0\hbar\omega}$$

How do We Tune the Permittivity ?



$$\omega_p^2 = \frac{Ne^2}{\varepsilon_0 m^*}$$

$$\varepsilon' = \varepsilon_B - \frac{\omega_p^2}{\omega^2 + \Gamma_d^2}$$

$$\varepsilon'' = \frac{\omega_p^2 \Gamma_d}{\omega^3 + \Gamma_d^2 \omega}$$

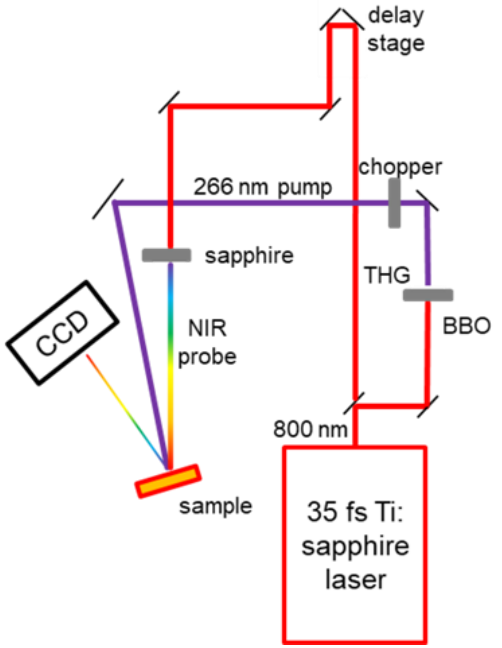
Optically pumping with an interband pump, generating electron hole pairs

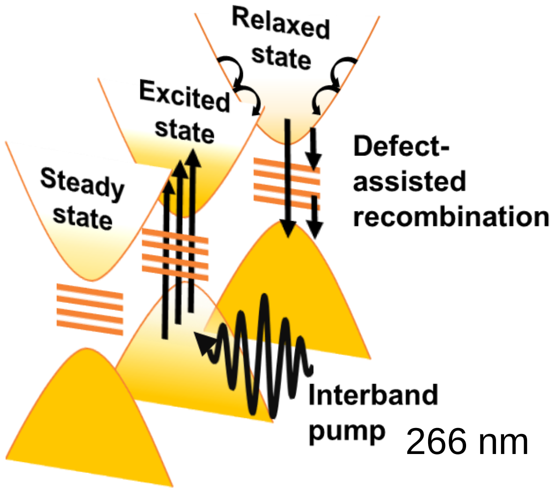
Tuning is a dynamic method: Instantaneous, reversible results

Interesting works on Tuning done by O. Muskens, H. Atwater, R. Boyd, V. Sorger, N. Kinsey, H. Lee and I. Brener

