The 8th International Conference on Surface Plasmon Photonics (SPP8)

Plenary session

Date May 24, 2017

Time 09:00-09:45

Room International Conference Hall (4F)

Professor

Vladimir Shalaev

Purdue University, USA

Enabling Practical Nanophotonics with Plasmonics

Broadening the Applications Realm for Metasurfaces

Vladimir M. Shalaev
Purdue University, USA

Symmetry and Conservation

Emmy Noether

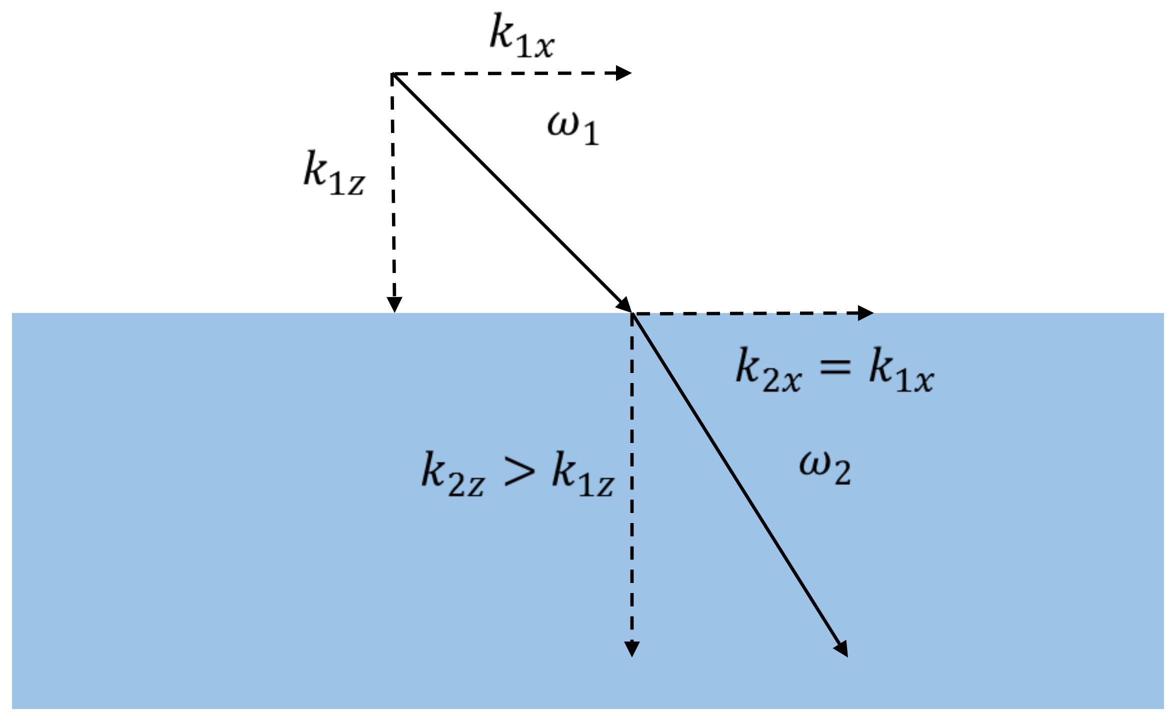
Symmetry

$\Longleftrightarrow$

Conservation Law

Translational Symmetry $\Longleftrightarrow$ Conservation of Momentum

$$k_{2x} = k_{1x}$$



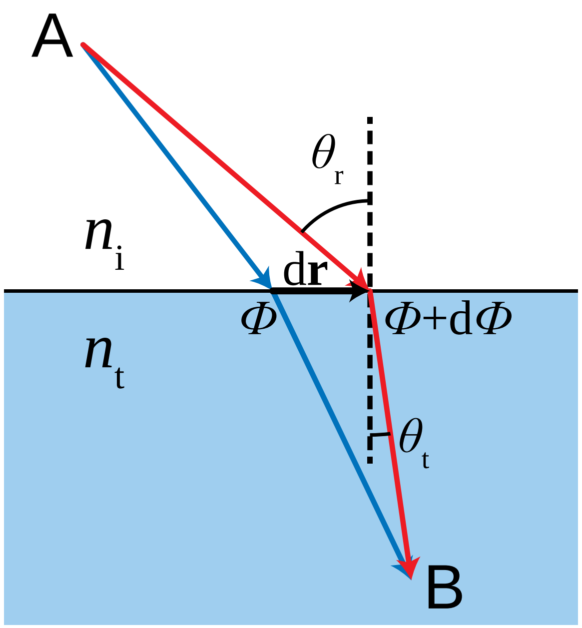
Temporal Symmetry $\Longleftrightarrow$ Conservation of Energy

$$\omega_1 = \omega_2$$

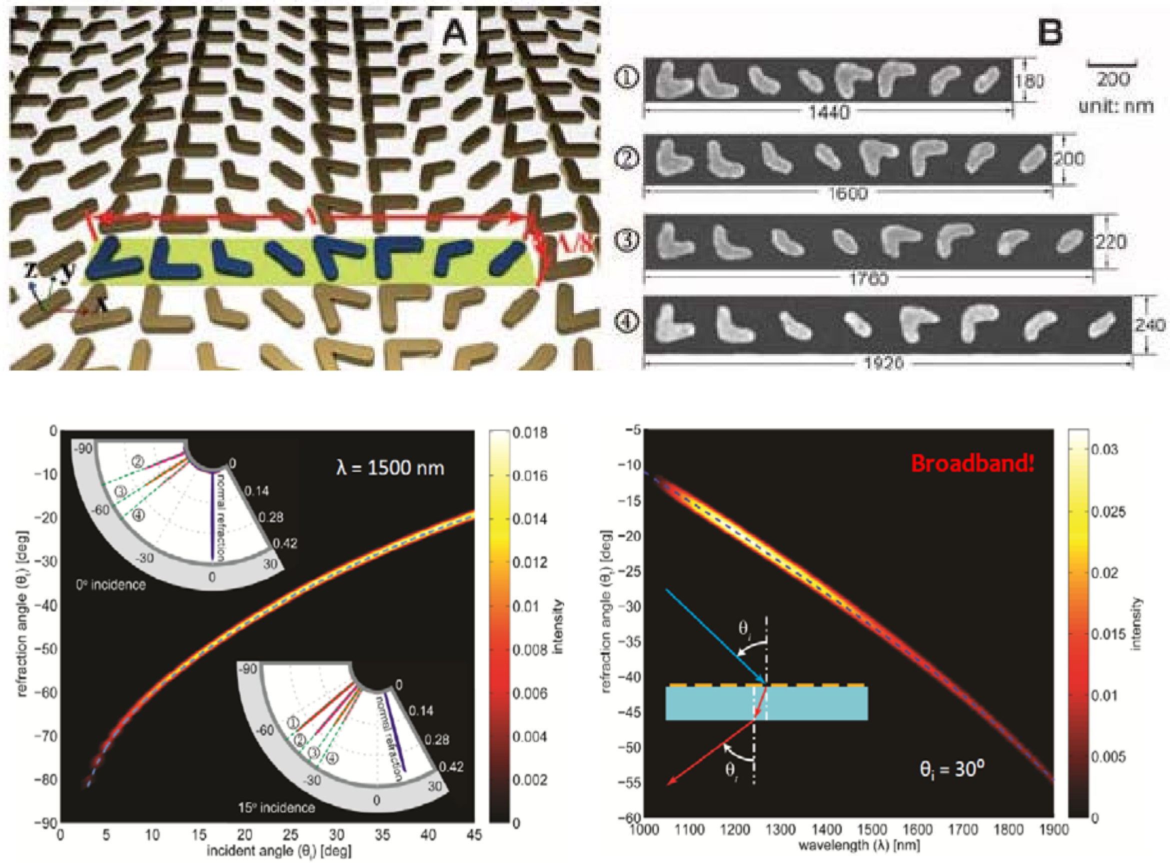
Metasurfaces: Breaking Symmetry

Metasurface breaks translational invariance and introduces phase gradient

Complete control over transverse momentum



N. Yu *at al* Science (2011)
Capasso's Group



Ni et al, *Science* *335* (2012)

Seminal work on metasurfaces: Hasman, Capasso, Zheludev, Lalanne, Fainman/Levy, Tsai, Bozhevolnyi, Zhang, Smith, Atwater,…

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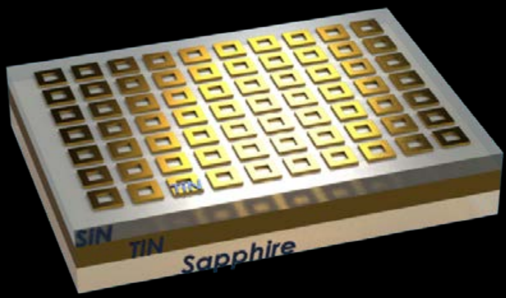
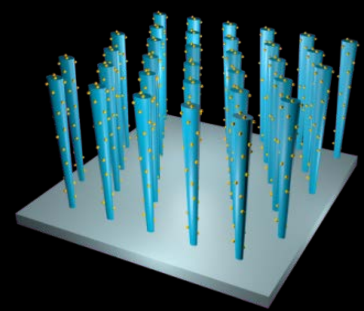
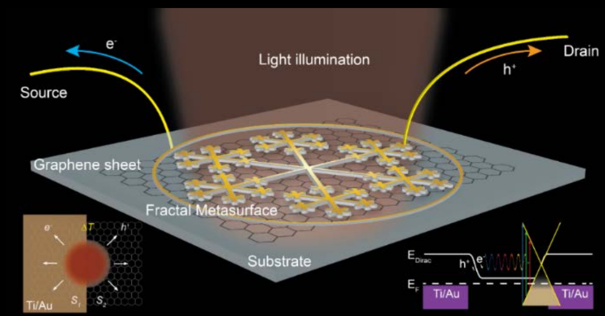
Thermophotovoltaics



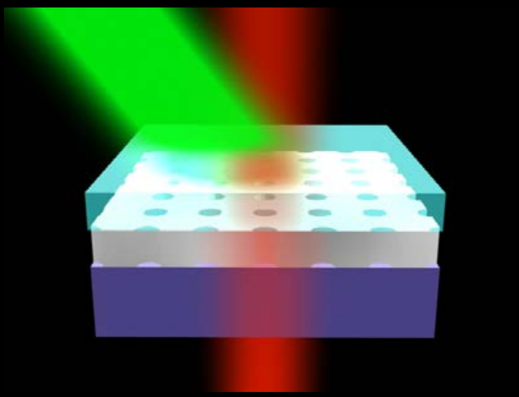
Catalysis



Photodetectors

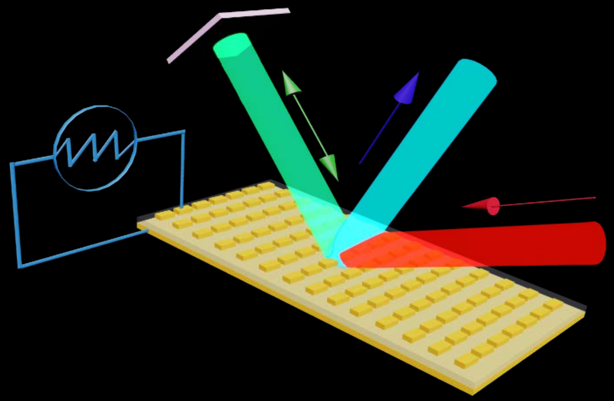


Nanolaser/Spaser

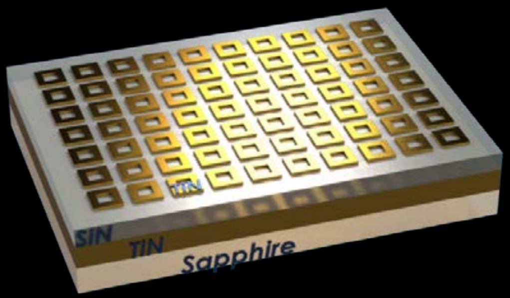


Nanotweezer

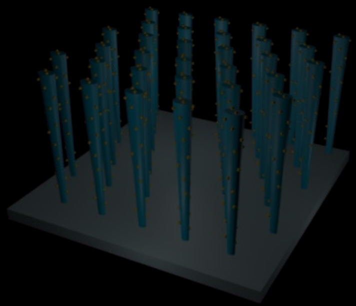
Ultrafast Control



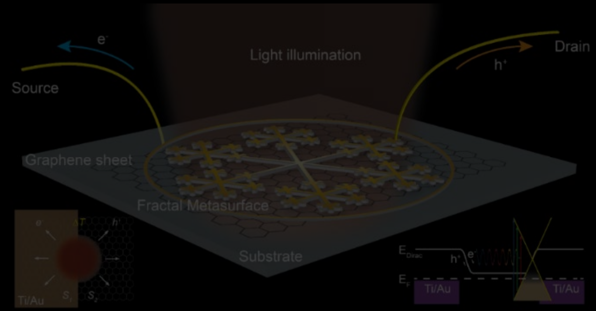
Thermophotovoltaics



Catalysis



Photovoltaics



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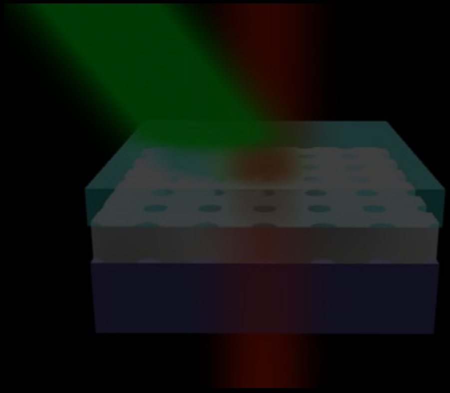

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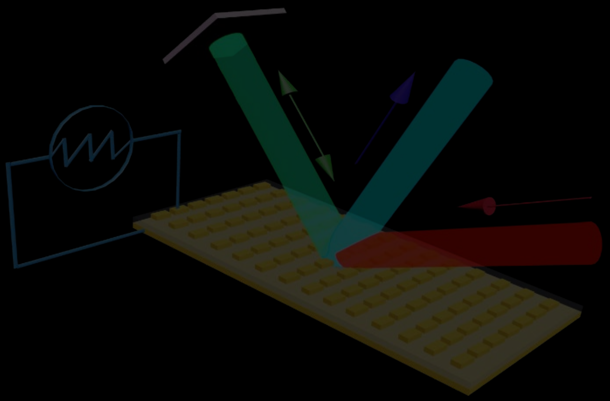
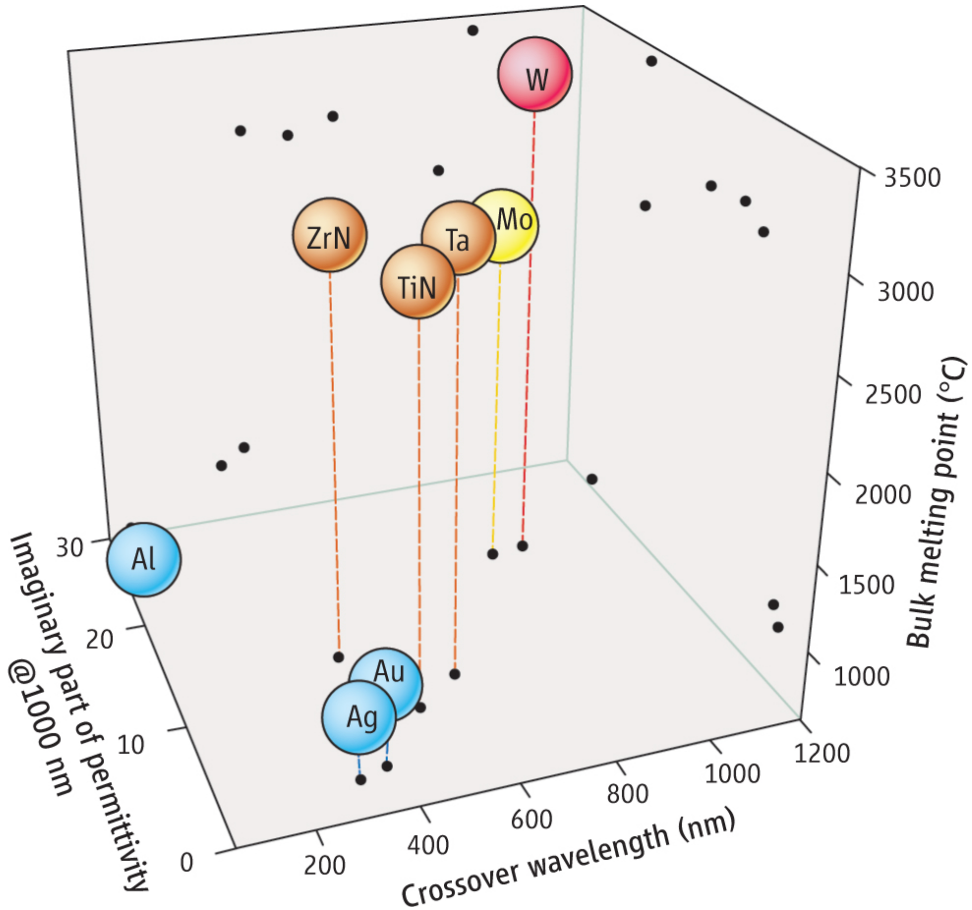


Refractory Plasmonics

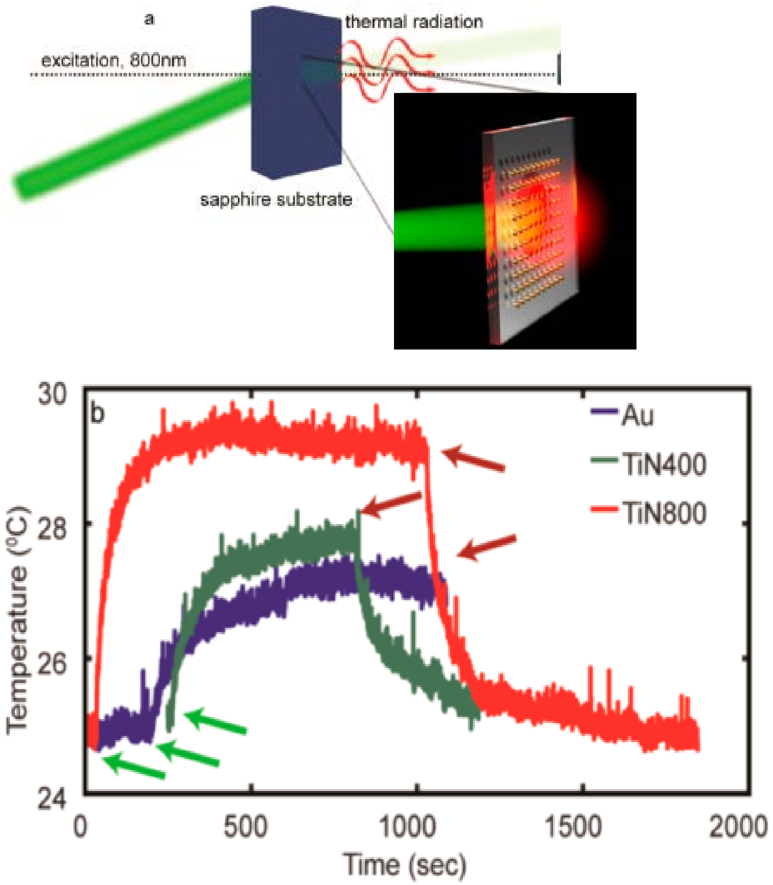


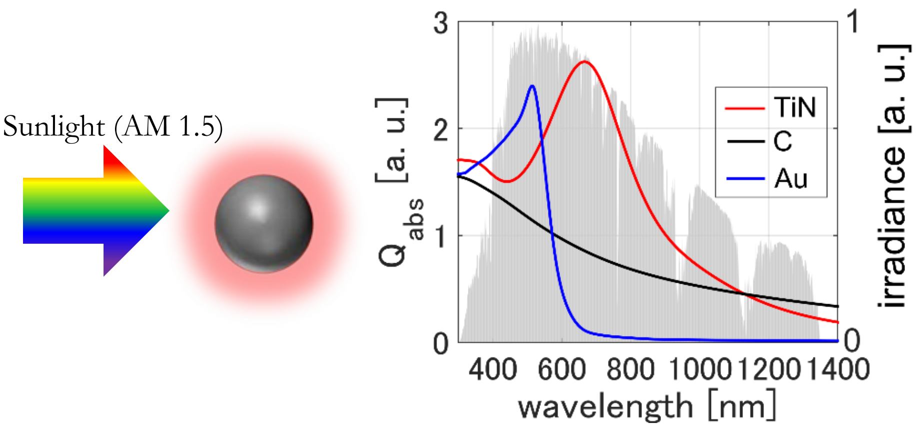
- Plasmonic metals
  - Low melting points
  - Soft
- Refractory metals
  - Lossy, non-plasmonic
- **Transition metal nitrides**
  - **Mimic Au optical properties**
  - **High melting point**
  - **Hard materials**

