THz near-field Imaging and Spectroscopy:

Technology, Capabilities and Novel Applications

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CLEO 2021 Tutorial
May 13 | STh2C.5 | Terahertz Imaging and Detection

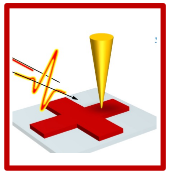
Short THz pulse sources and THz-TDS

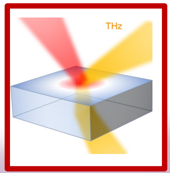
PC Detectors

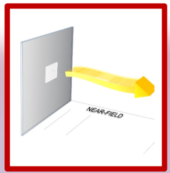
Electro-optic Sampling

FET and CMOS THz Detection

QCL and Self-mixing Detection

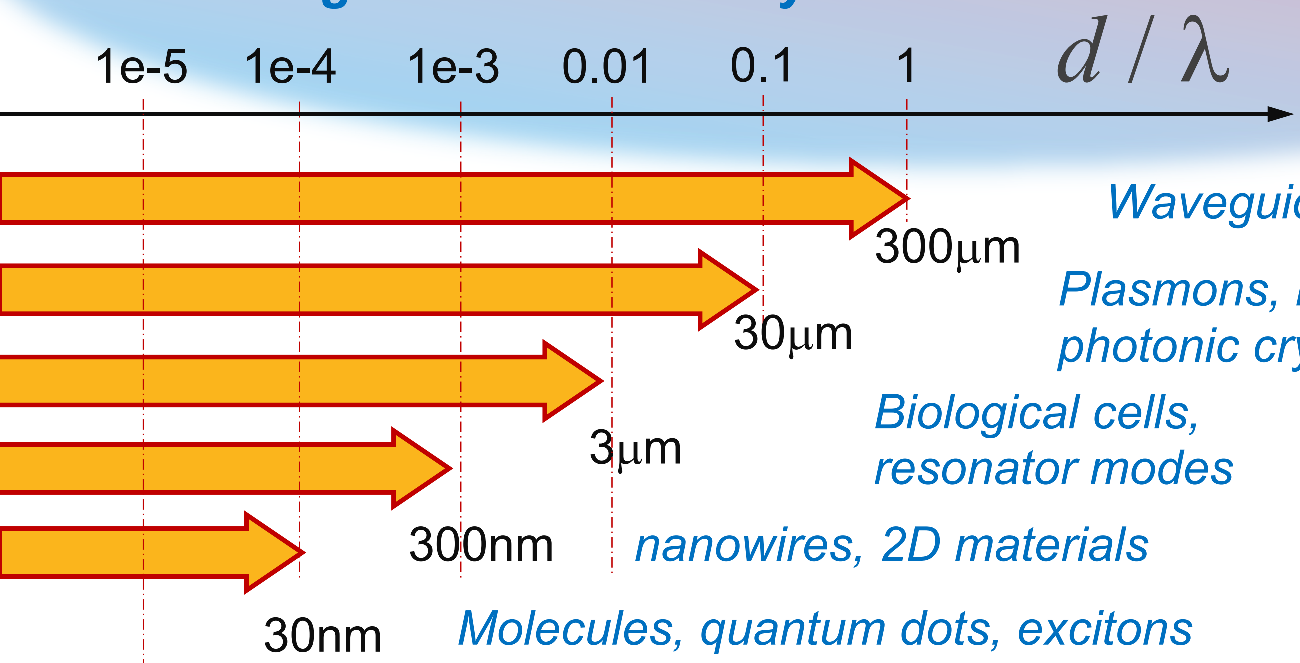






Broad range of THz Instrumentation

