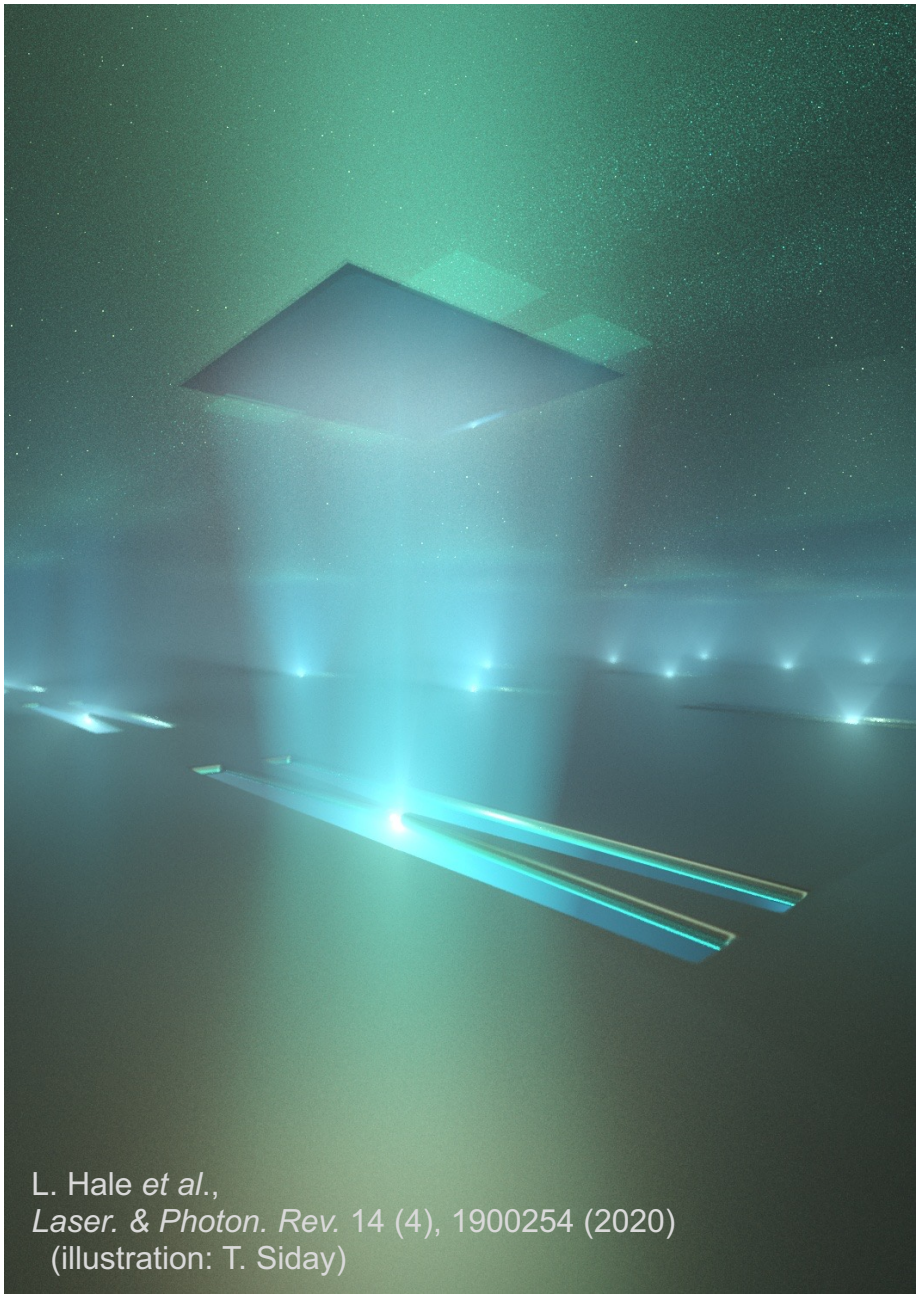
PART 2

THz near-field Imaging and Spectroscopy:

Fundamentals, Technology and Current Trends

Oleg Mitrofanov
UCL



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

Winter College on Optics (ICTP)
Terahertz Optics and Photonics
Trieste, Italy
Feb 6-17, 2023

Tutorial Topics

Fundamentals of THz near-field microscopy

Examples:

Microscopy and Spectroscopy of THz resonators

Imaging of THz surface plasmon waves

Image interpretation

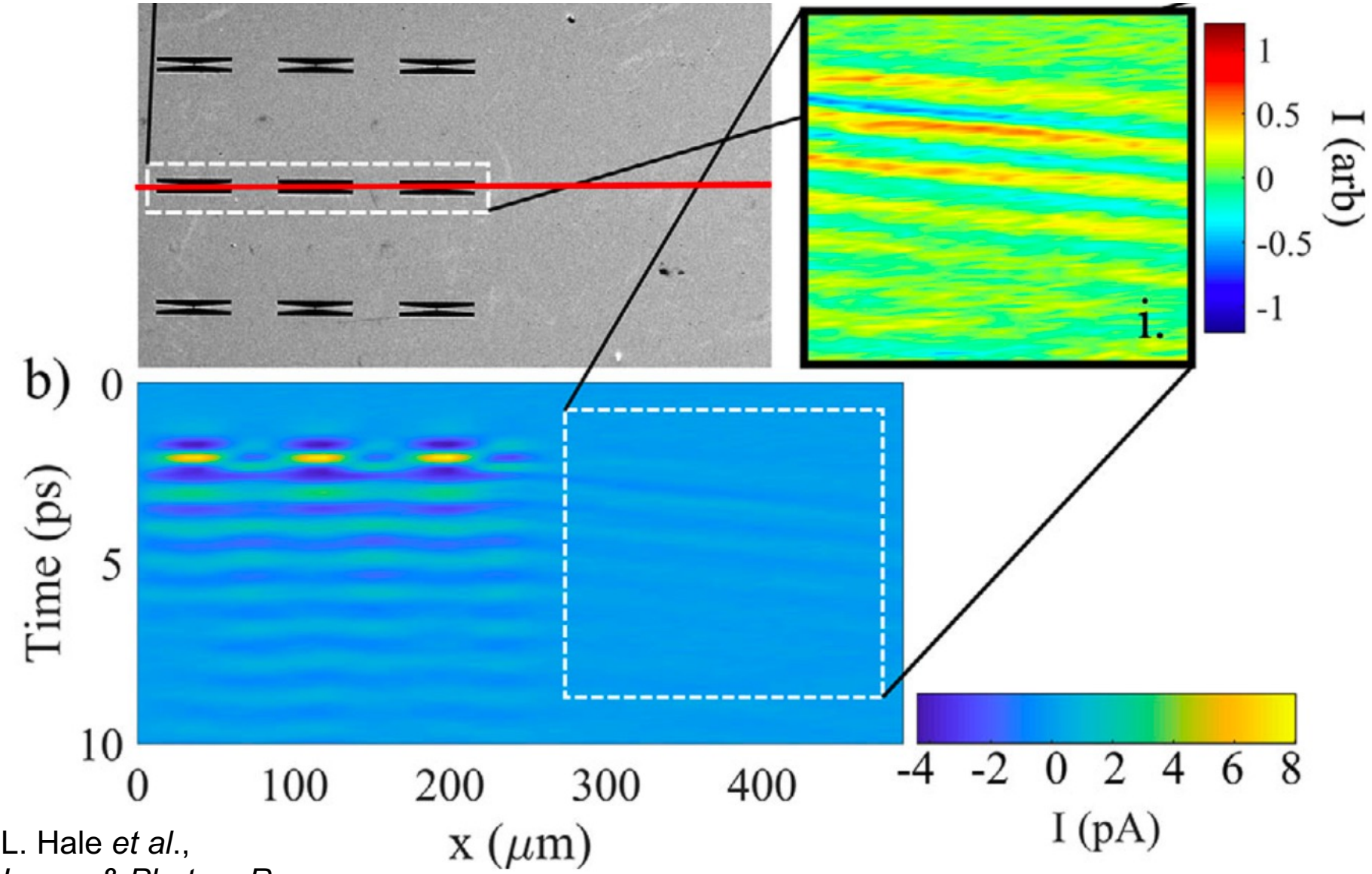
Technology:

Subwavelength aperture and Scattering tip probes

Improving sensitivity in THz microscopy

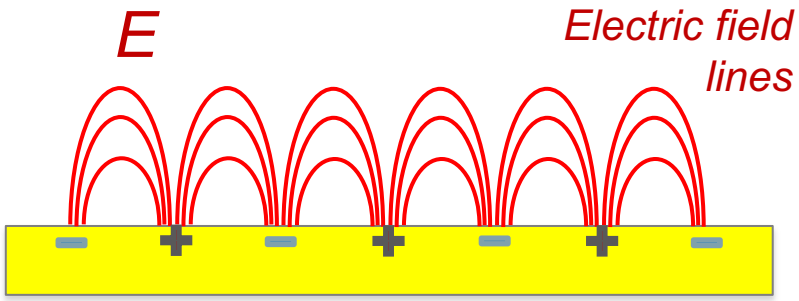
Current Trends in THz microscopy methods

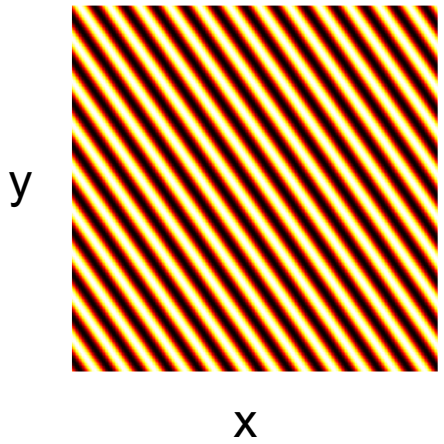
Surface plasmon waves – THz-a-SNOM

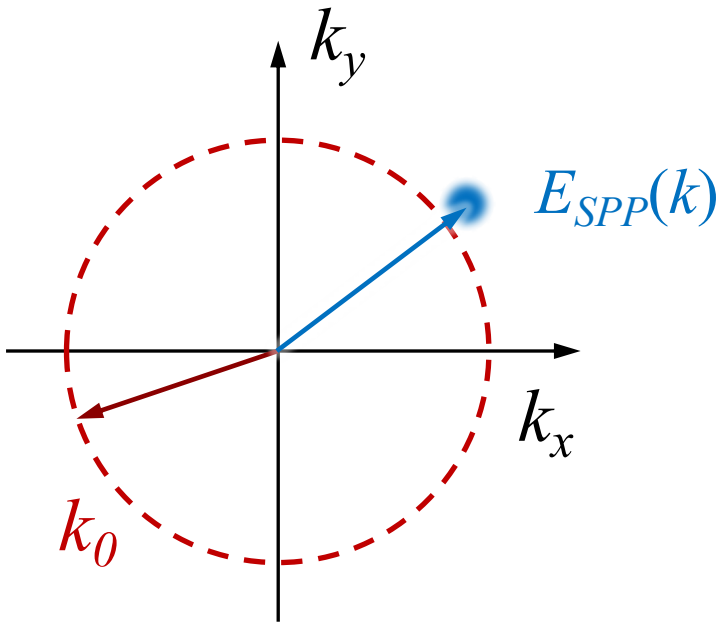


L. Hale *et al.*,
Laser. & Photon. Rev.
14, 1900254 (2020)

THz surface plasmon waves



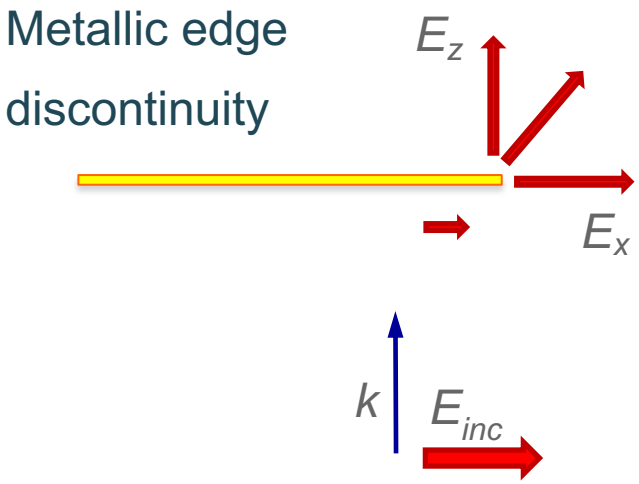




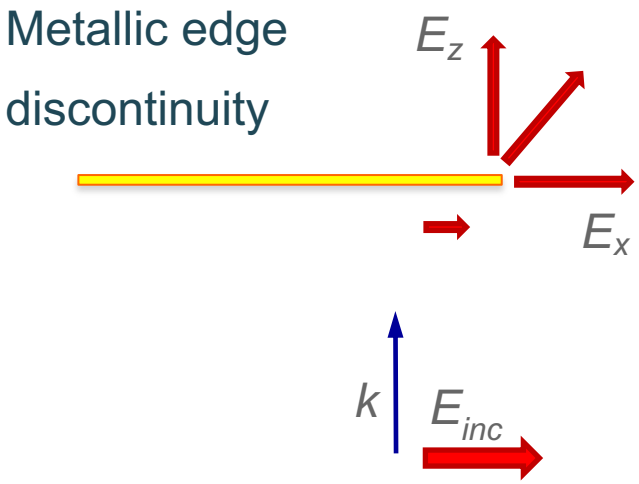
How are SPP waves excited?

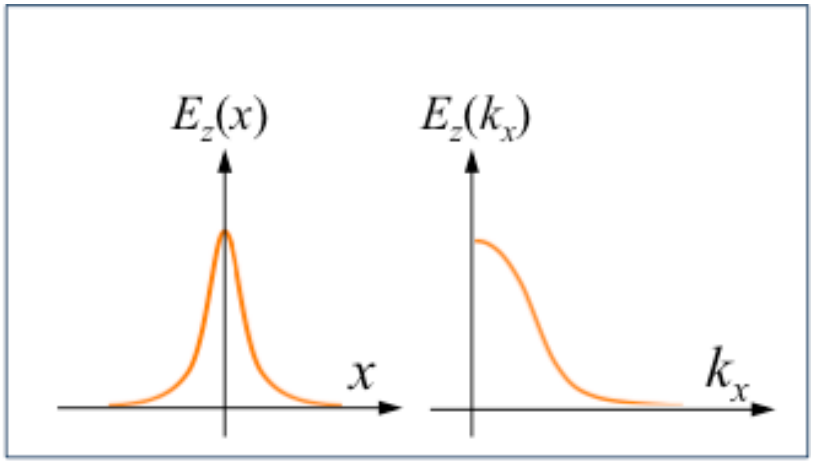
Why are they detected?

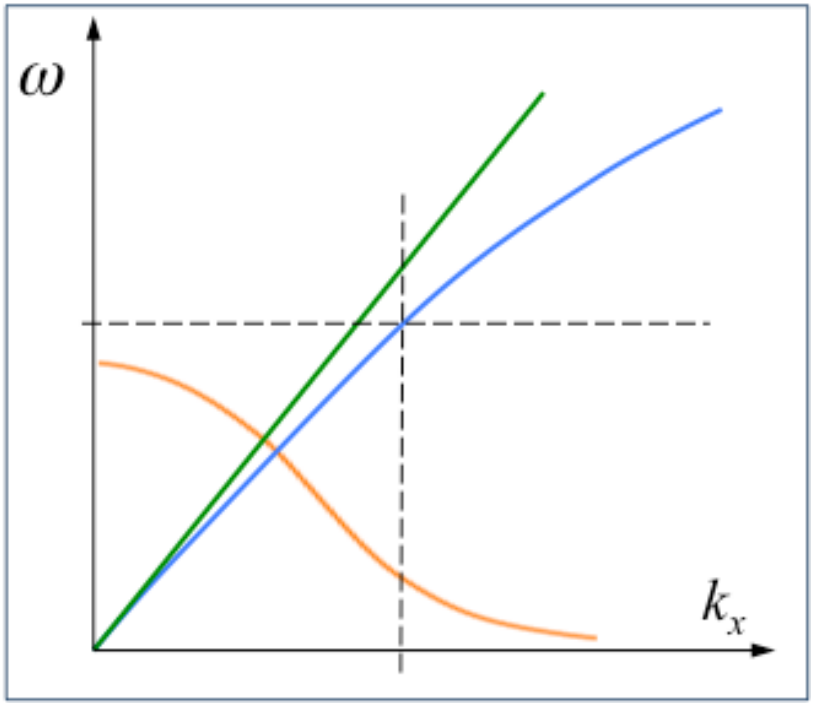
Excitation of THz surface plasmon waves



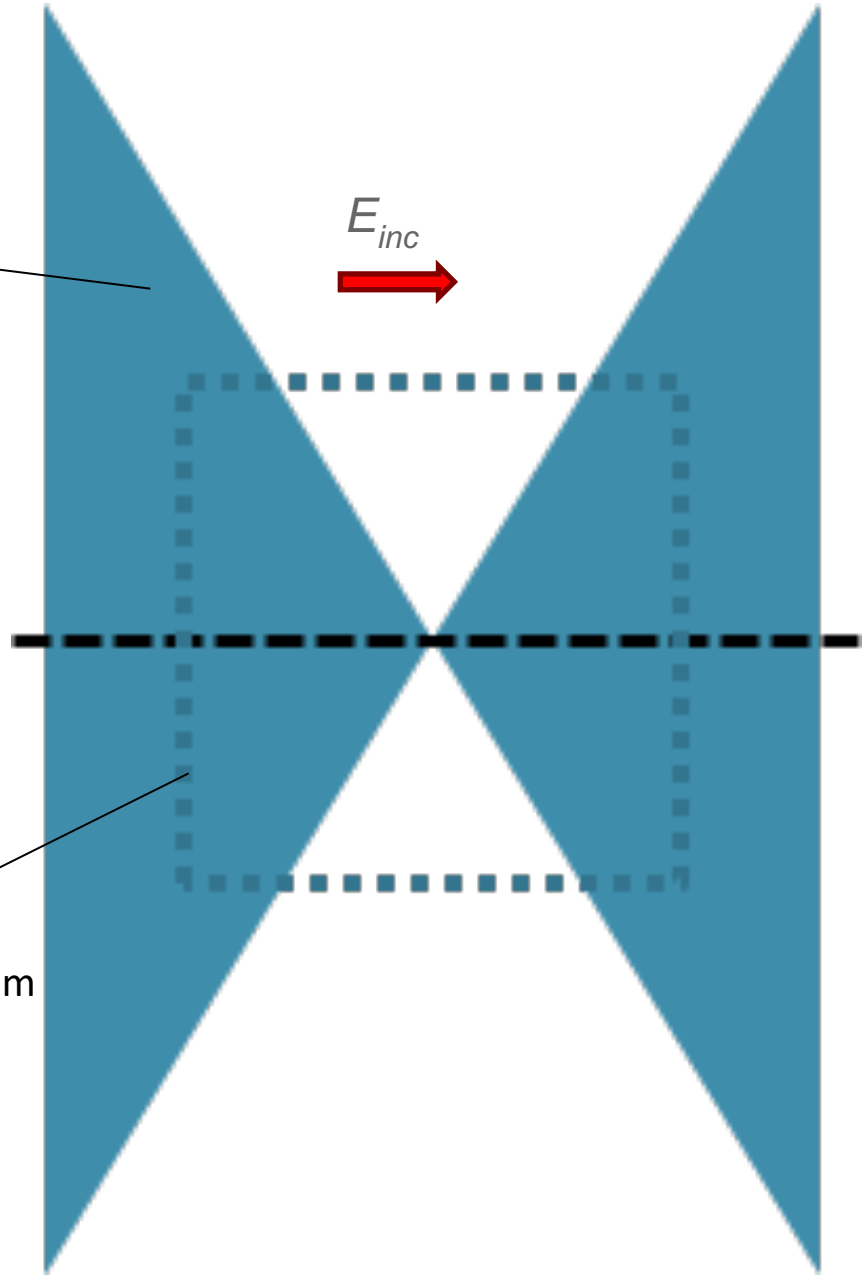
Excitation of THz surface plasmon waves





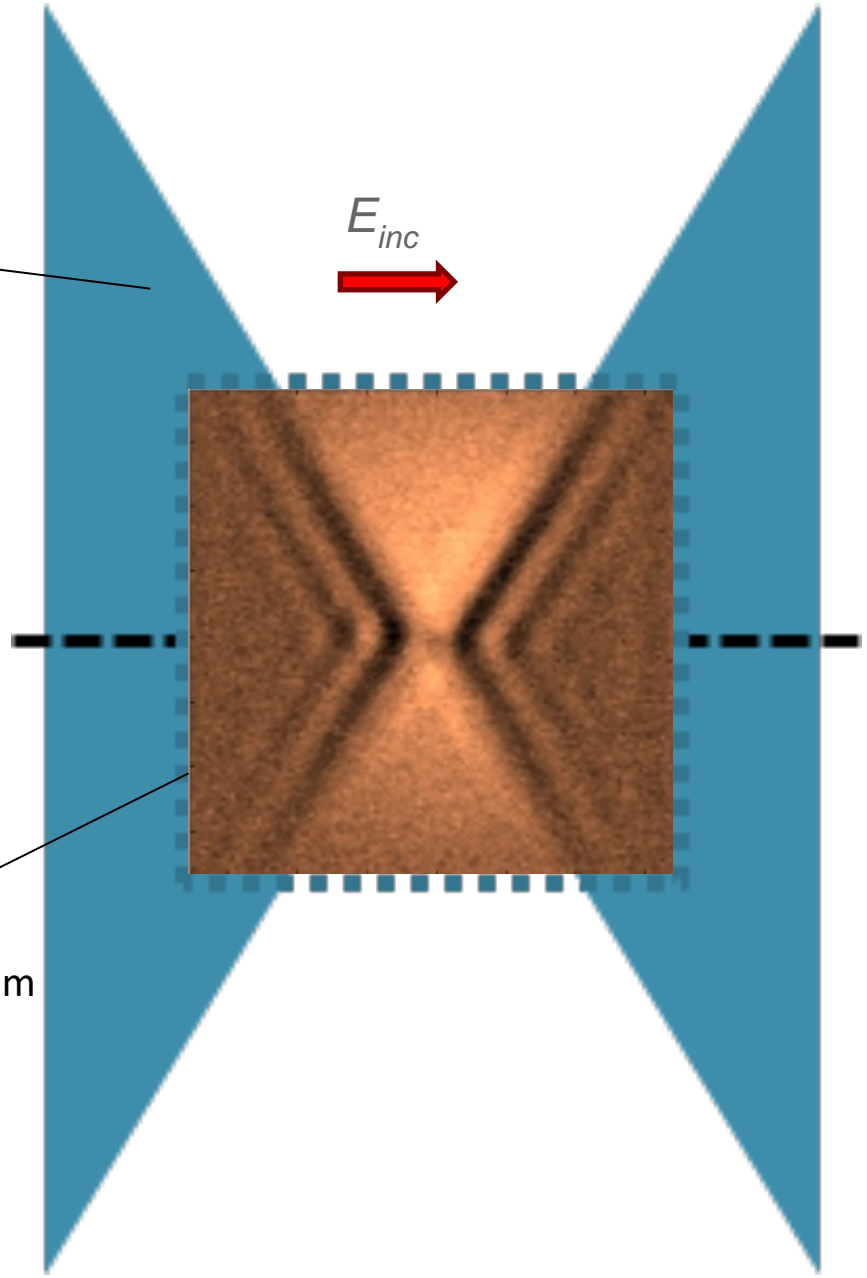


Generation of surface waves at metallic edges



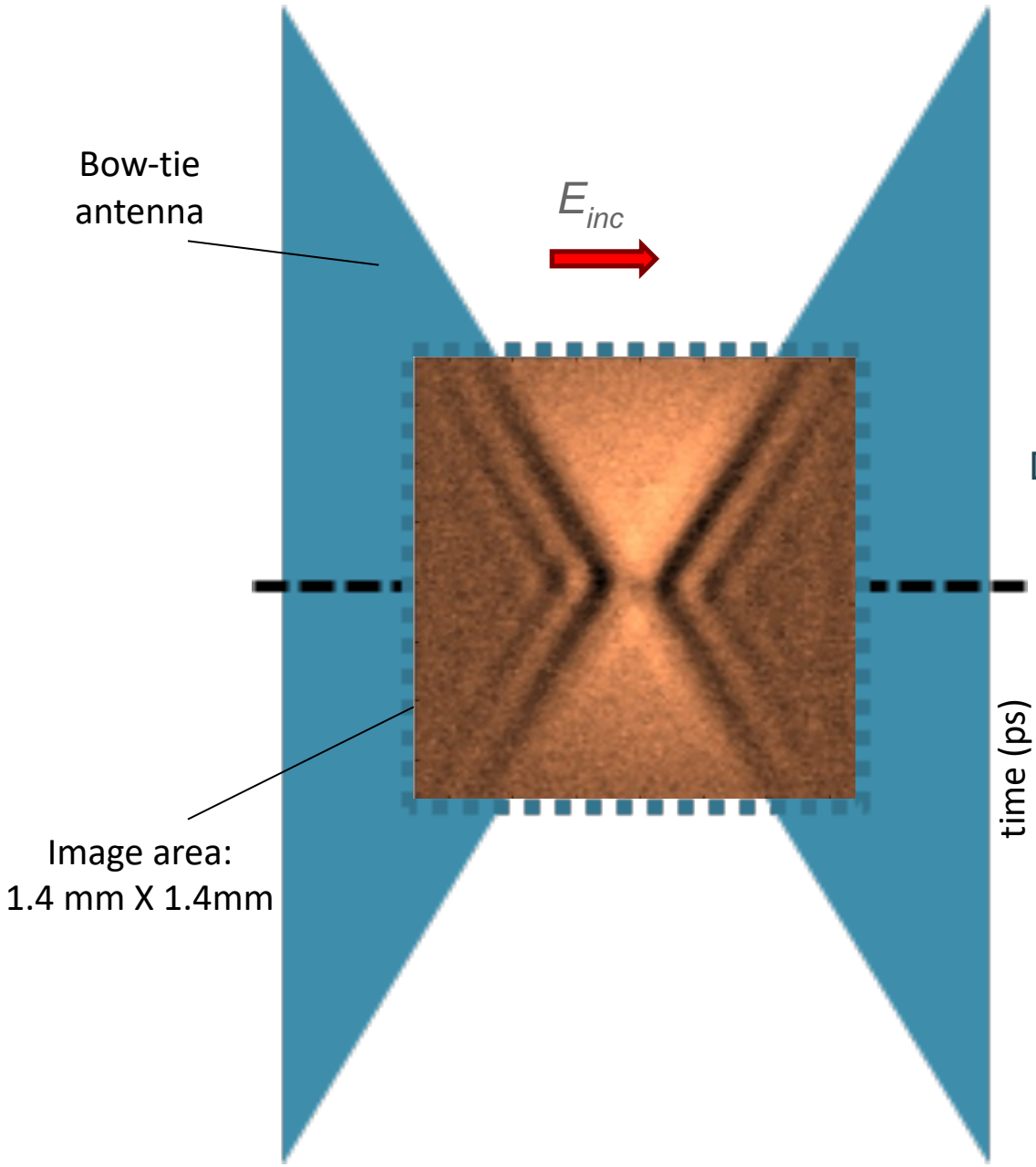
Mueckstein *et al.*, J.of IRMMW 32, 1031 (2011)

