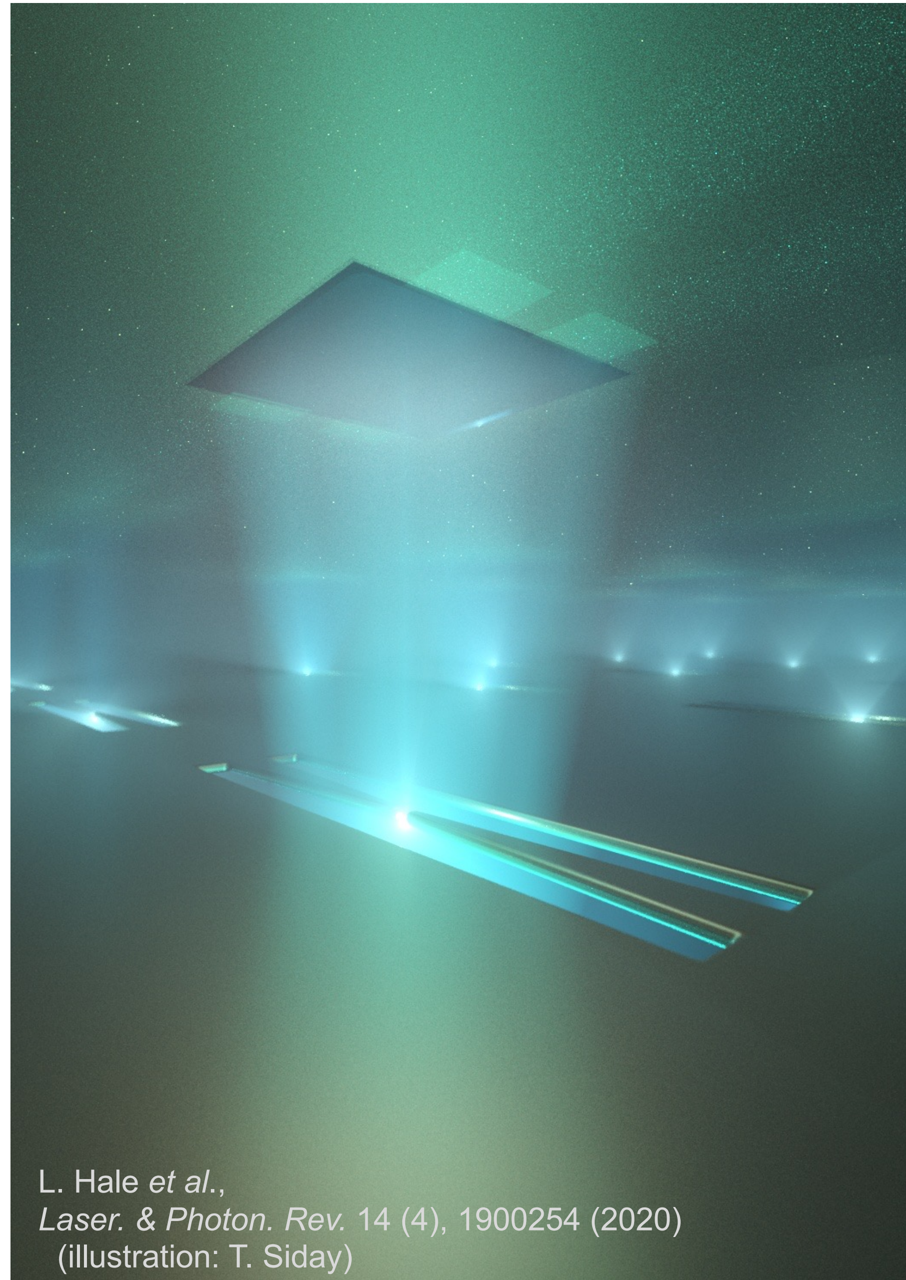
Microscopy with THz waves:

Techniques and Applications

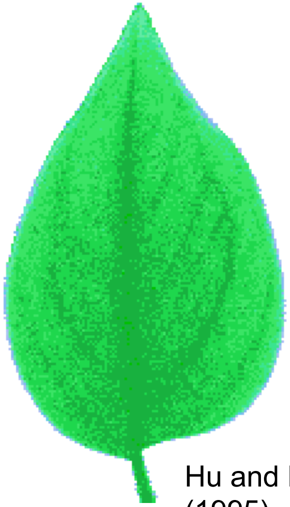
Oleg Mitrofanov
UCL

Optical Systems and Quantum Devices
For MIR and THz Technologies
Frejus, France
Jun 27-Jul 1, 2022



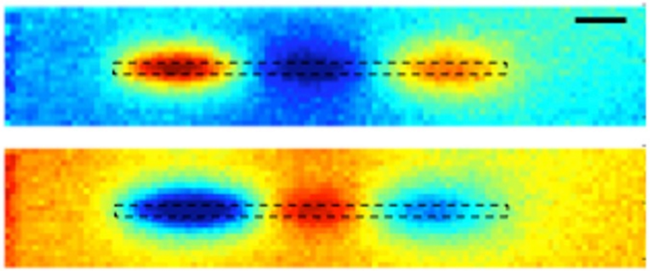
L. Hale *et al.*,
Laser. & Photon. Rev. 14 (4), 1900254 (2020)
(illustration: T. Siday)

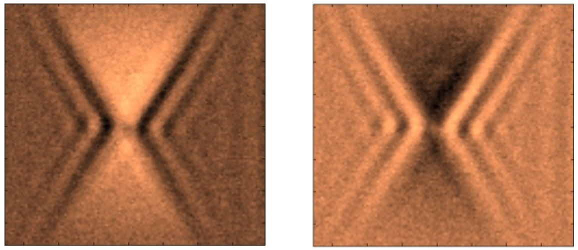
THz Imaging

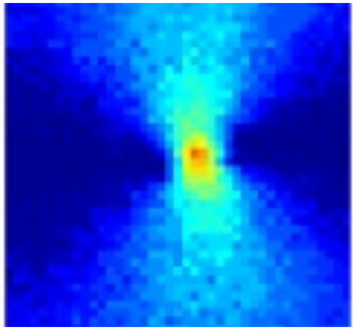


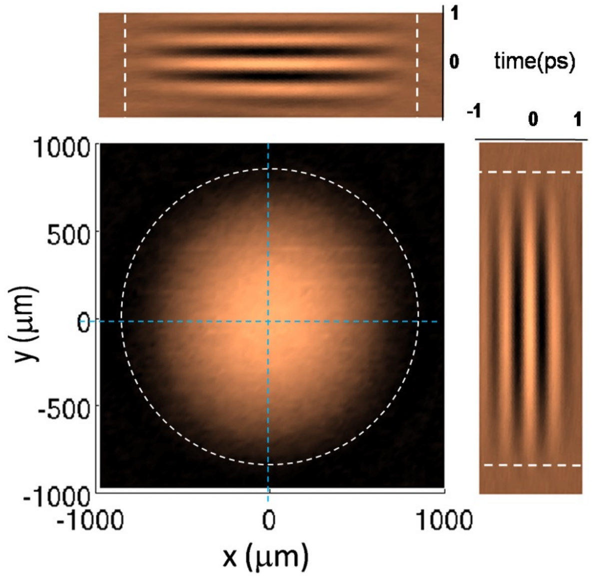
Hu and Nuss
(1995)

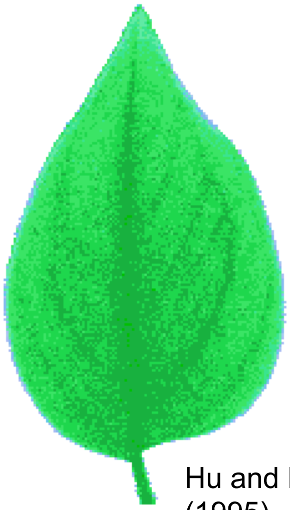
THz Imaging



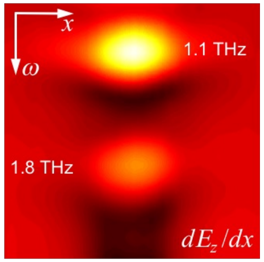


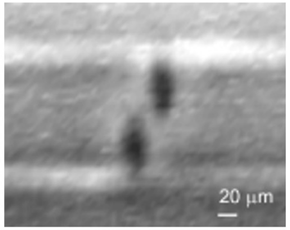


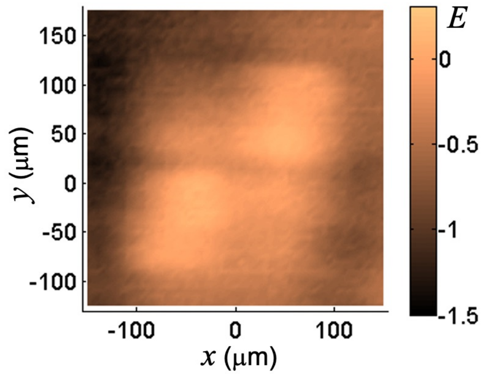


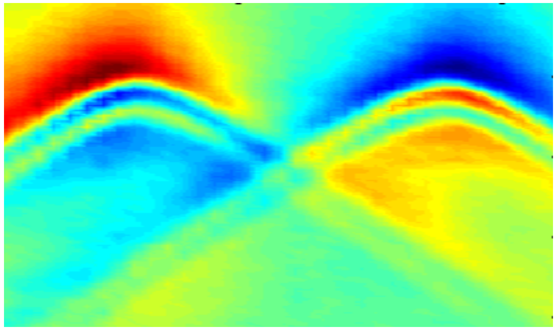


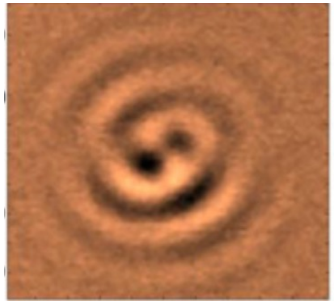
Hu and Nuss (1995)

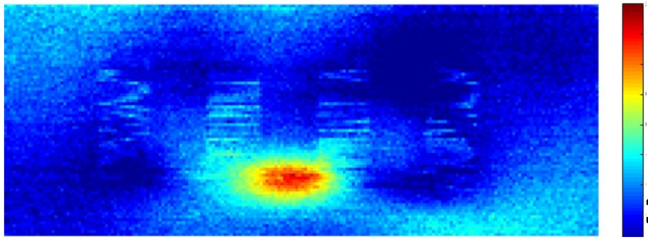






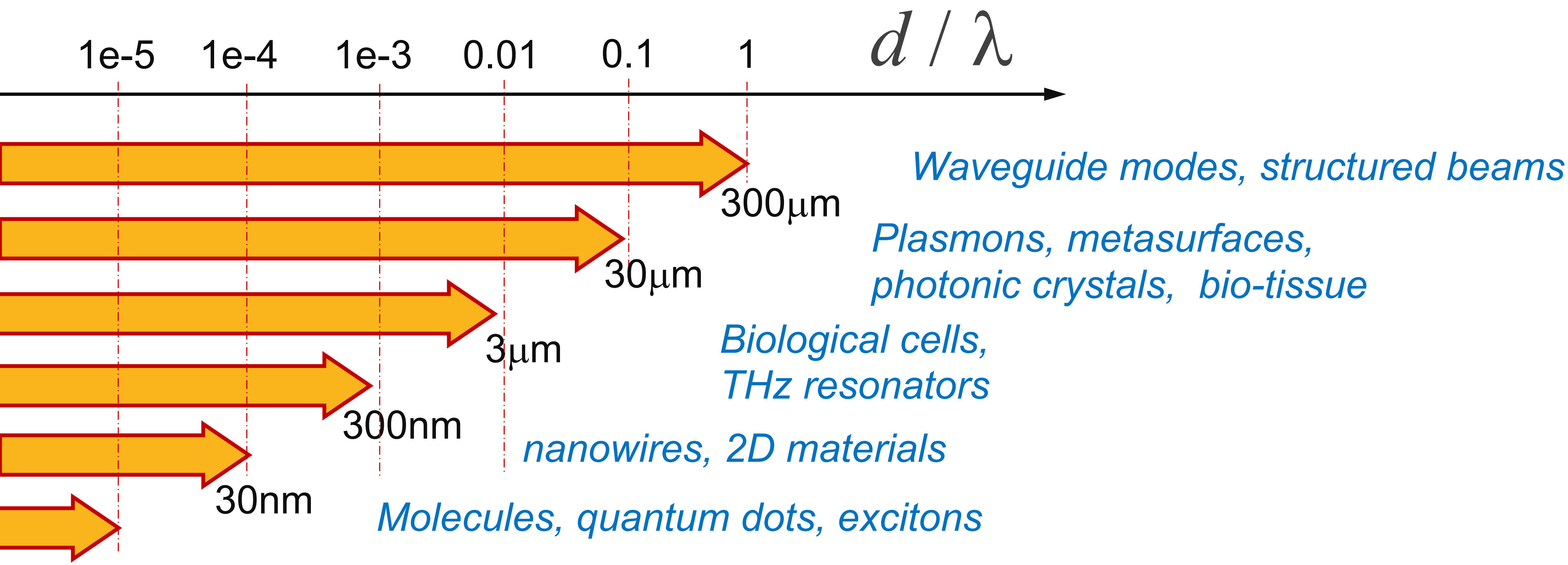






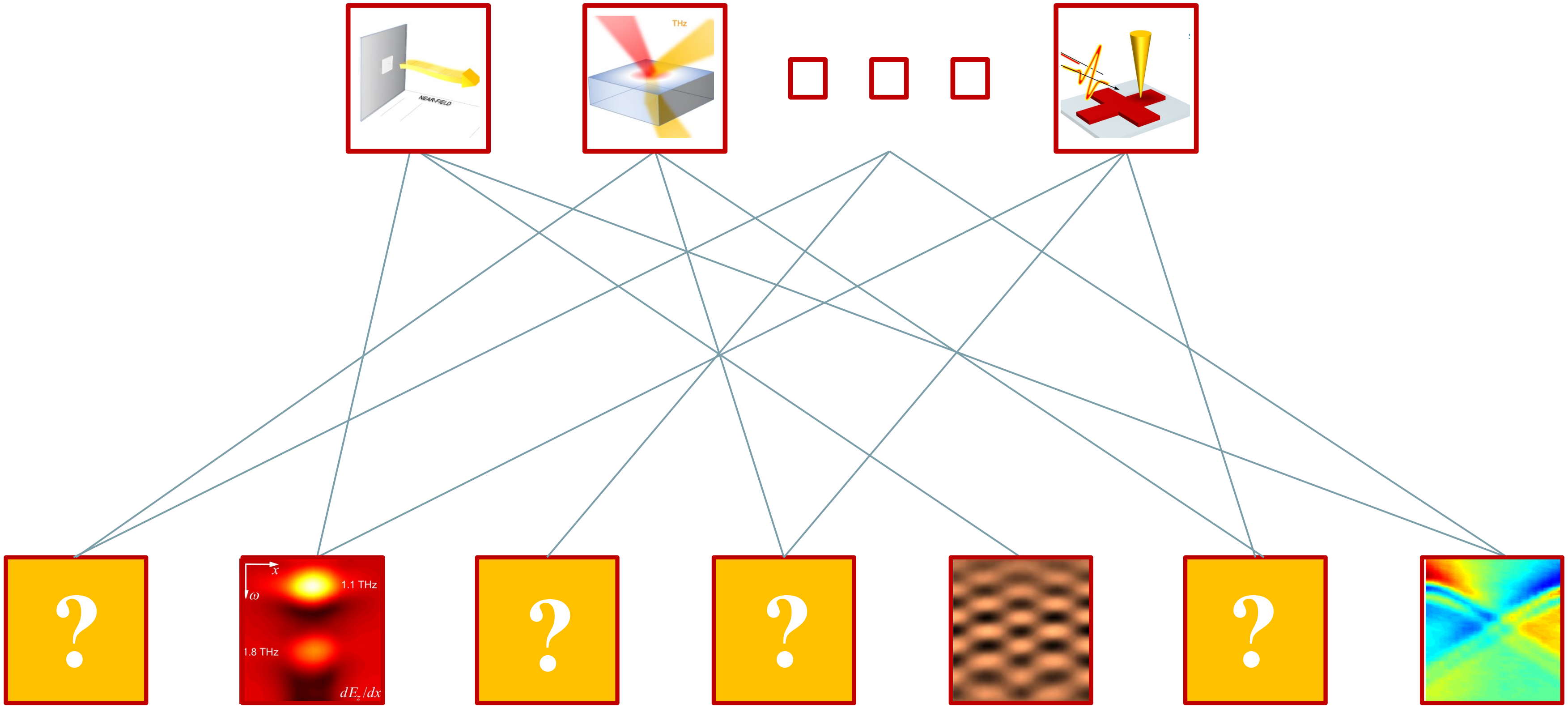
THz Near-Field Microscopy Application Space

Wide range of
subwavelength size systems



How do we enable THz imaging?

THz near-field Microscopy Approaches



THz near-field microscopy applications

Right instrument for a given problem

Appropriate problems for a given instrument

Tutorial Scope and Aims

Fundamentals of THz near-field microscopy

Microscopy and Spectroscopy of THz resonators

Imaging of THz surface plasmon waves

Subwavelength aperture and Scattering tip probes

Image interpretation

Improving sensitivity in THz microscopy

Overview of THz microscopy methods

Spatial Resolution

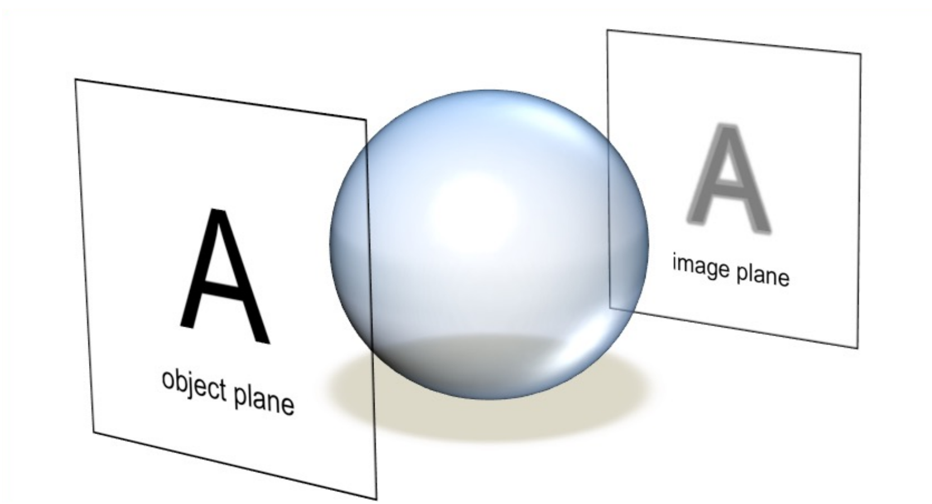
$$d = \frac{\lambda}{2n \sin\alpha}$$

Ernst Abbe (c. 1873)

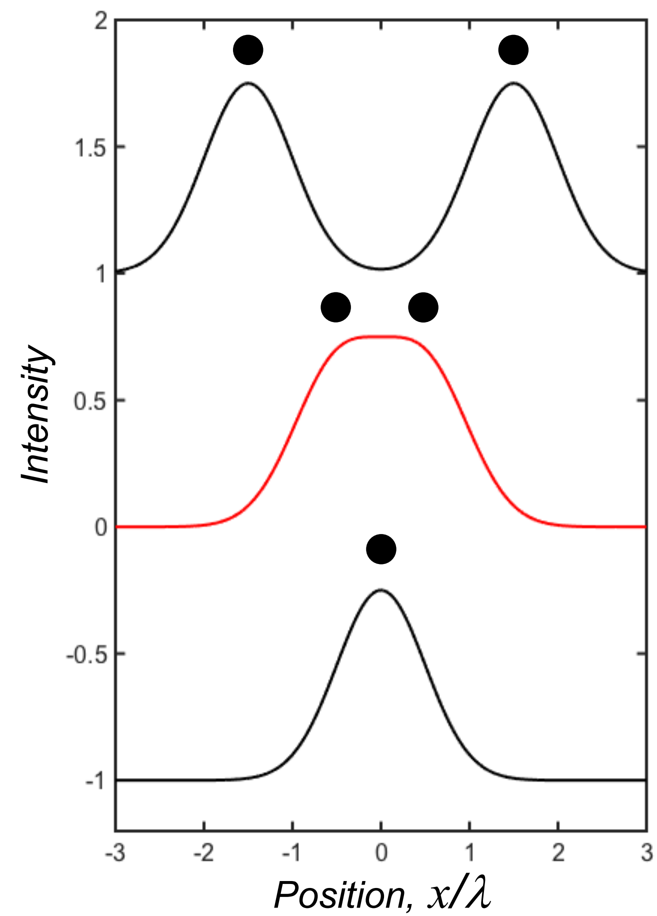
Spatial Resolution

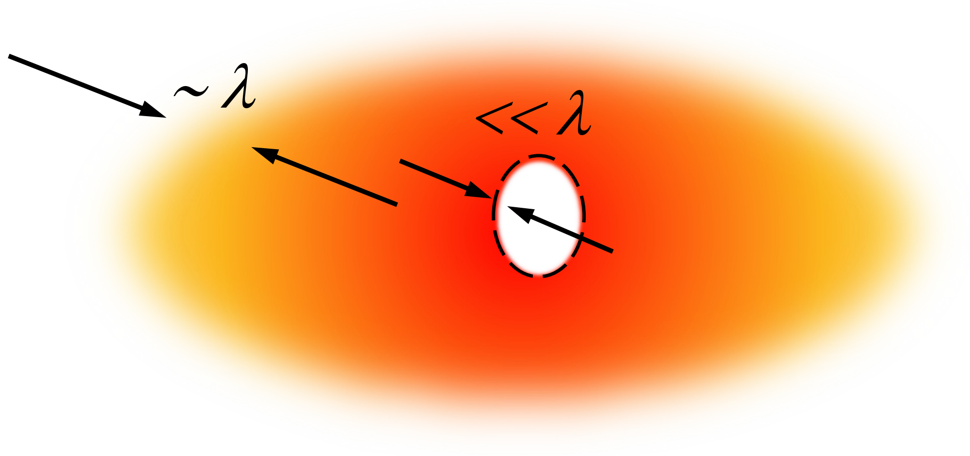
$$d = \frac{\lambda}{2n \sin \alpha}$$

Ernst Abbe (c. 1873)

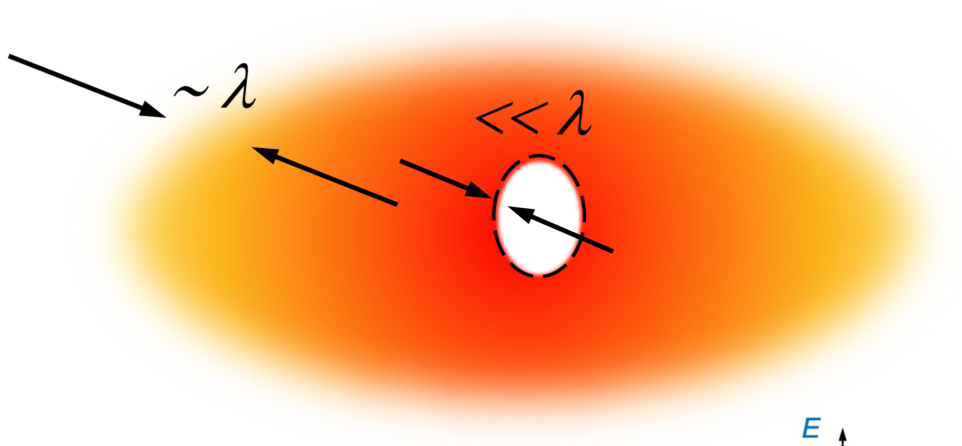


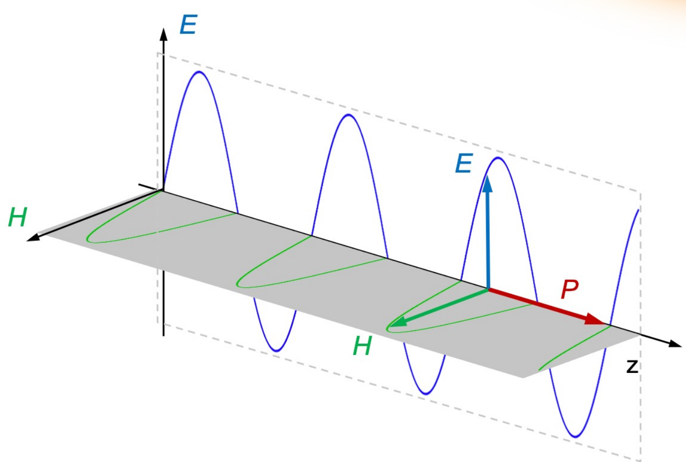
Far-Field – propagating waves:
point-spread function
limits resolving two points

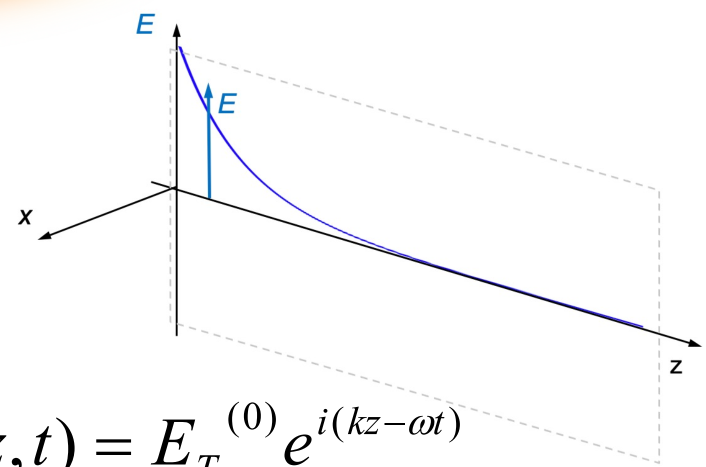



$\sim \lambda$
$<< \lambda$

Spatial Resolution







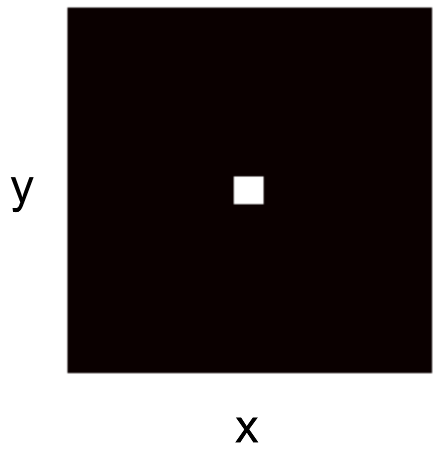
$$E_T(z,t) = E_T^{(0)} e^{i(kz-\omega t)}$$

Evanescent waves allow EM wave confinement on subwavelength scale

Angular spectrum representation of EM fields

How to include Evanescent Waves into analysis framework?

