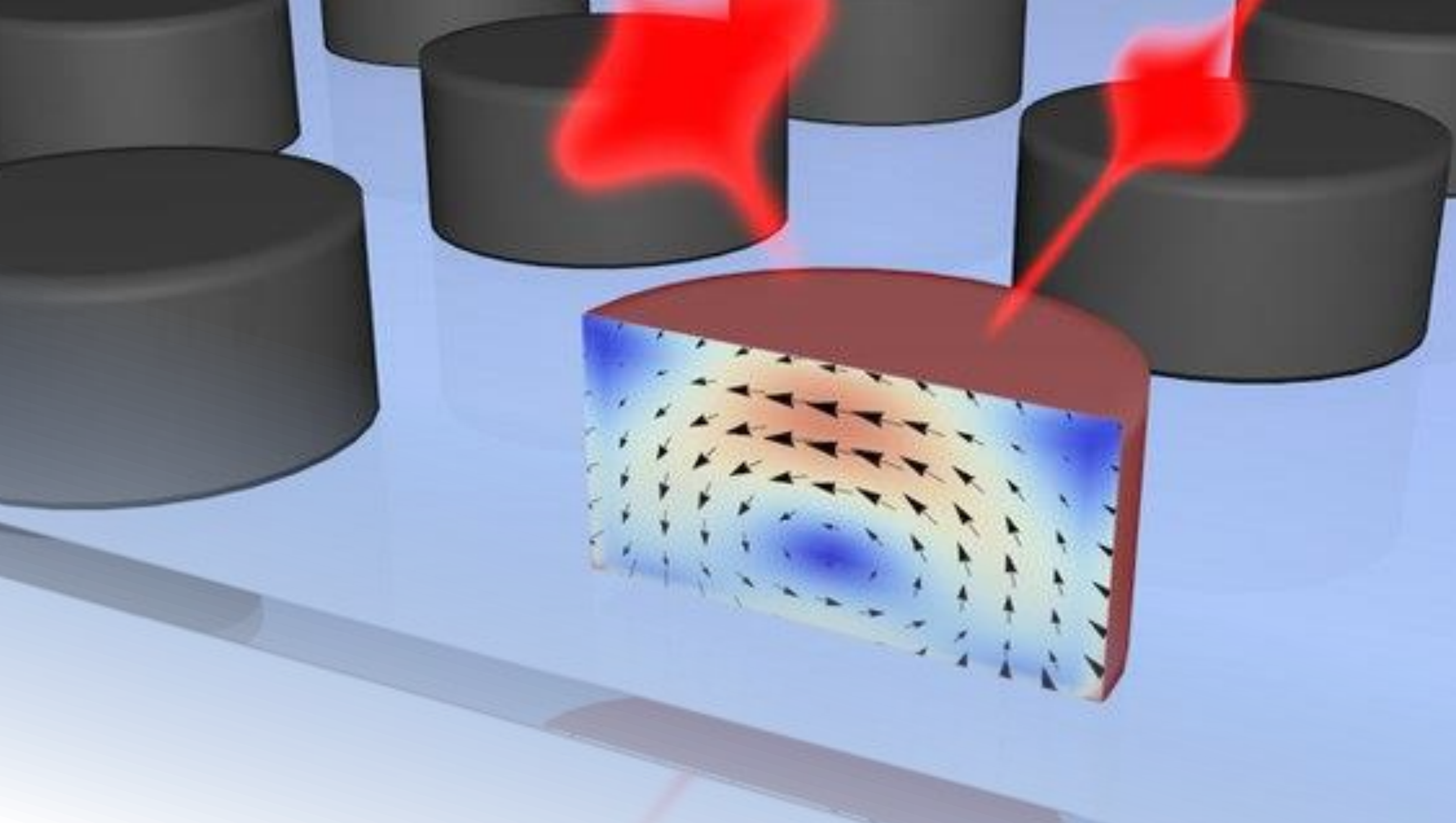
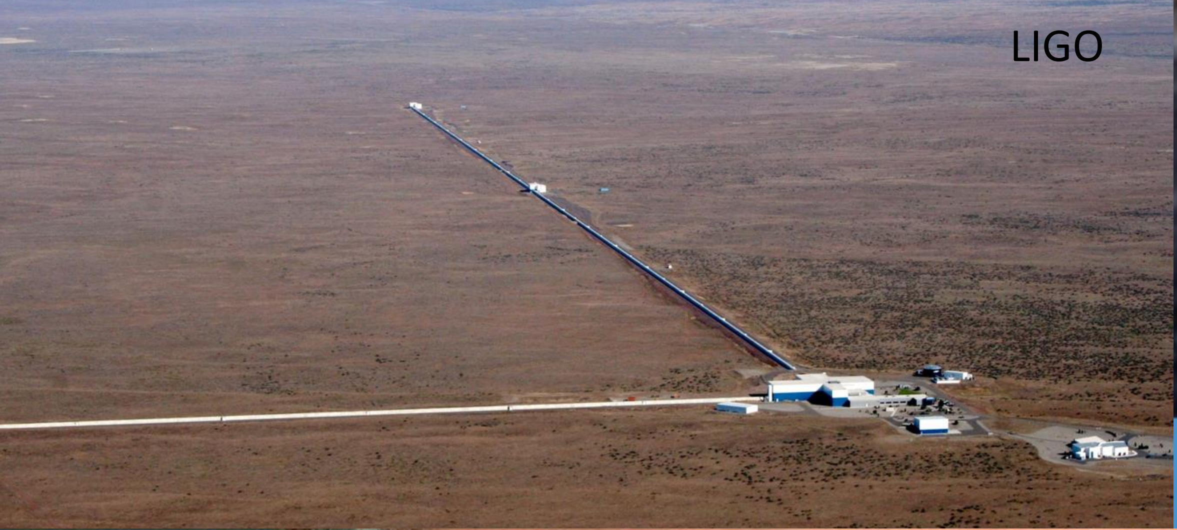
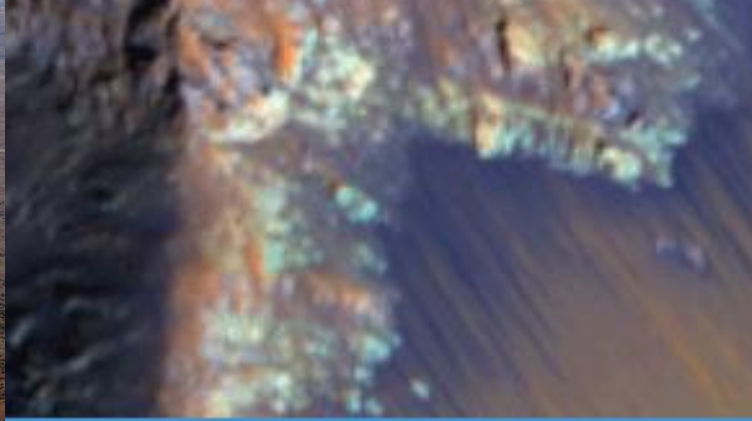


Nanophotonics:
Keeping up with Moore’s Law

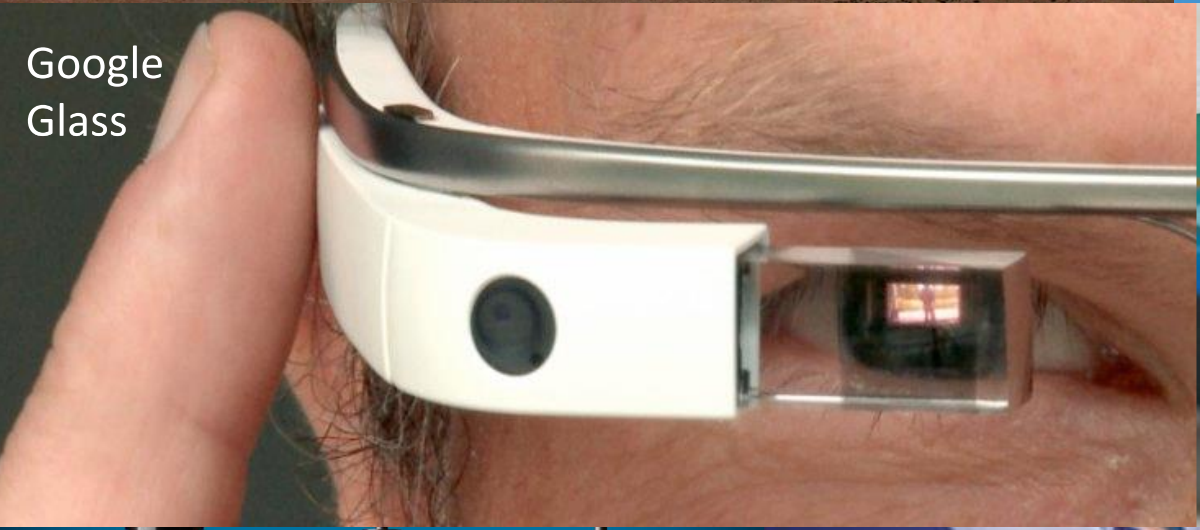
INTERNATIONAL YEAR OF LIGHT 2015

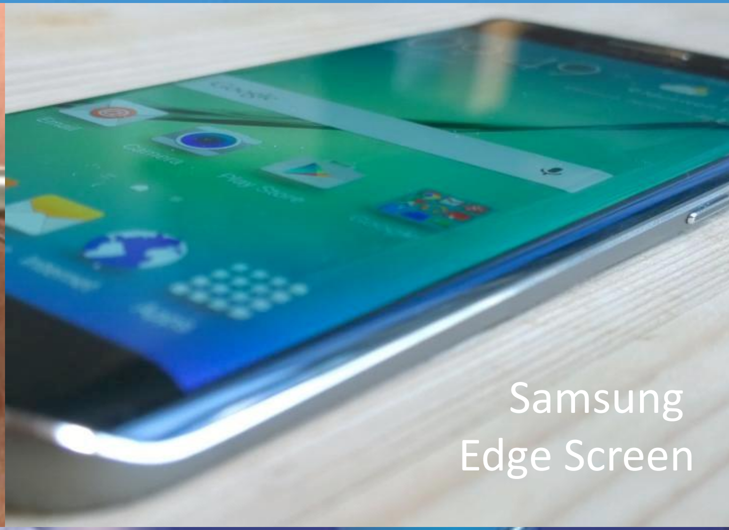
"…a global initiative adopted by the United Nations to raise awareness of how optical technologies promote sustainable development and provide solutions to worldwide challenges in energy, education, agriculture, communications and health."

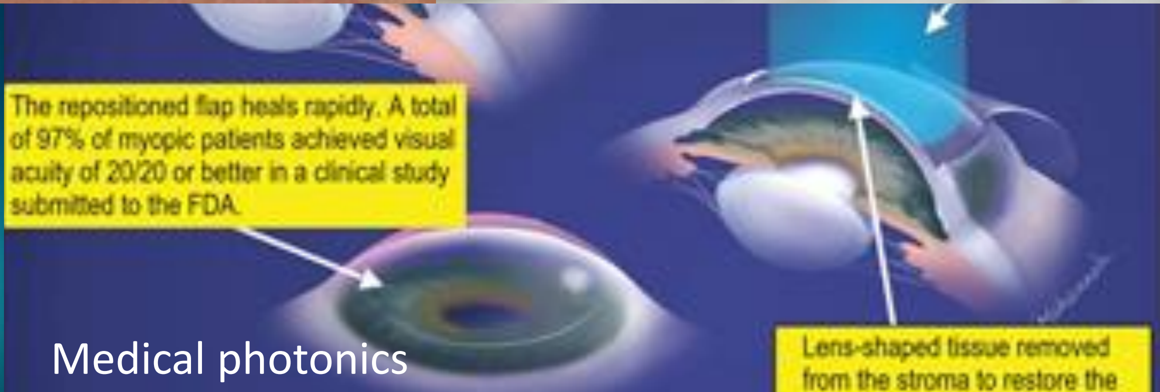




Mars water (source: NASA)

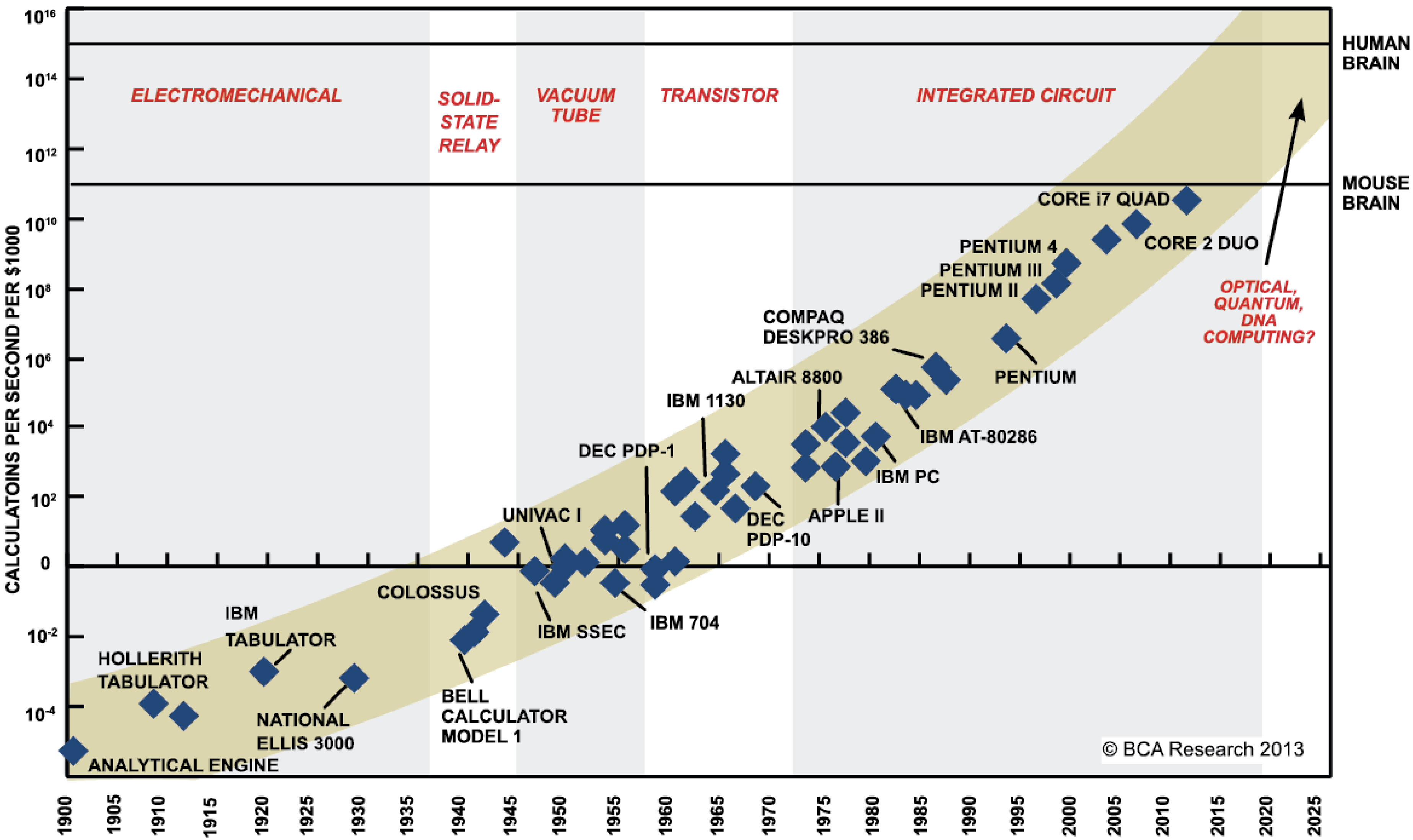




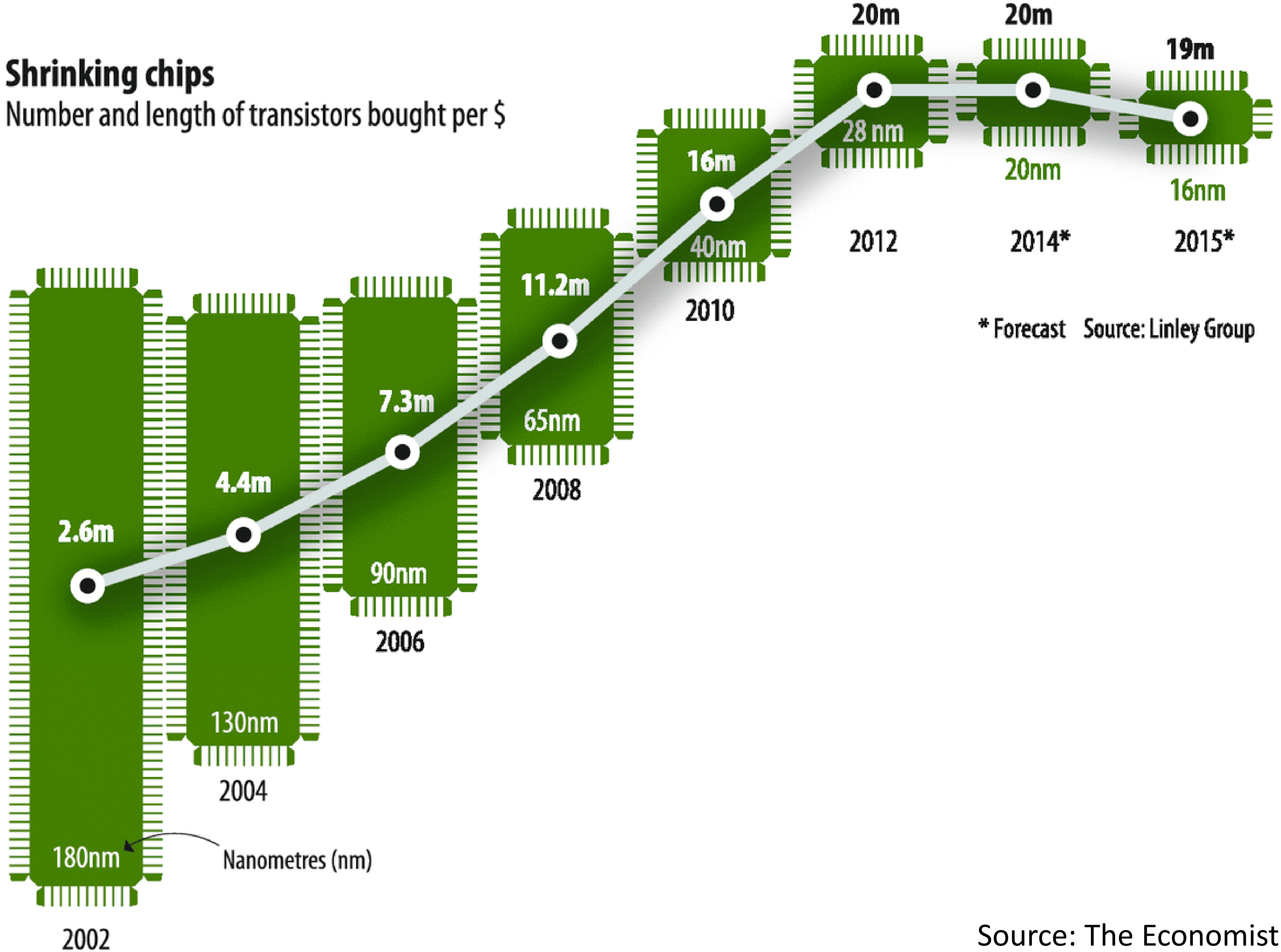



ROGERS
4:20 PM
69%
Notifications
Leanna Lofte sent you a message from Poke. To see it, get the app.
29 minutes ago
James Guimond and Torval van den Hoogen invited you to try I want...
5 hours ago
Shawn Mozen has invited you to like his Page Agatsu Inc.
7 hours ago
Dominick Izzo-Tactical Combat invited you to Izzo Tactical Combat Martial ...
Yesterday at 6:42 PM
Alexis Cornellier has invited you to like his Page MacQuébec.
Yesterday at 9:16 AM
Grappling Industries posted in Grappling Industries Montreal: Pans Edition ...