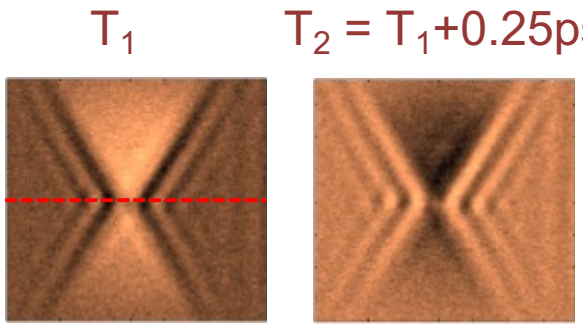
Generation of surface waves at metallic edges



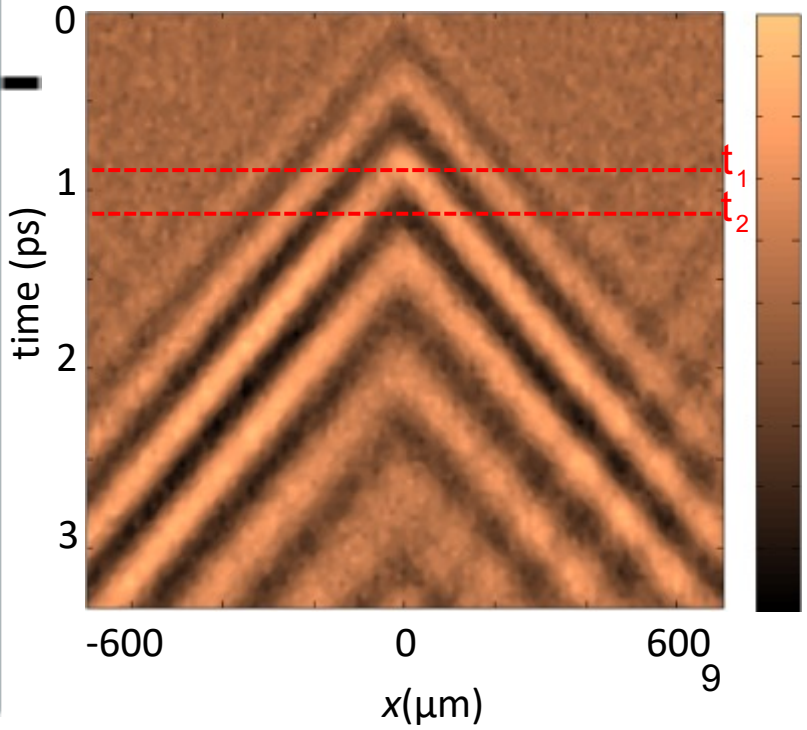
Mueckstein *et al.*, J.of IRMMW 32, 1031 (2011)

Generation of surface waves at metallic edges



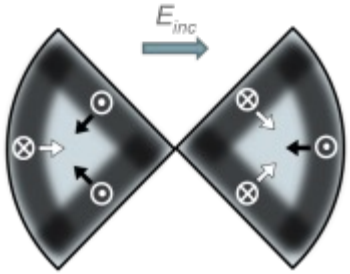


Distinctive signature of surface wave:

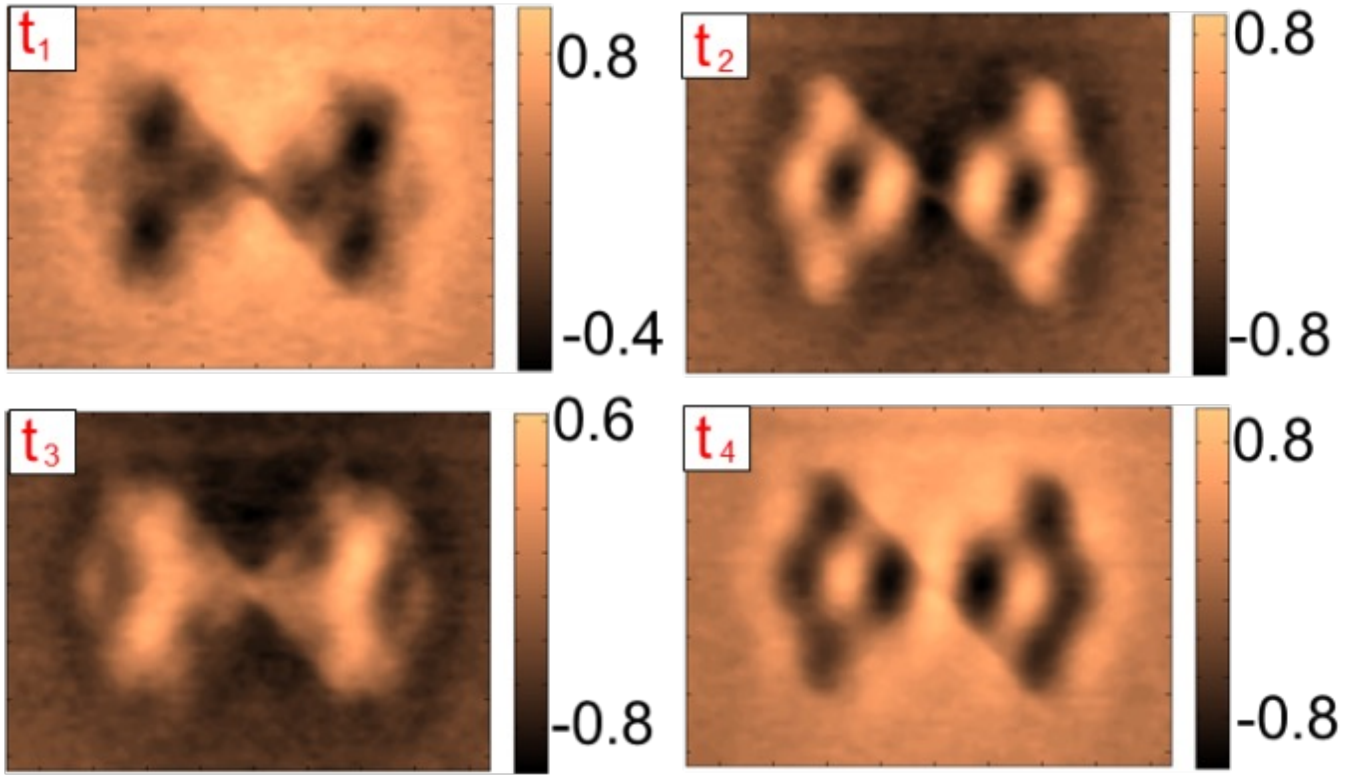


Mueckstein *et al.*, J.of IRMMW 32, 1031 (2011)

THz surface plasmon waves

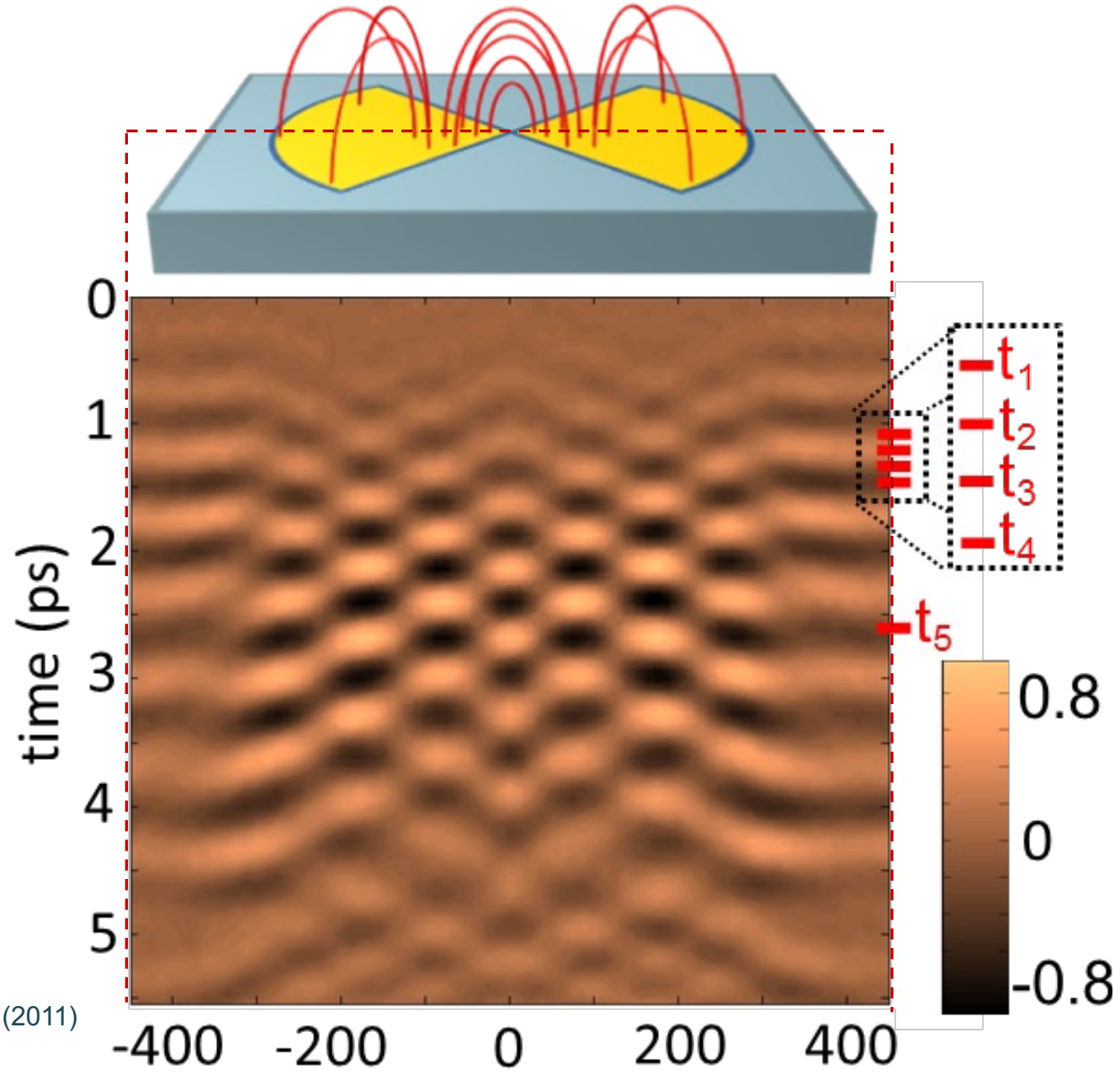


Consecutive images ("frames") ~0.13 picosecond apart



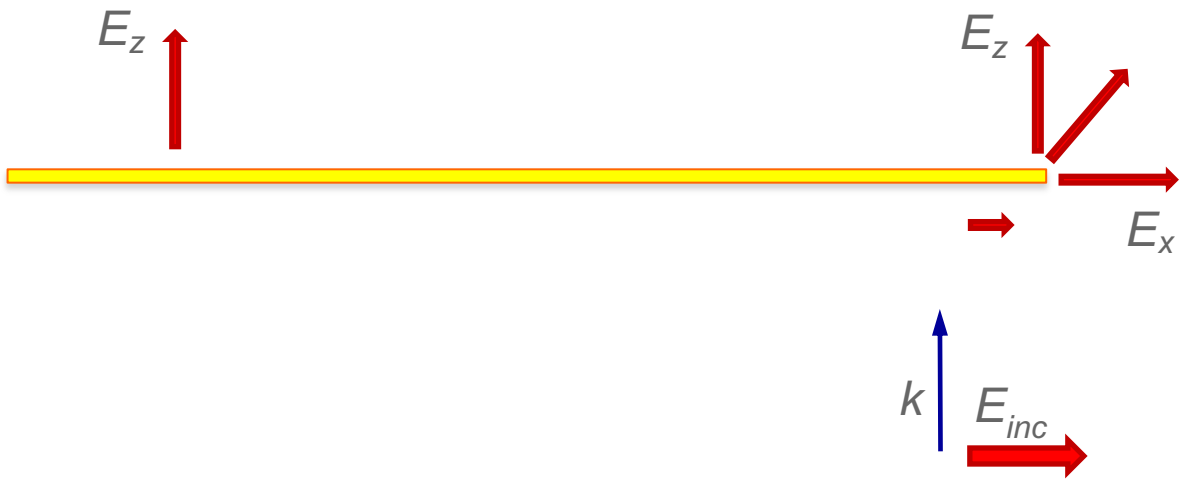
Mueckstein *et al.*, J.of IRMMW 32, 1031 (2011)

SPP resonance on the bow-tie surface

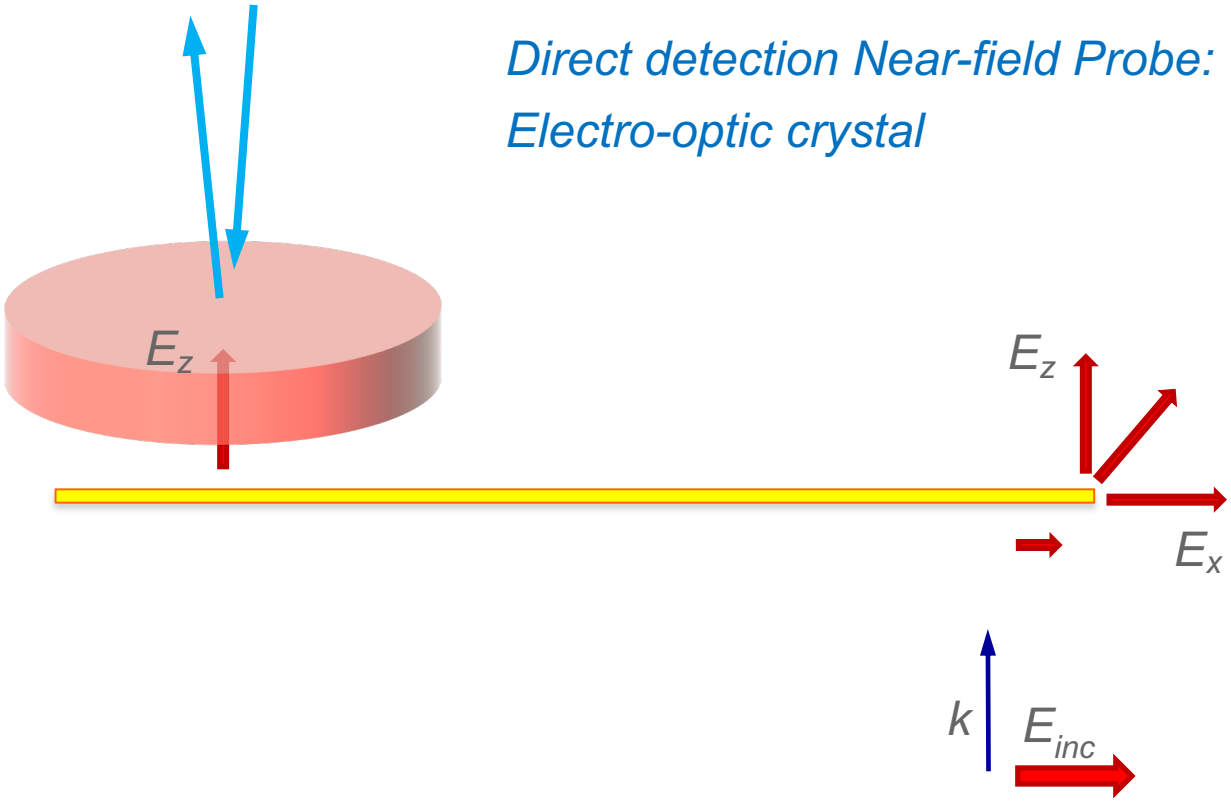


Mueckstein *et al.*,
J.of IRMMW 32, 1031 (2011)

Detection of surface waves



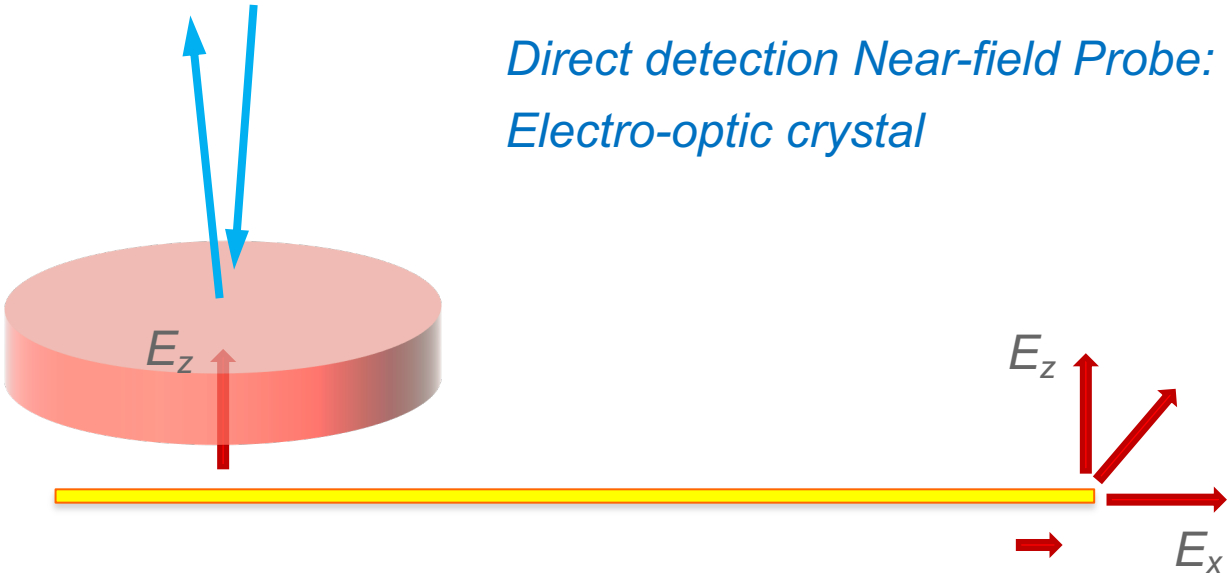
Detection of surface waves

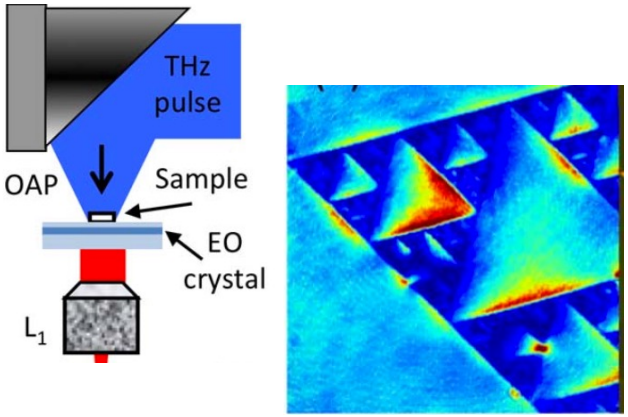


Detection of surface waves

Direct detection Near-field Probe:

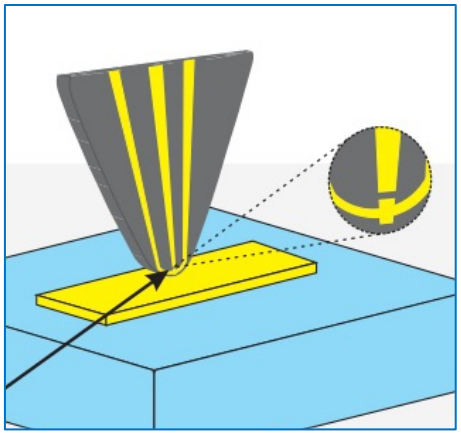
Electro-optic crystal





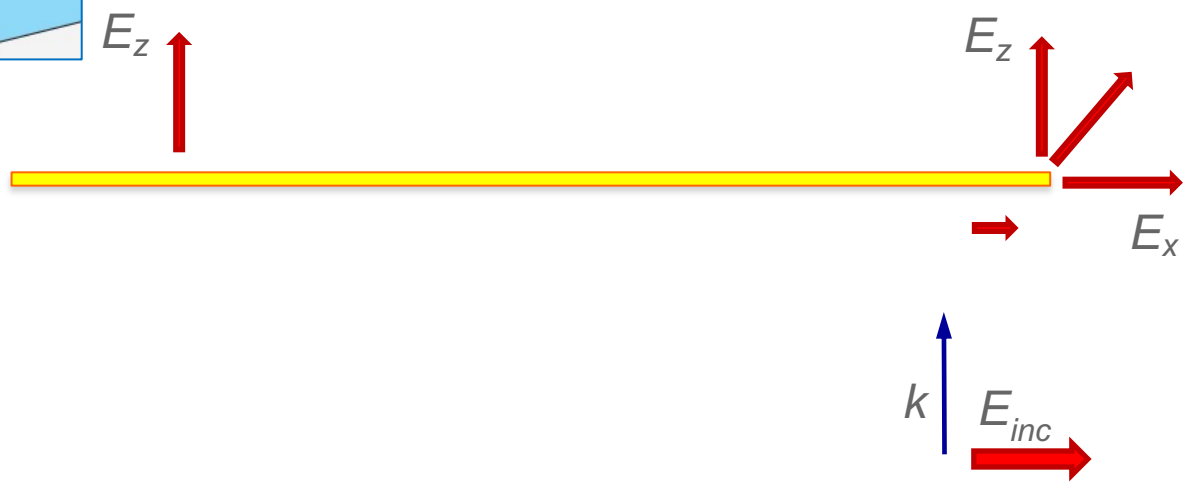
Blanchard & Tanaka (2016)

Detection of surface waves



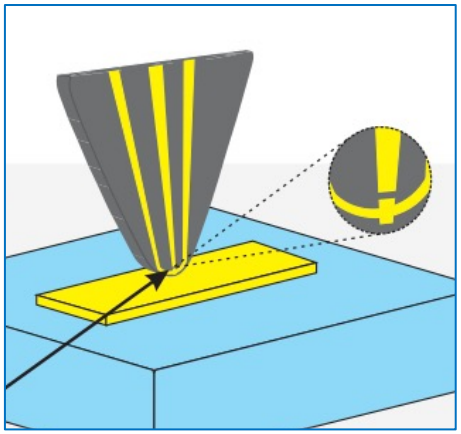
Direct detection Near-field Probe:

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



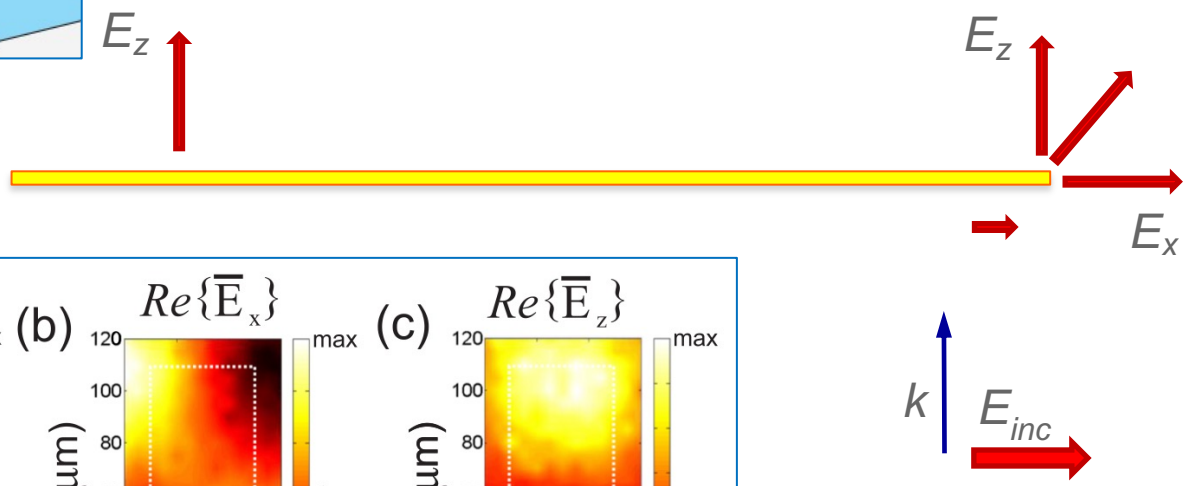
Bhattacharya and Rivas,
APL Photonics 1, 086103 (2016)