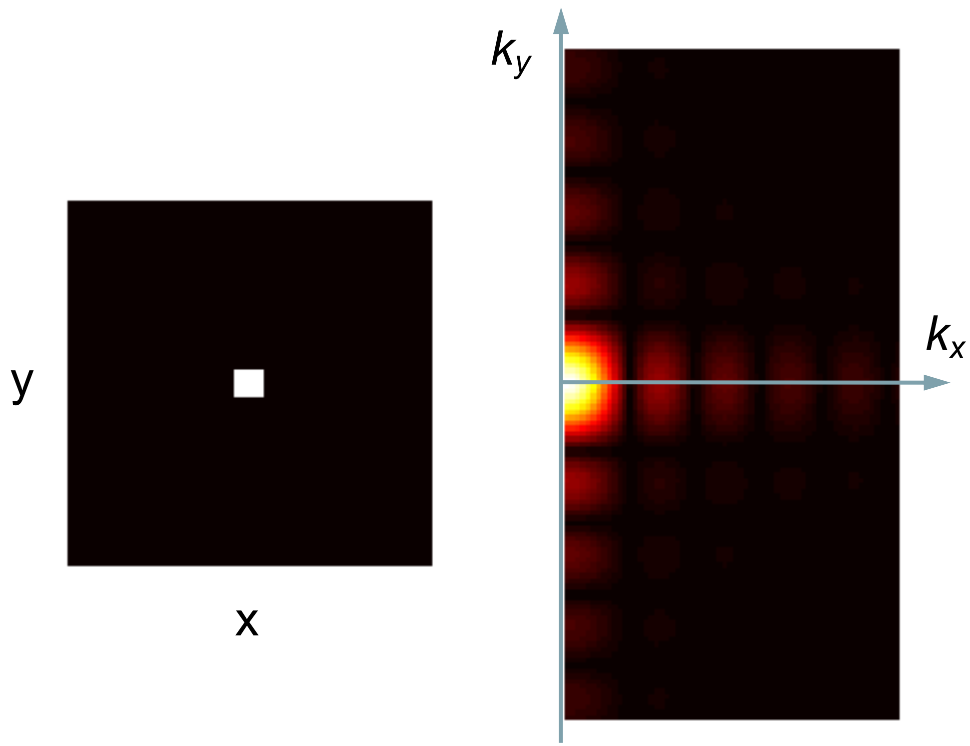
Angular spectrum representation of EM fields



Spatial distribution

2D Fourier transform

E(x,y) is a superposition of waves $E(k)\, e^{ikr+i\phi}$



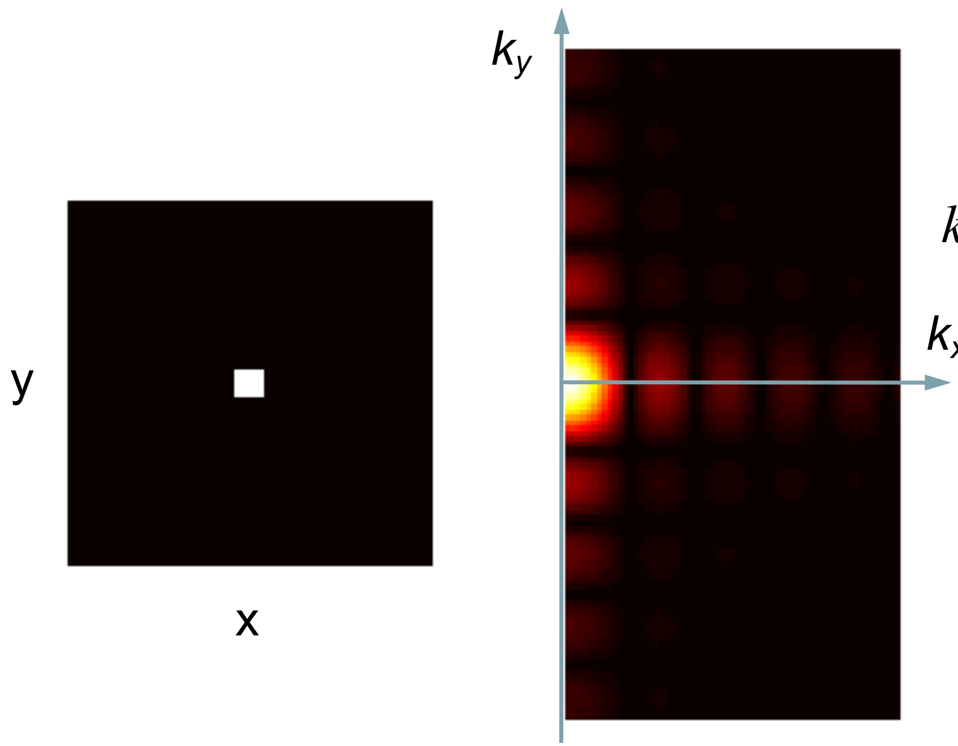
Spatial distribution ⟷ *k-space distribution*

Fourier Transform

Angular spectrum representation of EM fields

2D Fourier transform

E(x,y) is a superposition of waves $E(k)\, e^{ikr+i\phi}$



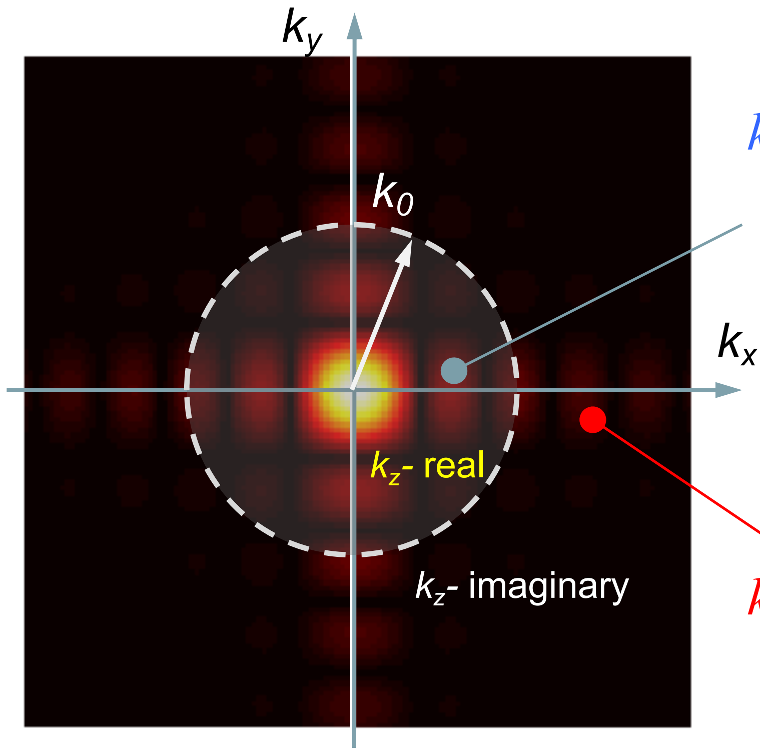
$$k_x^2 + k_y^2 + k_z^2 = k_0^2$$

Spatial distribution ⟷ *k-space distribution*

Fourier Transform

Angular spectrum representation of EM fields

$$k_x^2 + k_y^2 + k_z^2 = k_0^2$$



$$k_t < k_0 = 2\pi / \lambda$$

$$k_z^2 > 0$$

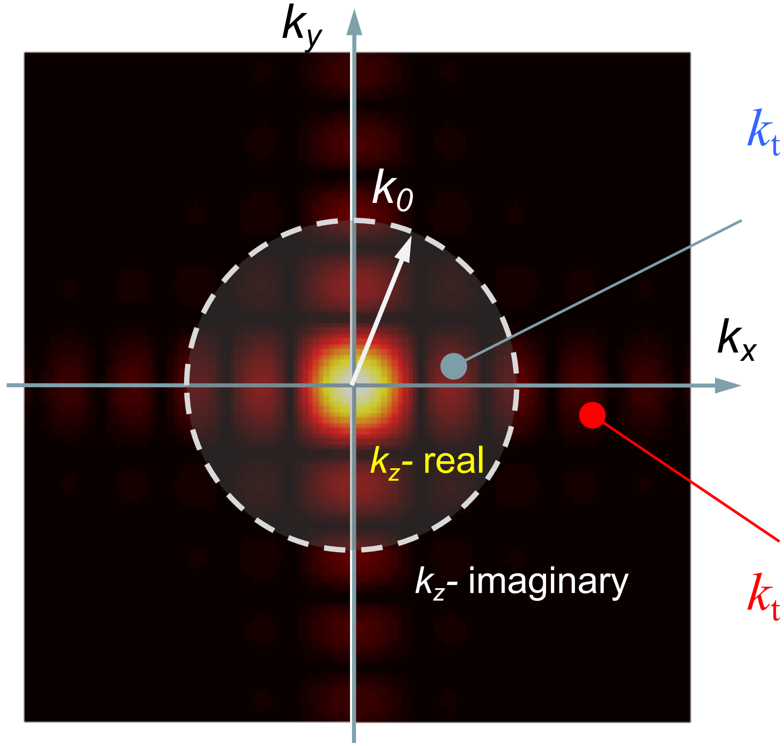
$$k_t > k_0 = 2\pi / \lambda$$

$$k_z^2 < 0$$

Any subwavelength field distribution contains imaginary k_z components – evanescent waves, localized near objects and interfaces

$$k_x^2 + k_y^2 + k_z^2 = k_0^2$$

$$d=\frac{\lambda}{2n\sin\alpha}$$



$k_t < k_0 = 2\pi/\lambda$

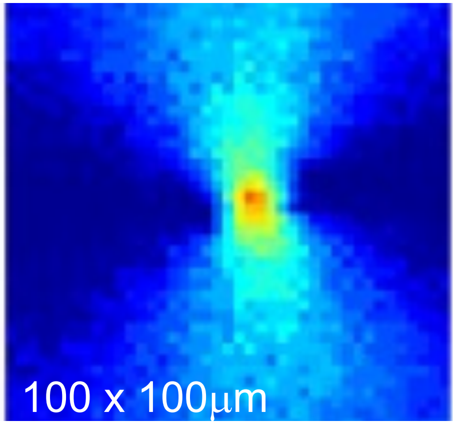
$k_z^2 > 0$

$k_t > k_0 = 2\pi/\lambda$

$k_z^2 < 0$

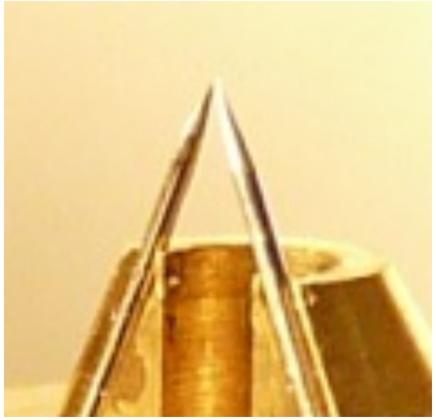
Any subwavelength field distribution contains imaginary k_z components – evanescent waves, localized near objects and interfaces

THz Field Confinement



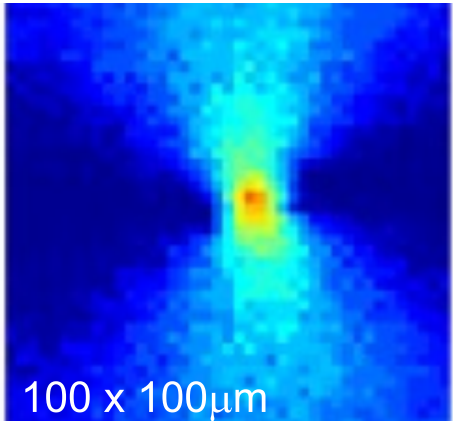
$\lambda \sim 200\ \mu m$

$d < 10\ \mu m$



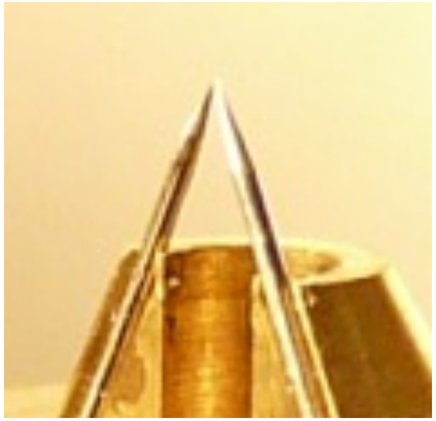
Opt. Express **20**, 6197 (2012)

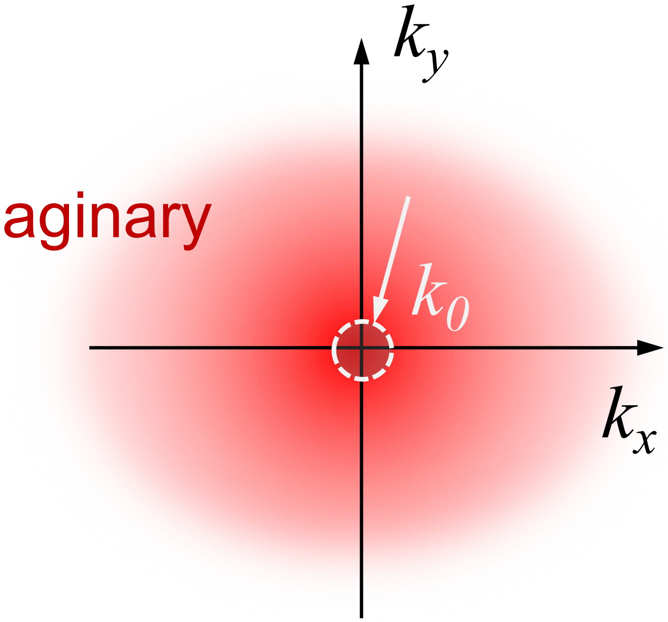
THz Field Confinement



$\lambda \sim 200\ \mu m$

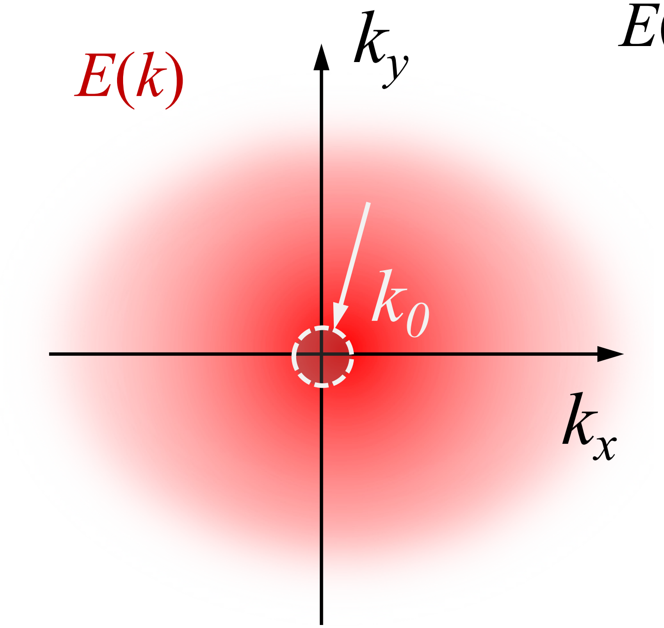
$d < 10\ \mu m$

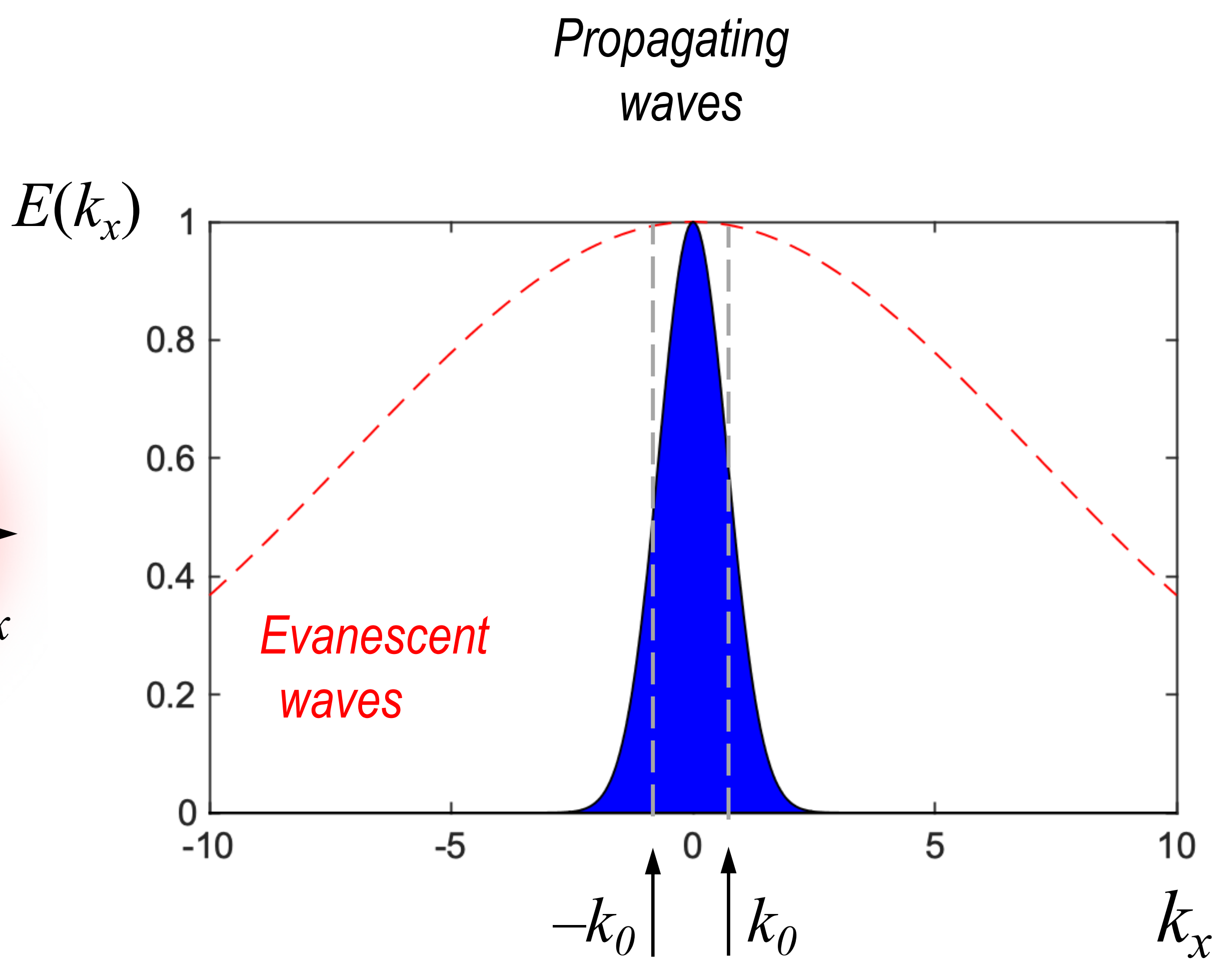




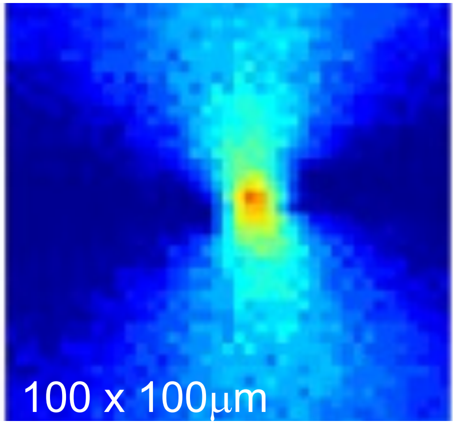
Opt. Express **20**, 6197 (2012)

Representation in k-space



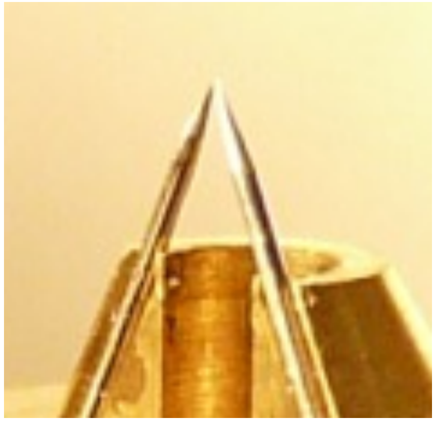


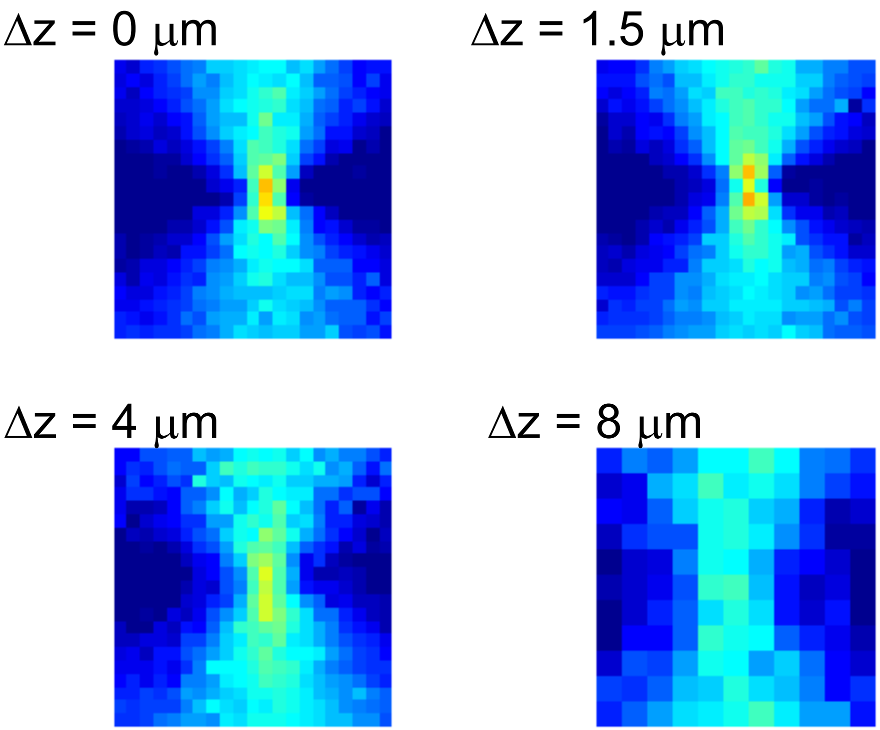
THz Field Confinement

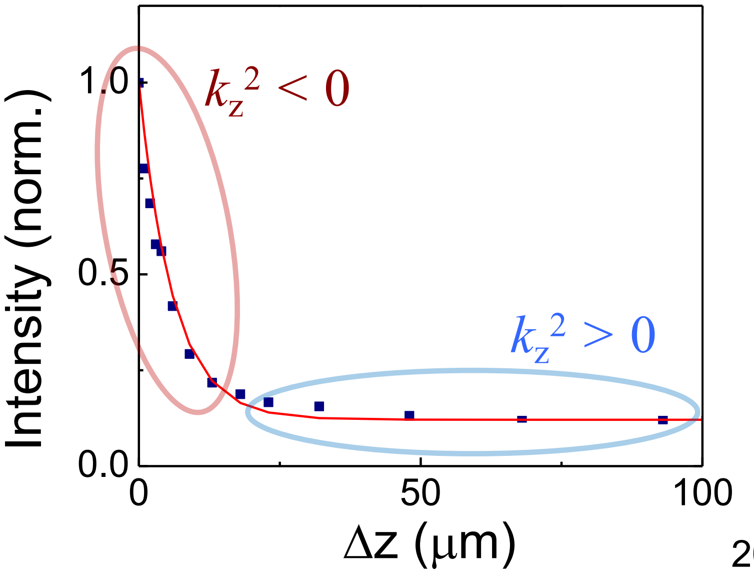


$\lambda \sim 200\ \mu m$

$d < 10\ \mu m$

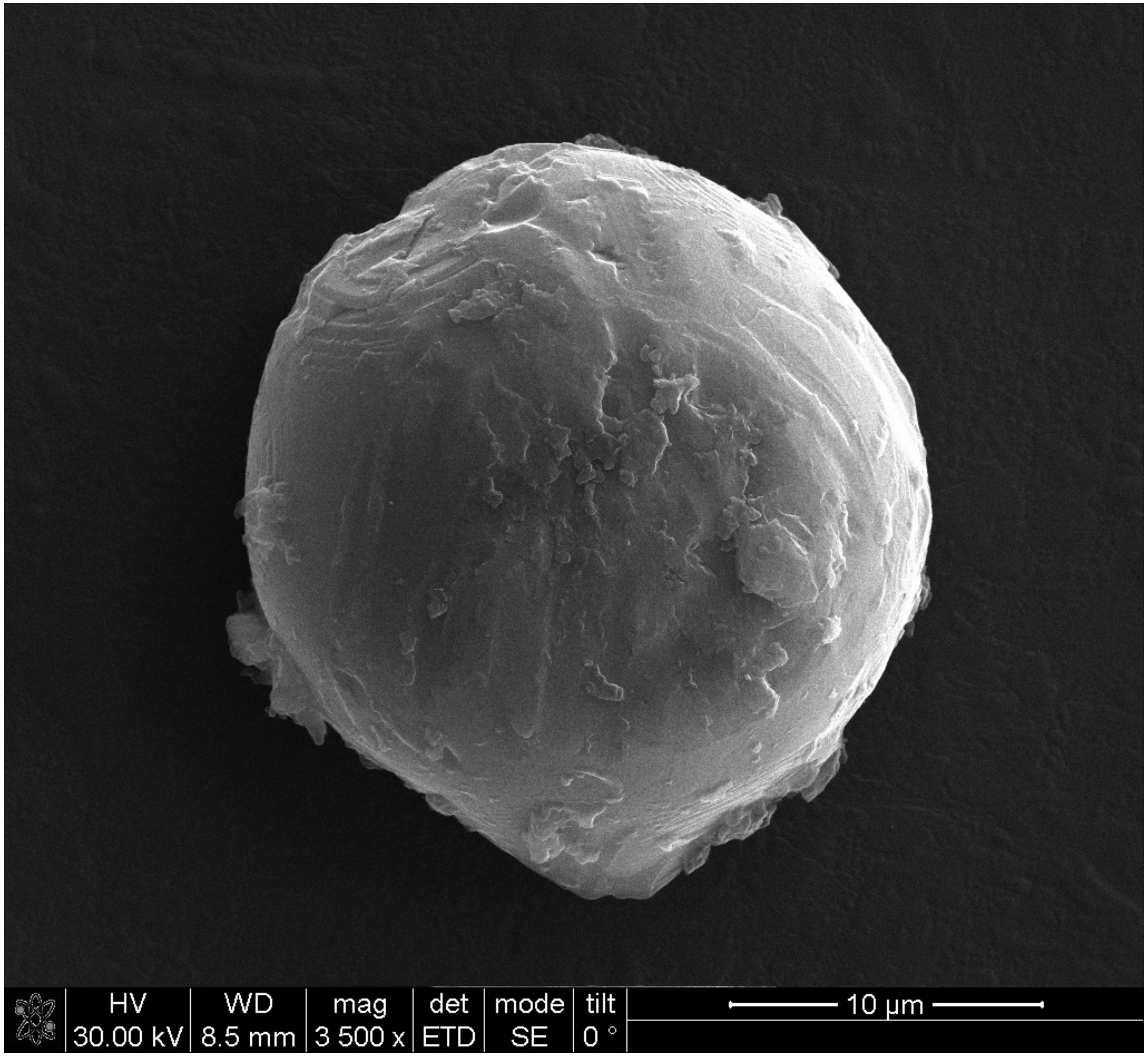






Opt. Express **20**, 6197 (2012)

High permittivity Dielectric Resonator



TiO$_2$ sphere:

$d \sim 20\ \mu m \qquad \lambda_{MD} \sim 300 \mu m$

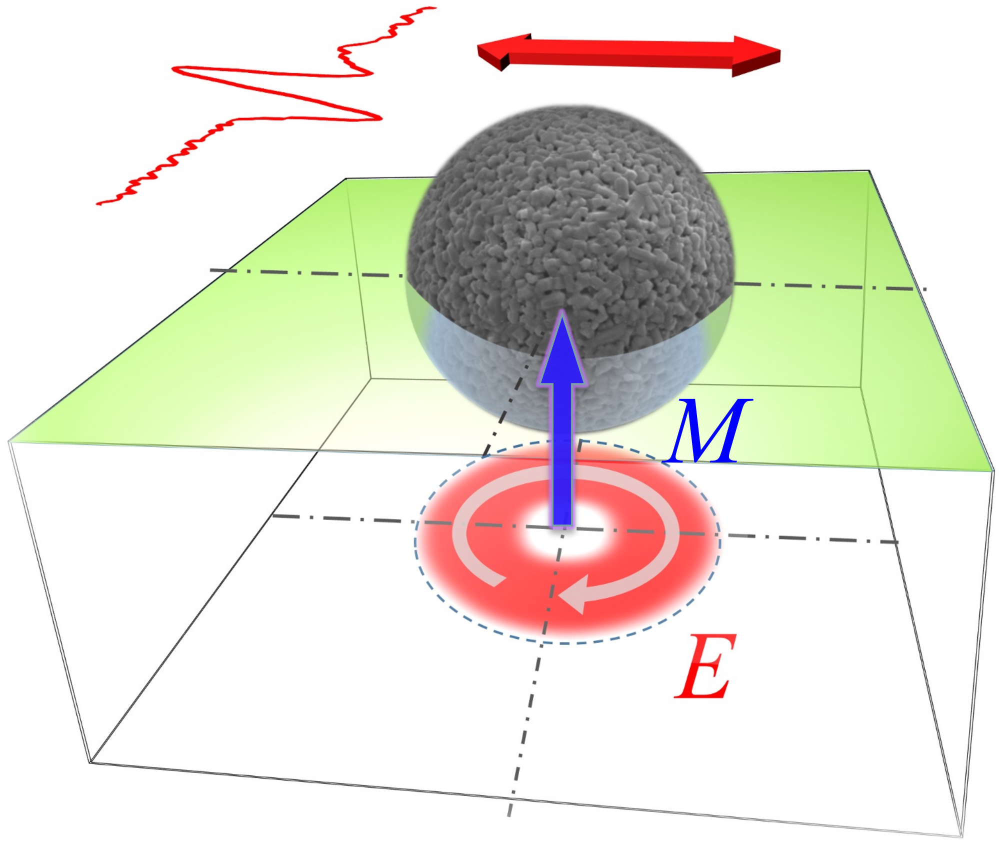
$d / \lambda \sim 0.07$

Mie resonances in TiO_2 spheres

$\varepsilon \sim 80\text{-}100$

$d \sim 20\ \mu m$

$\lambda_{MD} \sim 300\mu m$



$d / \lambda \sim 0.07$

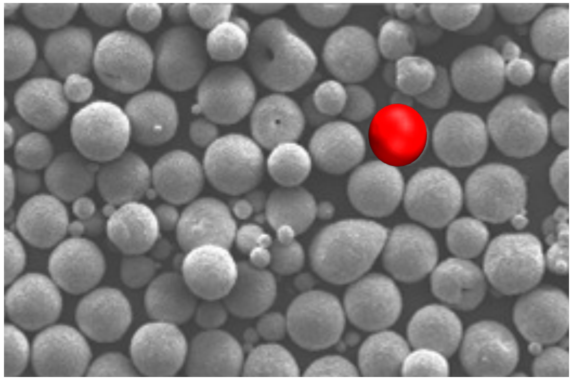
$k_t >> k_0$

Optics Express, 22, 23034 (2014)

Probing of single resonator – Scattering view

Sub-wavelength size
of TiO_2 resonators

$d \sim 20\ \mu m \qquad \lambda_{MD} \sim 300 \mu m$

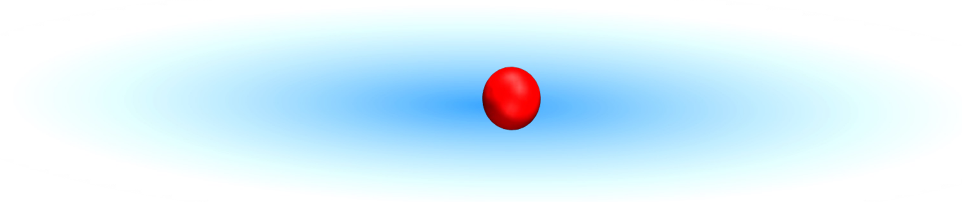


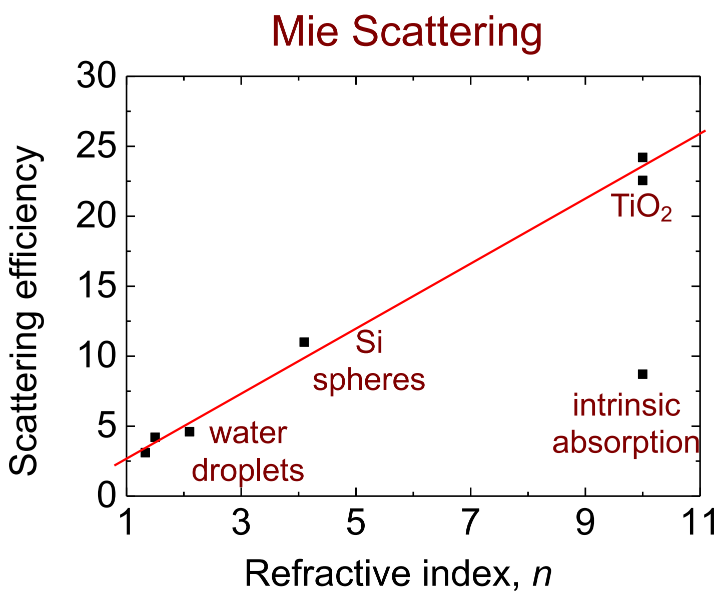
What is far-field effect
due to single resonator?