Broad range of scales and systems



Waveguide modes, structured beams

Plasmons, metasurfaces, photonic crystals, bio-tissue

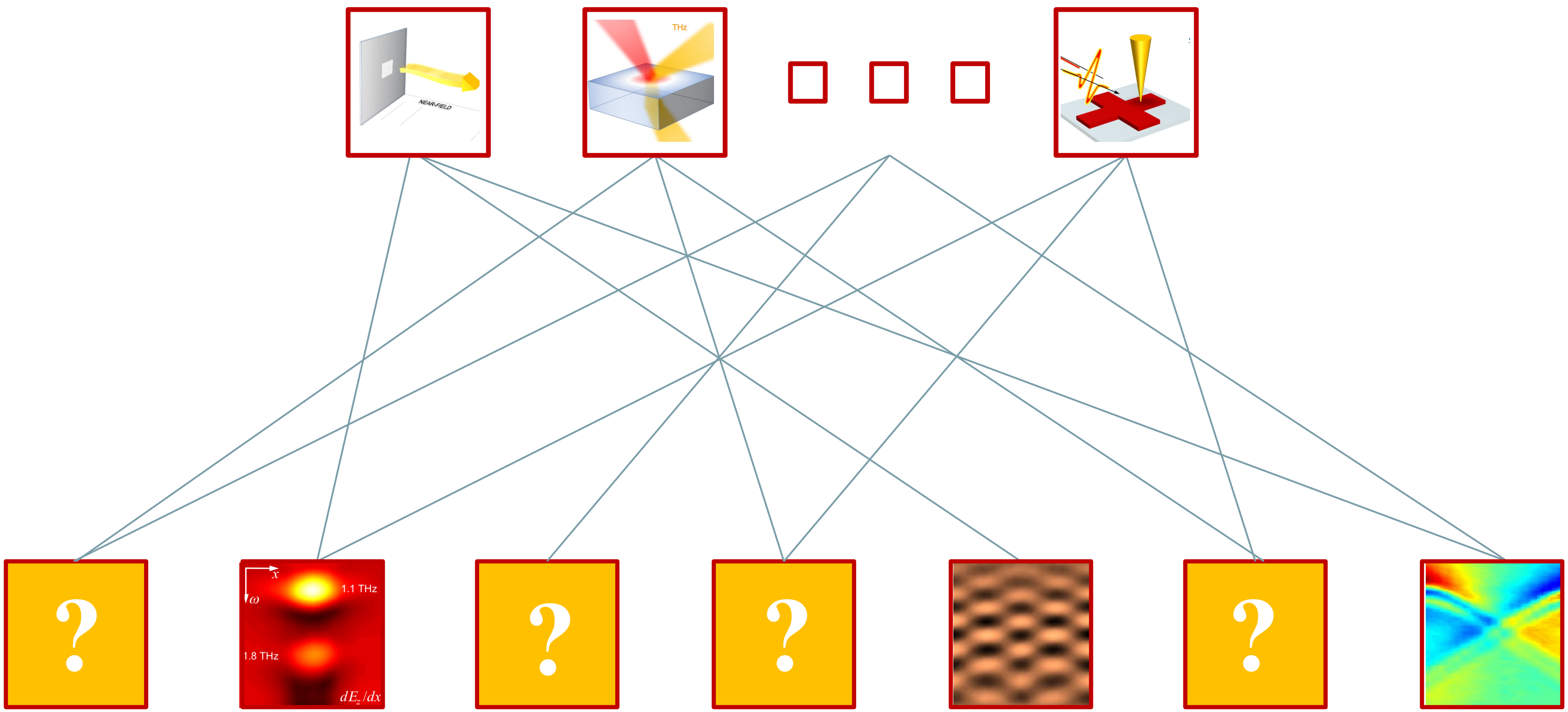
Biological cells, resonator modes

nanowires, 2D materials

Molecules, quantum dots, excitons

Tutorial Scope and Aim

Approaches in THz near-field microscopy

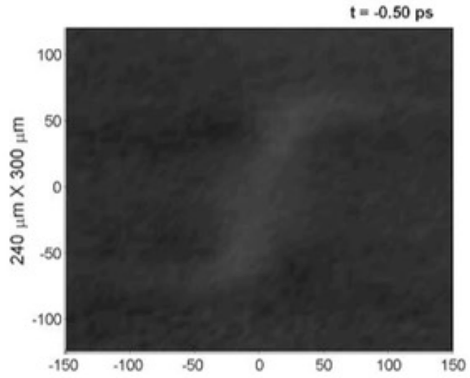


THz near-field microscopy applications

Right instrument for a given problem

Appropriate set of problems for a given instrument

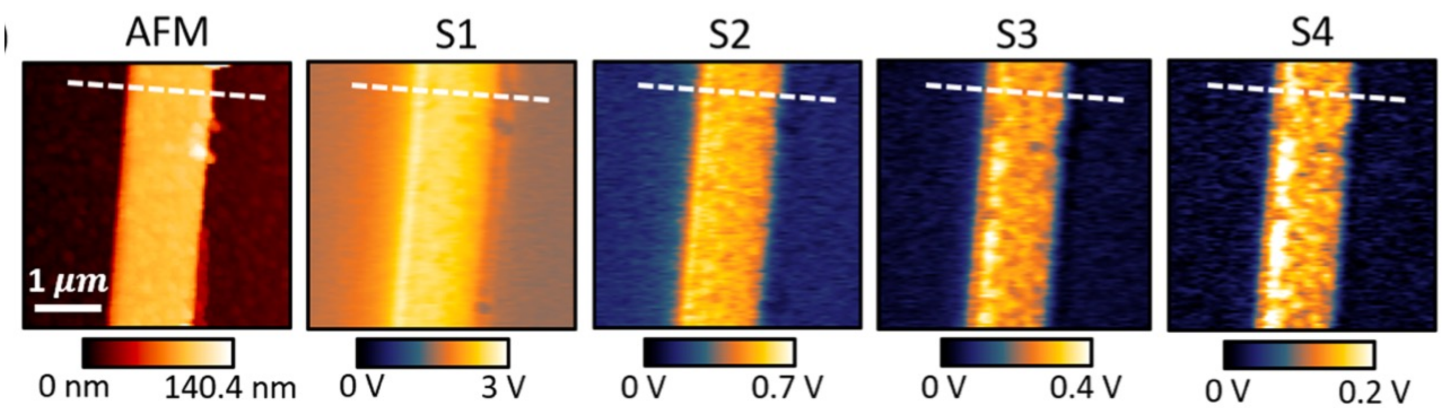