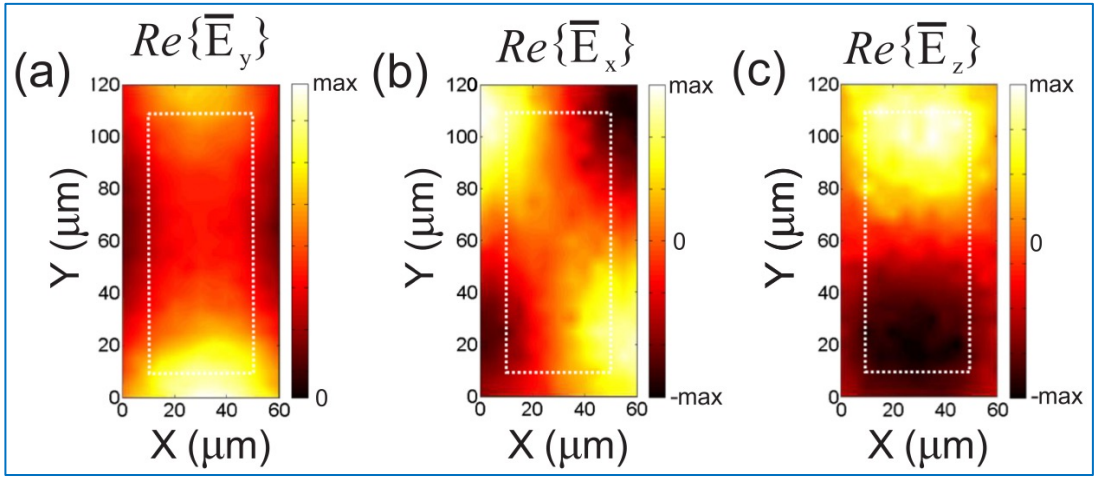
Detection of surface waves



Direct detection Near-field Probe:

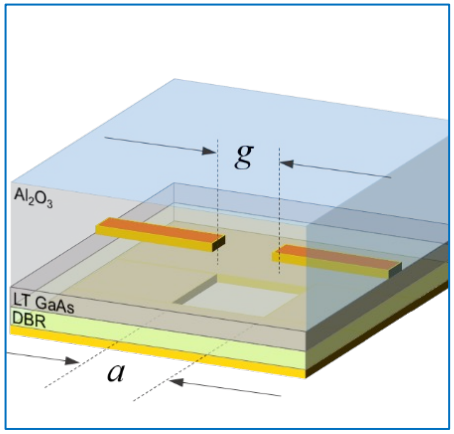
Commercial Tera-Spike probe / Protemics
www.protemics.com



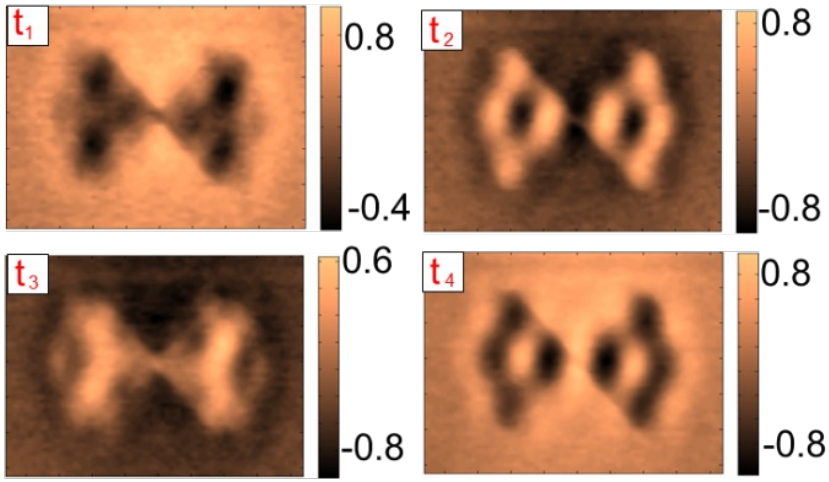


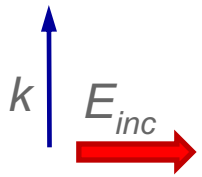
Bhattacharya and Rivas,
APL Photonics 1, 086103 (2016)

Detection of surface waves



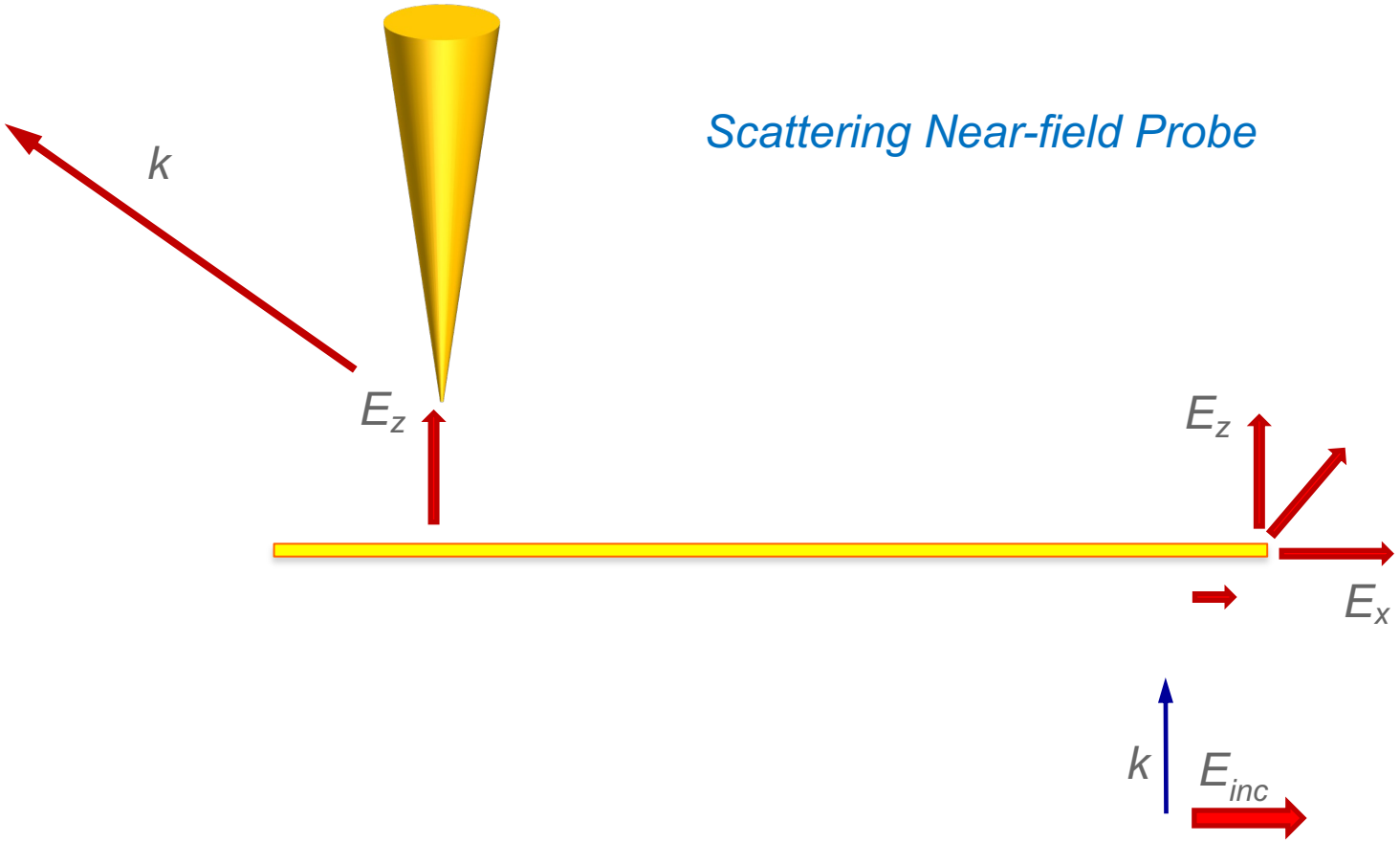
Direct detection Near-field Probe:
Aperture with THz detector





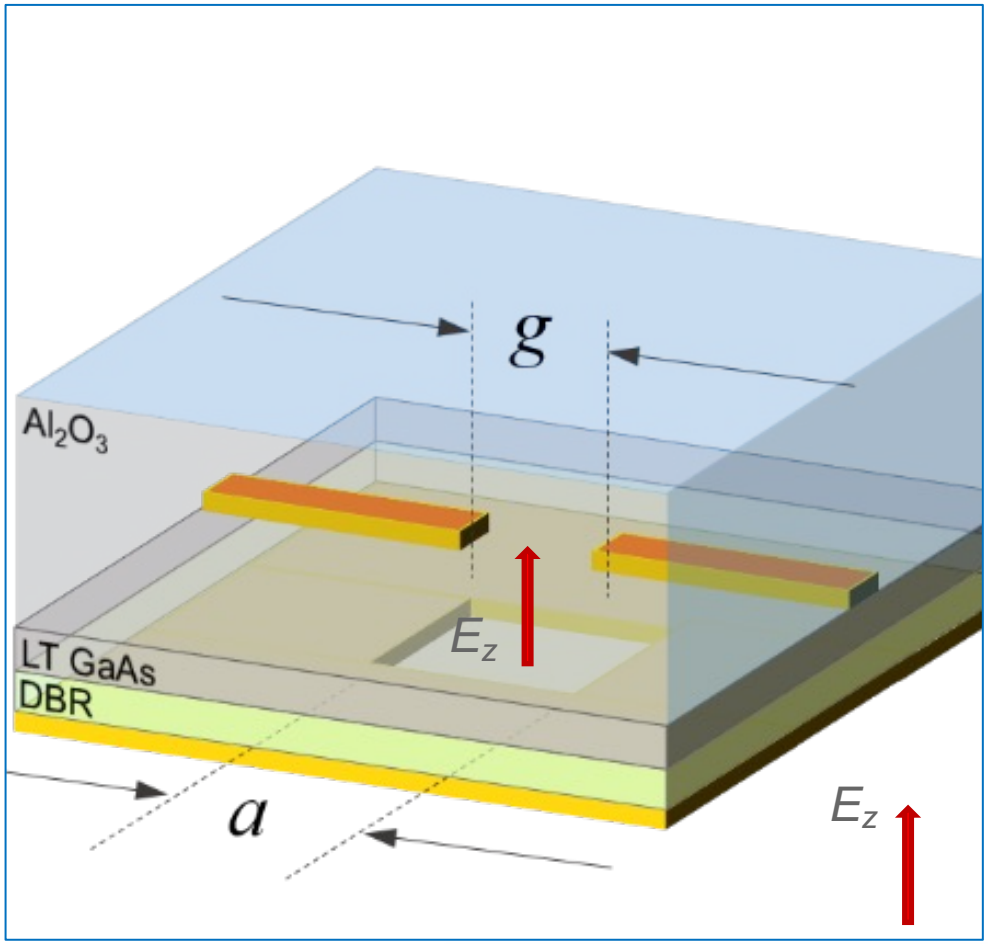
Mueckstein *et al.*, J.of IRMMW 32, 1031 (2011)

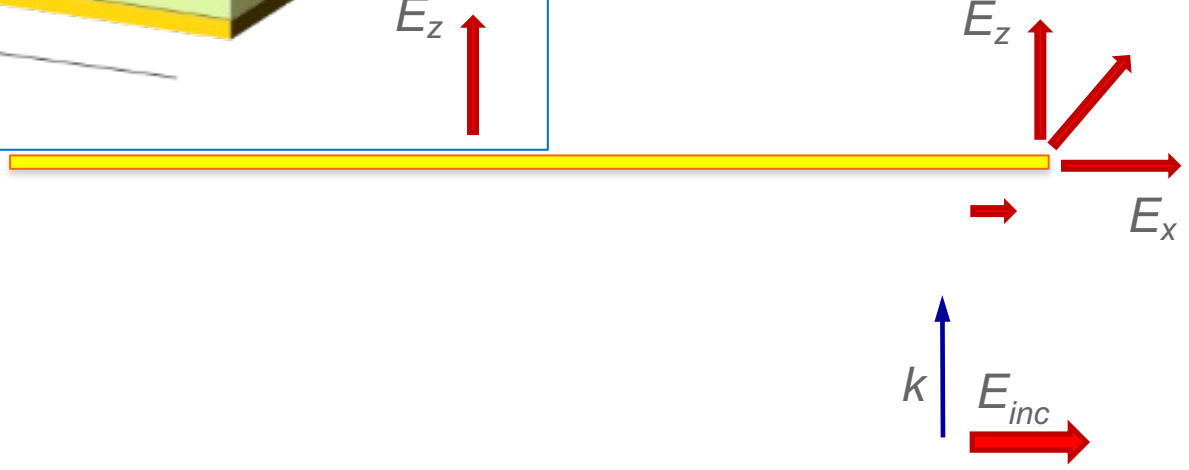
Detection of surface waves



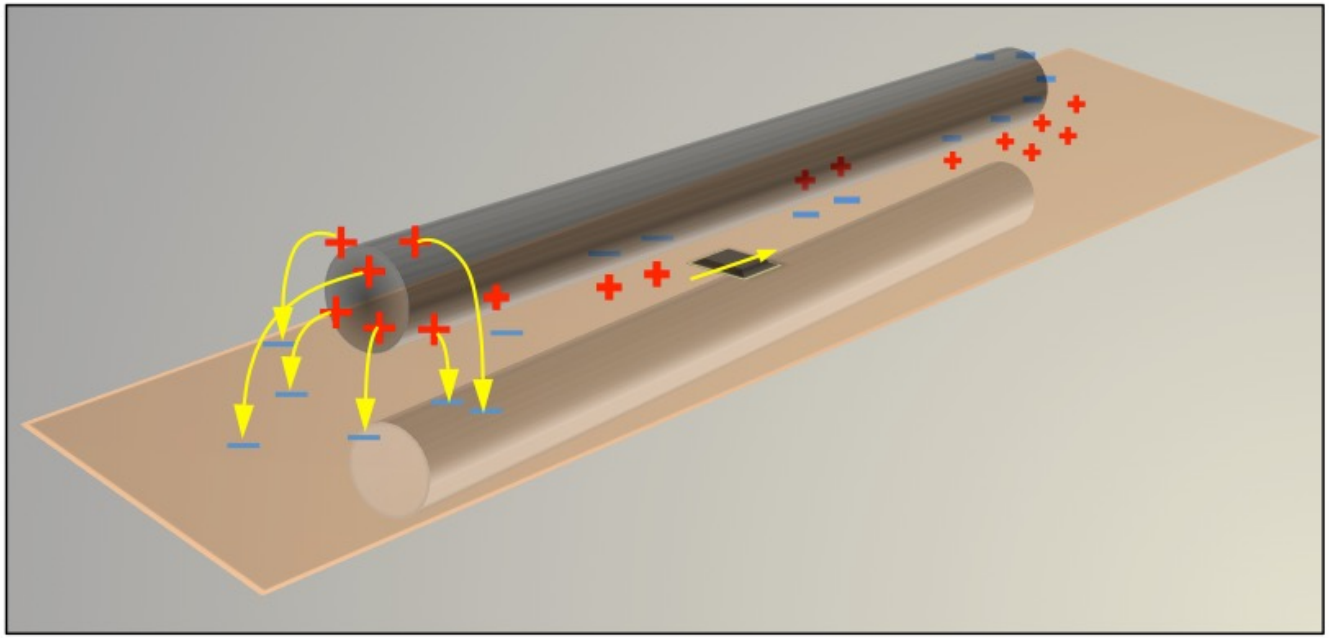
What is detected in THz NF microscopy?

Aperture Near-field Probe?

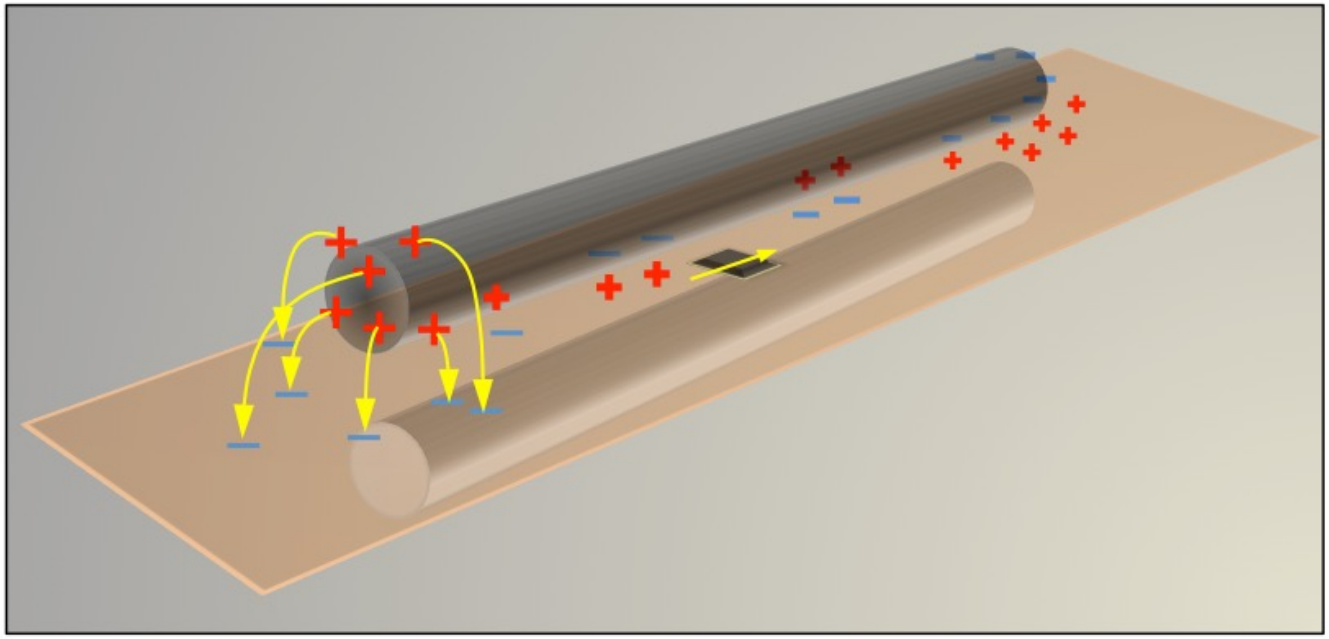




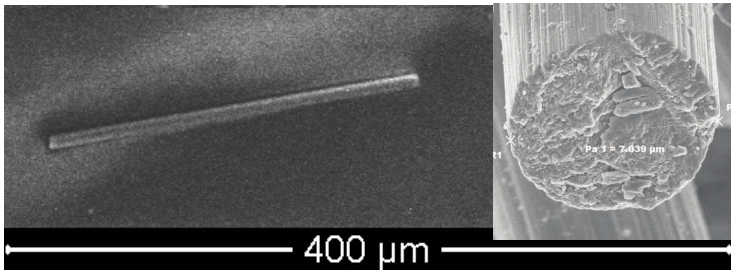
Surface plasmon resonances

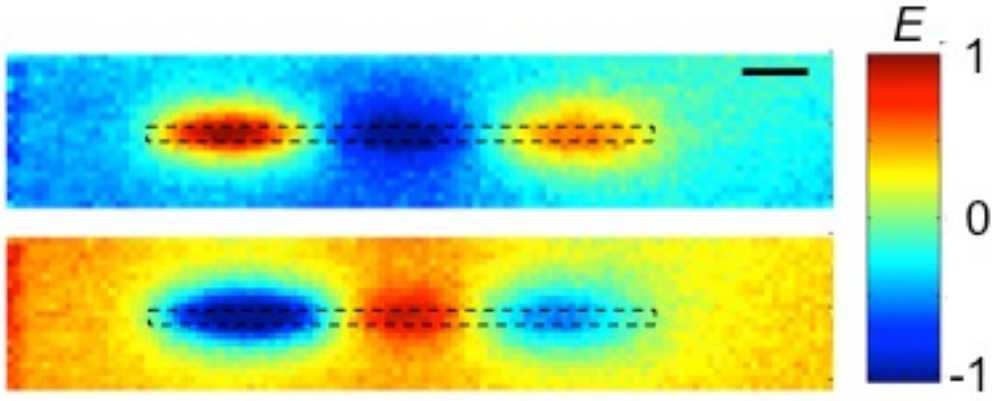


Surface plasmon resonances



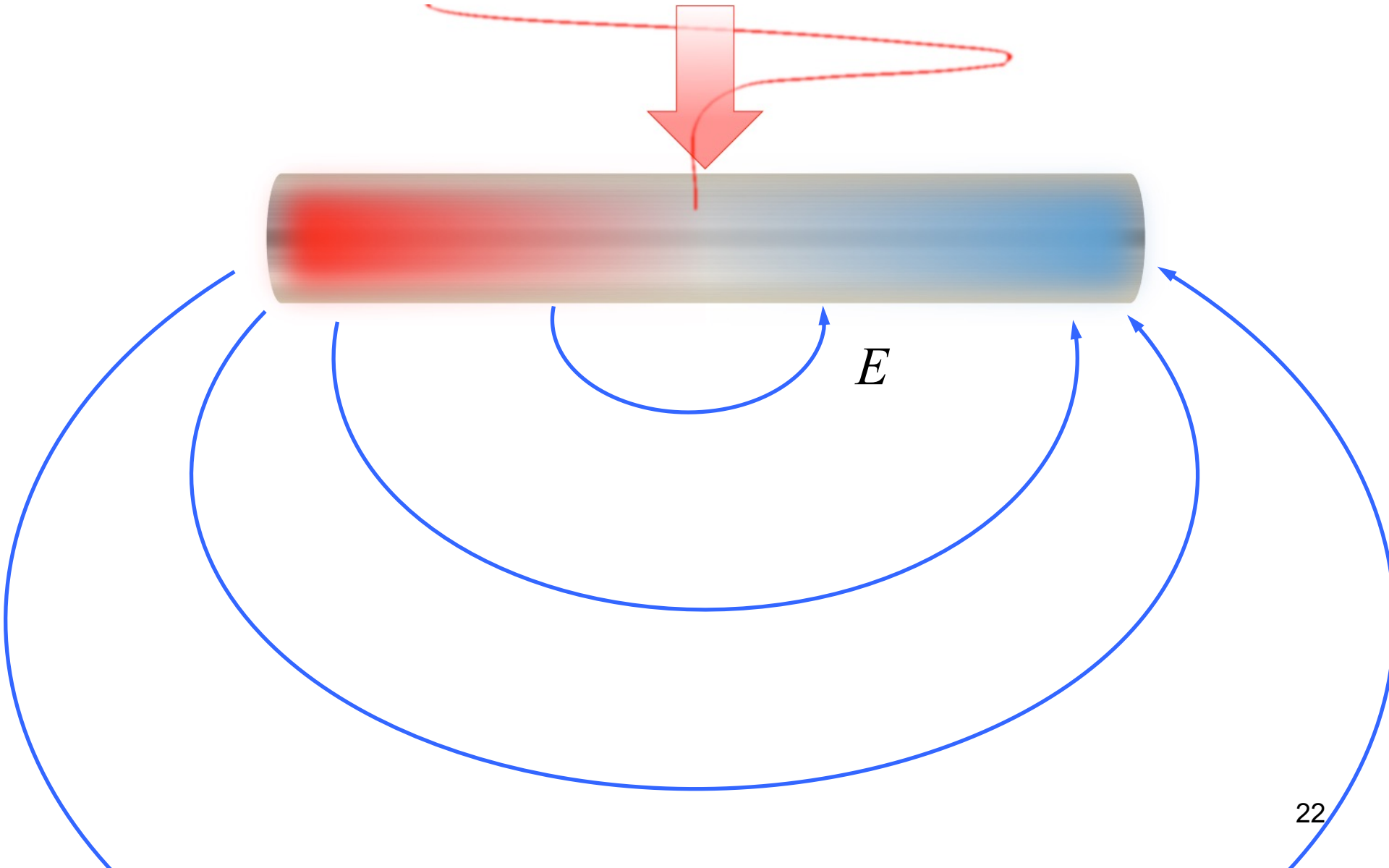
Conductive carbon fibres:
6.5 μm diameter, 50-250 μm long