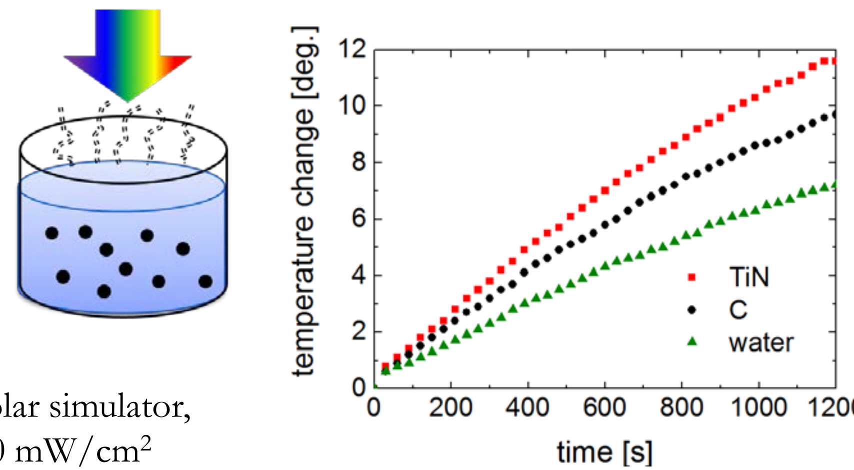
Transition Metal Nitrides can be the solution
for high temperature applications

U. Guler, A. Boltasseva, V. M. Shalaev, Science 344, 263 (2014)

TiN: Local Heating Applications







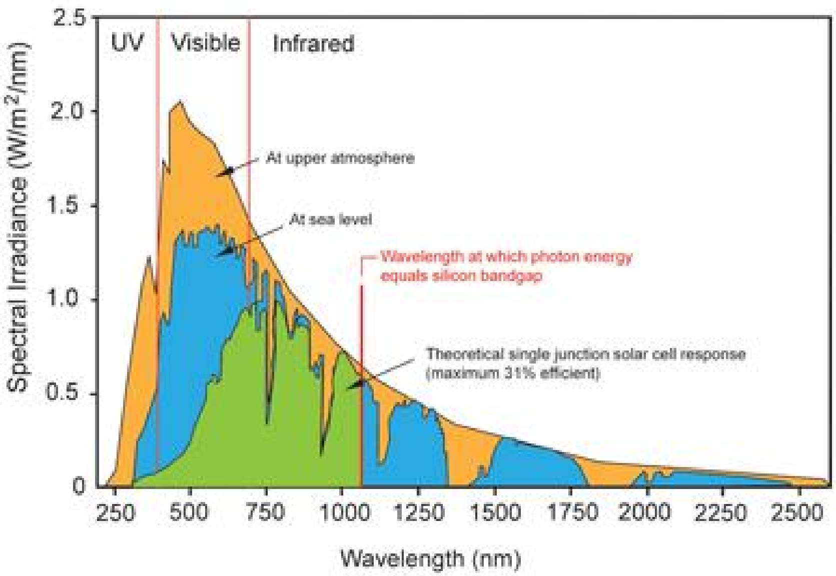
solar simulator,
80 mW/cm^2

TiN outperforms Au and carbon in local heating applications

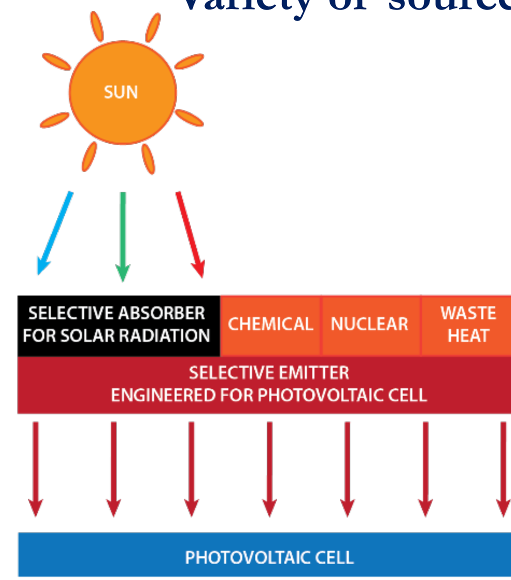
Urcan Guler *et al.* NL 13 (12) (2013)

S. Ishii *et al.* J. Phys. Chem. C 120 (2016)

Thermophotovoltaics: How it Works



Variety of sources possible!



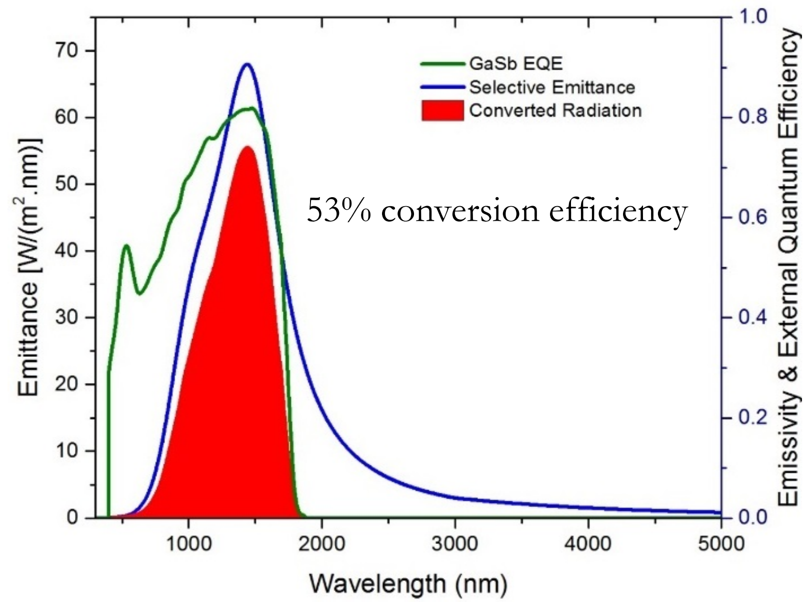
Blackbody @ 1500° C

22% matches with PV cell response

Re-shape the emission for better match (53%)

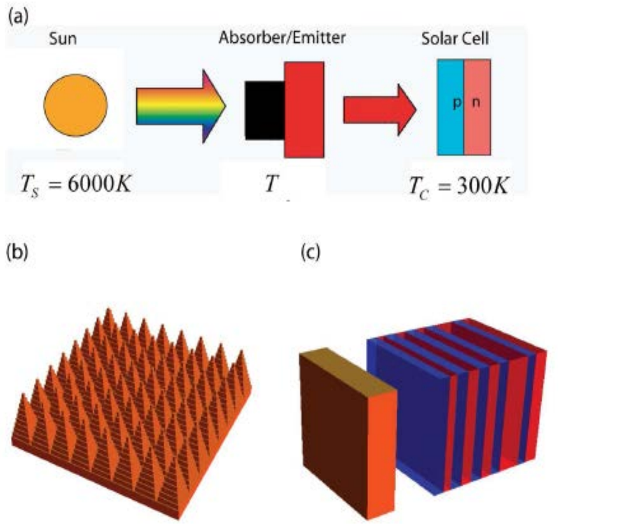
36% of original BB radiation is emitted

64% of the energy is conserved



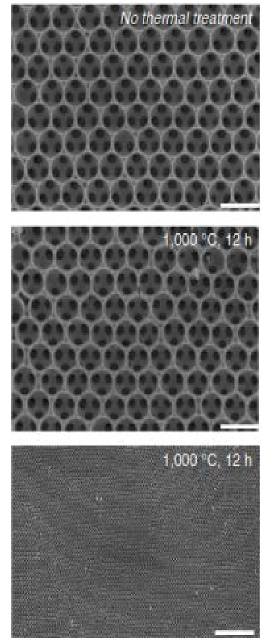
U. Guler et al., Mater. Today 18 (4), 227-237 (2015)

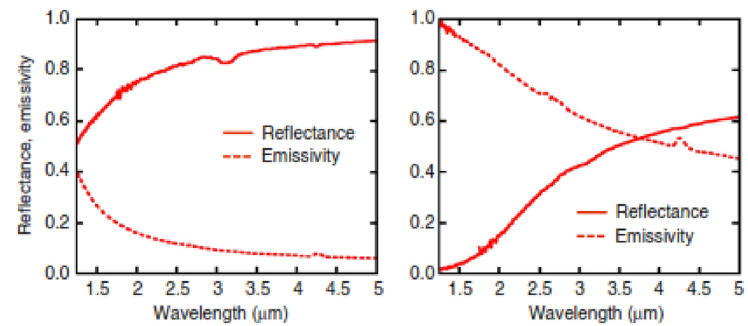
Current S/TPV Approaches

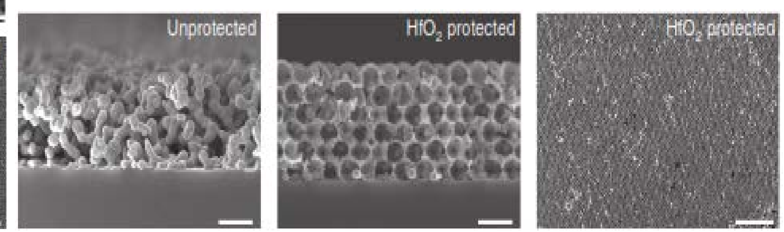


E. Rephaeli and S. Fan, Opt. Exp. 17, 15145 (2009)

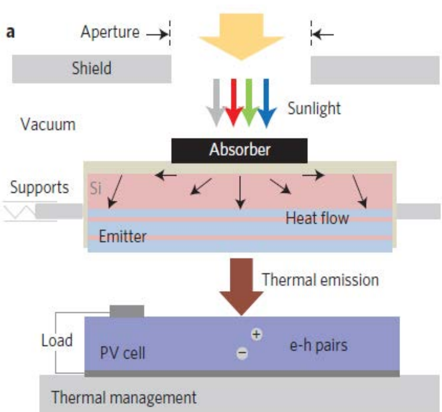
Photonic crystals

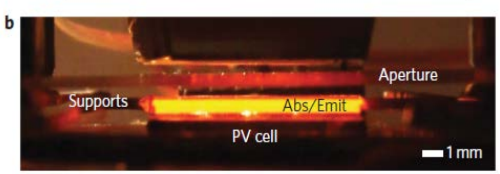




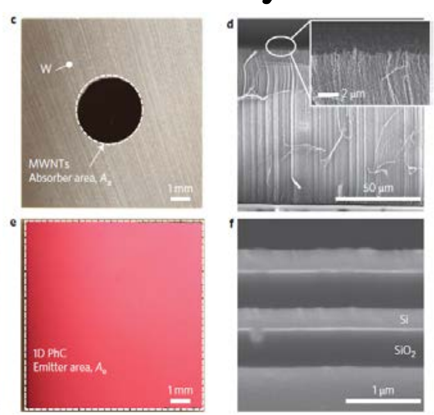


Arpin et al., Nature Comm. 4, 2630 (2013)

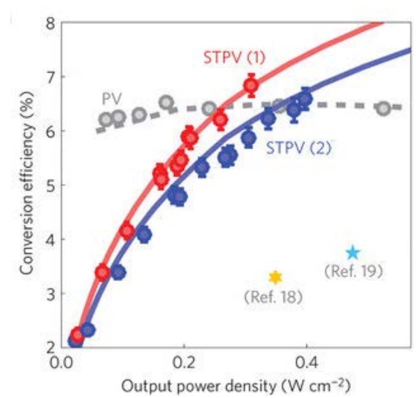




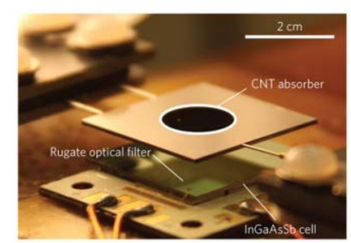
Efficiency 3.2%



A. Lenert et al., Nat. Nano. 9, 126-130 (2014).

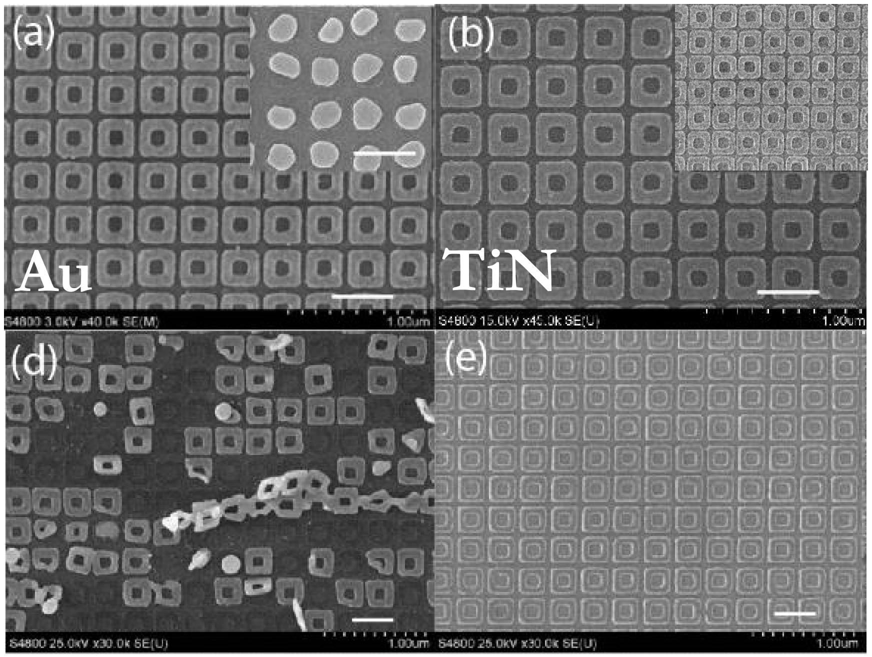


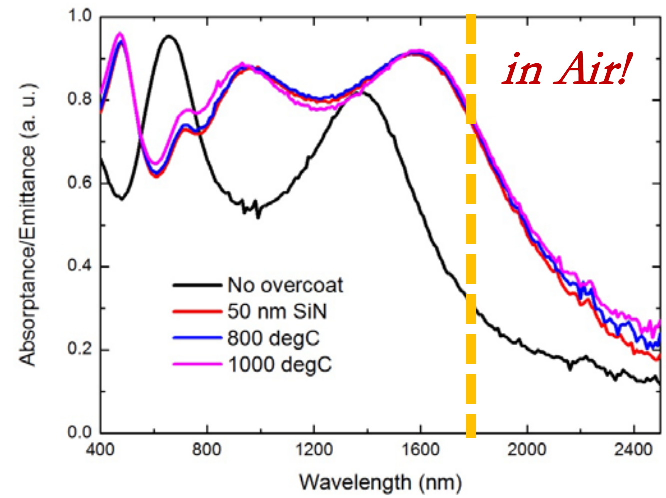
Efficiency 6.8%

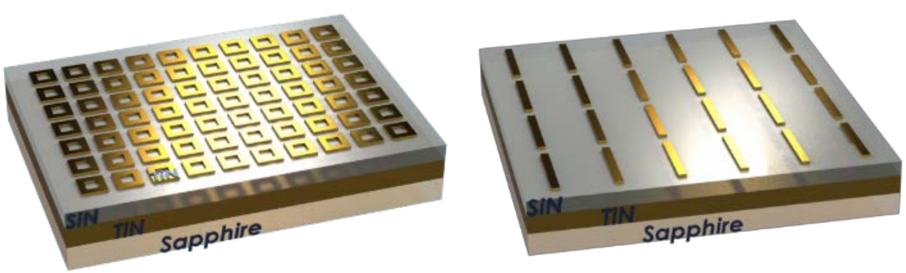


D. M. Bierman et al., Nat. Energy 1, 16068 (2016)

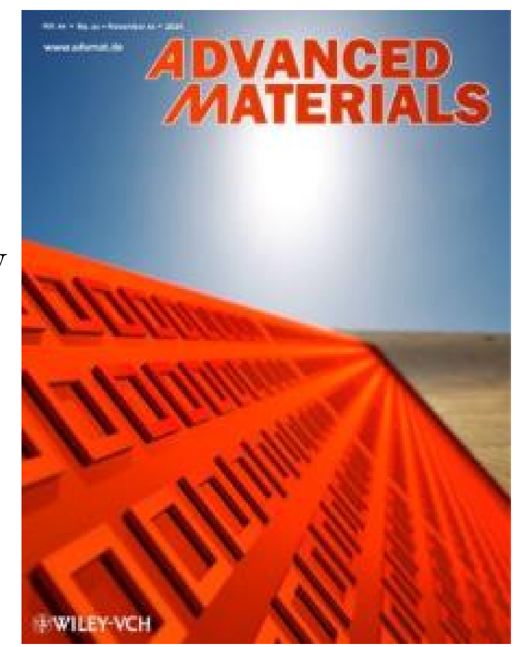
Refractory Metamaterials







Reliable Operation
At 1500 °C
High Conversion
Efficiency
High Power Density



W. Li et al., Adv. Mater. 26, 7959 (2014)

T-dependent optical properties

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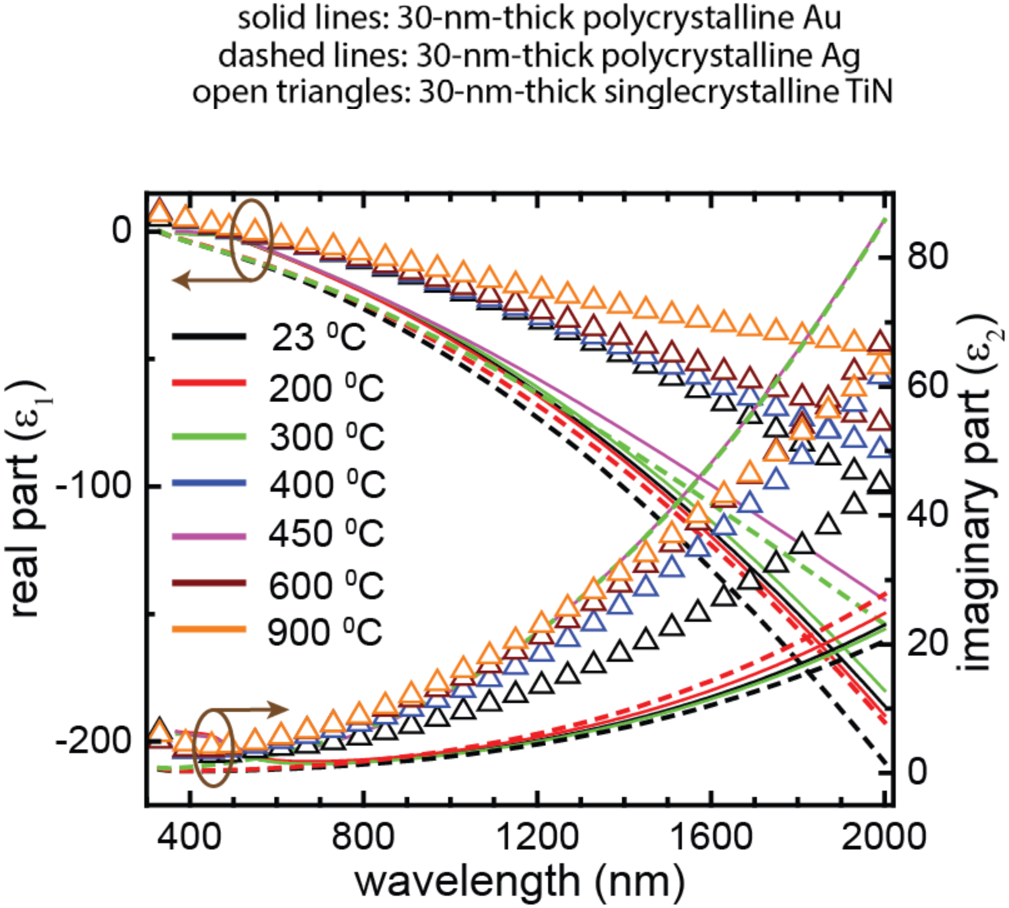
Optical properties deviate at elevated temperatures

Custom built temperature dependent spectroscopic ellipsometer

Optical properties of TiN become comparable to Au and Ag at temperatures over 450° C



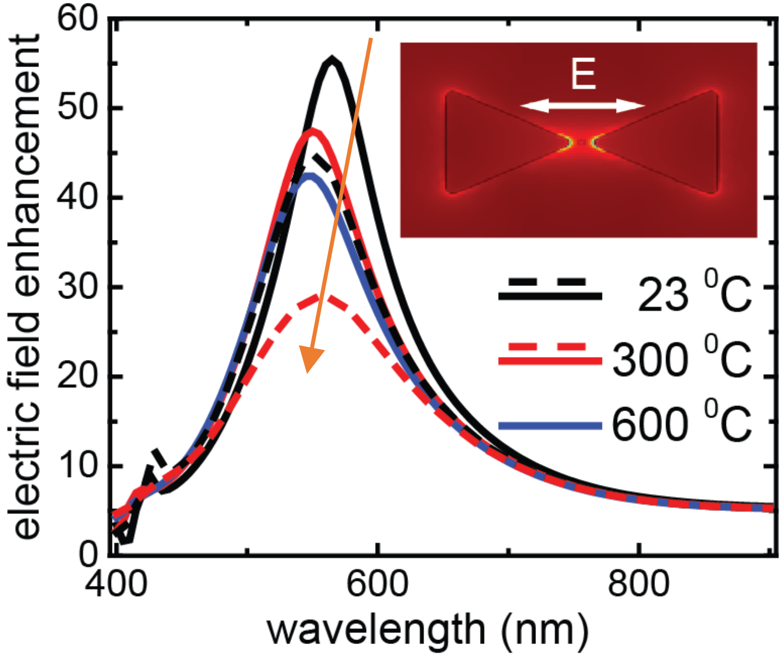
H. Reddy *et. al*, Opt. Mat. Exp. **6**, 9 (2016)
H. Reddy *et al*, ACS Photonics (2017)
H. Reddy *et al*, ACS Photonics (2017)