‘Right Instrument for the Job’



Time-resolved (sub-ps) THz surface-plasmon waves
on a THz antenna …

… recorded with one of the first THz near-field systems ~20 years ago

OM et al. *J. Select. Topics Quant. Electron.* **103**, 600 (2001) nm-scale resolution – imaging of subwavelength metallic structures

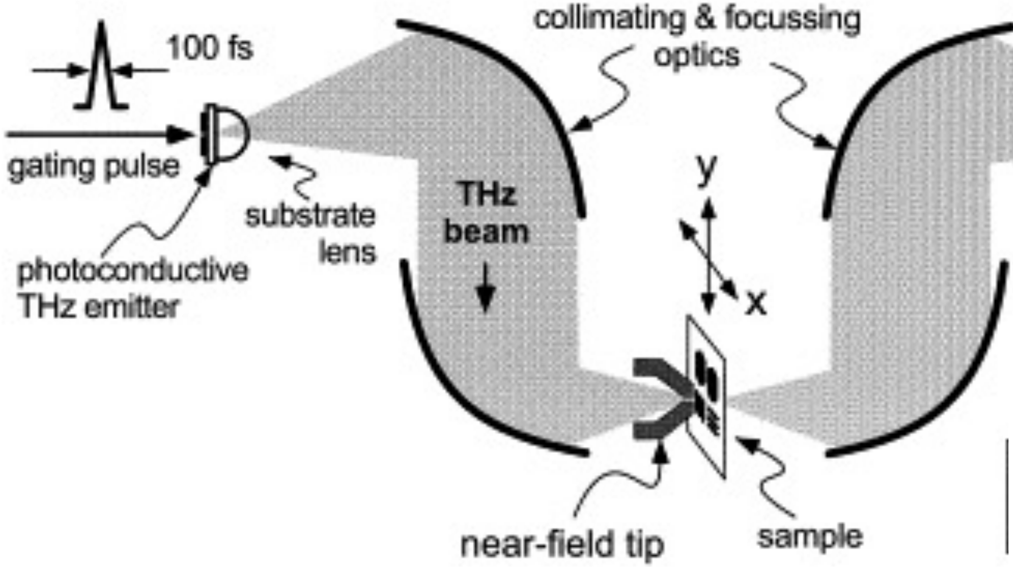


X. Chen et al. *ACS Photonics* **7**, 687 (2020)

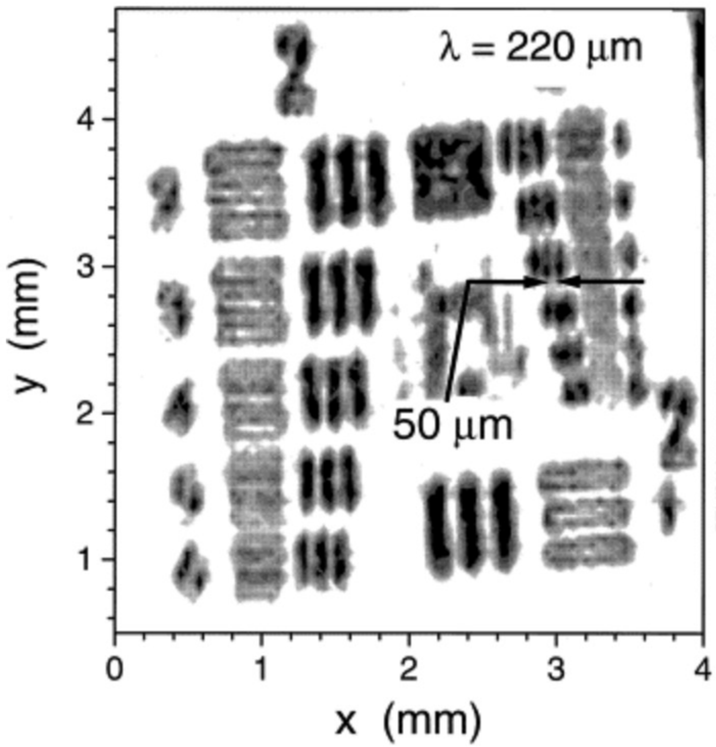
Excellent material contrast,
but observation of THz surface-plasmon waves is not as straight forward