Probing of single resonator – Scattering view

Sub-wavelength size of TiO_2 resonators

$d \sim 20\ \mu m \qquad \lambda_{MD} \sim 300 \mu m$





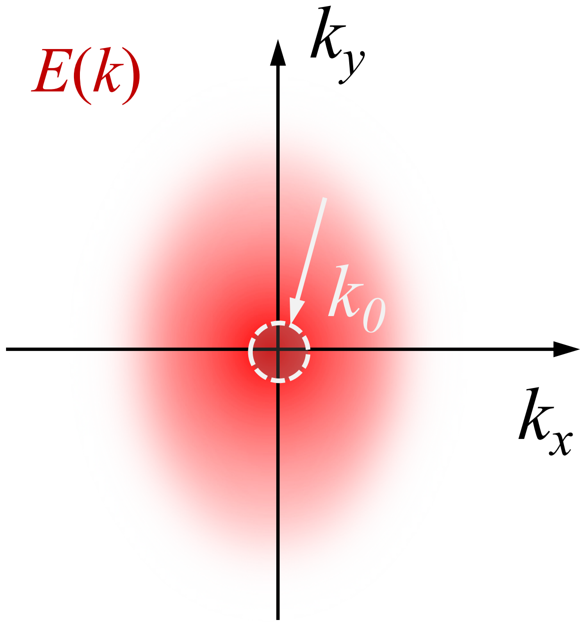
Total scattered power reduces due to the physical cross-section scaling with n $^{-2}$

Far-field total extinction by a single TiO_2 sphere

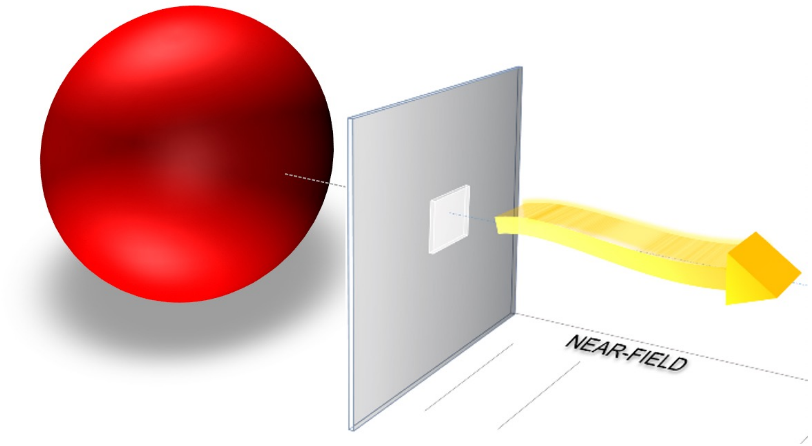
0.1-1.0%

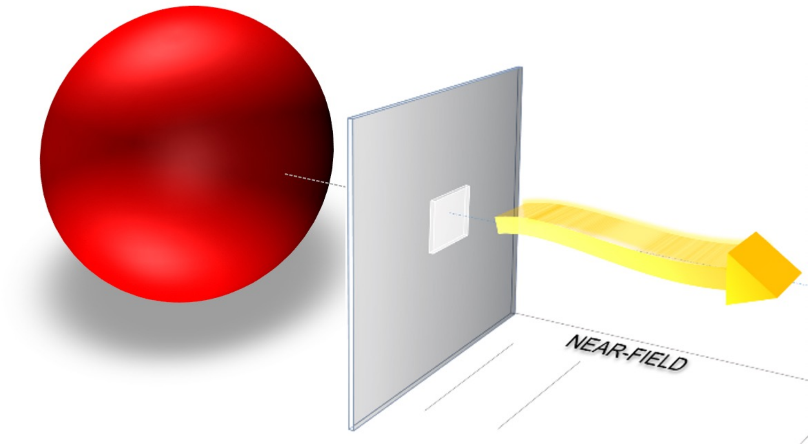
(*est. for typical THz-TDS*)

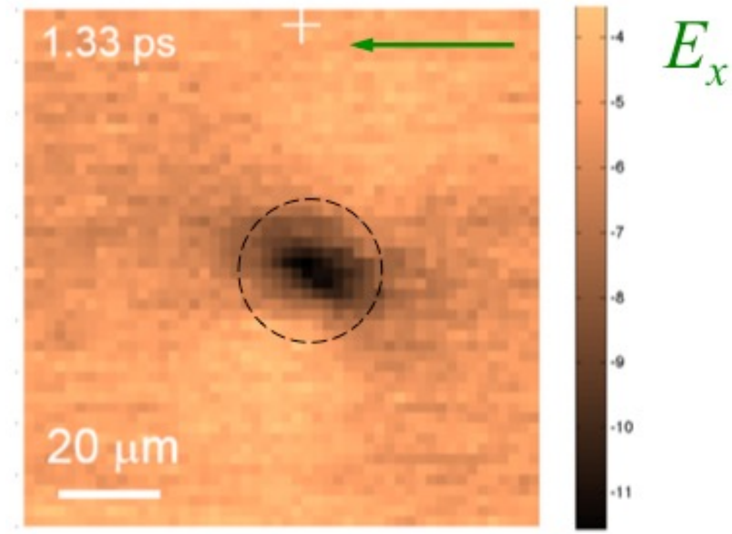
Resonance Mode representation in k-space



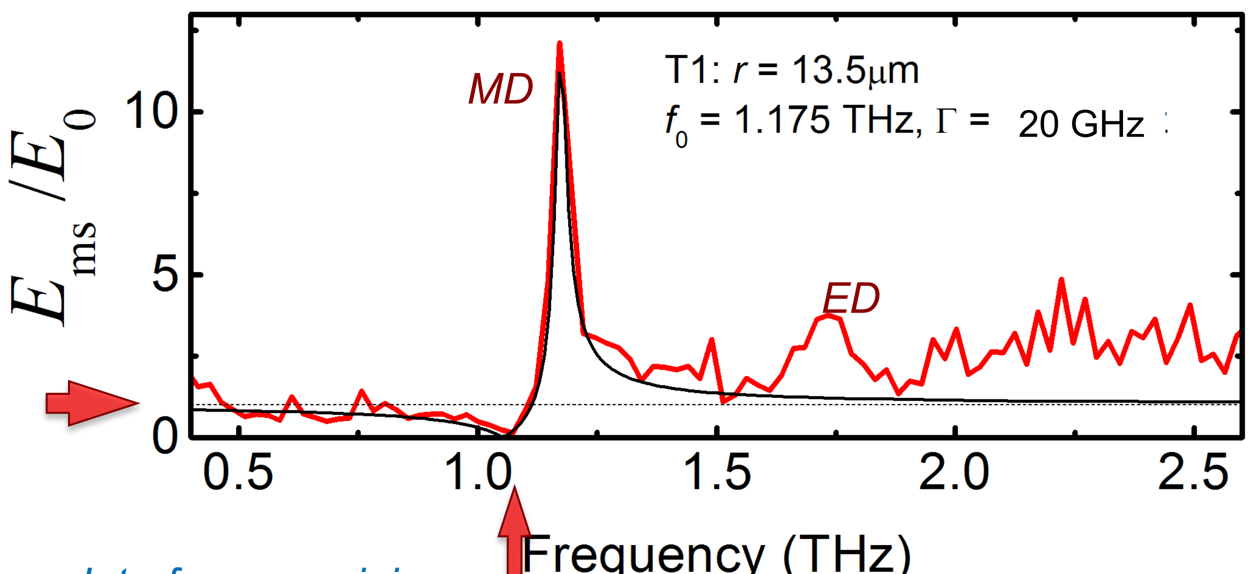
NF probing using subwavelength aperture







Enhancement factor and width to quantify the resonator

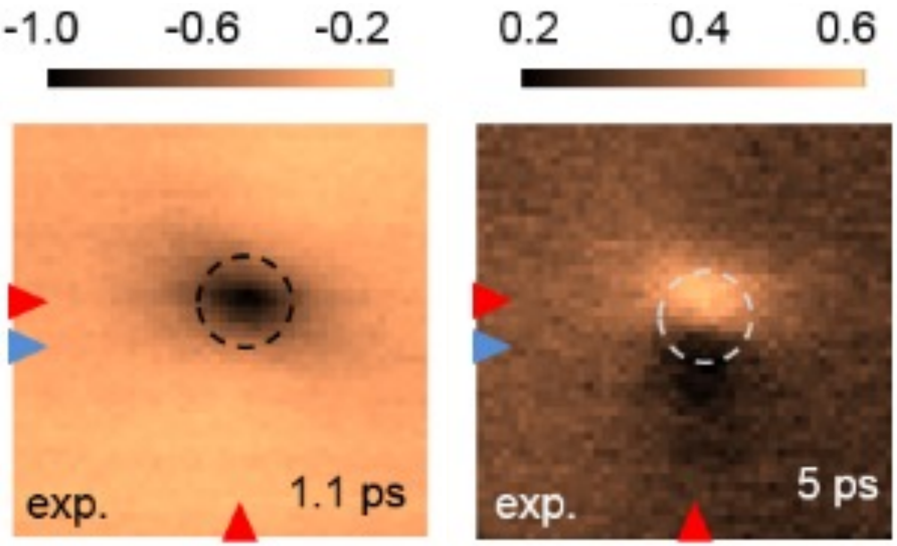


No effect on transmission away from resonance

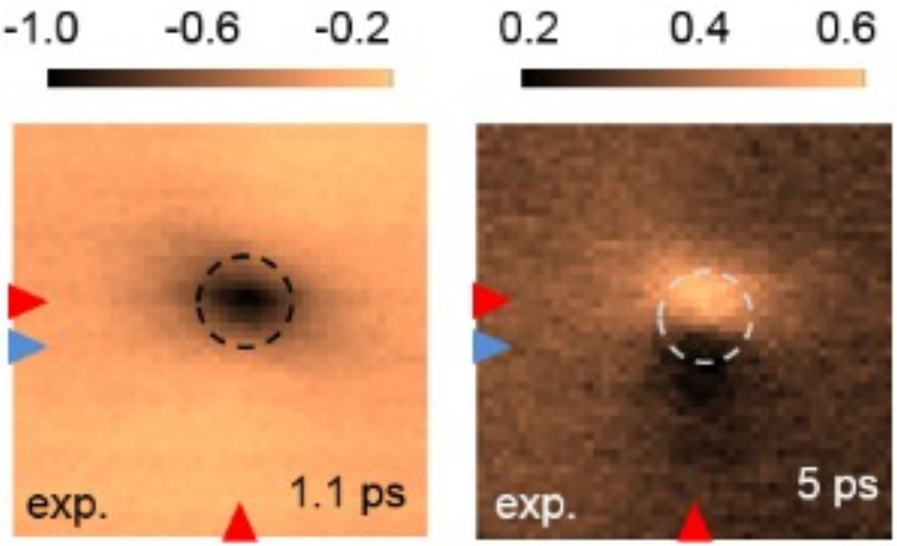
Interference minimum (Fano line-shape)

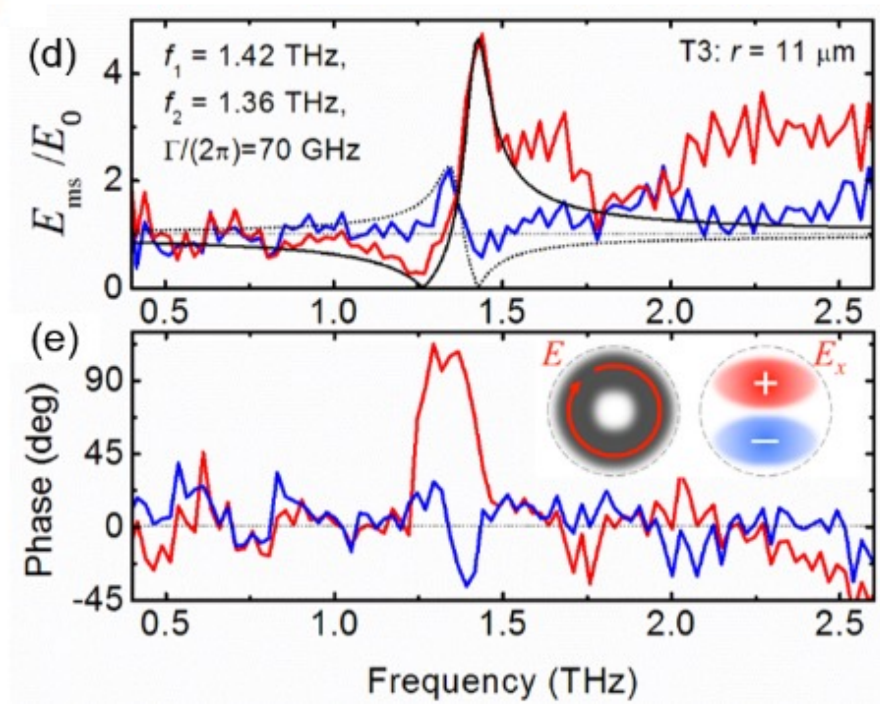
Optics Express, 22, 23034 (2014)

Near-field structure in time-domain

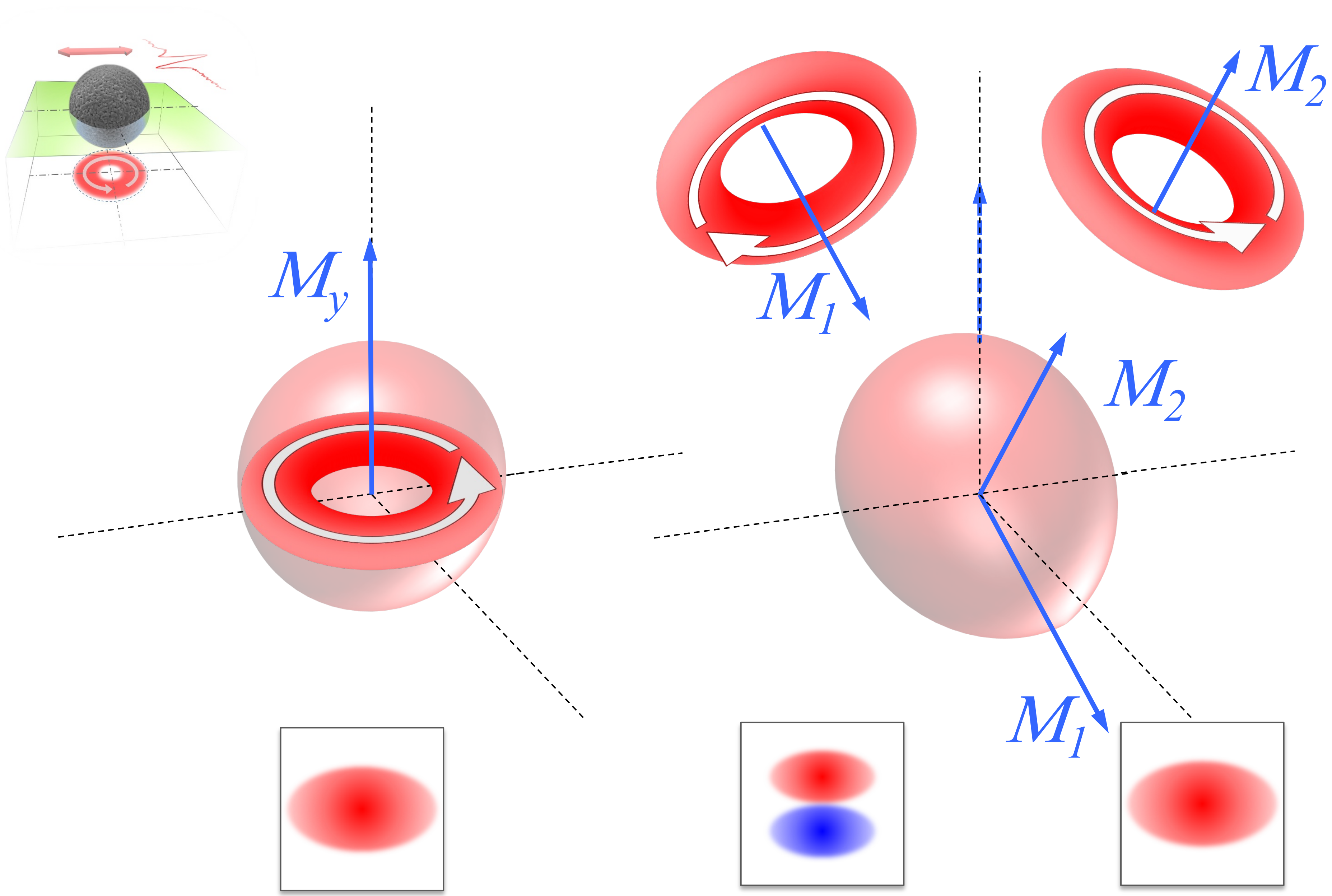


Near-field structure in time-domain

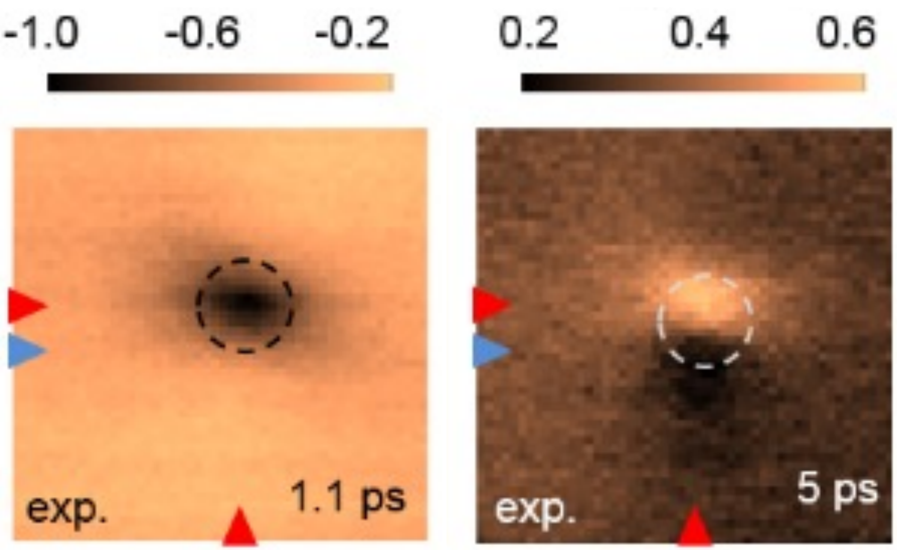


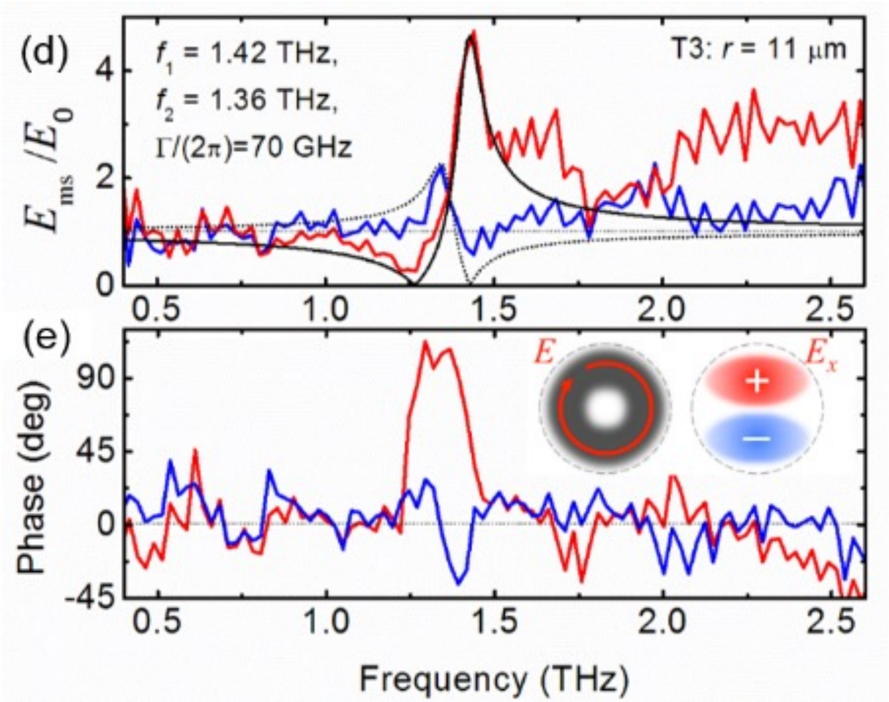


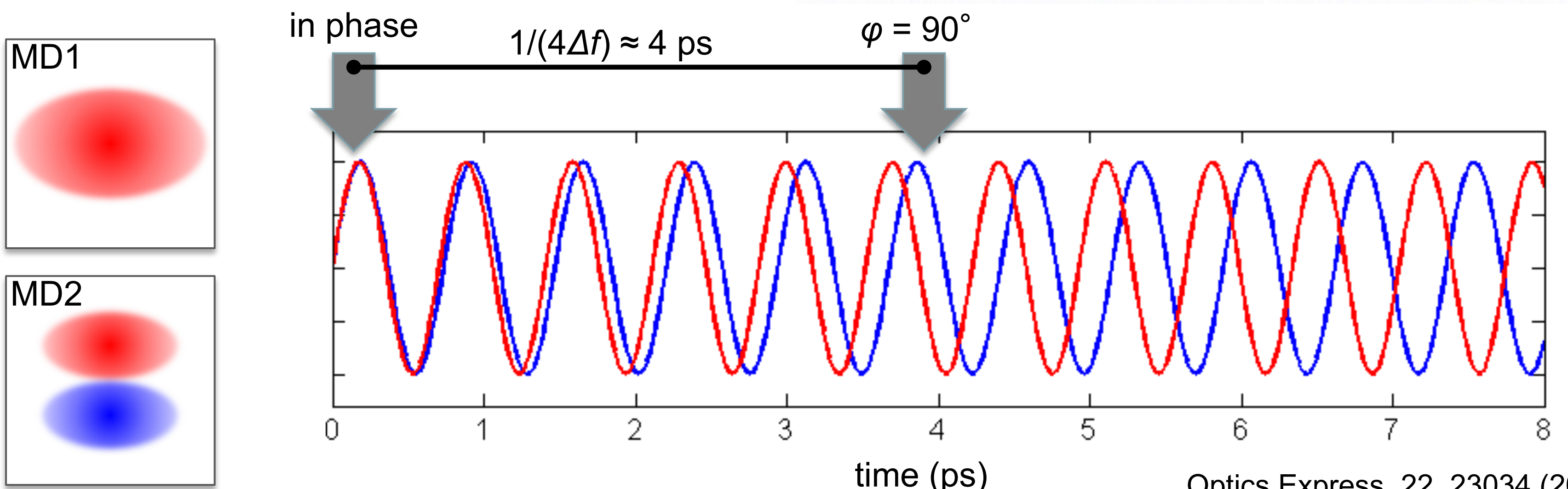
Resonator non-sphericity



Resonator non-sphericity







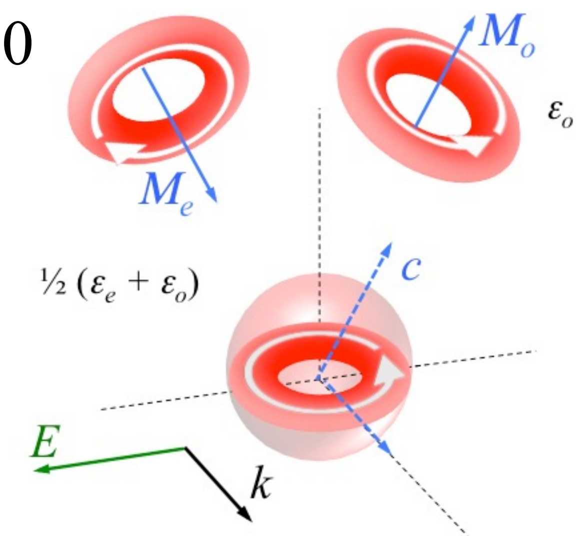
Optics Express, 22, 23034 (2014)

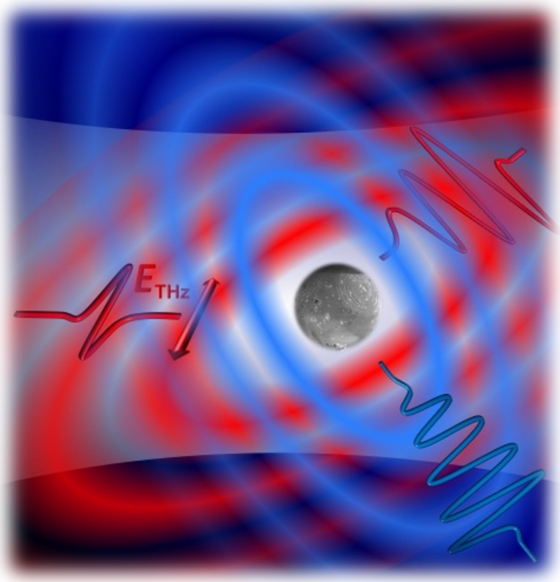
Anisotropic Dielectric THz Resonators:

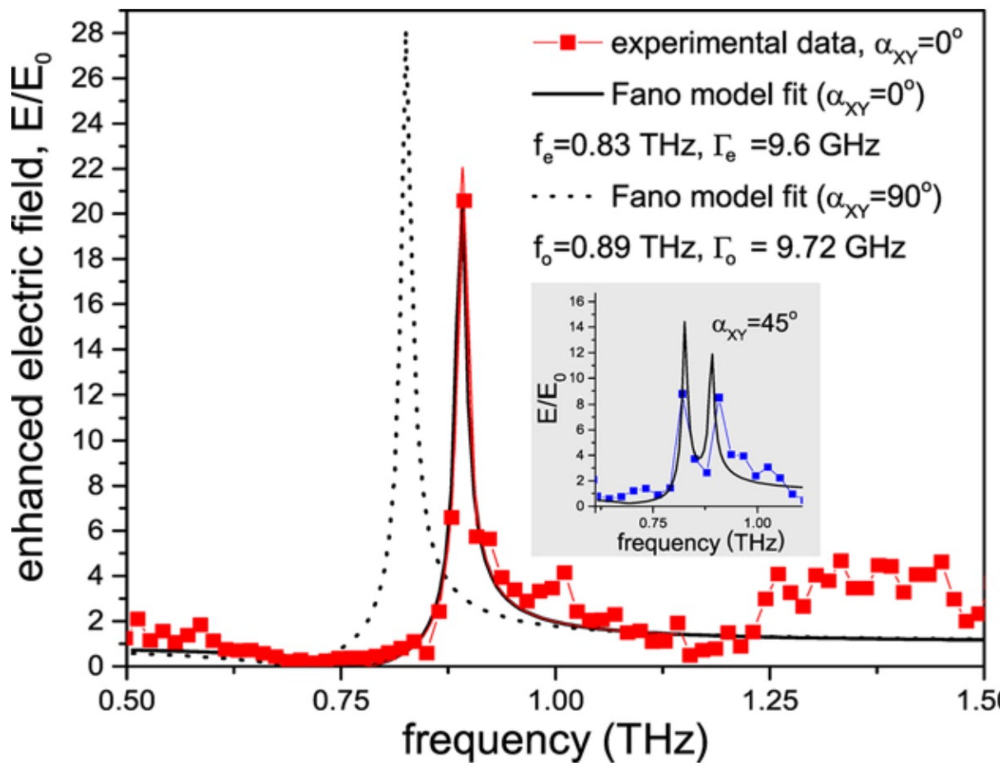
Single crystal TiO_2:

$\varepsilon_e = \sim 150$;