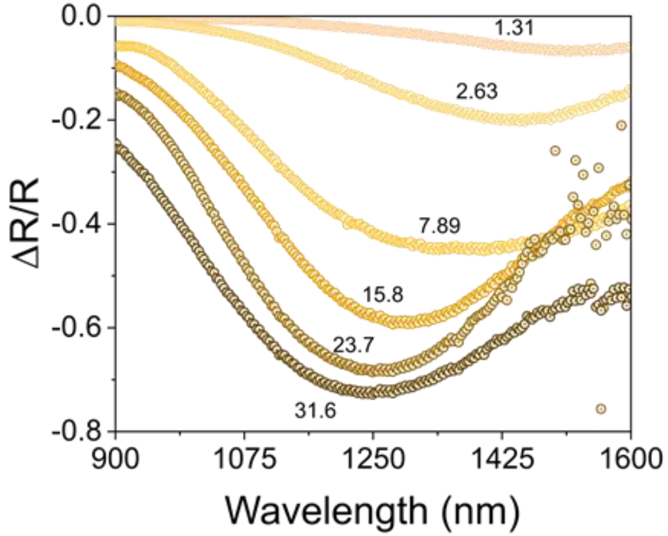
Interband Pump – Near Infrared Probe

Pump-probe schematic

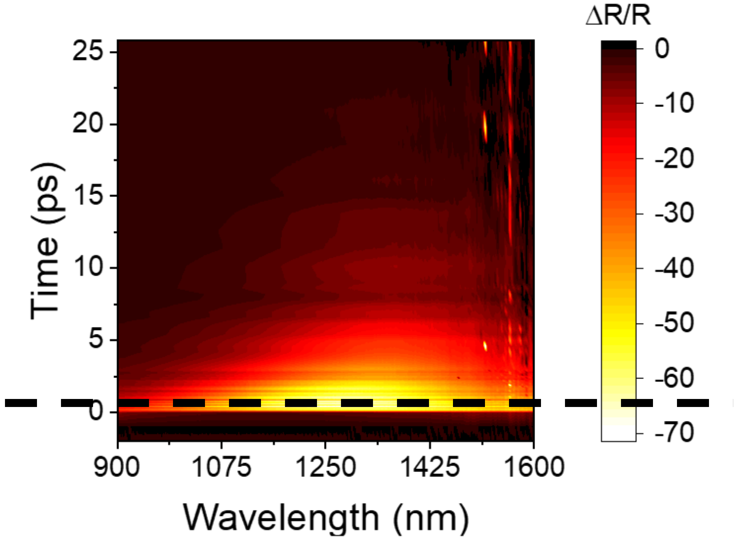




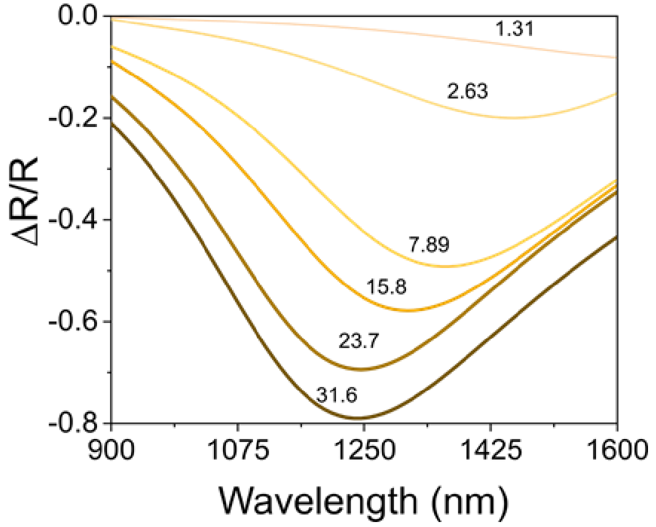
Reflectance extracted



ΔR/R captured vs pump-probe delay

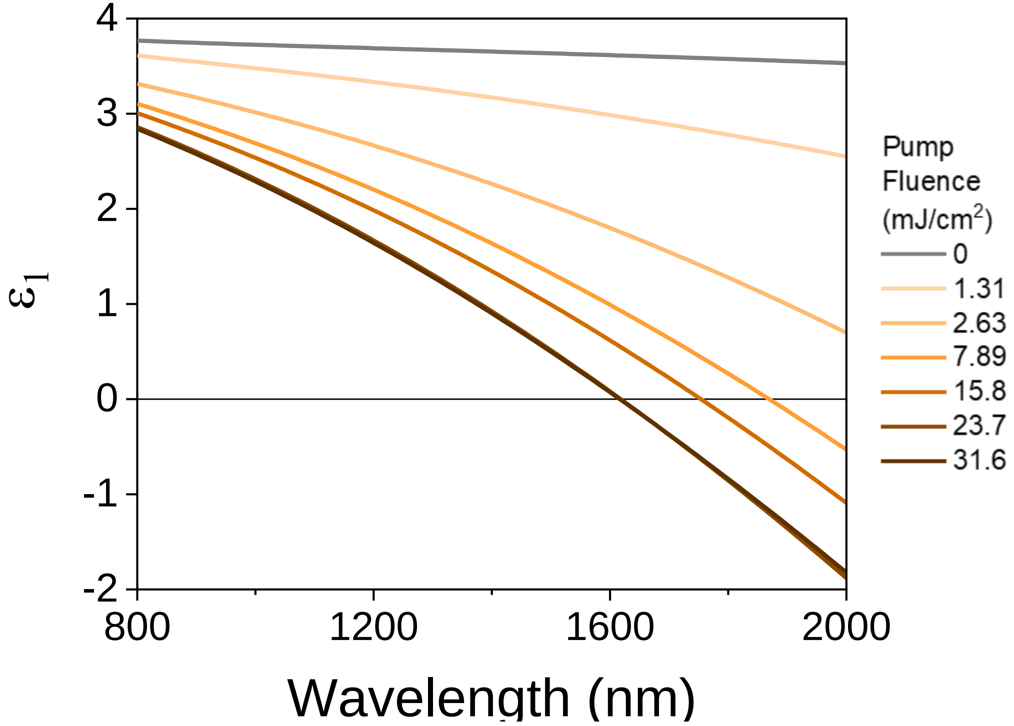


Drude Parameters extracted from fits



Unity Order Permittivity Changes at Telecom Wavelengths

Extraordinary permittivity modulation (-4 at 1600 nm) saturates at 23 mJ/cm^2

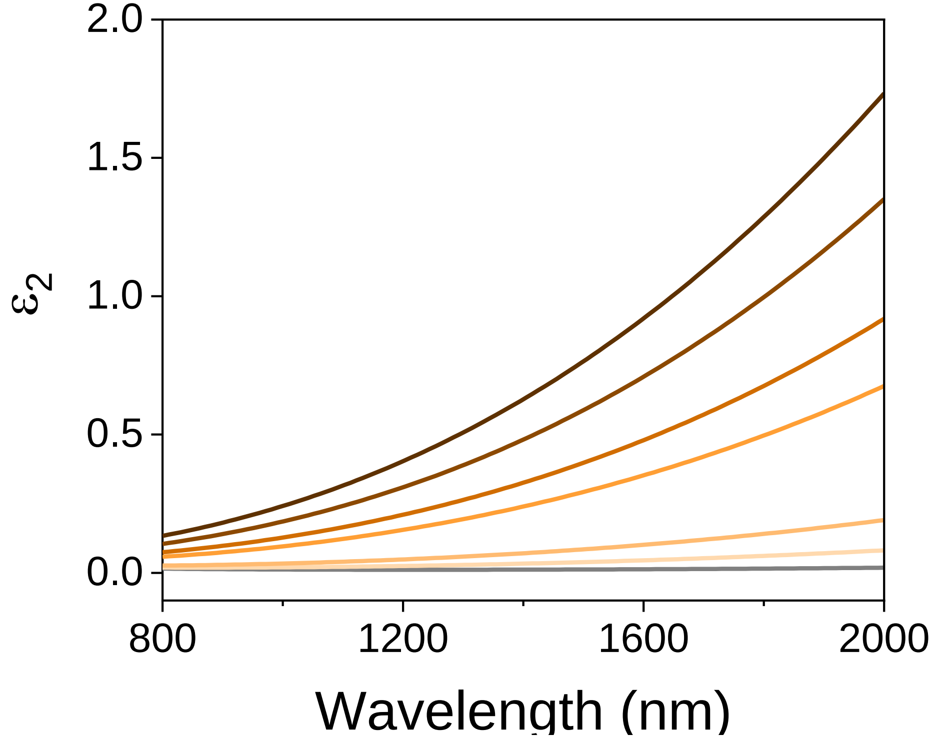


N saturates due to saturable absorption

As N rises, m* rises due to non parabolic band

$$\omega_p^{\ 2} = \frac{Ne^2}{\varepsilon_0 m^*} \qquad \varepsilon' = \varepsilon_B - \frac{\omega_p^{\ 2}}{\omega^2 + \Gamma_d^{\ 2}}$$

With increased power, the absorption in the films increase

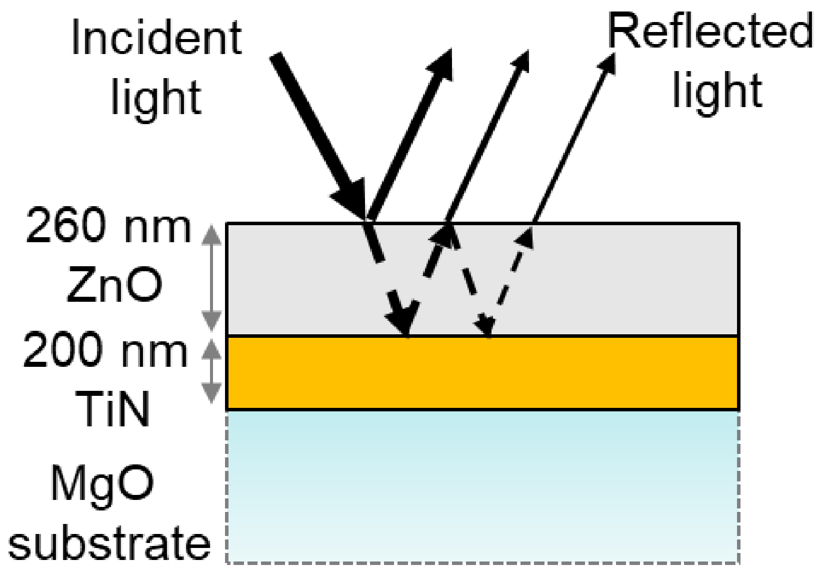


Increased free carrier concentration and heating of the lattice increases the scattering **Γ**

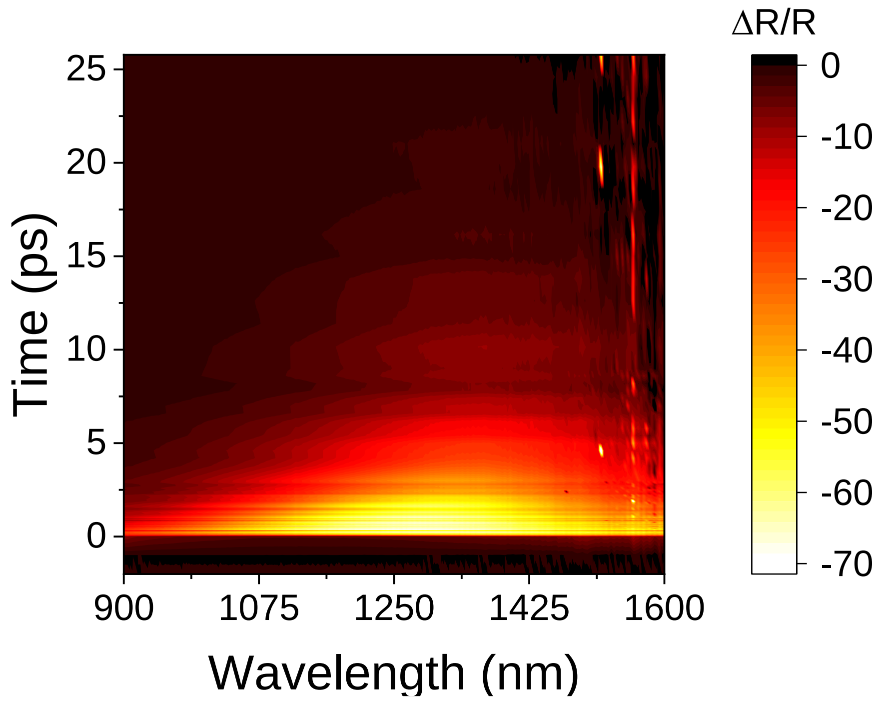
$$\varepsilon'' = \frac{\omega_p^{\ 2}\Gamma_d}{\omega^3 + \Gamma_d^{\ 2}\omega}$$

Large, Broadband Modulation in Planar Mirrors Without Lithography

Lithography-free mirror



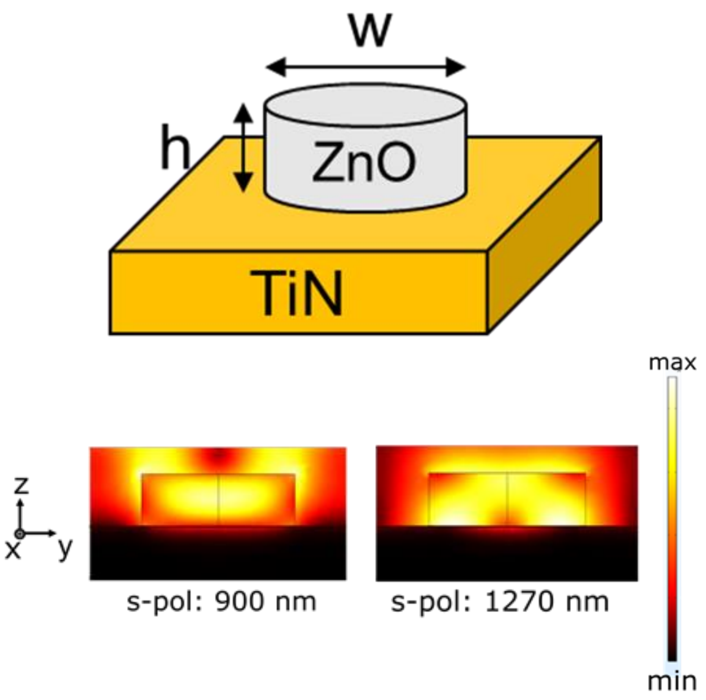
Broadband modulation of 70% at telecom
Without Doping or patterning



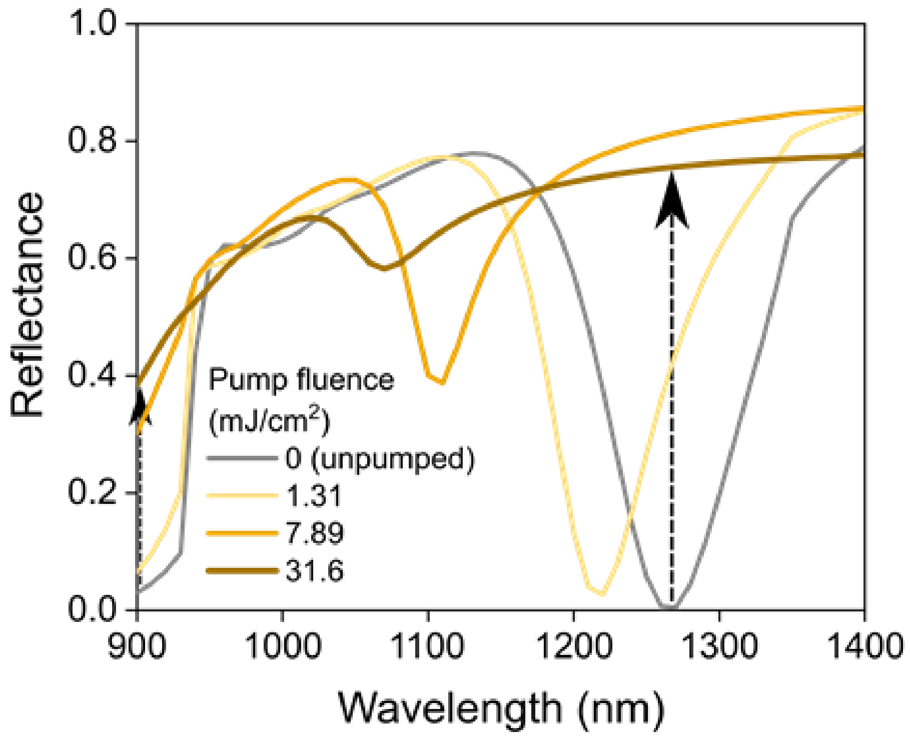
20ps response time!