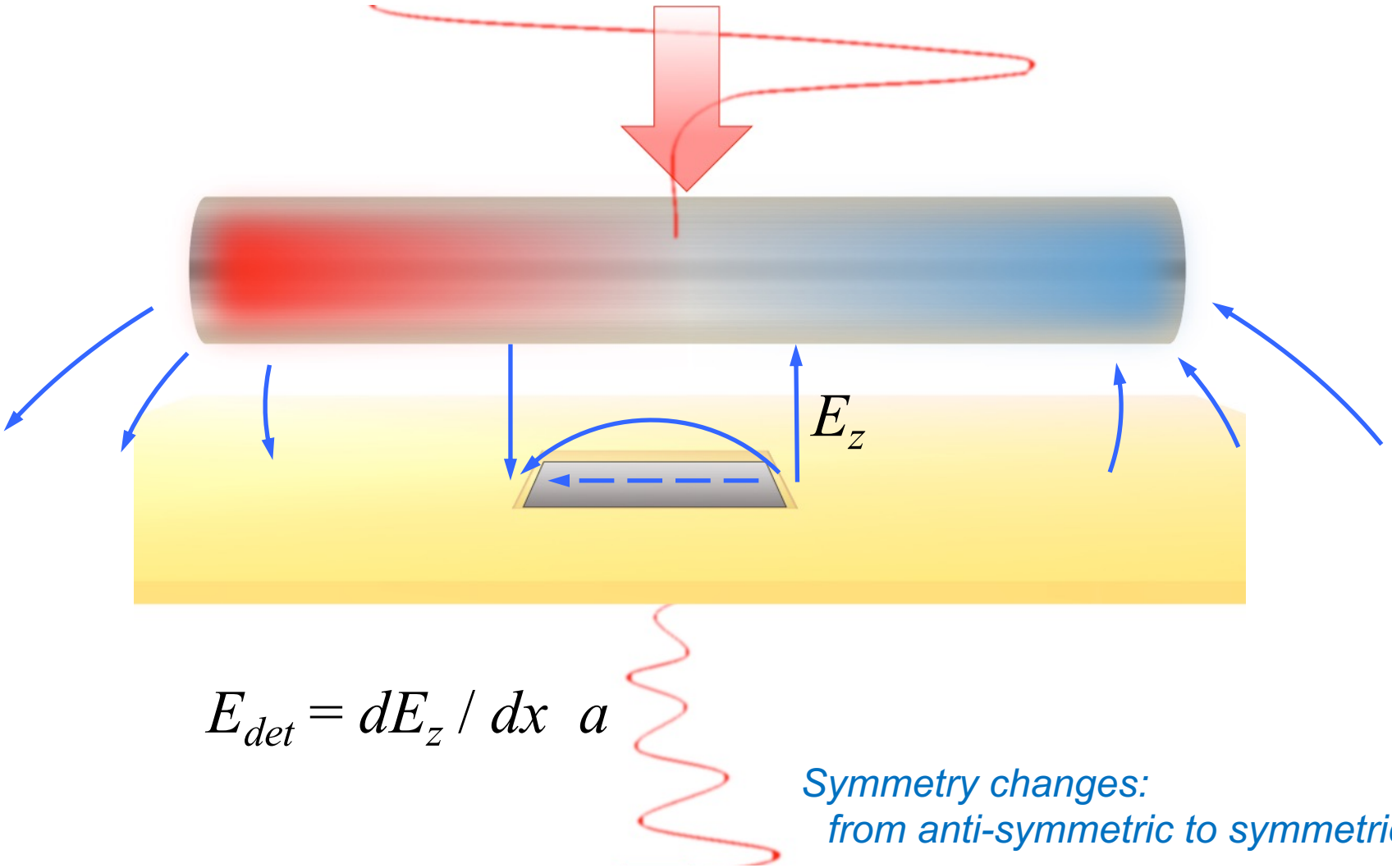


IEEE Trans. THz S&T 6, 382 (2016)

THz Surface plasmons – Mapping with Aperture



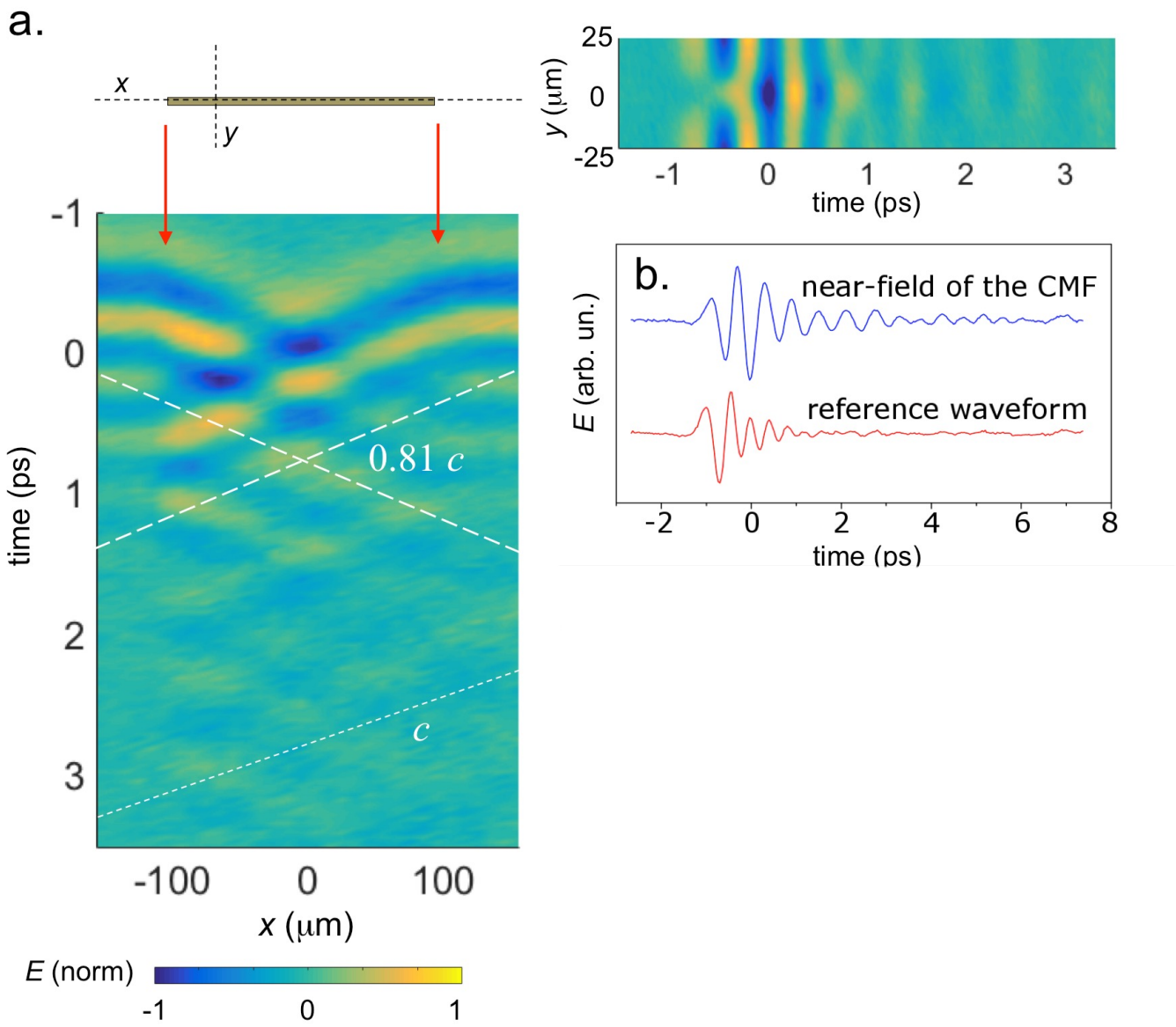
THz Surface plasmons – Mapping with Aperture



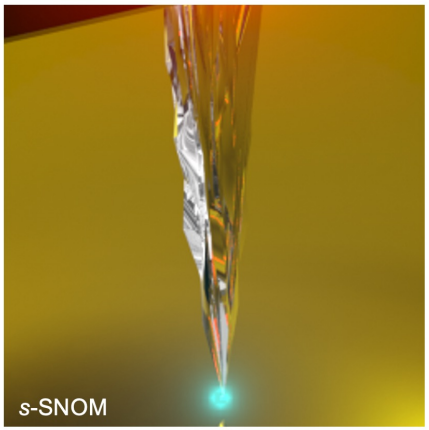
$$E_{det} = dE_z / dx \;\; a$$

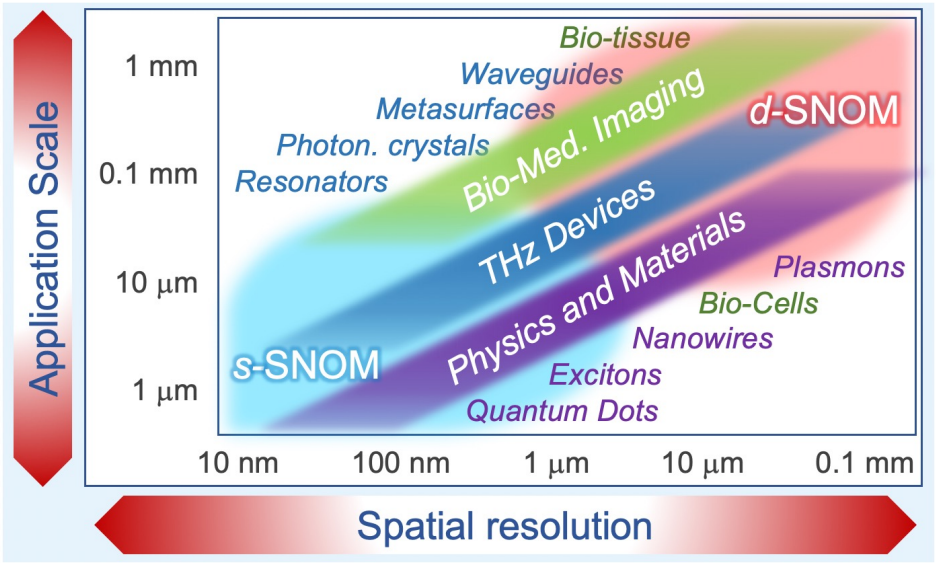
Symmetry changes:
from anti-symmetric to symmetric

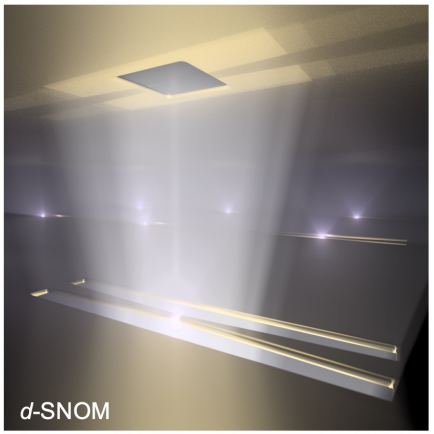
Surface plasmon resonances



THz Near-Field Microscopy Application Space





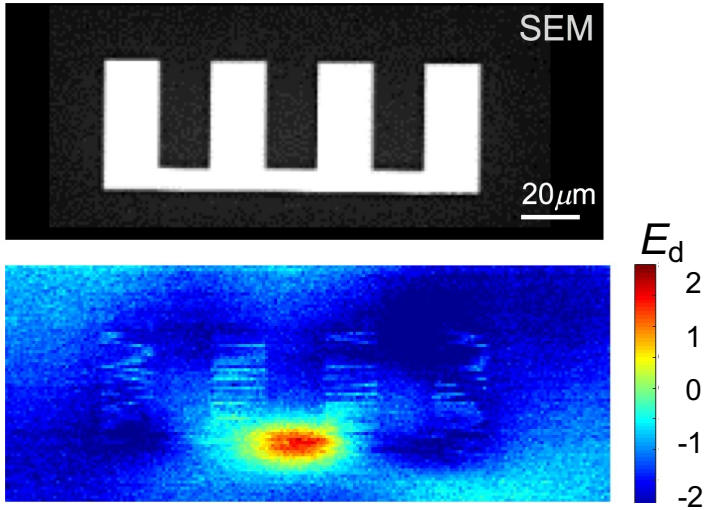


Boland et al. THz Roadmap (2023)

What is the property or quantity of interest?

Graphics: Tom Siday

THz surface plasmon resonances



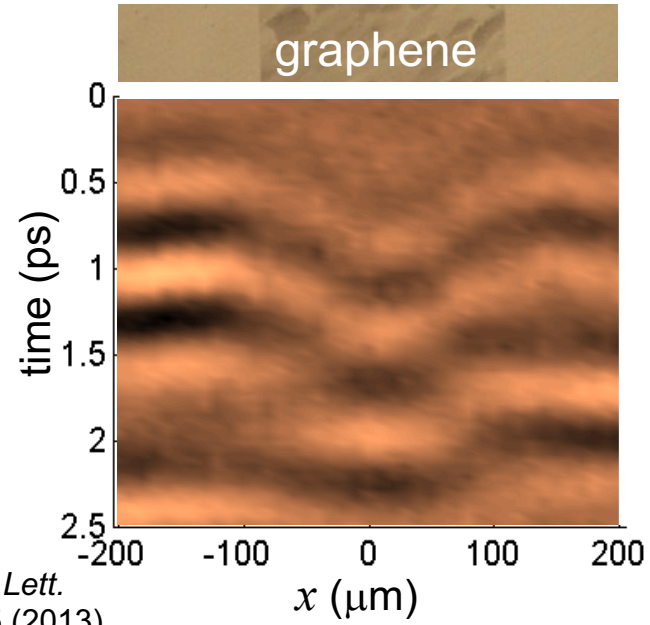
Appl. Phys. Lett. 110 (6), 061109 (2017)

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)



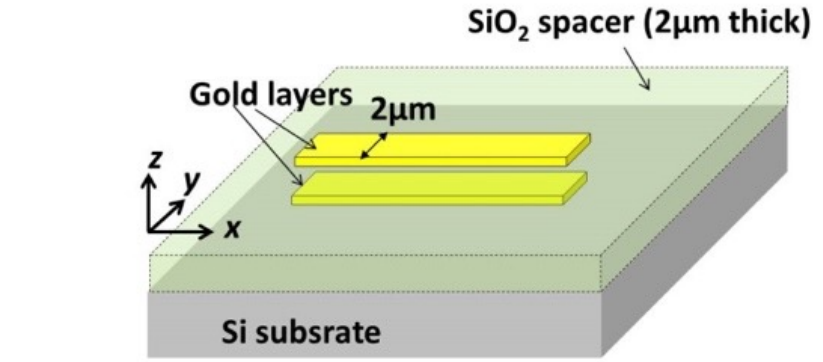
Appl. Phys. Lett.
103, 111105 (2013)

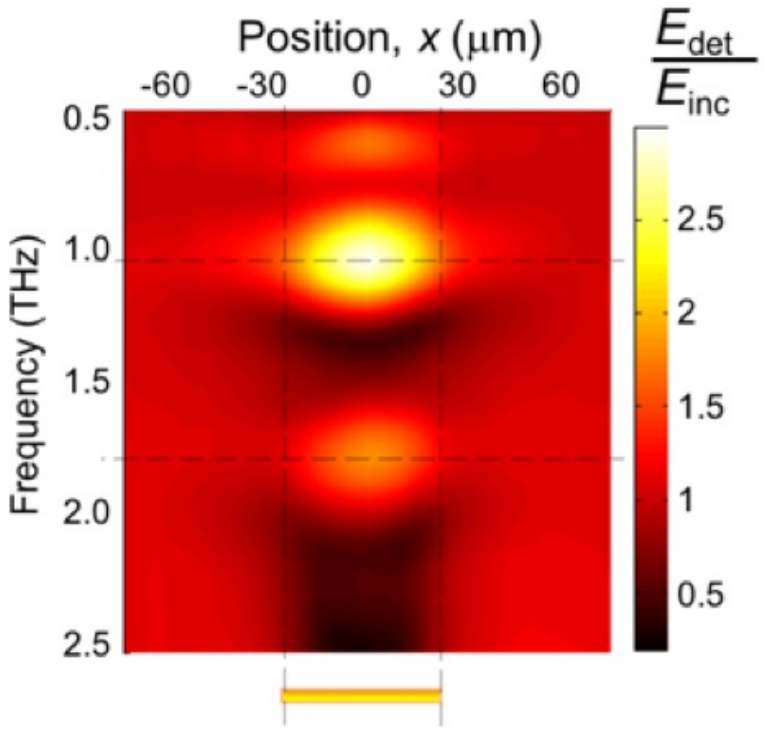
OM, Todorov, et al.,
Optics Express 26 (6), 7437 (2018)

THz surface plasmon resonances

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

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

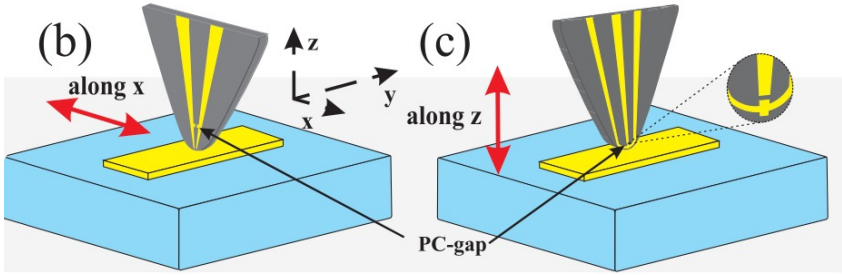




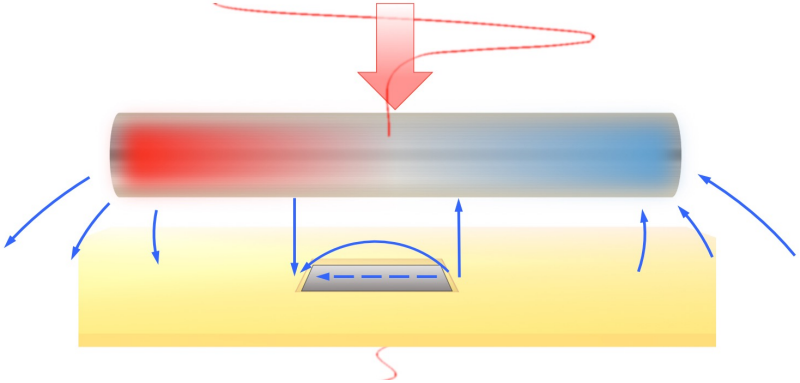
OM, Todorov, et al.,
Optics Express 26 (6), 7437 (2018)

What is detected in THz NF microscopy?

E - field



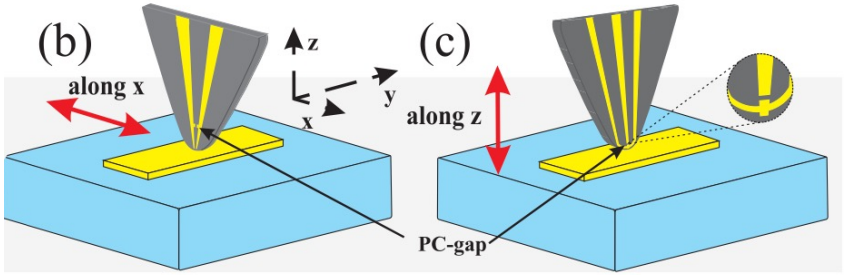
Bhattacharya and Rivas,
APL Photonics 1, 086103 (2016)



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

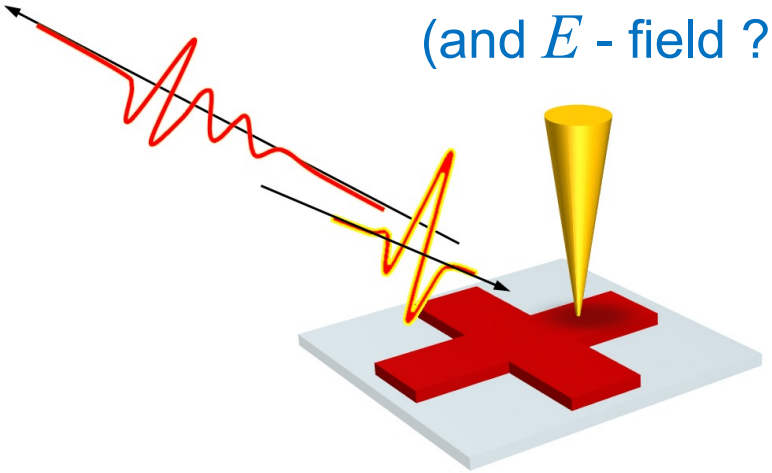
What is detected in THz NF microscopy?

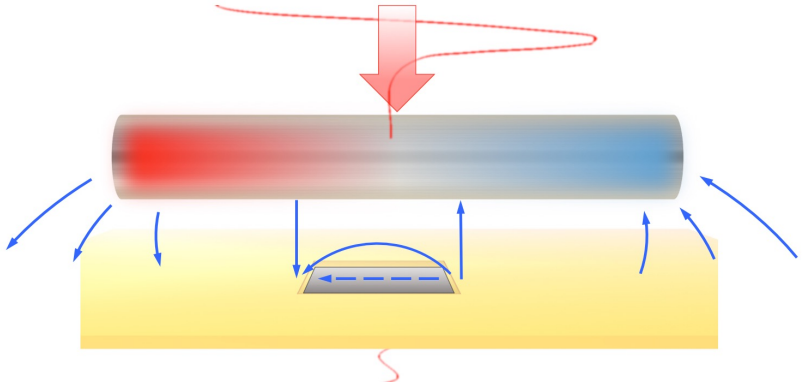
E - field



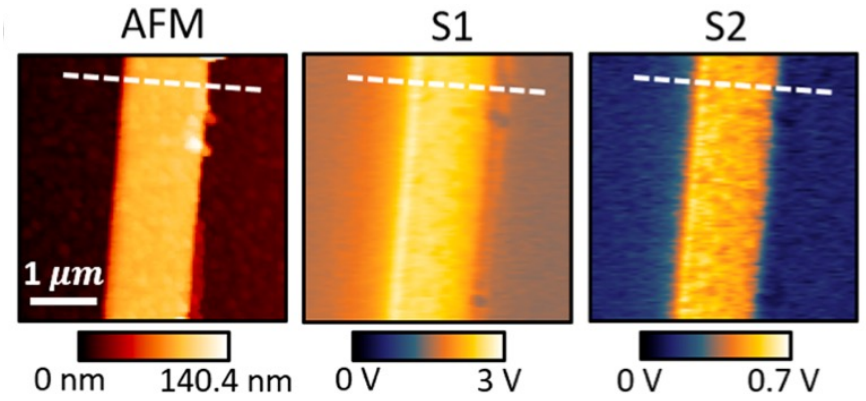
Bhattacharya and Rivas,
APL Photonics 1, 086103 (2016)

ε - dielectric constant
(and E - field ?)