$\varepsilon_o = \sim 70$



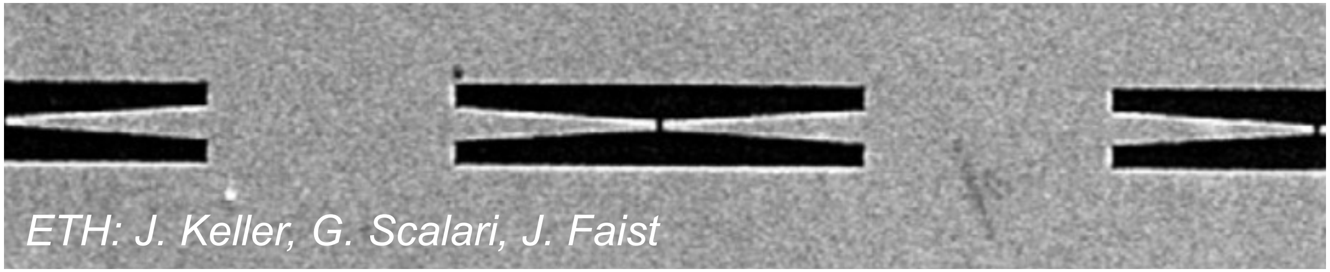


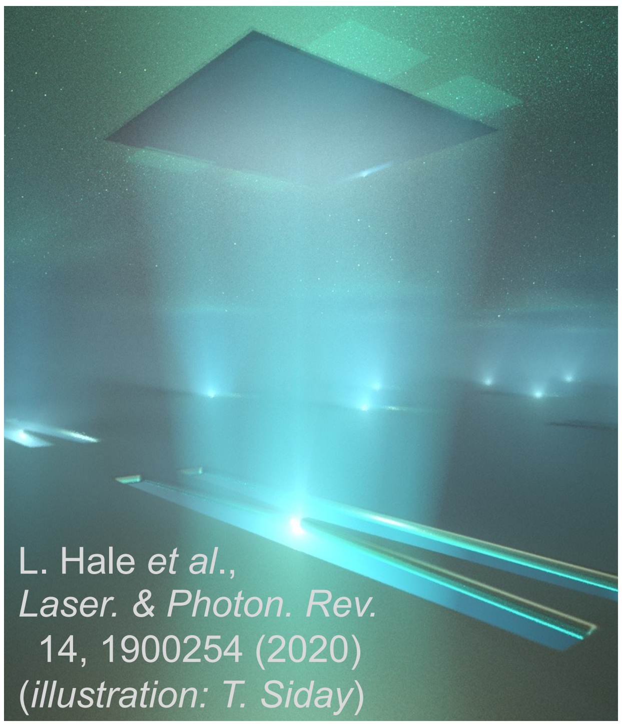


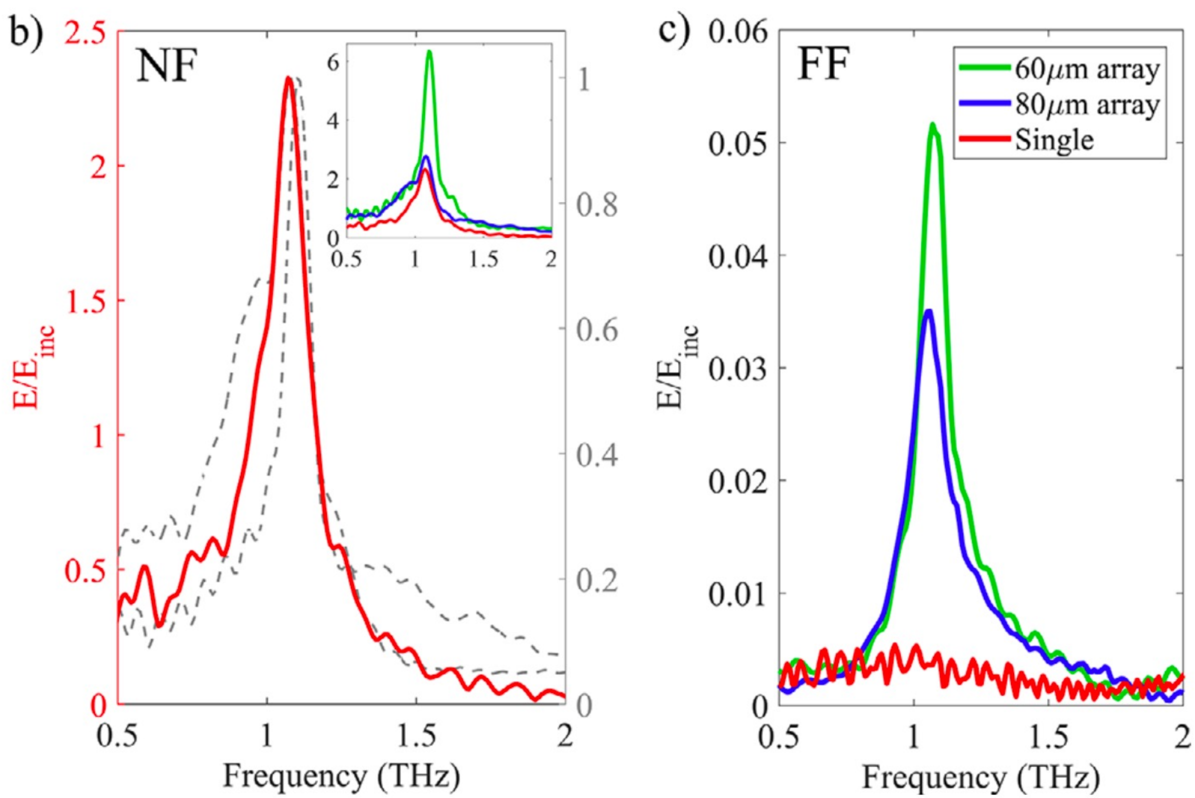
Near-field spectroscopy allows 'seeing' two modes

I. Khromova et al.,
Laser and Photon. Reviews (2016)

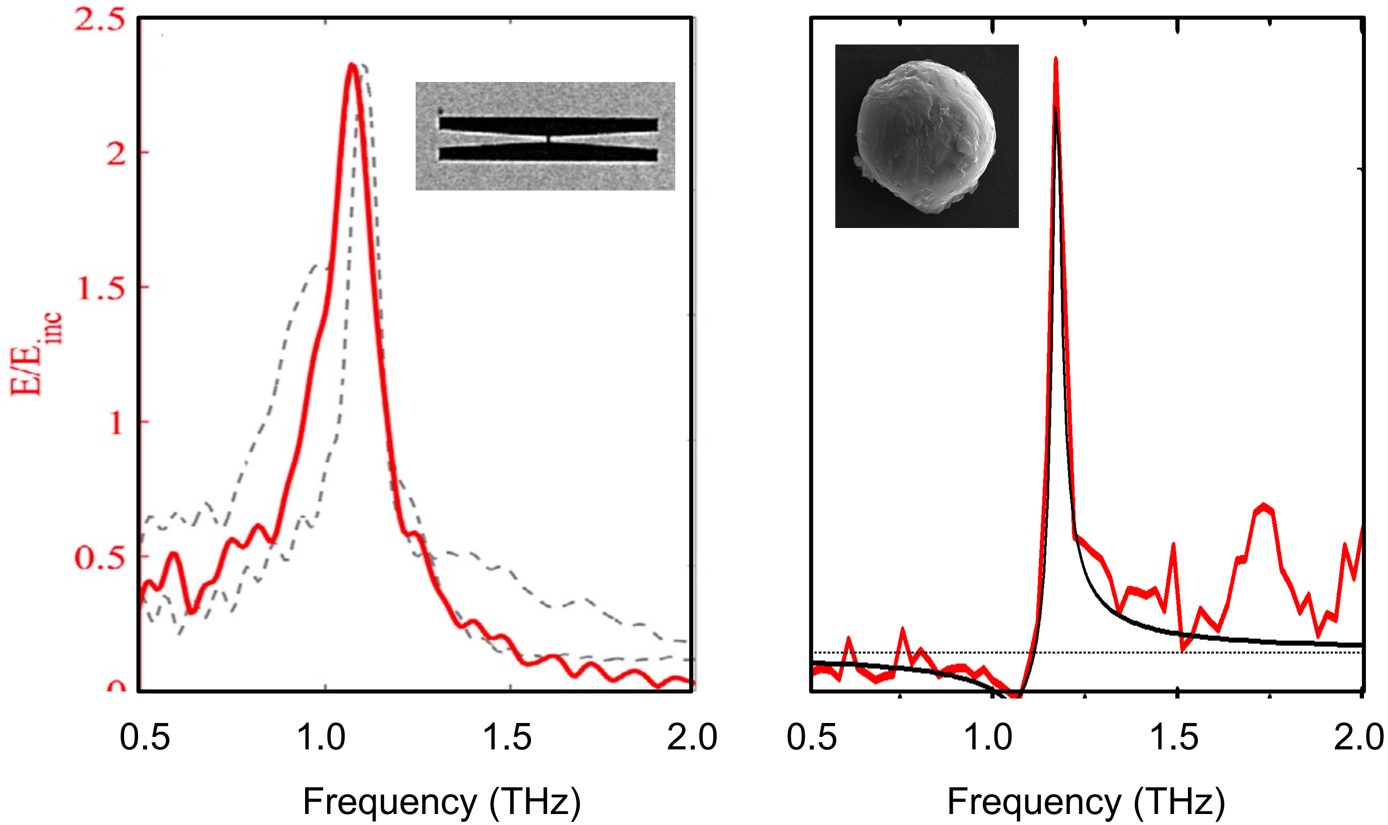
Single resonator sensitivity – Plasmonic resonator







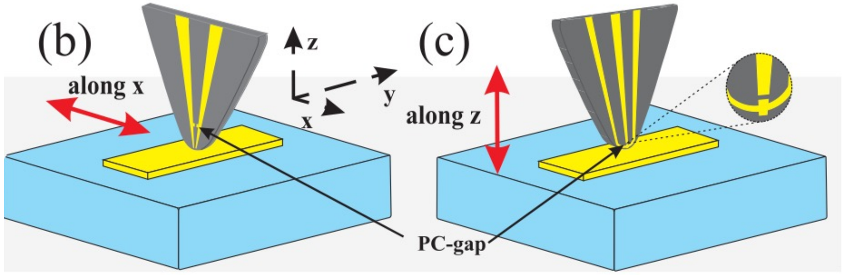
What is detected in THz NF microscopy?

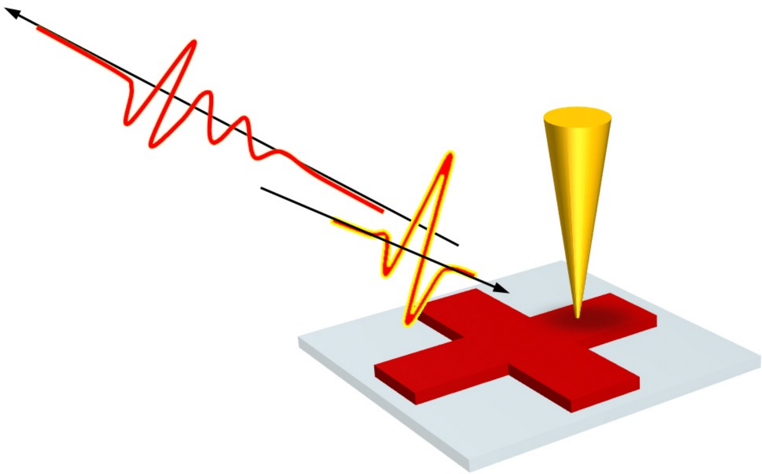


What is detected in THz NF microscopy?

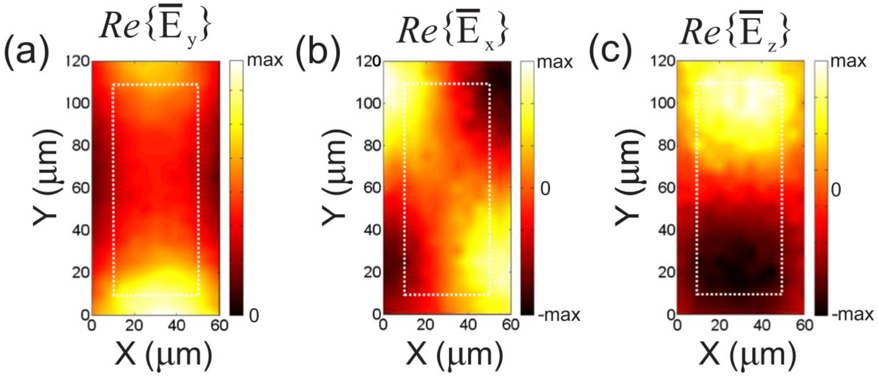
E - field

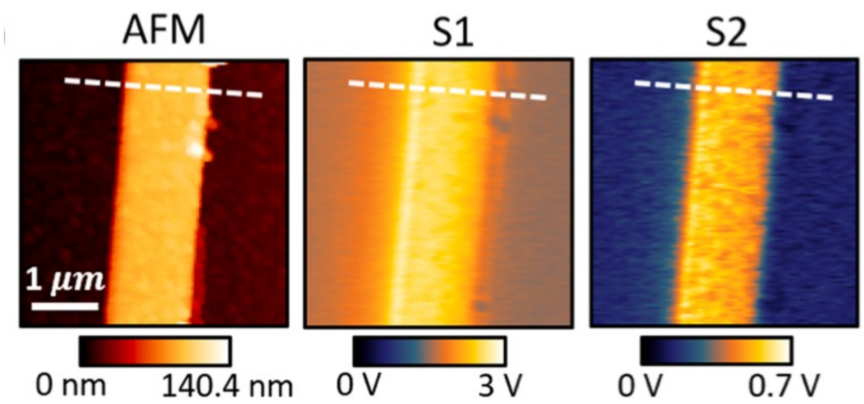
ε - dielectric constant





Commercial Tera-Spike probe / Protemics
www.protemics.com

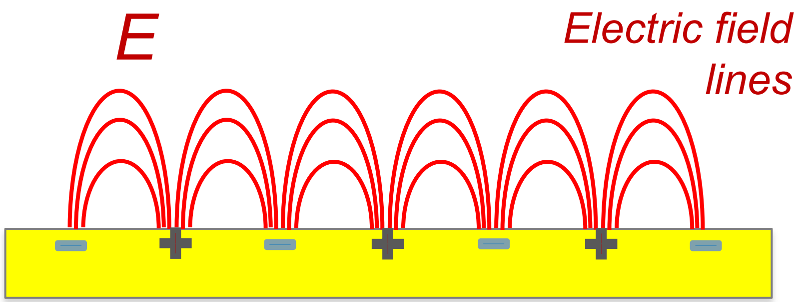


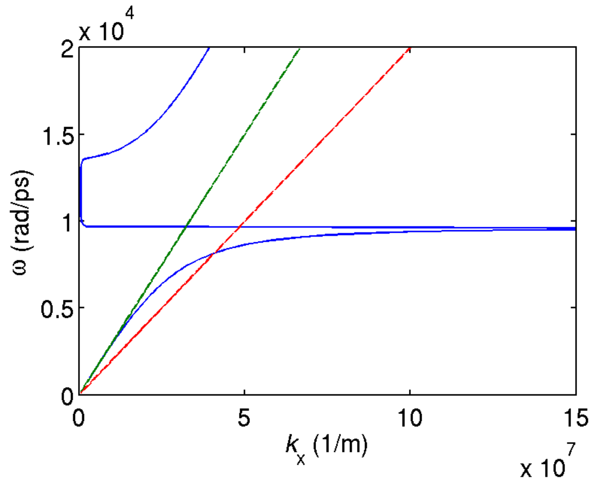


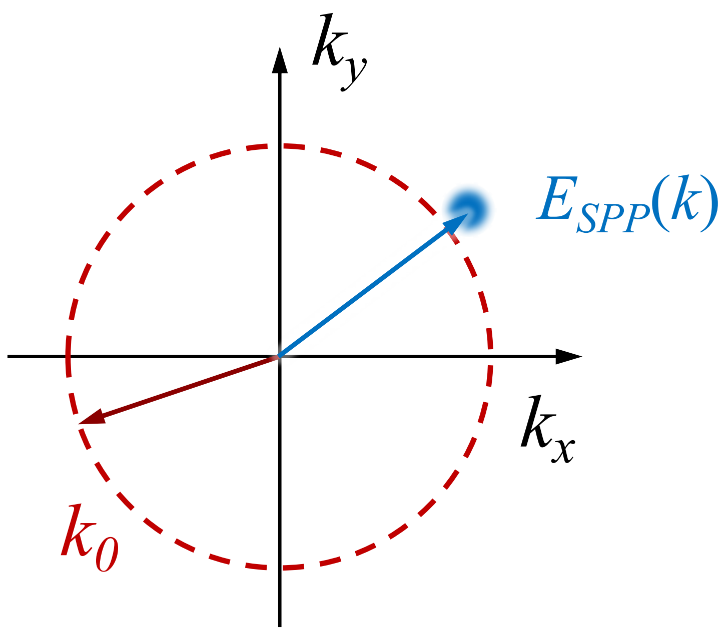
Bhattacharya and Rivas,
APL Photonics 1, 086103 (2016)

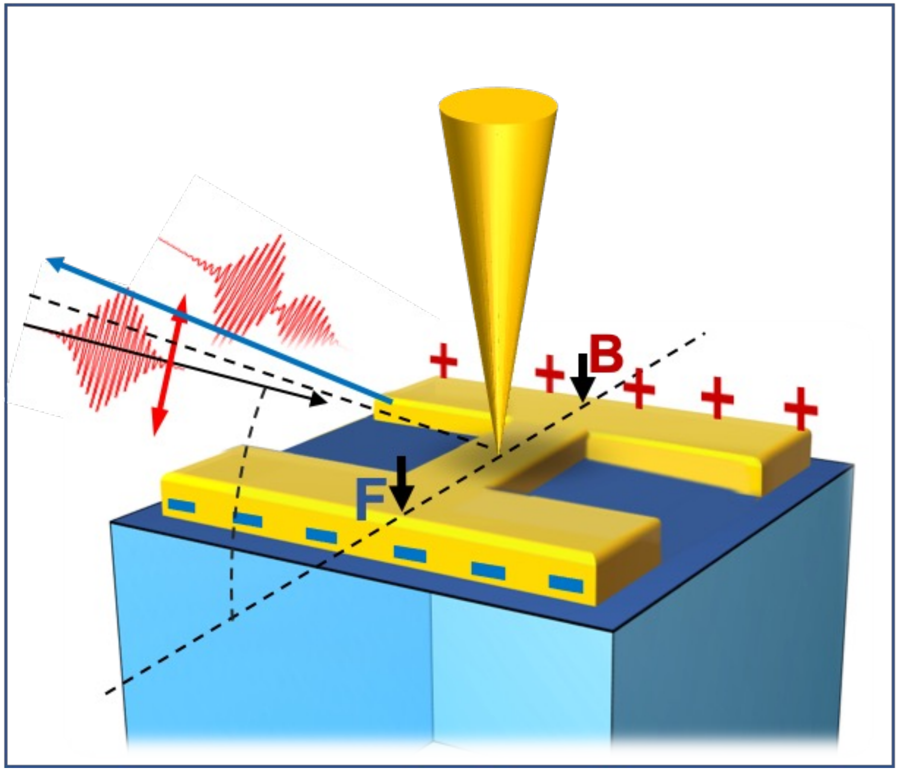
X. Chen et al. *ACS Photonics* **7**, 687 (2020)

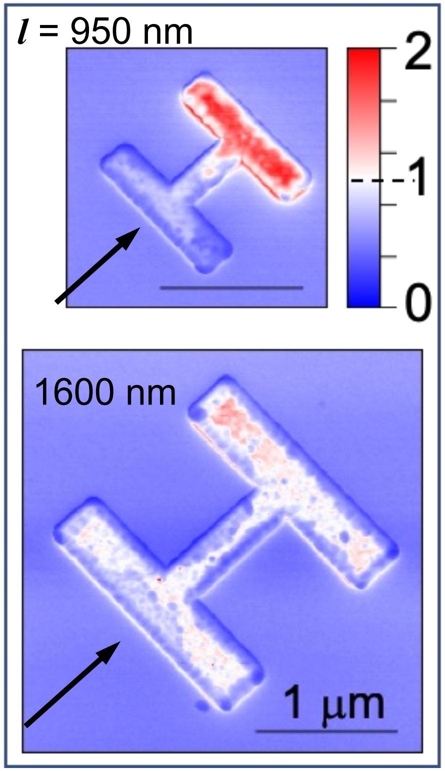
THz surface plasmon waves







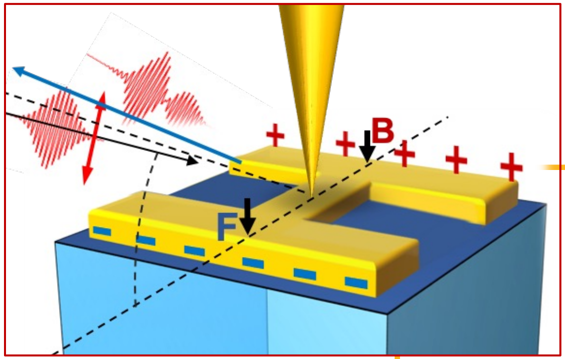


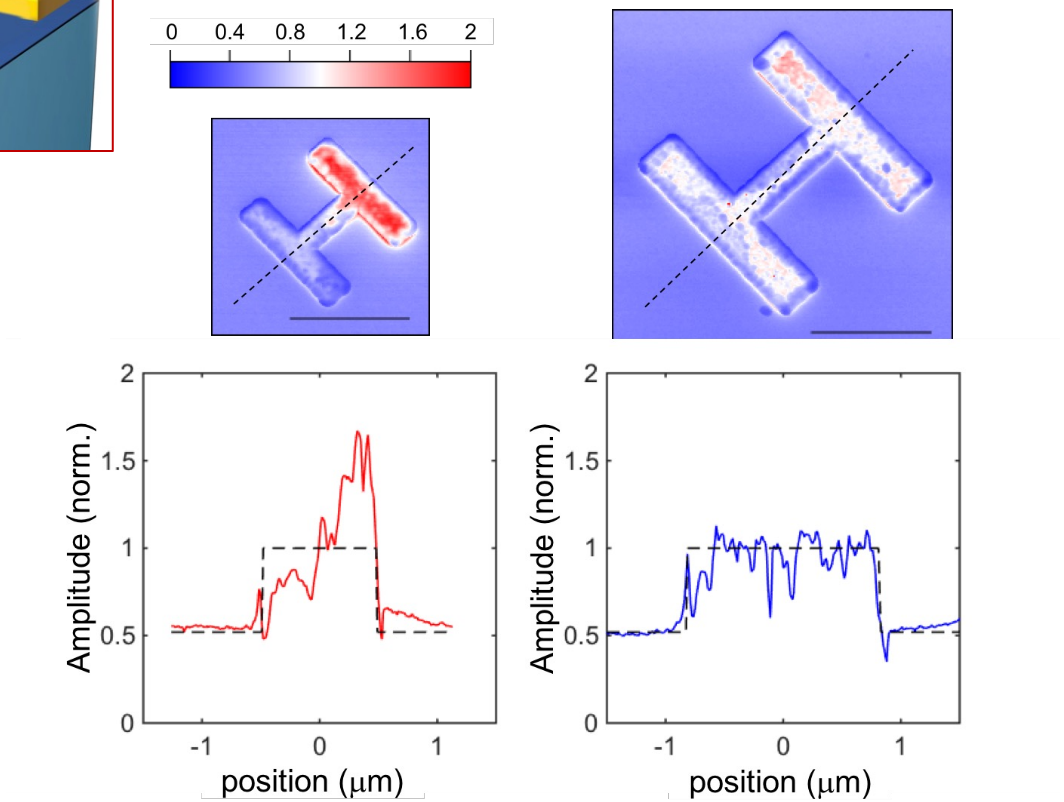


CW excitation (QCL)
λ: 10 μm (1000 cm^{-1})

Wang et al., *Nano Lett.* 2019, 19, 4620−4626

Surface plasmon waves – s-SNOM





E – field

+

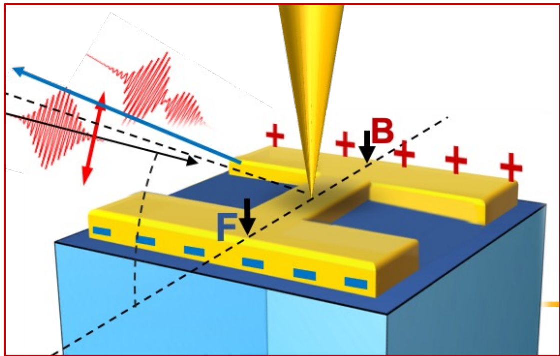
$\mathcal{E}$ - dielectric constant

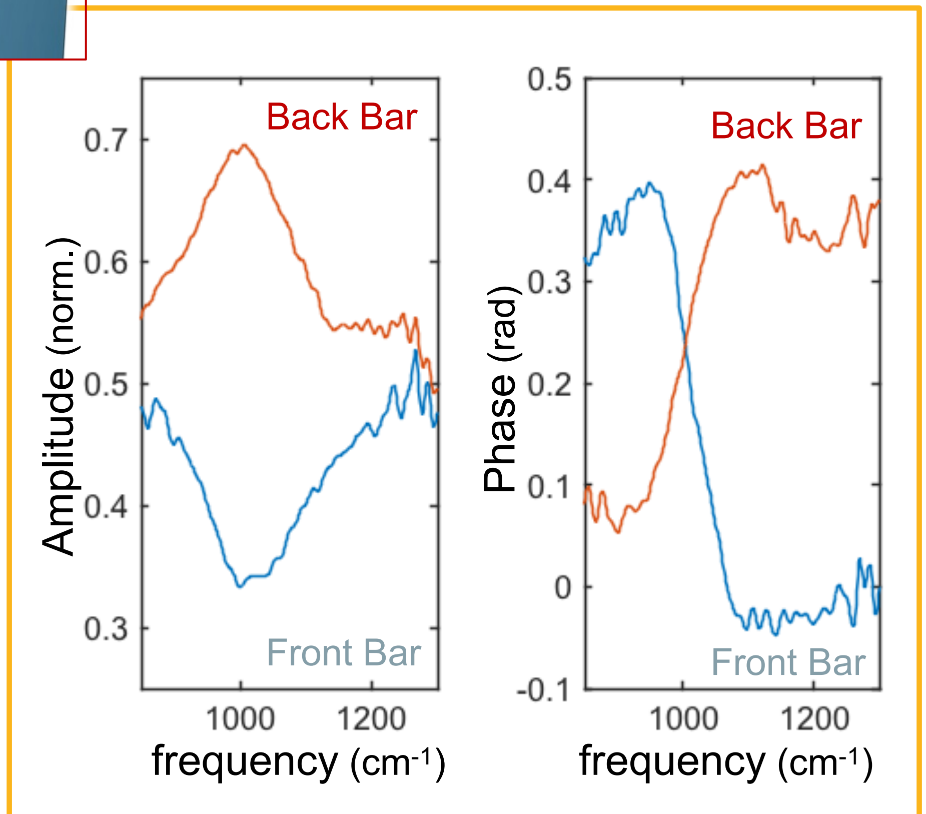
$\mathcal{E}$ - dielectric constant

Antenna resonance is superimposed over the material contrast

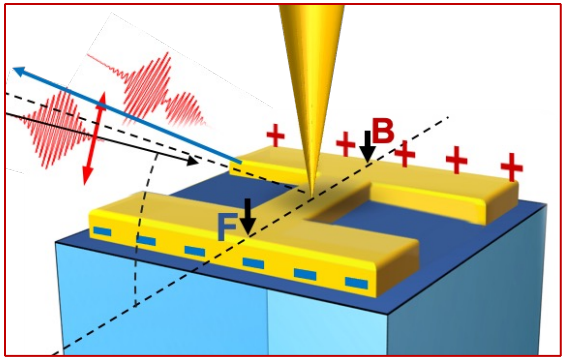
Wang et al., *Nano Lett.* 2019, 19, 4620−4626