Selective Enhancement at Specific Wavelengths: Design

Hybrid Plasmonic Resonators

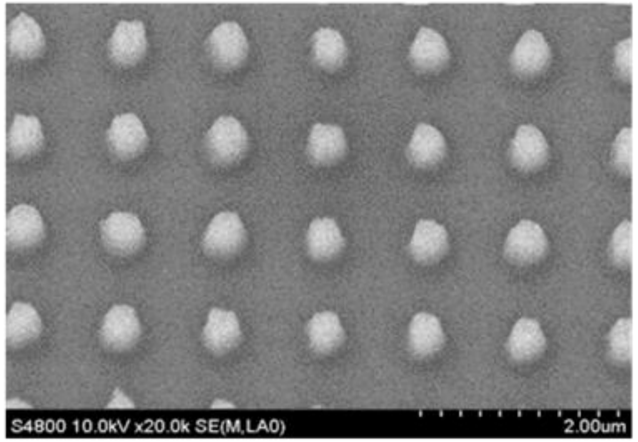


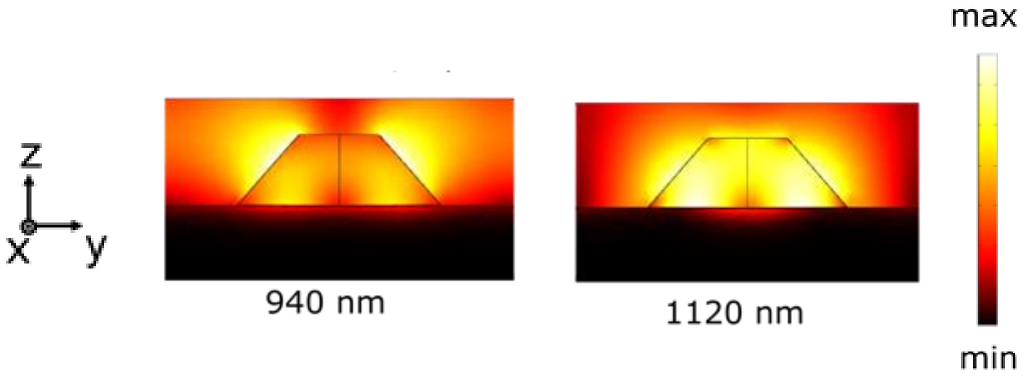
Resonance shifts under a pump



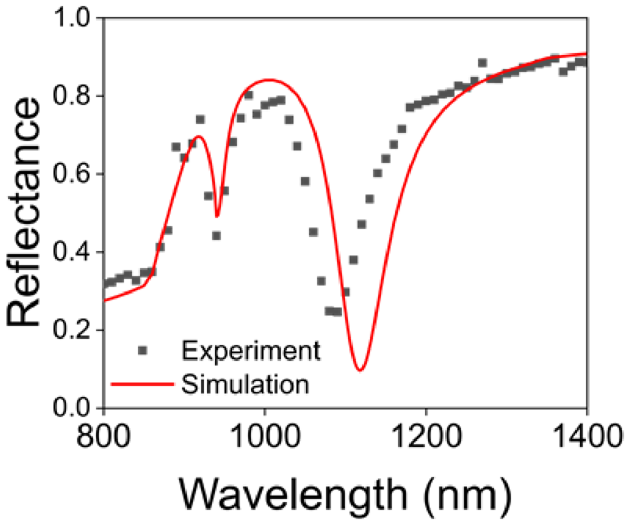
Selective Enhancement at Specific Wavelengths

ZnO nanodisks on TiN

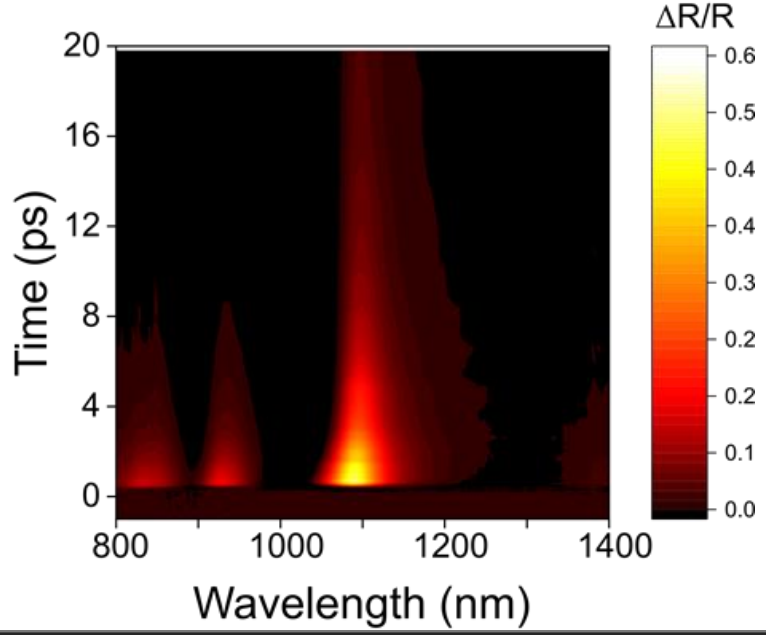




Steady-state resonance shows two dips

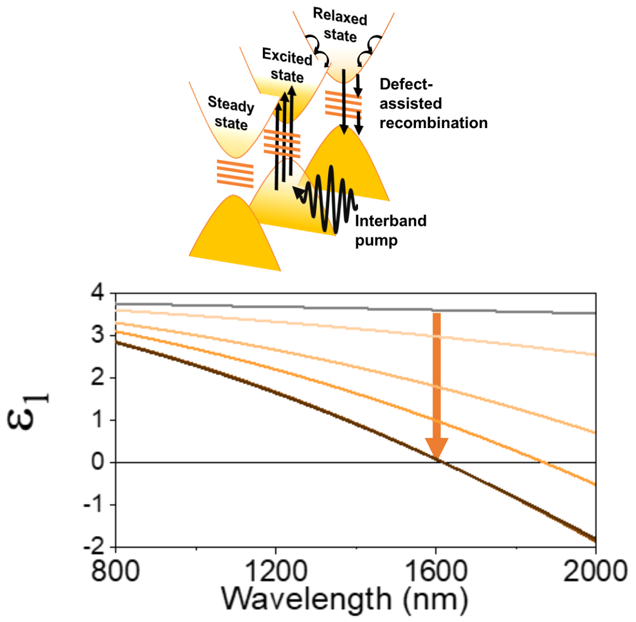


Maximum change of 55% at 7.8 mJ/cm^2 with 20 ps Response time

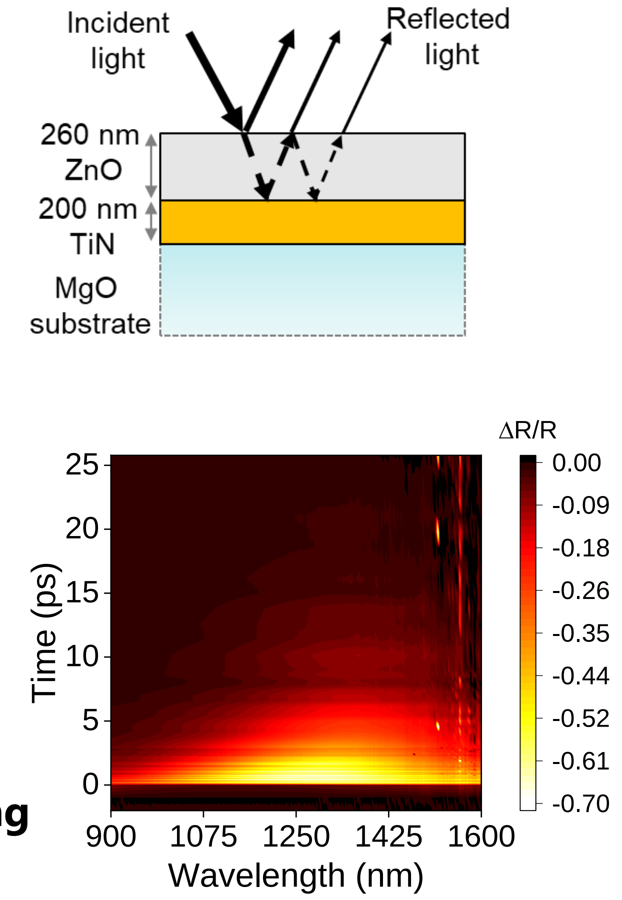


Summary

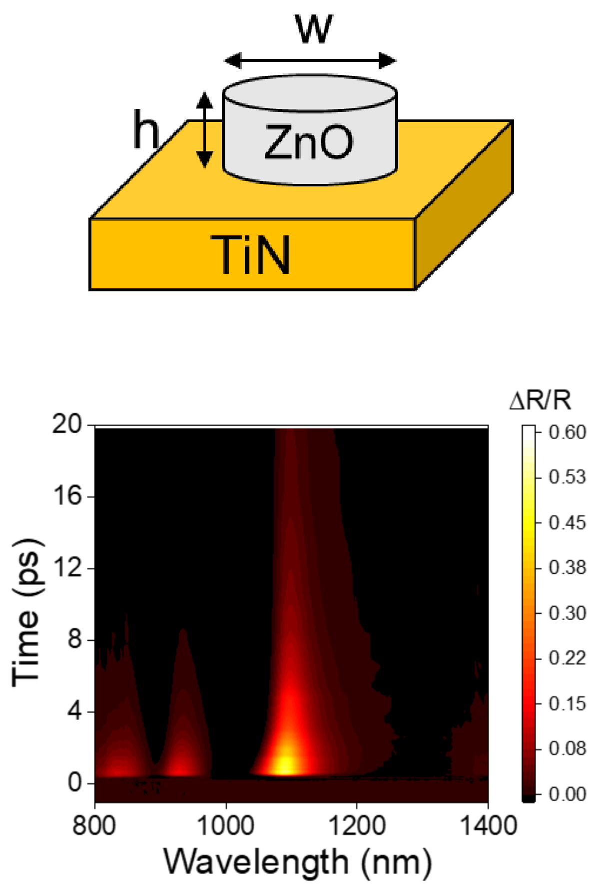
Large optical changes
are demonstrated
In UNDOPED ZnO
by interband pumping