Left: Osborne Executive PC (1982), 4 MHz clock
Right: iPhone 1 (2007), 400 MHz clock

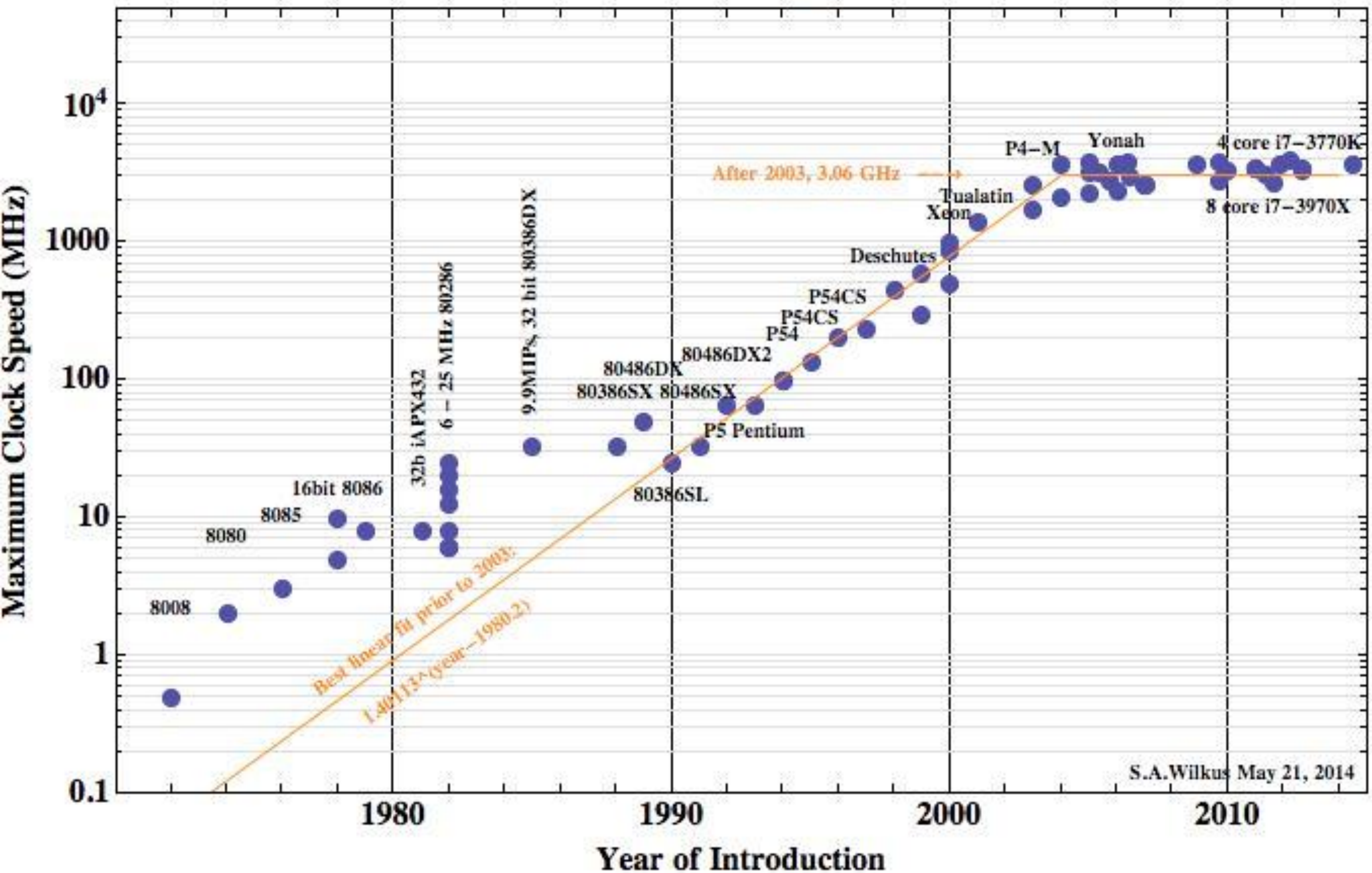


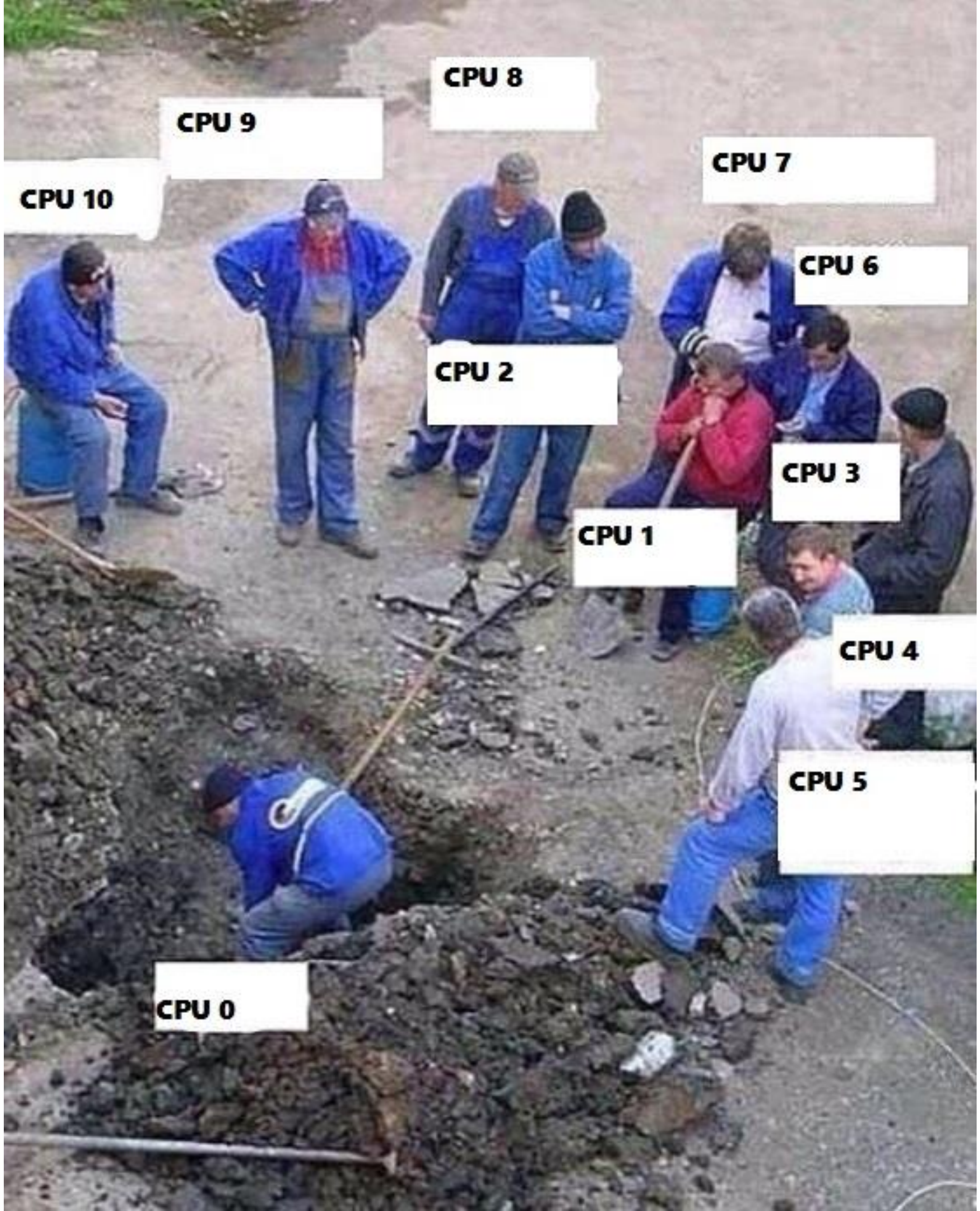
SOURCE: RAY KURZWEIL, "THE SINGULARITY IS NEAR: WHEN HUMANS TRANSCEND BIOLOGY", P.67, *THE VIKING PRESS*, 2006. DATAPOINTS BETWEEN 2000 AND 2012 REPRESENT BCA ESTIMATES.



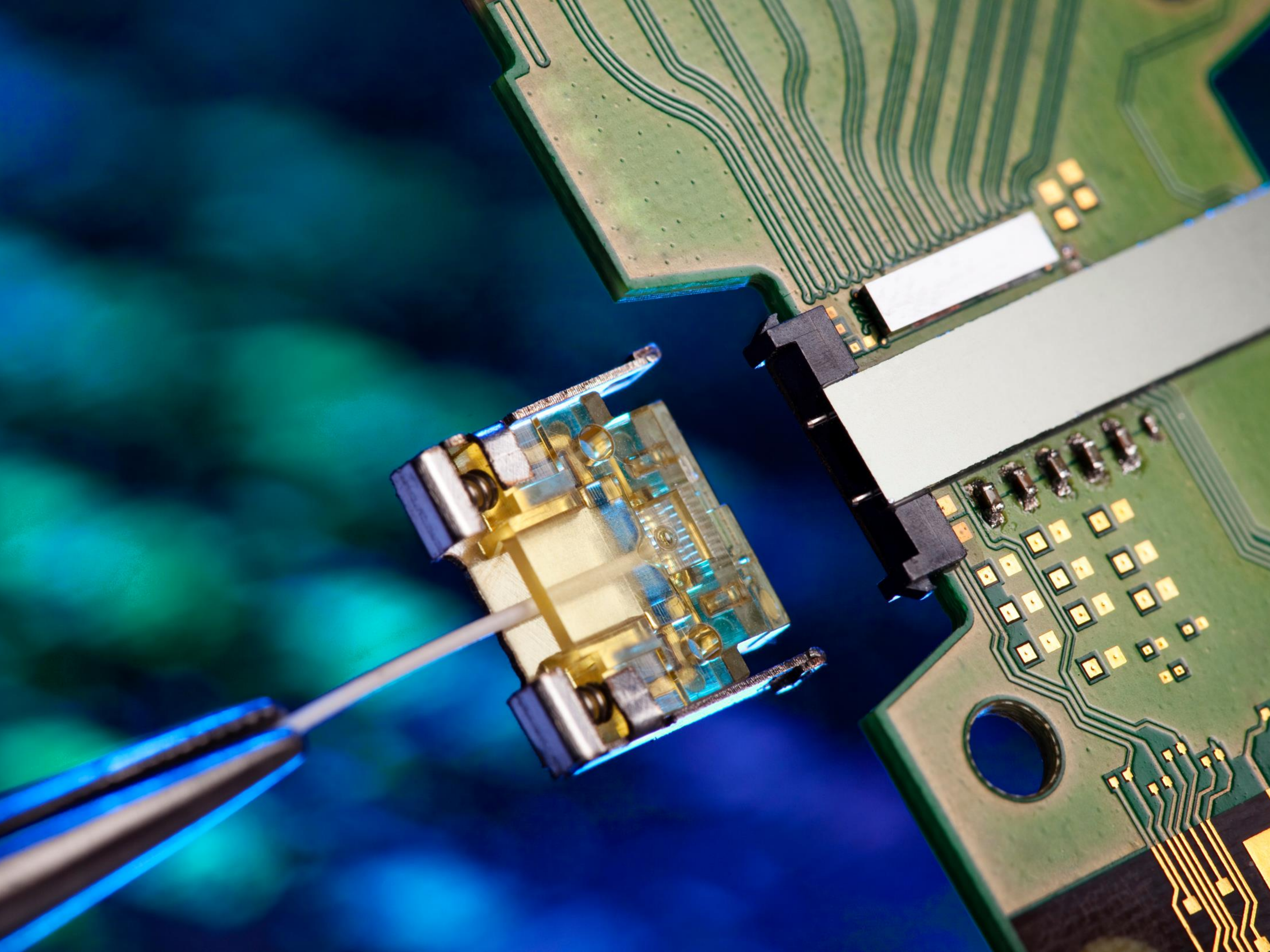
Source: The Economist

μProcessor Clock Speed Trends

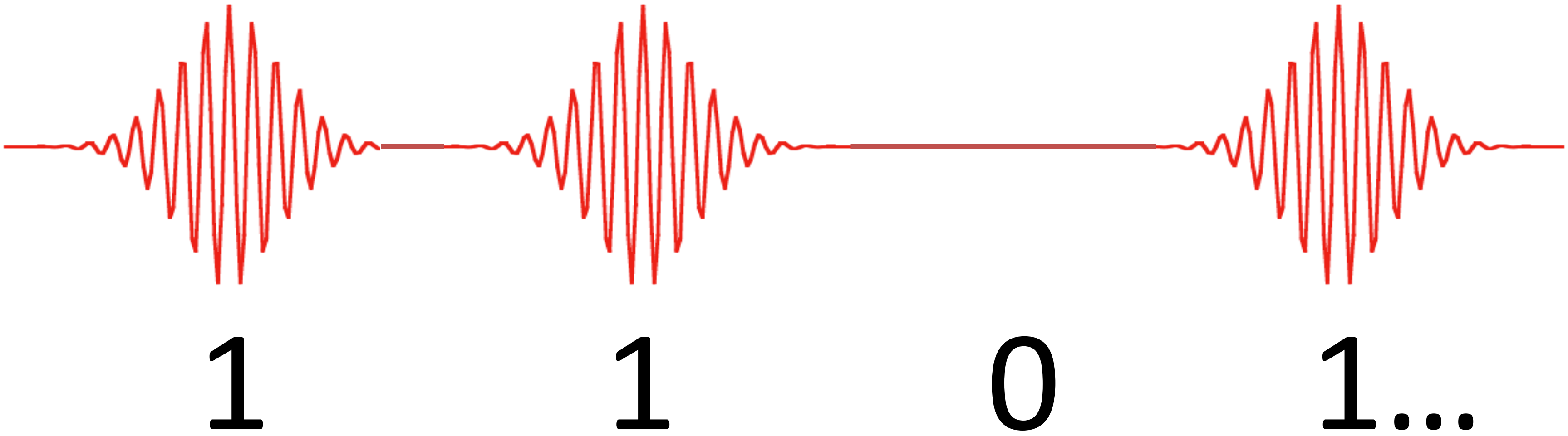



CPU 8
CPU 9
CPU 10
CPU 7
CPU 6
CPU 2
CPU 3
CPU 1
CPU 4
CPU 5
CPU 0

Photonics

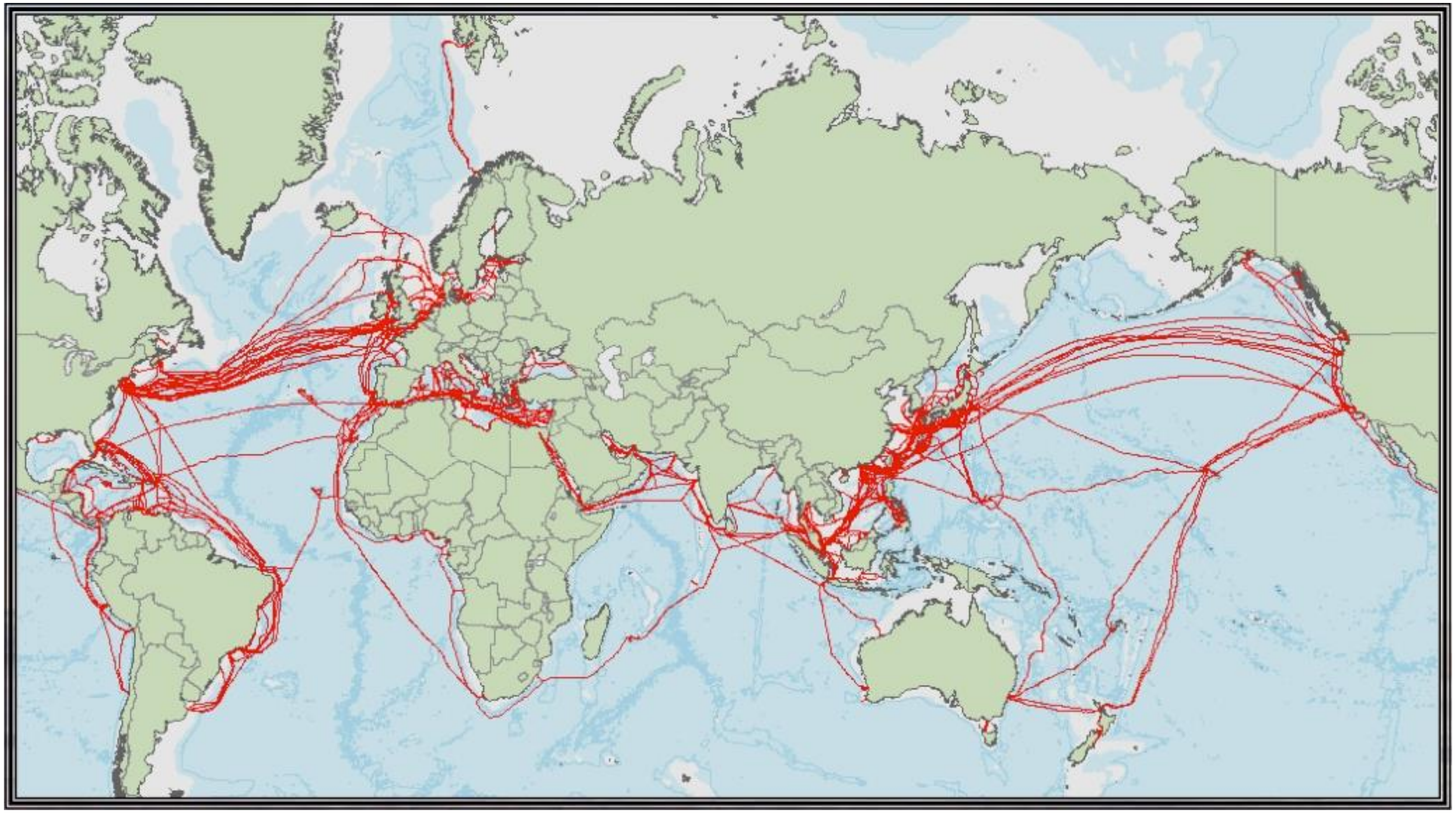


Femtosecond laser pulses



~100 Tbps

Photonic telecommunications

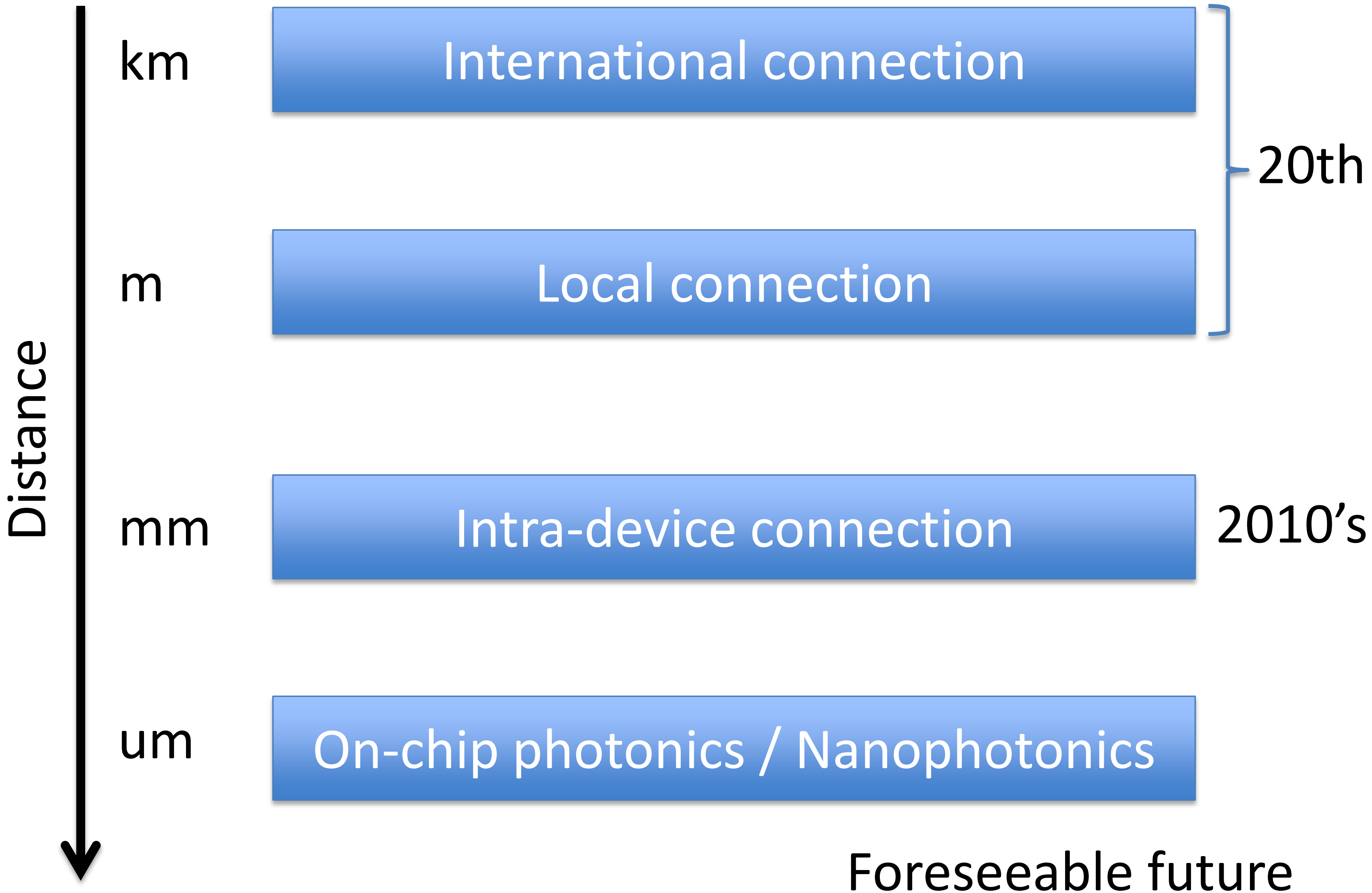


110.9-Tbit/s SDM transmission over 6,370 km using a full C-band seven-core EDFA

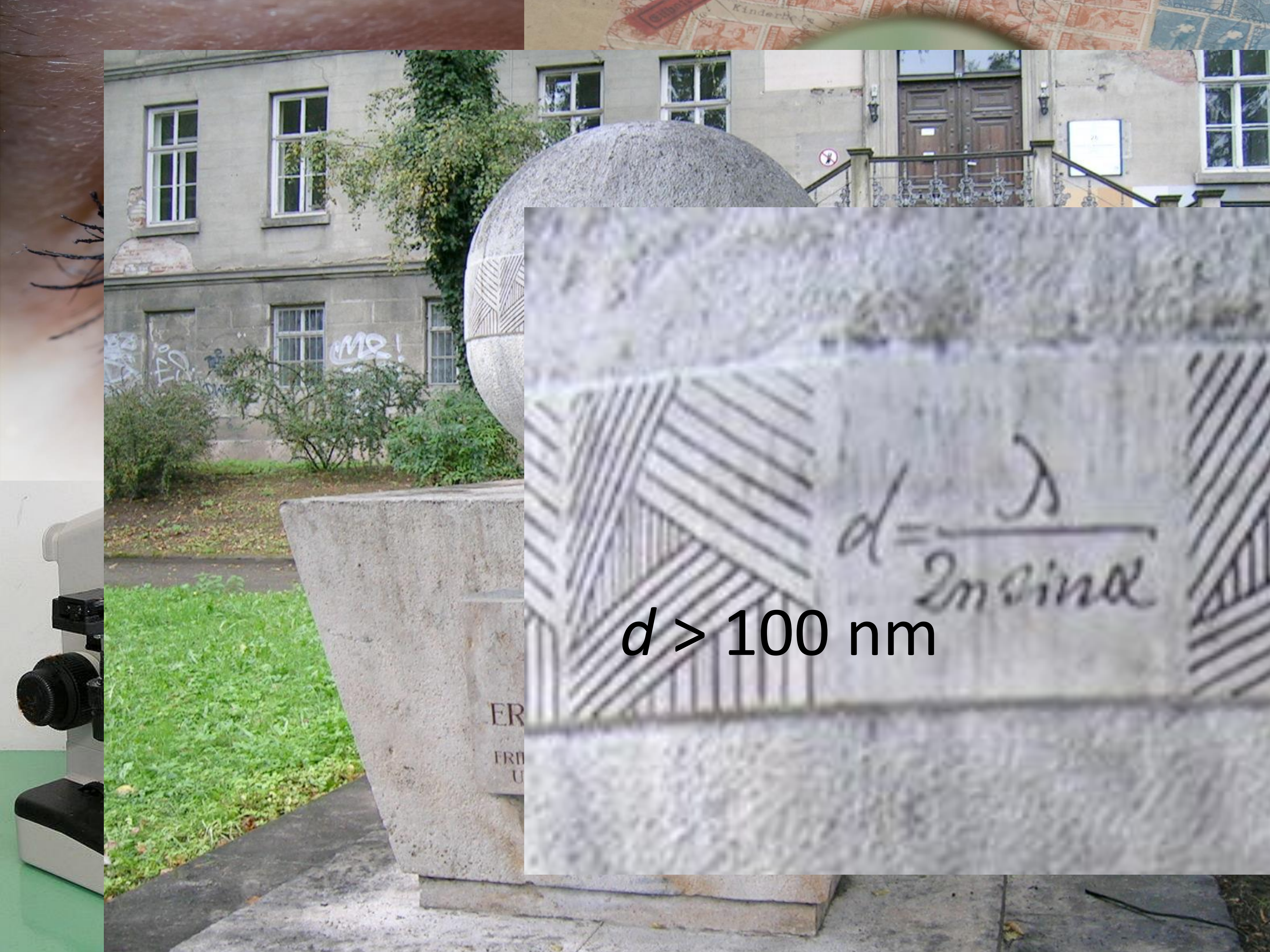
Koji Igarashi,[1,*] Koki Takeshima,[1] Takehiro Tsuritani,[1] Hidenori Takahashi,[1] Seiya Sumita,[1] Itsuro Morita,[1] Yukihiro Tsuchida,[2] Masateru Tadakuma,[2] Koichi Maeda,[2] Tsunetoshi Saito,[2] Kengo Watanabe,[2] Katsunori Imamura,[2] Ryuichi Sugizaki,[2] and Masatoshi Suzuki [1]