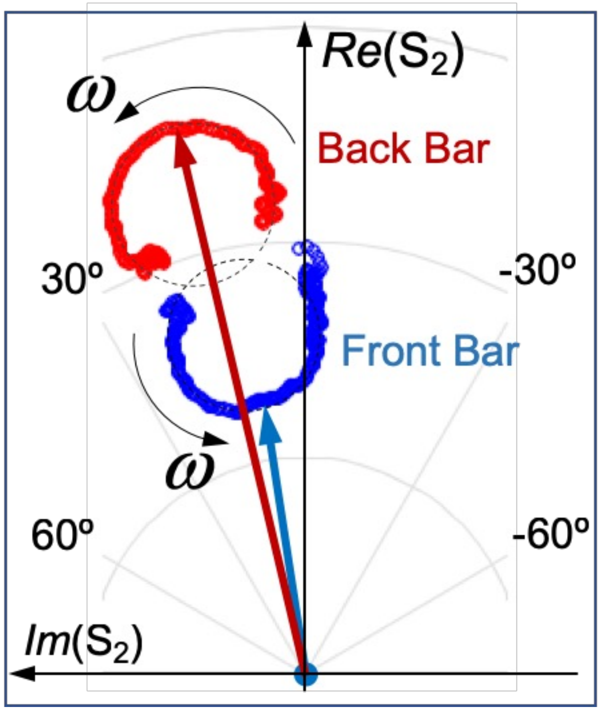
s-SNOM – nano-FTIR

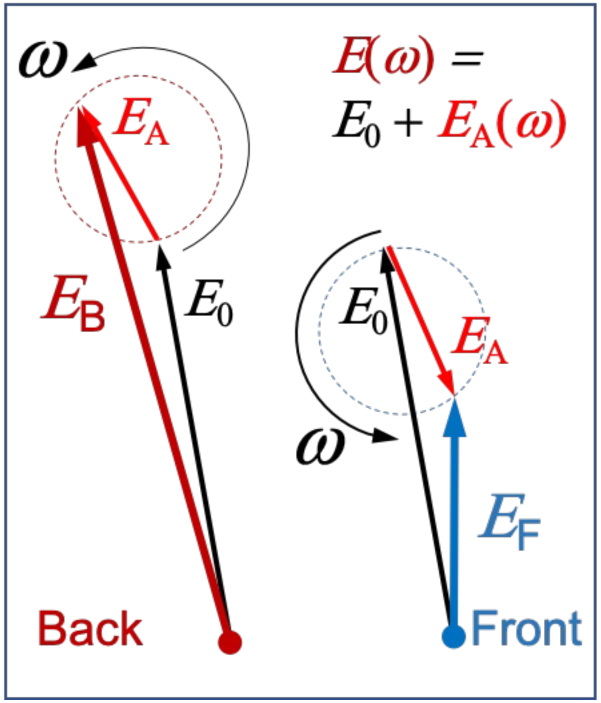




Wang et al., *Nano Lett.* 2019, 19, 4620−4626



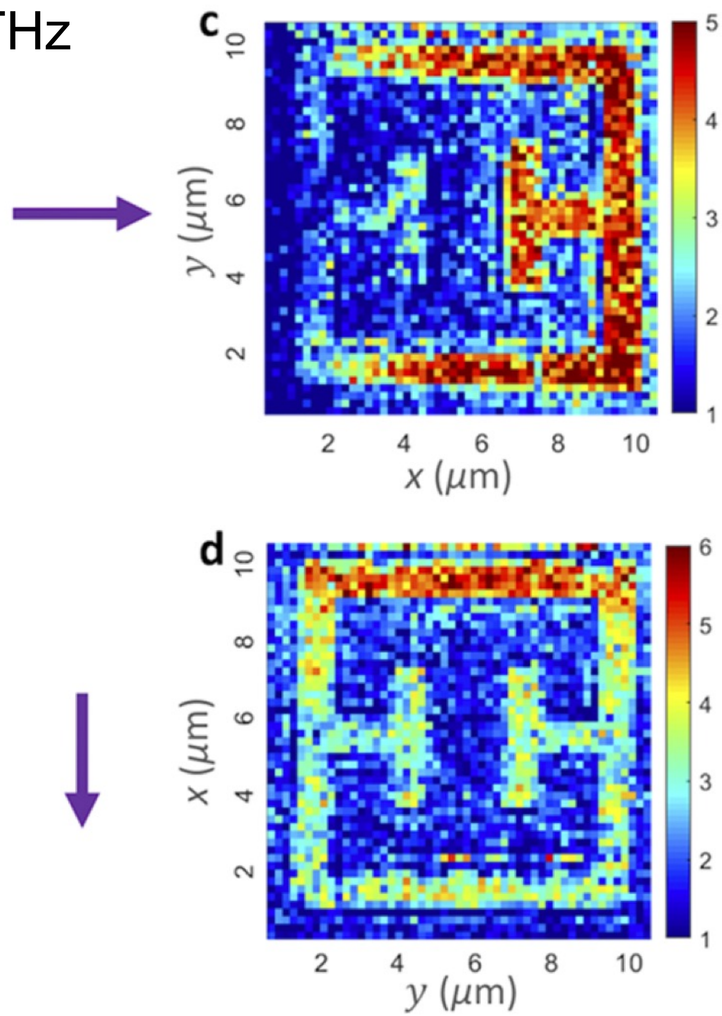




Wang et al., *Nano Lett.* 2019, 19, 4620−4626

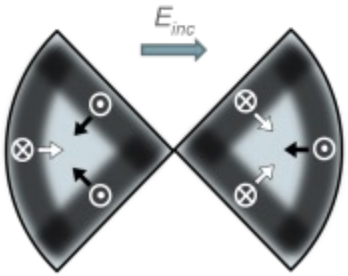
Surface plasmon resonances – THz-s-SNOM

3.45 THz

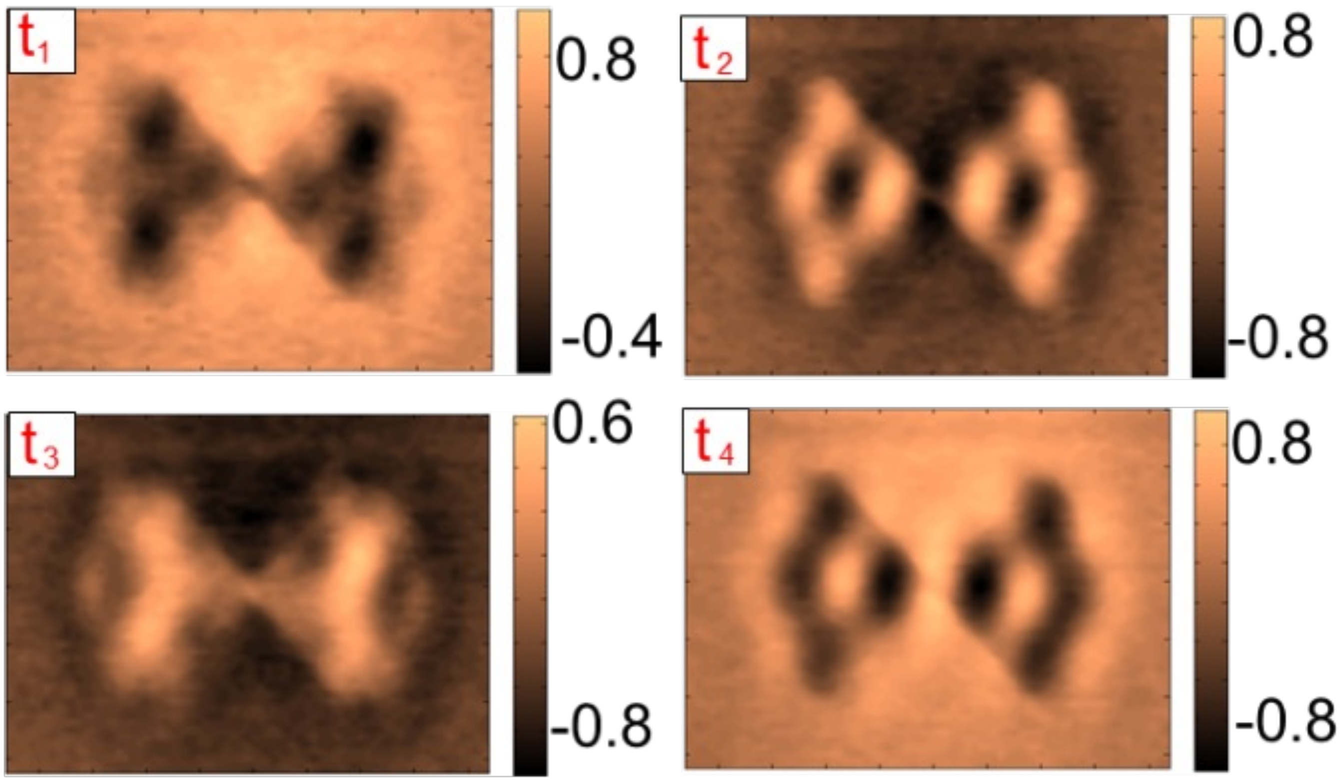


N. Sulollari *et al.*,
APL Photon. 6, 066104 (2021)

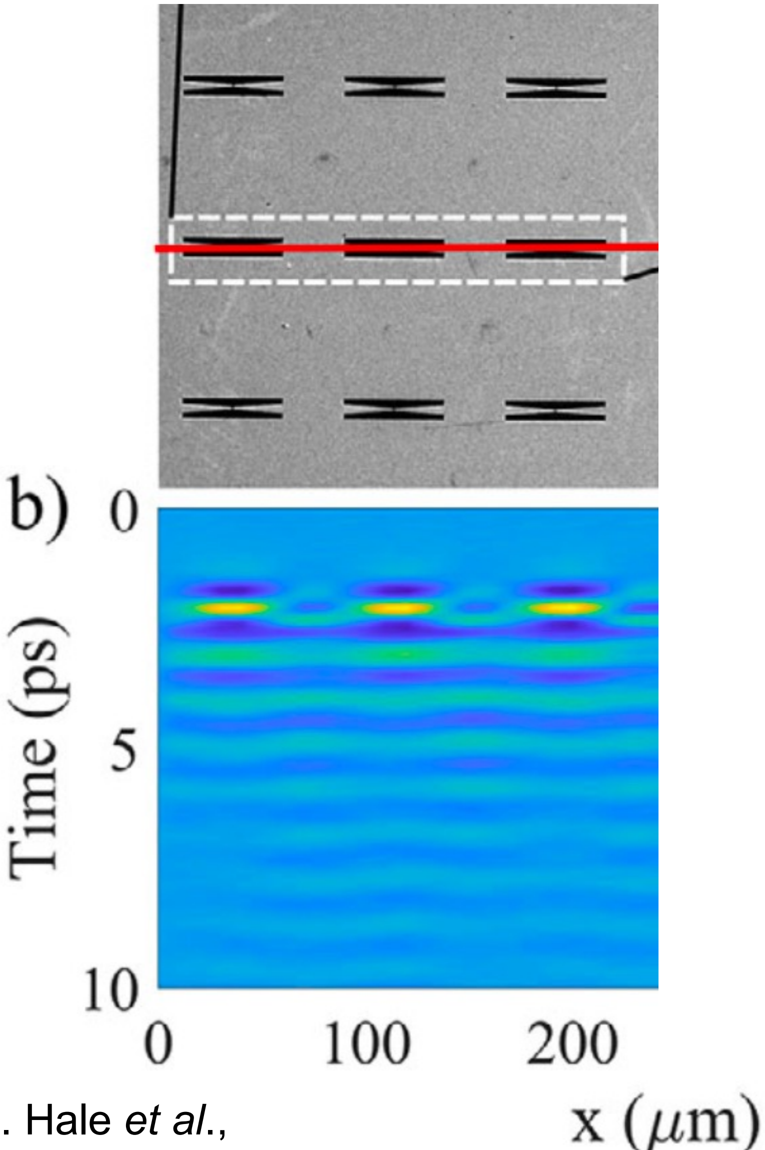
THz SPP patterns



Consecutive images ("frames") ~0.13 picosecond apart

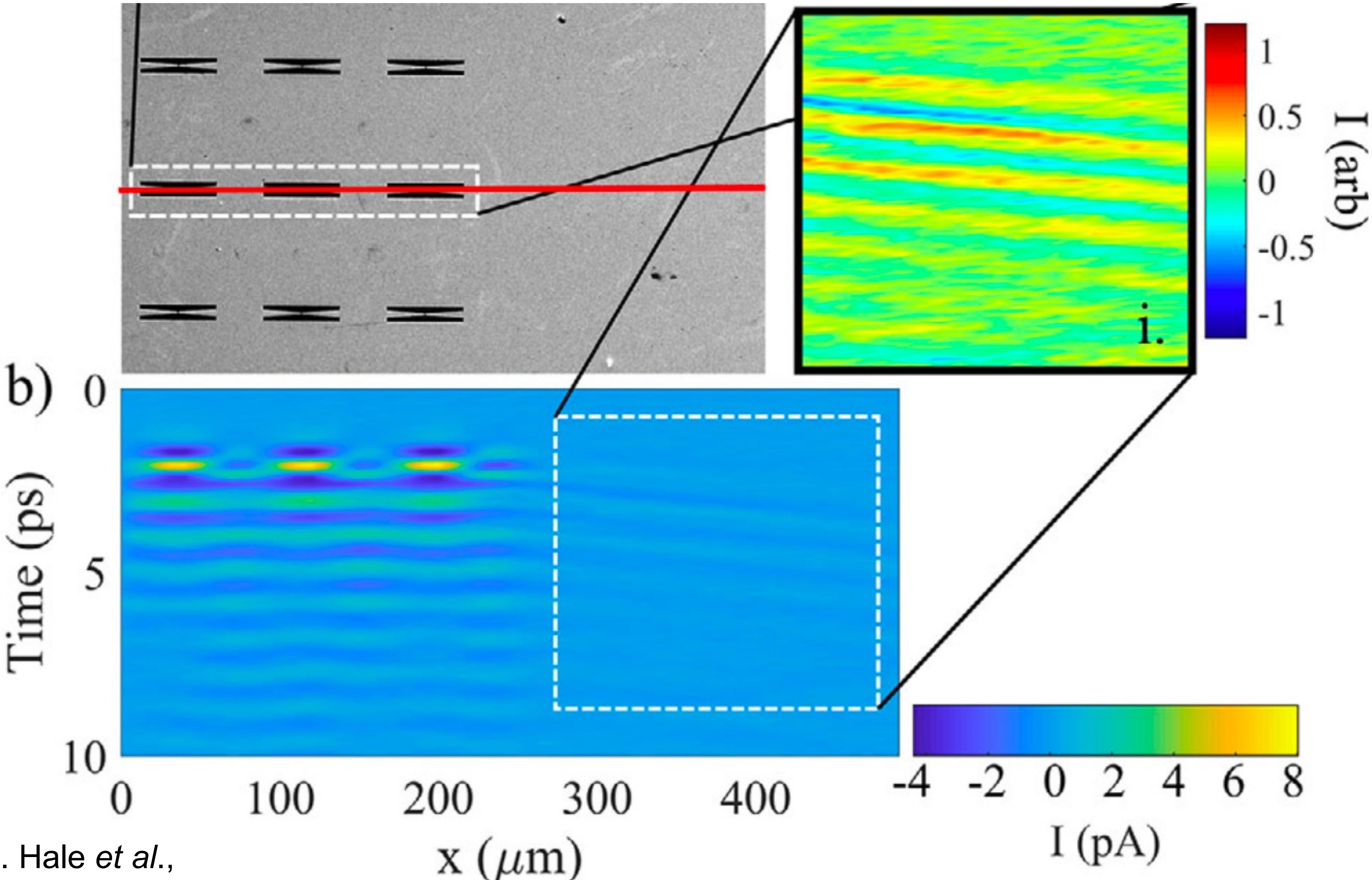


Mueckstein *et al.*, J.of IRMMW 32, 1031 (2011)



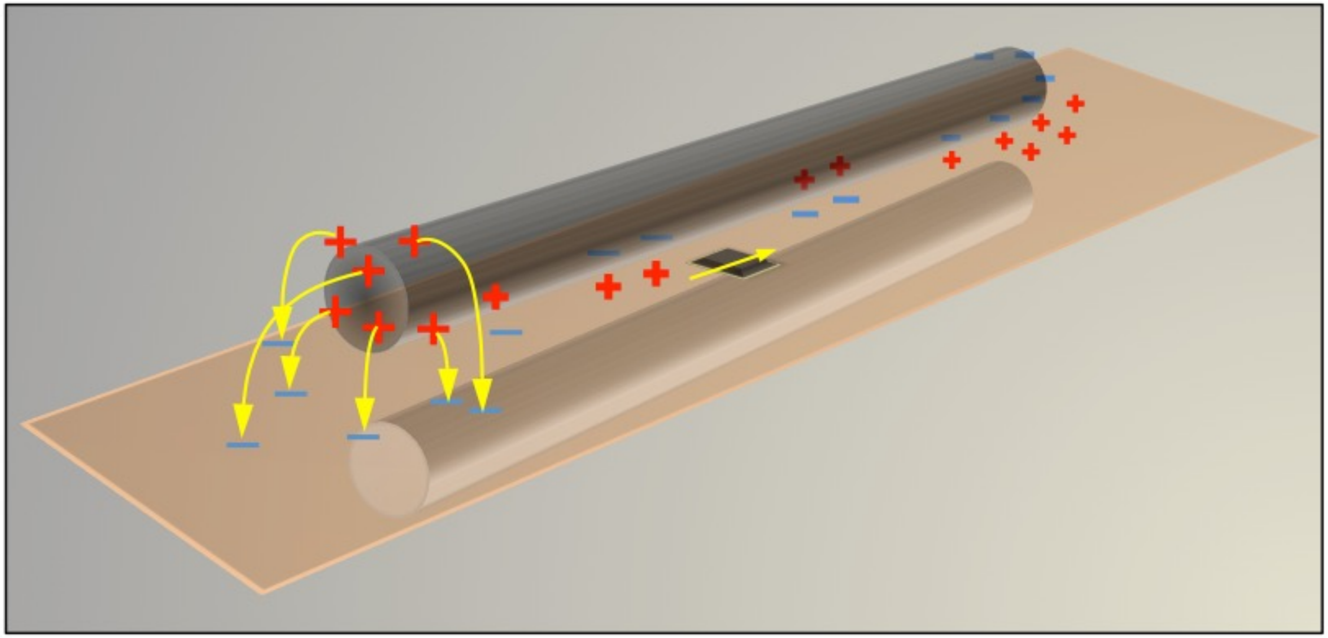
L. Hale *et al.*,
Laser. & Photon. Rev.
14, 1900254 (2020)

Surface plasmon waves – THz-a-SNOM

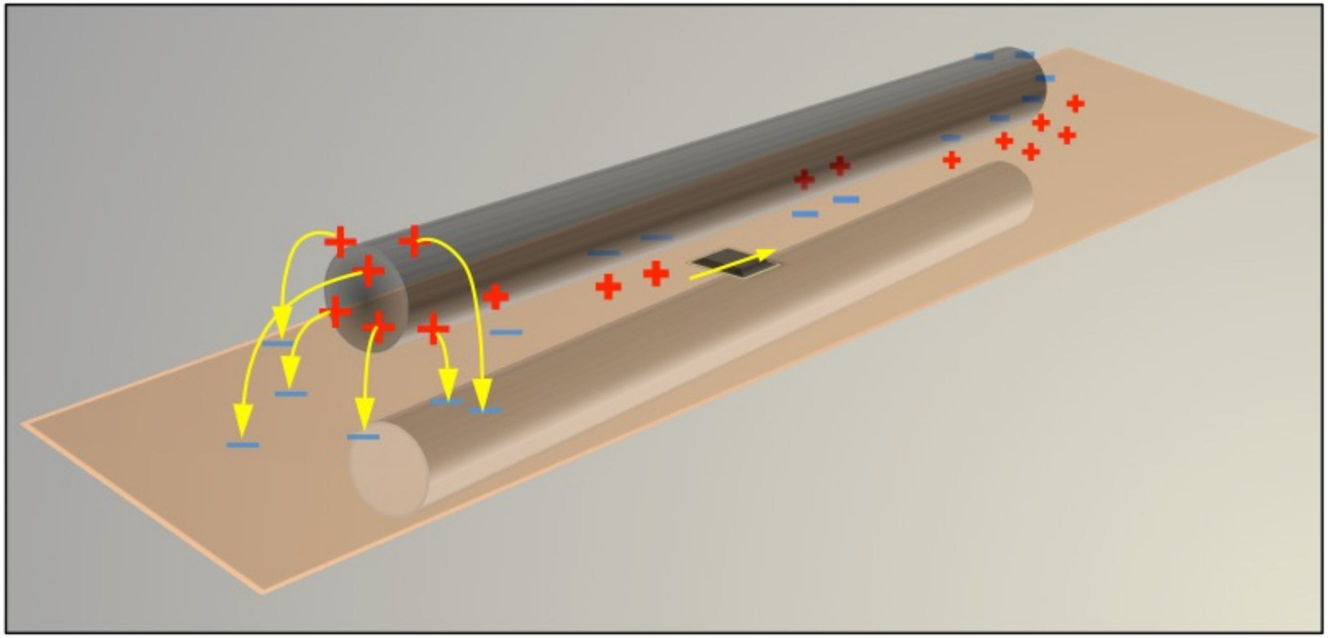


L. Hale *et al.*,
Laser. & Photon. Rev. 14, 1900254 (2020)

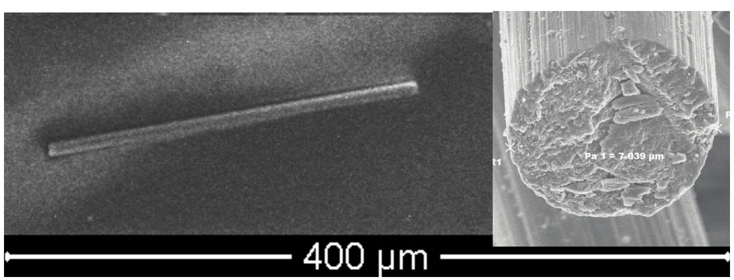
Surface plasmon resonances

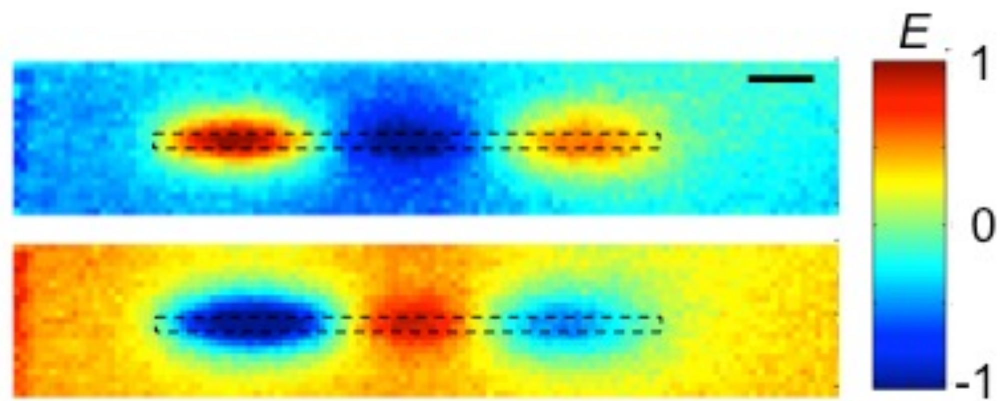


Surface plasmon resonances



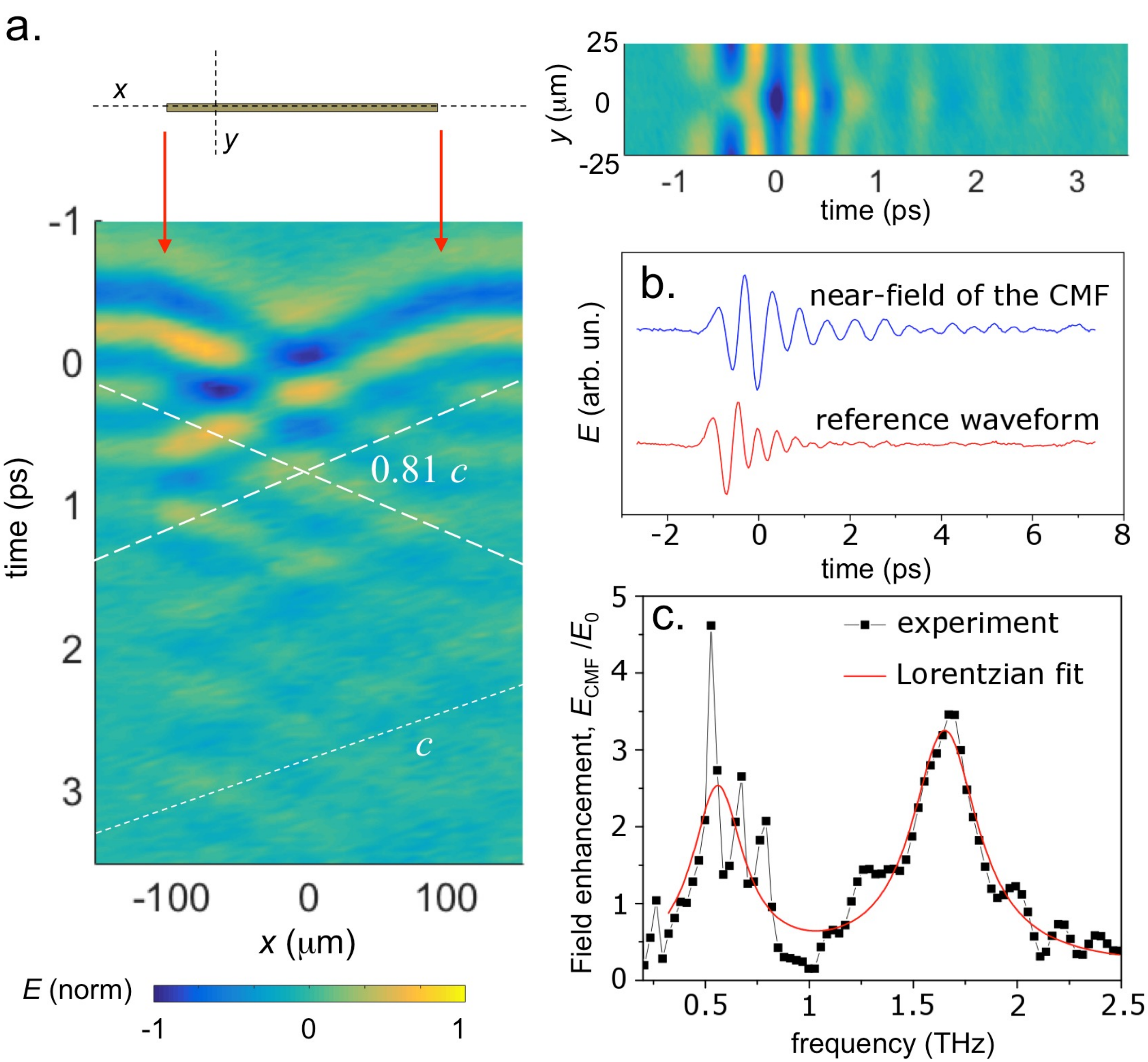
Conductive carbon fibres:
6.5 μm diameter, 50-250 μm long



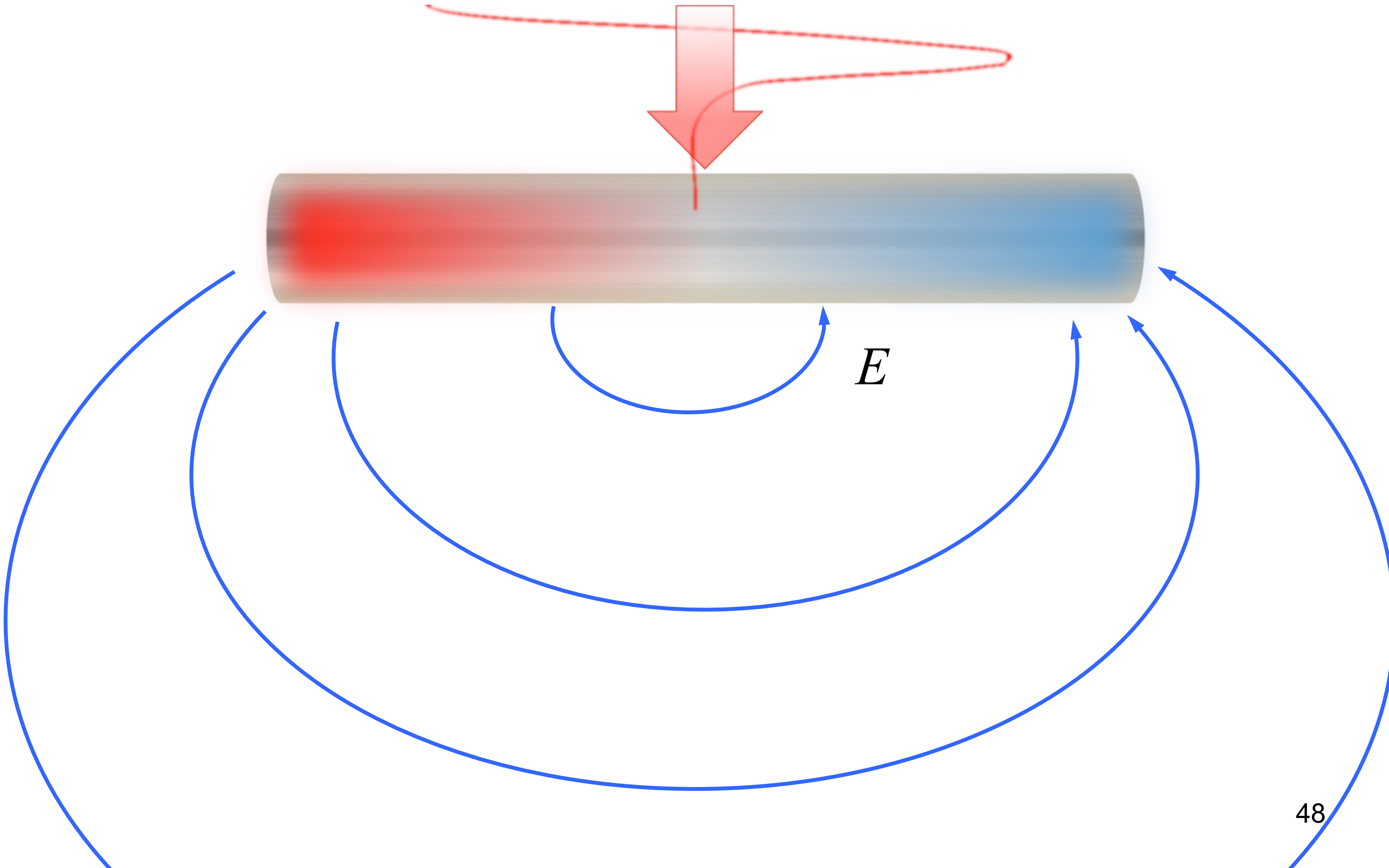


IEEE Trans. THz S&T 6, 382 (2016)