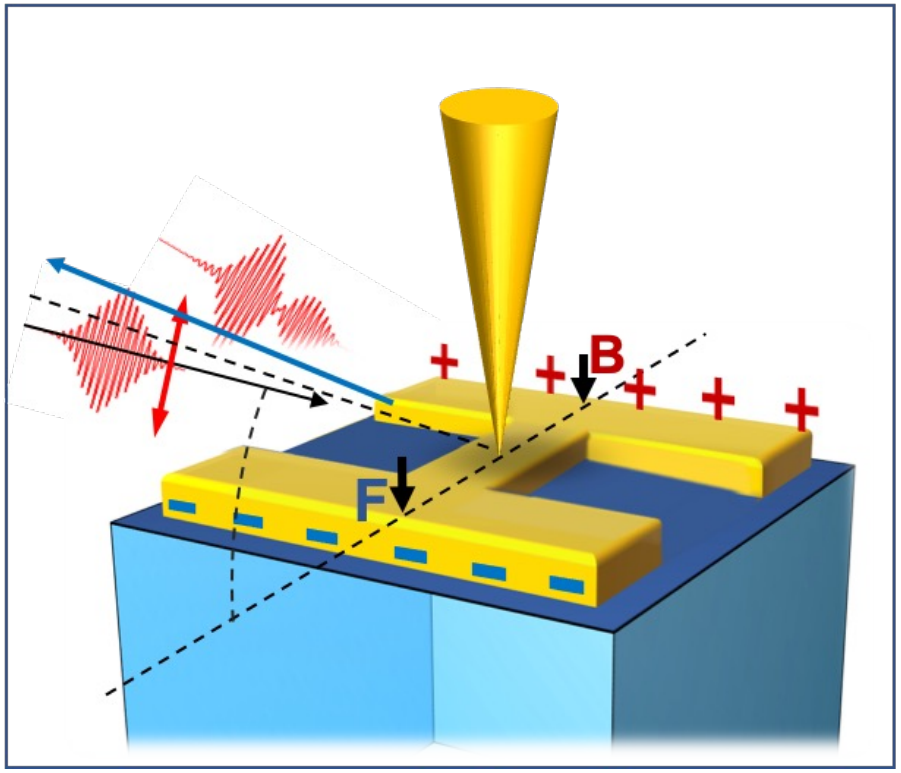


IEEE Trans. THz S&T 6, 382 (2016)



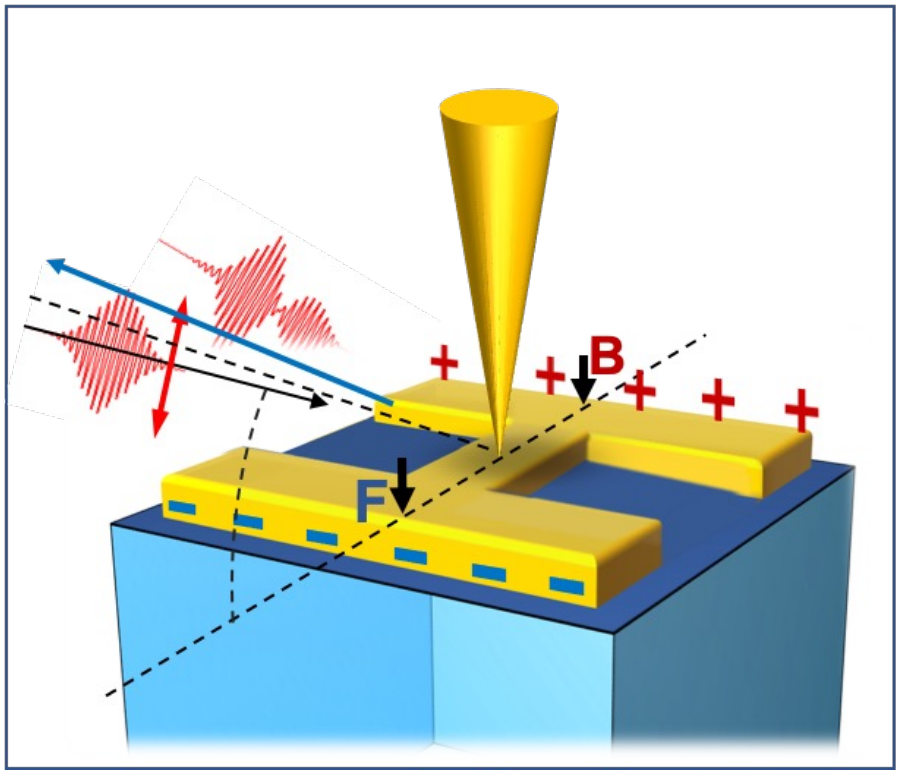
X. Chen et al. *ACS Photonics* **7**, 687 (2020)

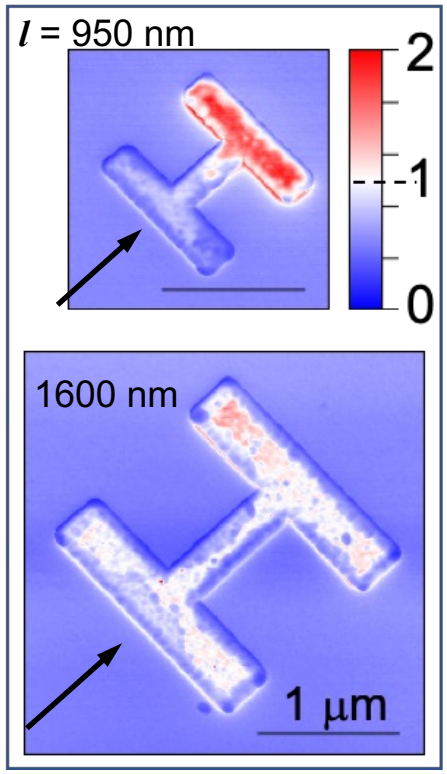
Multiple signal contributions – s-SNOM



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

Multiple signal contributions – s-SNOM

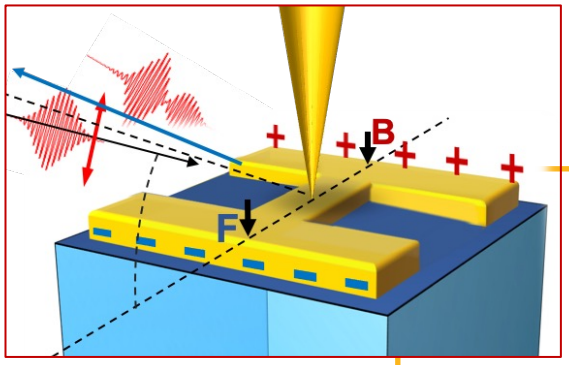


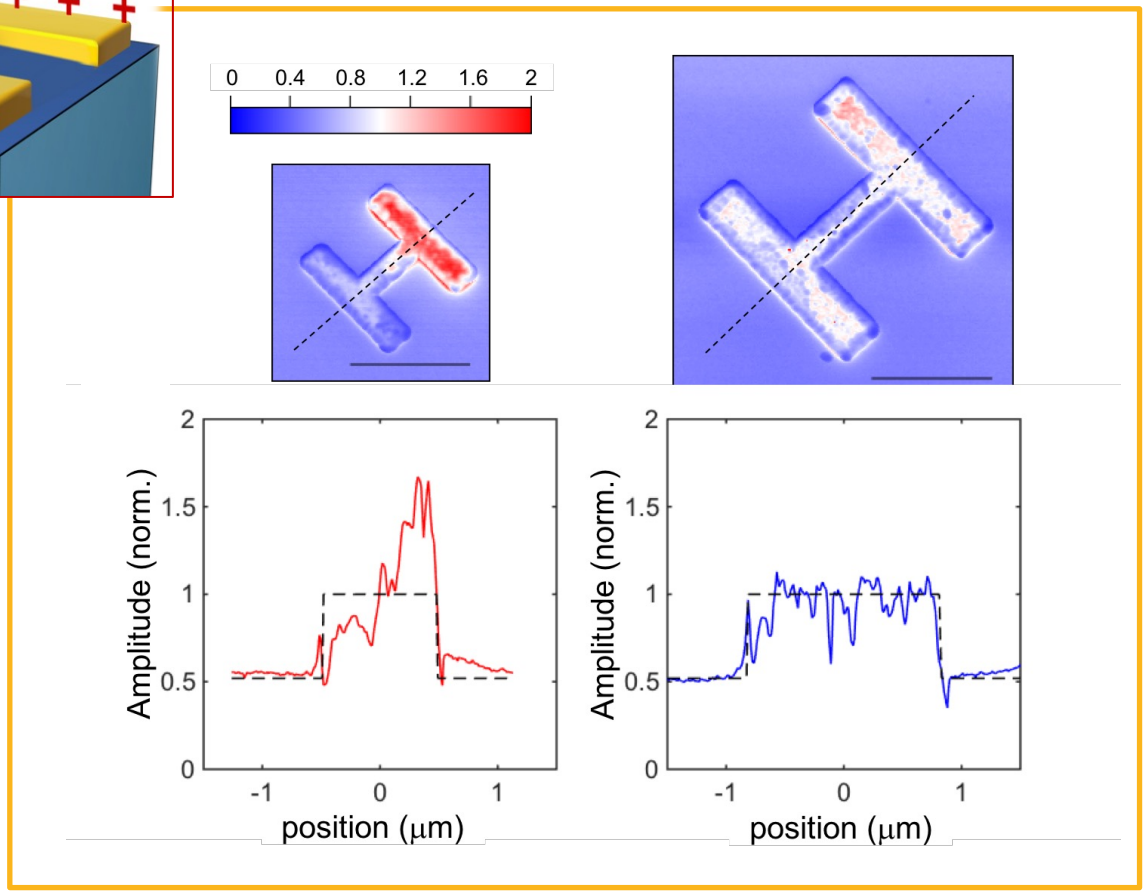


CW excitation (QCL)
λ: 10 μm (1000 cm^{-1})

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

Surface plasmon waves – s-SNOM





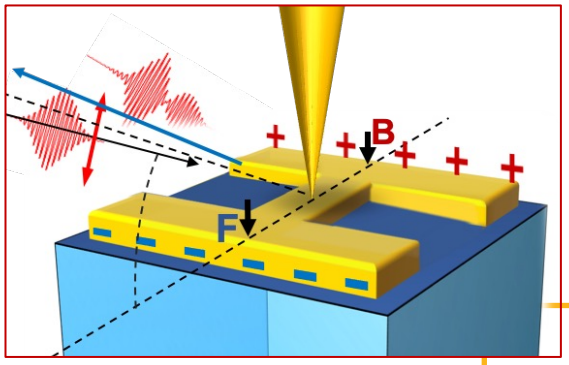
E – field
+
ε - dielectric constant

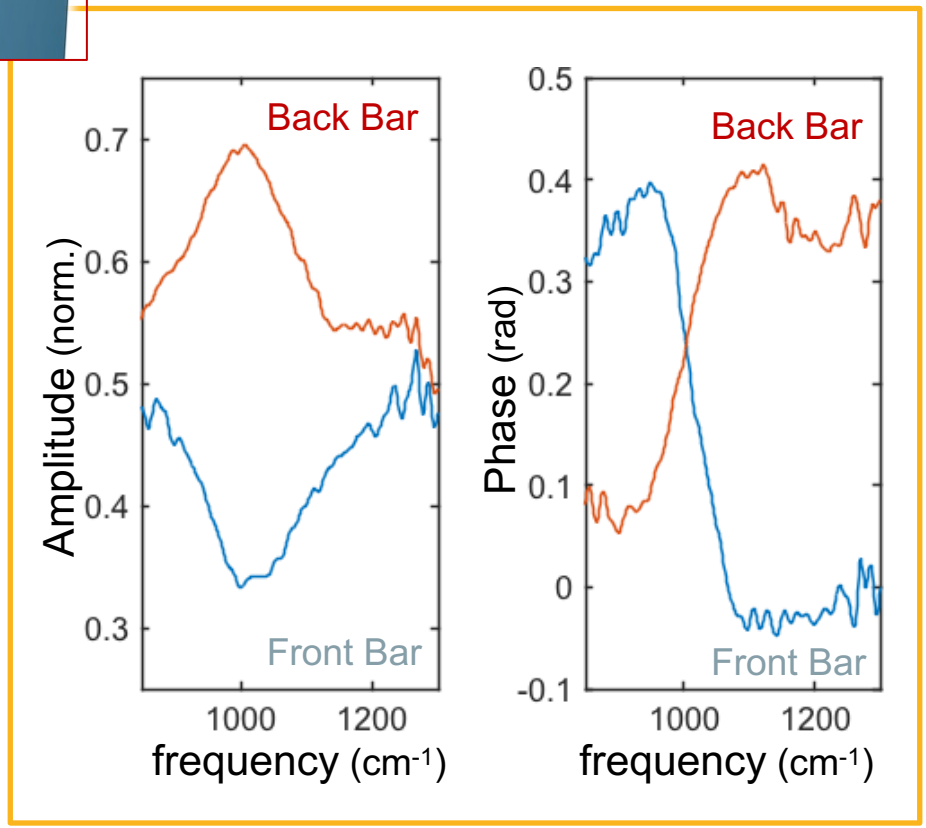
ε - dielectric constant

Antenna resonance is superimposed over the material contrast

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

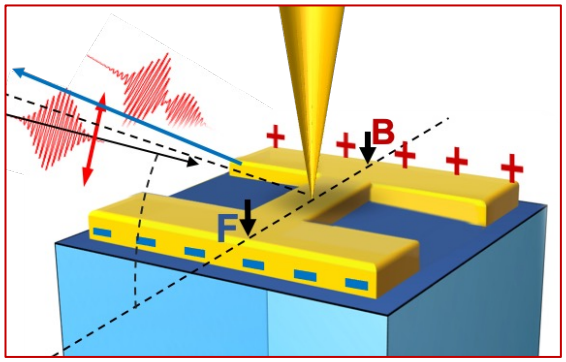
s-SNOM – nano-FTIR

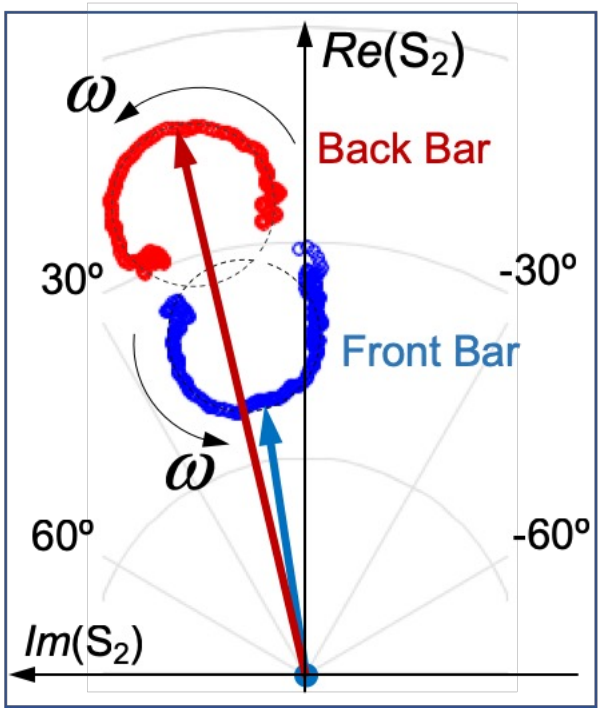


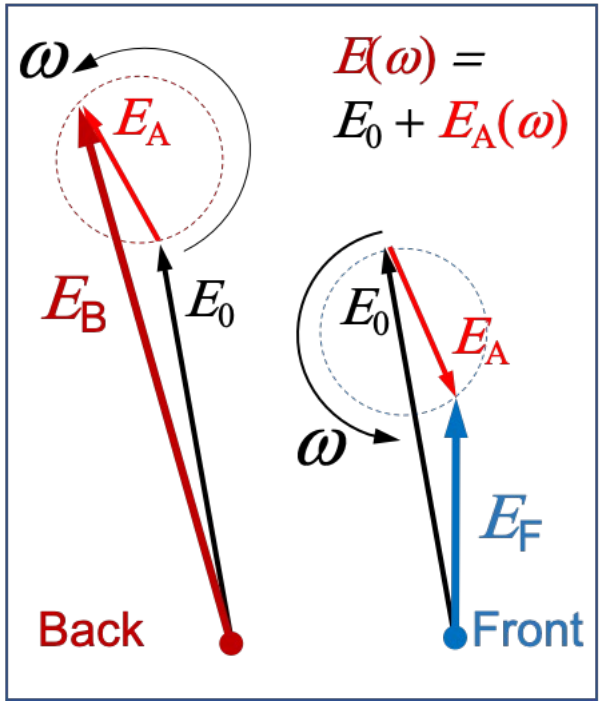


Wang et al., *Nano Lett.* 2019, 19, 4620−4626

s-SNOM – nano-FTIR



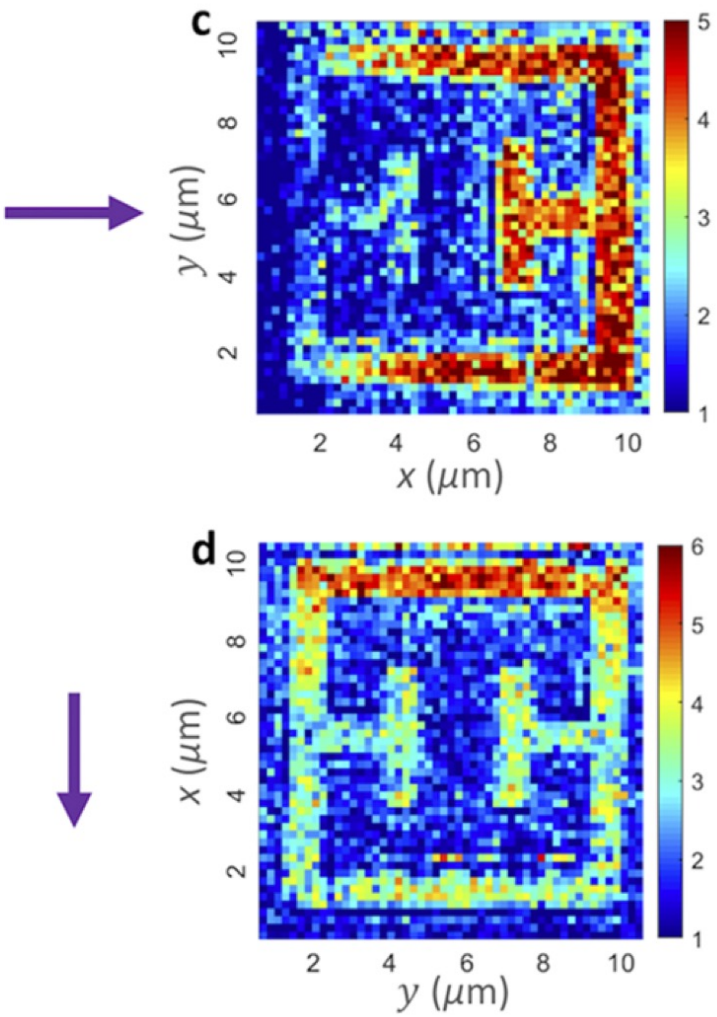


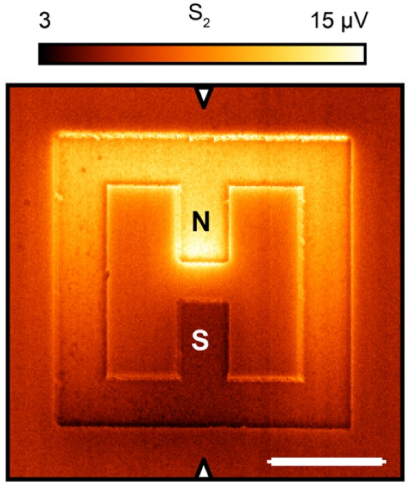


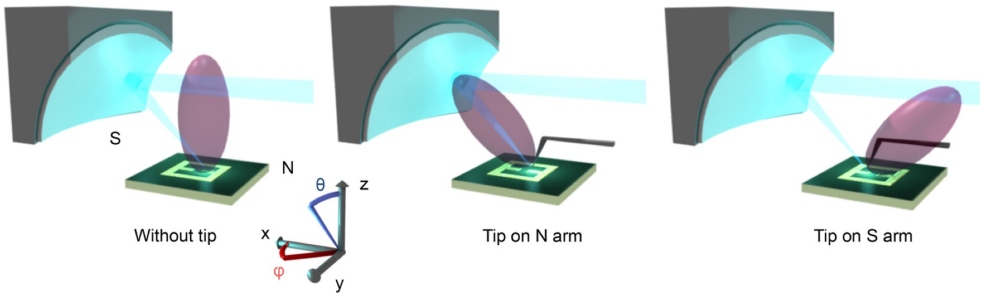
Wang et al., *Nano Lett.* 2019, 19, 4620−4626

Surface plasmon resonances – THz-s-SNOM

3.45 THz



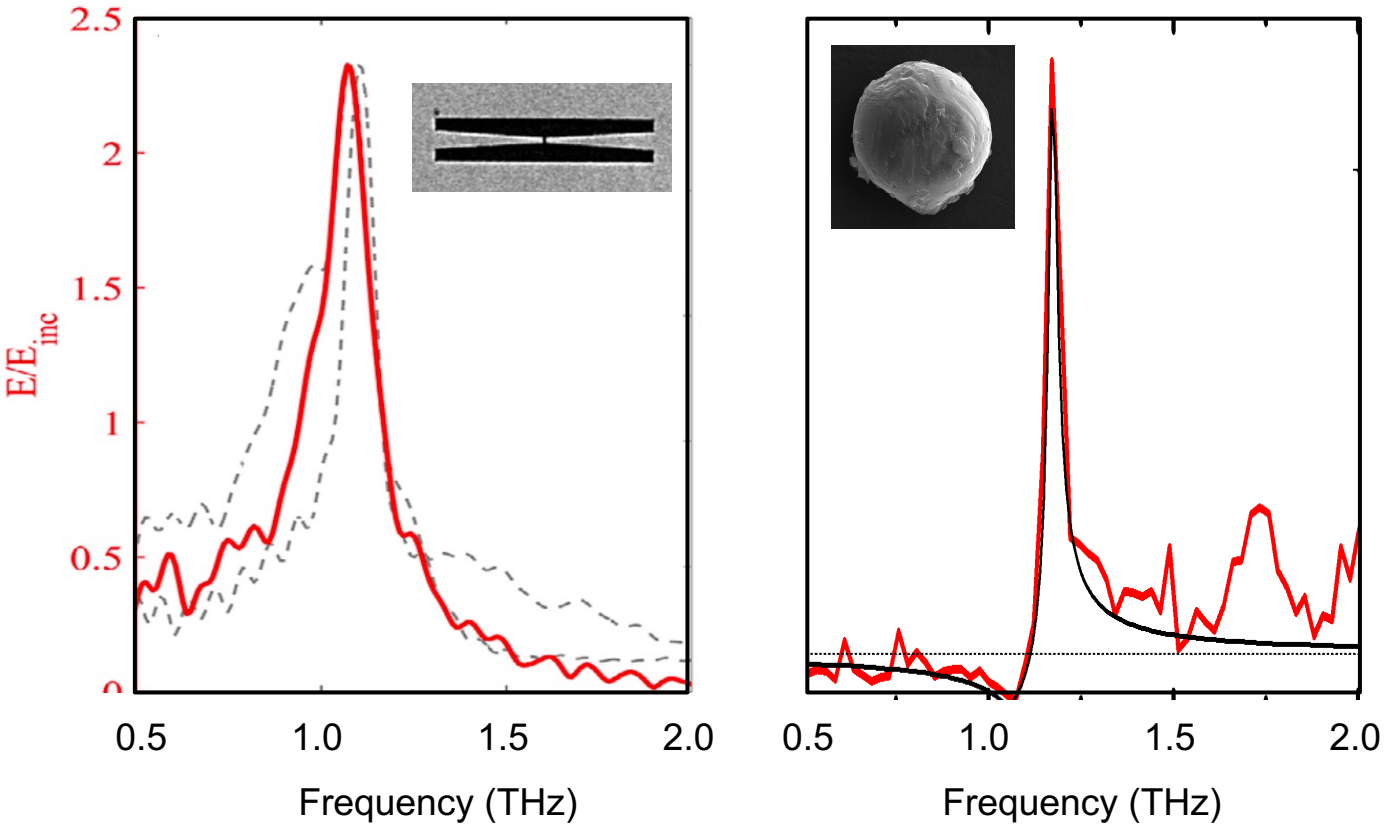




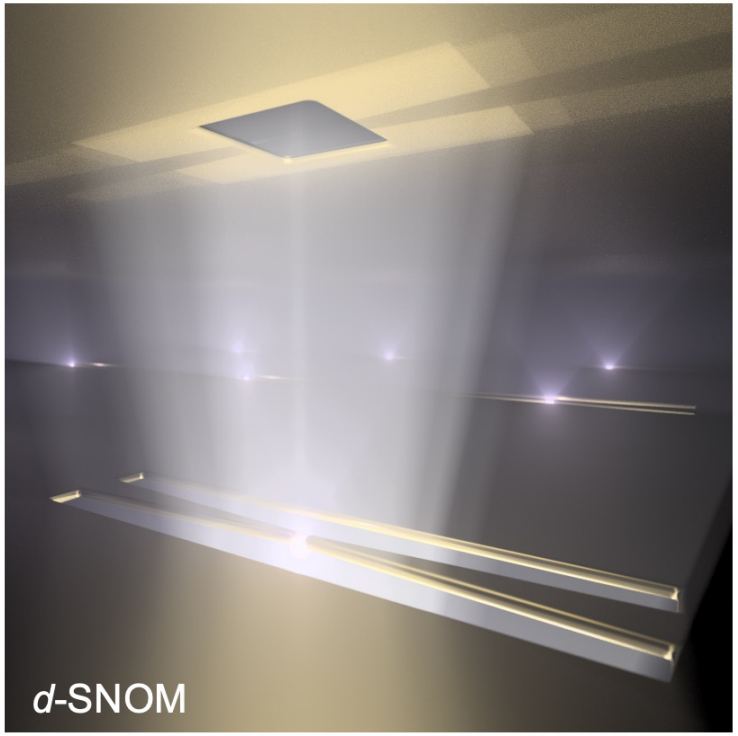
N. Sulollari *et al.*,
APL Photon. 6, 066104 (2021)

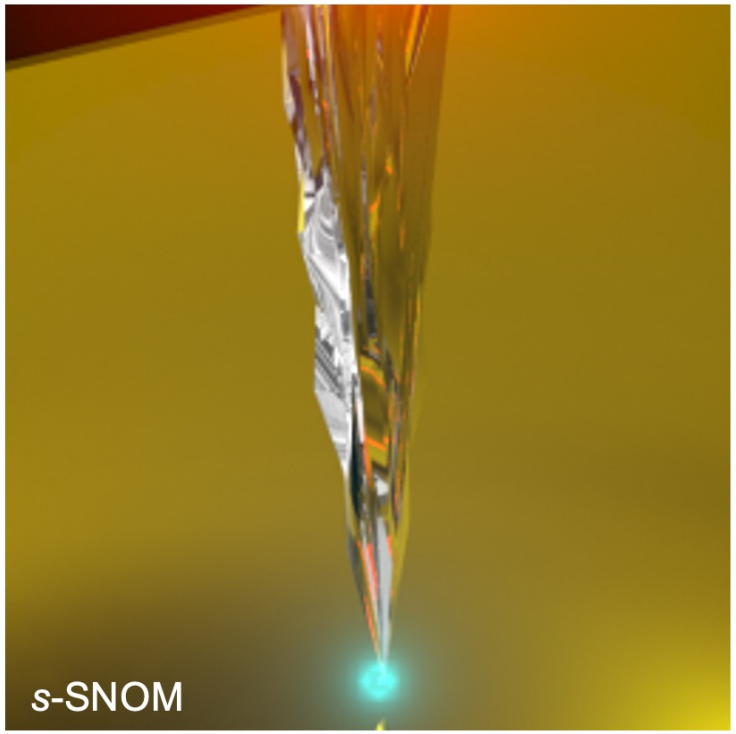
L.Thomas, T.Hannotte, C.Santos *et al.*,
ACS Appl. Mater. Interfaces (2022)

What is detected in THz NF microscopy?