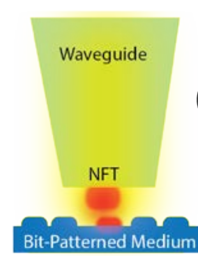
See also work by A. Zayats, J. Dionne, D. Norris, and Y. Sivan

T-Induced Deviations are Important

- Temperature of a plasmonic near field transducer in HAMR: 300-500 ^{0}C

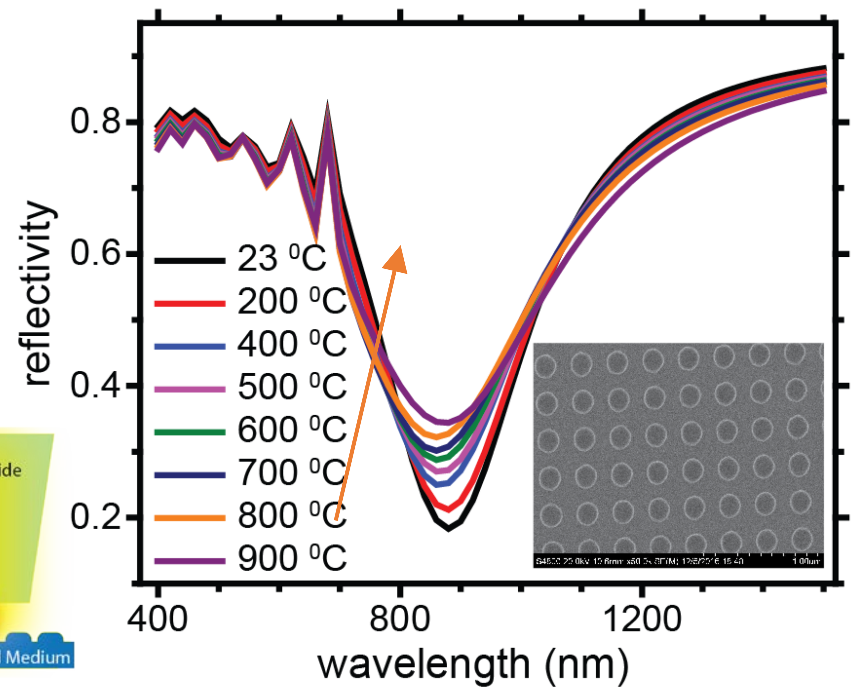
solid lines: single crystalline Ag film
dashed lines: polycrystalline Ag film





Maximum field enhancement reduces by 50% and 17% in single crystalline and polycrystalline cases, respectively

Plasmonic response
of arrays of TiN nanodisks



LSPR strength reduces with temperature

H. Reddy *et al*, ACS Photonics (2017)
H. Reddy *et al*, ACS Photonics (2017)

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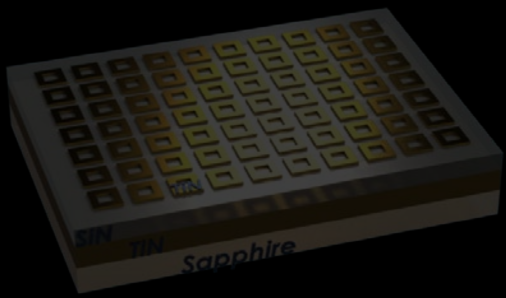
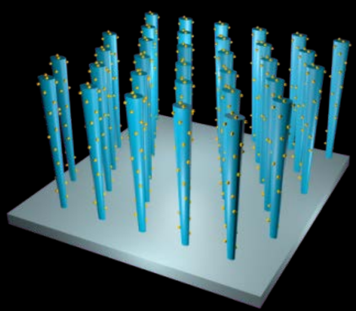
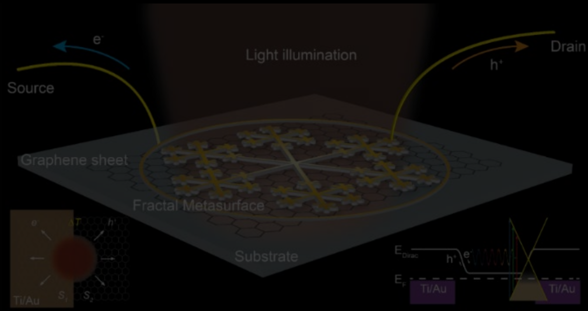
Thermophotovoltaics



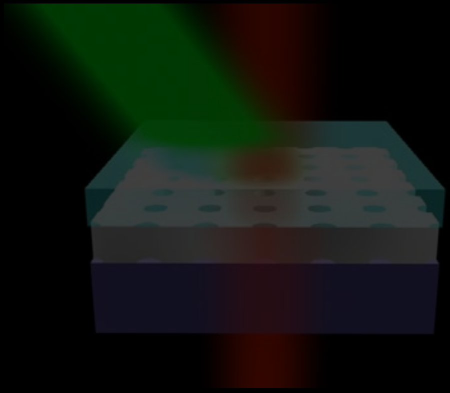
Catalysis



Photovoltaics

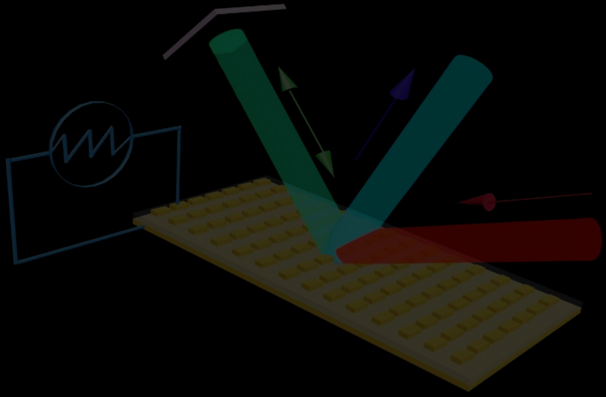


Nanolaser/Spaser



Nanotweezer

Ultrafast Control



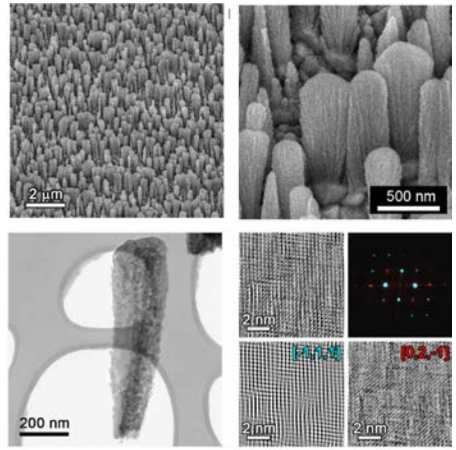
Plasmonic TiN for Water Splitting

GLAD for single-crystal TiO2 nanowires:

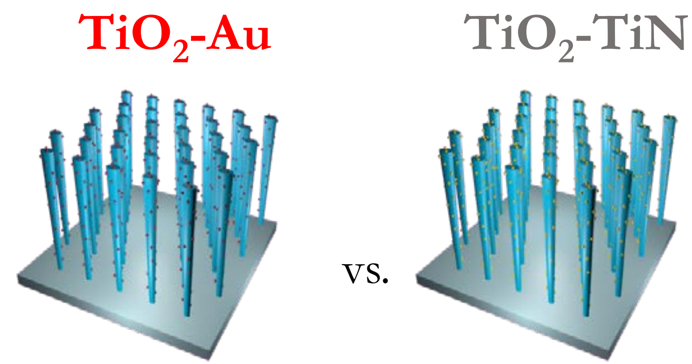
Broadband hot electron generation and transmission in TiN/TiO_2

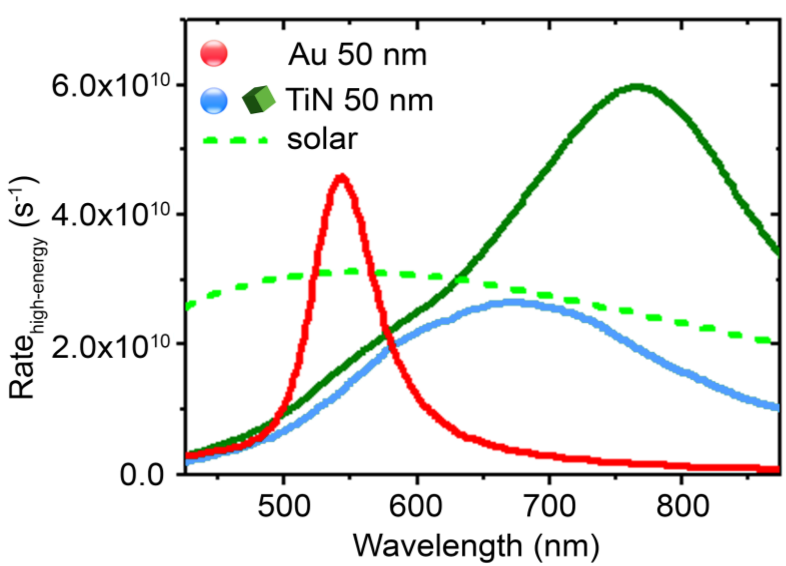
Rate of hot electrons with **TiN colloids is 2x larger than with Au nanoparticles**

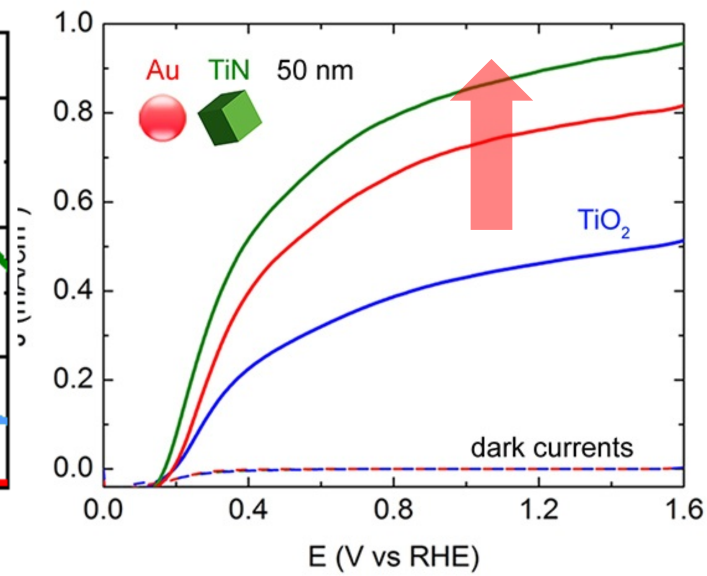
(broader absorption and Ohmic vs Shotcky contact)



TiN vs Au decorated TiO2 nanowires:



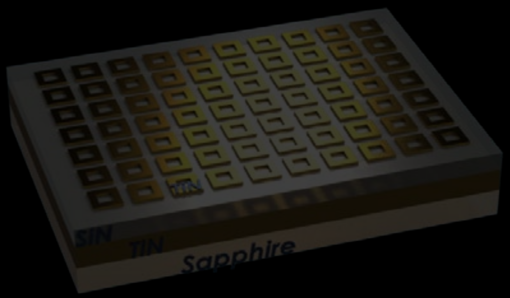




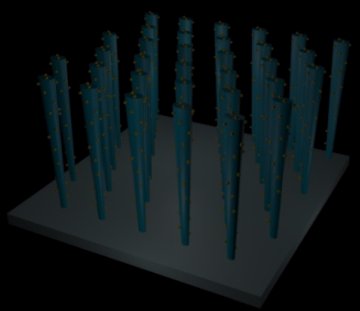
See also work by Halas and Norlander groups
Moskovits group

Naldoni *et al*, Nanophotonics **5**, 112-133 (2016); Naldoni *et al*, Adv. Opt. Mater. DOI: 10.1002/adom.201601031 (2017)
S. Ishii et al ACS Photonics (2016)

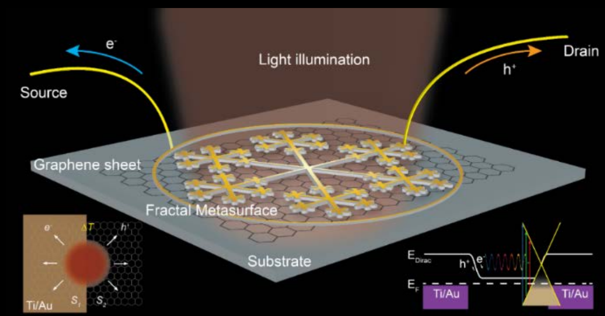
Thermophotovoltaics



Catalysis



Photodetectors



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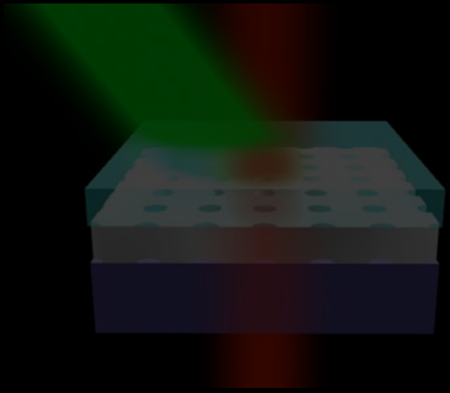

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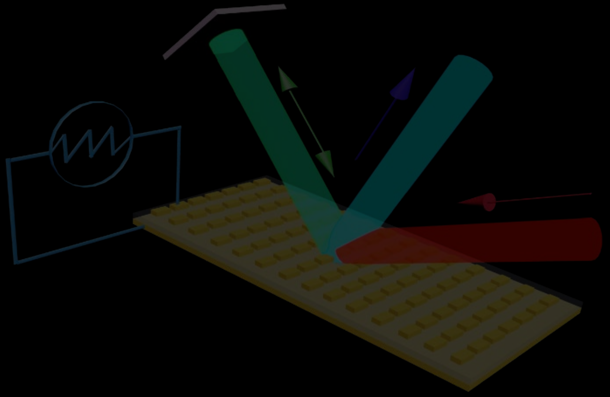
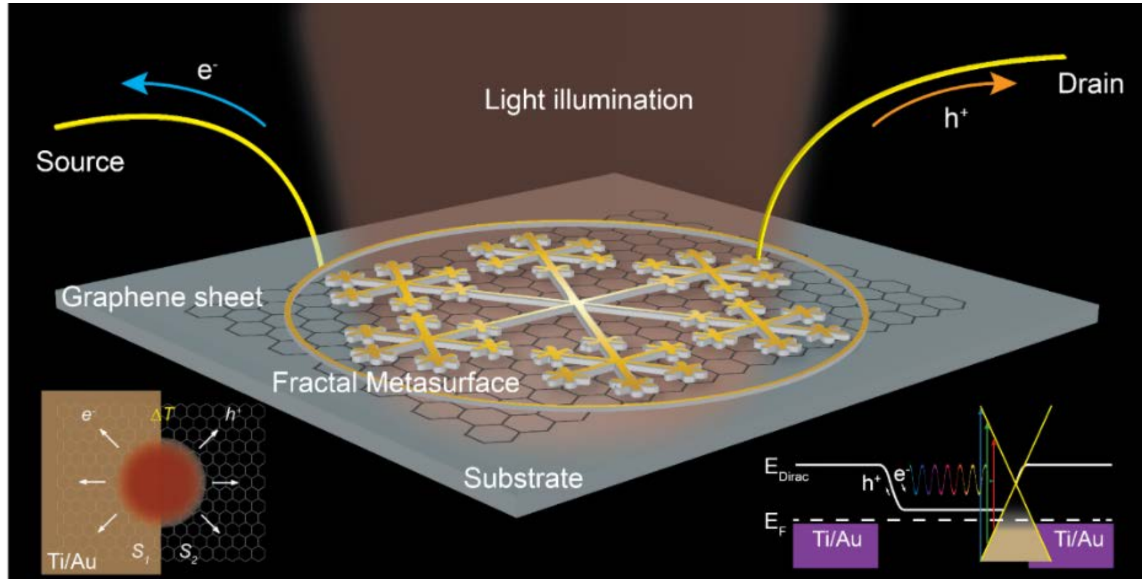


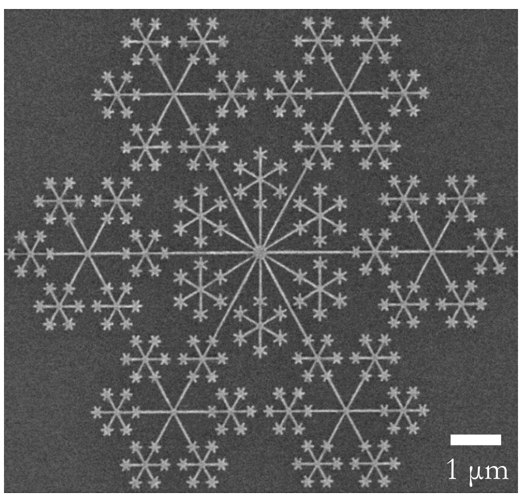
Graphene Photodetector with Fractal Metasurface

Snowflake fractal (Au) metasurfaces for graphene photodetector

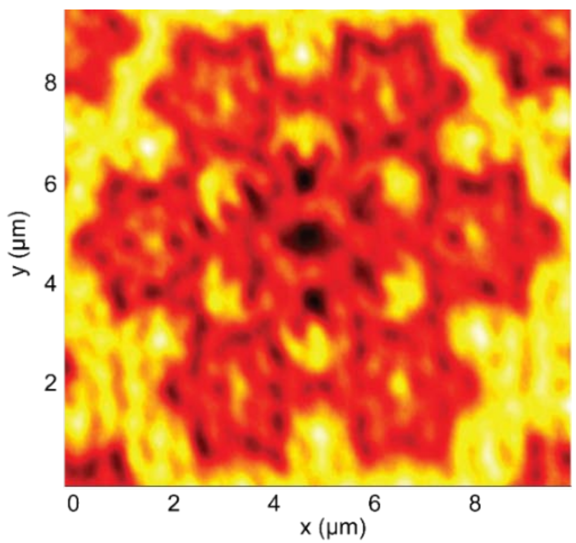
Broadband absorption and polarization insensitive response