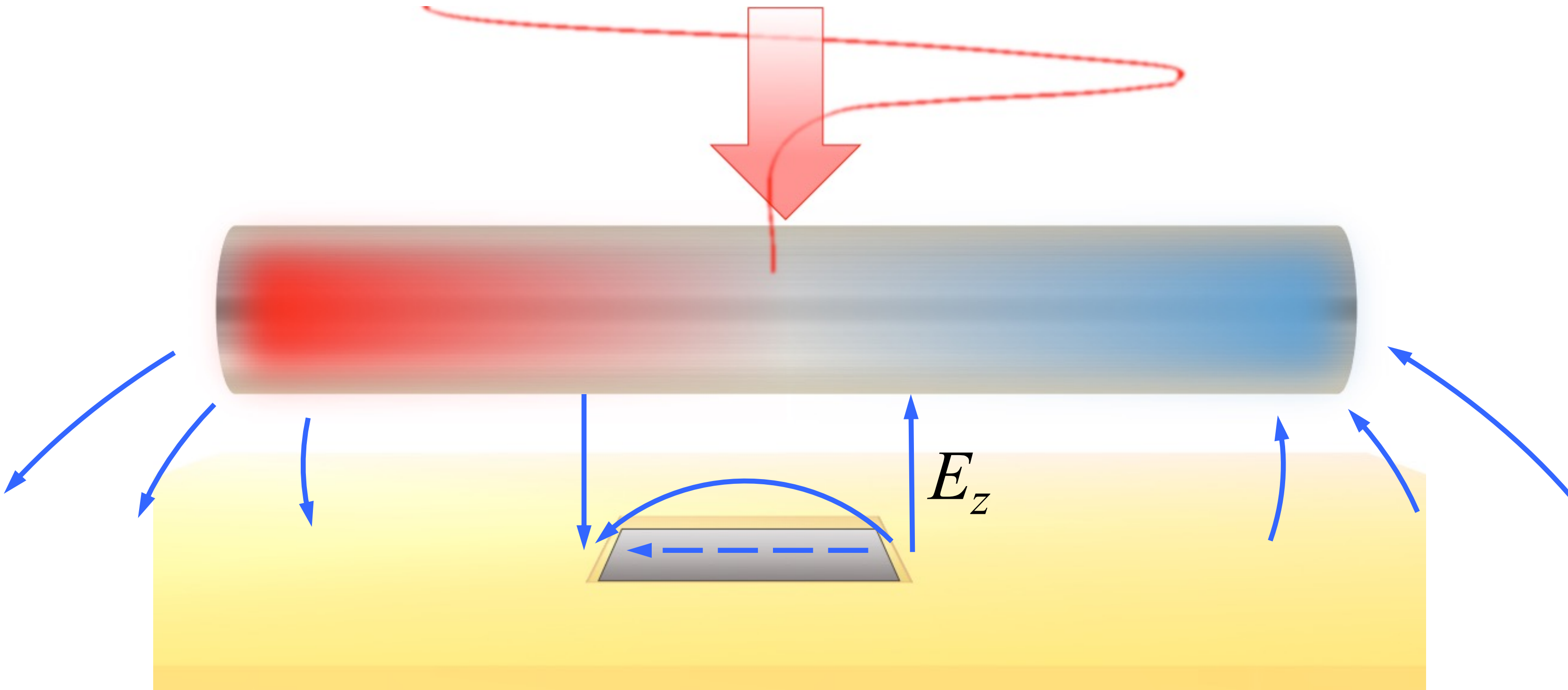
Surface plasmon resonances



THz Surface plasmons – Mapping with Aperture



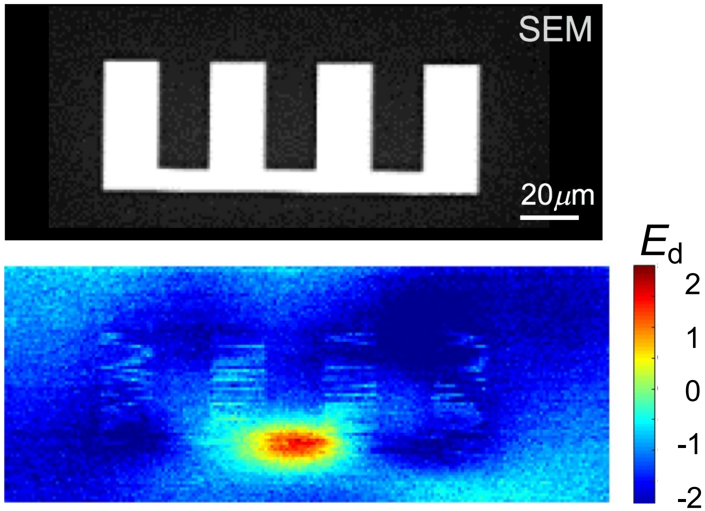
THz Surface plasmons – Mapping with Aperture



$$E_{det} = dE_z / dx \quad a$$

Symmetry changes:
from anti-symmetric to symmetric

THz Surface plasmon resonances



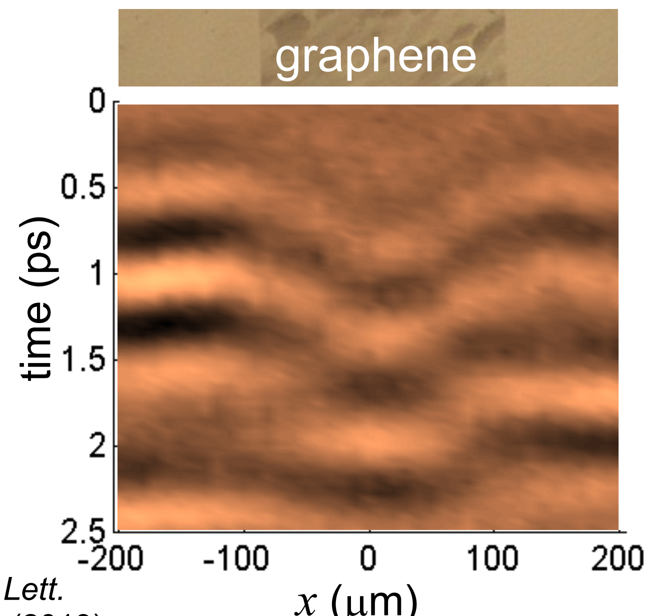
Appl. Phys. Lett. 110 (6), 061109 (2017)

Appl. Phys. Lett. 103, 111105 (2013)

OM, Todorov, et al., *Optics Express 26 (6), 7437 (2018)*

THz Surface plasmon resonances

Appl. Phys. Lett. 110 (6), 061109 (2017)



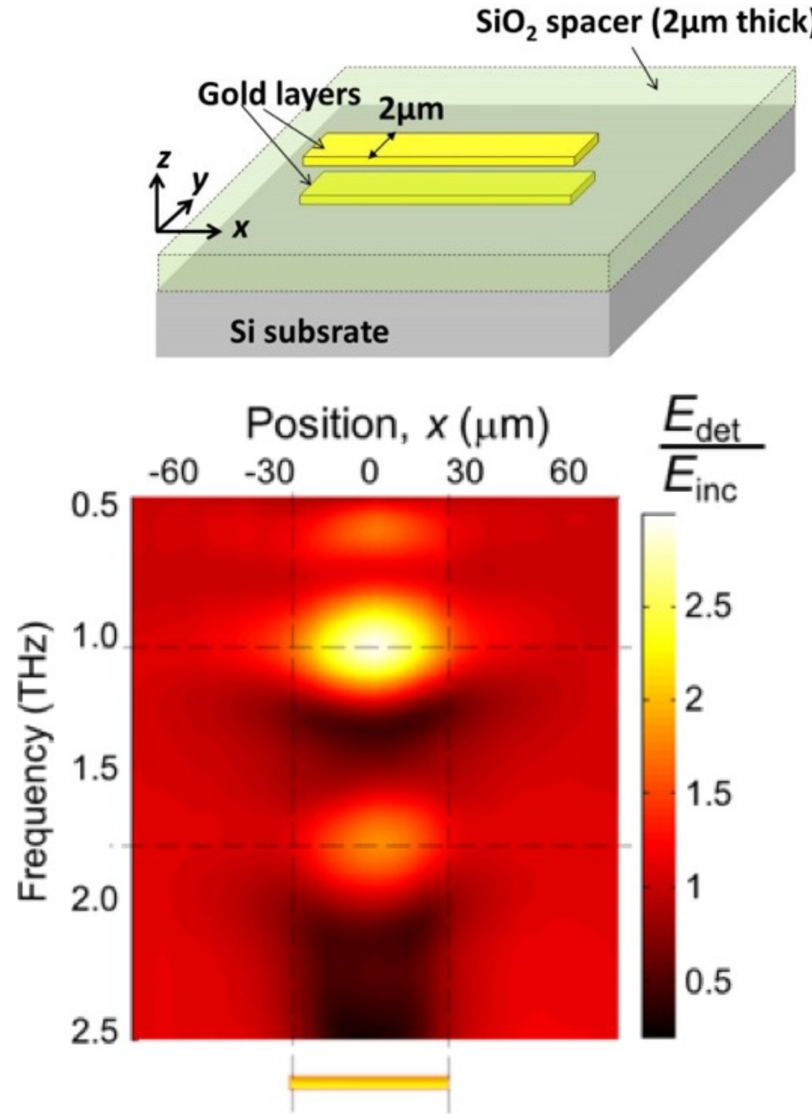
Appl. Phys. Lett.
103, 111105 (2013)

OM, Todorov, et al.,
Optics Express 26 (6), 7437 (2018)

THZ Surface plasmon resonances

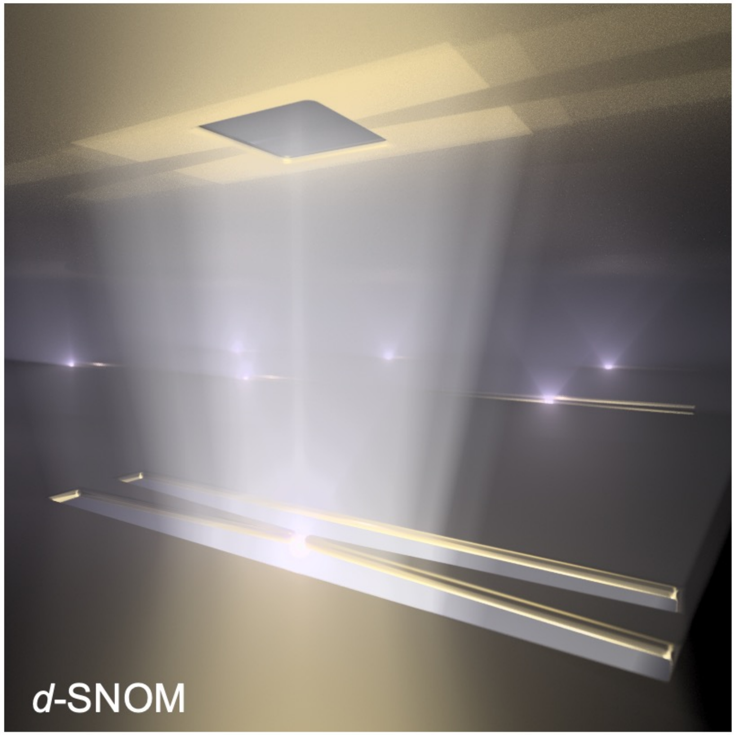
Appl. Phys. Lett. 110 (6), 061109 (2017)

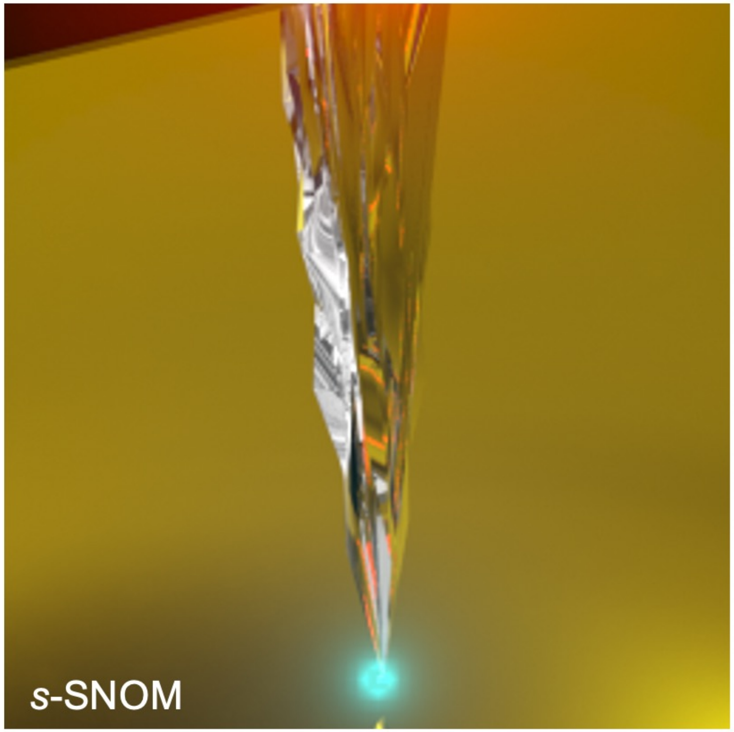
Appl. Phys. Lett. 103, 111105 (2013)



OM, Todorov, et al., *Optics Express 26 (6), 7437 (2018)*

THz NF Microscopy Probes

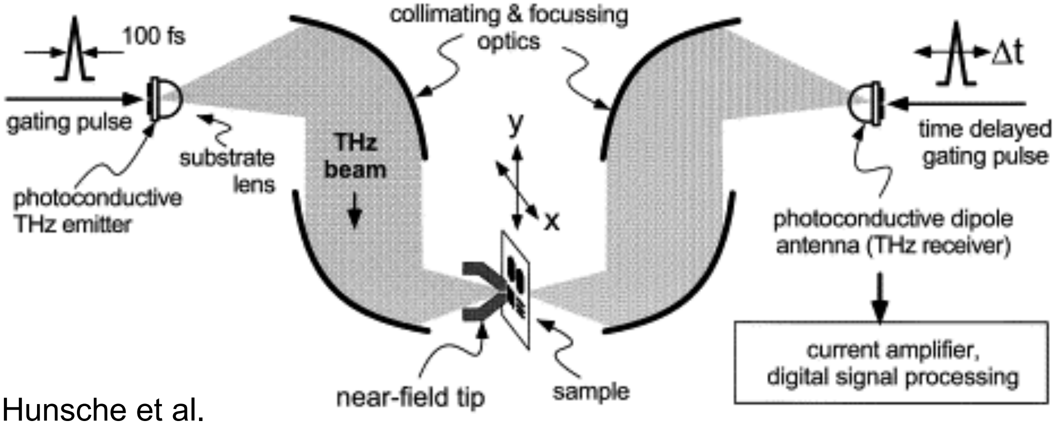




Graphics: Tom Siday

Aperture-type THz Near-Field Microscopy

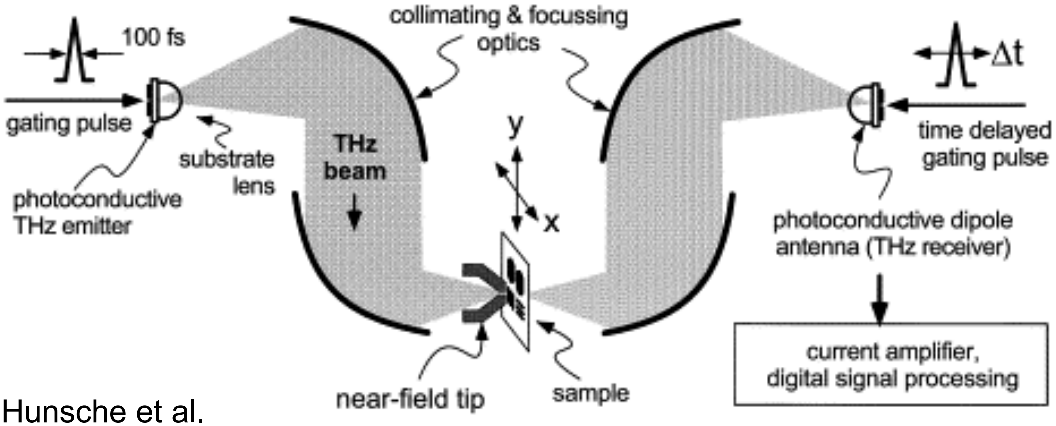
First demonstration of aperture-type THz microscopy (50-80 μm resolution)



Hunsche et al.
OPTICS COMM (1998)

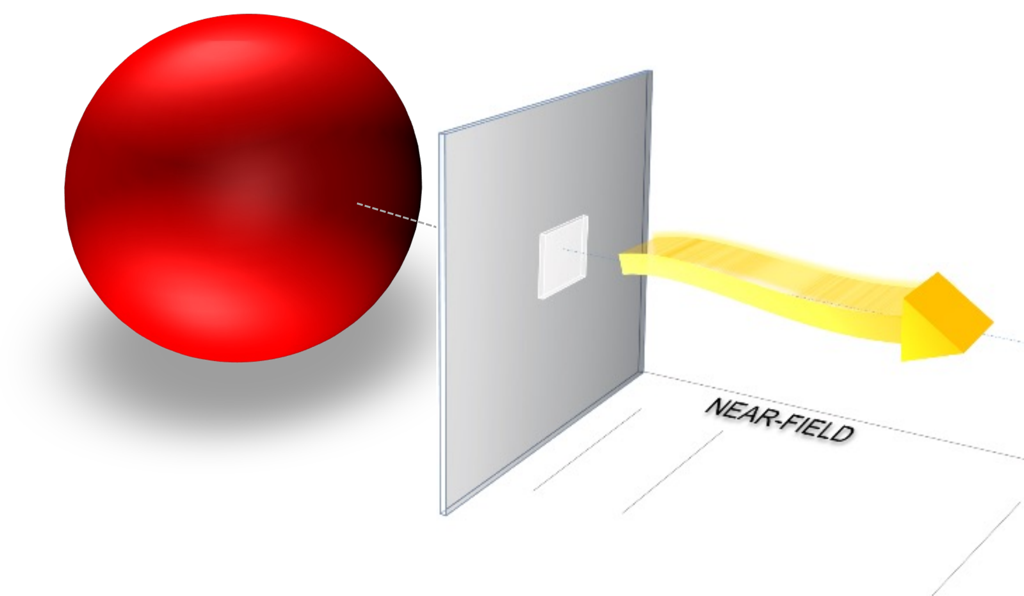
Aperture-type THz Near-Field Microscopy

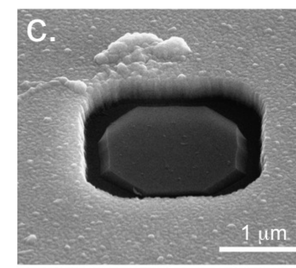
First demonstration of aperture-type THz microscopy (50-80 μm resolution)

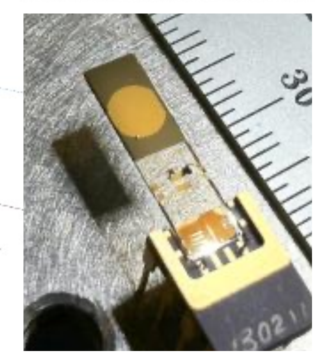


Hunsche et al.
OPTICS COMM (1998)

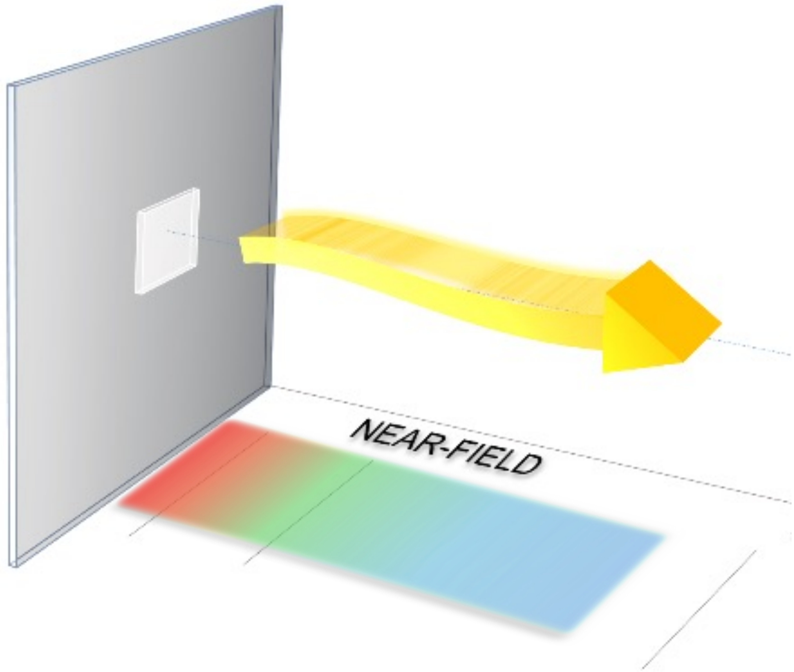
Modern aperture-type THz microscopy
2-5 μm resolution





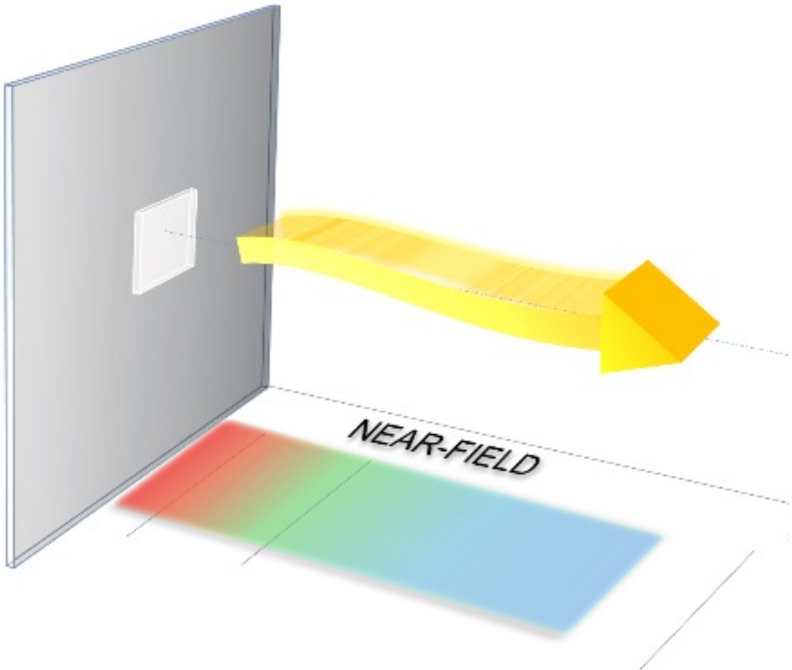


Aperture-type THz Near-Field Microscopy

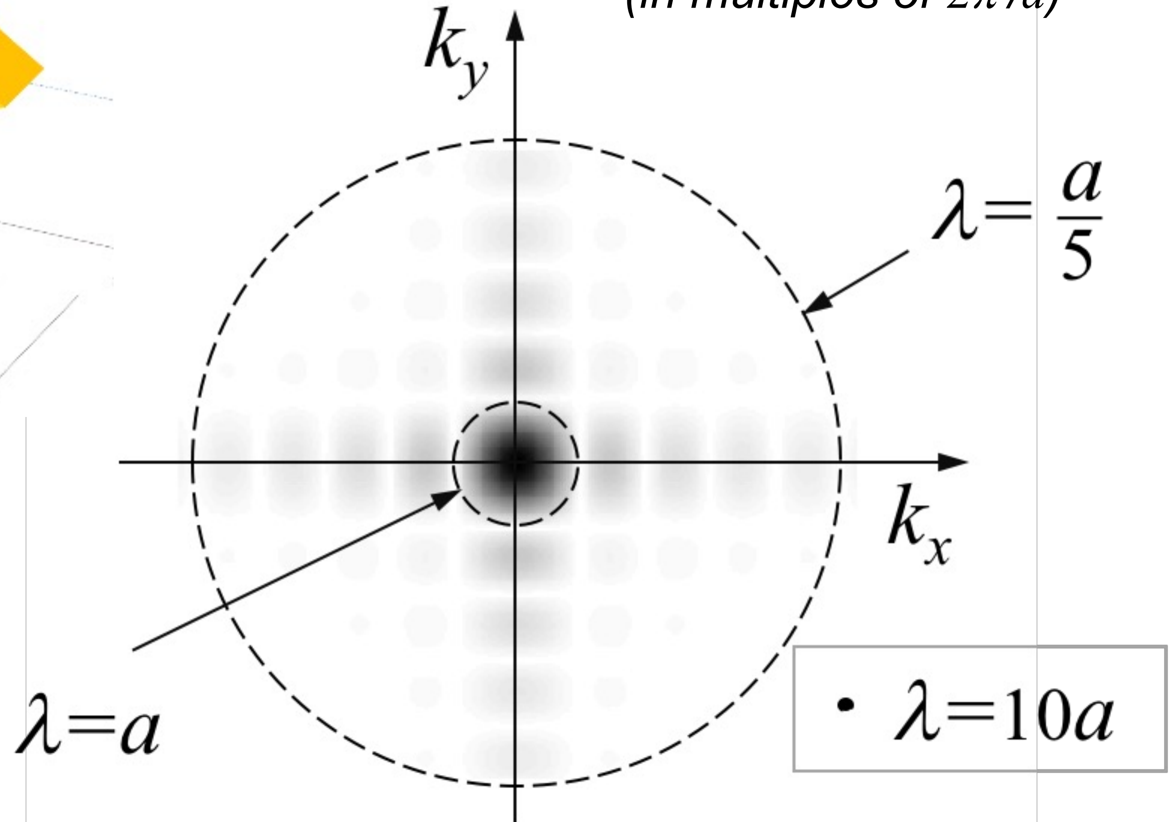


How much light passes through a subwavelength aperture?

Aperture-type THz Near-Field Microscopy

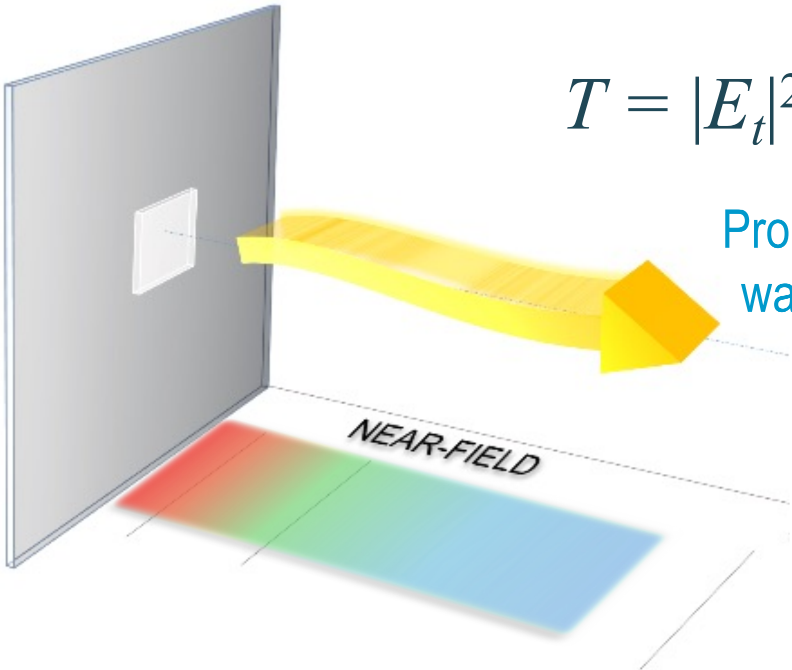


Angular spectrum representation of aperture field (in multiples of $2\pi/a$)

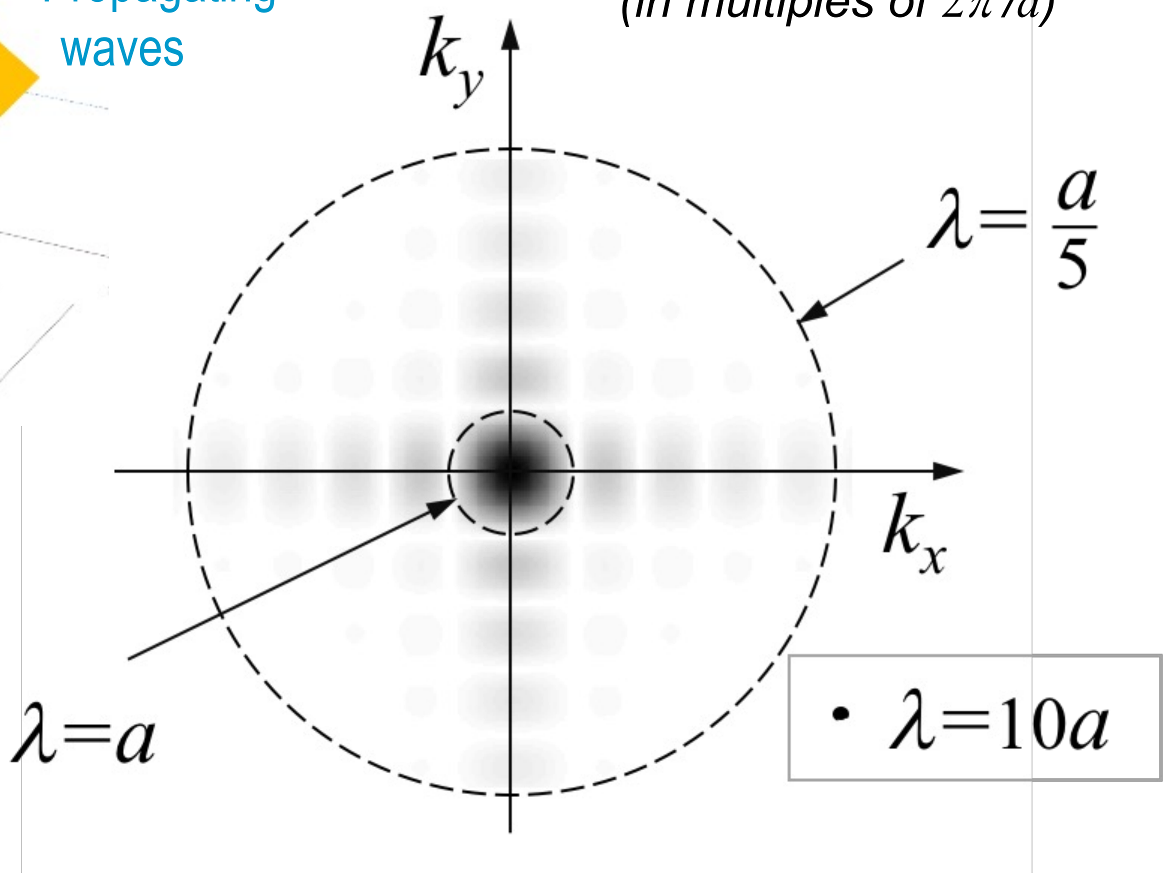


Aperture-type THz Near-Field Microscopy

$$T = |E_t|^2 / |E_{inc}|^2 \sim a^6$$

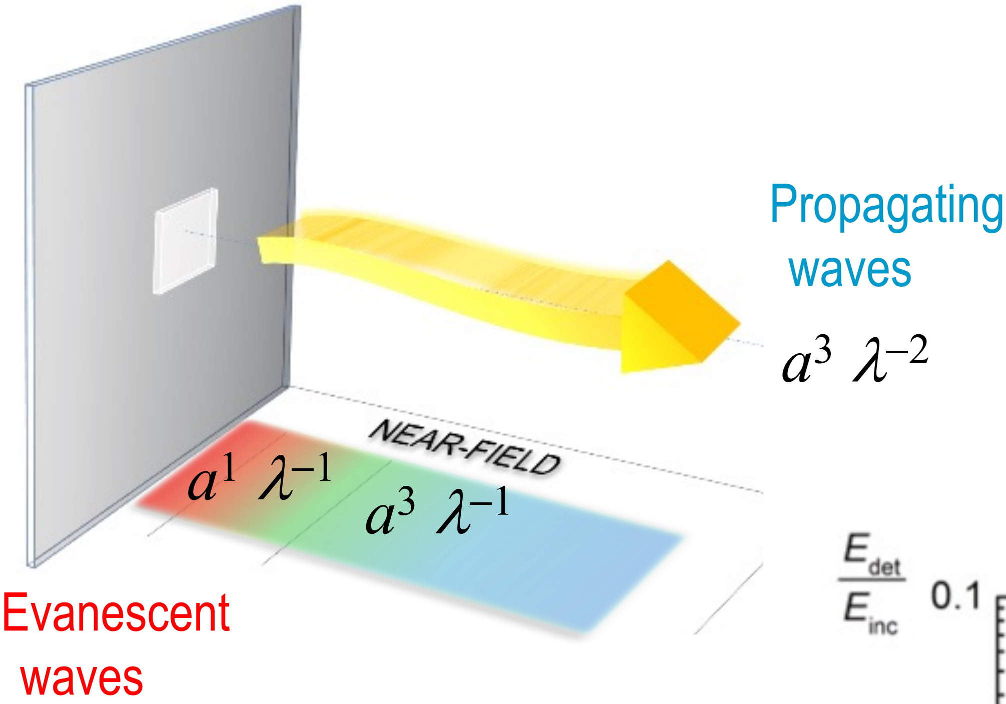


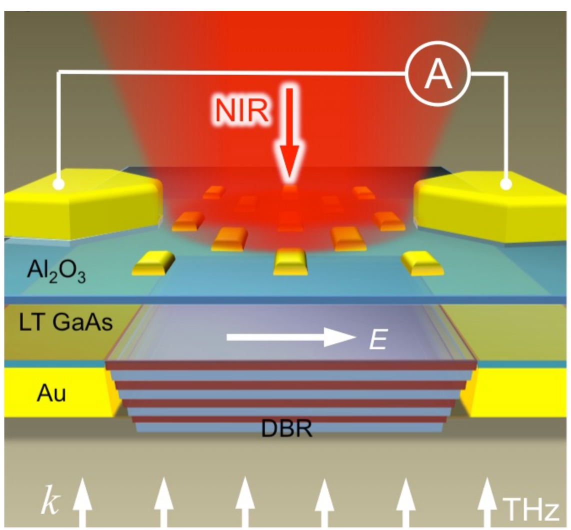
Angular spectrum representation of aperture field (in multiples of $2\pi/a$)