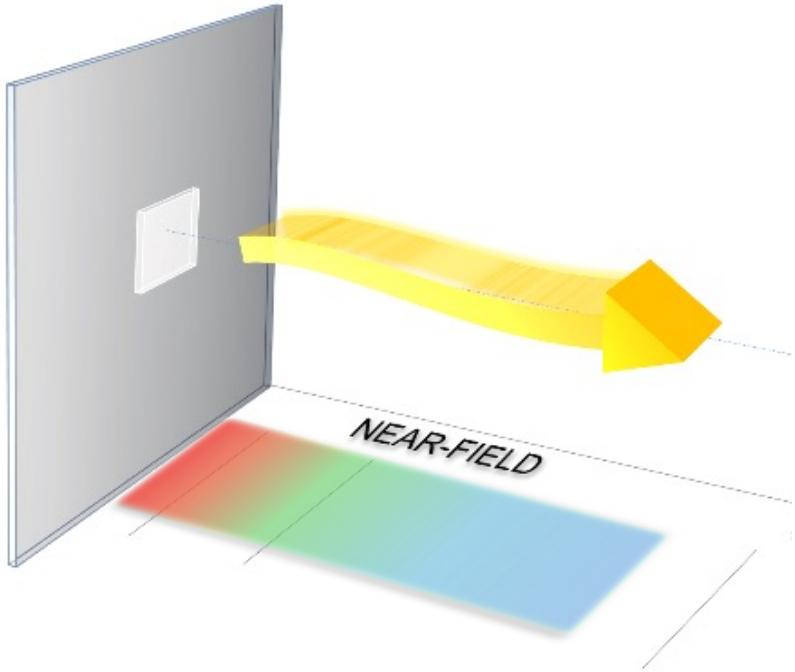
THz microscopy challenges





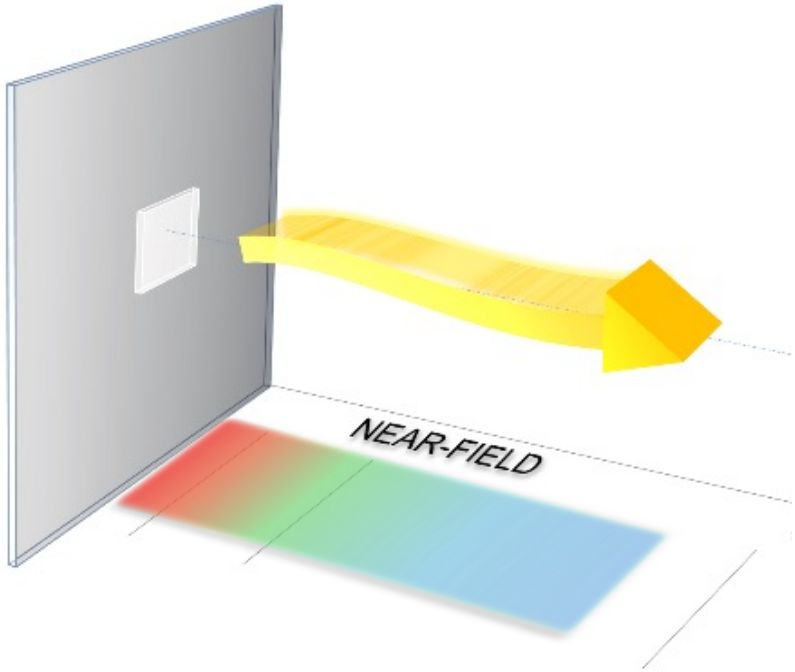
Graphics: Tom Siday

Aperture-type THz Near-Field Microscopy

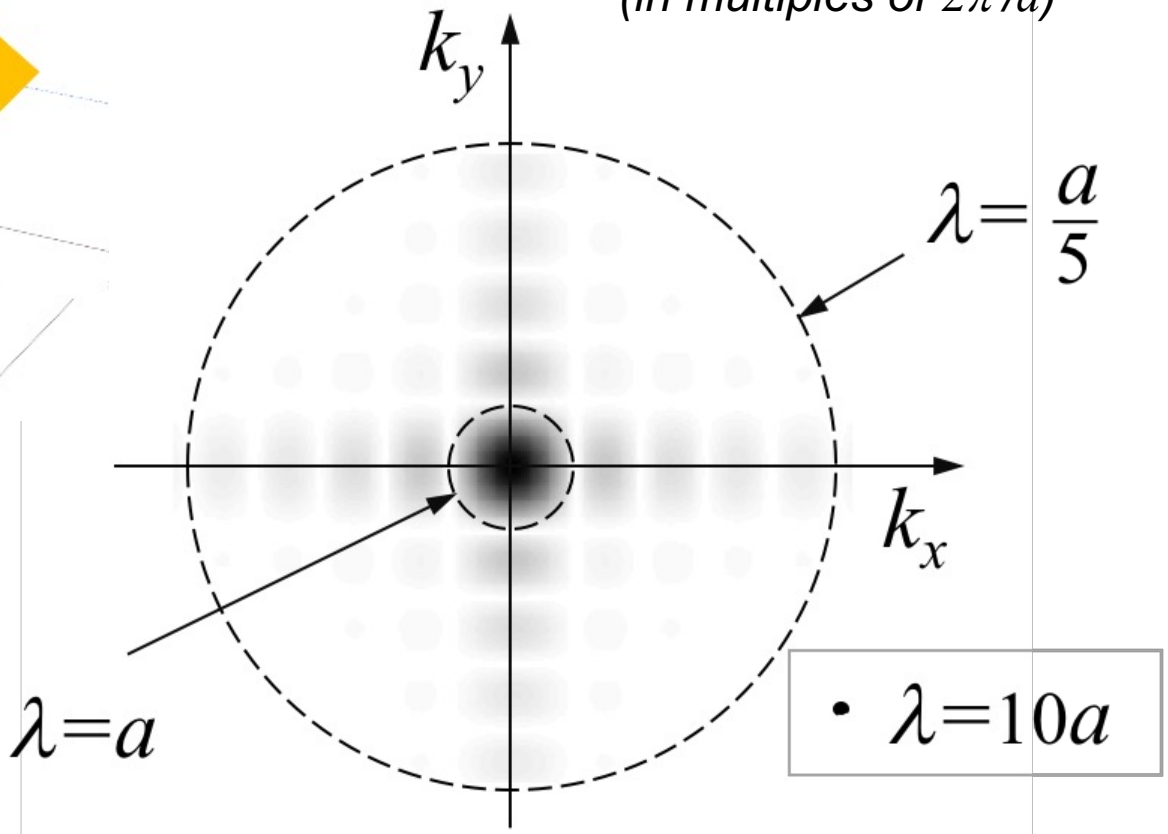


How much light passes through a subwavelength aperture?

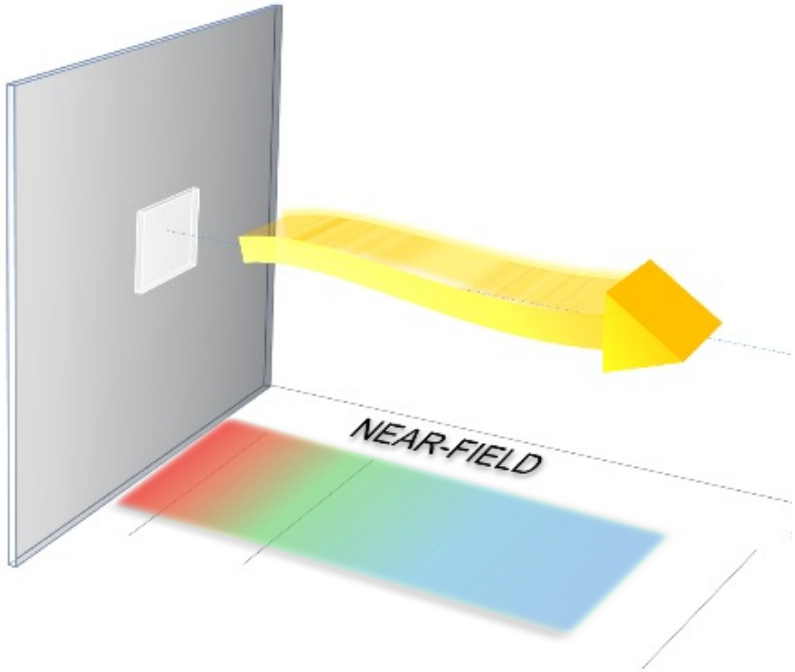
Aperture-type THz Near-Field Microscopy



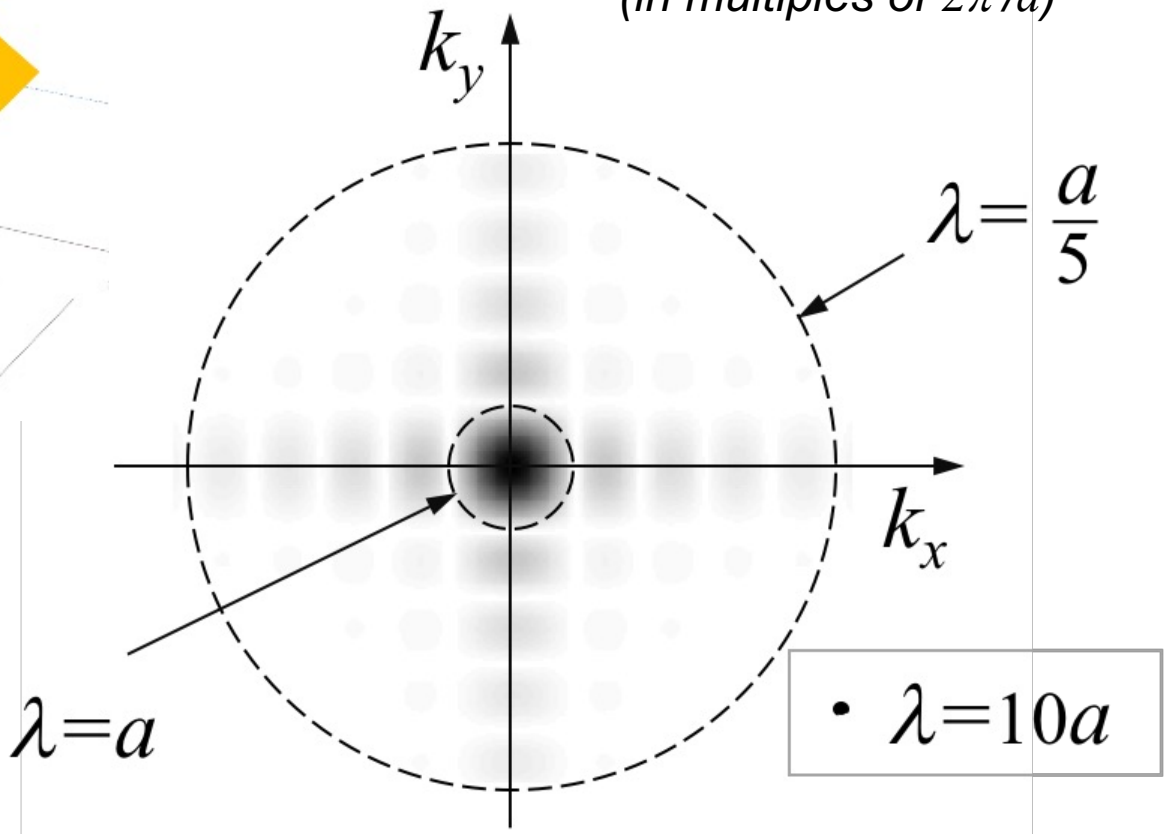
Angular spectrum representation of aperture field (in multiples of $2\pi/a$)



Aperture-type THz Near-Field Microscopy

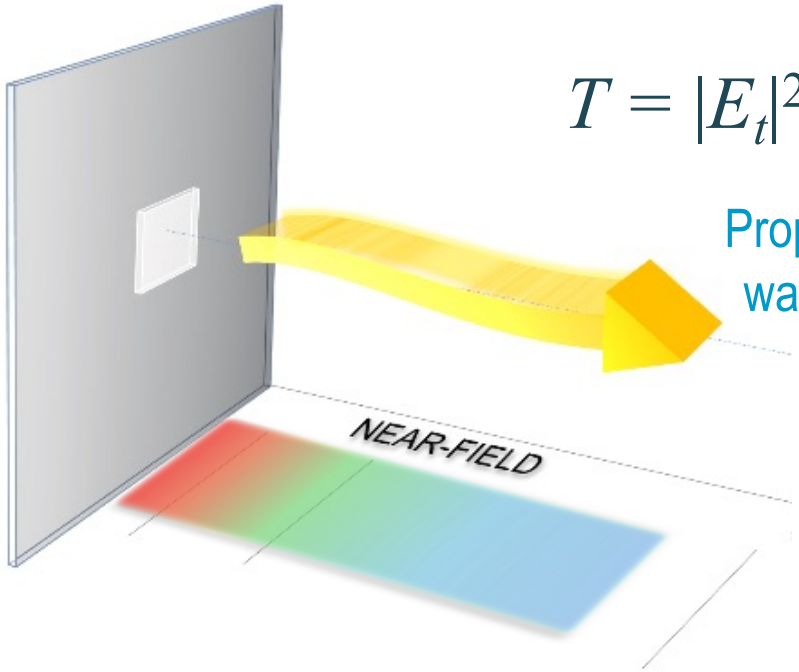


Angular spectrum representation of aperture field (in multiples of $2\pi/a$)



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

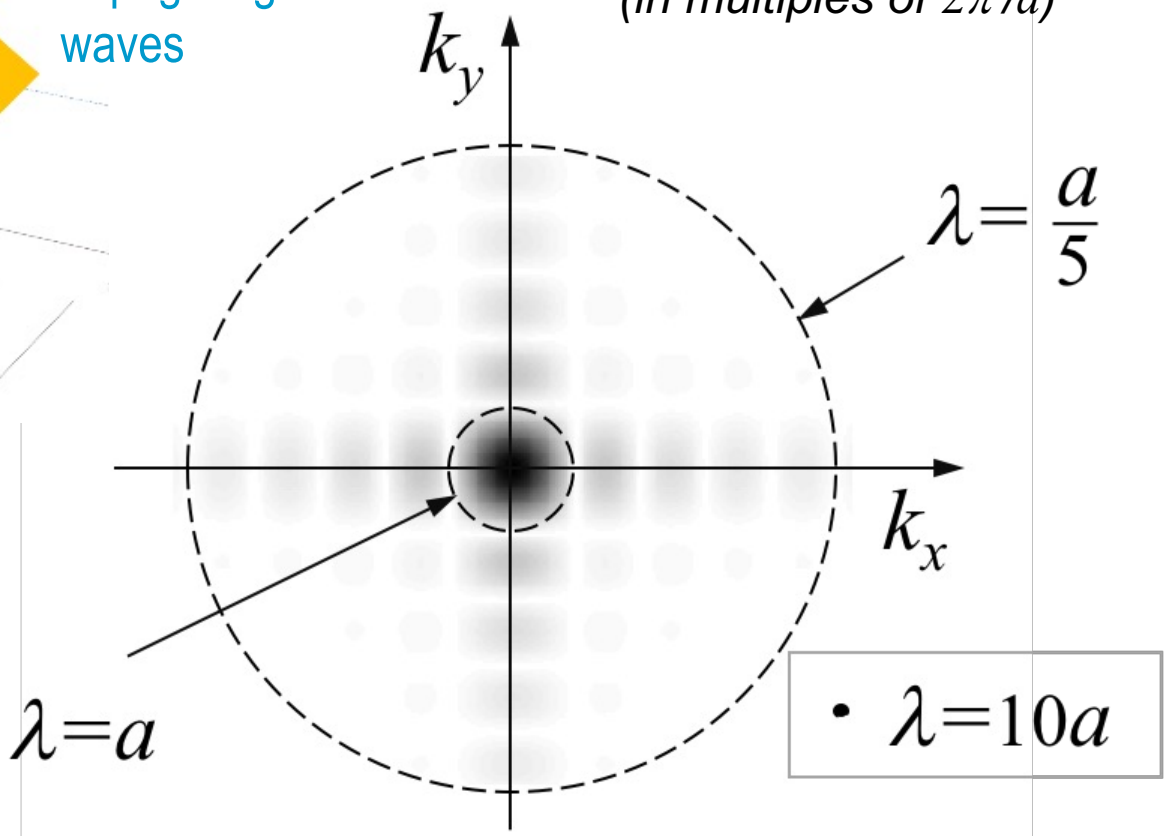
Aperture-type THz Near-Field Microscopy



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

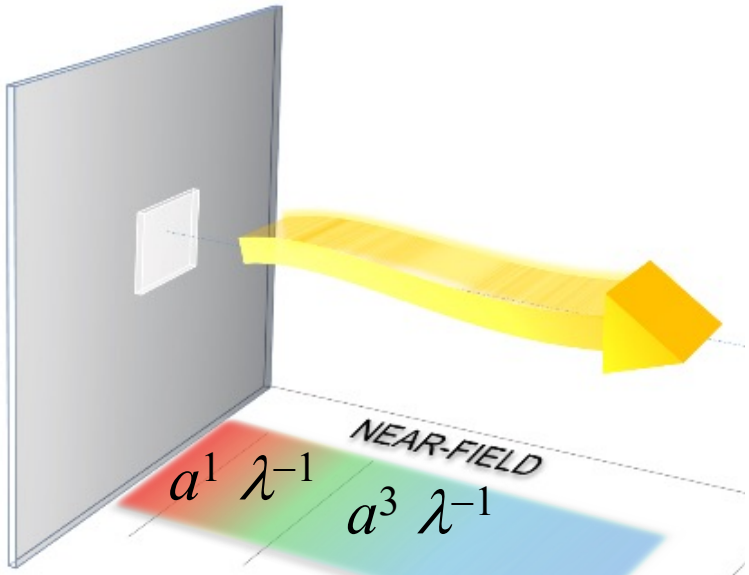
Propagating waves

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



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

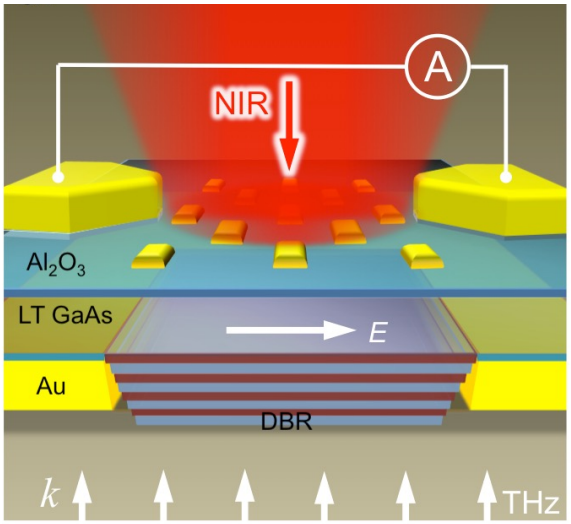
Aperture-type THz Near-Field Microscopy

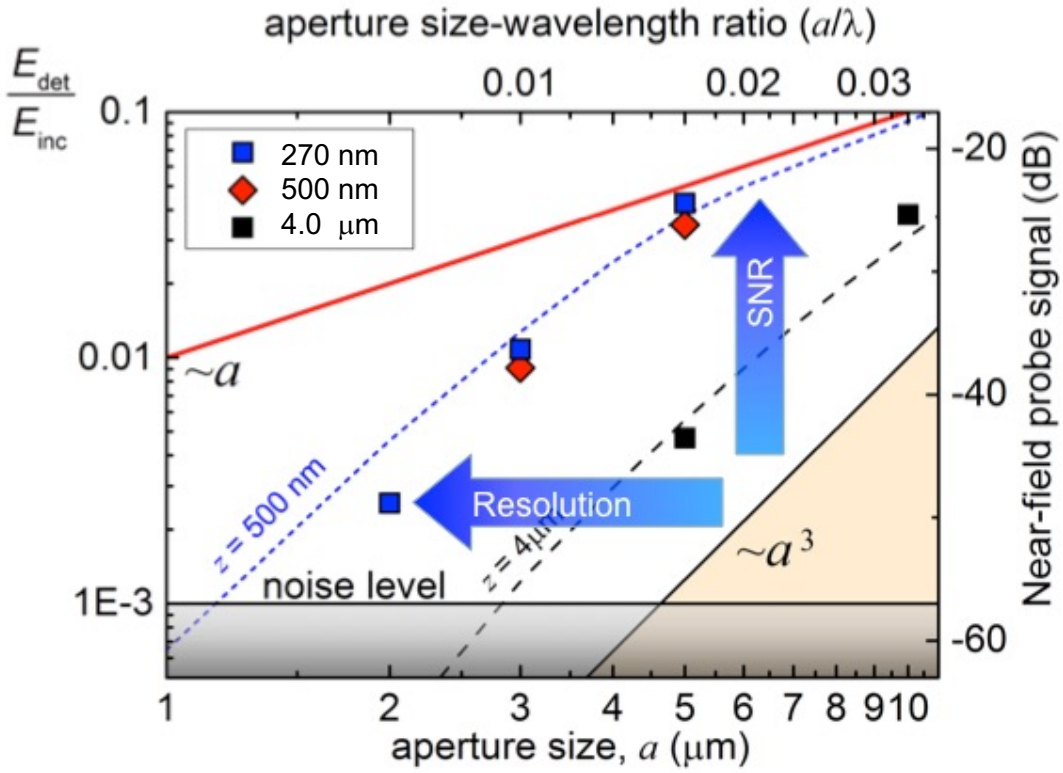


Propagating waves

$a^3\ \lambda^{-2}$

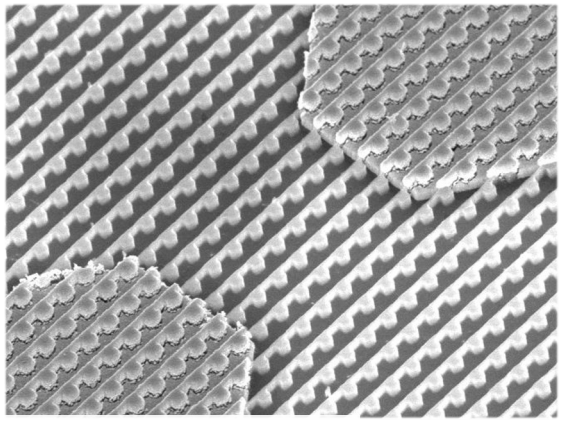
Evanescent waves





Integrated THz Near-Field Detectors

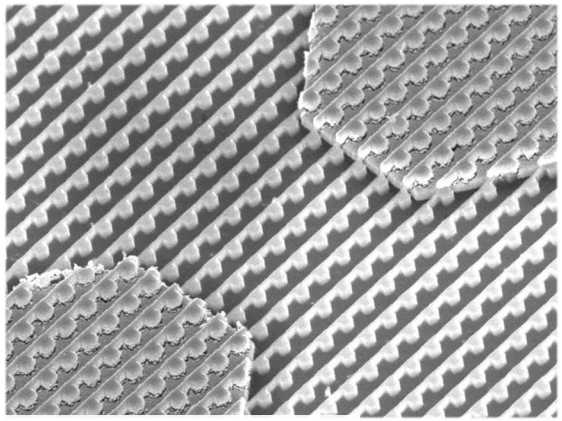
Ultrathin Photoconductive Metasurfaces (THz-TDS)



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

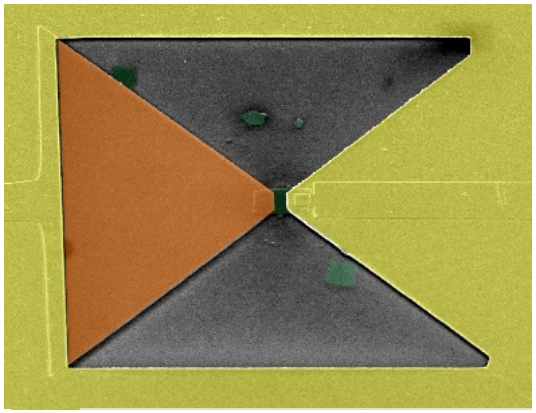
Integrated THz Near-Field Detectors

Ultrathin Photoconductive Metasurfaces (THz-TDS)



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

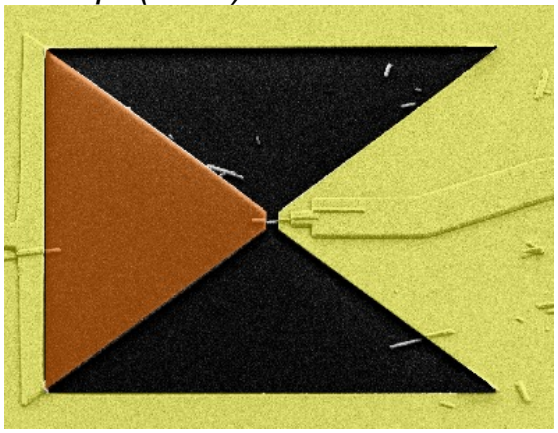
FET-based 2D materials

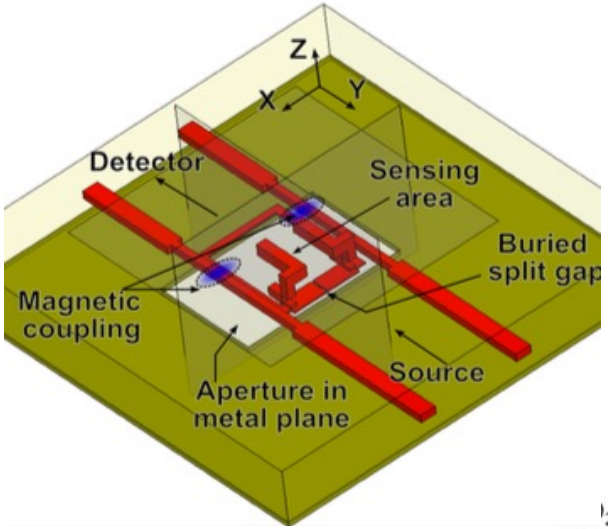


Giordano et al. Optica (2018)