[1]*KDDI R&D Laboratories Inc., 2-1-15 Ohara, Fujimino, Saitama 356-8502, Japan*
[2]*Furukawa Electric Co. Ltd., 6 Yawata-kaigandori, Ichihara, Chiba 290-8555, Japan*
[*]*ko-igarashi@kddilabs.jp*


STATION
4
3
2

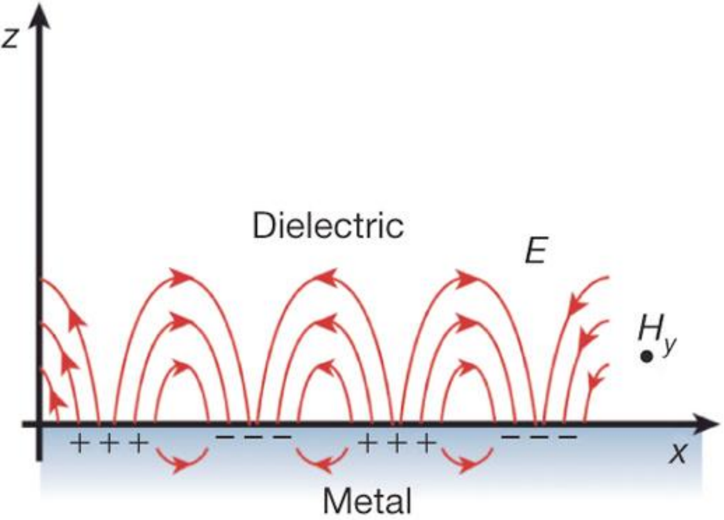


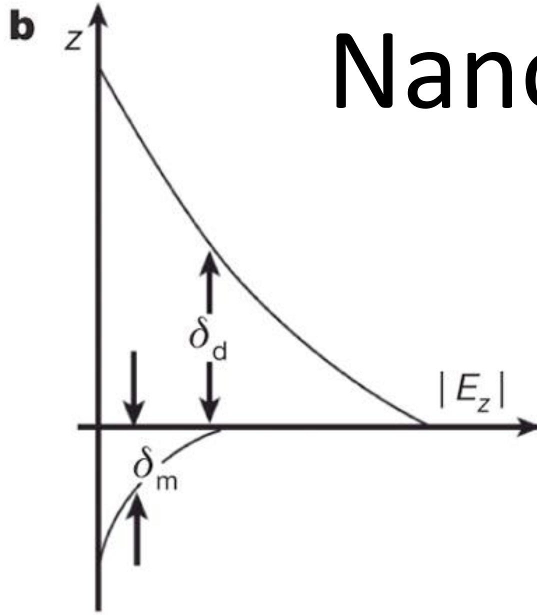
Distance
km
International connection
m
Local connection
20th
mm
Intra-device connection
2010's
um
On-chip photonics / Nanophotonics
Foreseeable future

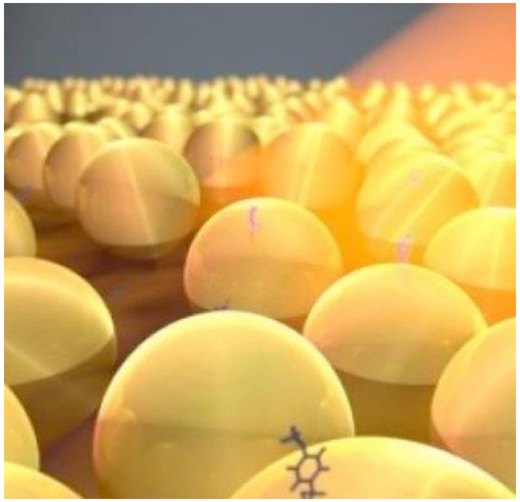


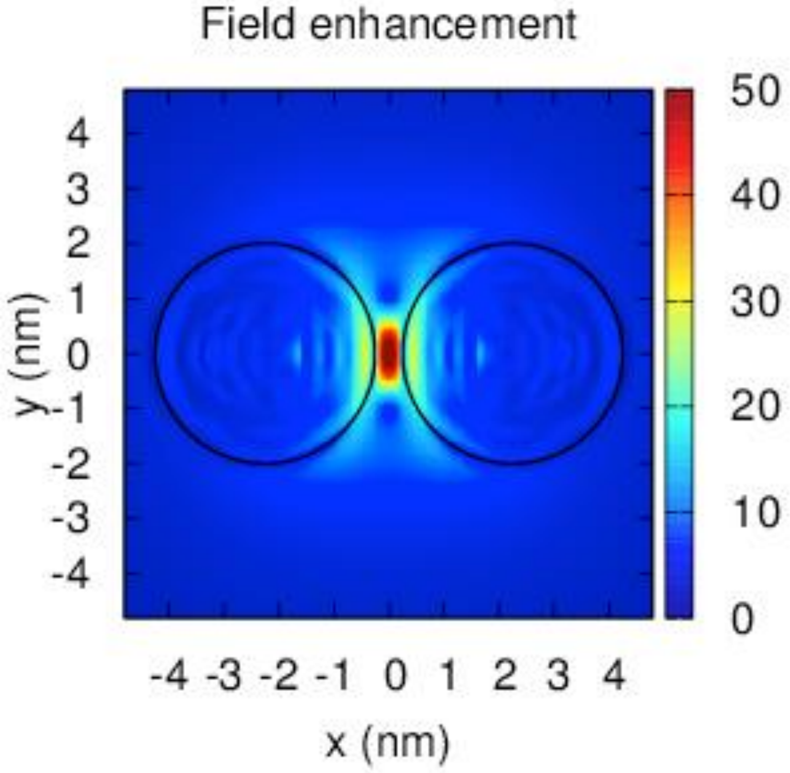
$d > 100$ nm

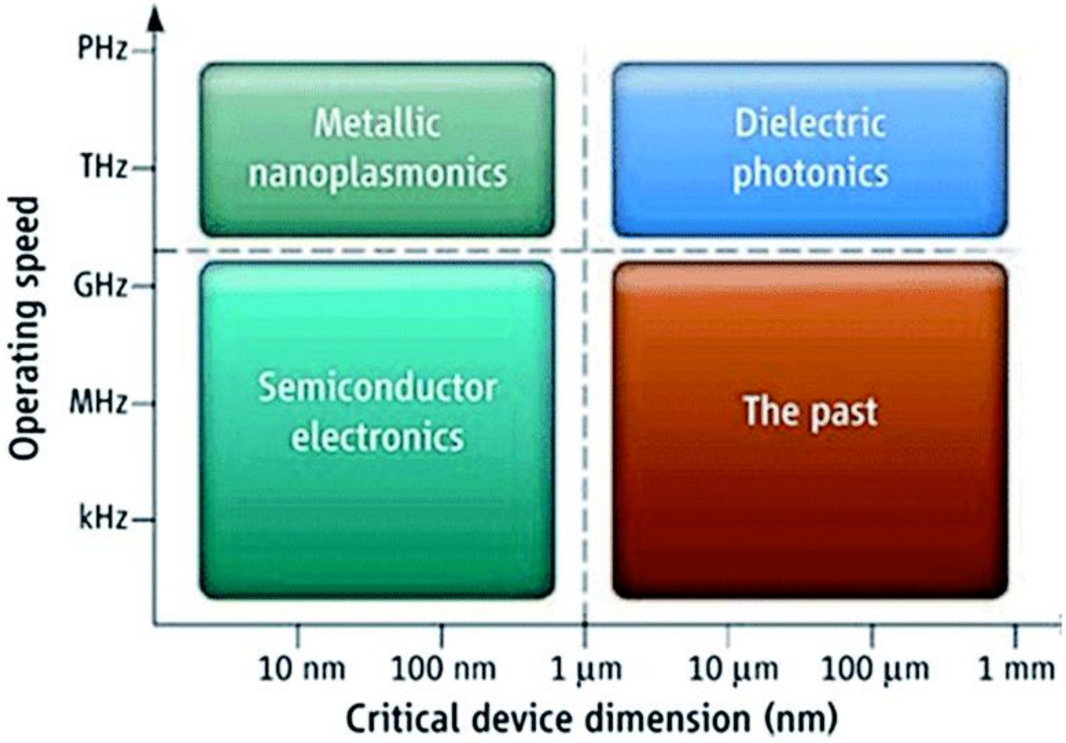
Nanoplasmonics





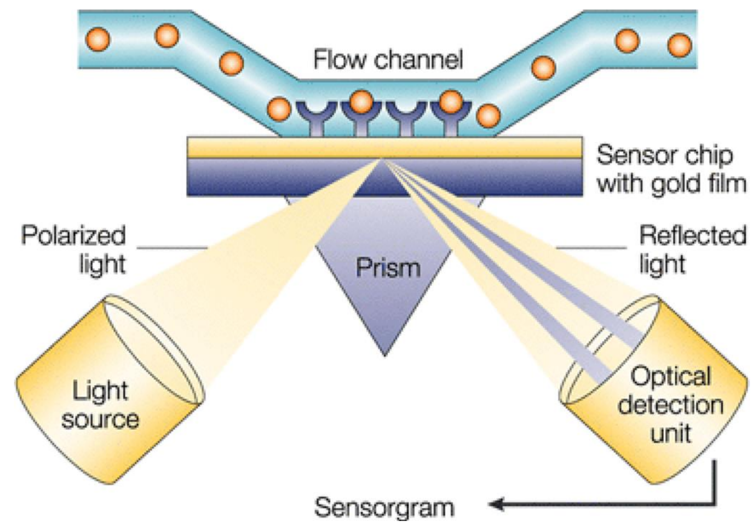






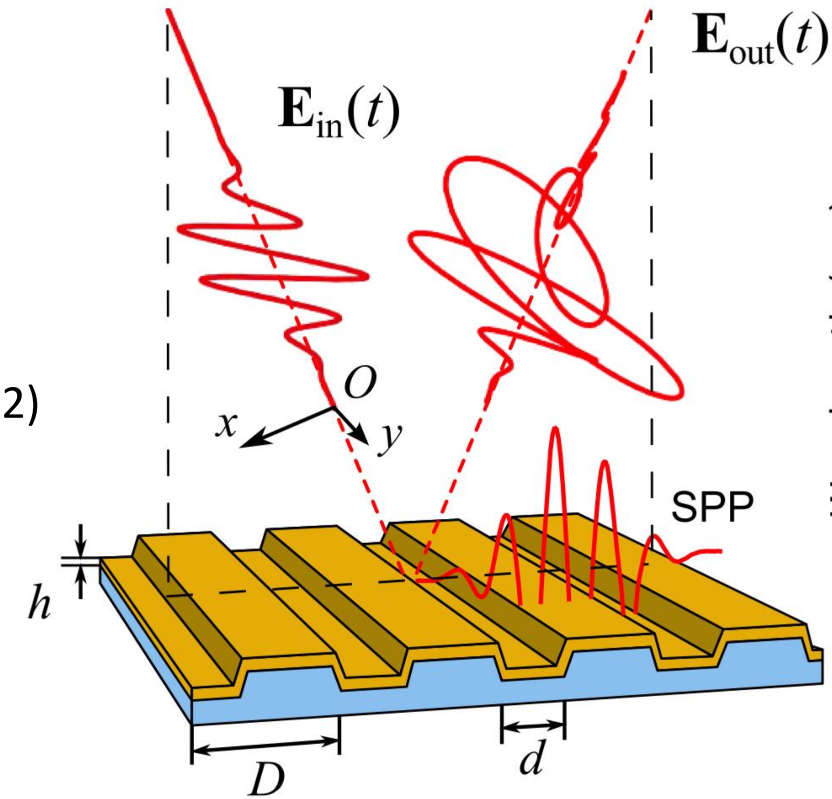
Nanoplasmonics timeline

- Romans, 4 A.D.: SPP in nanoparticle impregnated glasses
- Ritchie (1957): observation of SPP by electron beams
- Kretschmann, Raether, Otto (1968): optical excitation of SPP
- Surface plasmon sensing (review Homola et al. Sensors Actuat. B, 1999)
- Plasmonic crystals (Barnes, 2000)
- Nanoplasmonics proto-devices and metamaterials (21st century) (Ebbesen, Pendry, Shalaev, Bozhevolnyi, Zheludev, Gabitov, Atwater, Brongersma, Tsai, Zhang, Litchinitser …)

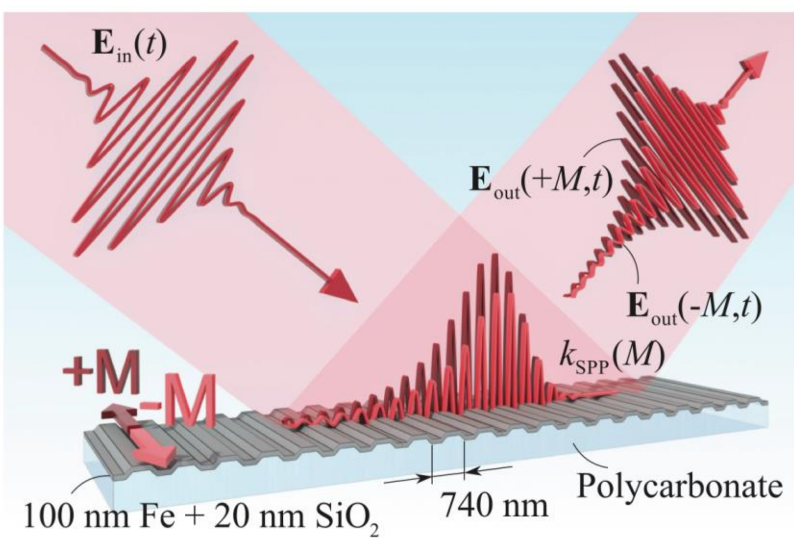


Nanoplasmonics in MSU

Plasmonic nanostructures as polarizers and wave plates:
Shcherbakov et al., *Phys. Rev. B* **82,** 193402 (2010)
Shcherbakov et al., *JETP Lett.* **90**, 433–437 (2009)



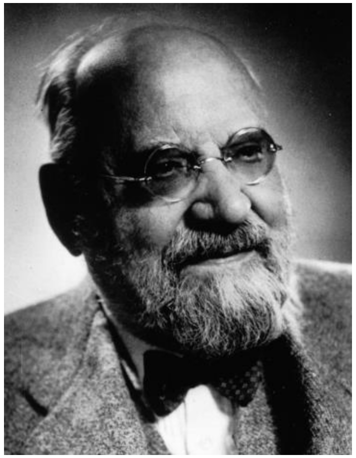
Femtosecond pulse shaping with plasmonic nanostructures:
Shcherbakov et al., *Phys. Rev. Lett.* **108**, 253903 (2012)
Vabishchevich et al., *JETP Lett.* **92**, 575–579 (2010)



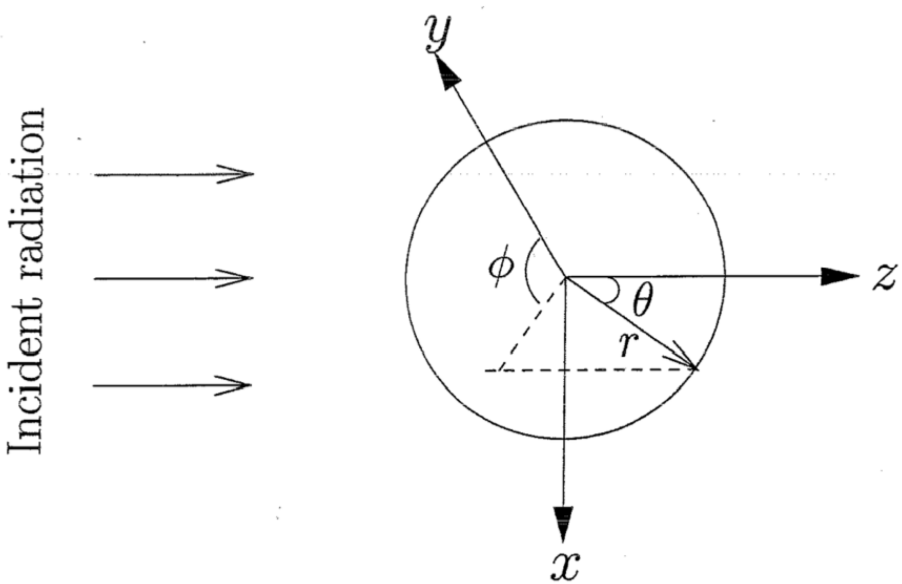
Near-field plasmonics:
Shcherbakov et al., *Physica C* **479**, 183–185 (2012)
Tsema et al., *Opt. Express* **20**, 10538 (2012)
Shcherbakov et al., *JETP Letters* **93**, 720–724 (2011)

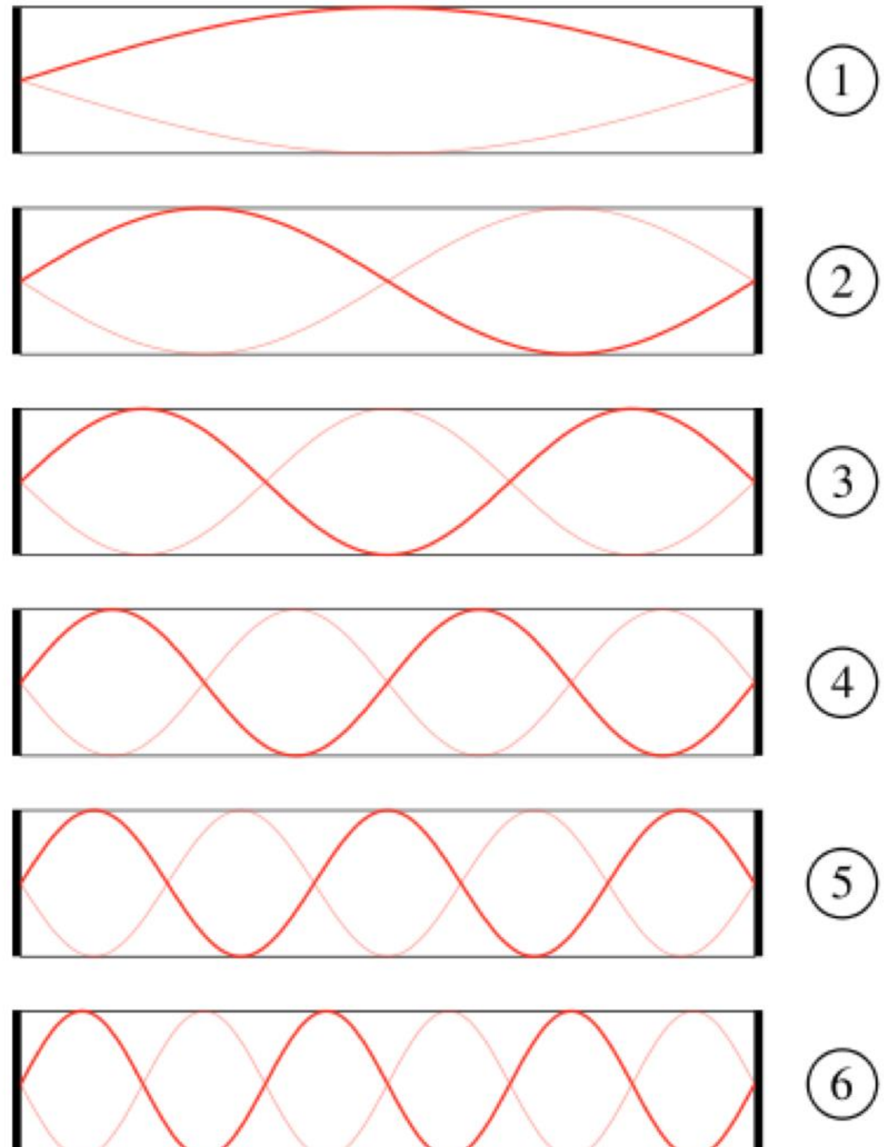
All-dielectric nanophotonics

Mie-type resonances in high-index nanoparticles

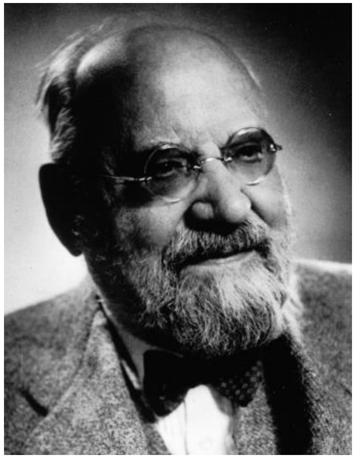


Gustav Mie (1869 – 1957)