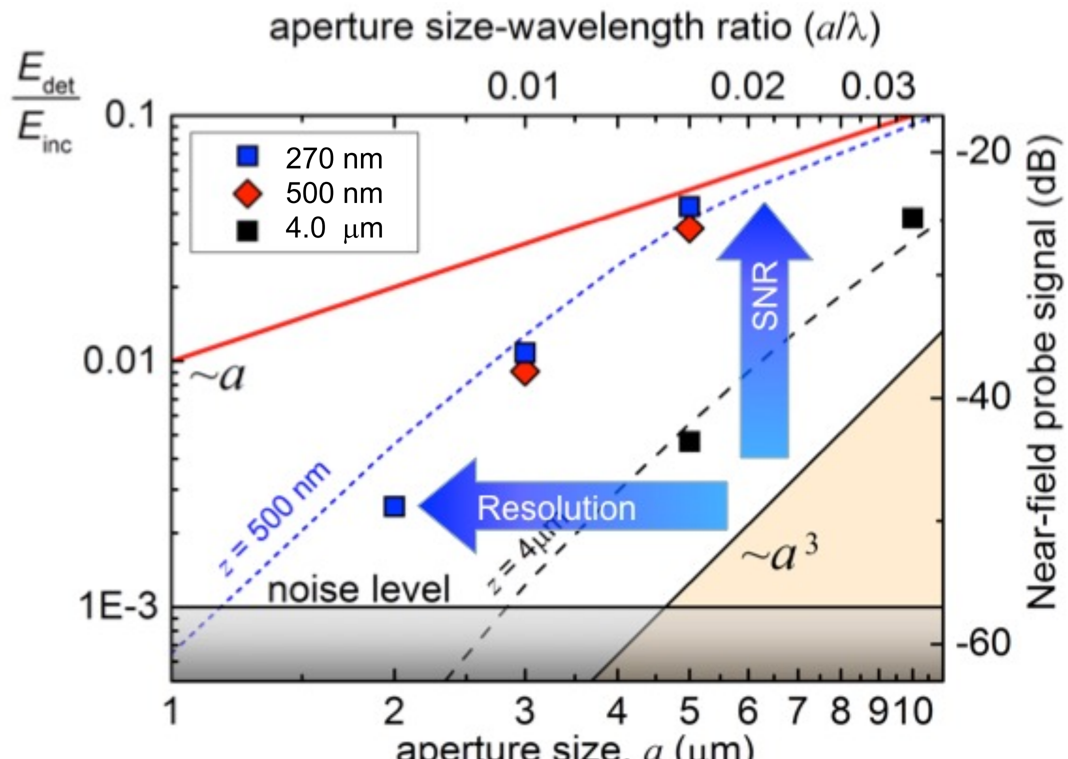


Most waves in spectrum have imaginary k, i.e. evanescent

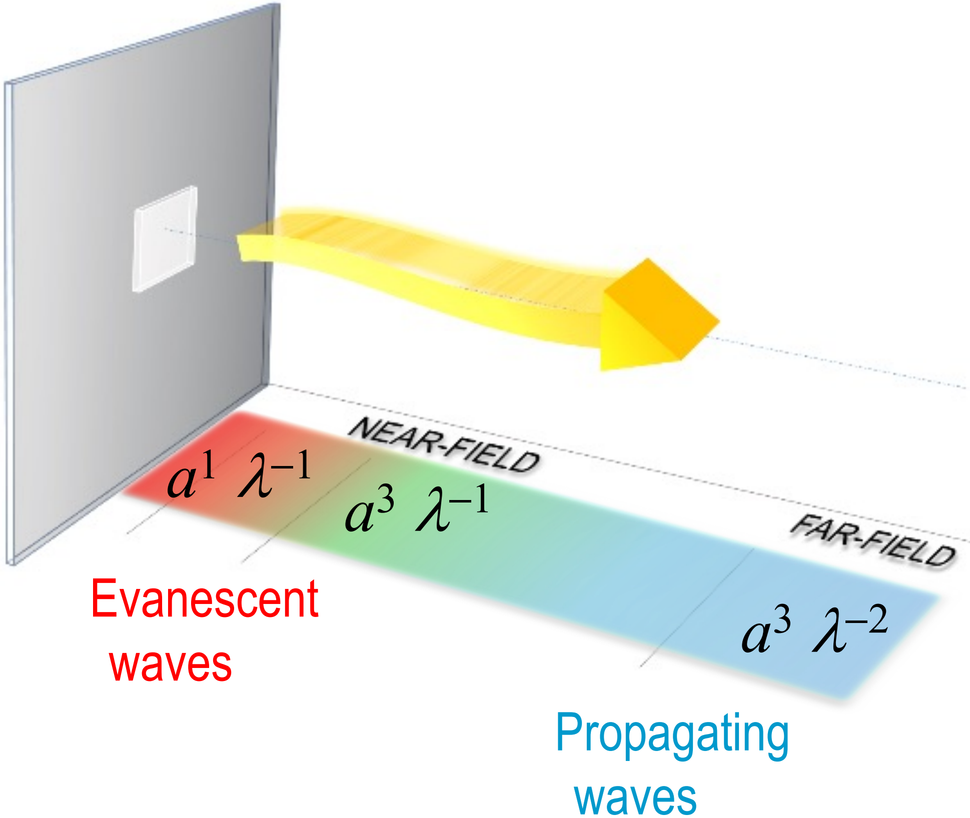
Aperture-type THz Near-Field Microscopy

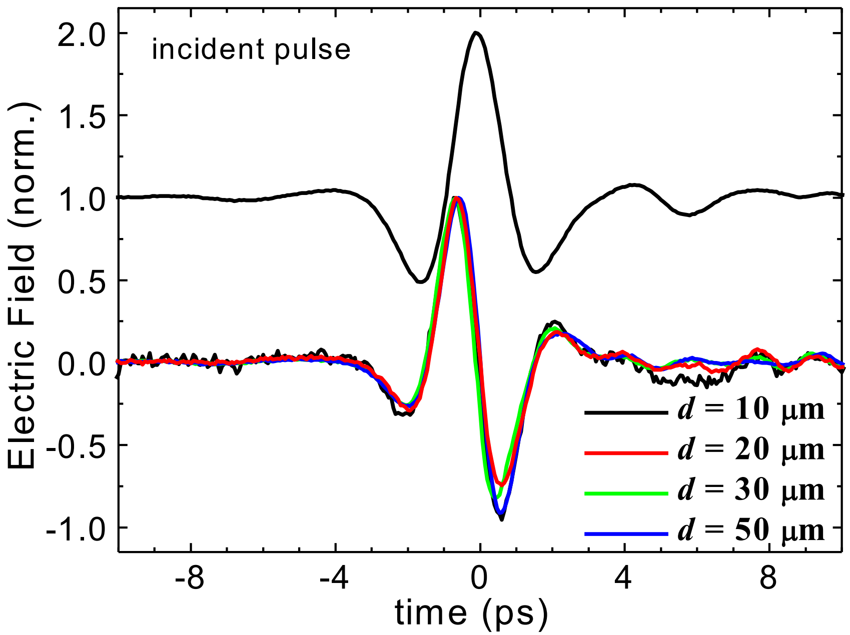






Aperture-type THz Near-Field Microscopy





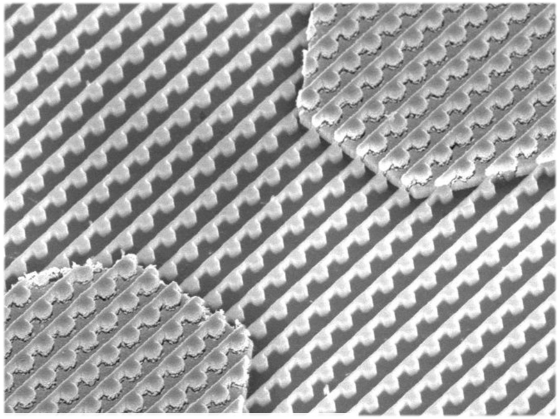
$$E(\omega) \sim \omega$$

$$\phi(\omega) = \pi/2$$

Waveform deformation is independent of the aperture size

Integrated THz Near-Field Detectors

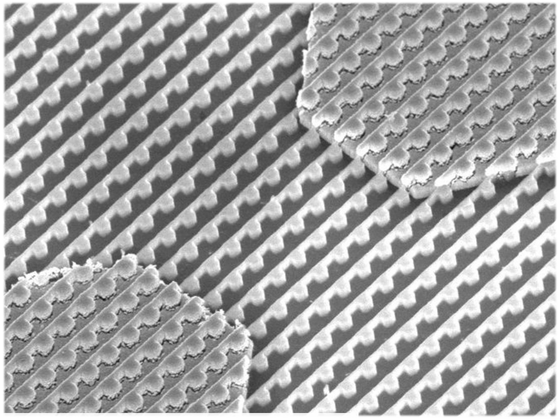
Ultrathin Photoconductive Metasurfaces (THz-TDS)



Siday et al. Nano Lett. (2019)
Hale et al. Optics Lett. (2021)

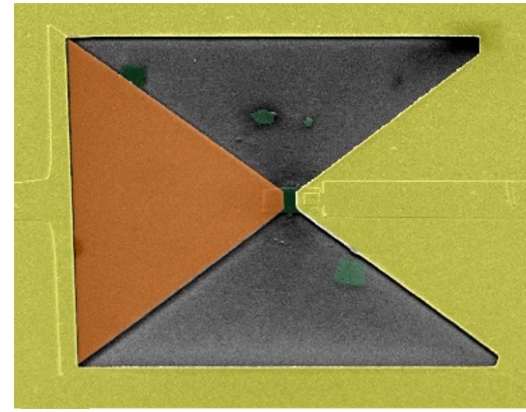
Integrated THz Near-Field Detectors

Ultrathin Photoconductive Metasurfaces (THz-TDS)



Siday et al. Nano Lett. (2019)
Hale et al. Optics Lett. (2021)

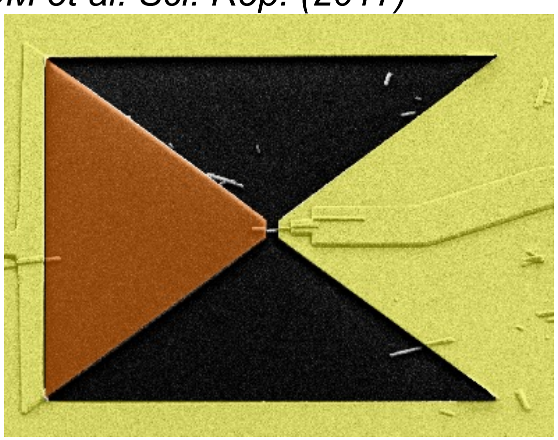
FET-based 2D materials

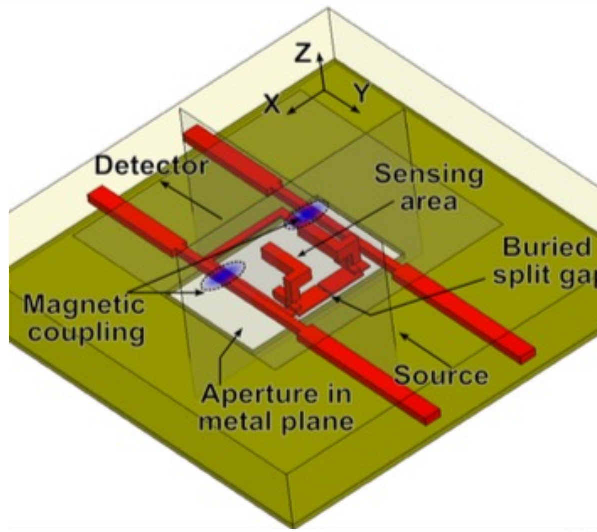


Giordano et al. Optica (2018)

InAs nanowire detectors

OM et al. Sci. Rep. (2017)



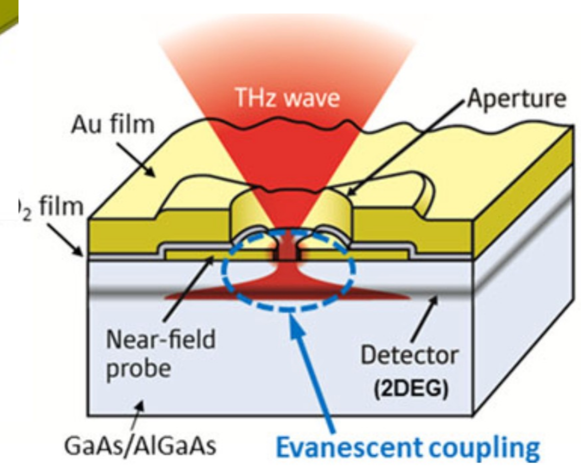


CMOS-based detectors

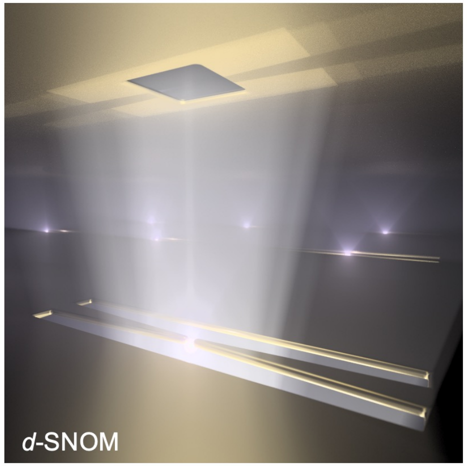
Grzyb et al. (2016)

2DEG detectors

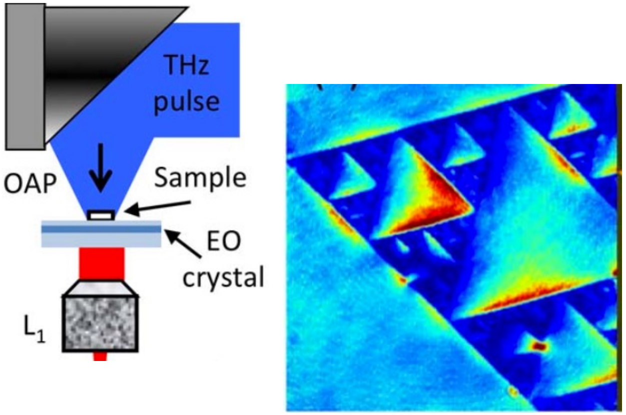
Kawano et al. (2008)



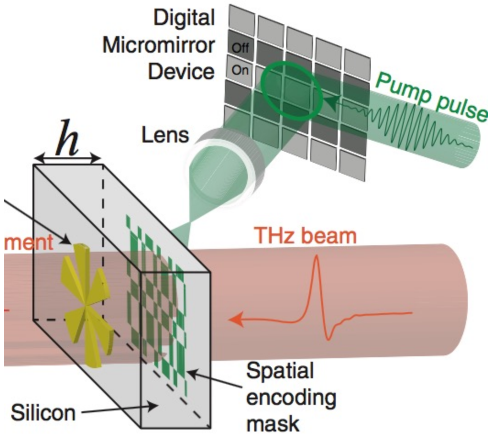
Direct detection THz Near-Field Microscopy



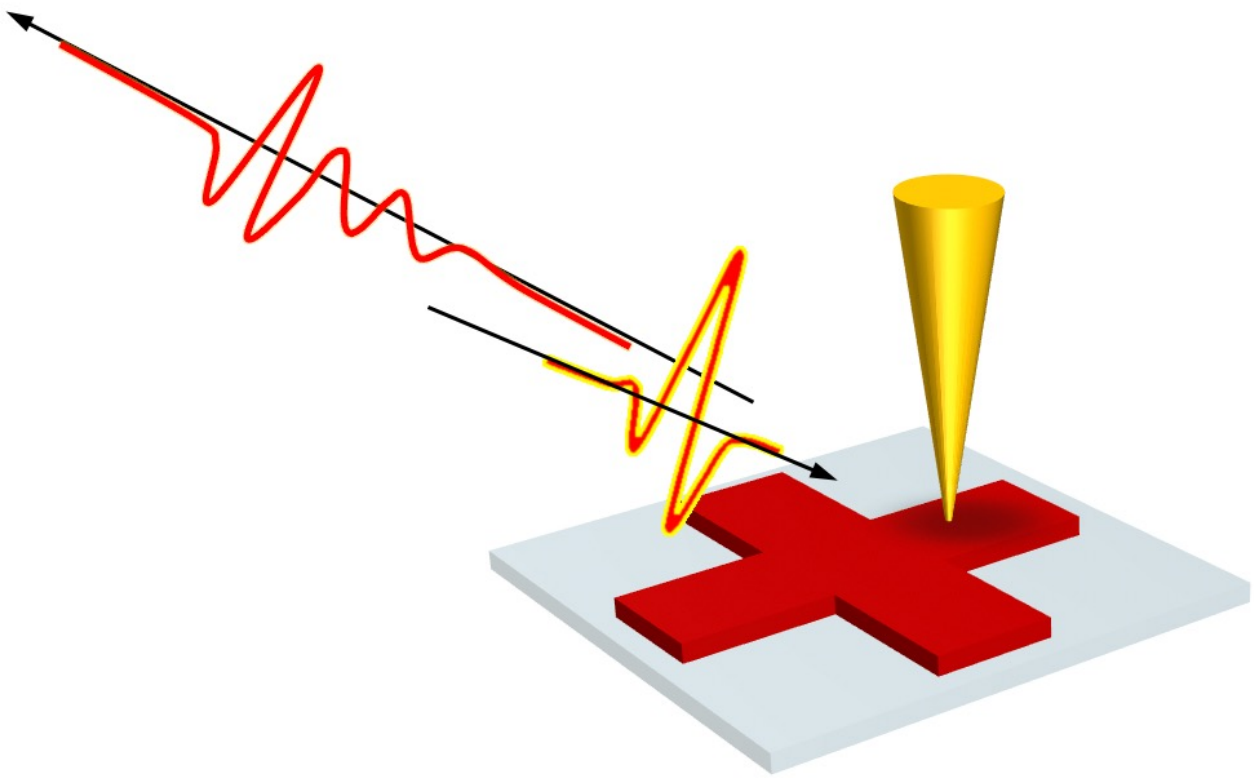
Graphics: Tom Siday



Blanchard & Tanaka (2016)



Stantchev (2016)

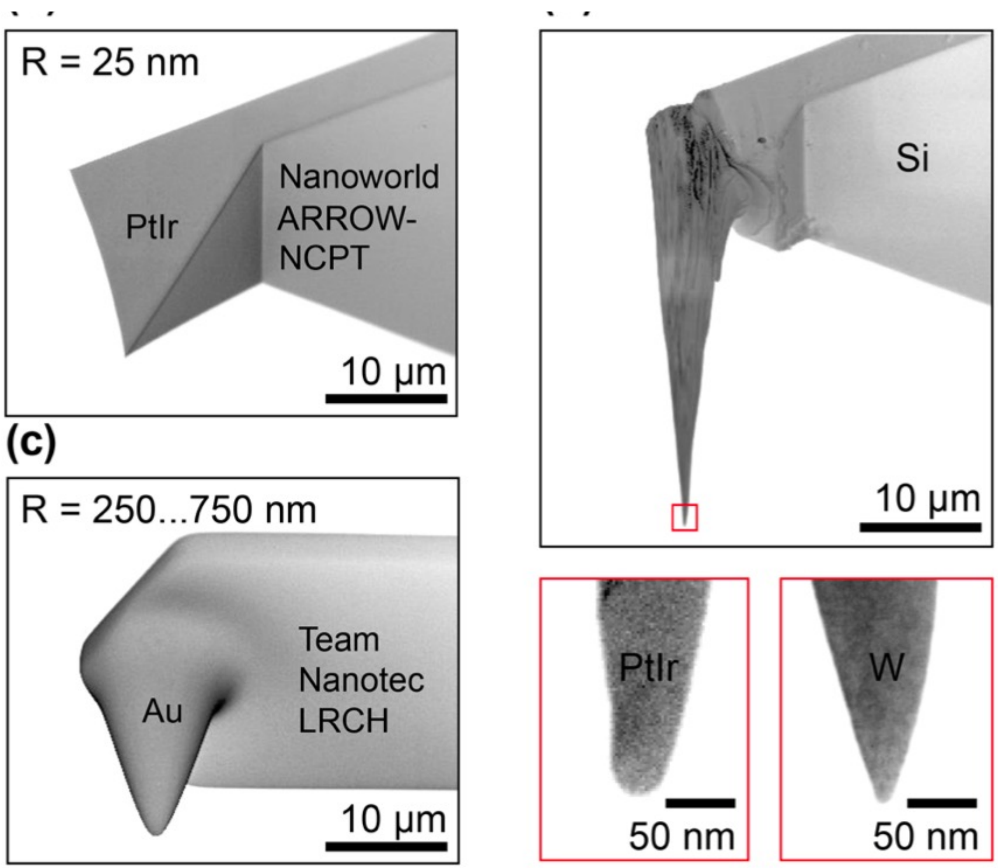


Enhancement of Scattering from the Probe

Two Main Factors affecting the Scattering efficiency:

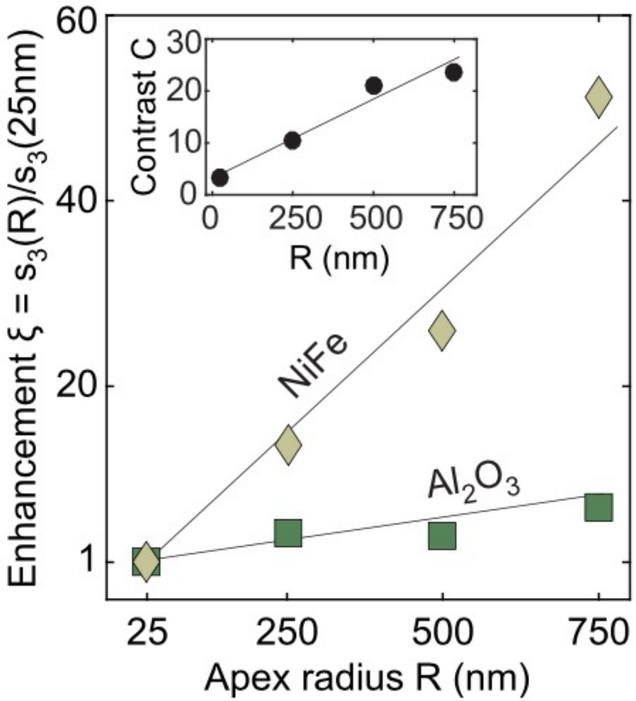
Tip apex size

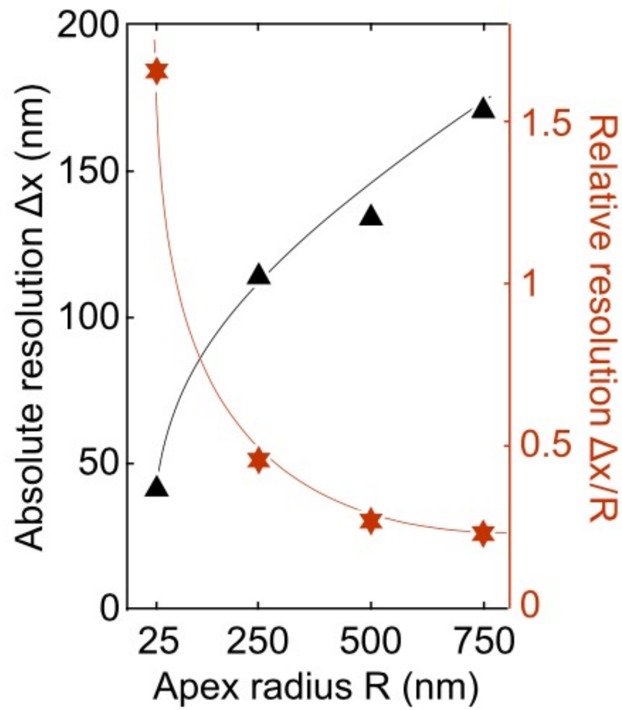
Tip shaft length

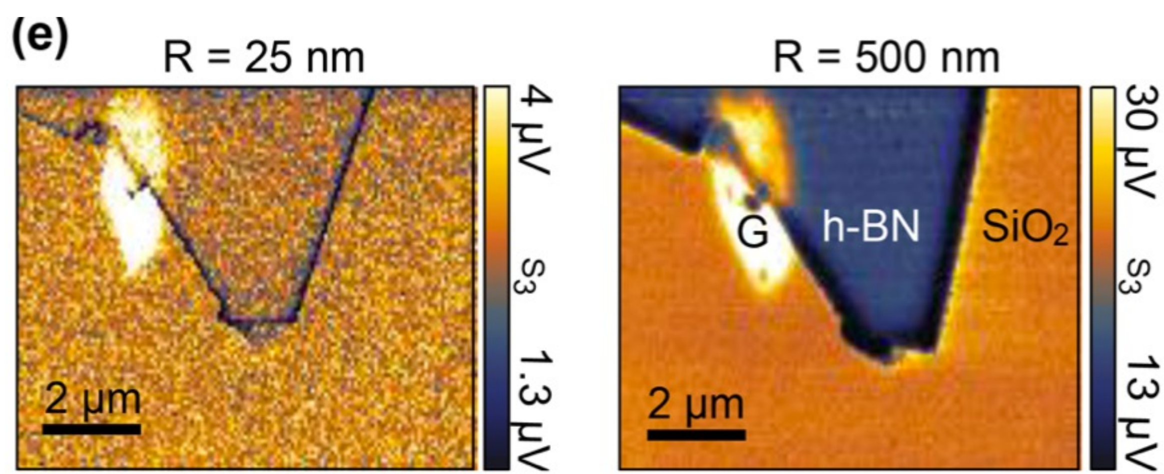


C. Maissen et al.,
ACS Photonics 6, 1279 (2019)

THz s-SNOM Imaging







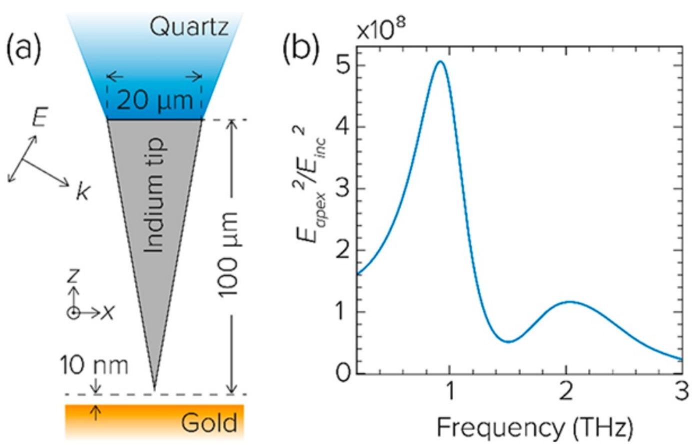
C. Maissen et al.,
ACS Photonics 6, 1279 (2019)