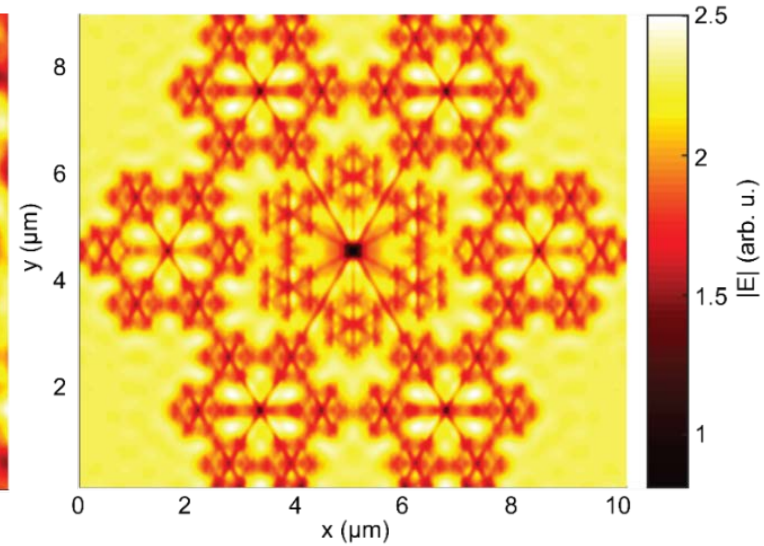
SEM image



NSOM scan



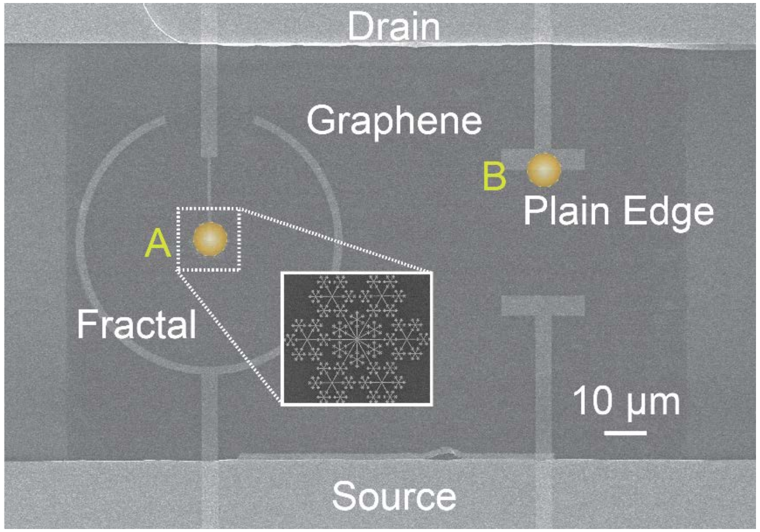
Simulation

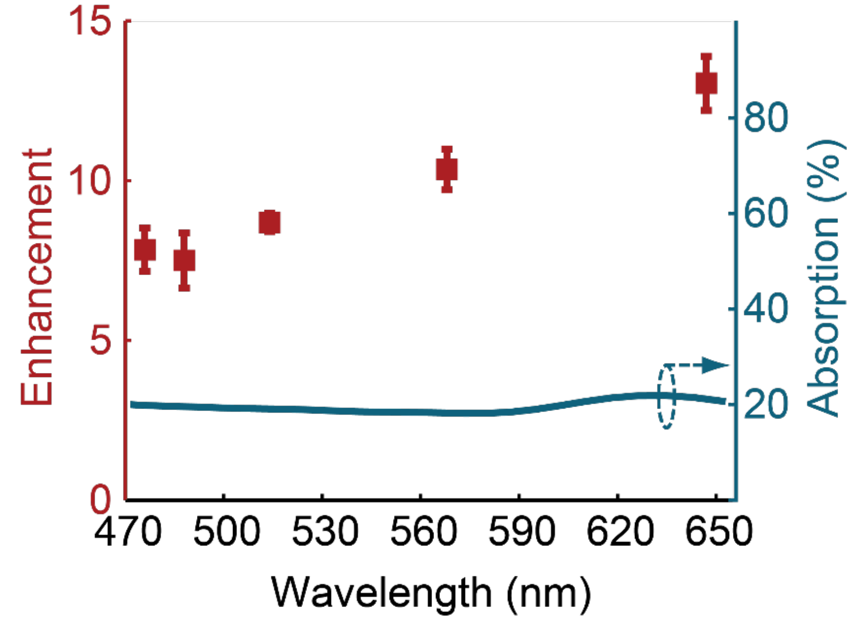


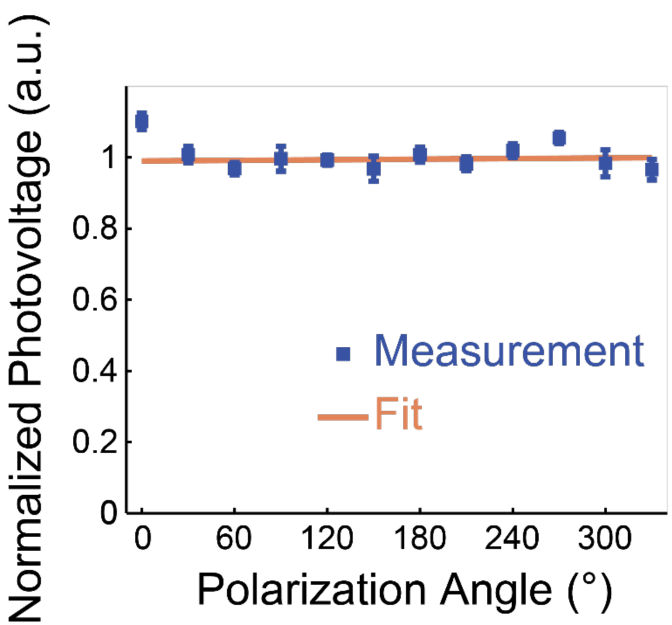
J. Fang *at al* Nano Letters (2016)

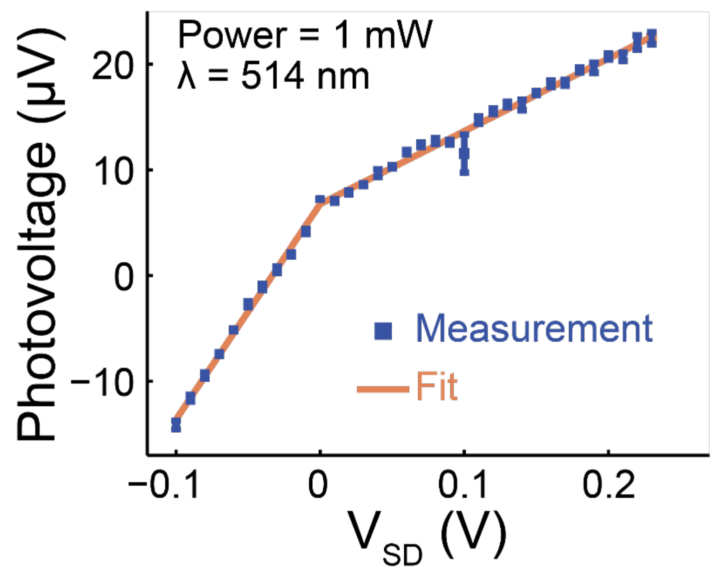
2D materials for PV/PTE photodectors:
Halas/Nordlander, Atwater, Muller, Koppens groups

Graphene Photodetector with Fractal Metasurface

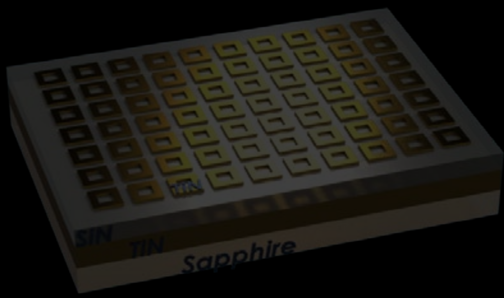








Thermophotovoltaics



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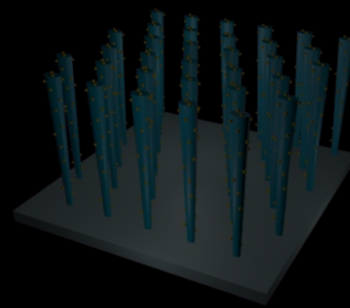
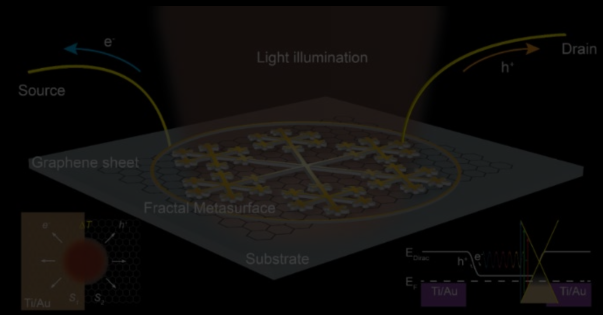


Photovoltaics



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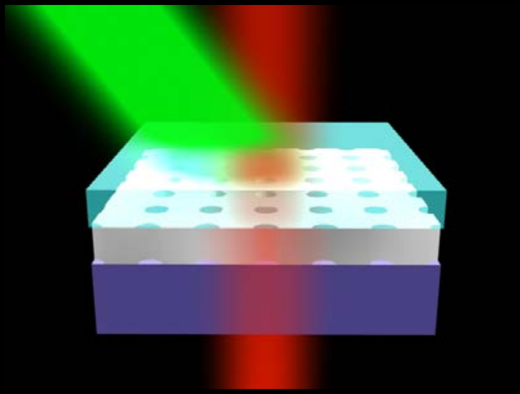
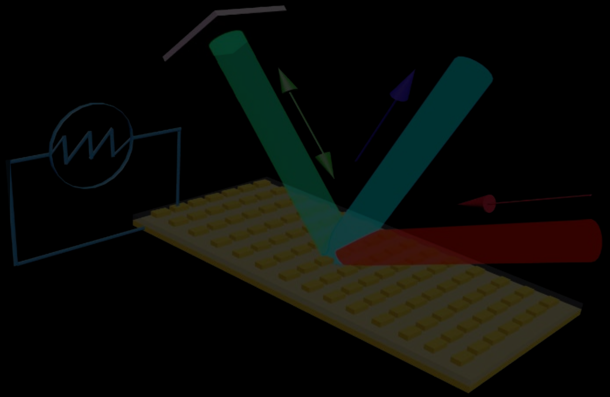


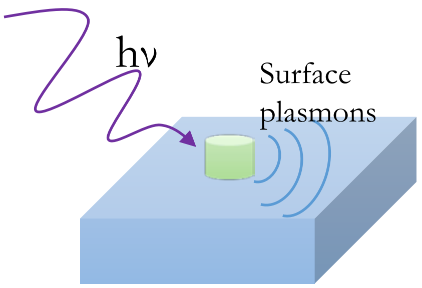
Nanotweezer

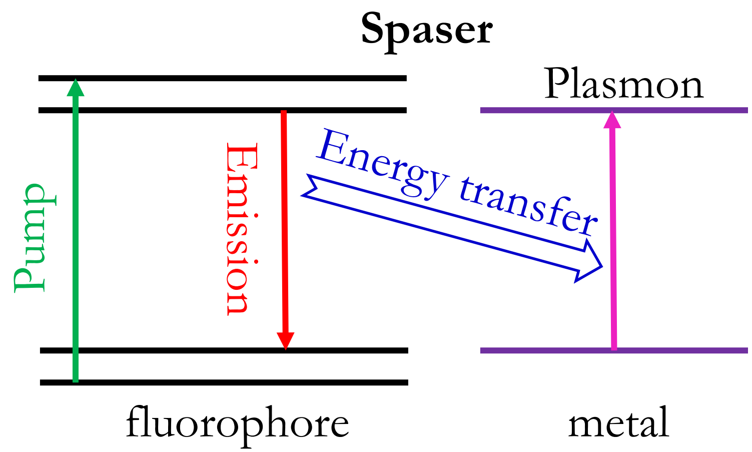
Ultrafast Control



Plasmonics Nanolasers and Spasers

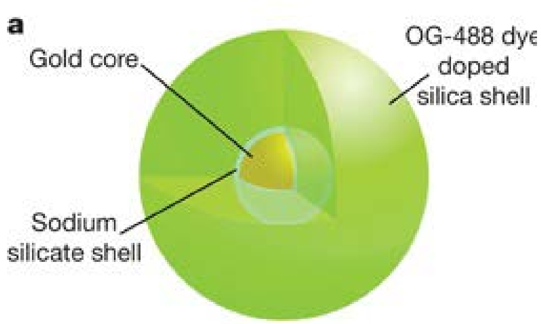
Plasmonic approach to achieve coherent optical sources at nanoscale



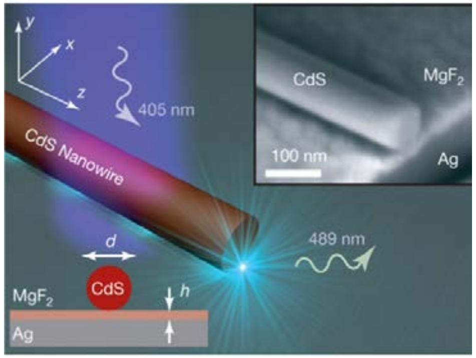


D. Bergman, M.I. Stockman, Physical Review Letters **90**, 027402 (2003)
M. I. Stockman, Nature Photonics **2**, 327 (2008)

Proof of Concepts



M. A. Noginov et al., Nature 460, 110 (2009).
Noginov, Shalaev, Wiesner groups



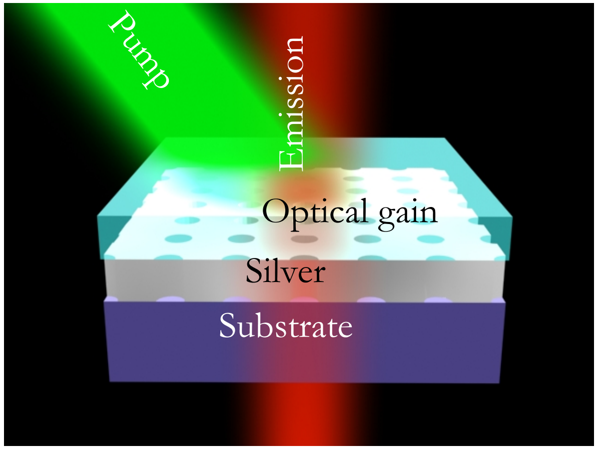
R. F. Oulton et al., Nature 461, 629 (2009).
Xiang Zhang group

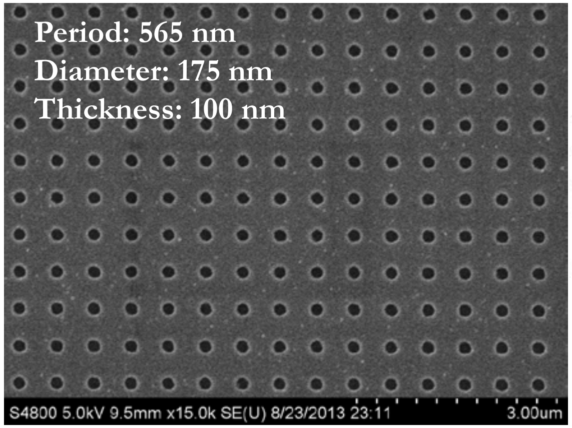
See also work by groups:
M. T. Hill, M. K Smit, CZ Ning
Y. Fainman
G. Shvets, C.-K. Shih, S. Gwo
S. Bozhevolnyi, R. Quidant
D. J. Norris
J. B. Khurgin
N. Zheludev
T. Odom
M. P. van Exter

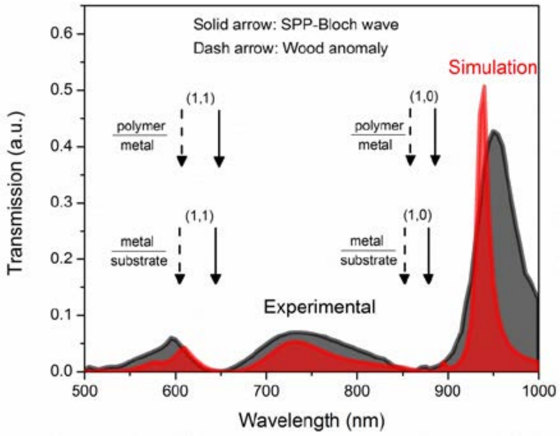
Active metasurfaces for lasing: Highly directional spasing hole array

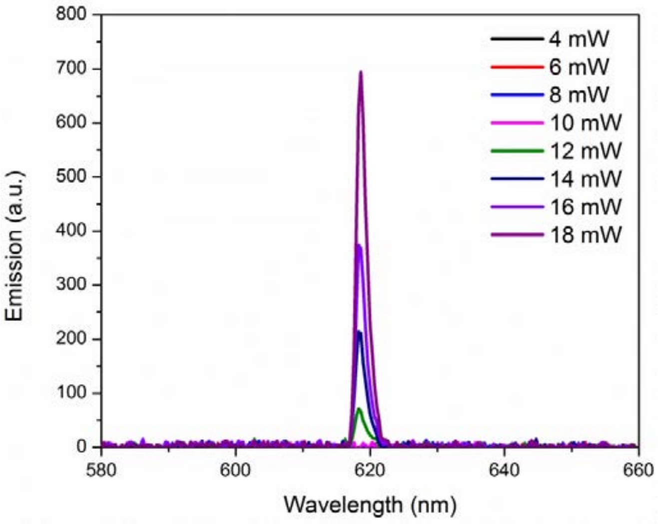
PURDUE UNIVERSITY

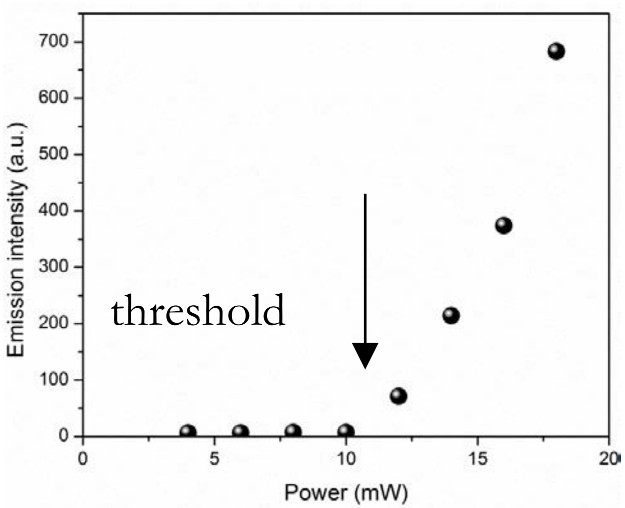
Room temperature, single-mode lasing

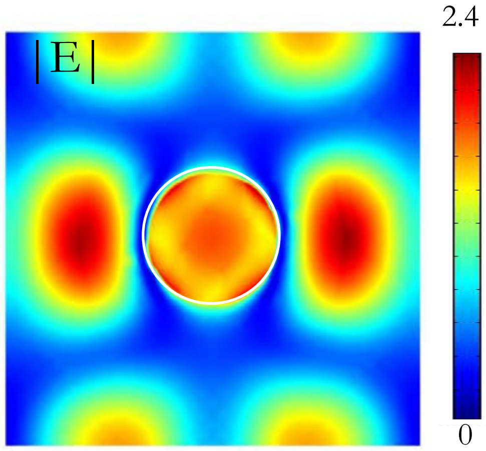












Strong mode coupling

Meng et al., Laser & Photonics Reviews 8, 896-903 (2014)

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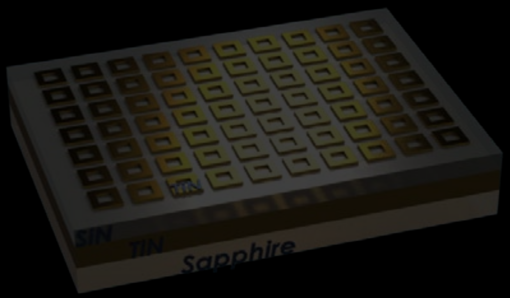
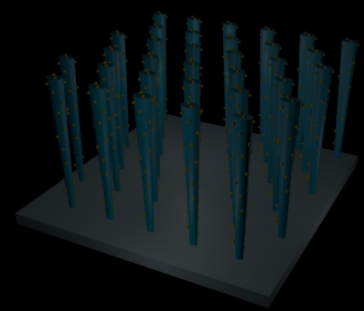
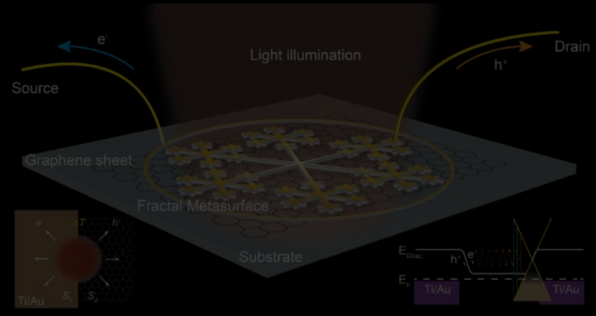
Thermophotovoltaics



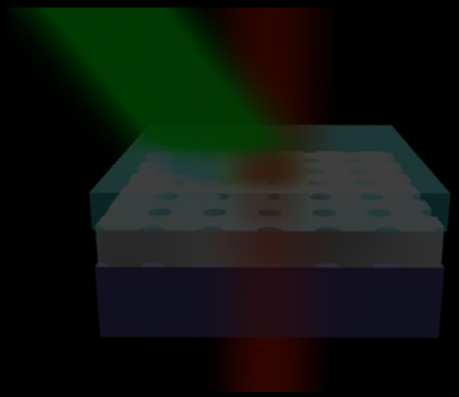
Catalysis



Photovoltaics

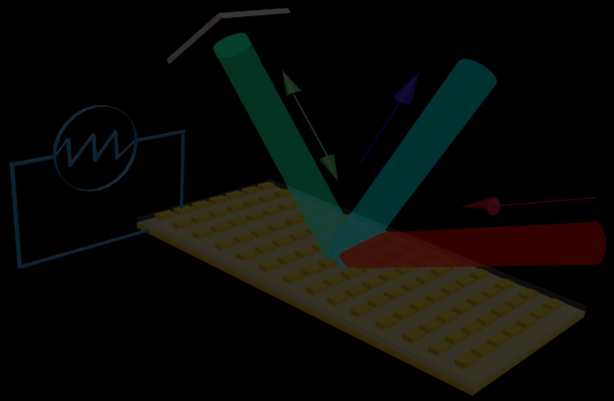


Nanolaser/Spaser

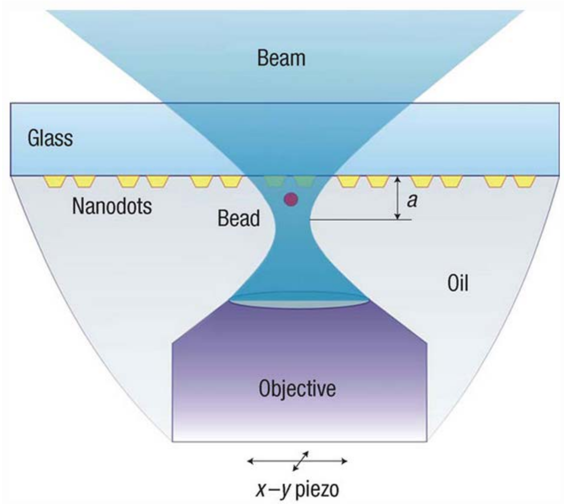


Nanotweezer

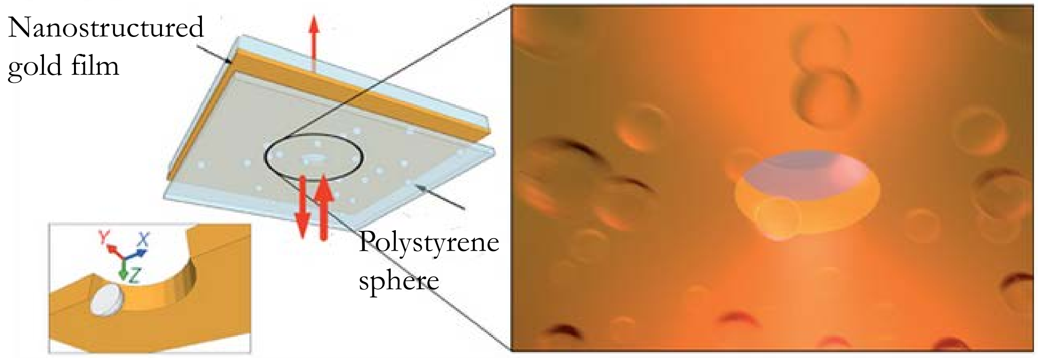
Ultrafast Control



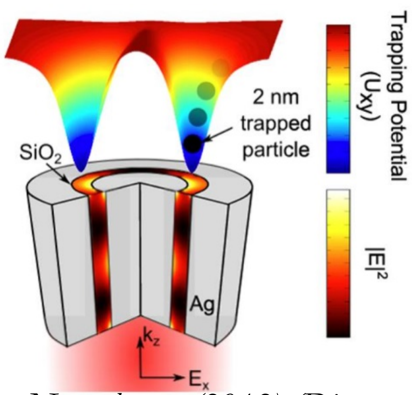
Plasmon Nano-Optical Trapping



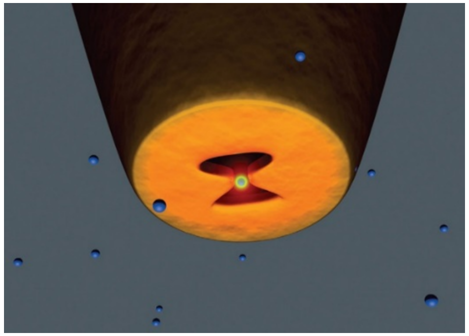
Grigorenko et al. *Nature Photonics* (2008)