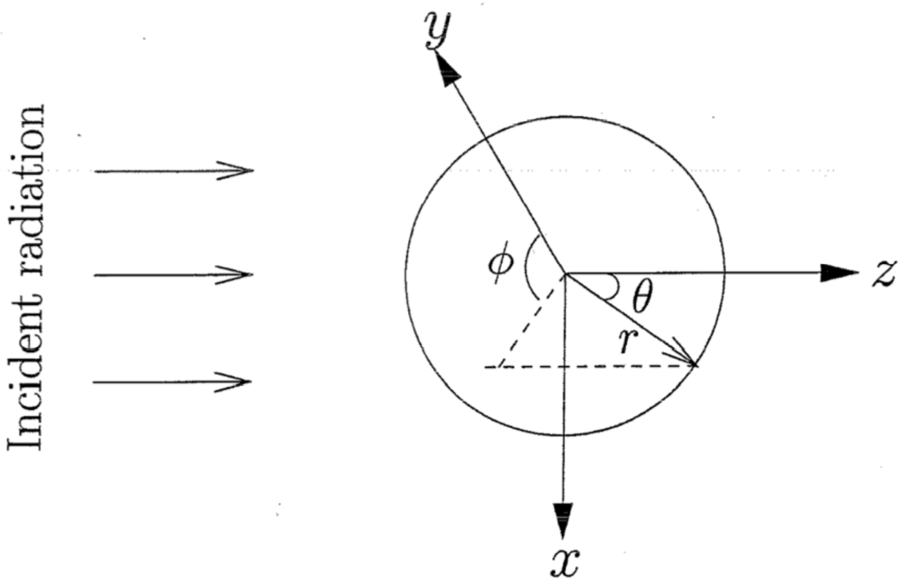




Mie-type resonances in high-index nanoparticles

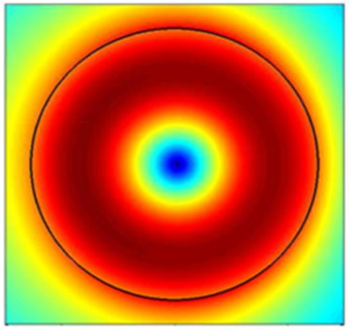


Gustav Mie (1869 – 1957)

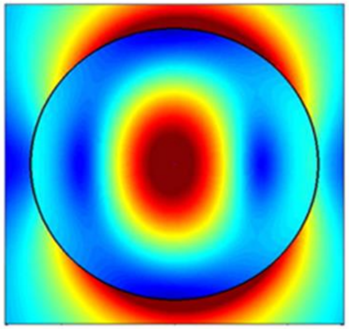


$|E|^2$ maps

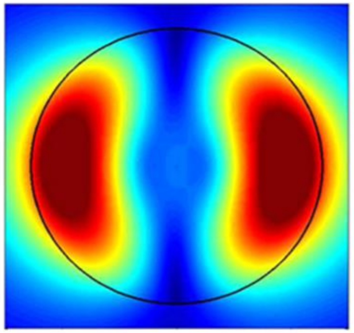
(1) Magnetic dipolar



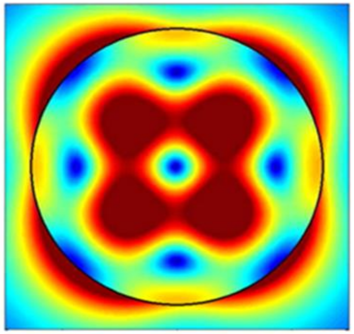
(2) Electric dipolar



(3) Magnetic quadrupolar

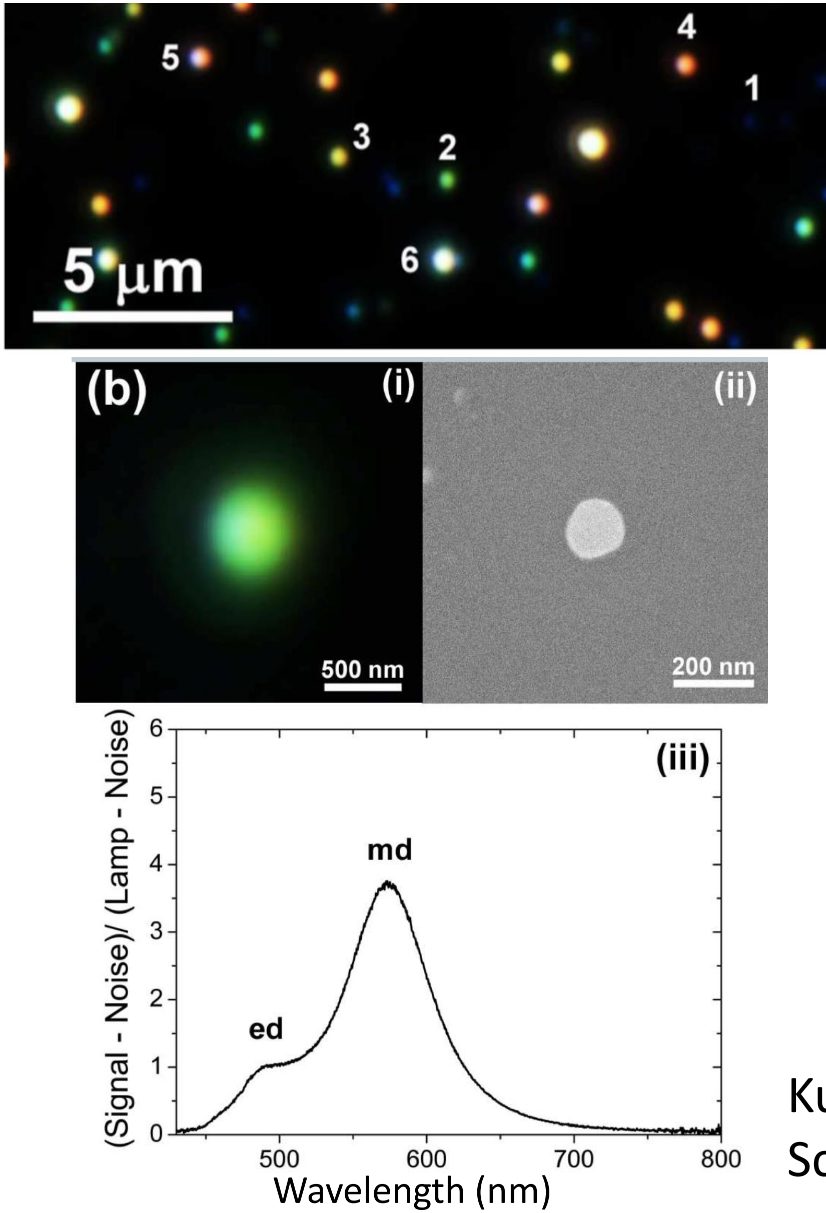


(4) Electric quadrupolar

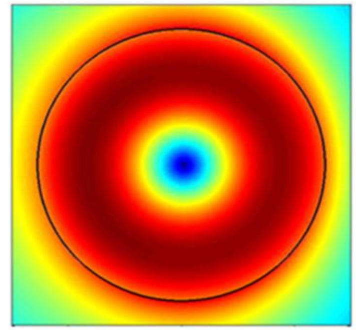


$n \gtrsim 2$ needed

Mie-type resonances in high-index nanoparticles

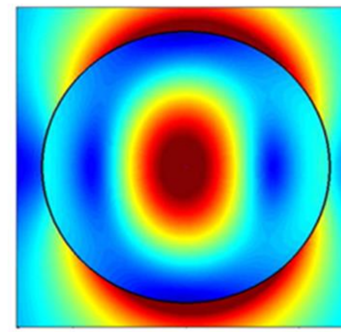


(1) Magnetic dipolar

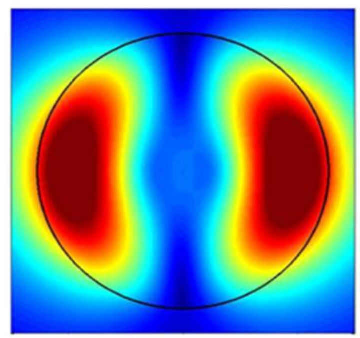


$|E|^2$ maps

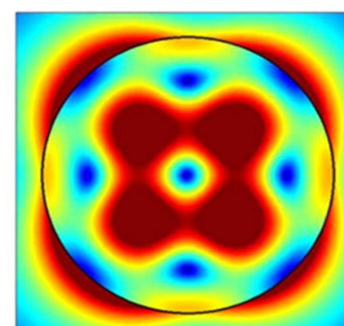
(2) Electric dipolar



(3) Magnetic quadrupolar

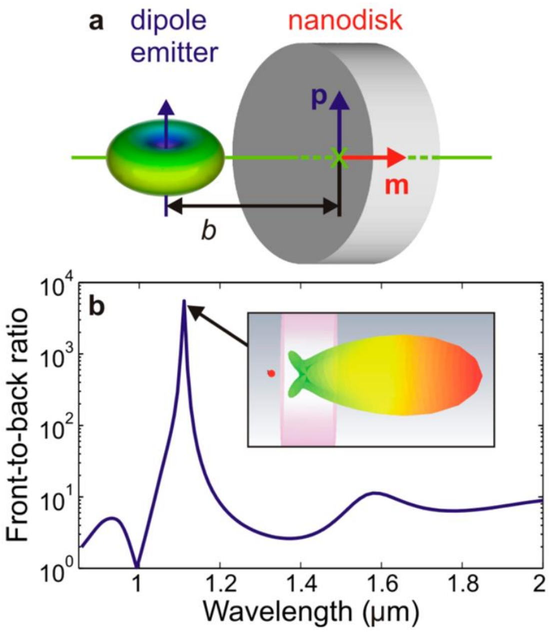


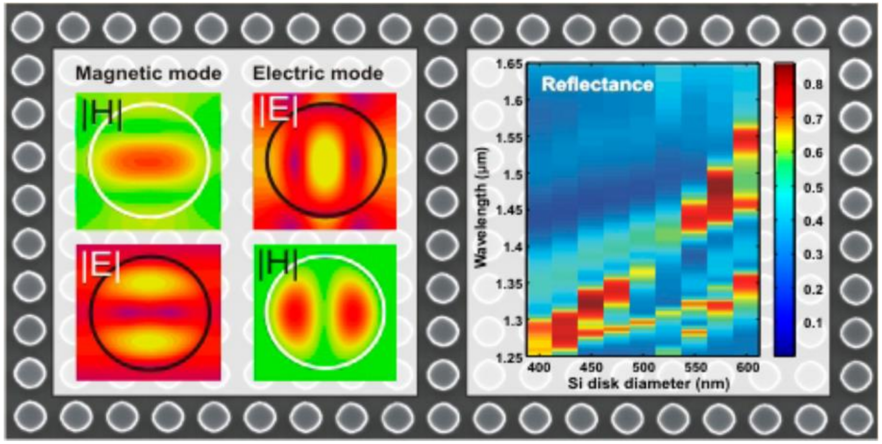
(4) Electric quadrupolar



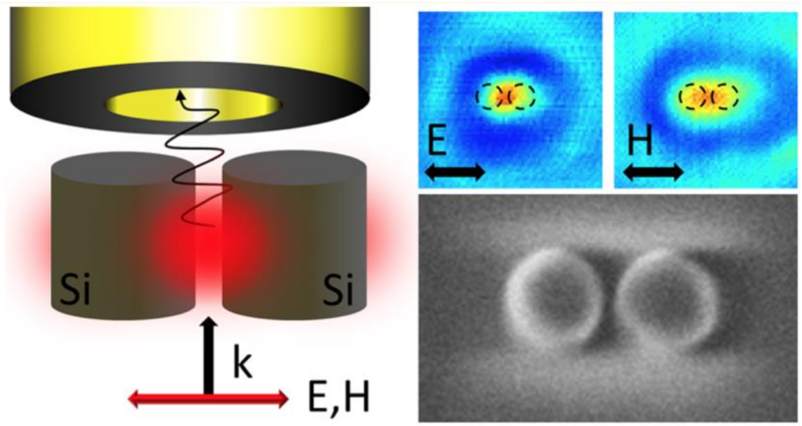
Kuznetsov et al.,
Sci. Rep. **2**, 492 (2012)

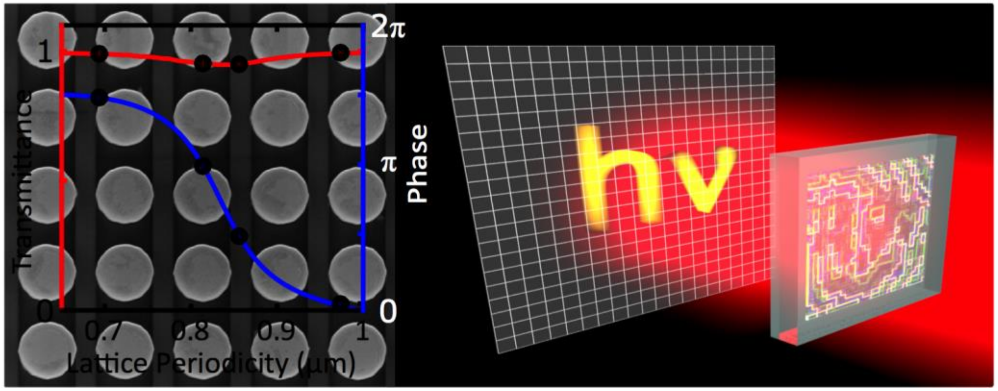
Mie-type resonances in high-index nanoparticles





Staude et al., ACS Nano 7, 7824–7832 (2013)

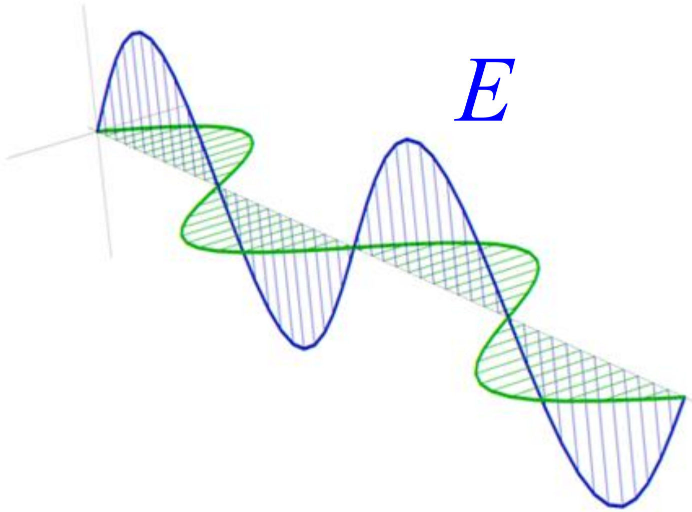


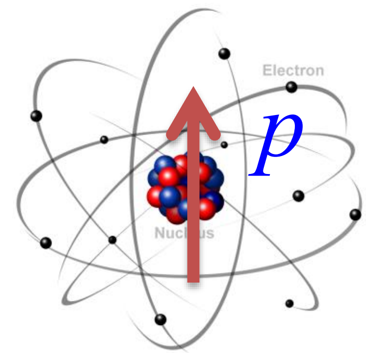


Bakker et al., Nano Letters 15, 2137−2142 (2015)

Chong et al., ACS Photonics (accepted, 2016)

Nonlinear
all-dielectric nanophotonics





Polarization (CGS):

$$\tilde{P} = \chi^{(1)}\tilde{E}(t) + \chi^{(2)}\tilde{E}^2(t) + \chi^{(3)}\tilde{E}^3(t) + \ldots$$

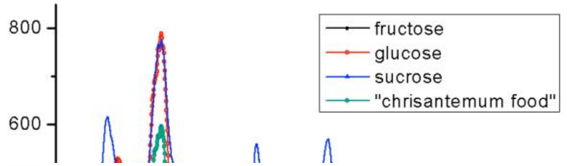
for $E \sim E_{atomic}$

Boyd "Nonlinear Optics," 2nd ed., p. 565

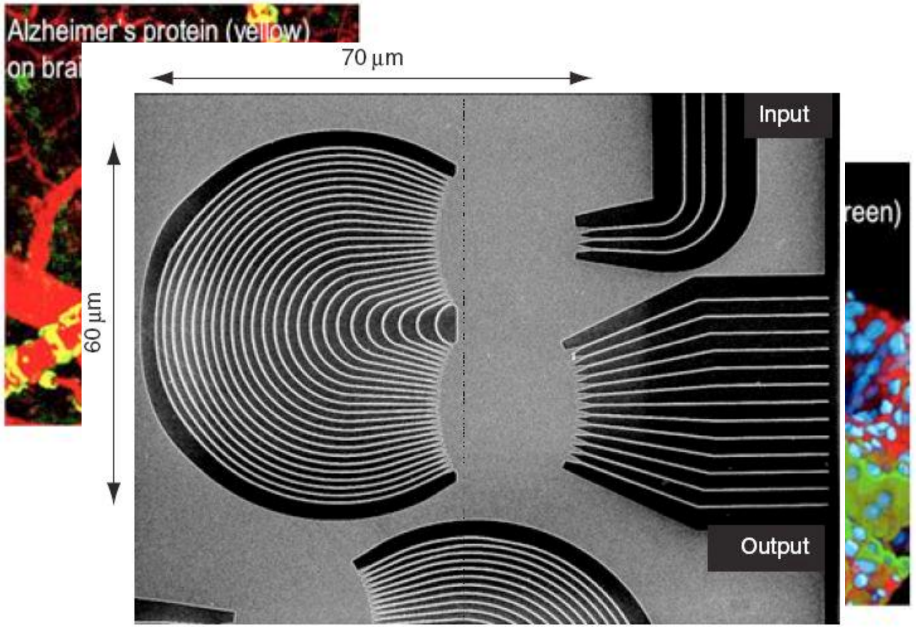
Nonlinear Optics

$$\tilde{P} = \chi^{(1)}\tilde{E}(t) + \chi^{(2)}\tilde{E}^2(t) + \chi^{(3)}\tilde{E}^3(t) + \dots$$

If $\tilde{E}(t) \propto e^{i\omega t}$ $\quad \propto e^{2i\omega t}$



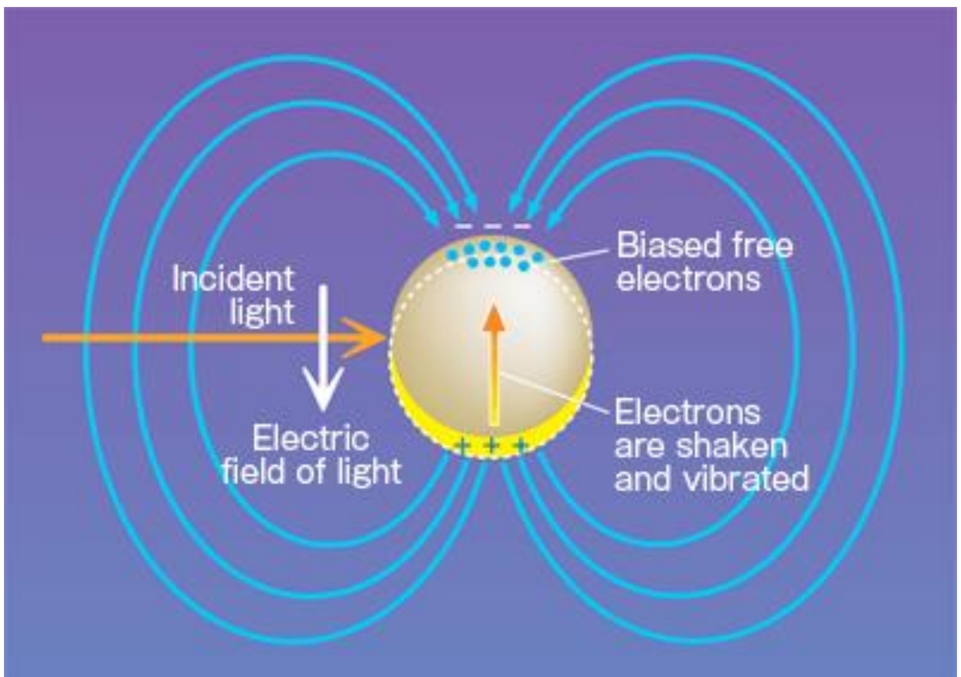
- Tunable laser sources
- Chem analysis
- Multiphoton microscopy
- All-optical telecom
- etc…

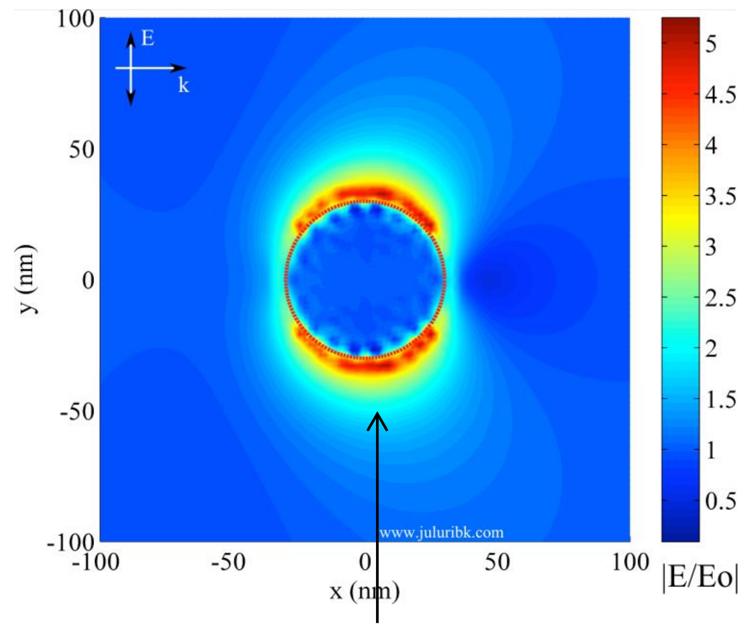


Plasmon-Enhanced Nonlinear Optics

$$\tilde{P} = \chi^{(1)}\tilde{E}(t) + \chi^{(2)}\tilde{E}^2(t) + \chi^{(3)}\tilde{E}^3(t) + \ldots$$

$$\text{If } \tilde{E}(t) \propto e^{i\omega t} \qquad \propto e^{2i\omega t} \qquad \propto e^{3i\omega t}$$





local-field enhancement

= enhanced N.O.

http://juluribk.com/2010/05/26/ddscat-and-electric-field-at-plasmon-resonance/

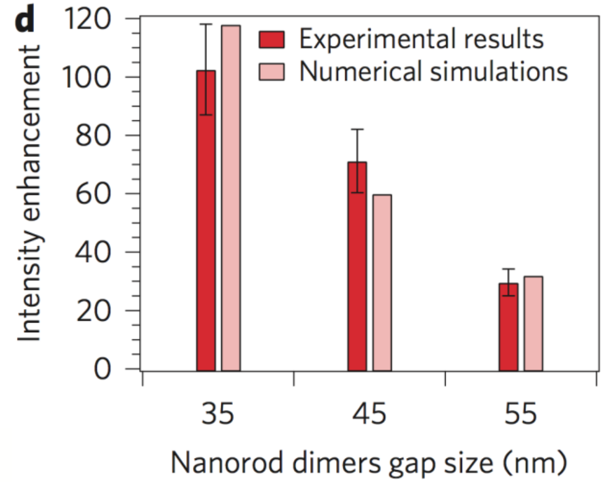
http://www.hamamatsu.com/eu/en/technology/innovation/nanophotonics/index.html