Planar metal-backed ZnO mirror
Can be used to demonstrate
broadband modulation with ps
response time



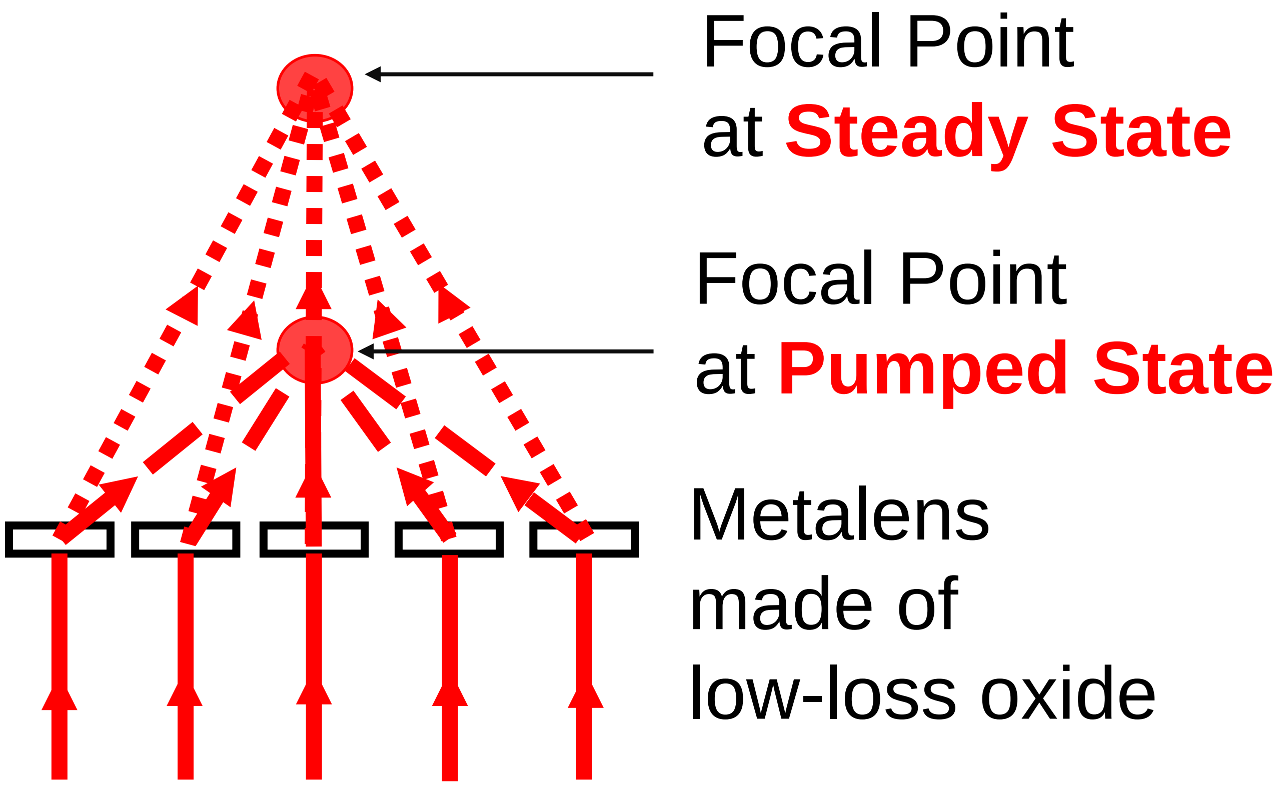
The resonances can be selectively
enhanced at specific wavelengths
With simple resonant structures



Application: All optical switching

Transient permittivity data useful for designing dynamic polarization switches, HMMs, etc

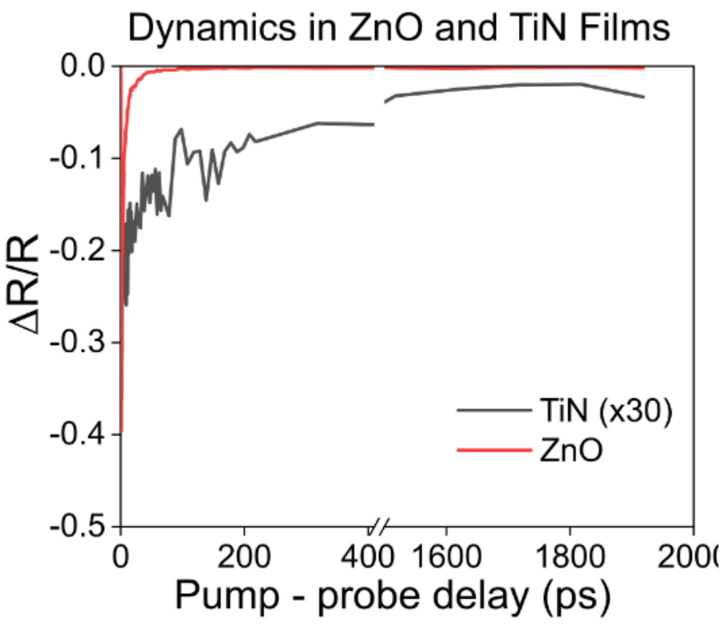
Tunable focusing, polarization rotators, filters, etc

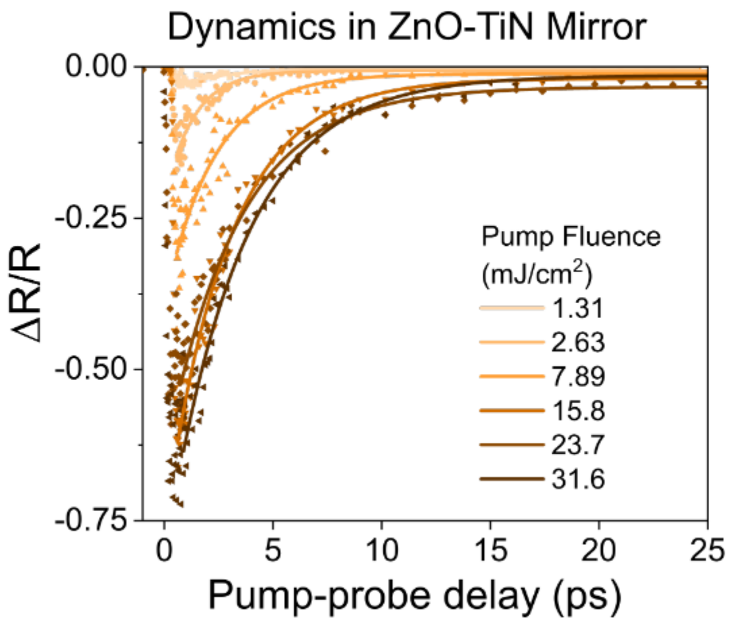


Impact

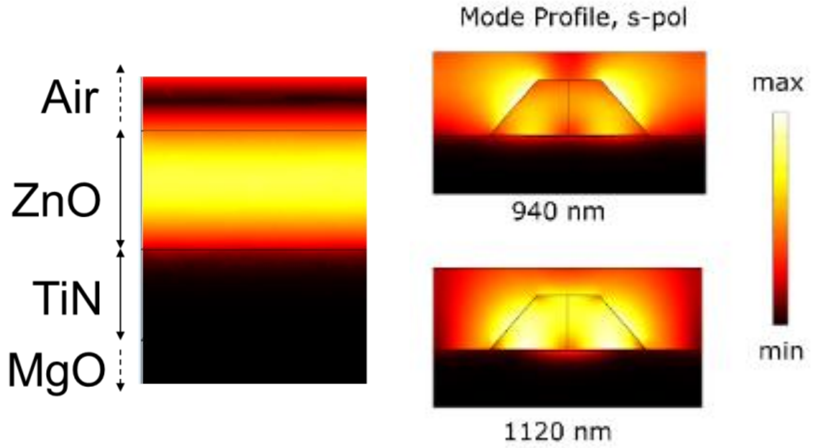
- Focusing high power beams used to burn off tissue
- All-optical scanning

The Switches are Fast, Despite the Slower Response of TiN





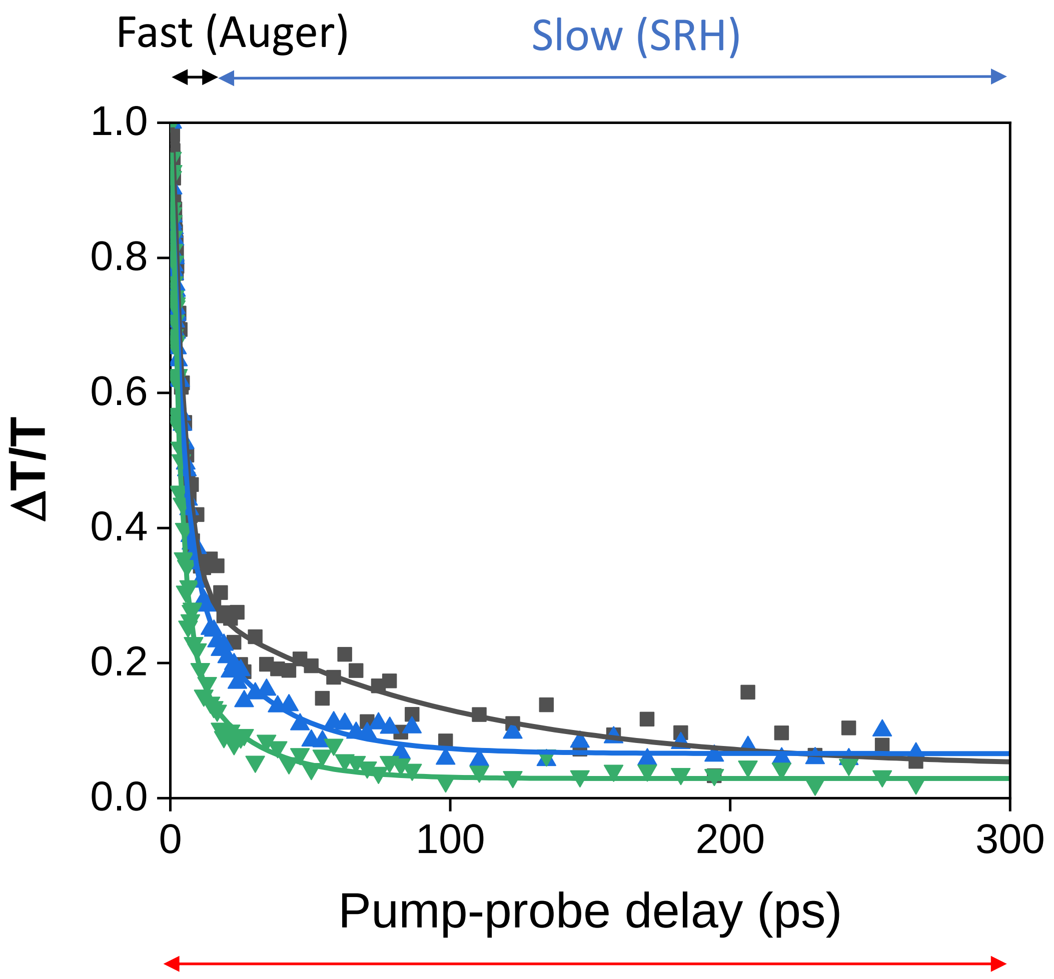
Most of the light matter interaction happens in the ZnO