Nature Physics (2009) (Quidant group, ICFO Spain)

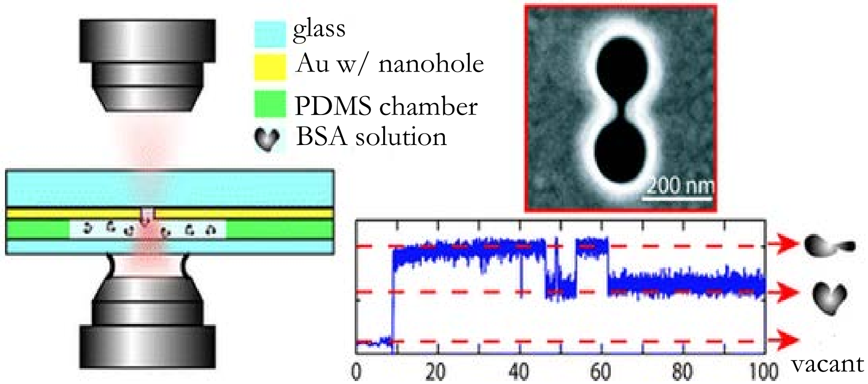


Nano letters (2012) (Dionne group, Stanford)



Berthelot, J. *et al. Nature Nanotechnology* (2014)

Trapping single Protein



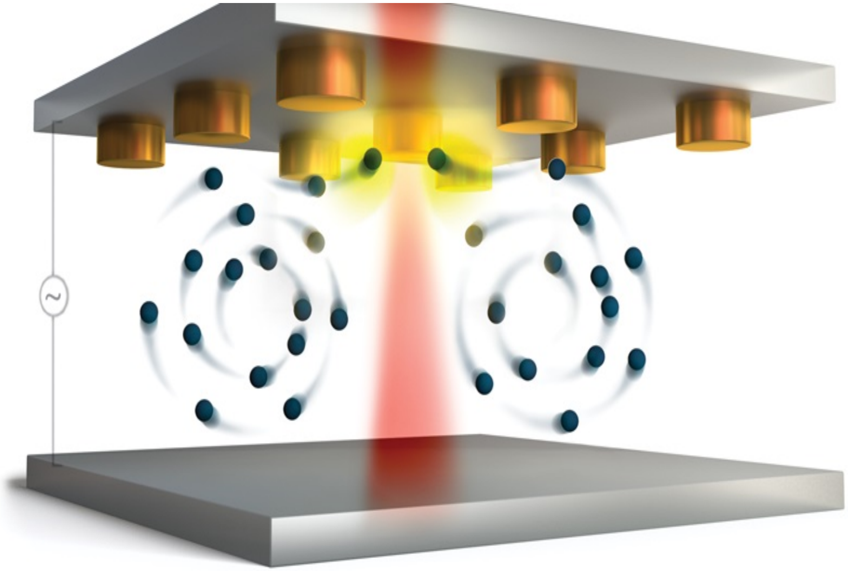
Nano letters (2011) (Gordon group, Univ Victoria)

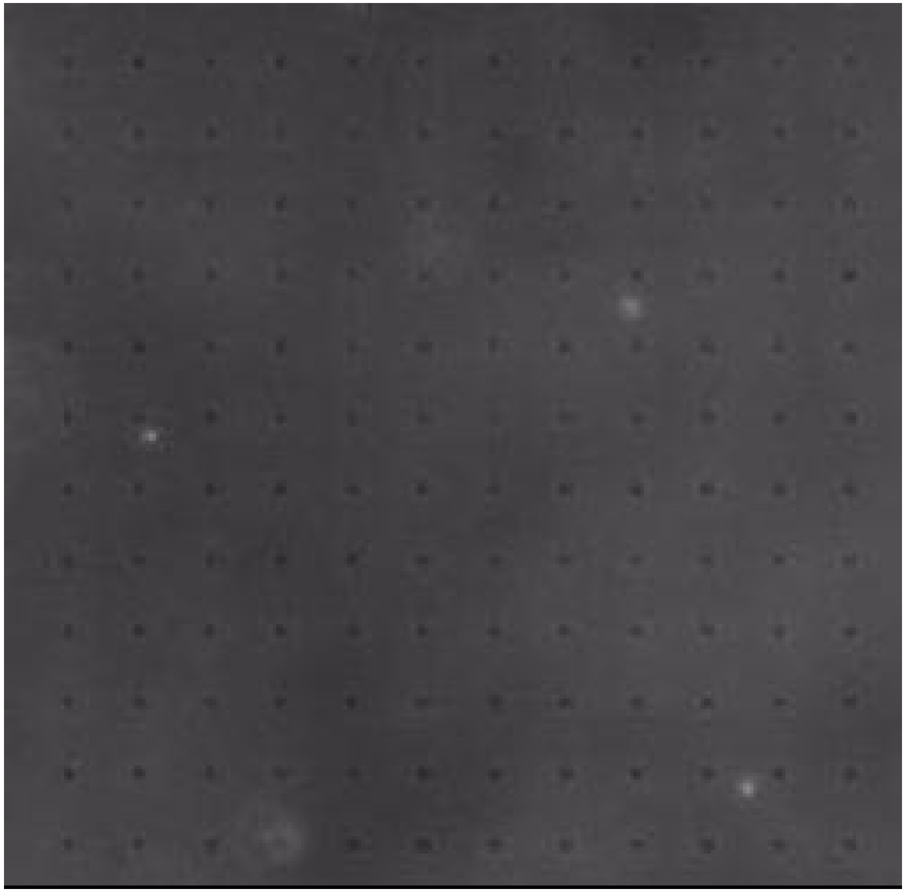
See also works from the groups of: Kenneth Crozier (U Melbourne), Lambertus Hesselink (Stanford), Kimani Touissaint (UIUC), Xiang Zhang (UC Berkeley) and Yasuyuki Tsuboi (Osaka, Japan)

Hybrid Electrothermalplasmonic Nanotweezer (HENT)

PURDUE UNIVERSITY

Addresses the *long-standing* challenge to rapidly load a plasmon trap





Fast and precise delivery to plasmonic hotspots

High resolution nanoparticle trapping

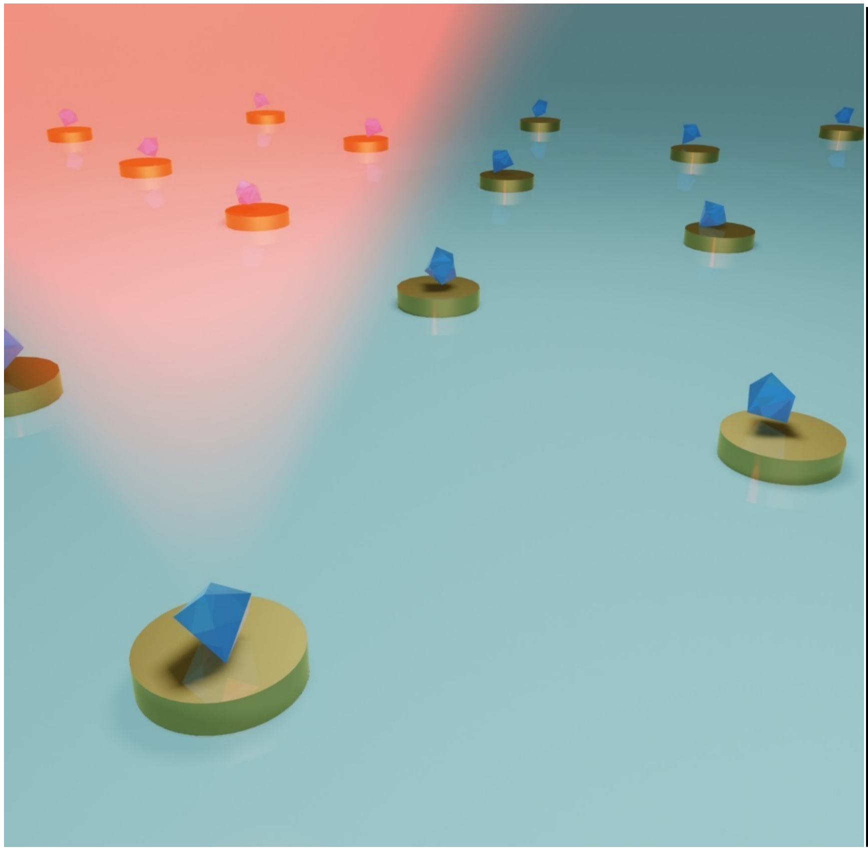
Ability to immobilize trapped object

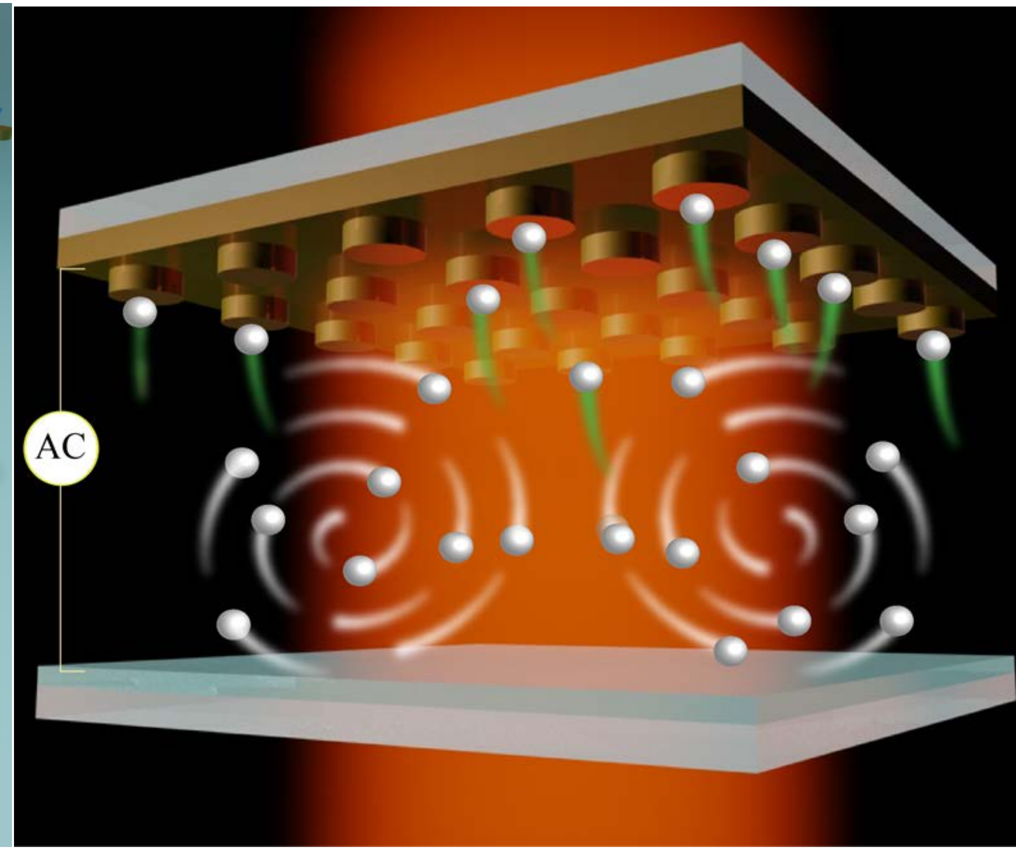
J. Ndukaife *et al* Nat Nanotechnol. (2016)
News and Views: Y. Tzuboi Nat Nanotechnology (2016)
J. Ndukaife *et al* Science (2016)

Directed Spatially Selective Self (DS^3) Assembly

PURDUE UNIVERSITY

A scheme for high throughput parallelized assembly of nanodiamonds on nanophotonic structures

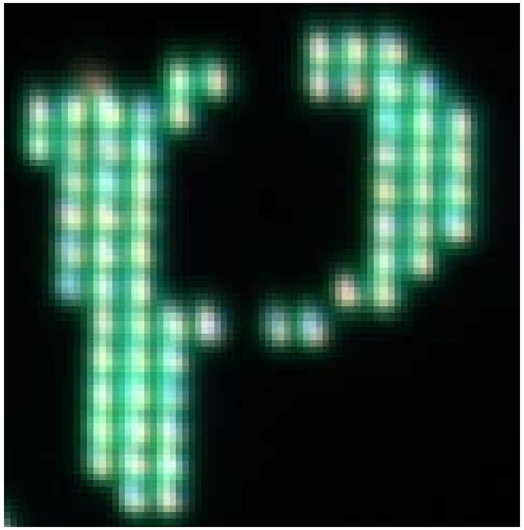


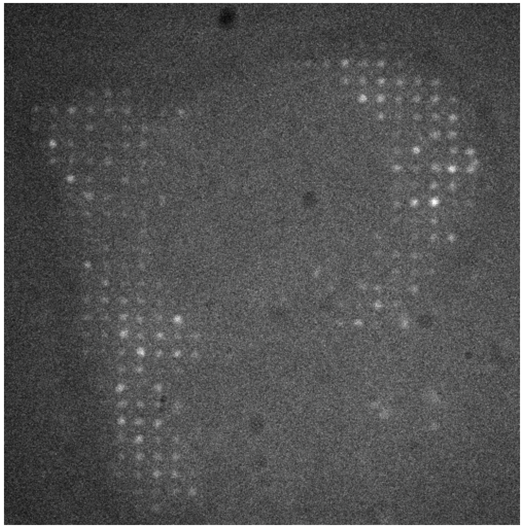


J. Ndukaife *et al* Manuscript in Preparation

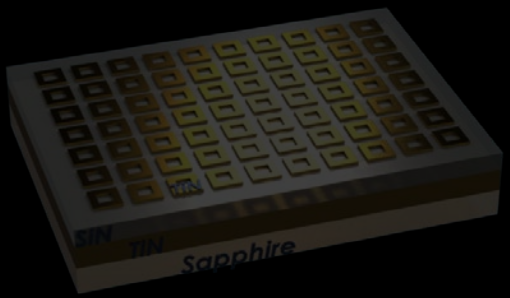
Large-Scale Assembled Nanodiamonds on Plasmonic Antennas

100 nm Nanodiamonds are positioned on each nanoantenna and not in the space between!

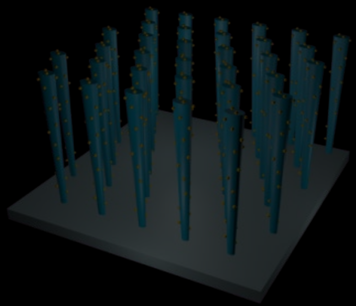




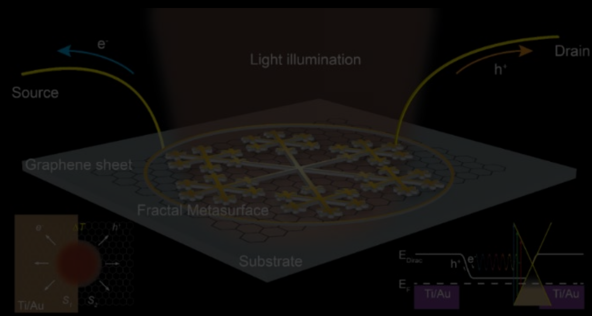
Thermophotovoltaics



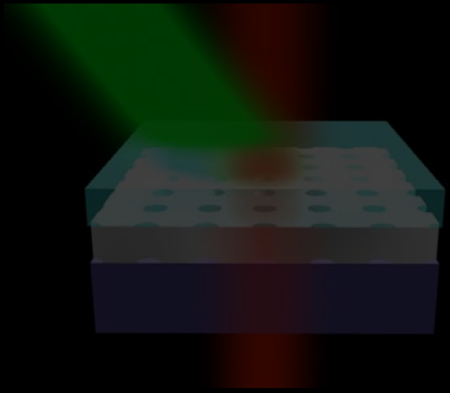
Catalysis



Photovoltaics

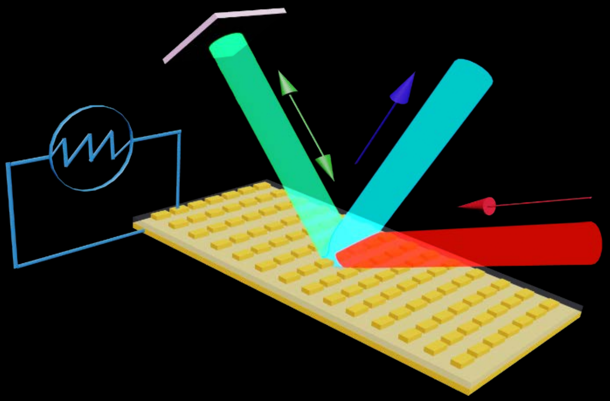


Nanolaser/Spaser



Nanotweezer

Ultrafast Control



TCOs are Metallic Semiconductors

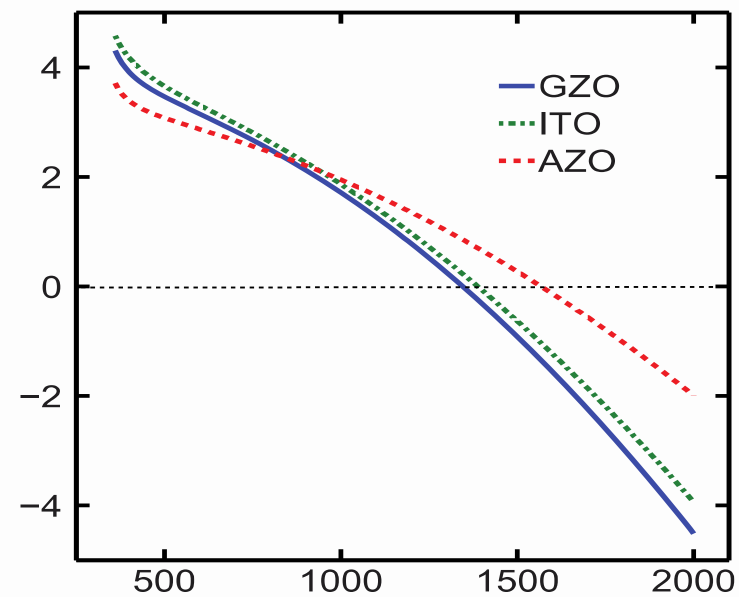
PURDUE UNIVERSITY

Large free-carrier concentrations make TCOs metallic

- Dopants: Aluminum, Indium, Gallium
- Concentrations of 10^{21} cm^{-3}
- Defect Centers: Hydrogen, Oxygen, Zinc

Wide bandgaps reduce visible absorption

- Bandgaps > 3eV
- Transparent over visible spectrum



see work by groups:
H. A. Atwater
O. L. Muskens
M. Brongersma
V. J. Sorger
M. A. Noginov
C. B. Murray
D. J. Milliron
R. P. H. Chang
M. Wegener
S. Franzen
T. W. Odom
A. Lavrinenko
S. Sadofev/Benson group