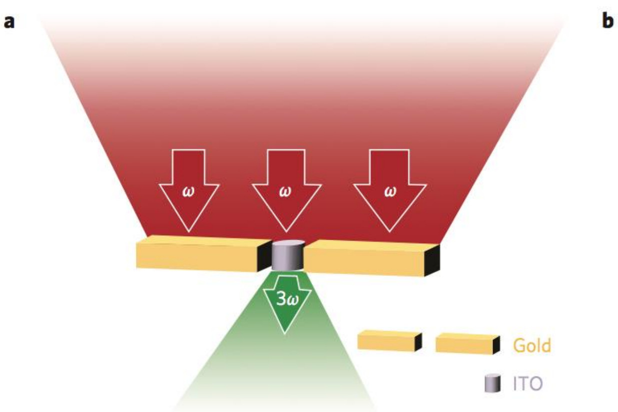
Plasmon-Enhanced Optical Harmonic Generation

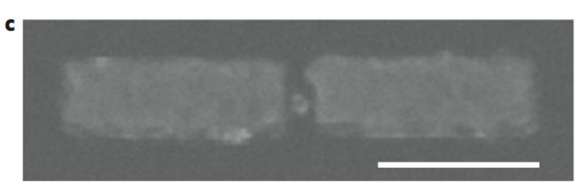
nature nanotechnology | LETTERS
PUBLISHED ONLINE: 9 MARCH 2014 | DOI: 10.1038/NNANO.2014.27

Third-harmonic-upconversion enhancement from a single semiconductor nanoparticle coupled to a plasmonic antenna

Heykel Aouani[1†*], Mohsen Rahmani[1†], Miguel Navarro-Cía[2] and Stefan A. Maier[1]



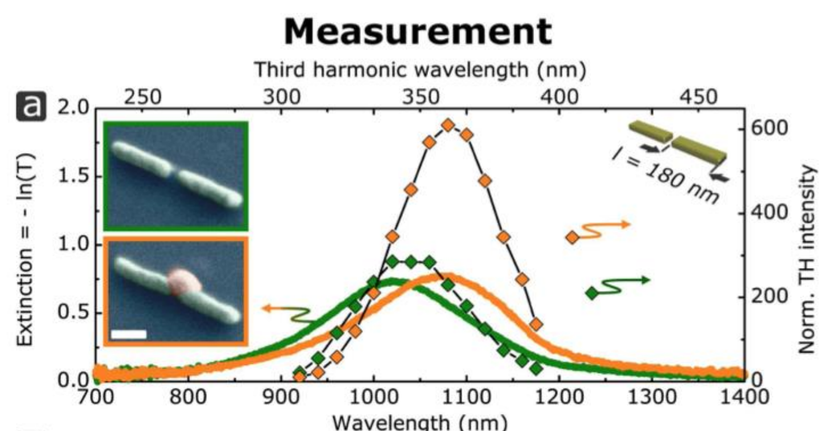




NANO LETTERS | Letter
pubs.acs.org/NanoLett

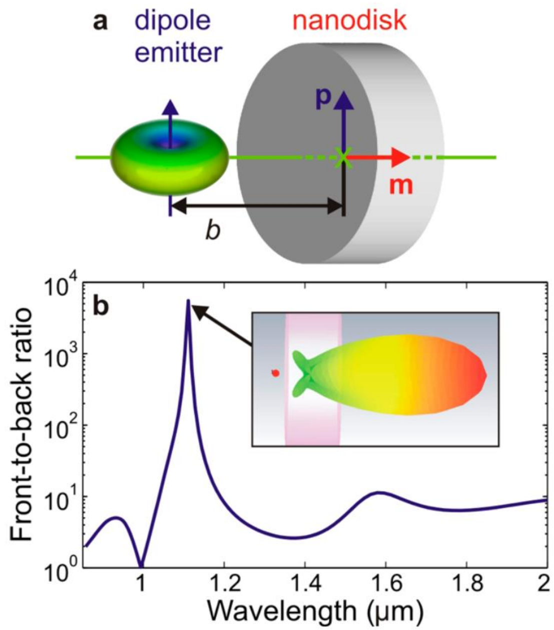
Doubling the Efficiency of Third Harmonic Generation by Positioning ITO Nanocrystals into the Hot-Spot of Plasmonic Gap-Antennas

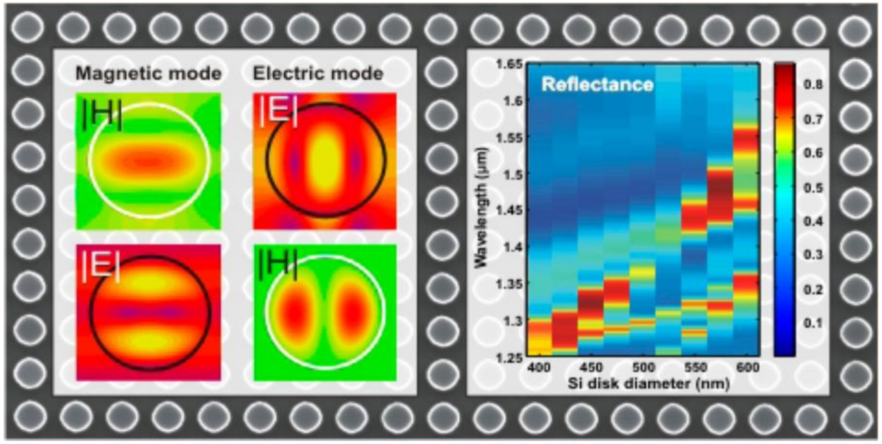
Bernd Metzger,[†] Mario Hentschel,[*,†,‡] Thorsten Schumacher,[†,‡,§] Markus Lippitz,[†,‡,§] Xingchen Ye,[∥] Christopher B. Murray,[∥,#] Bastian Knabe,[⊥,○] Karsten Buse,[⊥,○] and Harald Giessen[†]



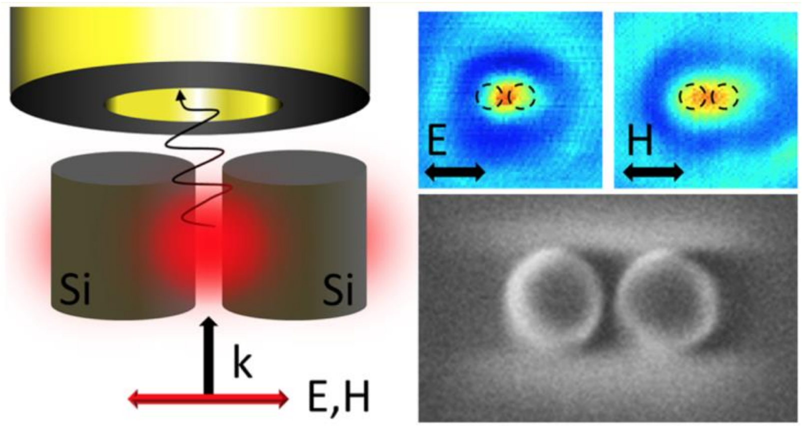
Maximum conversion ~10^{-7}

Mie-type resonances in high-index nanoparticles

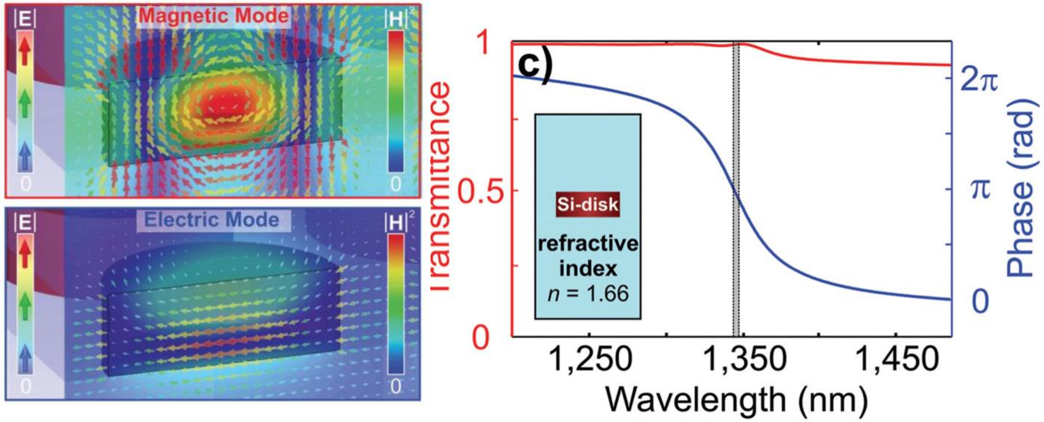




Staude et al., ACS Nano 7, 7824–7832 (2013)

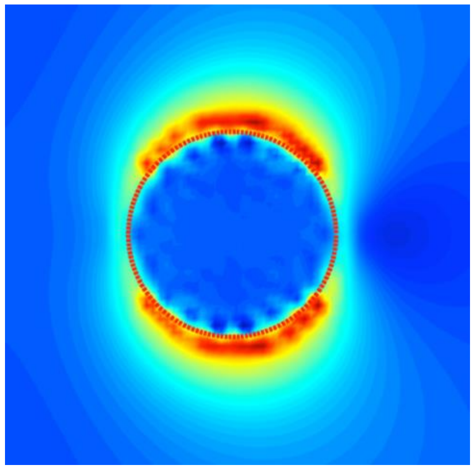


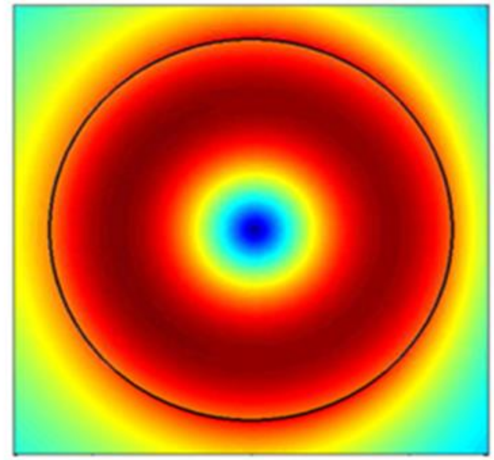
Bakker et al., Nano Letters 15, 2137−2142 (2015)



Decker et al., Adv. Opt. Mat. 3, 813–820 (2015)

Why high-*n* nanoparticles?





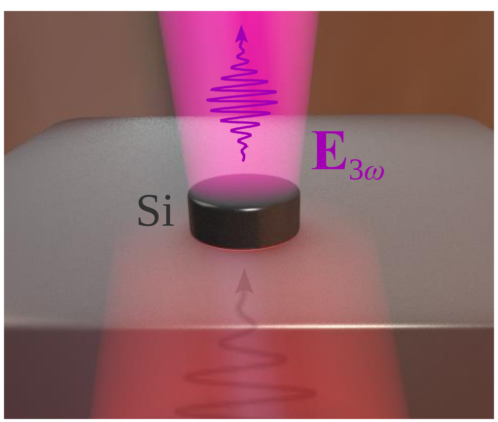
Noble metal vs. high-*n* dielectric

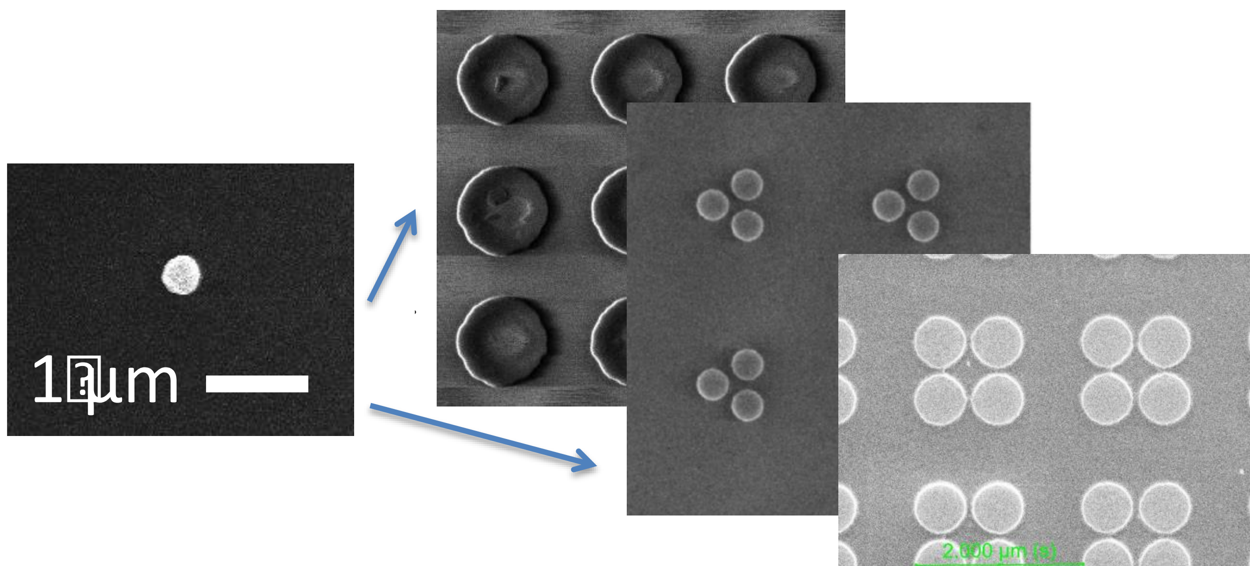
- Si: approx. same $\chi^{(3)}$ as gold
- Near-IR (inc. telecom) — no linear absorption
- The mode is mostly inside the NL medium

Nonlinear optics of Mie-resonant NPs

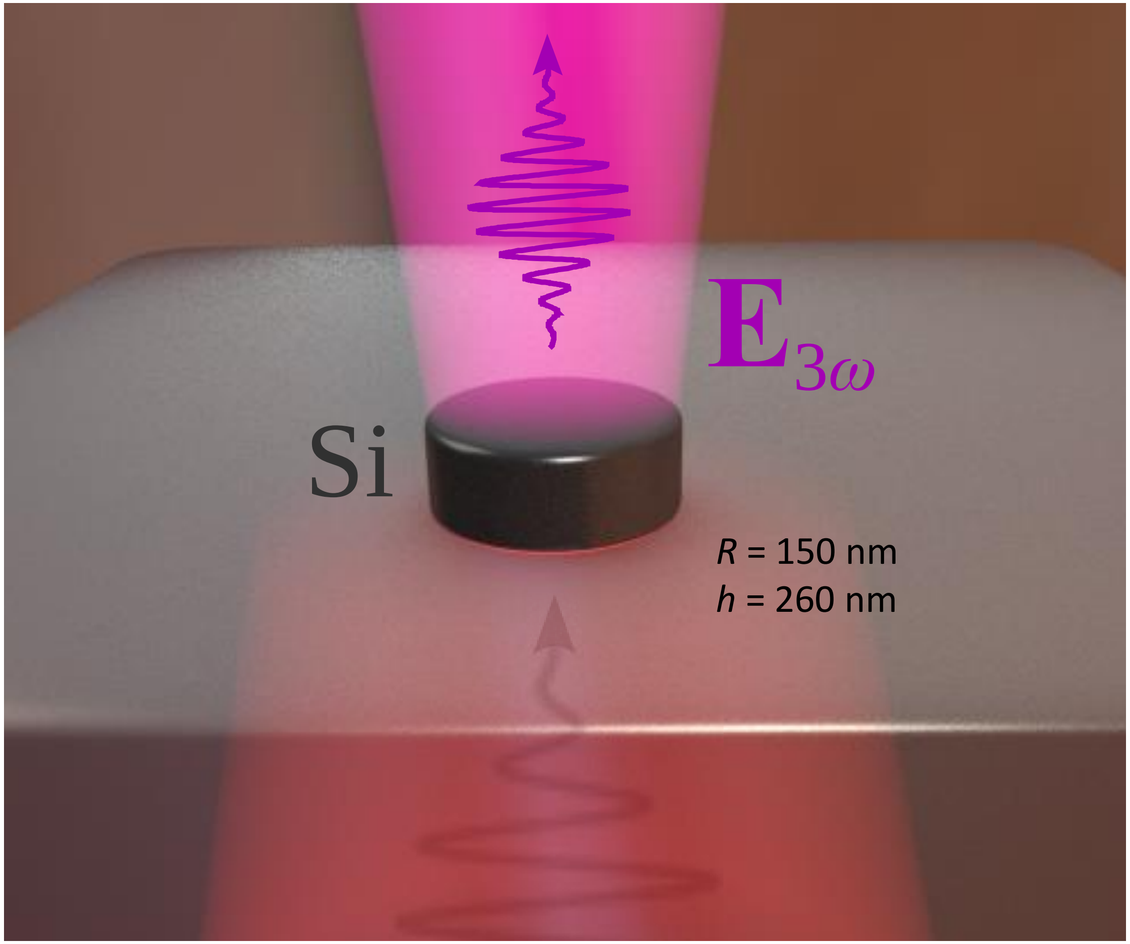
Goals:

- THG enhancement
- Magnetic vs. electric resonances
- THG in coupled nanoparticles: oligomers and metasurfaces

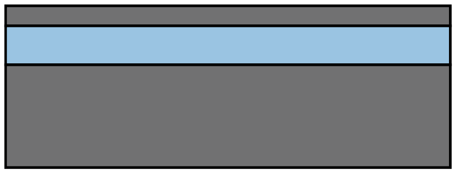




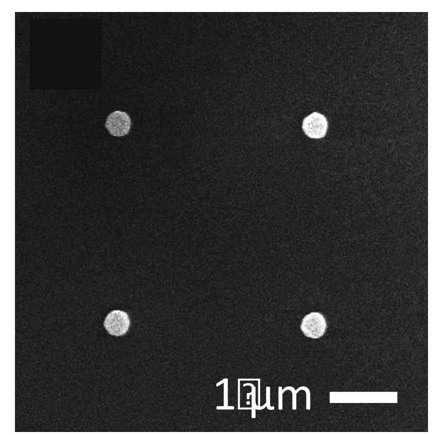
Nonlinear optics of silicon nanoparticles



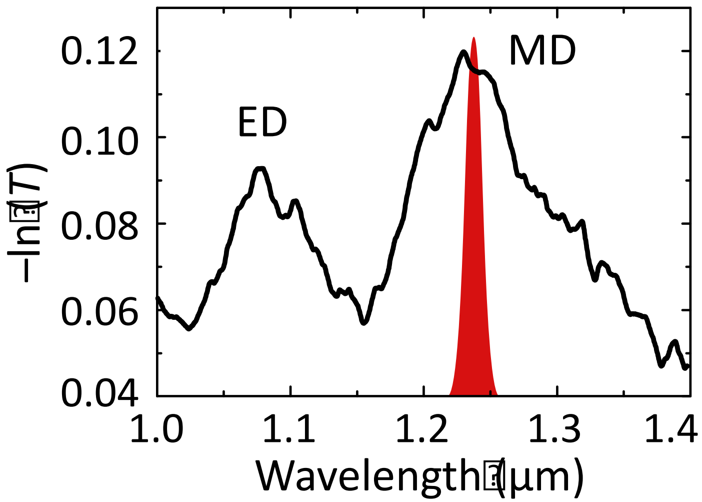
Si nanodisks: fabrication

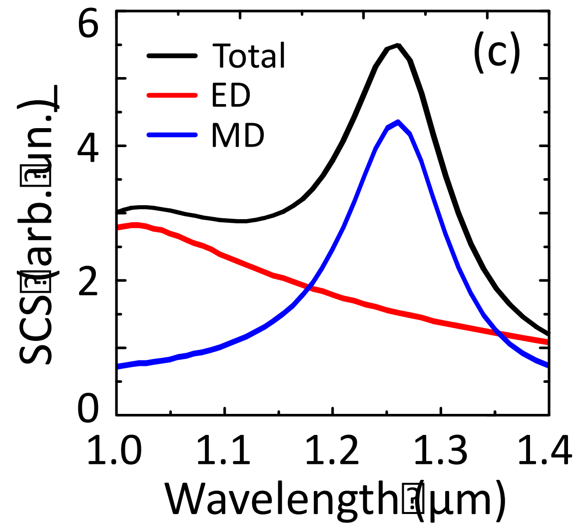


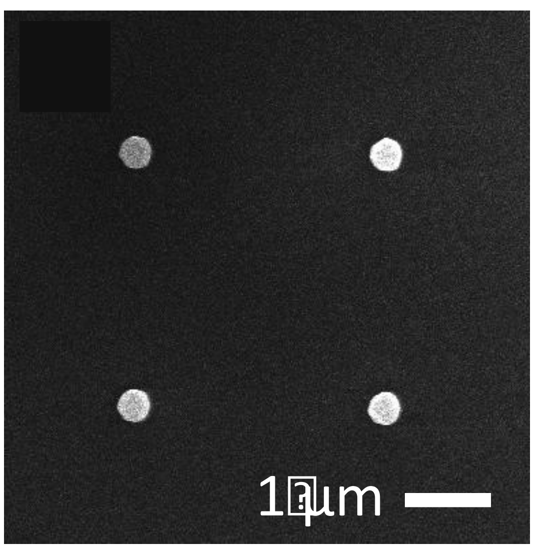
Silicon on insulator wafer

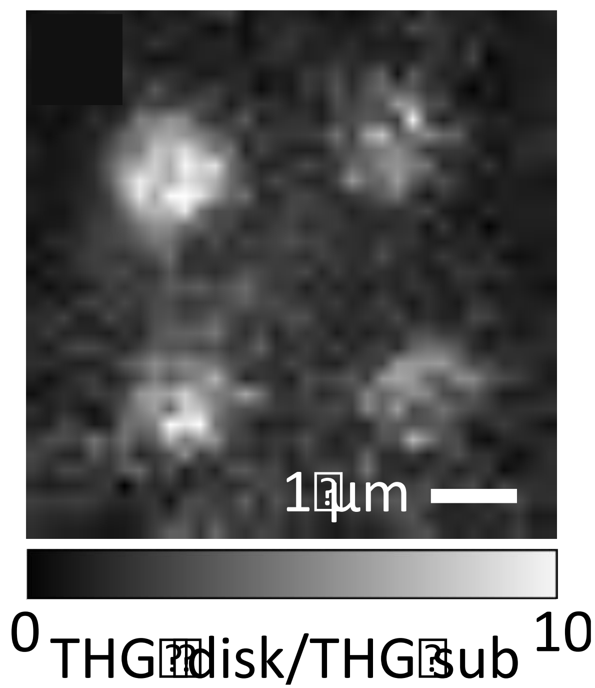


Third-harmonic generation microscopy





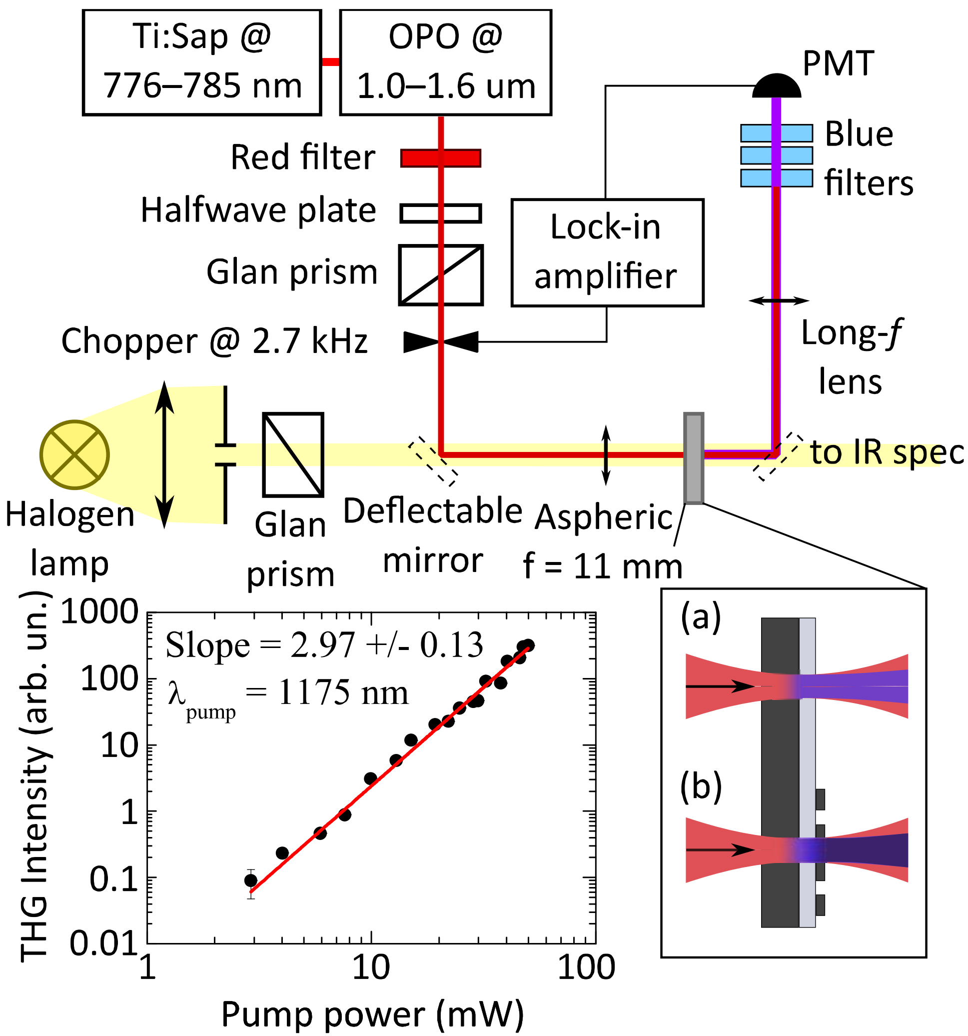




Olympus FluoView FV1000
+ Coherent Chameleon Ultra II
+ Coherent OPO
pump @ 1240 nm