As a result, ZnO dictates the modulation dynamics, even when TiN is excited

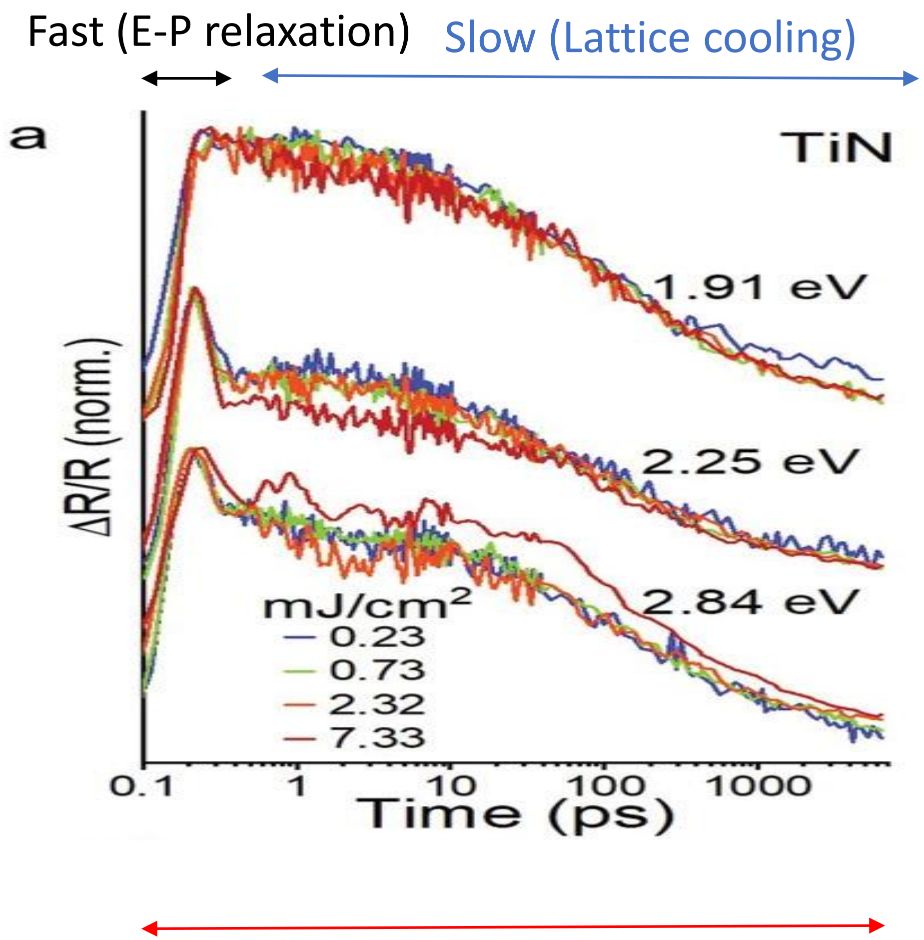
Can we **control** the **speed** of an all-optical switch?

In Materials, Response Time is Dictated by the Slowest Dynamics



Overall time (slow)

Saha et. al, Adv. Func. Mat. (2019)

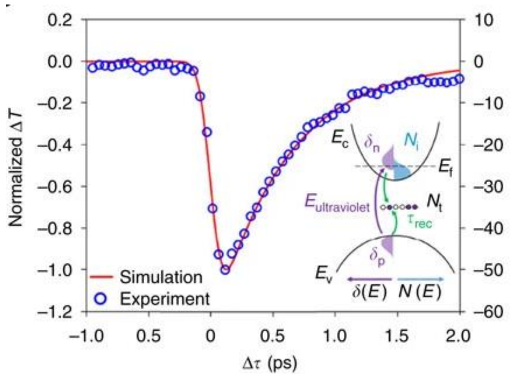


Overall time (slow)

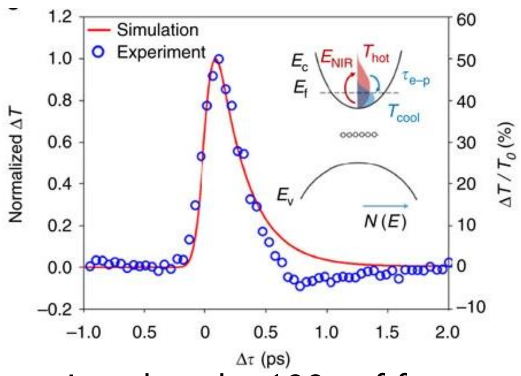
B. Diroll, S. Saha et. al, Adv. Opt. Mat. (2020)

Pump Induced Control of Switching Dynamics

Utilizing interband vs intraband Relaxation times



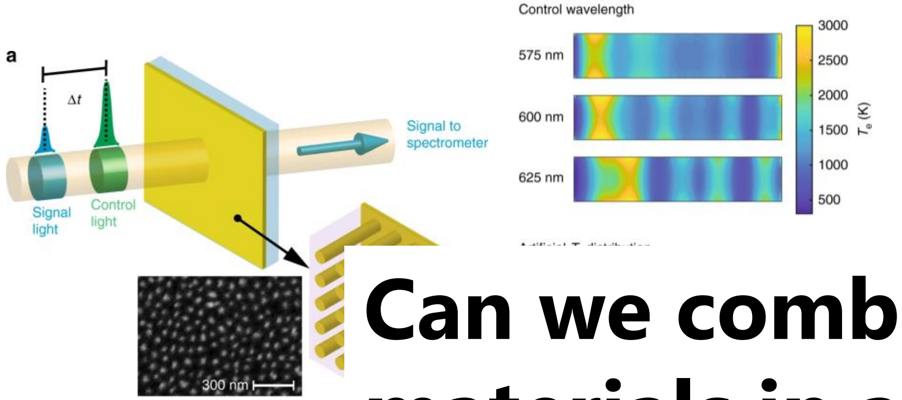
Interband – picoseconds

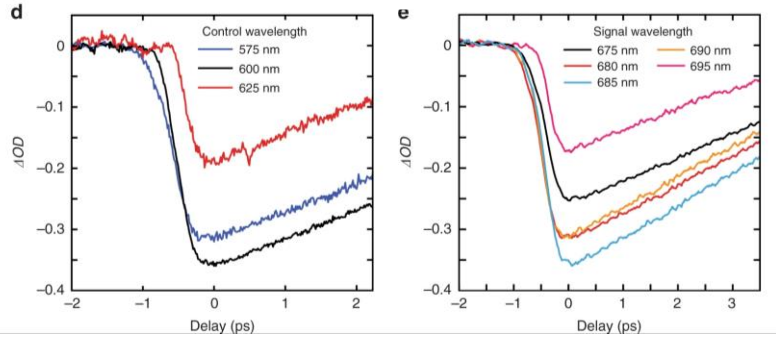


Intraband – 100s of fs

Clerici et al., *Nat Comm.* 2016

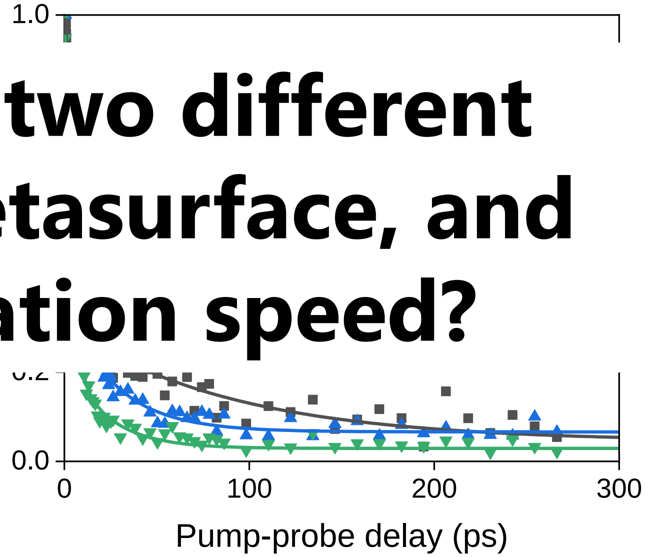
Controlling temperature distribution in nanorods controls the photon dynamics to an extent