Switching with TCOs

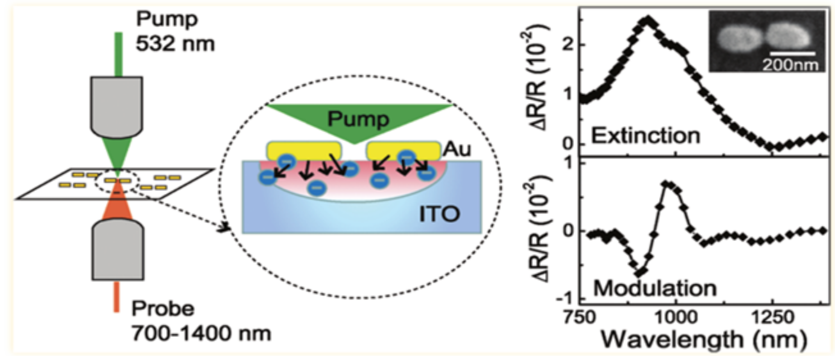
PURDUE UNIVERSITY

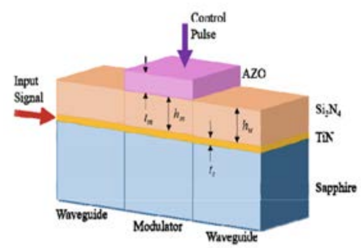
Dynamic/active control of TCO's carrier concentration i.e. plasma frequency:

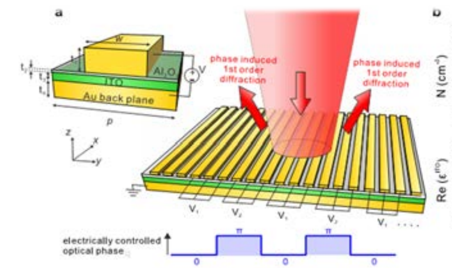
- Electrical bias for injection of additional free-electrons

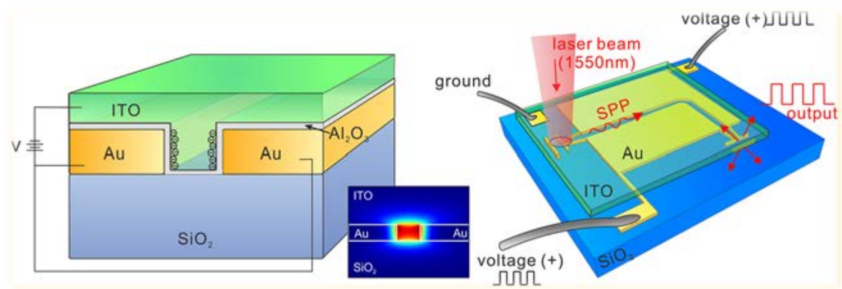
  e.g. MOS-type devices
- Optical pumping via the redistribution and/or addition of conduction electrons
- Post-deposition thermal annealing for thermal activation of donor defects
- Structural, opto-mechanical coupling

See also work of Atwater, Boyd, Muskens, Brongersma, Zheludev, Dal Negro, Odom, Ketterson, Chang, Sadofev/Benson and others









J. Kim *et al.*, *IEEE JSTQE* 19, 4601907 (2013)
M. Abb *et al.*, *Nano Lett.* 11, 2457 (2011)
N. Kinsey *et al. Optica* 2, 616 (2015)
H.W. Lee *et al.*, *Nano Lett.* 14, 6463 (2014)

Kerr Nonlinearity in AZO at ENZ point

PURDUE UNIVERSITY

$$n = n_0 + \Delta n = n_0 + n_2 I$$

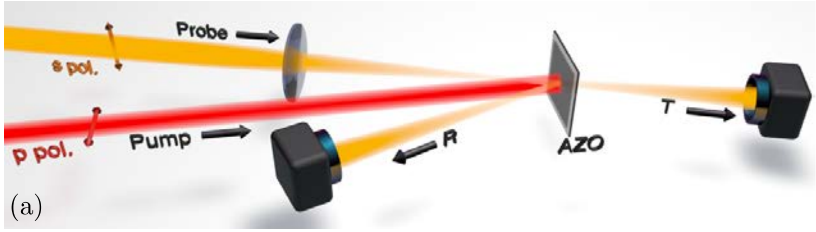
$$n_2 = n_{2r} + i\beta_2 \sim \frac{\chi^{(3)}}{n_0}$$

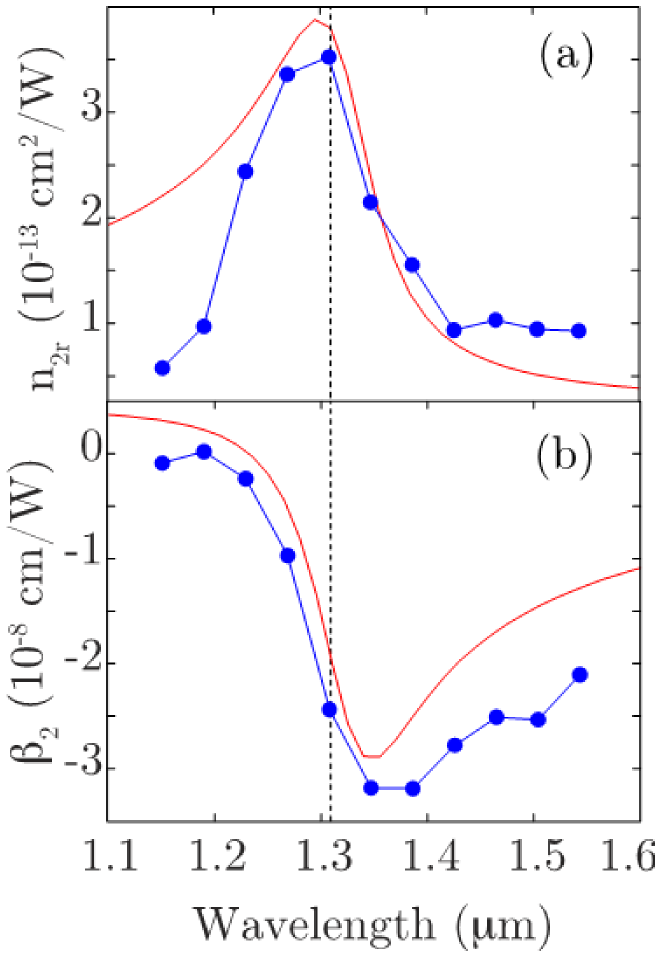
Kerr index is dependent on refractive index

- $n_2 \sim \chi^{(3)}/n_{probe}$

Pump-Probe Configuration

- 785 nm Pump
- Broadband NIR Probe: 1150-1550 nm
- $\chi^{(3)}(\omega_{pump}; \omega_{probe})$



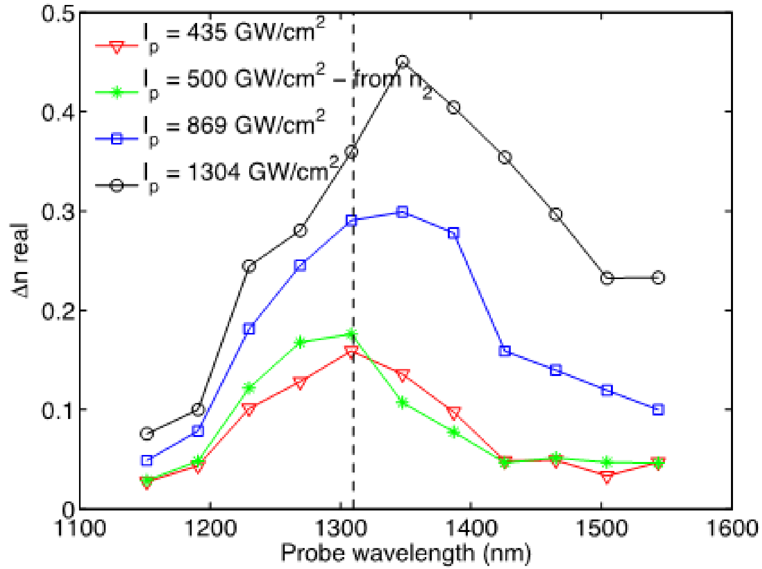


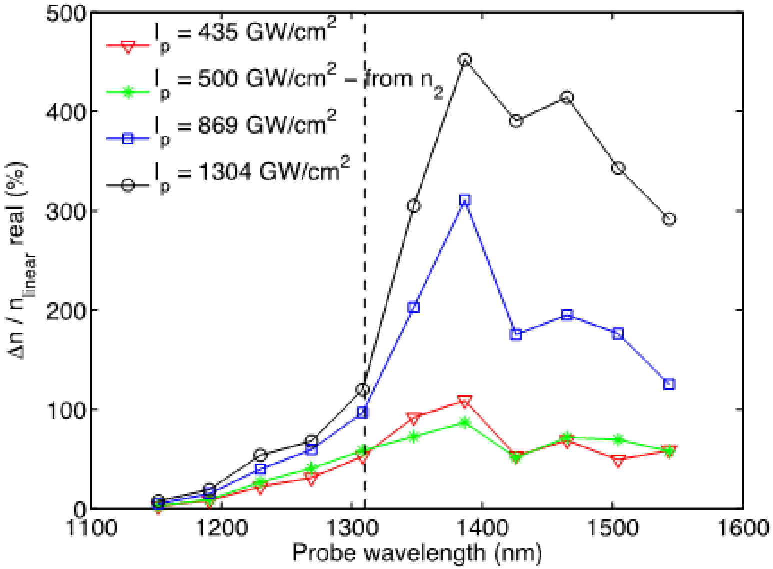
L. Caspani, *et al Phys. Rev. Lett.* **116**, 233901 (2016)

See also work by Boyd group

Optical Kerr Effect in AZO at ENZ point

Light-induced refractive index changes of the order of unity





Feasibility of dynamic light-induced metasurfaces/gratings by using shaped beams

Caspani, et al. PRL (2016)
see also work by Boyd, Science (2016)

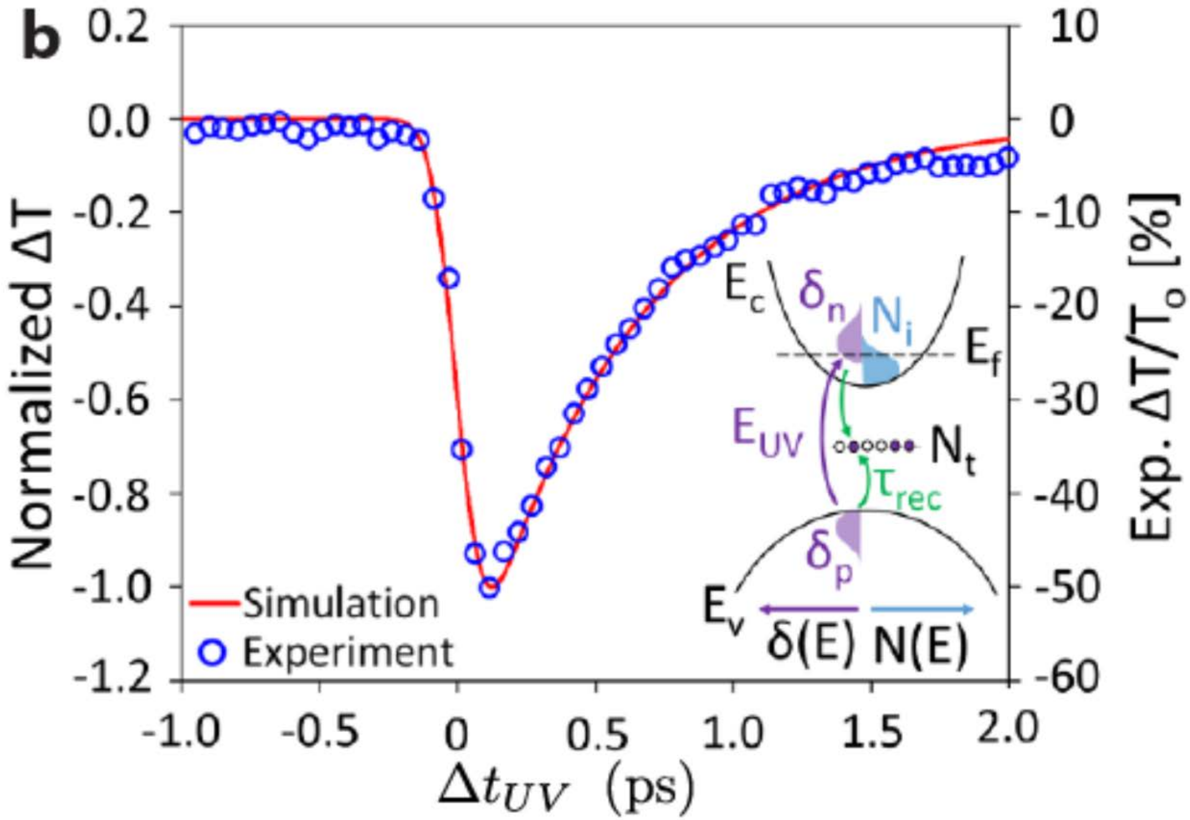
Interband Dynamics in TCOs

PURDUE UNIVERSITY

UV 262 nm pump induces large and sub-picosecond modulation in Al:ZnO thin films

Interband excitation promotes additional electrons into the conduction band, ***blue-shifting*** **the plasma frequency**

Fast recombination of free-carriers through band-gap vacancy/impurity states (Shokely-Reed Hall mechanism)



M. Clerici, et al. Nat. Comm (2017)

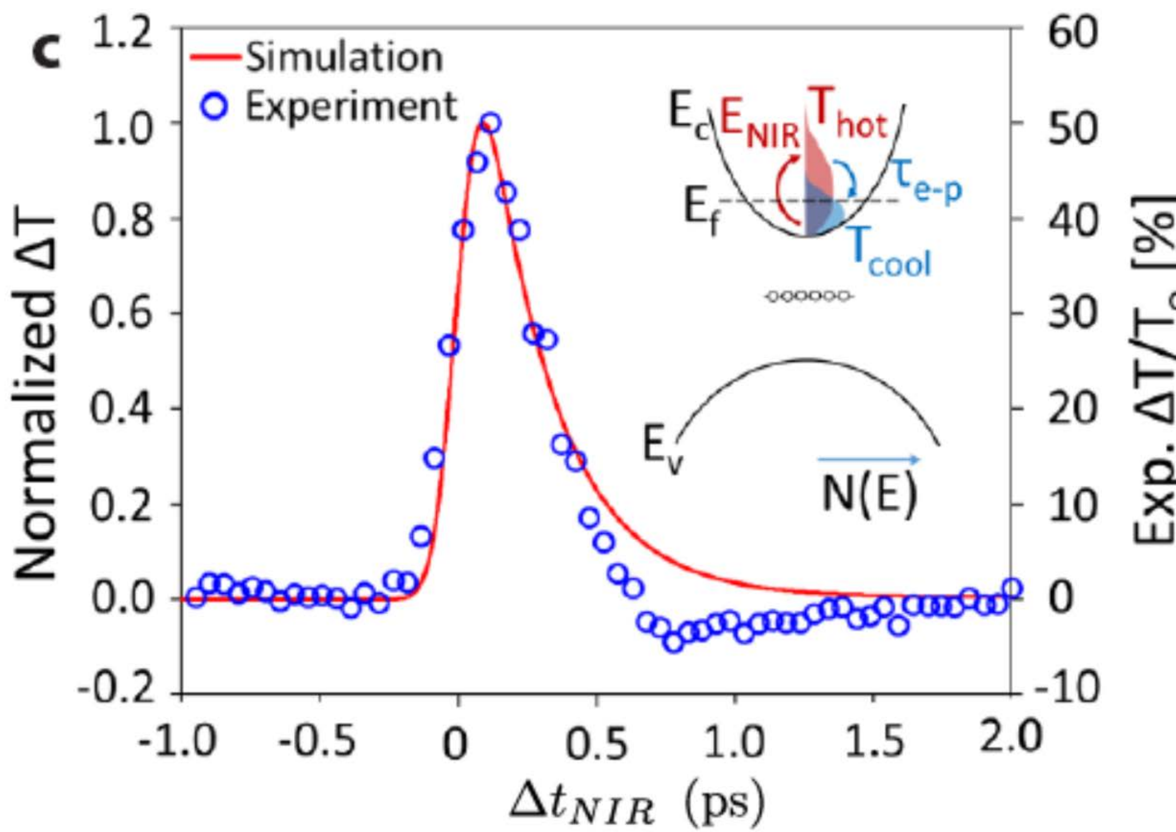
Intraband Dynamics in TCOs

PURDUE UNIVERSITY

NIR 787 nm pump also induces large and sub-picosecond transients in Al:ZnO thin films

Conduction electrons absorb low-energy pump and equilibrate to a new Fermi distribution; **plasma frequency is *red-shifted***

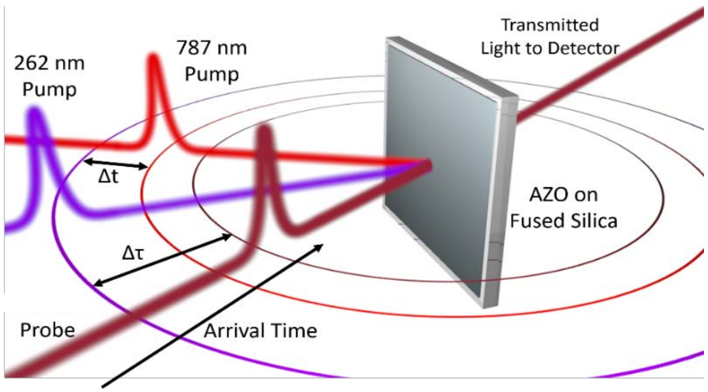
Fast relaxation because of anomalously large difference in electron and lattice heat capacities (slow lattice dn/dT doesn't contribute much)

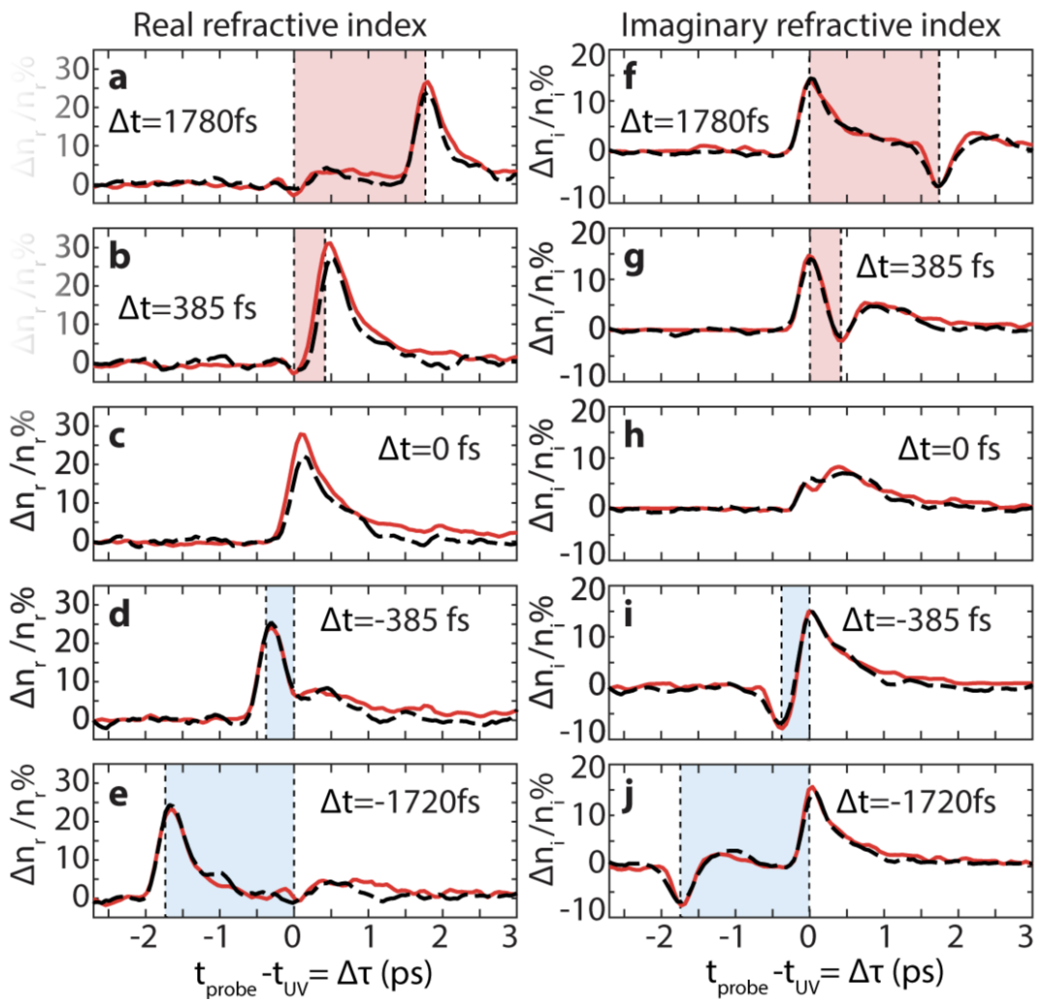


M. Clerici, et al. Nat. Comm (2017)

Simultaneous Nonlinearities

PURDUE UNIVERSITY



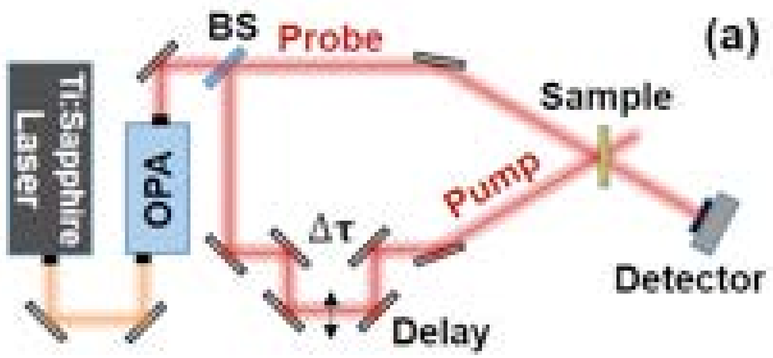


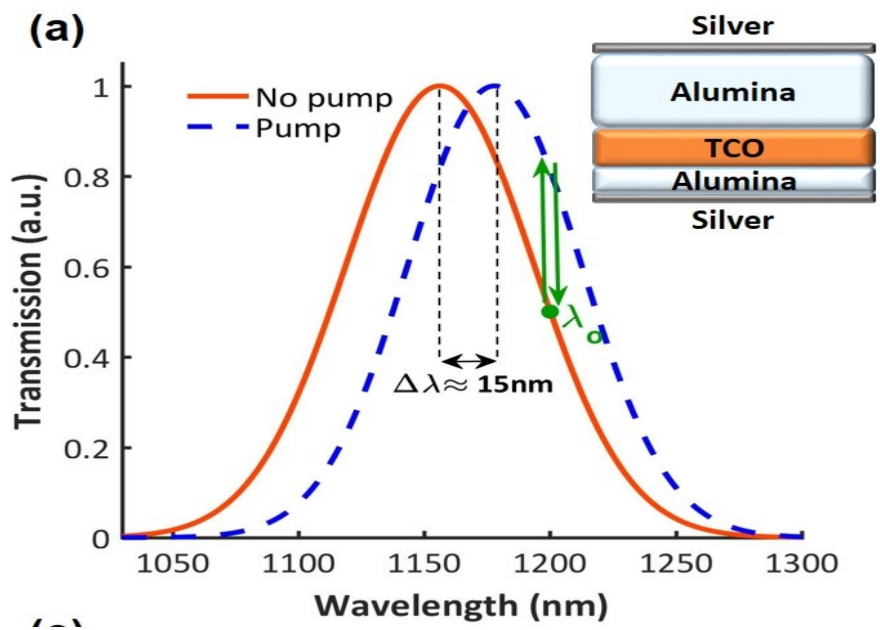
Engineered nonlinearities by controlling the delay between the two pumps