InAs nanowire detectors

Sci. Rep. (2017)

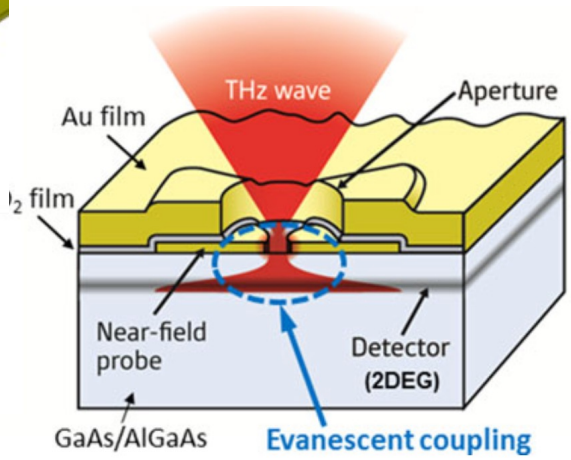




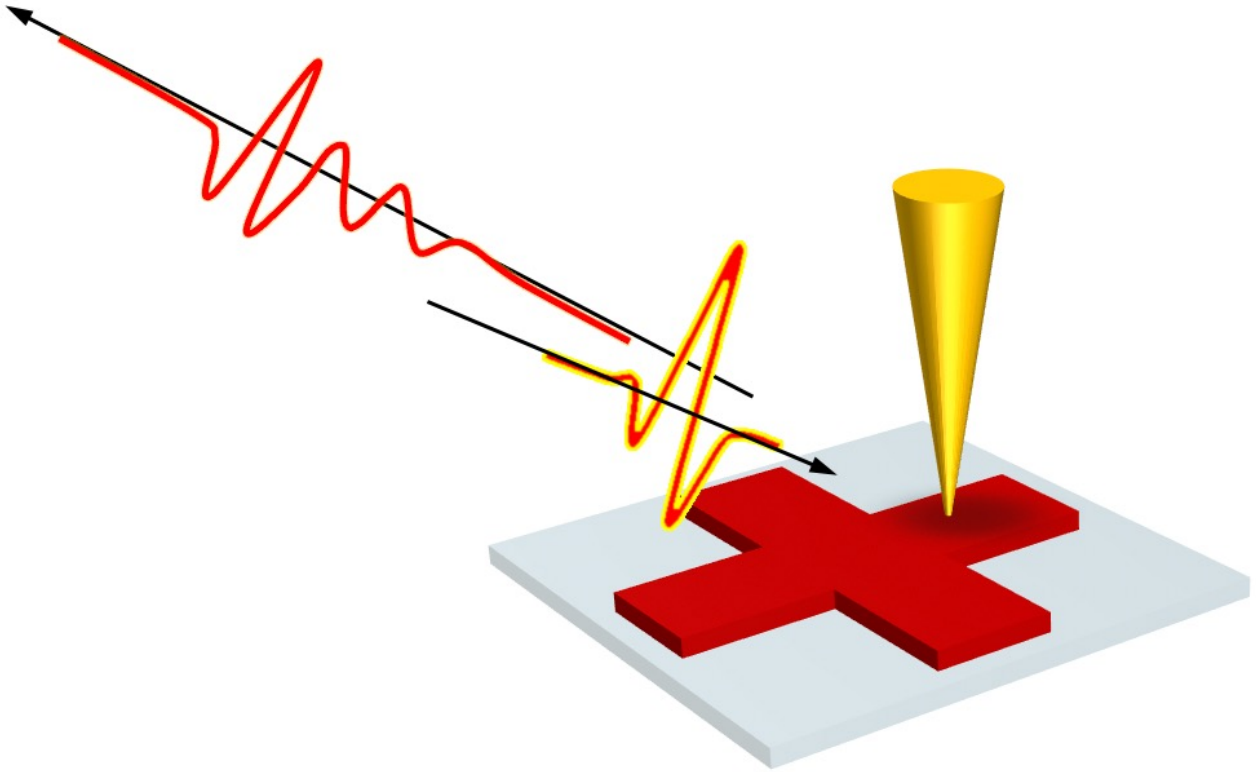
CMOS-based detectors
Grzyb et al. (2016)

2DEG detectors

Kawano et al. (2008)



Scattering Probe: THz-s-SNOM

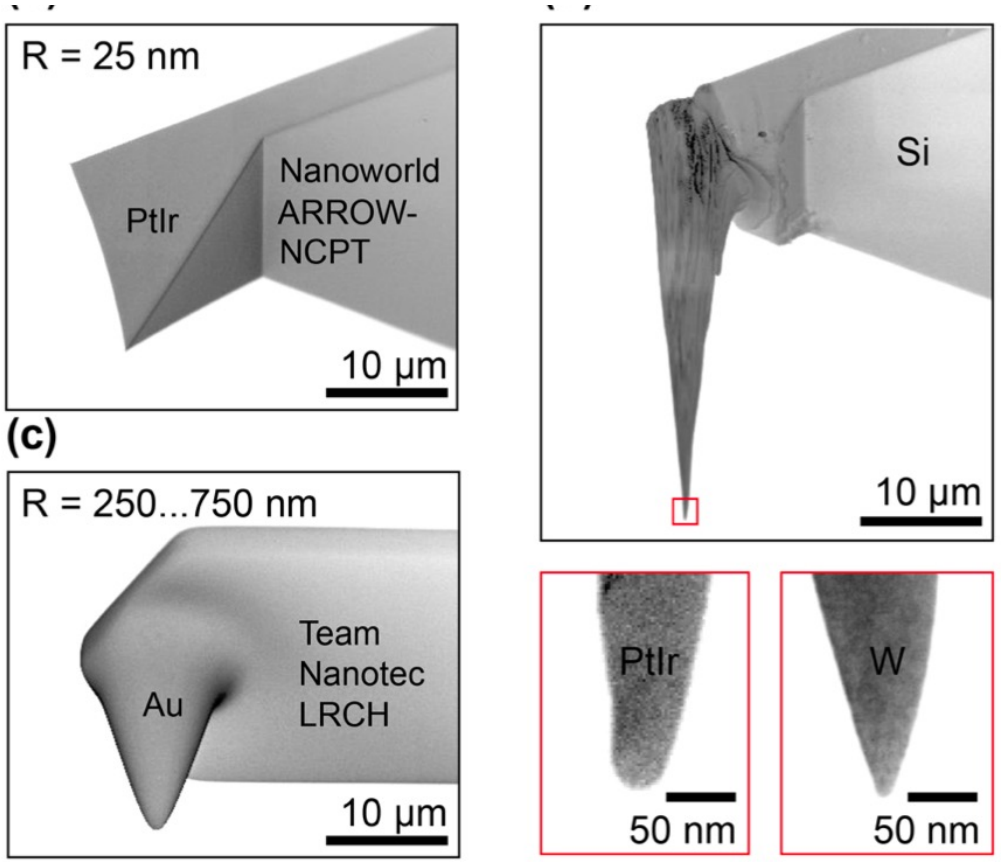


Enhancement of Scattering from the Probe

Two Main Factors affecting the Scattering efficiency:

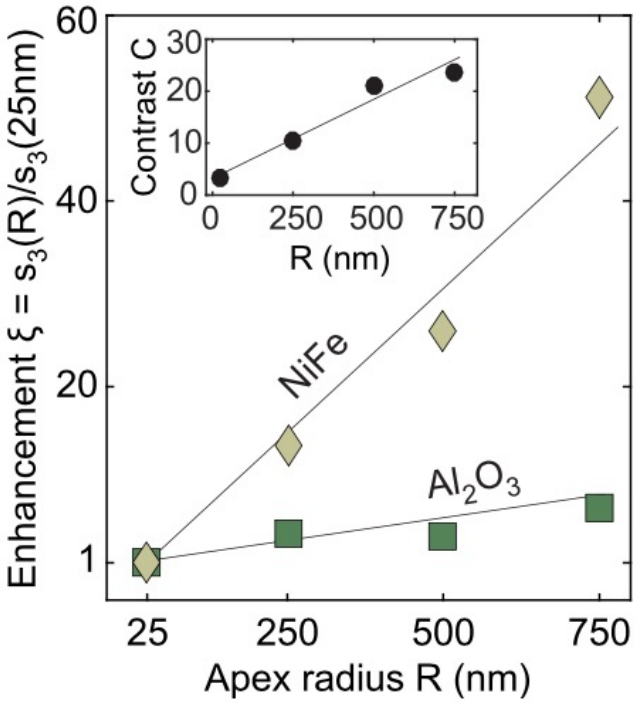
Tip apex size

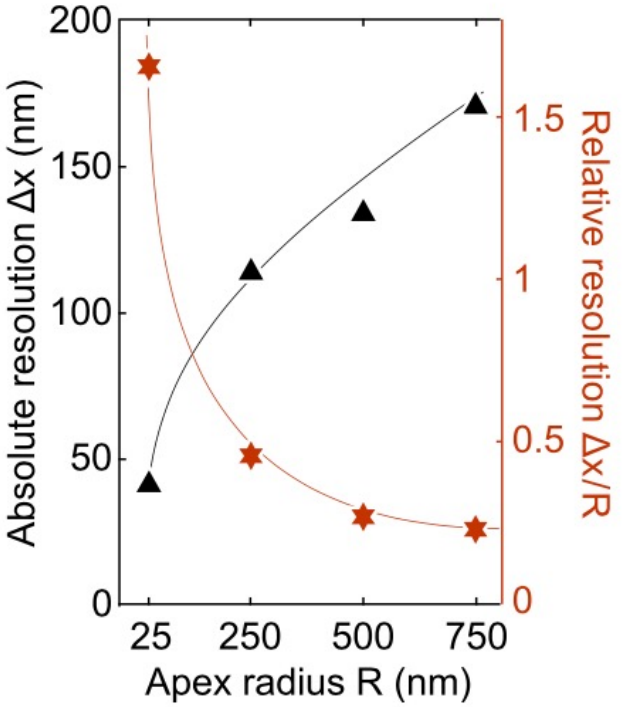
Tip shaft length

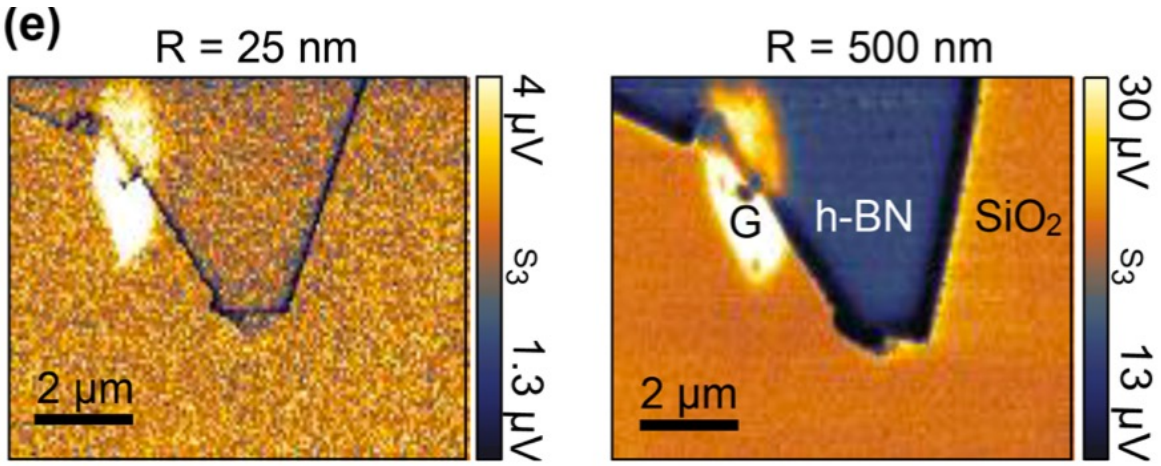


C. Maissen et al.,
ACS Photonics 6, 1279 (2019)

THz s-SNOM Imaging







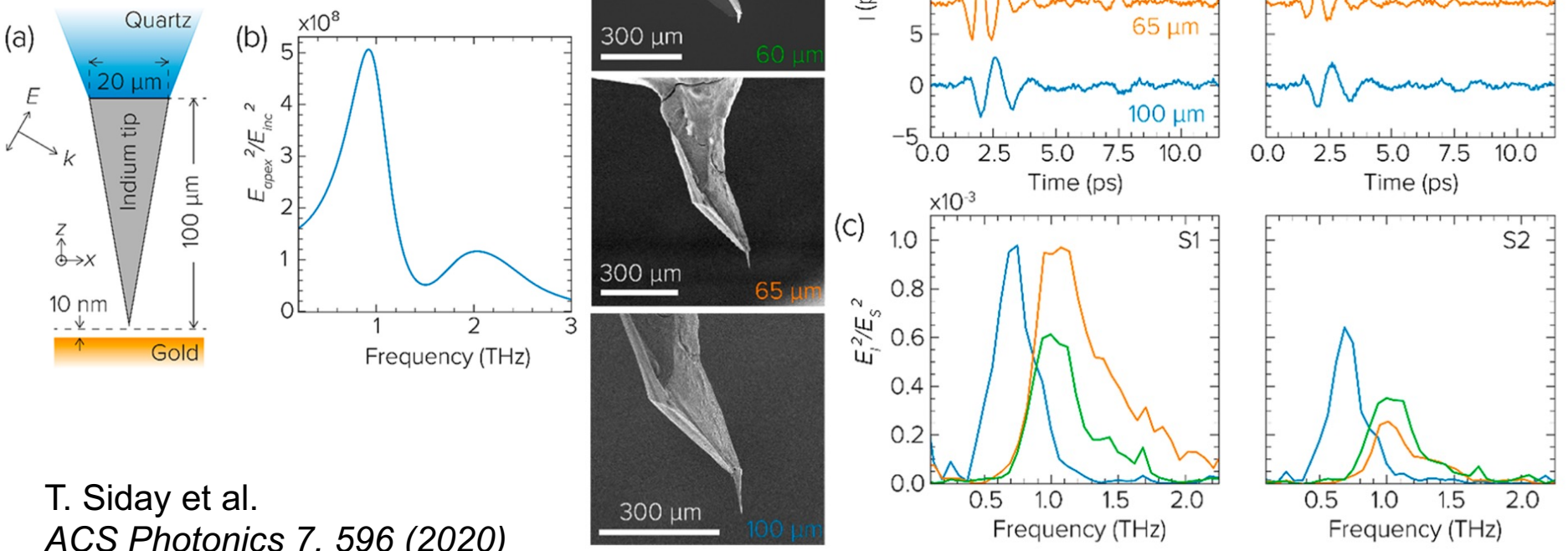
C. Maissen et al.,
ACS Photonics 6, 1279 (2019)

Enhancement of Scattering from the Probe

Two Main Factors affecting the Scattering efficiency:

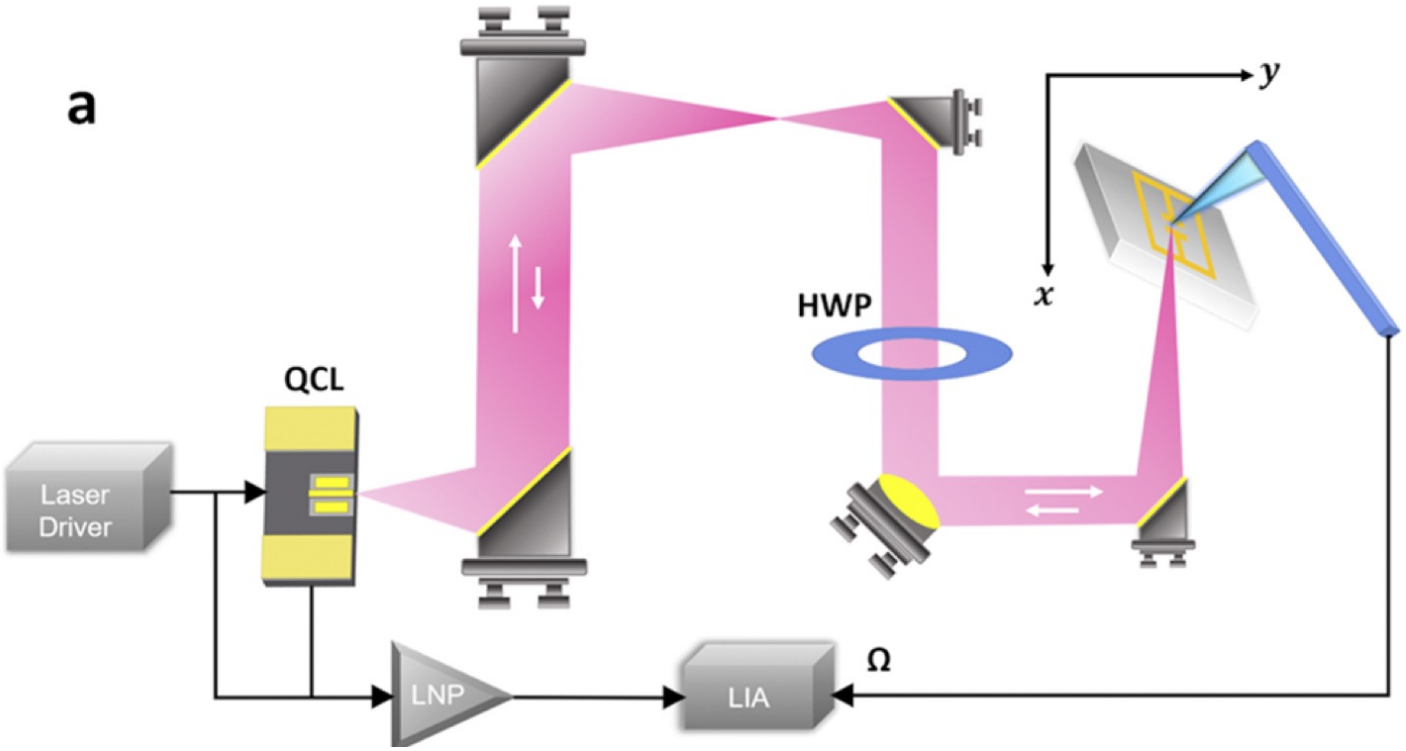
Tip apex size

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)

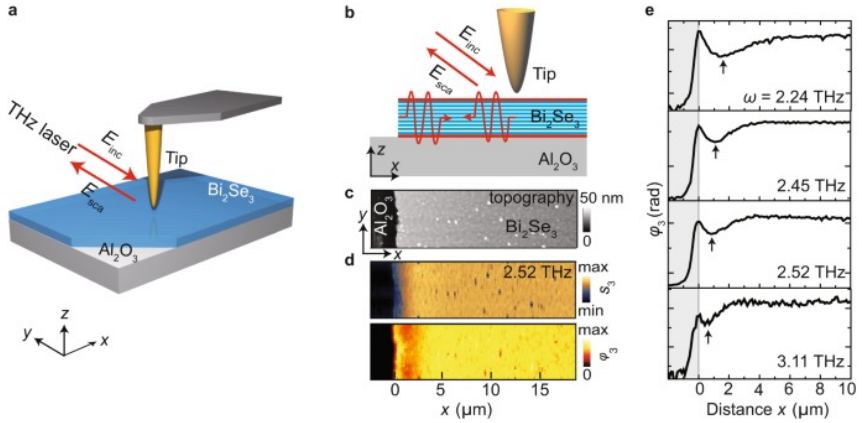
see also works:

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

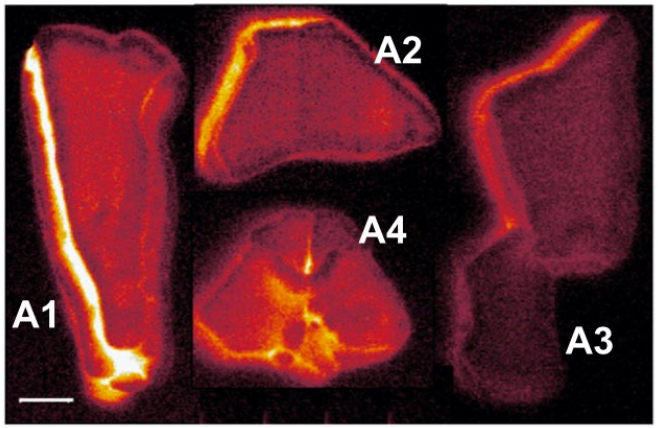
Miriam Vitiello (Optics Express 2018, … later work) – Neaspec

Research trends: Surface plasmons in novel materials

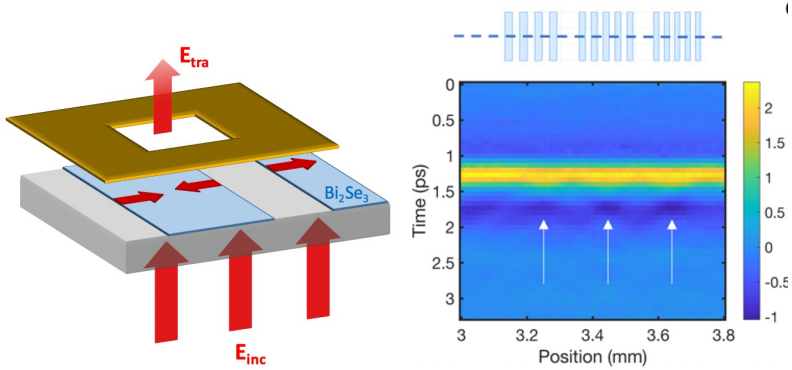
Previous THz s-SNOM studies on Bi_2Se_3

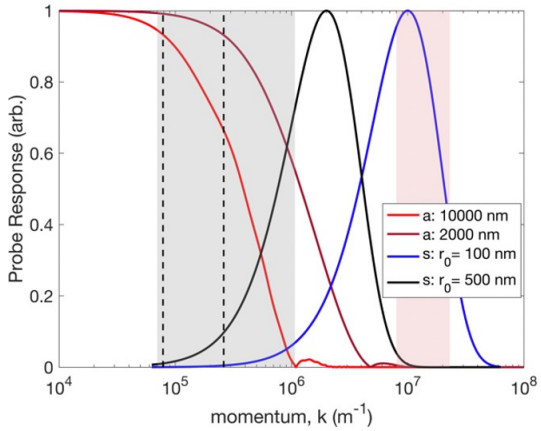


S. Chen *et al. Nature Comm.* (2022)



E. Pogna *et al. Nature Comm.* (2021)

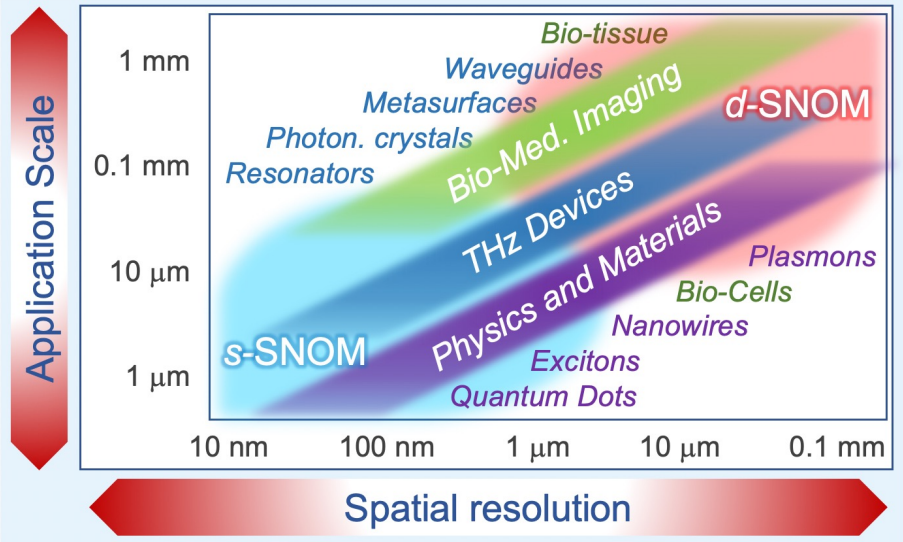


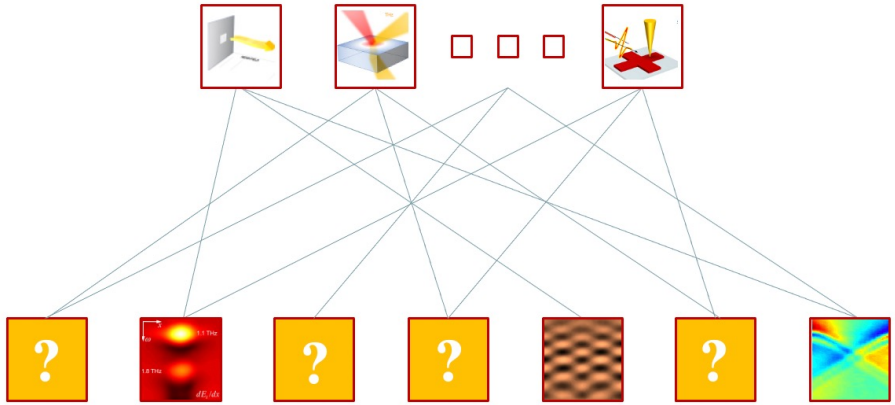


L. Hale *et al.* (under review)

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

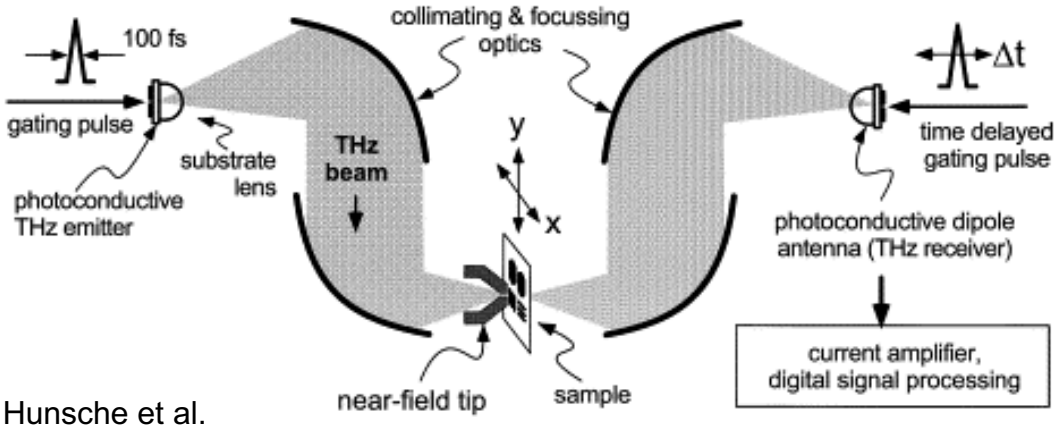
J. Keller, G. Scalari and J. Faist
ETH-Zurich