Zayats et al., *Nat Comm.* 2019

Controlling doping to control relaxation times

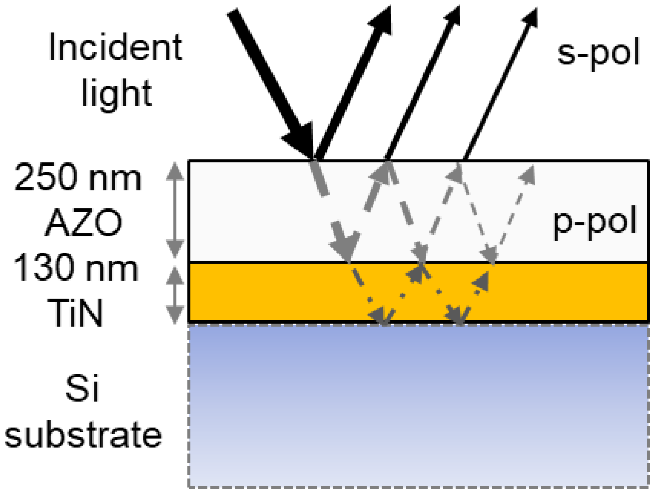


Saha et al., *Adv. Opt. Mat.* 2020

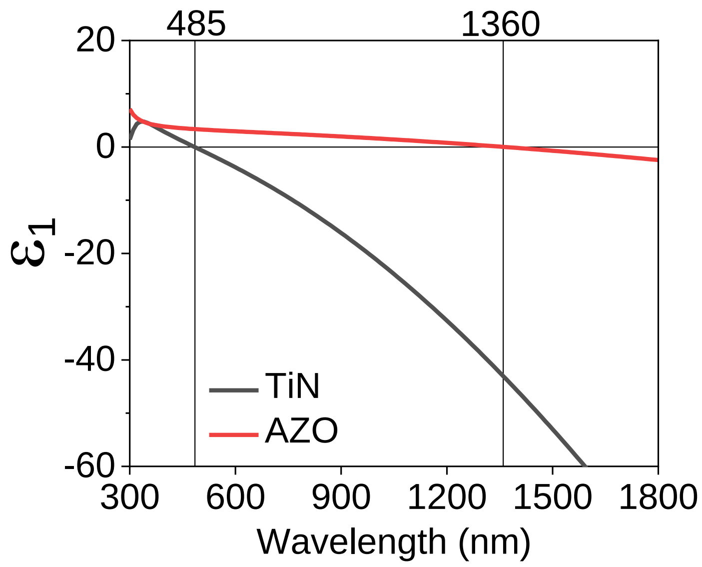
Can we combine two different materials in a metasurface, and control the operation speed?

Berreman Metasurface Strongly Absorbs p-polarized Light Near ENZ

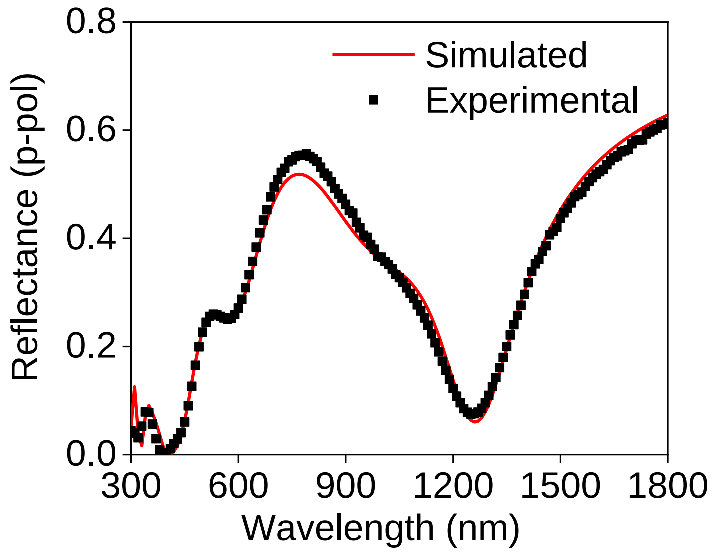
AZO film on TiN



ENZs of TiN and AZO

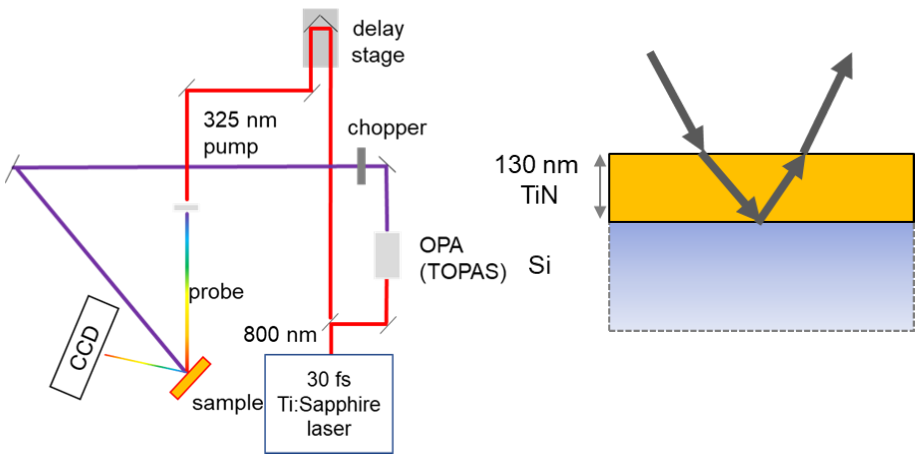


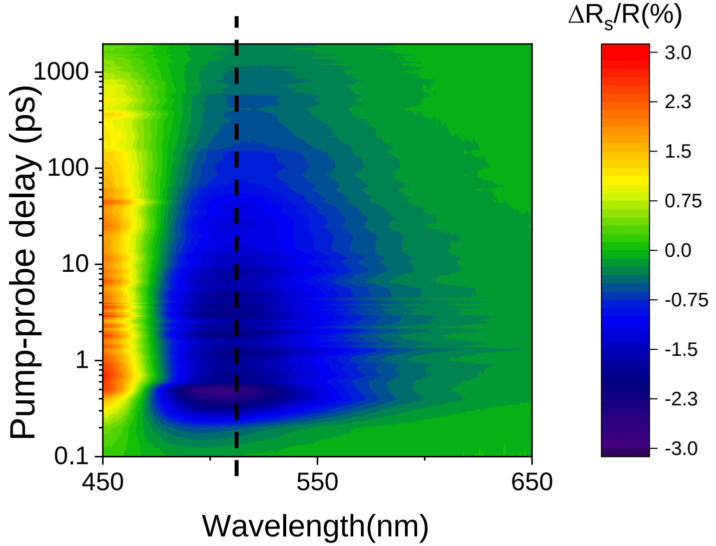
Near perfect
absorption near ENZ



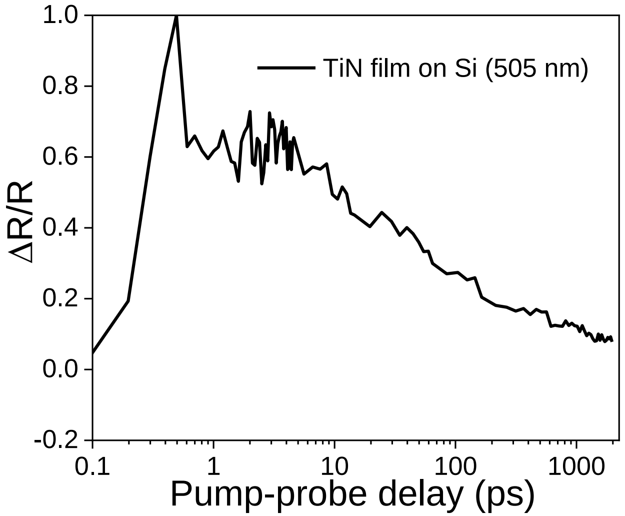
TiN is Slow (325 nm pump, Vis probes, 1.3 mJ/cm²)

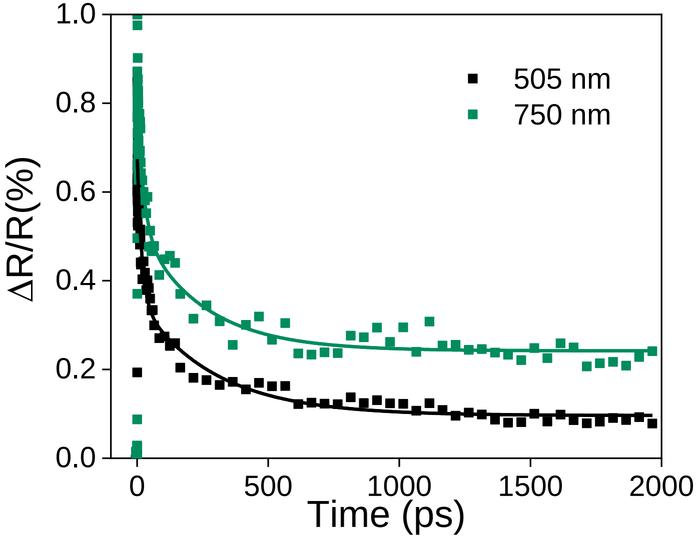
Experimental Setup





TiN Response time > 2 ns





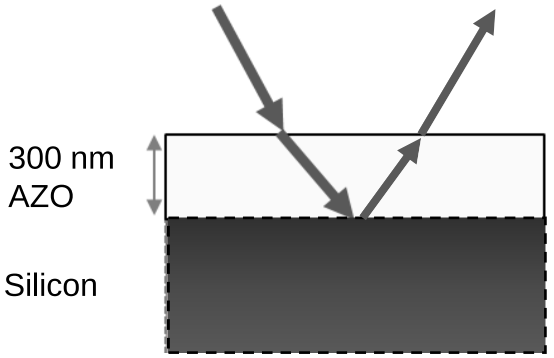
$$\left(\frac{\Delta R}{R}\right)(t) = A\, e^{\frac{-t}{\tau 1}} + B\, e^{\frac{-t}{\tau 2}} + C$$

Wavelength (nm)	A	B	C	τ_1 (ps)	τ_2 (ps)
505	0.33	0.26	0.096	17.3	287
750	0.29	0.28	0.24	24.3	242