M. Clerici, et al. Nat. Comm (2017)

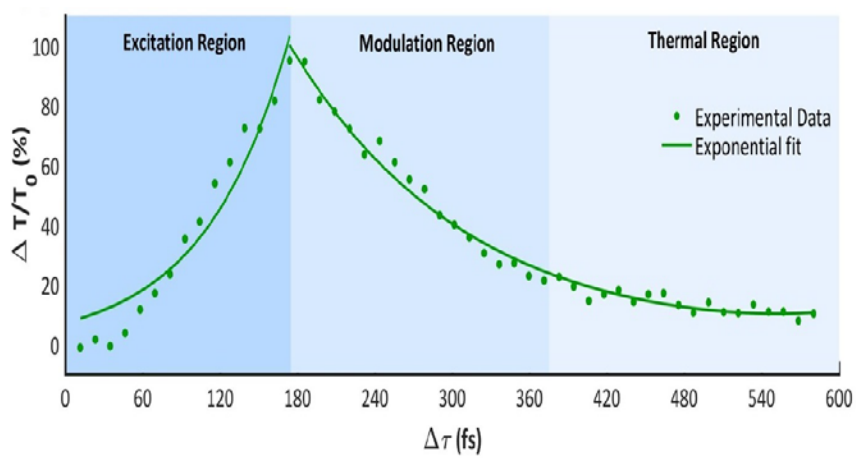
Feasibility of dynamic light-induced metasurfaces/gratings by using shaped beams

Ultrafast Metasurface Cavity





Optical pumped nanocavity incorporating Al:ZnO for ultrafast tunability



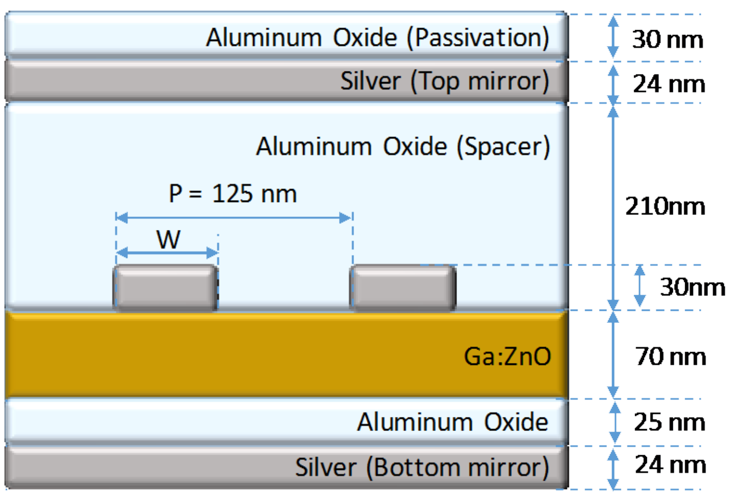
15 nm wavelength shift corresponding to a %100 change in transmission

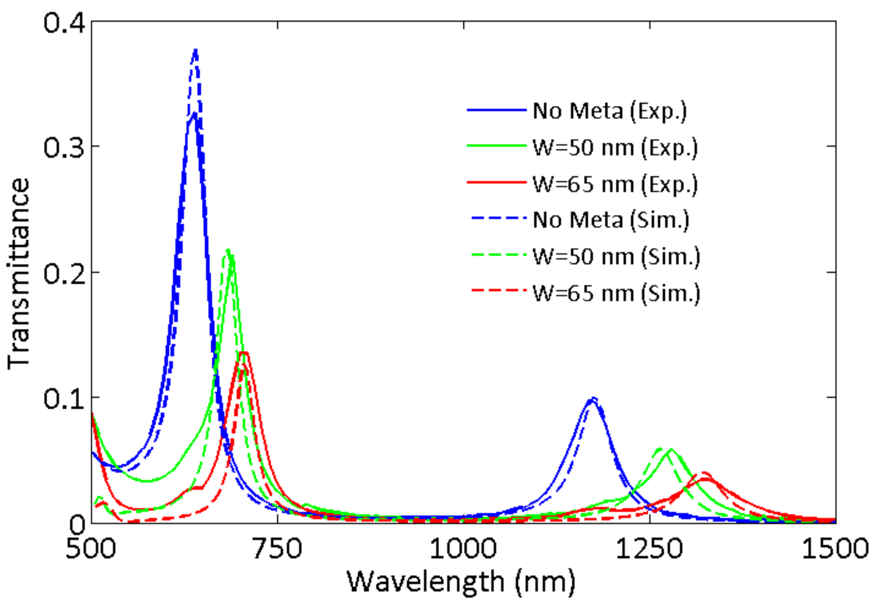
Ultrafast recombination time < 1 ps (pump 787 nm)

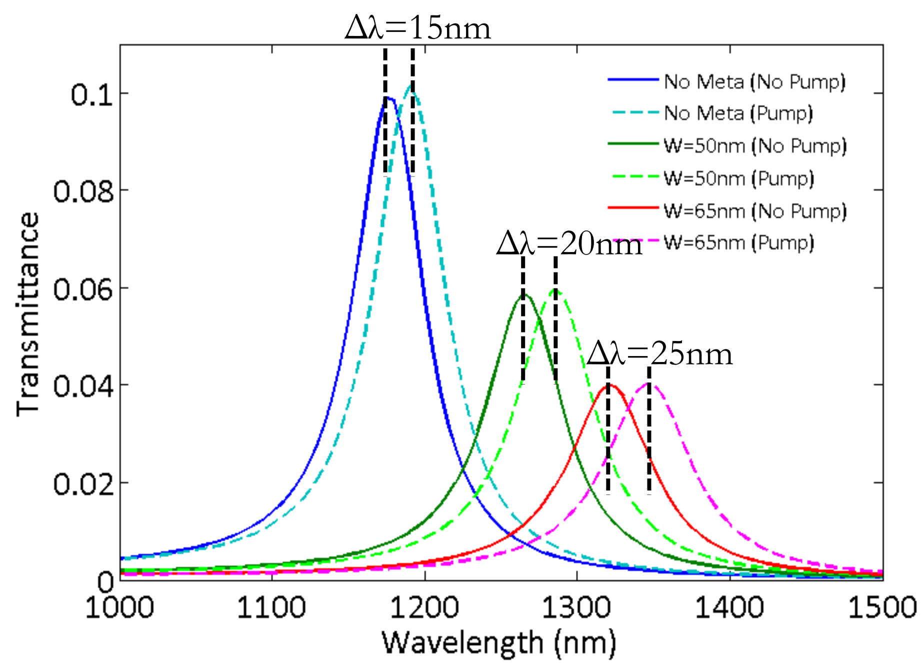
In collaboration with Heriot Watt (Marcello Ferrera) and former student Jongbum Kim

Metasurface Embedded Design

Cavity Sample with Al:ZnO layer



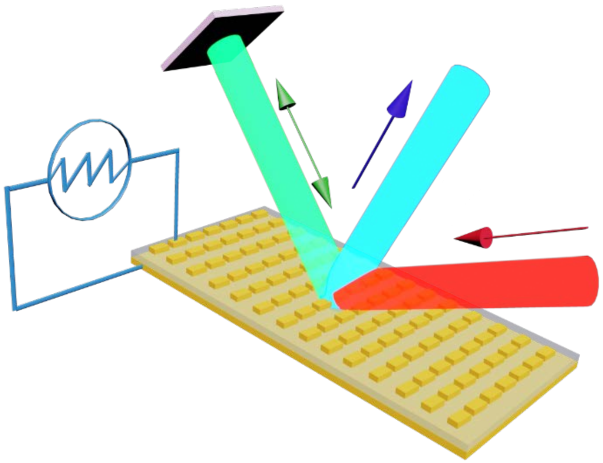




In collaboration with Heriot Watt (Marcello Ferrera)
and former student Jongbum Kim

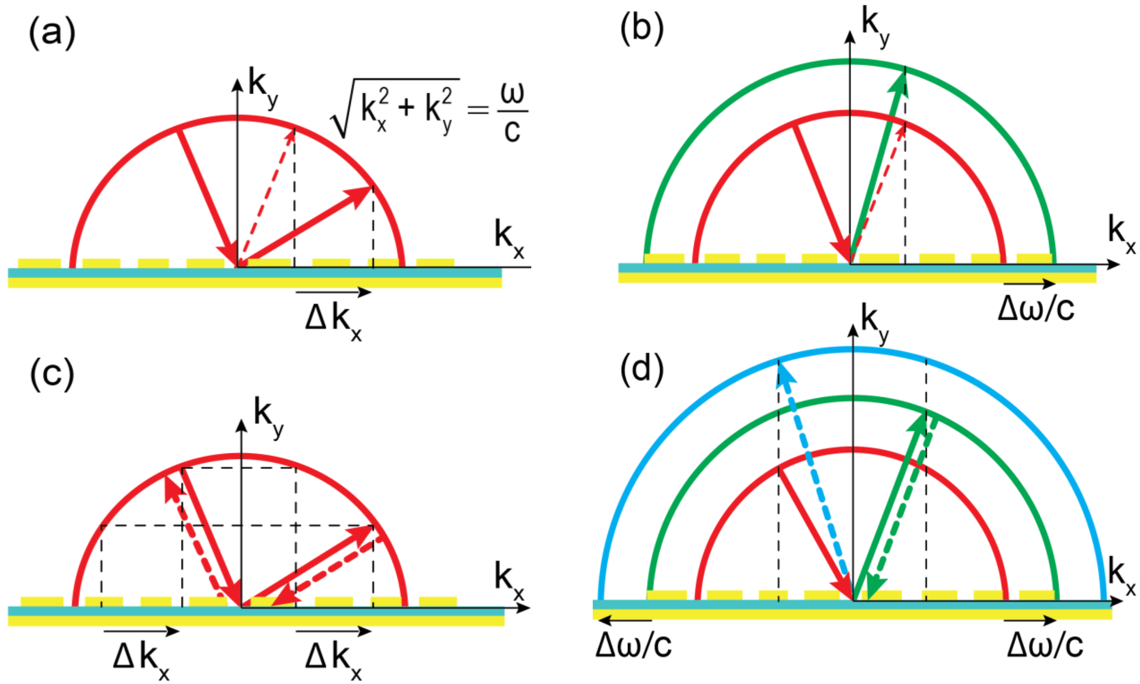
Time-Gradient Metasurface

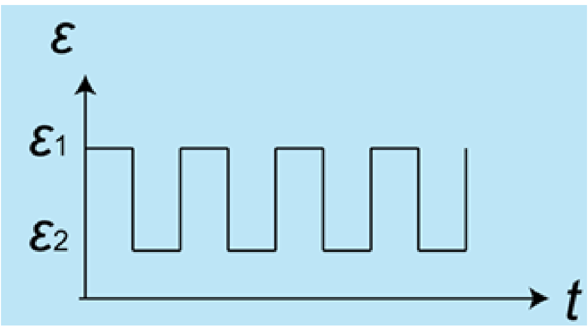
Non-reciprocal metasurfaces



Breaking translation symmetry and momentum conservation

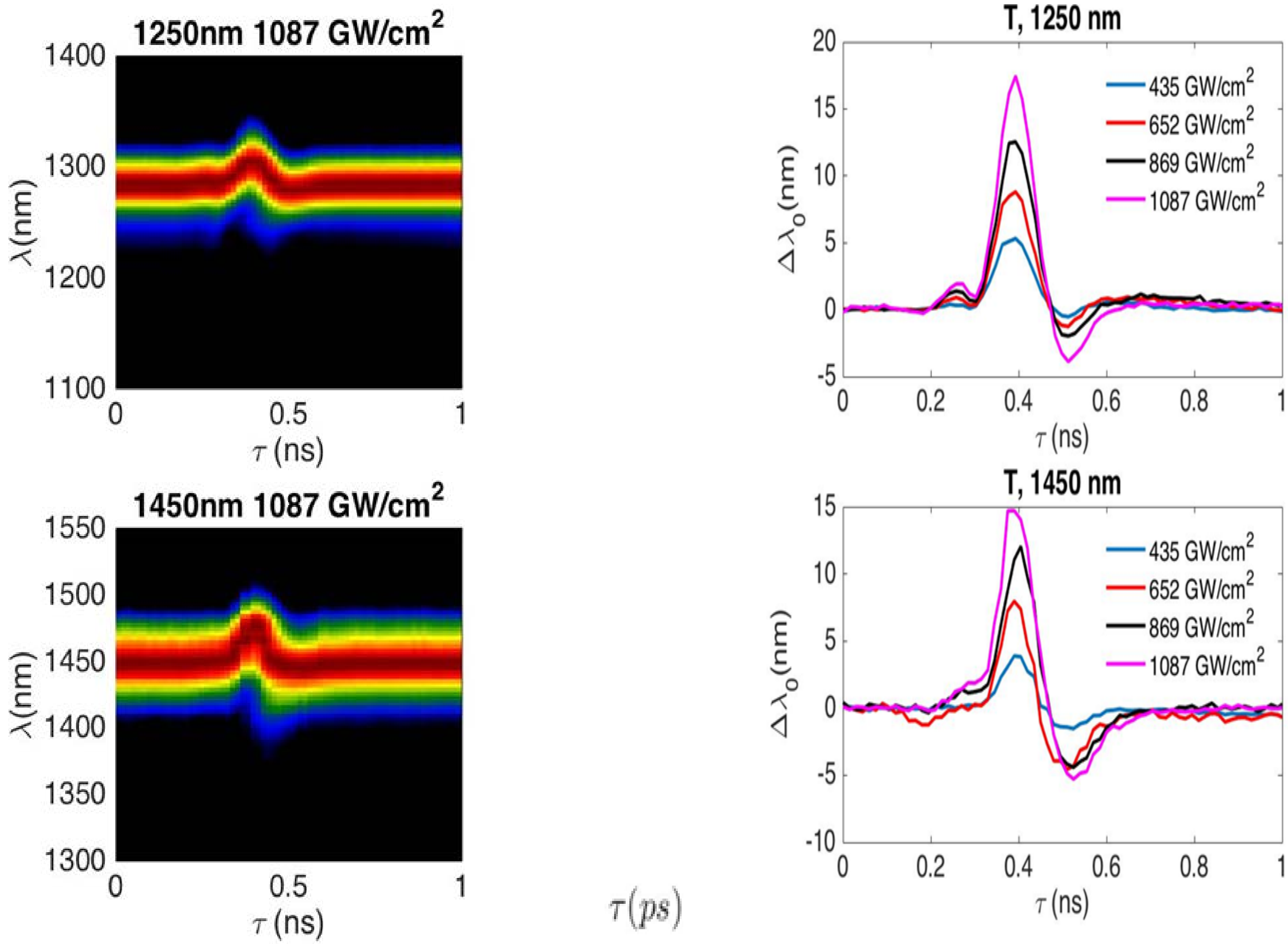
Breaking temporal symmetry and energy conservation





Photonic TIME crystals
space-time duality in Maxwell Eqs
-> forbidden k-zones

Optically Induced Time-Variation



$\tau(ps)$

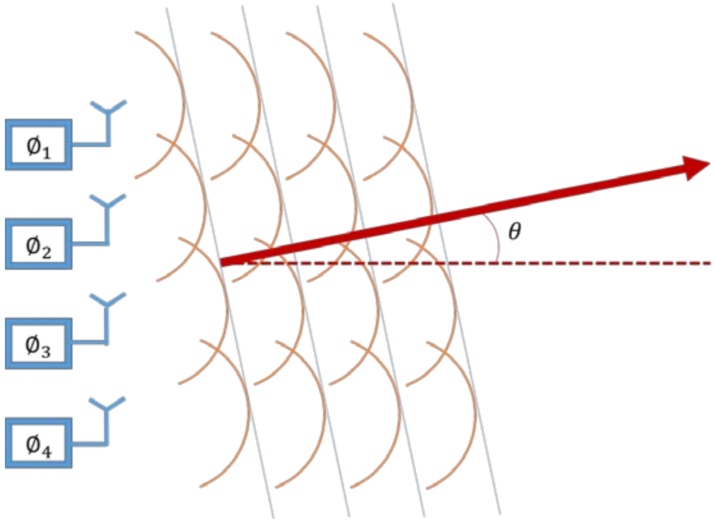
$w^2 = w_p^2 + k^2c^2$

k is fixed, w changes with w_p

- ω changes are on same order as change of ω_p (~ 135 nm), which occurs over time scale of 100-150fs
- Time inside AZO ~20fs, → $\Delta\lambda \sim 15 - 20nm$