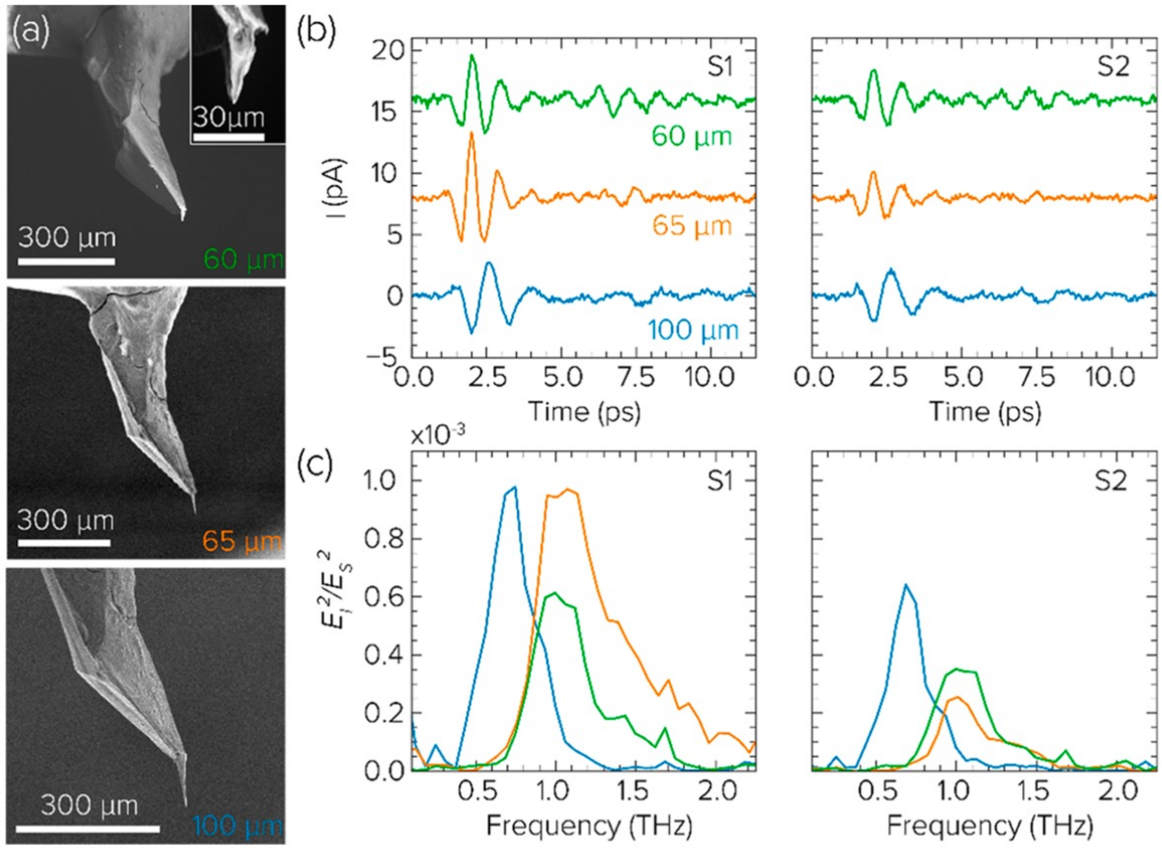
Enhancement of Scattering from the Probe

Two Main Factors affecting the Scattering efficiency:

Tip apex size

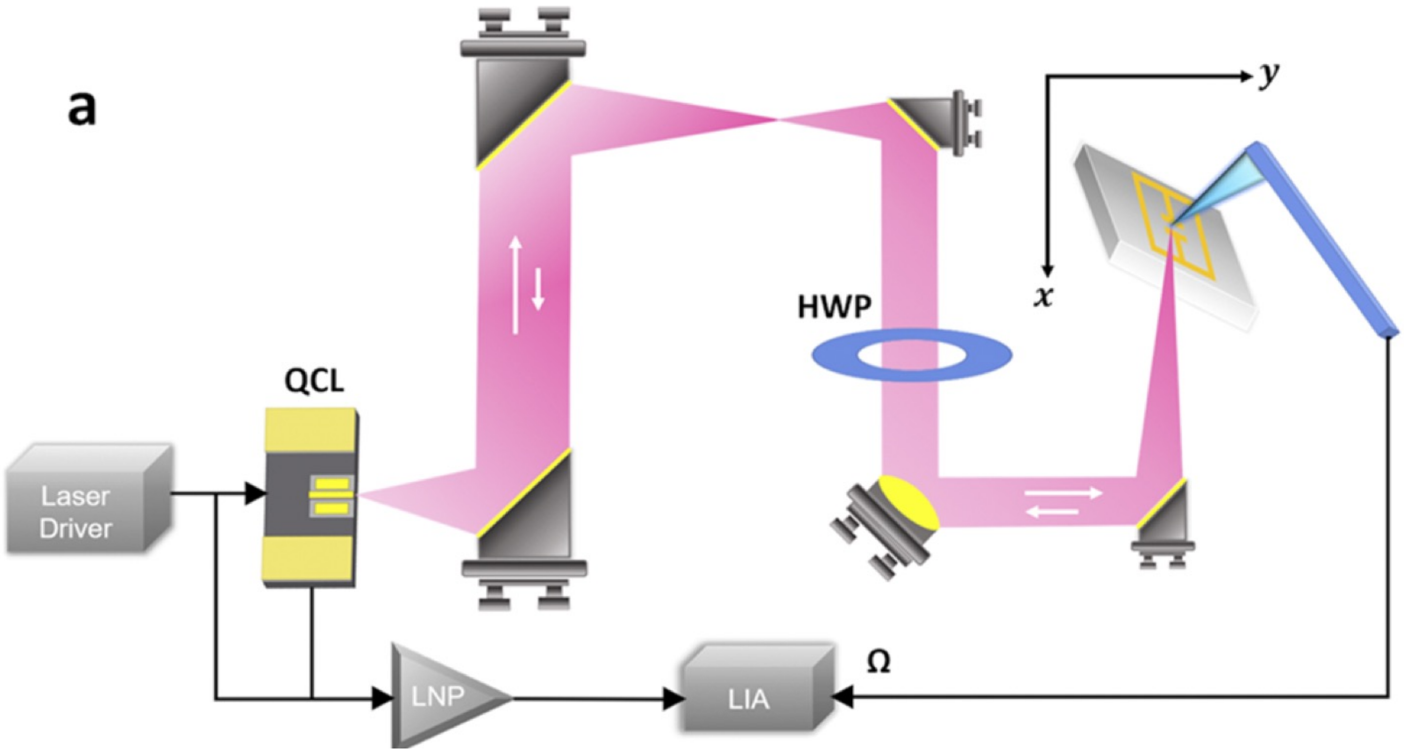
Tip shaft length





T. Siday et al.
ACS Photonics 7, 596 (2020)

Self-mixing effect in QCLs



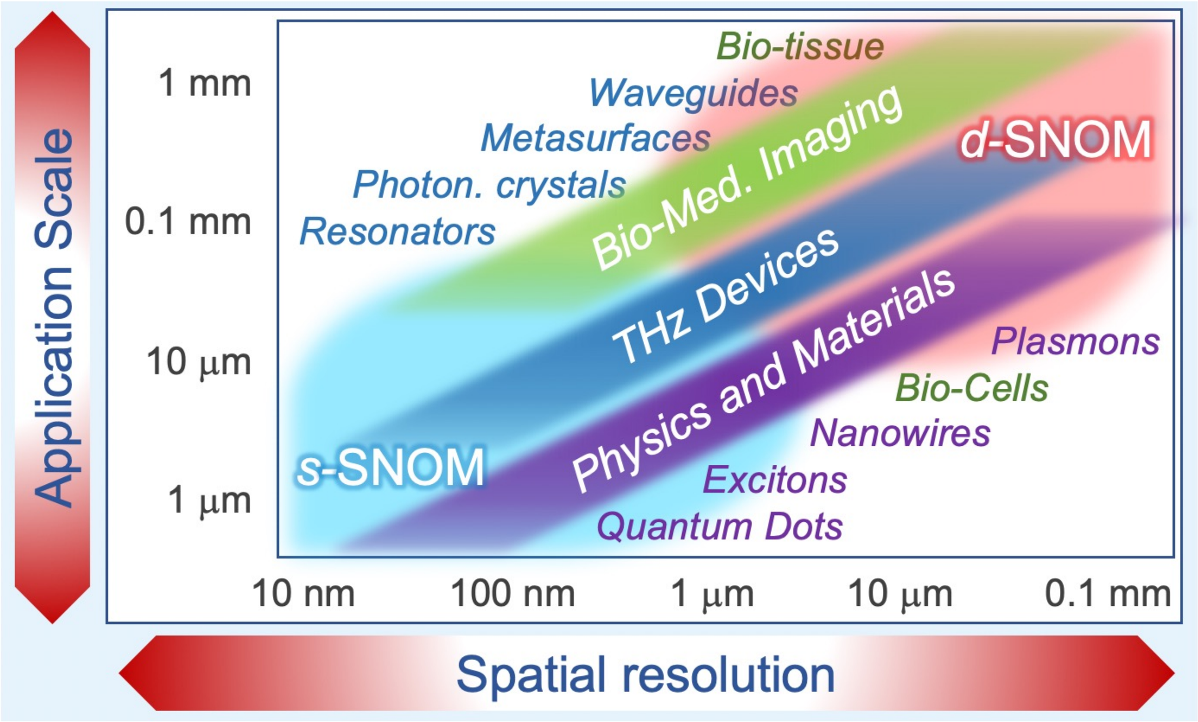
P. Dean et al. *Appl. Phys. Lett.* 108, 091113 (2016)

see also works:

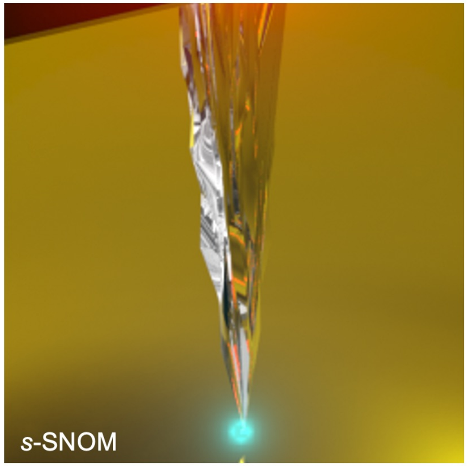
Riccardo Degl'Innocenti (ACS Photonics 2017 …) – Tunning fork Probe

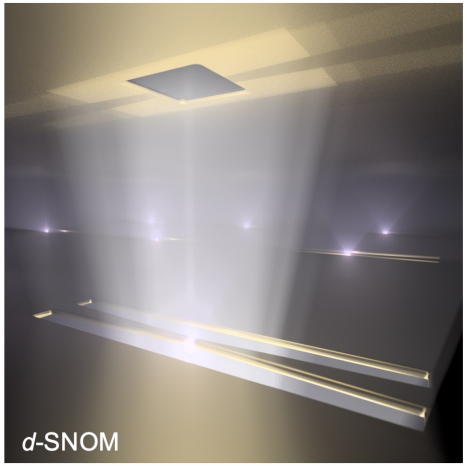
Miriam Vitiello (Optics Express 2018, … later work) – Neaspec

THz Near-Field Microscopy Application Space



Boland et al. THz Roadmap (2023)

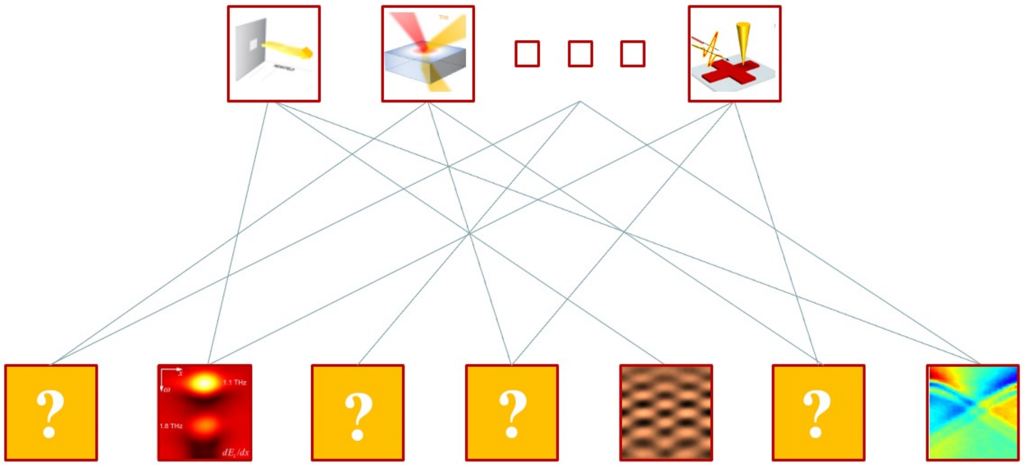




Graphics: Tom Siday

Concluding Remarks

As more THz near-field systems coming online,
the growing library of THz near-field images will help identify
appropriate instruments for phenomena of interest.



Explore and look out
for novel THz near-field imaging modalities and applications.

THz Near-Field Microscopy research
is just warming up, there is still so much to explore.

Acknowledgement

L. Hale, T. Siday (U. Regensburg), R. Hermans (*Industry*), A. Macfaden (*U. Cambridge*), R. Mueckstein (*Industry*), M. Navarro-Cia (U. Birmingham), M. Natrella (*Industry*), and R. Thompson
University College London

J. Reno, I. Brener, T. Harris, T.S. Luk and W. Pan
CINT, Sandia National Laboratories

L. Viti, M. C. Giordano, E. Dardanis, and M. S. Vitiello
CNR-Nano, Italy

W. Yu, C. Berger, W. A. de Heer, and Z. Jiang
Georgia Tech.

Y. Todorov, D. Gacemi, A. Mottaghizadeh and C. Sirtori
Univ. Paris Diderot, Paris, France

Z. Han, F. Ding and S. I. Bozhevolnyi
China Jiliang University and DTU, Denmark

J. Keller, G. Scalari and J. Faist
ETH-Zurich

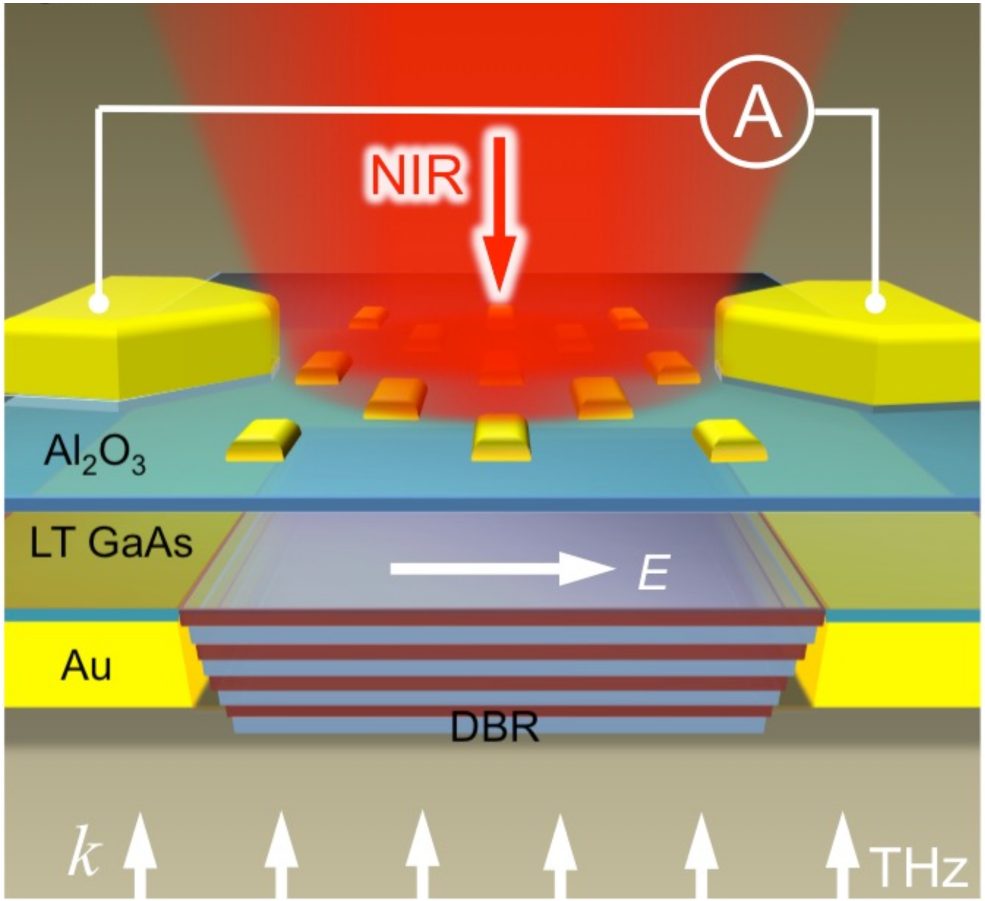
I. Khromova (*U. Navarra*) P. Mounaix (*CNRS, Bordeaux*), P. Kuzel (Czech Acad. Sci.)

Results/Graphs from other groups

Supporting Slides

Integrated THz Detector

Aperture-type THz microscopy probe with PC detector

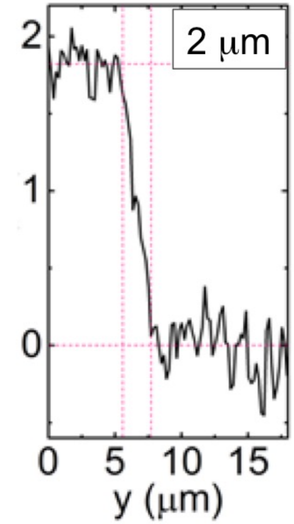


OM *et al.*, *ACS Photonics* (2015)

Potential Cryogenic Applications Require:

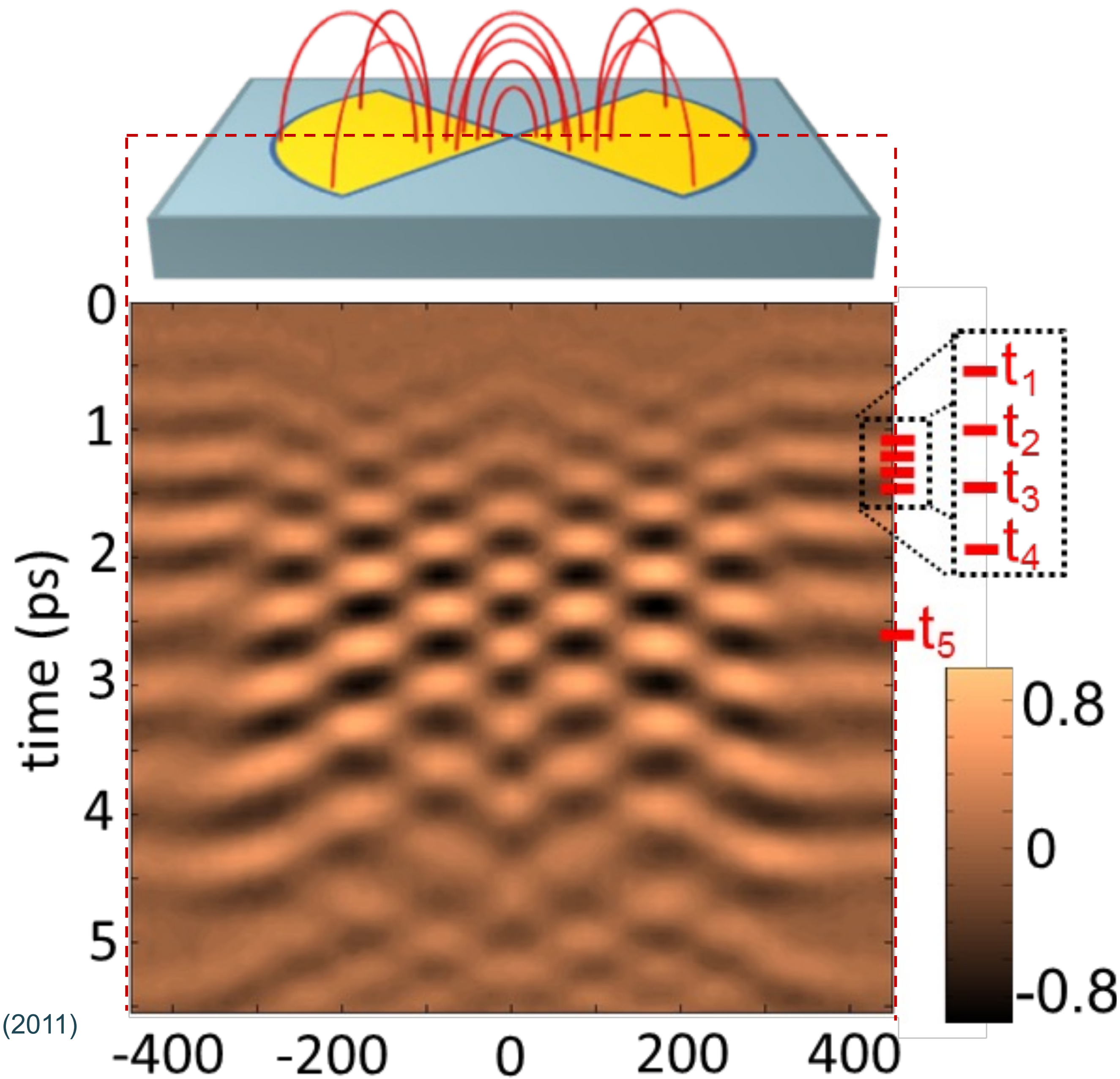
Nanoscale detectors

Integrated readout electronics



OM *et al.*
THz Sci. and Technology, IEEE Trans. (2016)

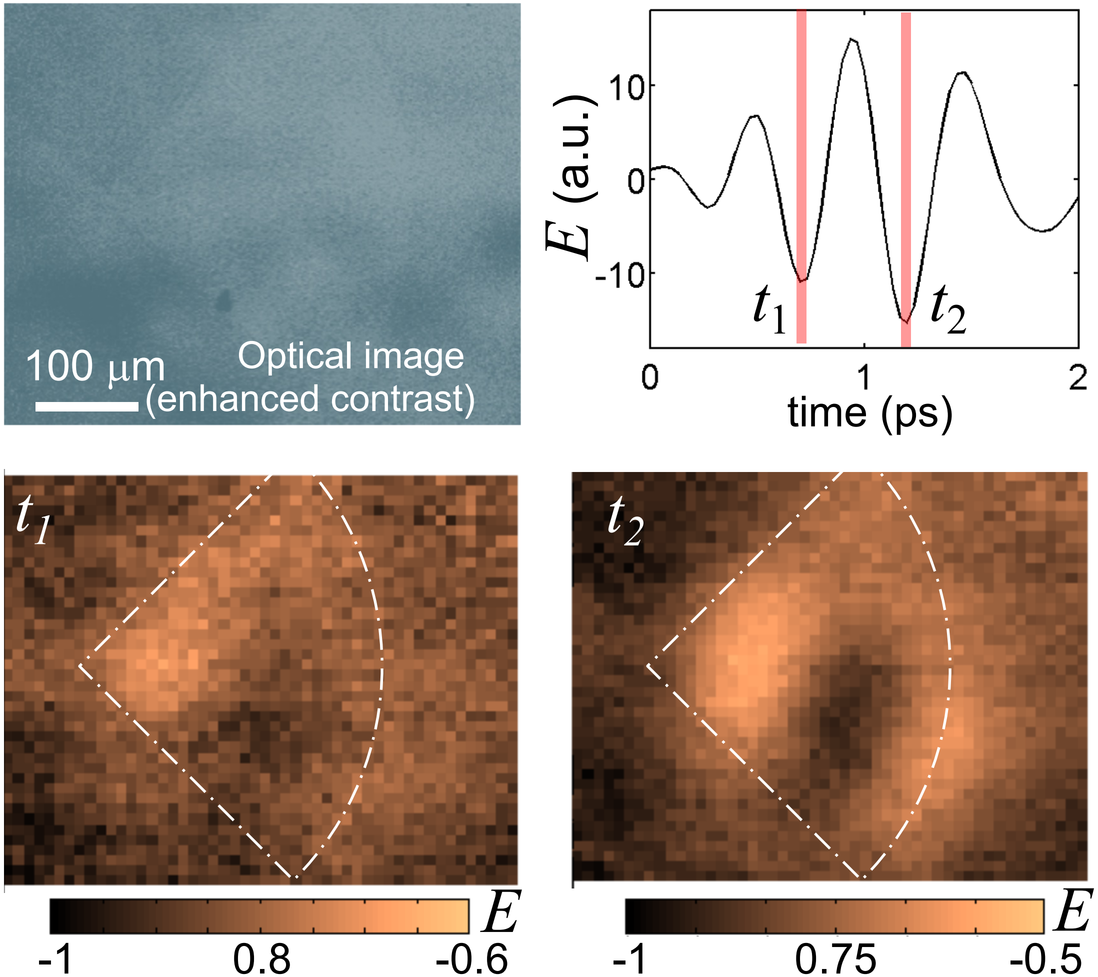
SPP resonance on the bow-tie surface

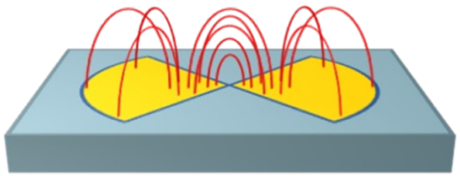


Mueckstein *et al.*,
J.of IRMMW 32, 1031 (2011)

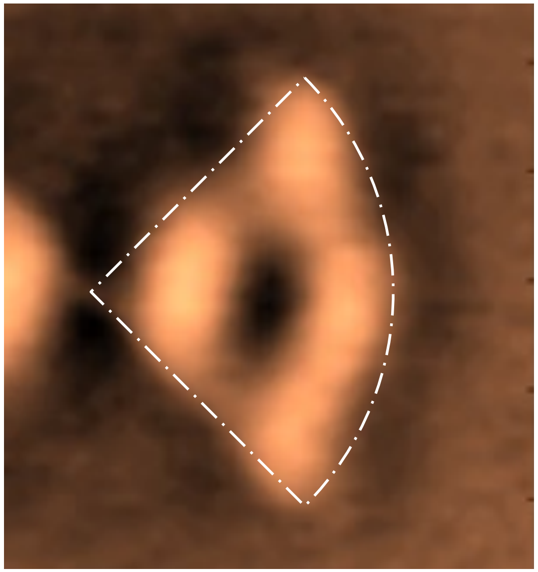
Surface Waves on Gr Bow-Tie Antenna

Epitaxial monolayer graphene - Gr on C-face SiC





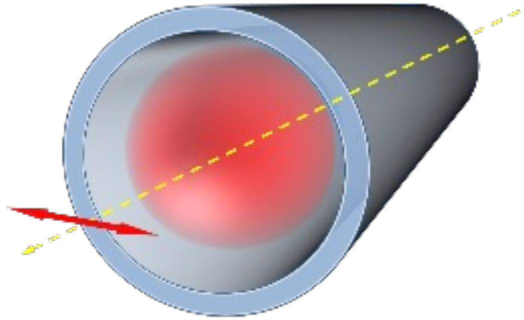
Metallic Bow-tie antenna

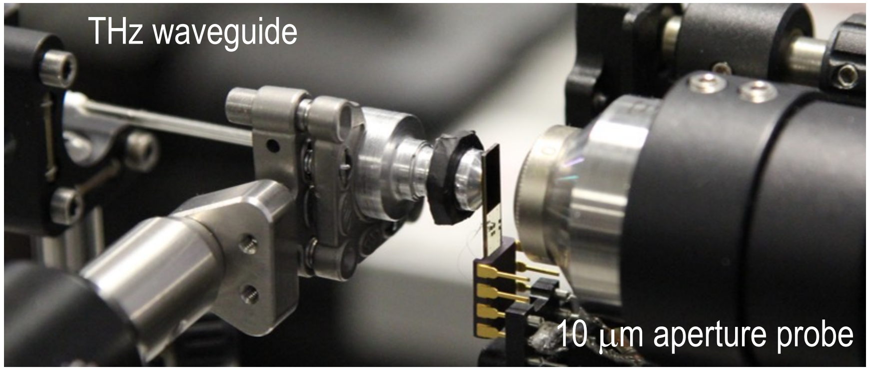


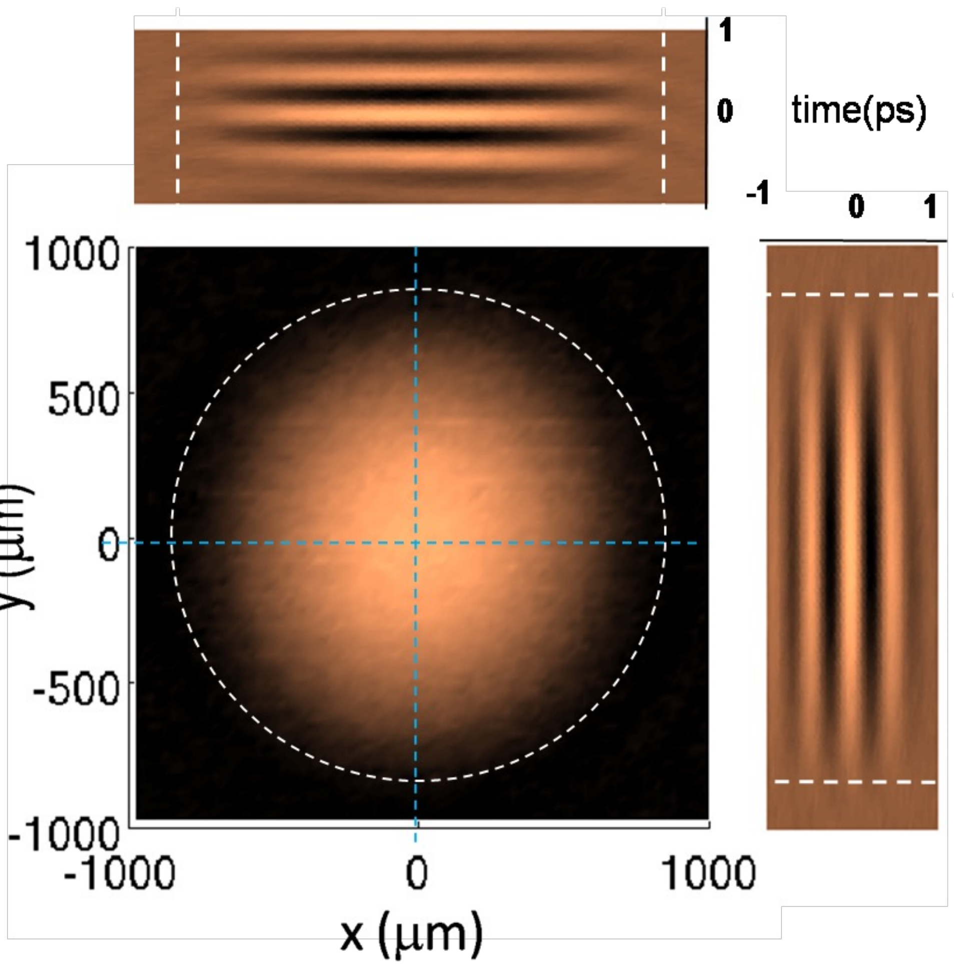
Mueckstein *et al.*,
J.of IRMMW 32, 1031 (2011)

OM *et al. Solid State Comm.* 224, 47-52 (2015)

Applications in THz technology research: *Waveguides*







APL. **94**, 171104 (2009)

Applications in THz technology research: *Waveguides*