Shcherbakov *et al.*,
Nano Lett. **14**, 6488–6492 (2014)

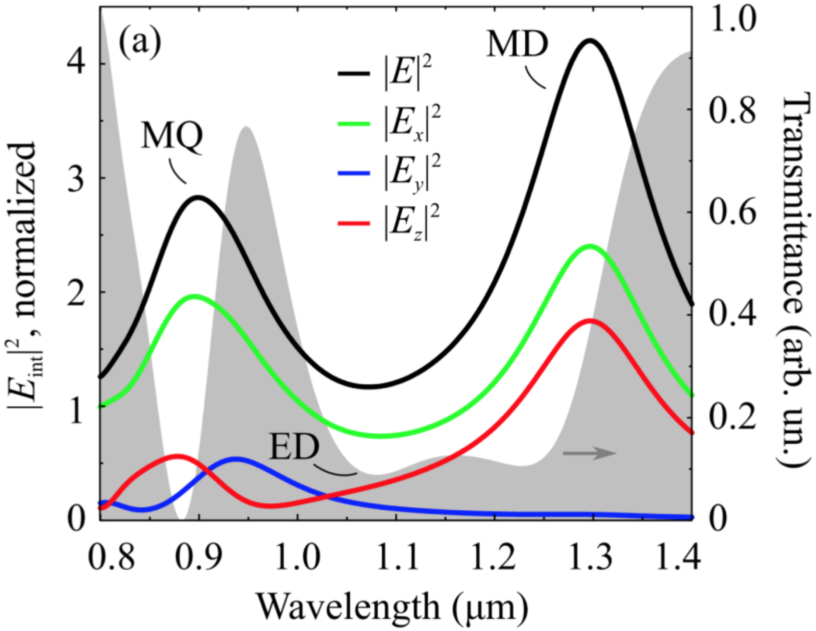
Third-harmonic generation spectroscopy

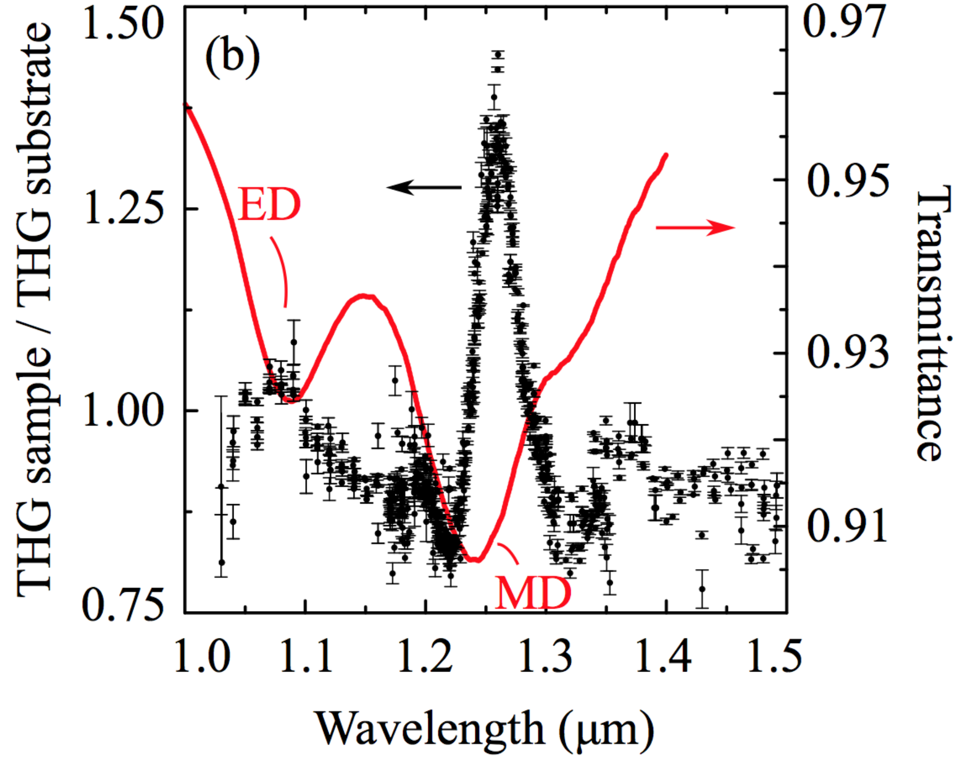


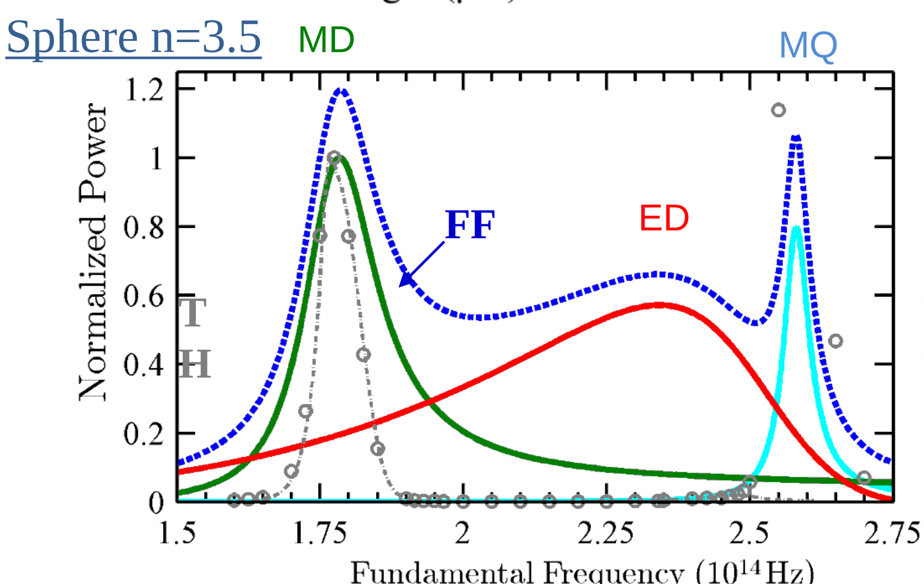
Experiment details

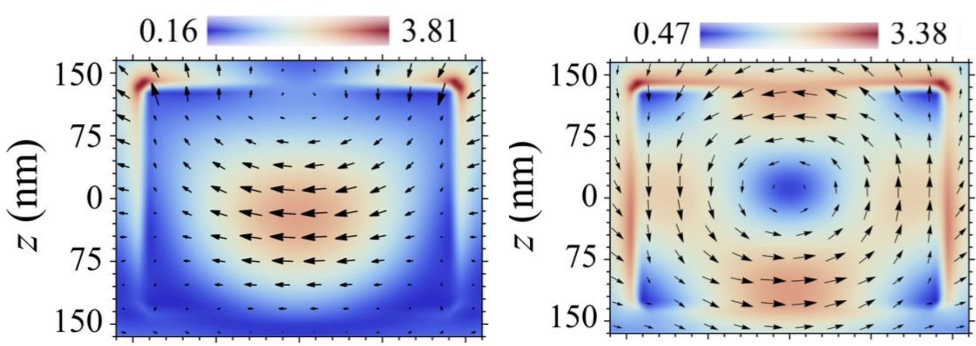
- ~10 GW/cm^2 max intensity
- 1.0–1.6 um pump tuning
- Normalization over THG from the Si substrate to remove $\chi^{(3)}$ dispersion
- Linear & nonlinear spectra acquired from the same spot

Electric and magnetic resonances: THG



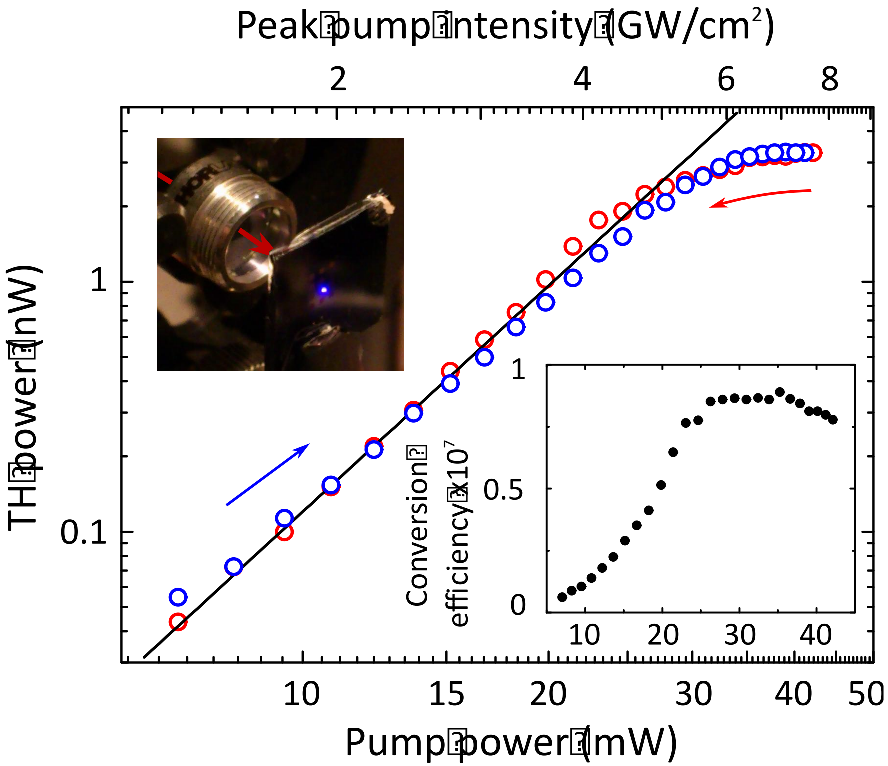


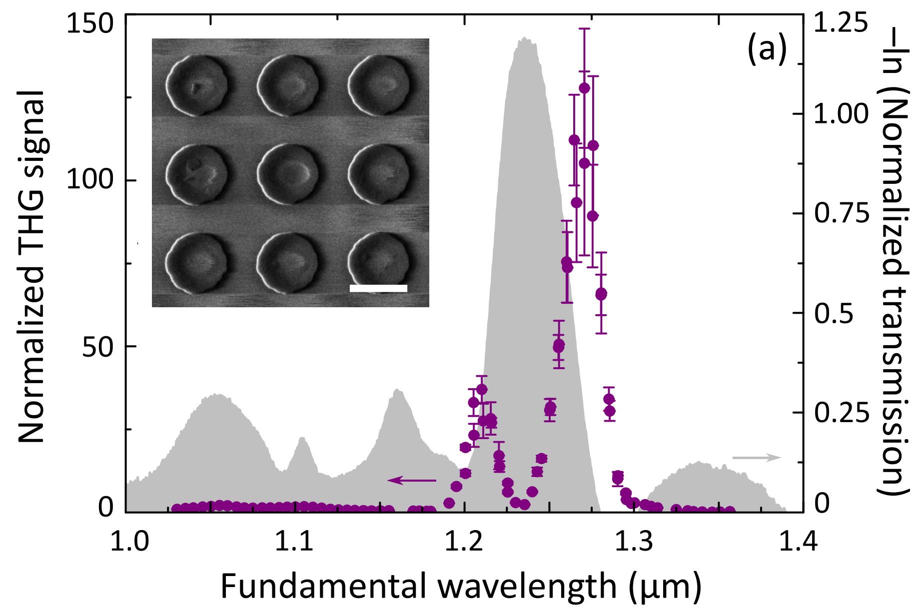




Melik-Gaykazyan et al. (submitted)

Higher TH yield by packing to form a metasurface

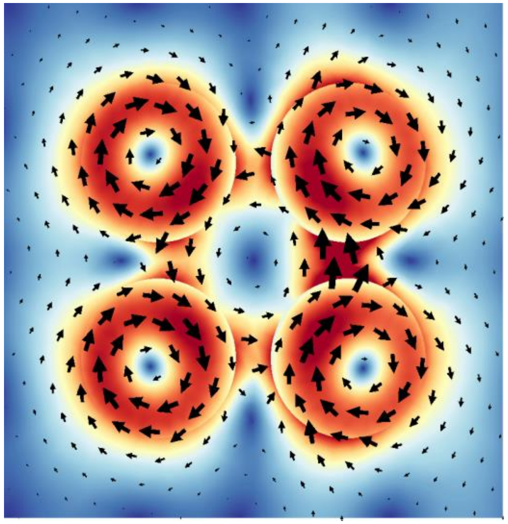


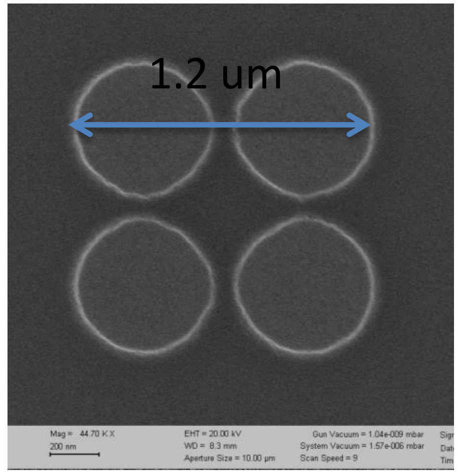


$$\tilde{P} = \chi^{(1)}\tilde{E}(t) + \chi^{(2)}\tilde{E}^2(t) + \chi^{(3)}\tilde{E}^3(t) + \ldots$$

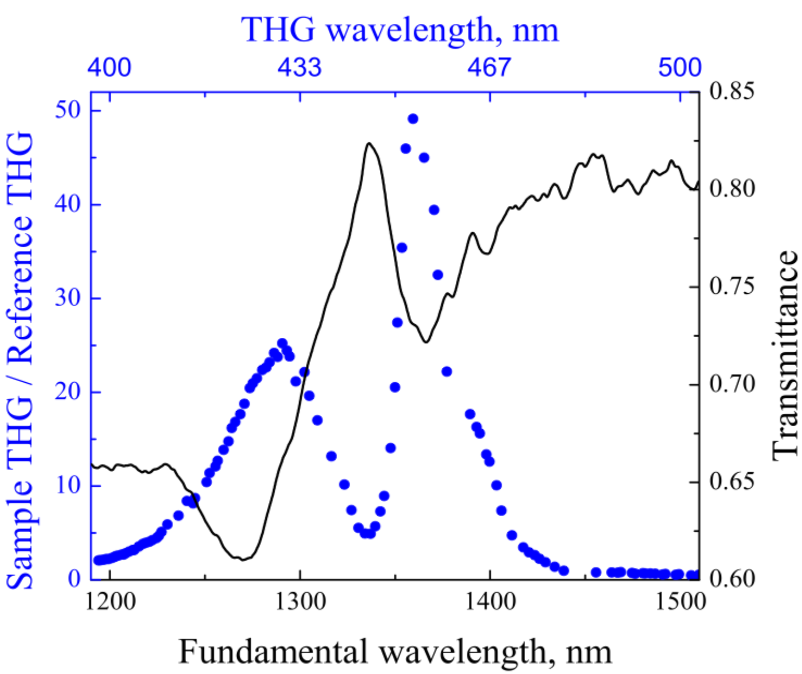
Shcherbakov *et al.*, Nano Lett. **14**, 6488–6492 (2014)

Tweaking the system a little





- Amorphous silicon
- Resonance spectrum = spectrum of the pulse
- No TH absorption

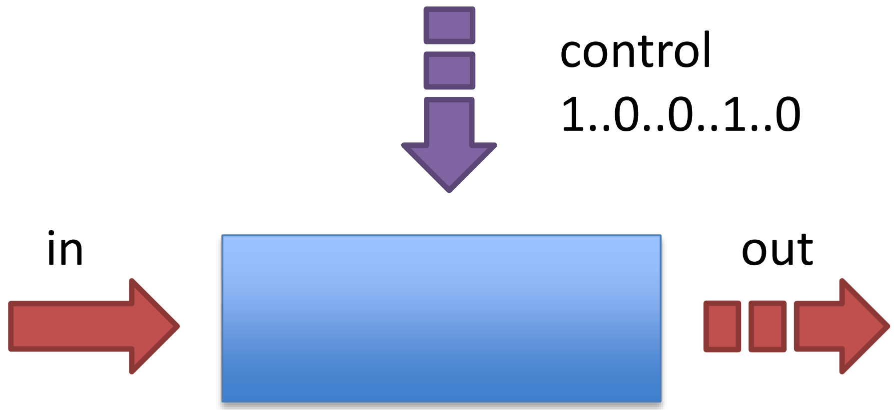


IR to blue conversion ~10^{-5}

Record set for a subwavelength object

Shorokhov et al. (submitted)

All-optical switching



incoherent approaches

— via solid-state excitations

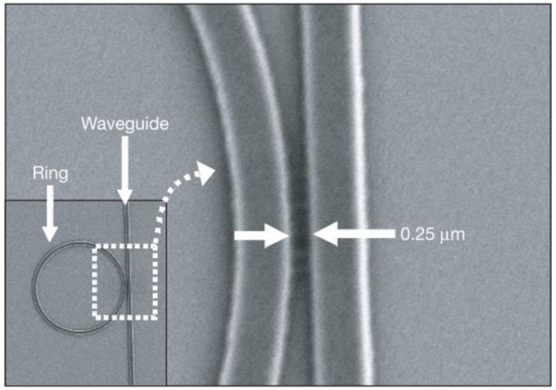
— relaxation time is a strong limiting factor

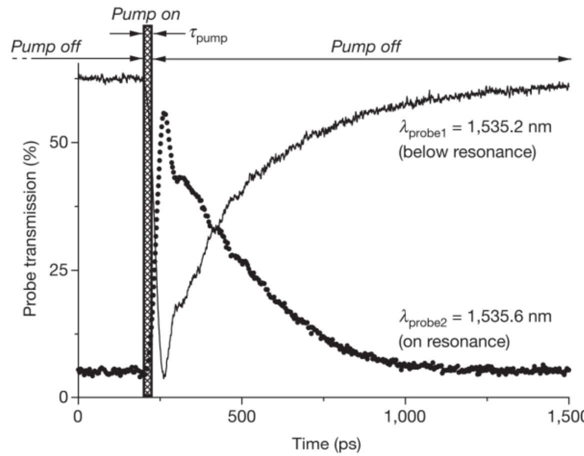
coherent approaches

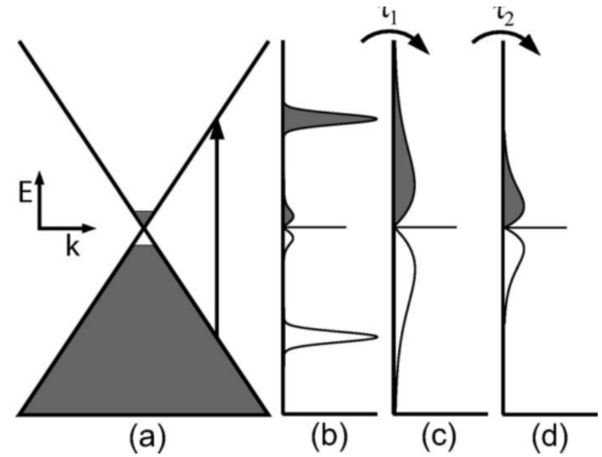
— via wave mixing or other multiphoton processes