Frequency-Array Metasurface

Conventional Phase-Array Metasurface

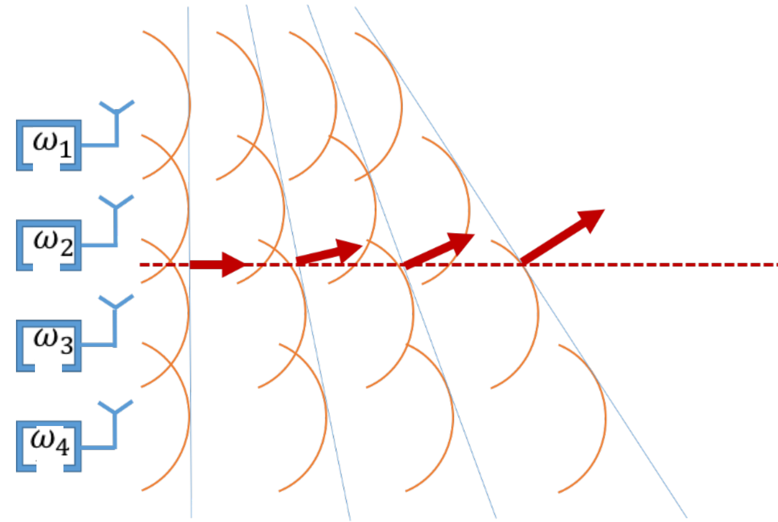


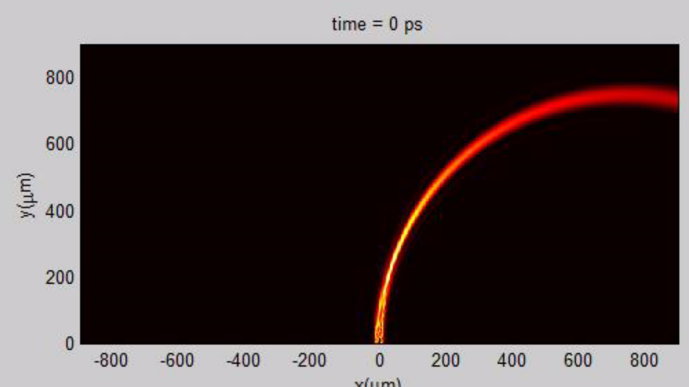
Electro-optical modulators (LC, LiN, gate-tunable MS)

$$E = \sum_{n=-N}^{N} \frac{e^{i(\omega_n t - k_n|r-r_n|)}}{\sqrt{|r-r_n|}}$$

$$d = 750\,nm \qquad \lambda_0 = 1.5\mu m$$

Frequency-Array Metasurface

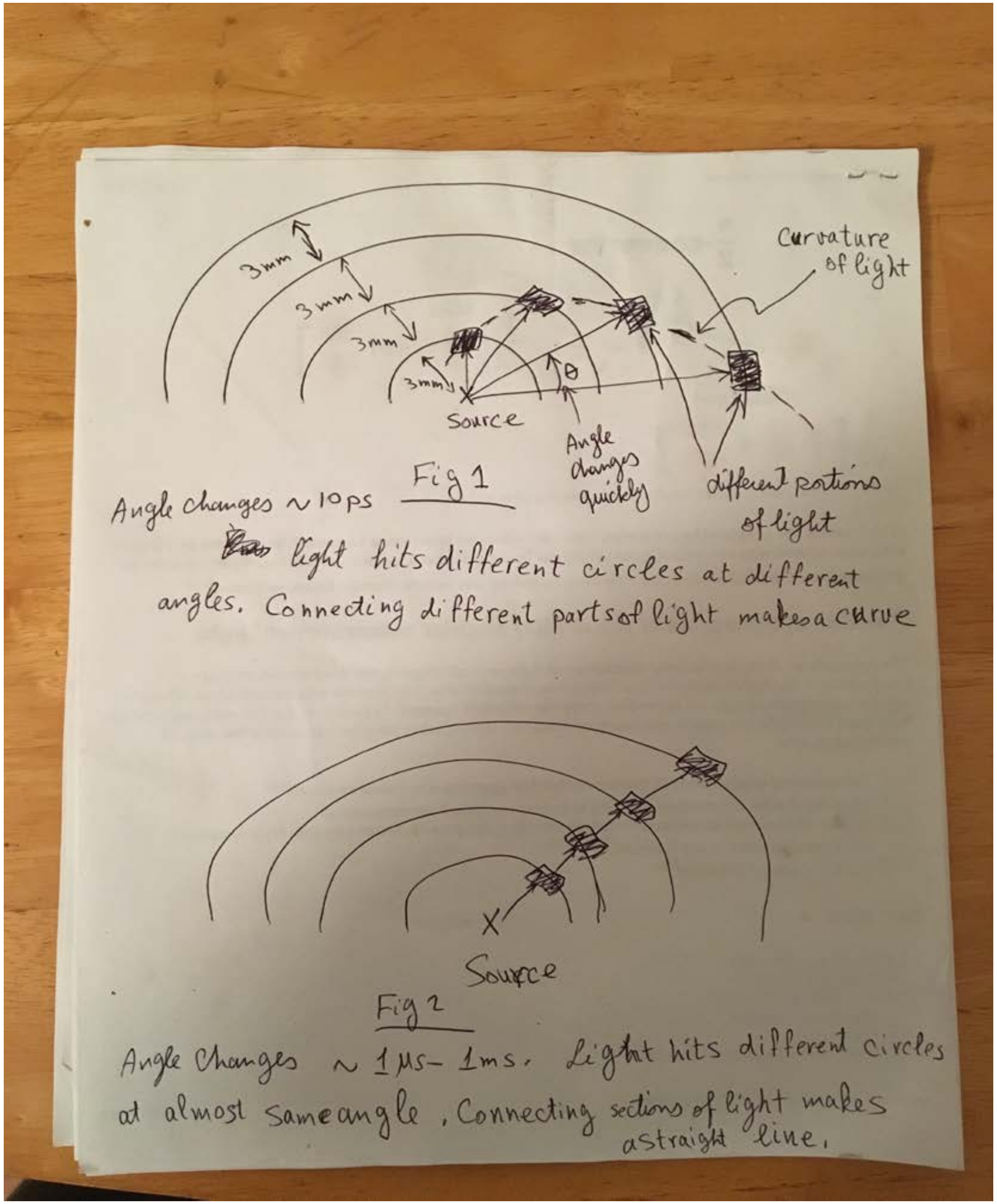




$$\Delta\omega = 2\pi\times 100\,GHz$$

with Amr Shaltout and Mark Brongersma

‘Curved’ light beam steering

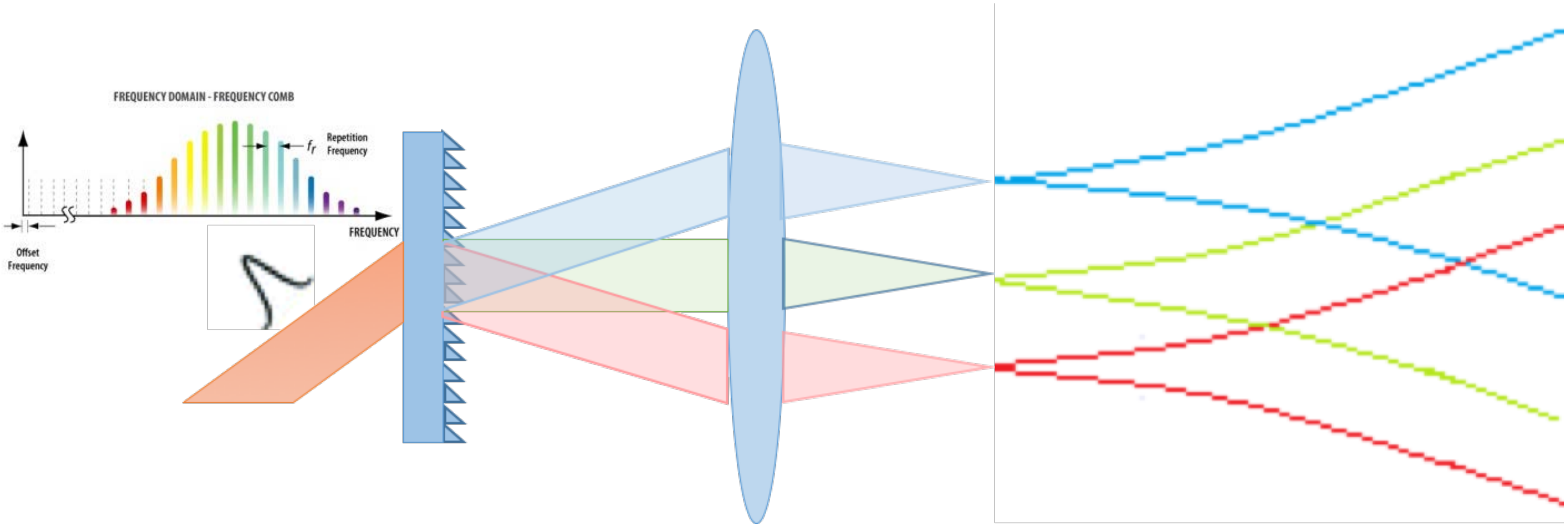


time of angular steering (~10ps) is comparable to propagation time of light -> light beam is curved

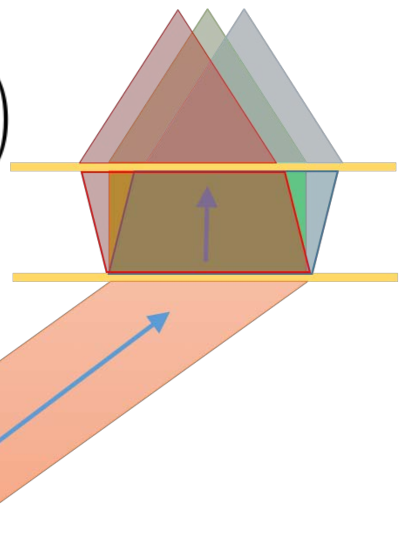
Similar to curved water stream when rotating fast a water horse

Slide courtesy: Amr Shaltout

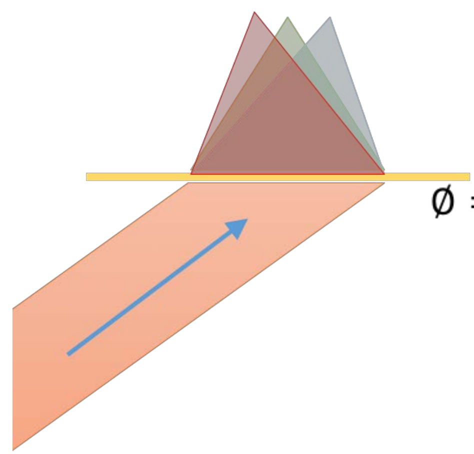
Phase Gradient Metasurface



$$\emptyset = k_0\left(f_c - \sqrt{f_c^2 + x^2}\right)$$

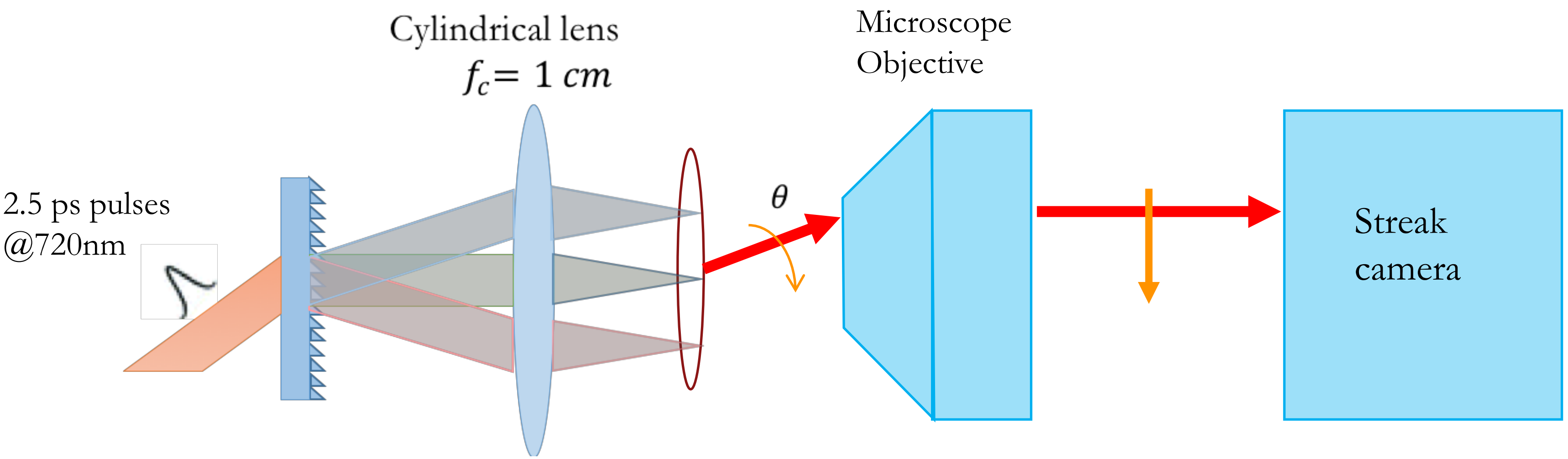


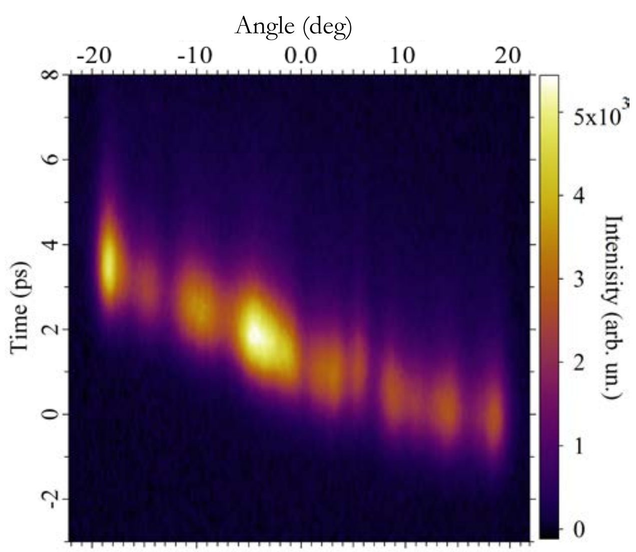
$$\emptyset = k_0 sin(\theta_i)x$$

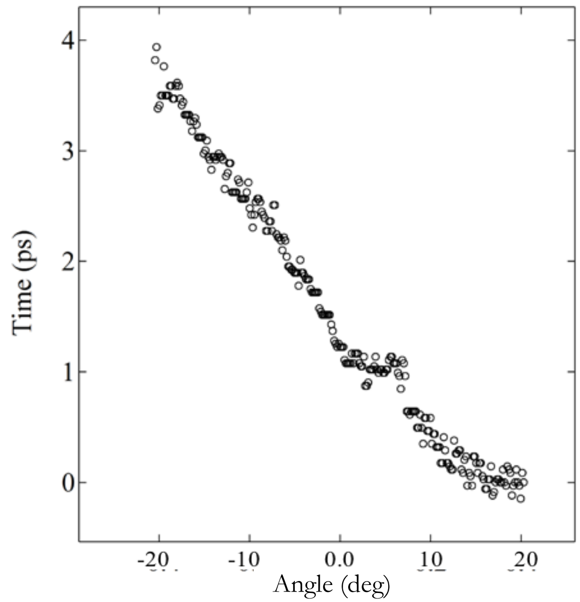


$$\emptyset = k_0\left(f_c - \sqrt{f_c^2 + x^2}\right) + k_0 sin(\theta_i)x$$

Experimental Observation







Application of Metasurfaces

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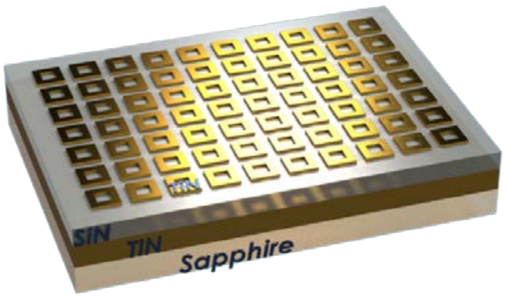
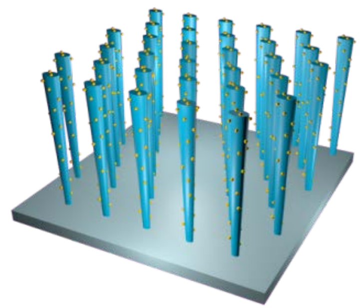
Broadening the Application Realm

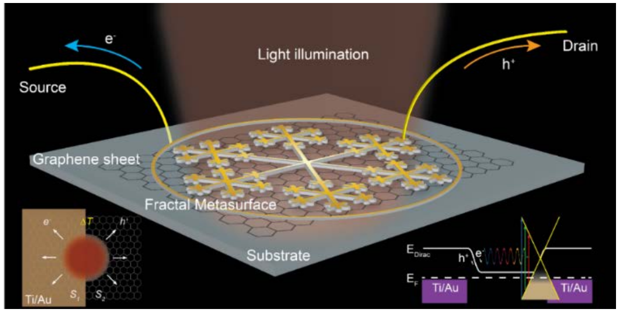
Thermophotovoltaics



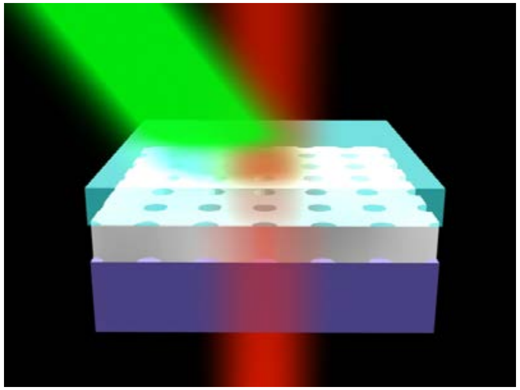
Catalysis



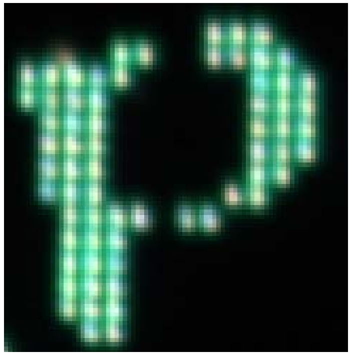
Photodetectors



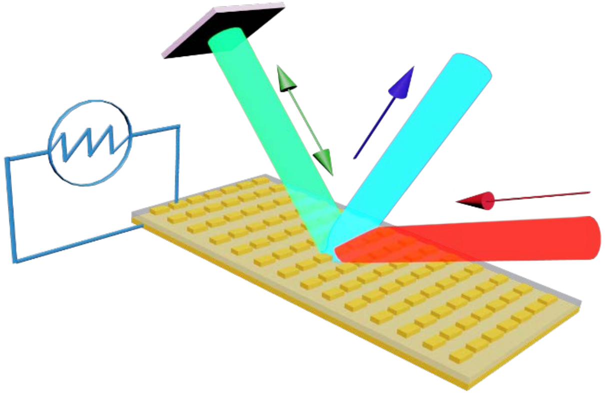
Nanolaser/Spaser



Nanotweezer



Ultrafast Space-Time Control



Future Applications

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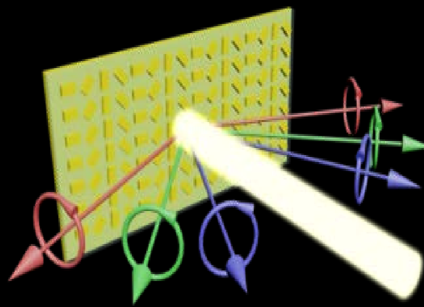
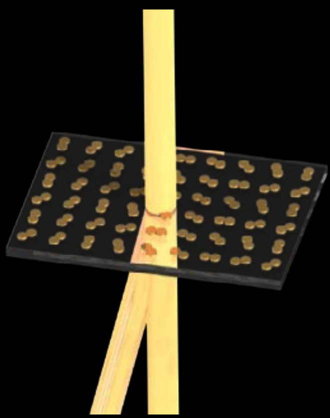
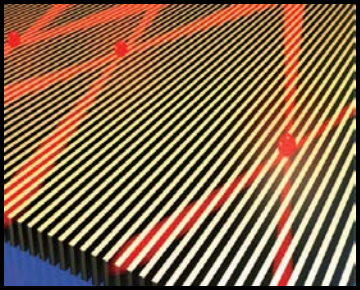
FLAT/WEARABLE OPTICS

- Reconfigurable lenses
- Dynamic holograms
- Beam steering
- Novel light sources
- Dynamic signal routing
- Ultra-fast, active devices
- Harsh-environment sensors
- Wearables/googles
- Augmented reality
- Wearable sensors
- Ultrafast space-time light modulators







TEAM AND SUPPORT

PURDUE UNIVERSITY

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- Harsha Reddy
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- Zhuoxian Wang
- Clayton DeVault
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- Prof. A. Kildishev (Purdue)
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- Prof. A. Alu (UTexas Austin)
- Prof. M. Brongersma (Stan.)
- Prof. M. Ferrera (Heriot-Watt)
- Prof. D. Faccio (Heriot-Watt)
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- Dr. P. West (Intel)
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- Dr. X Meng (Qilu Tech U)

Support

- Air Force Office of Scientific Research (FA9550-14-1-0138, MURI FA9550-14-1-0389)
- Army Research Office (57981-PH, 56154-PH-MUR, 63133-PH)
- Office of Naval Research (ONR-MURI N00014-10-1-0942, N00014-16-1-3003)
- National Science Foundation (NSF MRSEC 1120923, NSF DMR-1506775)

SELECTED PAPERS

PURDUE
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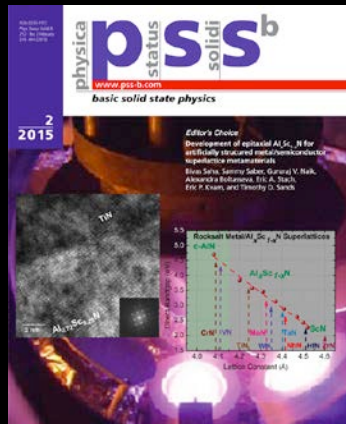

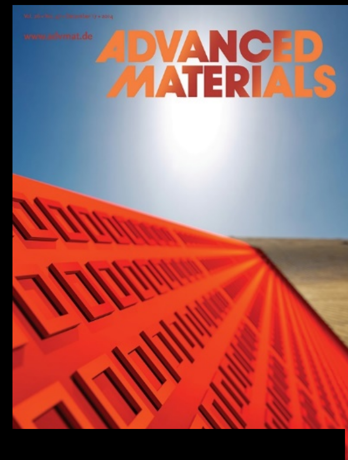

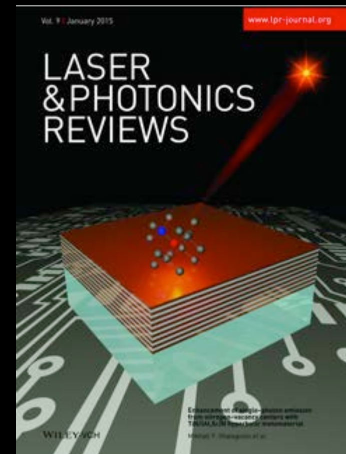

THANK YOU!

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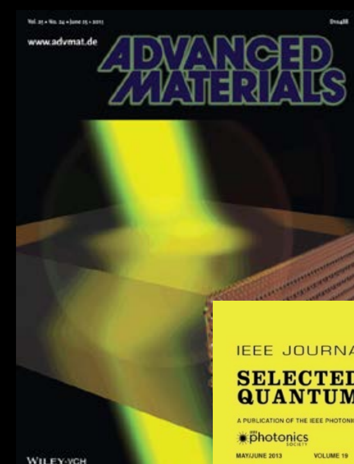

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