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

Results/Graphs from other groups

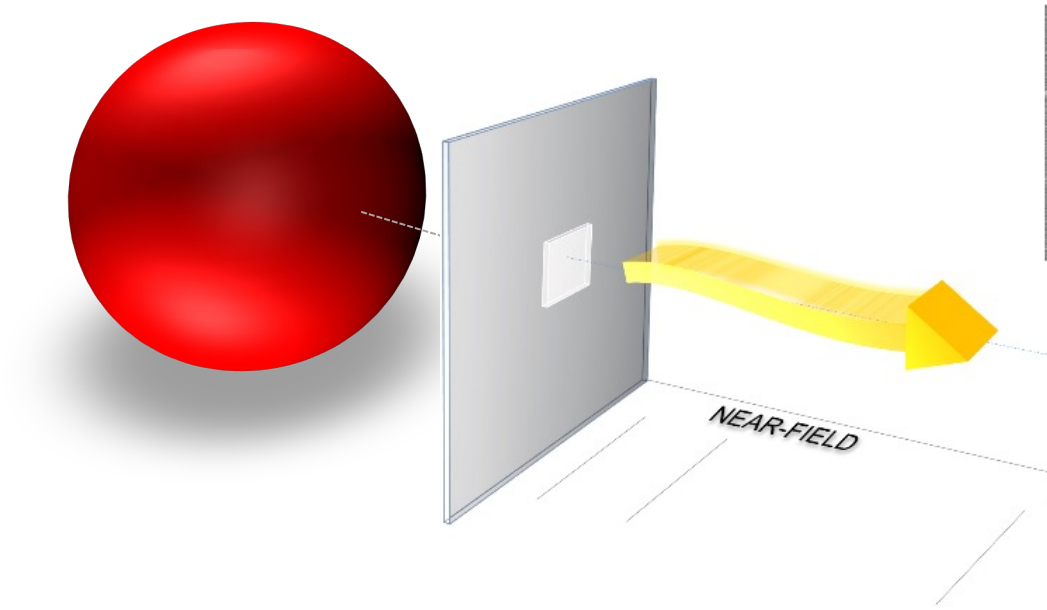
Aperture-type THz Near-Field Microscopy

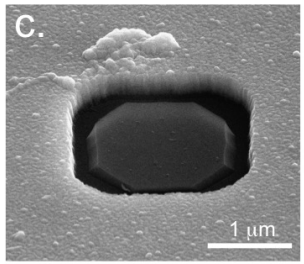
First demonstration of aperture-type THz microscopy (50-80 μm resolution)

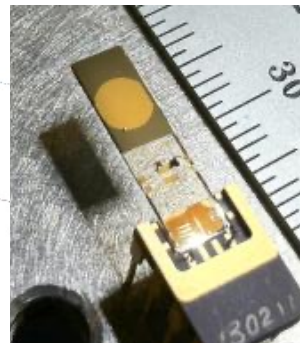


Hunsche et al.
OPTICS COMM (1998)

Modern aperture-type THz microscopy
2-5 μm resolution







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

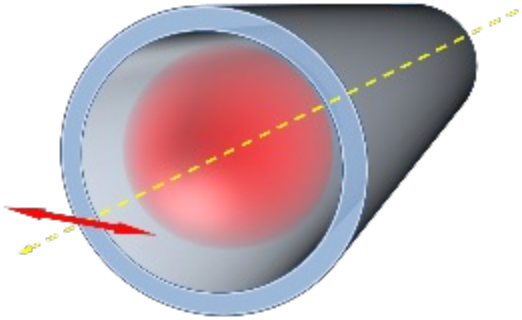
Z. Han, F. Ding and S. I. Bozhevolnyi
China Jiliang University and DTU, Denmark

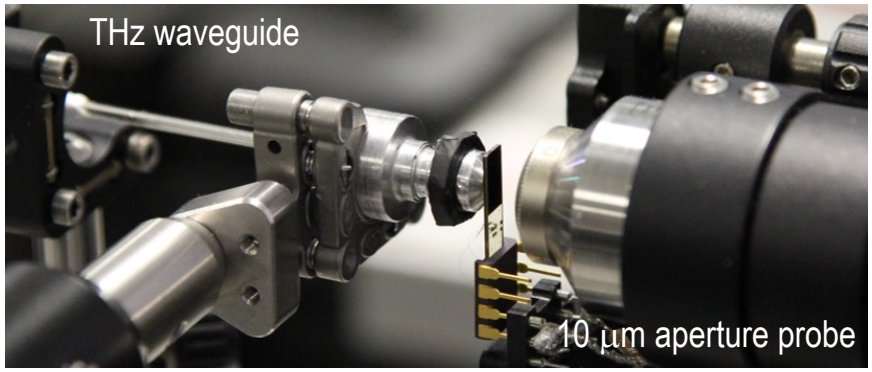
J. Keller, G. Scalari and J. Faist
ETH-Zurich

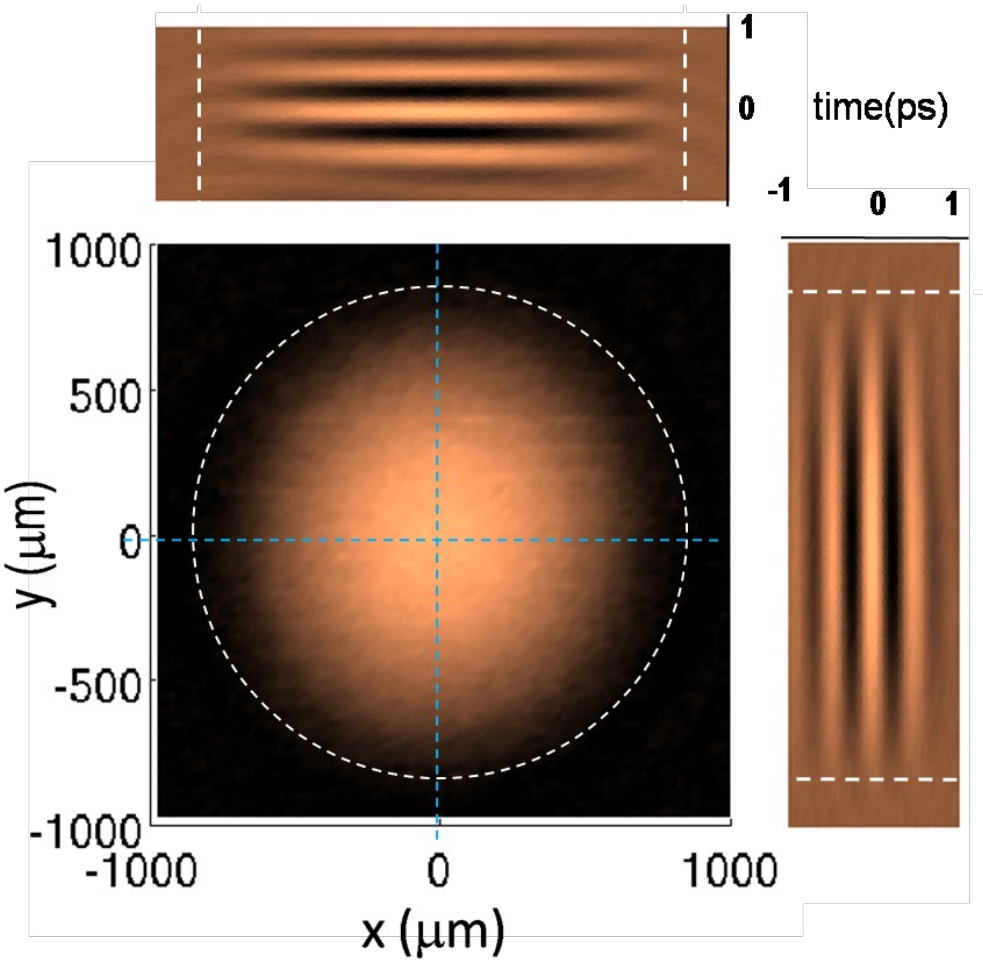
I. Khromova (*U. Navarra*) P. Mounaix (*CNRS, Bordeaux*), P. Kuzel (Czech Acad. Sci.)

Results/Graphs from other groups

Applications in THz technology research: *Waveguides*

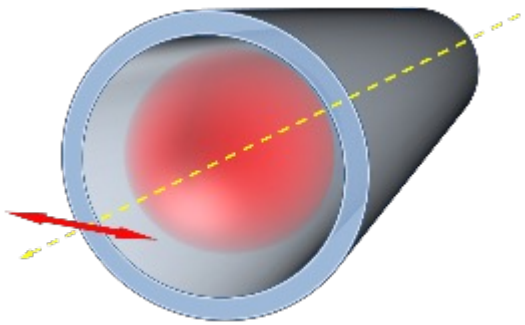


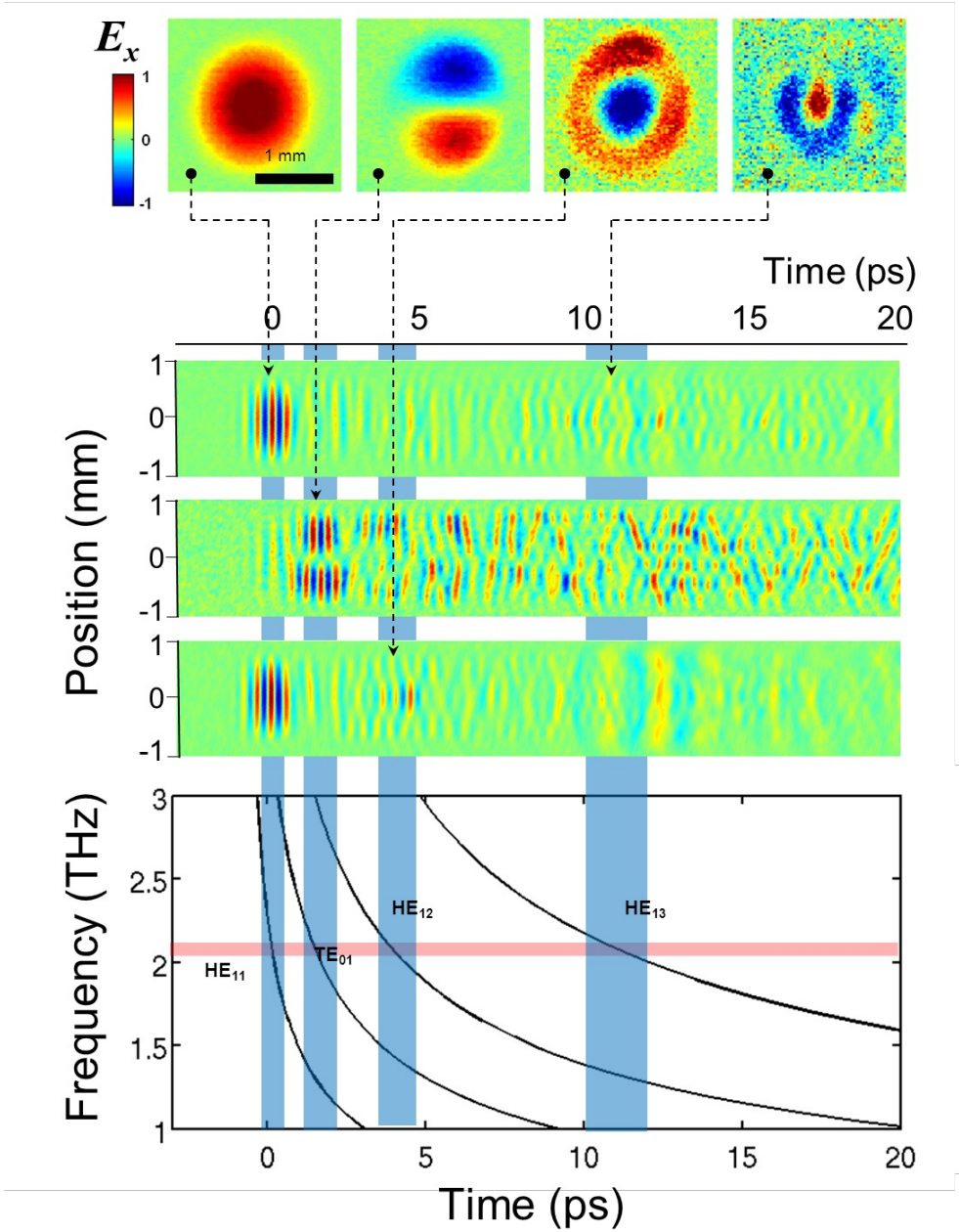




APL. **94**, 171104 (2009)

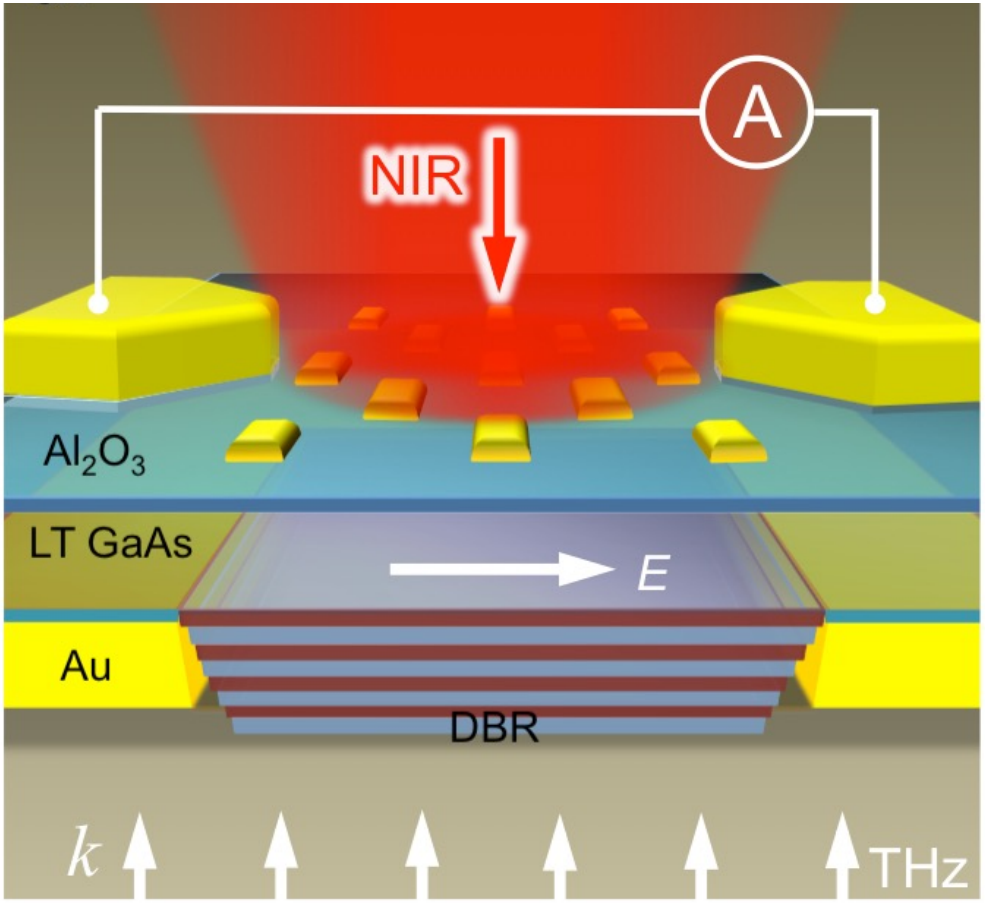
Applications in THz technology research: *Waveguides*





Integrated THz Detector

Aperture-type THz microscopy probe with PC detector

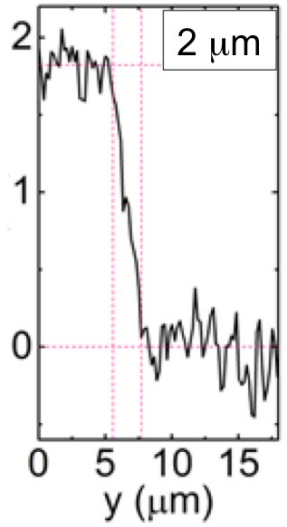


OM *et al.*, *ACS Photonics* (2015)

Potential Cryogenic Applications Require:

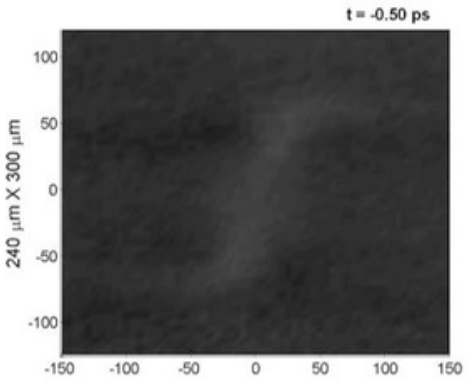
Nanoscale detectors

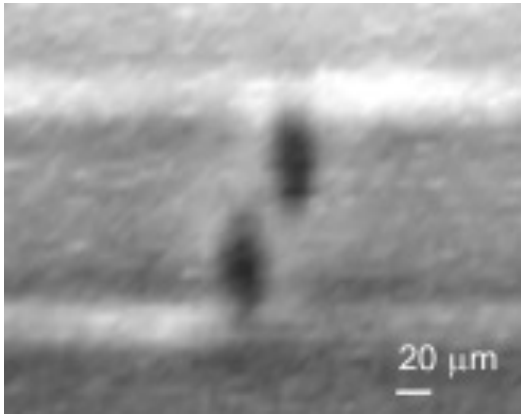
Integrated readout electronics

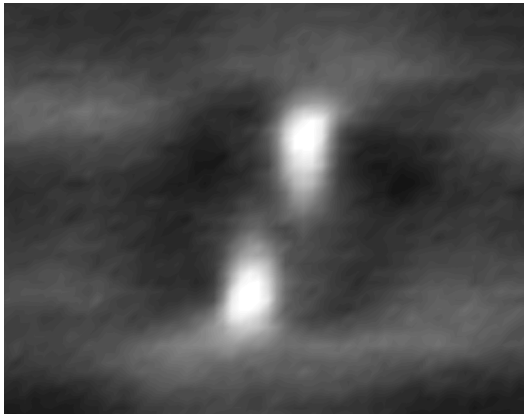


OM *et al.*
THz Sci. and Technology, IEEE Trans. (2016)

THz Surface Plasmon Waves



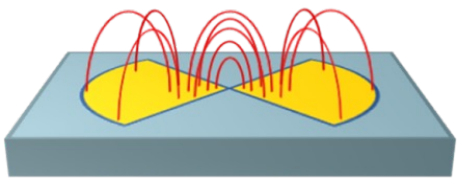


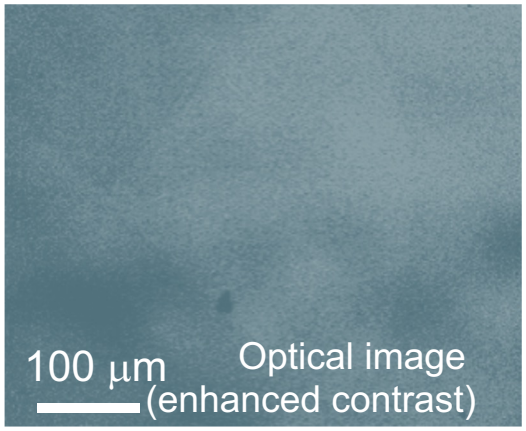


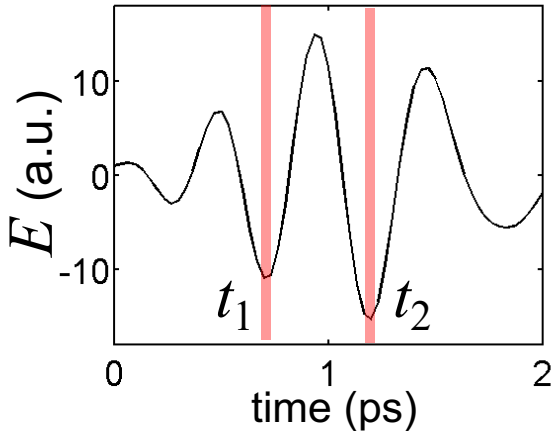
Mitrofanov et al.*J. STQE* **103**, 600 (2001)

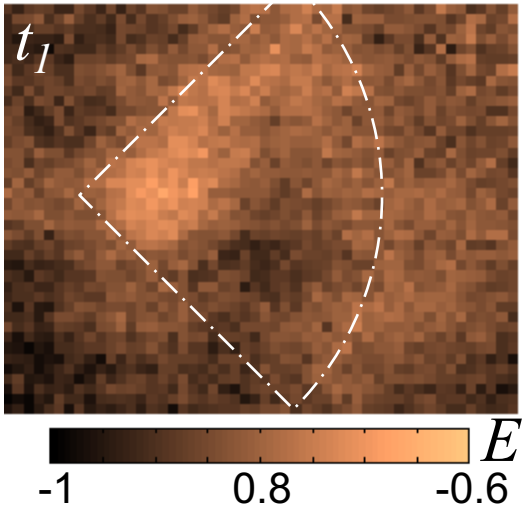
Surface Waves on Gr Bow-Tie Antenna

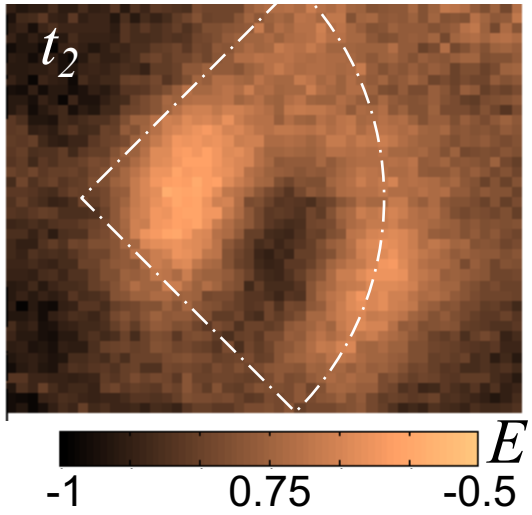
Epitaxial monolayer graphene - Gr on C-face SiC



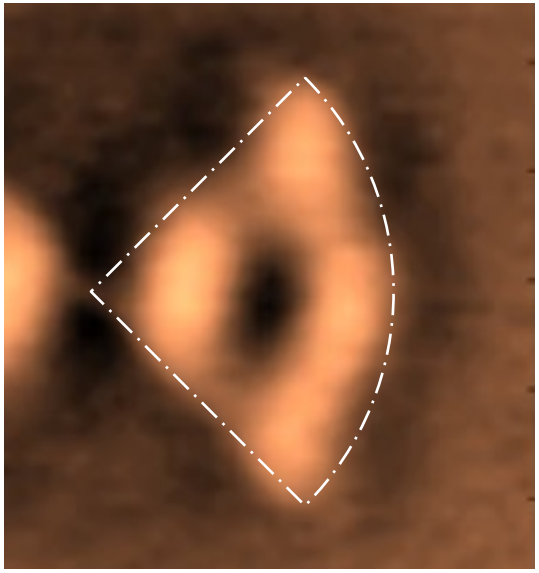








Metallic Bow-tie antenna



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

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