— no relaxation time

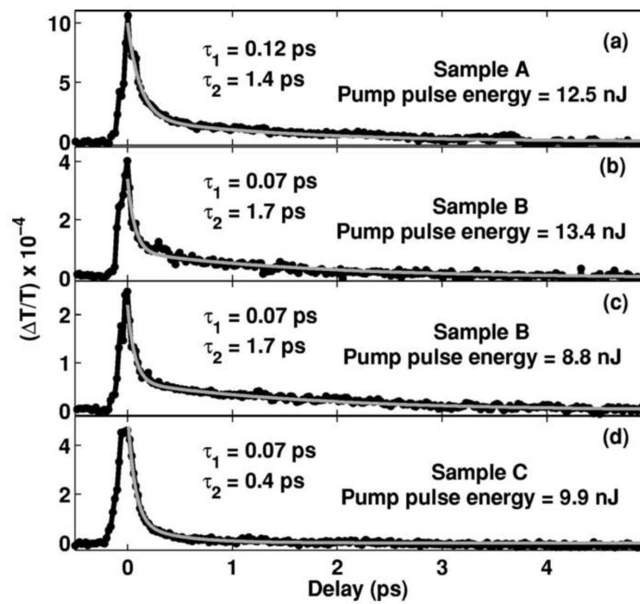
All-optical switching

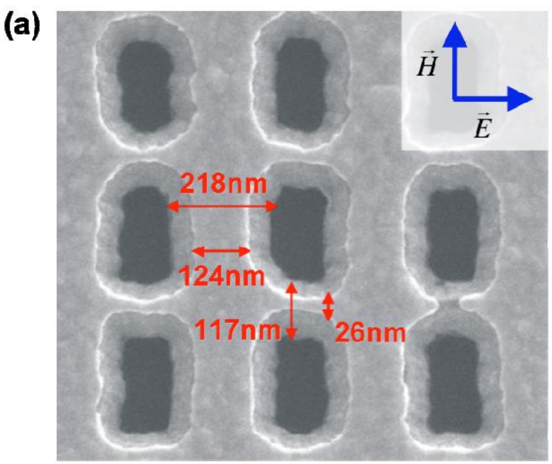


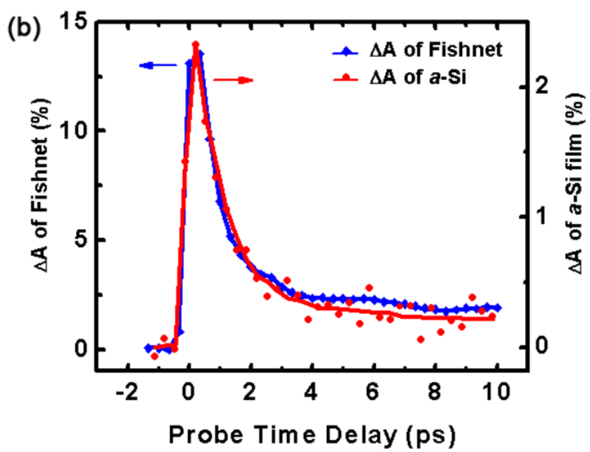




Almeida et al.,
Nature **431**, 1081-1084 (2004)





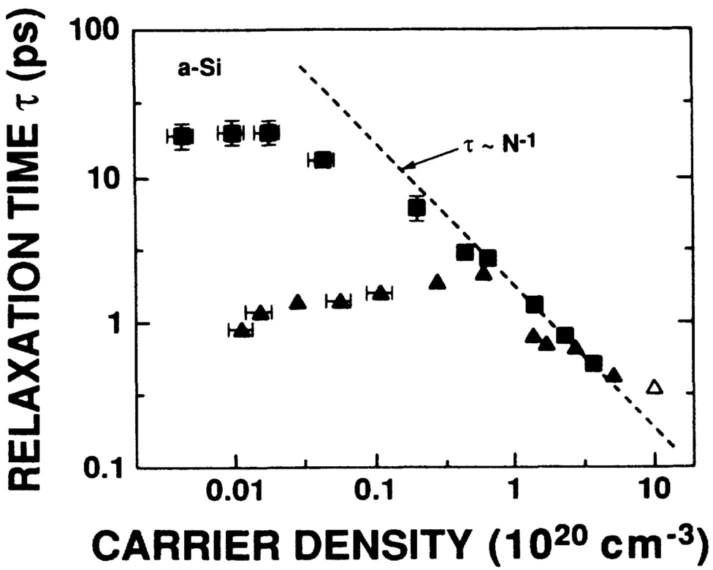


Cho et al., Opt. Express **17**, 17652 (2009)

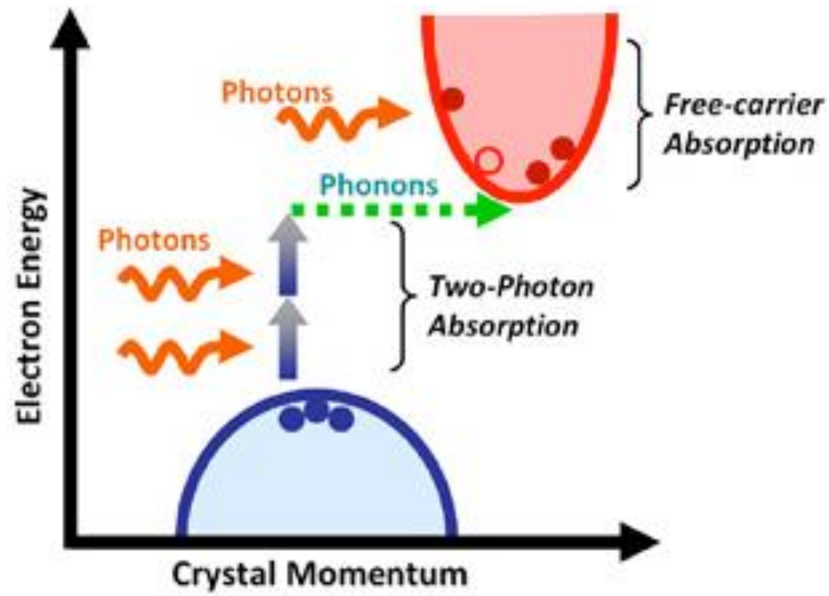
20k Google Scholar entries

Dawlaty et al.,
Appl. Phys. Lett. **92**, 042116 (2008)

Problems & a quest for instantaneous processes



- Cavity build-up time
  –> low-Q regime
- Two-photon absorption is OK
  but free carriers are the bottleneck



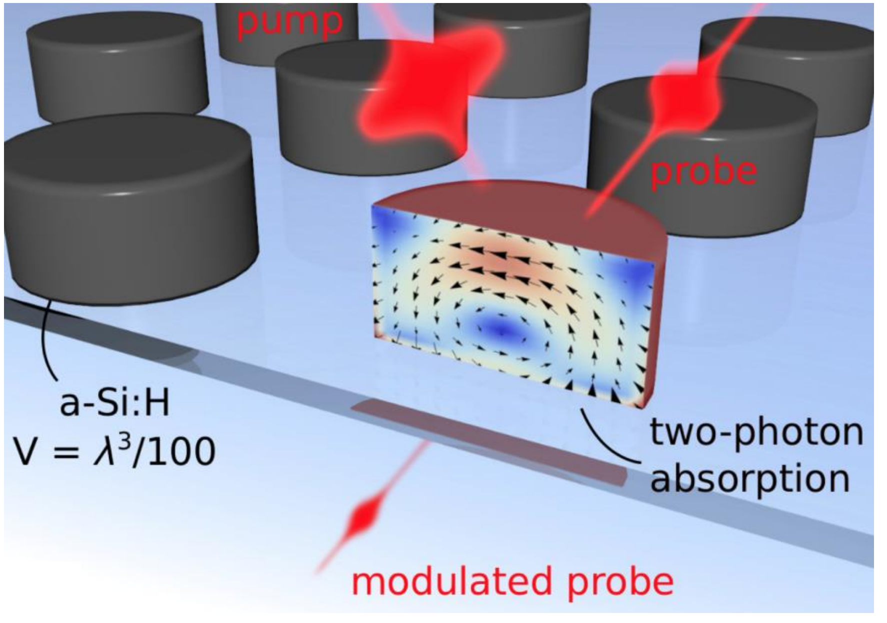
TPA all-optical switching:
Ren et al., Adv. Mater. **23**, 5540 (2011)
Liang et al. Opt. Express **13**, 7298 (2005)
Liang et al. Opt. Commun. **265**, 171 (2006)
Thomsen et al. Electron. Lett. **34**, 1871 (1998)
Hendrickson et al., Phys. Rev. A **87**, 023808 (2013)
…

Goals

- Two-photon absorption enhancement observation in Mie-resonant Si metasurfaces
- Femtosecond pump-probe measurements

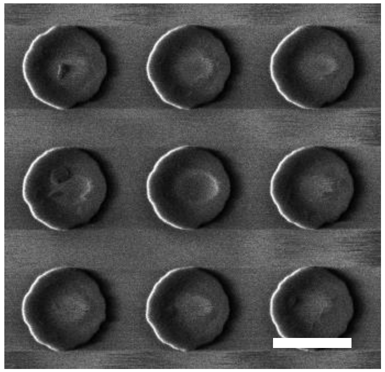
Why the magnetic Mie?

- Sufficient Q
- CMOS
- Confined mode



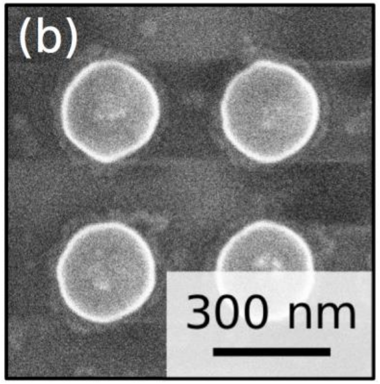
What form of silicon?

SOI c-Si –> e-beam –> plasma



I. Brener's group, Sandia

PECVD a-Si:H –> e-beam –> plasma



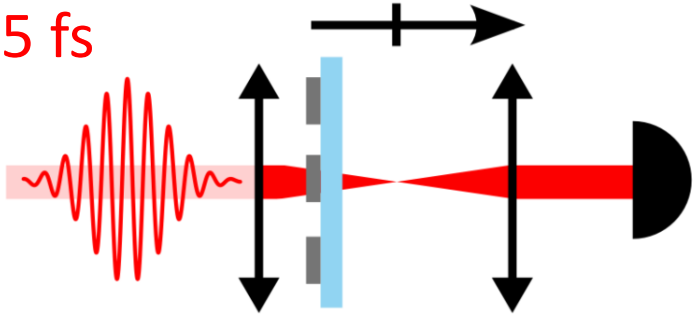
ANU group, Canberra

Nonlinear absorption: Im $\chi^{(3)}(\omega = \omega + \omega - \omega)$

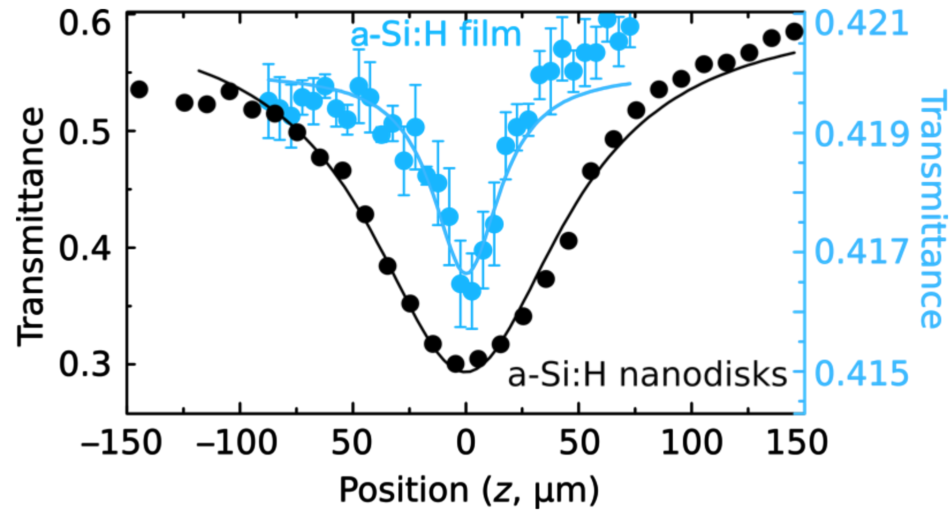
775 nm

45 fs

z-scan

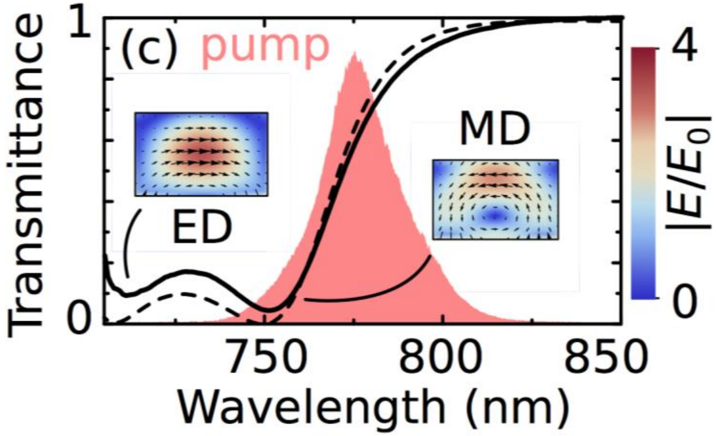


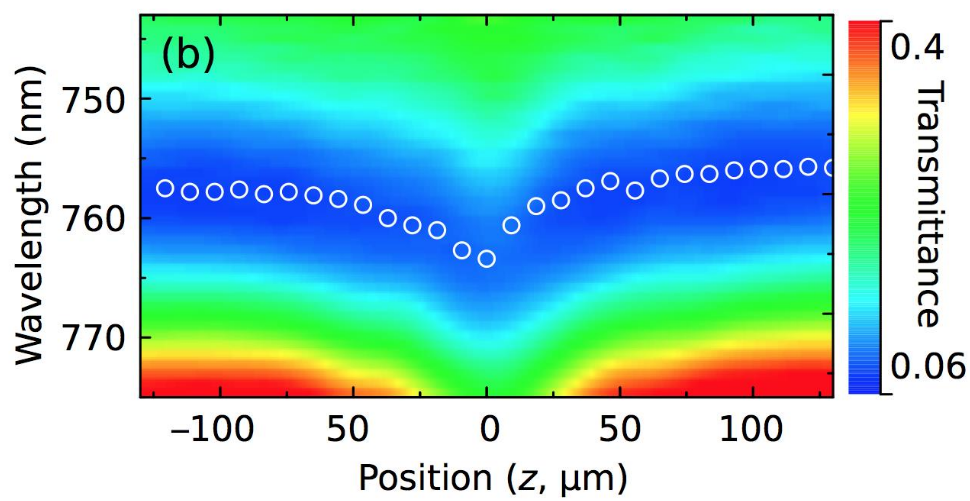
$$T(z) = 1 - \frac{1}{2\sqrt{2}} \frac{\beta_{sam} I L}{1 + \left(\frac{z}{z_0}\right)^2}$$



β_{film} = 0.07 cm/kW

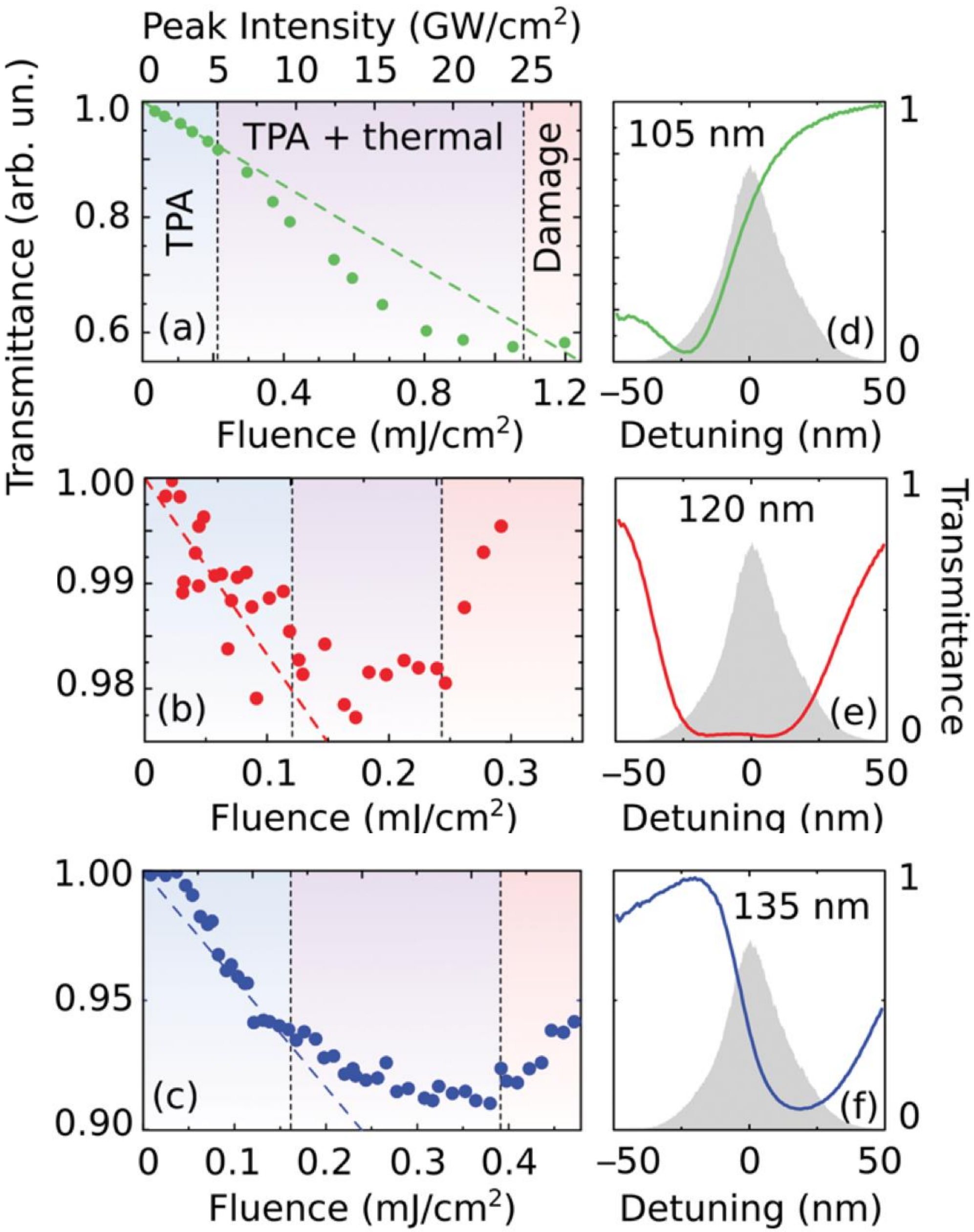
β_{sam} = 5.6 cm/kW (film x80)





<1 pJ per disk

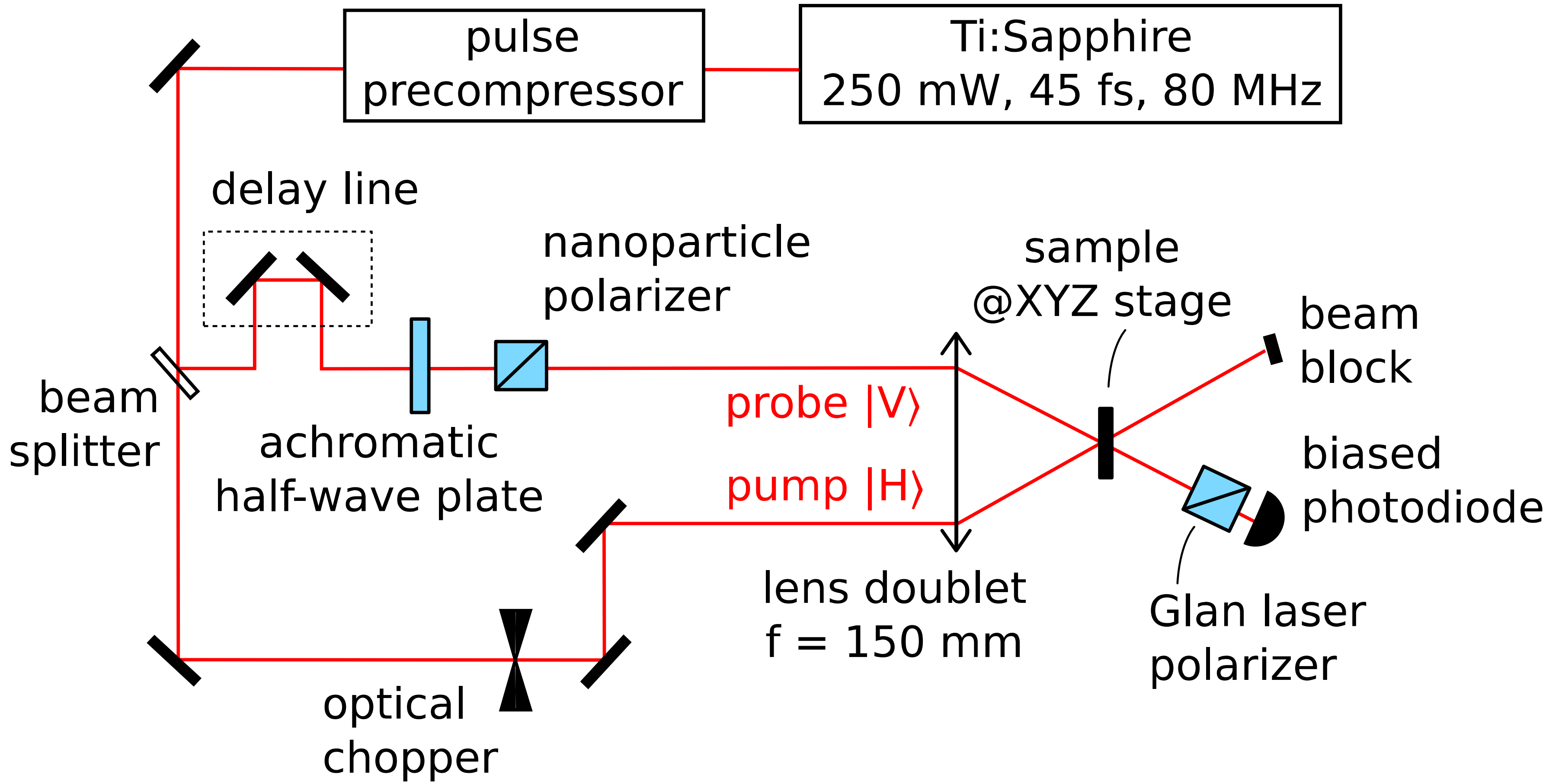
Further self-action



- $\mathrm{Re}[\chi^{(3)}] << \mathrm{Im}[\chi^{(3)}]$
- Don’t hit the resonance
- Damage fluences leave some room above