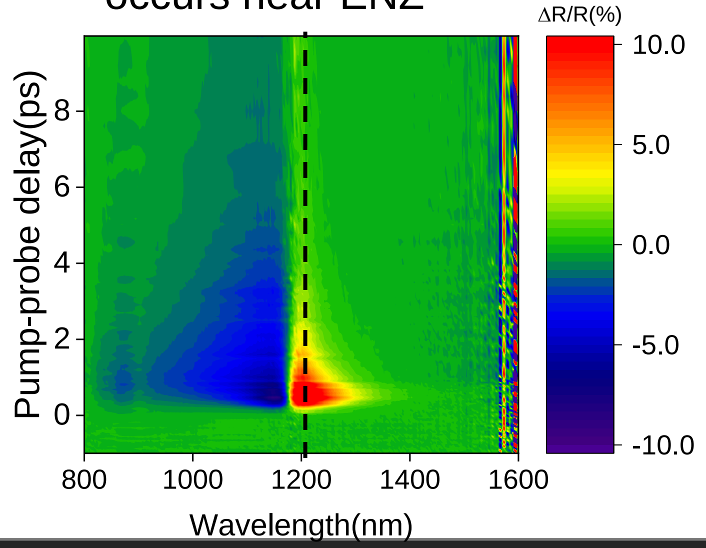
See also work by B. Diroll, S. Saha et al., Adv. Opt. Mat (2019), and H. George, N. Kinsey et al., Omex (2016)

AZO is Fast (325 nm pump, NIR probes, 1.3 mJ/cm^2)

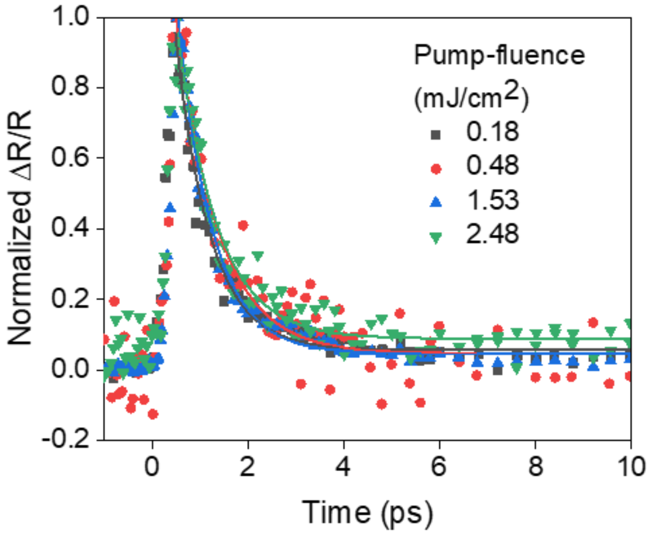
AZO is Fast



Maximum modulation occurs near ENZ



Sub 10 ps response time

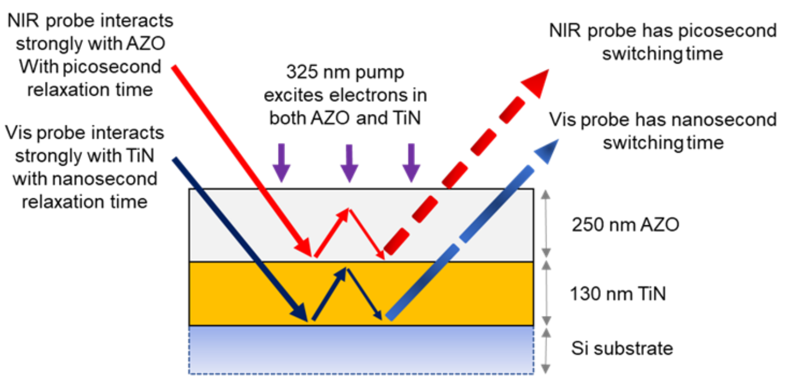


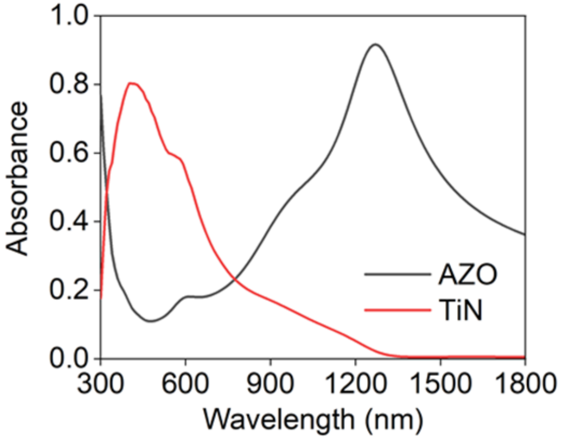
$$\left(\frac{\Delta R}{R}\right)(t) = D\,e^{\frac{-t}{\tau}} + E$$

Pump Fluence (mJ/cm^2)	D	E	τ (ps)
0.18	1.76	0.056	0.715
0.49	1.69	0.046	0.873
1.53	1.98	0.045	0.723
2.48	1.65	0.088	0.834

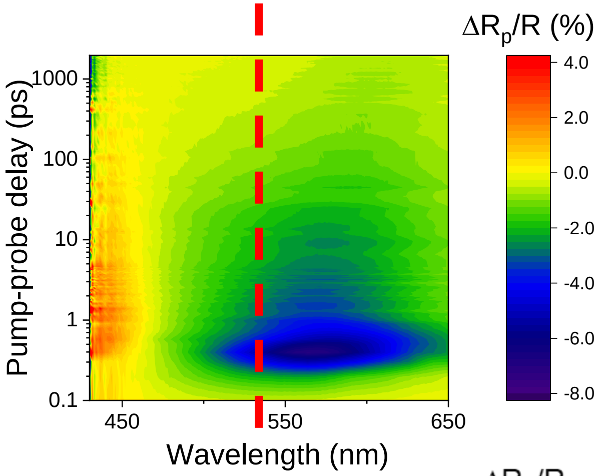
Metasurface Can Operate Both Fast and Slow

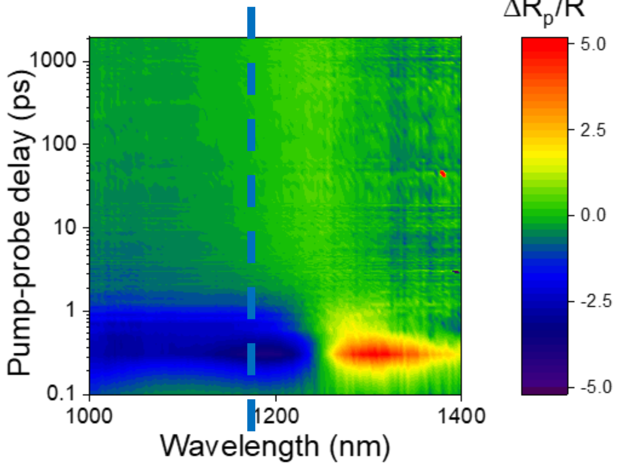
In the metasurface, light is strongly absorbed by the individual material close to the ENZ point



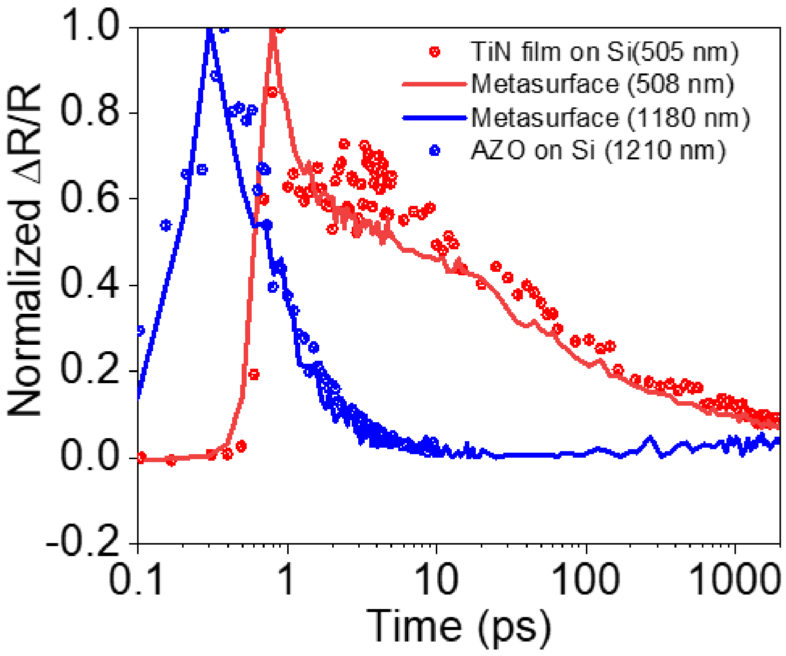


The metasurface reacts slowly near 500 nm, and fast near 1300 nm.