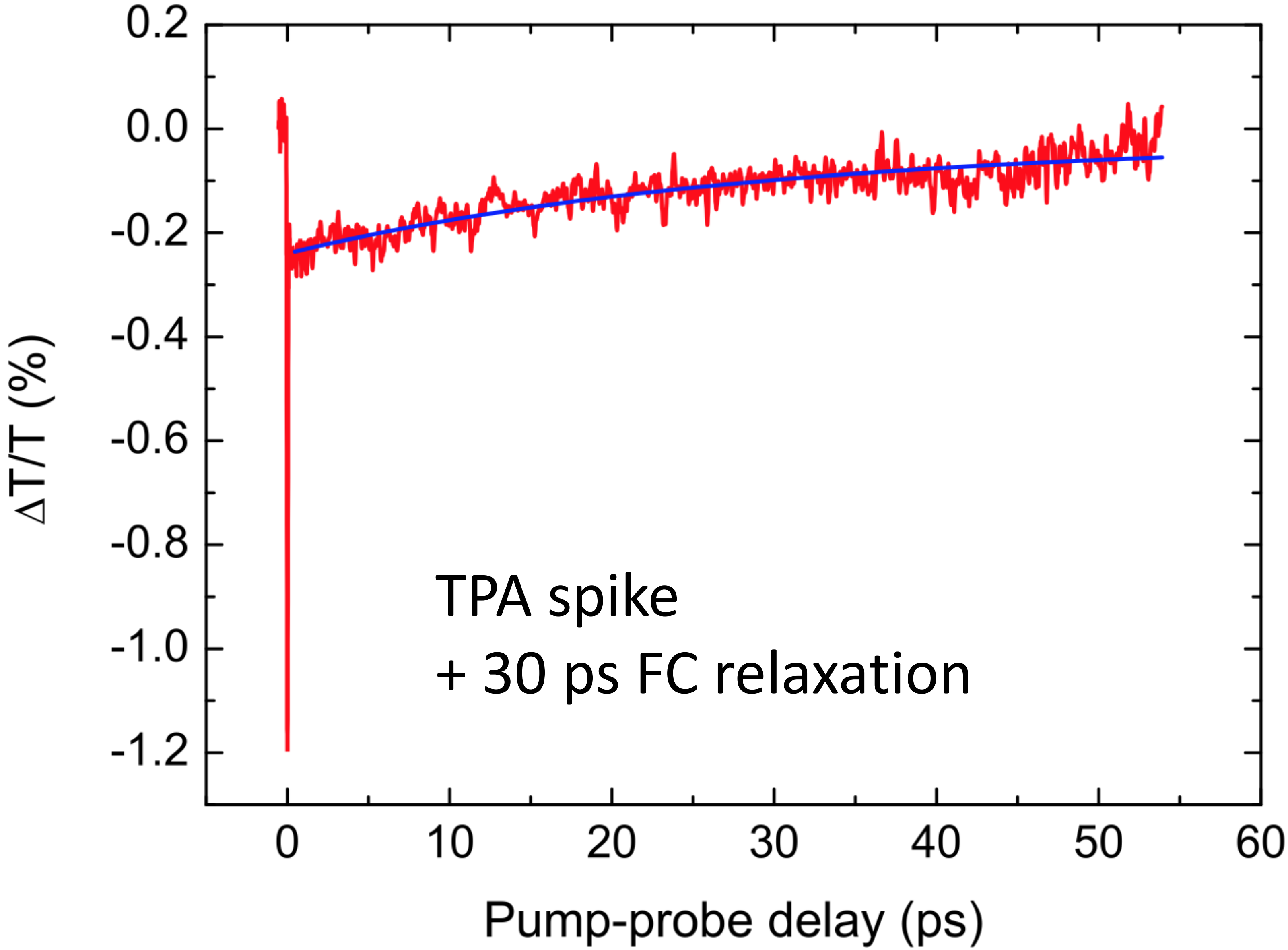
How fast is the nonlinearity?

Frequency-degenerate pump–probe

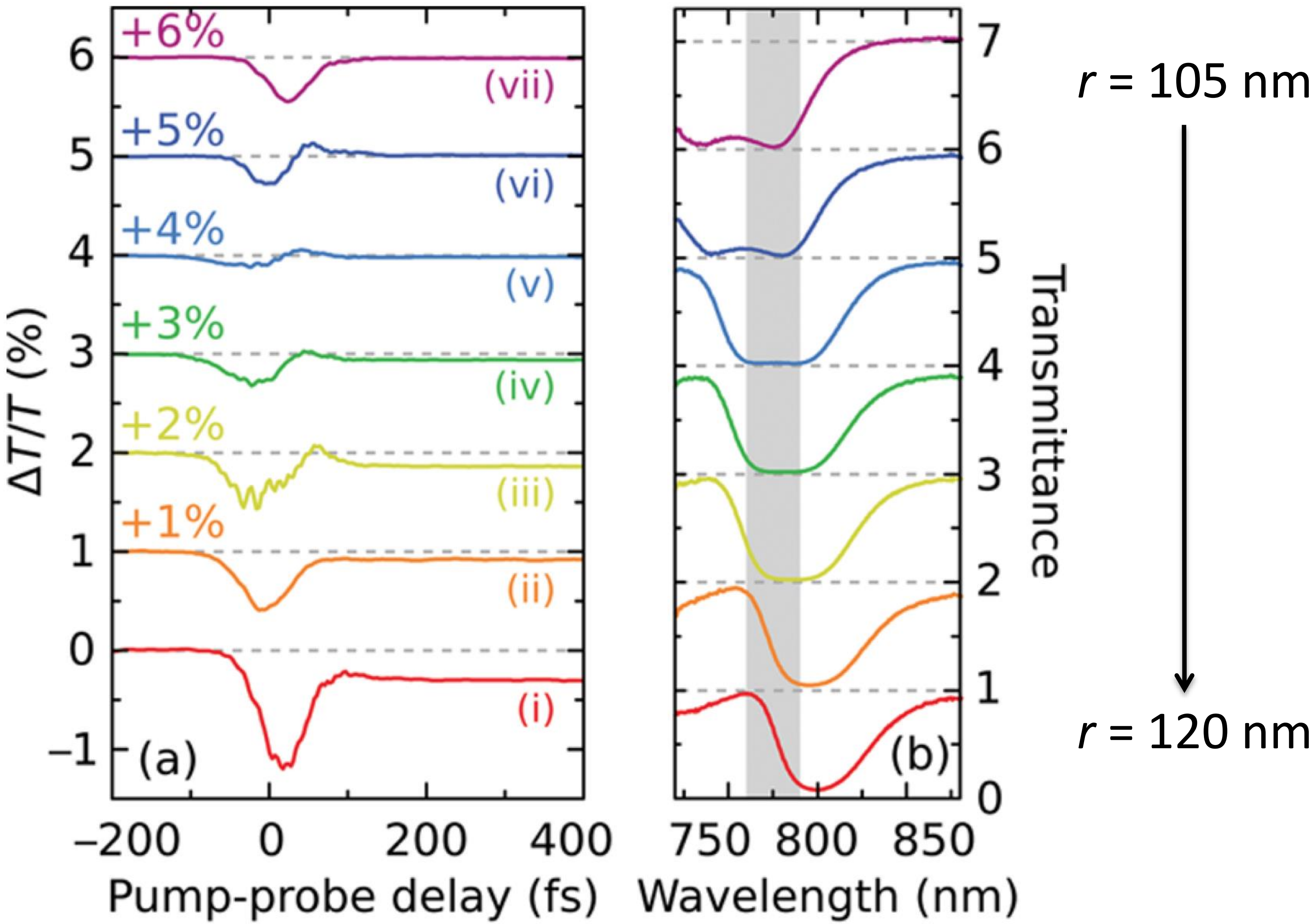


13 fJ per disk

Frequency-degenerate pump–probe



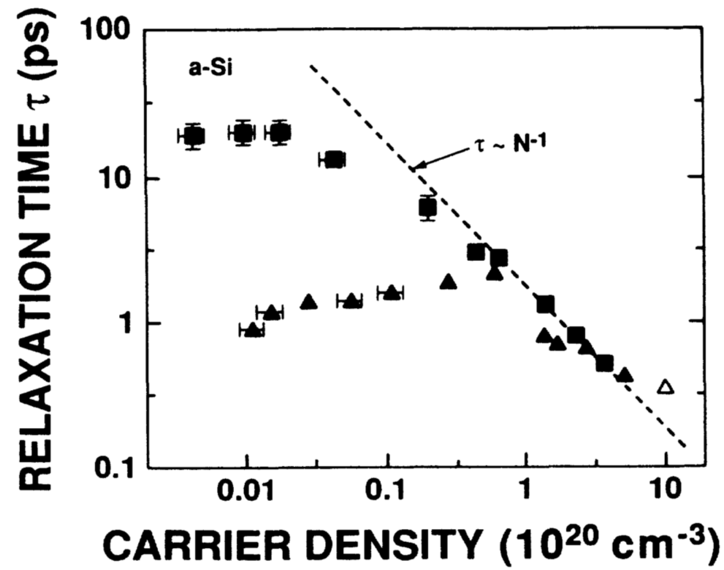
Frequency-degenerate pump–probe



TPA spike with the FC dispersion eliminated

Role of free carriers

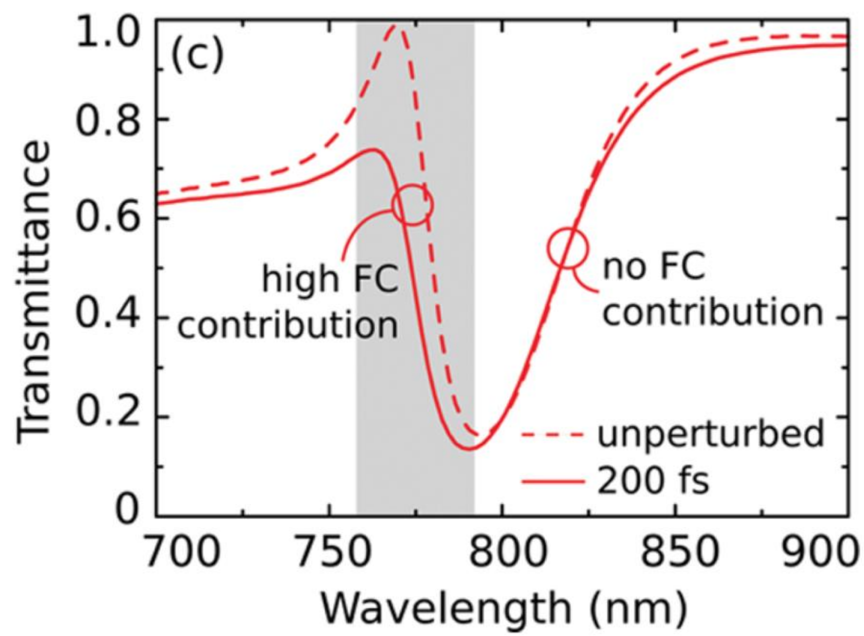
TPA –> carrier concentration N [cm^{-3}]
N ~ 10^{18} cm^{-3} in the experiment
Up to N ~ 10^{21} cm^{-3} shown previously
N ~ 5x10^{19} cm^{-3} used in calculations



$$\Delta\epsilon_1 = \frac{-Ne^2}{m^*\epsilon_0\left(\omega^2 + \tau_d^{-2}\right)},$$

$$\Delta\epsilon_2 = \frac{-\Delta\epsilon_1}{\omega\tau_d},$$

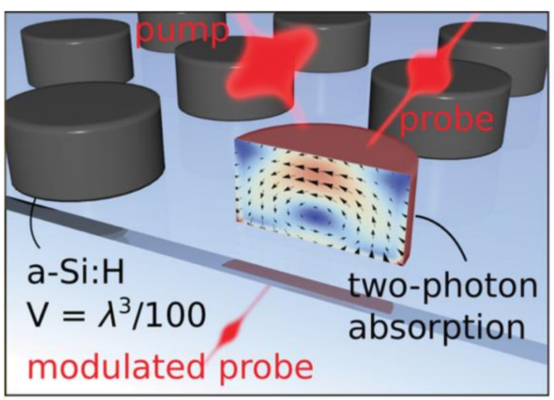
$$\frac{dN}{dt} = \frac{N_{max}}{\tau_p\sqrt{\pi}}e^{-\frac{t}{\tau_p}} - \gamma N^2 - \frac{N}{\tau_{tr}}$$



Pulse-limited low-power optical switching

TABLE I. Characteristics of micro- and nano-scale ultrafast switches.

Switching medium	Specific modulation $\ln(T_0/T)/E$, pJ^{-1}	Device volume, μm^3	Response time, ps	Wavelength, μm	Reference
Mangetic nanocavities	0.77	$4.5 \cdot 10^{-3}$	0.065	0.775	this work
Rectangular waveguide	full[a]	1.07	550	1.55	[4]
Micropillar cavity	$3 \cdot 10^{-3}$	34	300	0.926	[5]
Microring resonator	0.59	15.4	6.2	1.54	[6]
Photonic crystal cavity	3500	2	35	1.568	[7]
Plasmonic nanoantenna + ITO	$6 \cdot 10^{-5}$	$6 \cdot 10^{-4}$	500	1.05	[8]
Plasmonic waveguide	$7 \cdot 10^{-7}$	900	0.3	0.78	[9]
Plasmonic nanorod arrays	$1.1 \cdot 10^{-4}$	$1.6 \cdot 10^{-4}$	2	0.79	[10]
Split ring resonator metamaterial	0.75	$9 \cdot 10^{-3}$	0.115	0.89	[11]



NATURE MATERIALS | NEWS AND VIEWS

Dielectric nanostructures: Ultrafast responses

Maria Maragkou

Nature Materials **14**, 1086 (2015) | doi:10.1038/nmat4467

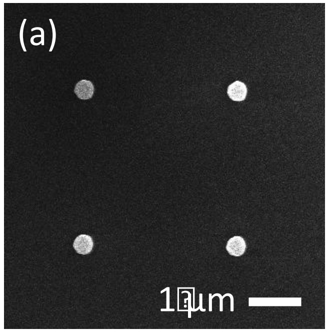
Published online 22 October 2015

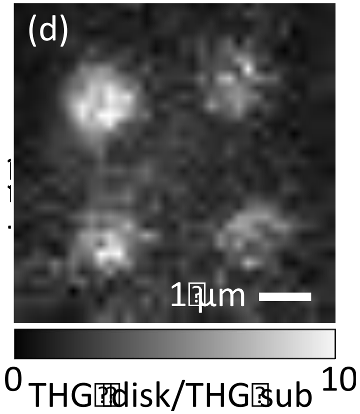
Nonlinear semiconductor metasurfaces: what's next?

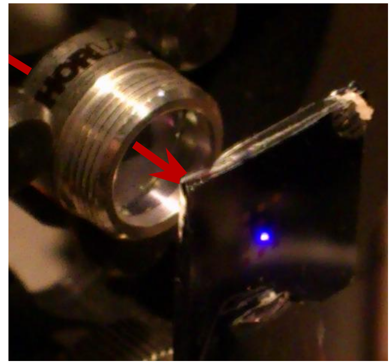
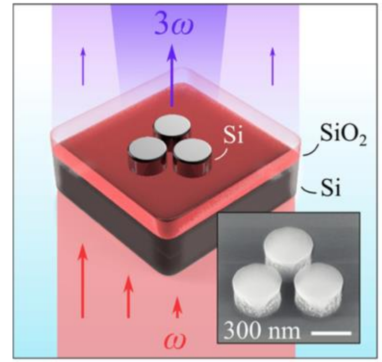
- Exploring the limits of conversion efficiencies: ~~THG~~, <u>SHG</u>, WM, HHG…
- Other third-order processes: <u>Kerr effect (SiC?)</u>, ~~TPA~~
- ~~Transient free-carrier-induced processes~~
- Other high-*n* materials (<u>GaAs</u>, GaP, InP, …)
- Coupling to emitters (NVs, QDs, TMDCs…)

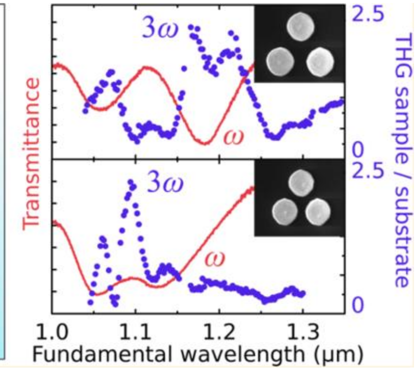
… and much more

Conclusions







[1] Shcherbakov et al., “Enhanced Third-Harmonic Generation in Silicon Nanoparticles Driven by Magnetic Response,” Nano Letters **14**, 6488–6492 (2014)

[2] Shcherbakov et al., “Nonlinear Interference and Tailorable Third-Harmonic Generation from Dielectric Oligomers,” ACS Photonics **2**, 578–582 (2015)

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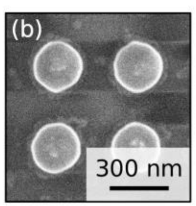
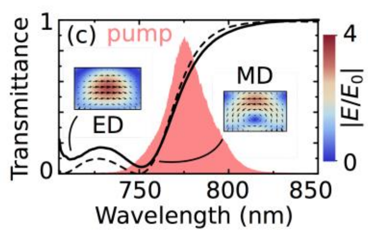
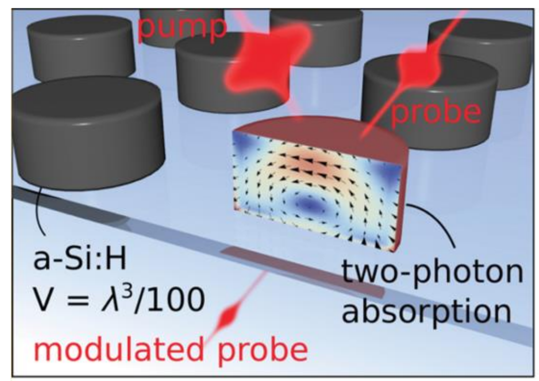
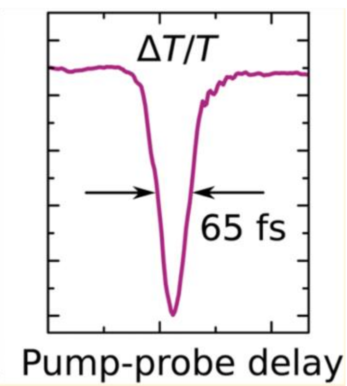
nanolab









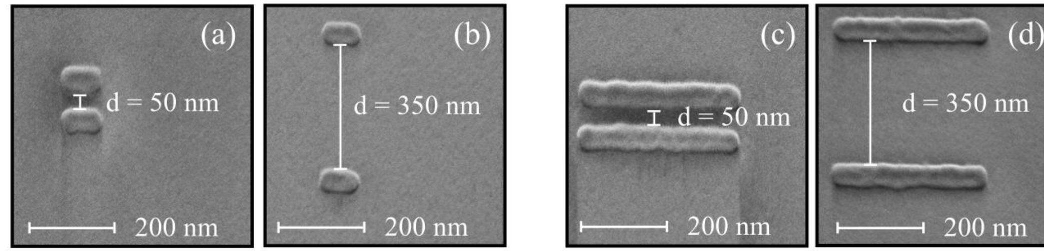
[3] Shcherbakov et al., “Ultrafast All-Optical Switching with Magnetic Resonances in Nonlinear Dielectric Nanostructures,” Nano Letters **15**, 6985–6990 (2015)

Financial support by Russian Science Foundation:
Nonlinear Optics of All-Dielectric Metamaterials project (#14-12-01144)

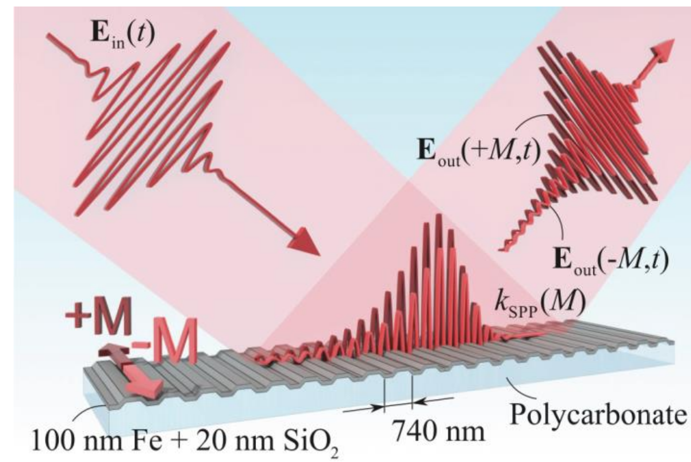
РНФ Российский научный фонд

Efforts in plasmonics

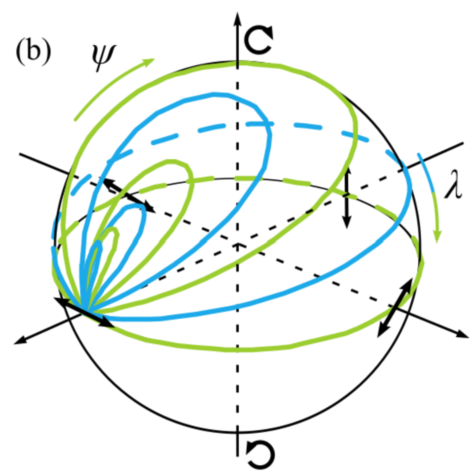
Plasmon rulers:
[4] Shcherbakov et al.,
Optics Letters **7**, 1571–1574 (2015).

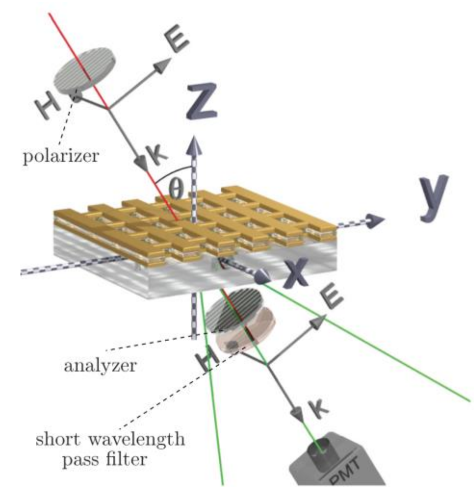


Ultrafast plasmonics:
[5] Shcherbakov et al.,
Physical Review B Rapids **90**, 201405(R) (2014).
[6] Shcherbakov et al.,
Physical Review Letters **108**, 253903 (2012).



Anisotropic plasmonic nanostructures
[7] Shcherbakov et al.,
Physica C **479**, 183 (2012).
[8] Shcherbakov et al.,
JETP Letters **93**, 720 (2011).
[9] Shcherbakov et al.,
Physical Review B **82**, 193402 (2010).
[10] Shcherbakov et al.,
JETP Letters **90**, 433 (2009).





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- Sandia group (Jason Dominguez, Igal Brener)

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