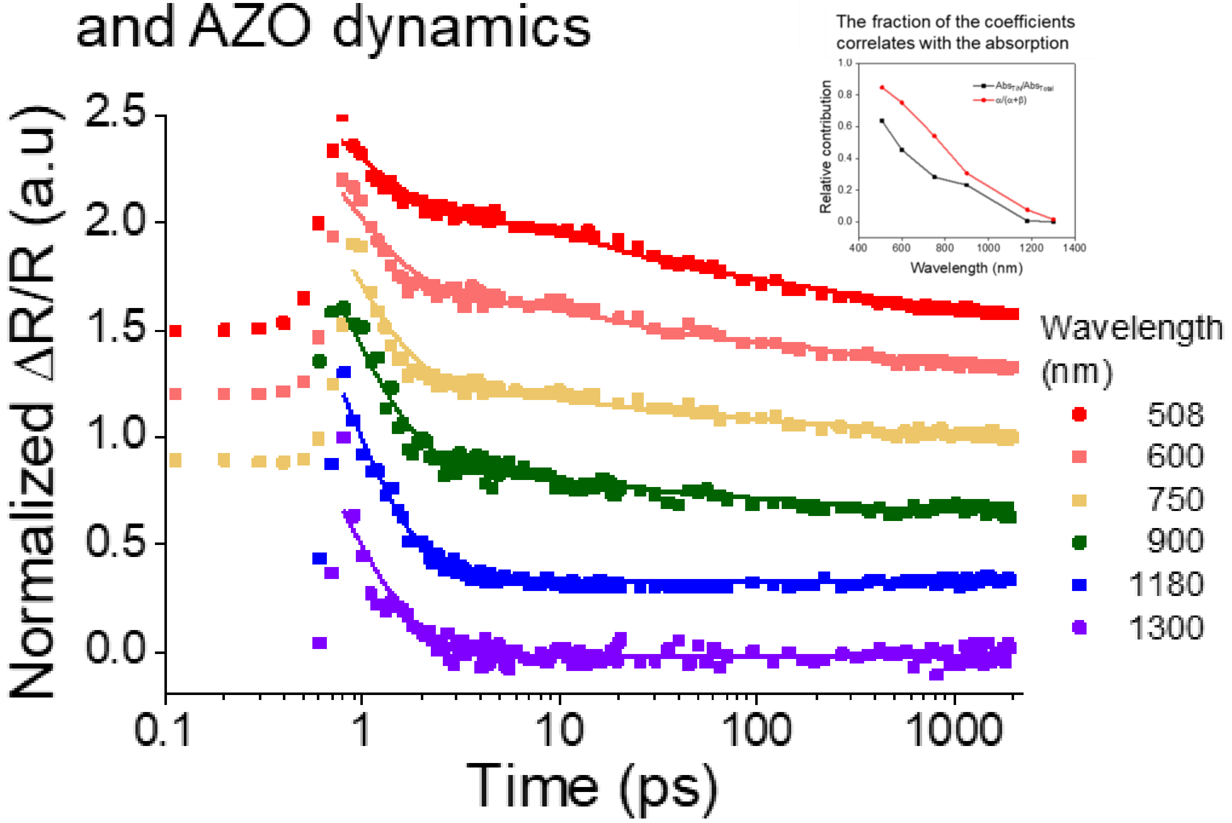
The metasurface switching responses (solid lines) near ENZ match well with that of the individual films (dots)

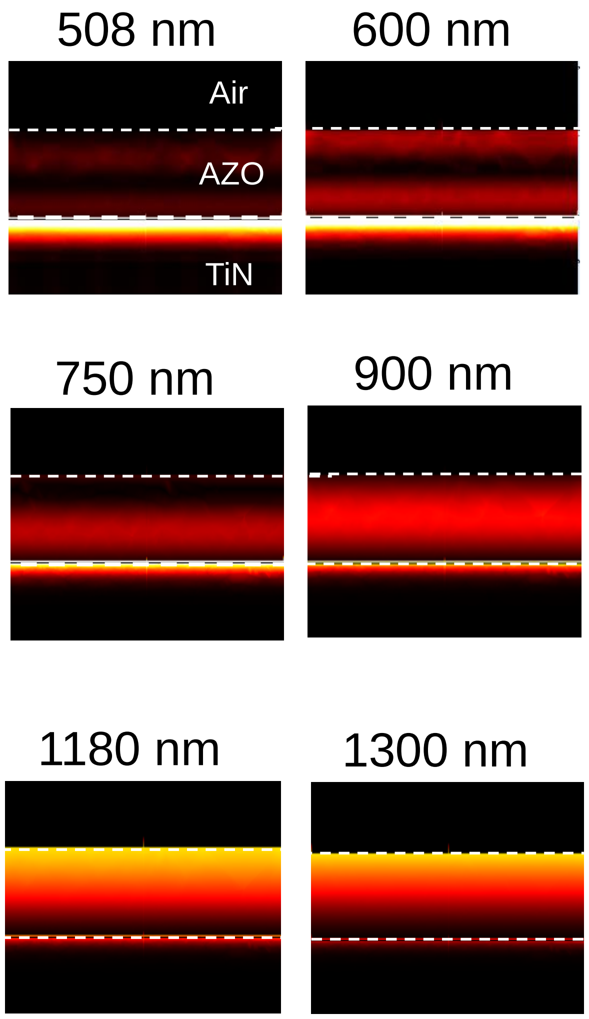


Designer Dynamics Determined by the Light Matter Interaction

$$\left(\frac{\Delta R}{R}\right)(t) = \boldsymbol{\alpha}\overbrace{\left(A e^{\frac{-t}{17.3}} + B e^{\frac{-t}{287}}\right)}^{\text{TiN response}} + \boldsymbol{\beta}\, \overbrace{e^{\frac{-t}{0.72}}}^{\text{AZO response}} + \Gamma$$

The decay as a weighted sum of the TiN and AZO dynamics



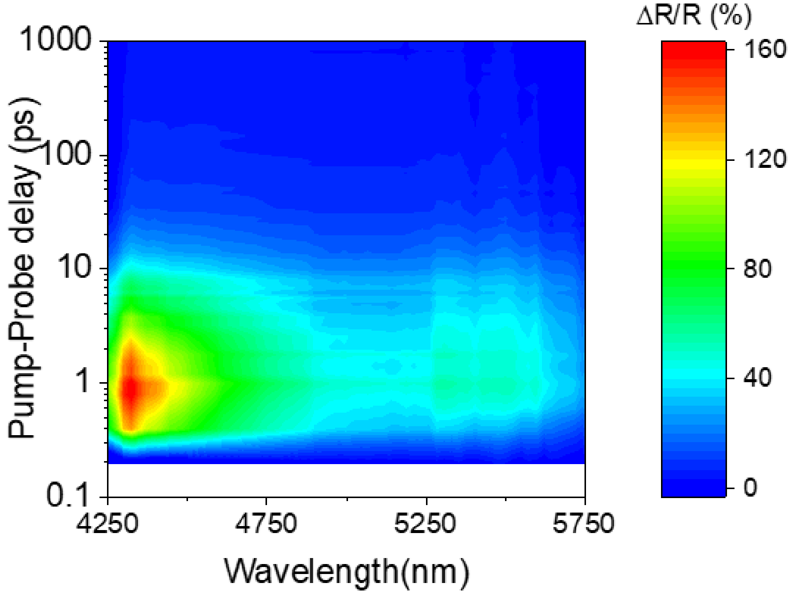


Final Summary

Understanding tuning and tailoring can help us understand the steady state and temporal dynamics of TCOs
A deeper understanding of the materials will help us develop new devices

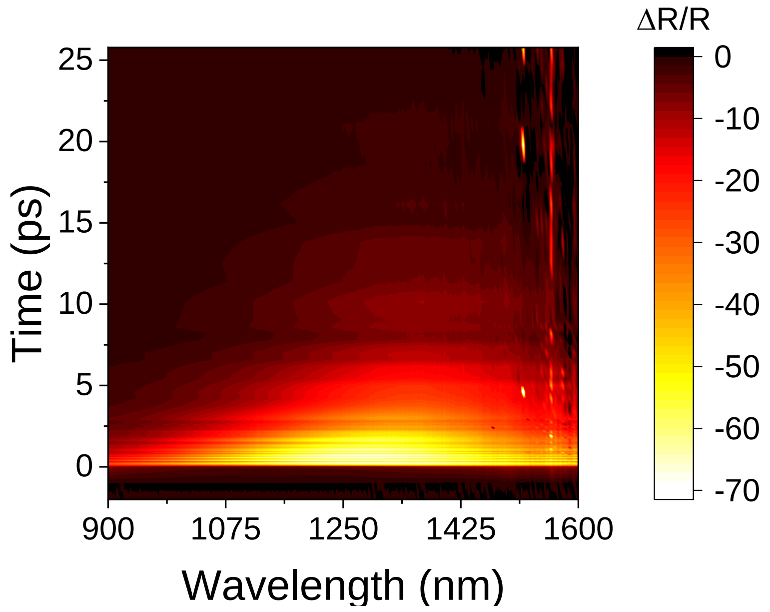
Y:CdO

- **ENZ Tailoring** with different doping
- Controlling **decay time** with dopants
- **Large modulation** in the MIR



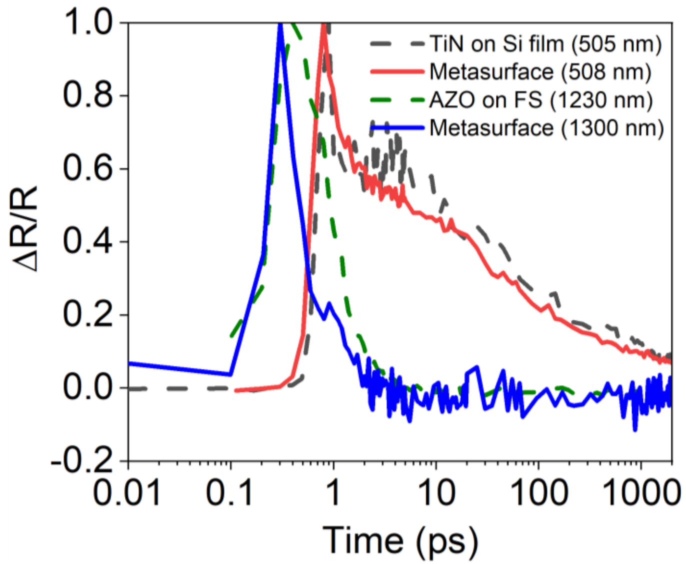
ZnO

- **Permittivity Tuning** with increased **pump fluence**
- Large modulation in the NIR



TiN-AZO

- **Fast** and **Slow** switching in the same Berreman metasurface
- **<10 ps** to **>3** ns switching time by controlling the probe



Acknowledgement

Work on Y:CdO published in Advanced Functional Materials

Work on ZnO modulators preprint in arxiv

Email:
Saha11 at purdue dot edu

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