see also: CLEO 2021 Session SW2K.5-7 (T. Hannotte, A. Pizzuto, M. Liu)

Early Development of THz Microscopes

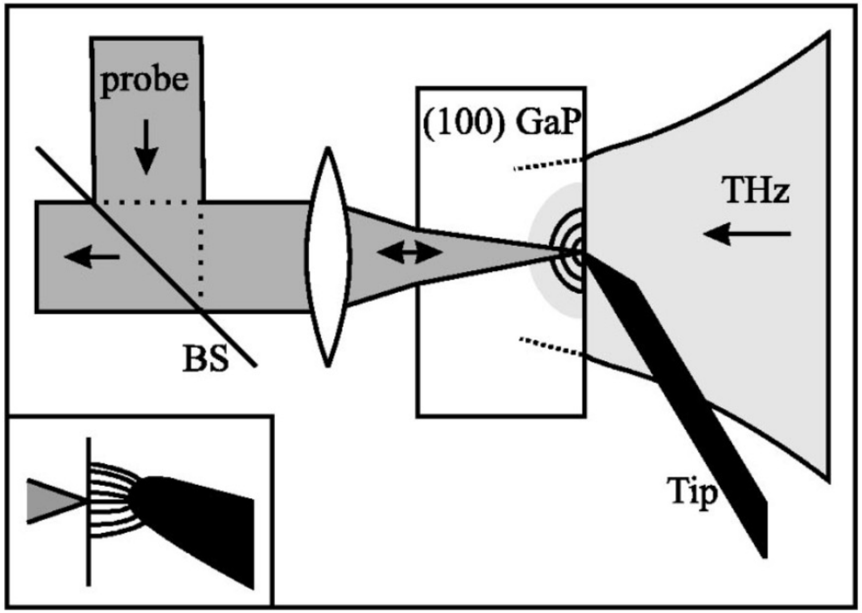


Hunsche et al. *OPTICS COMM* (1998)



Early Development of THz Microscopes

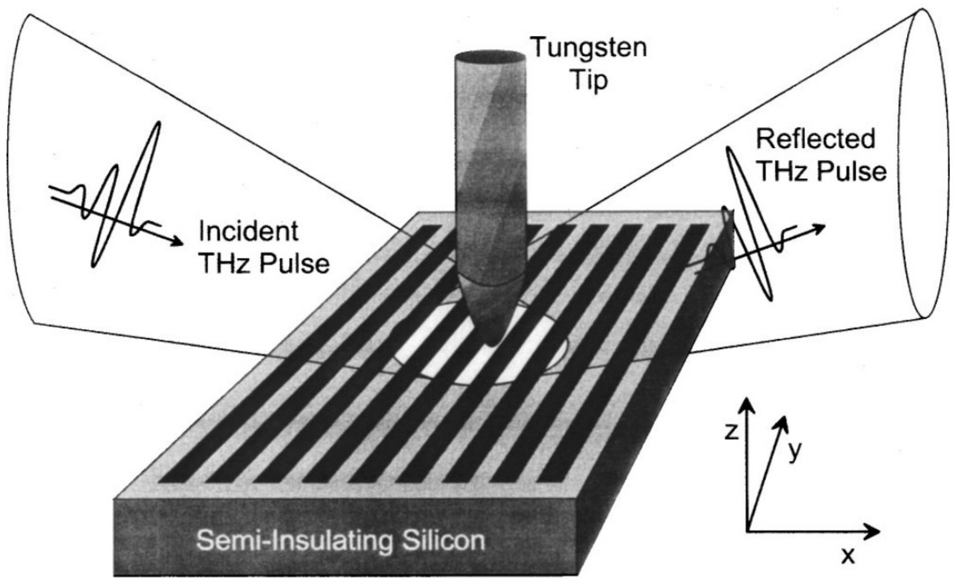
Electro-optic near-field probes (THz-TDS)

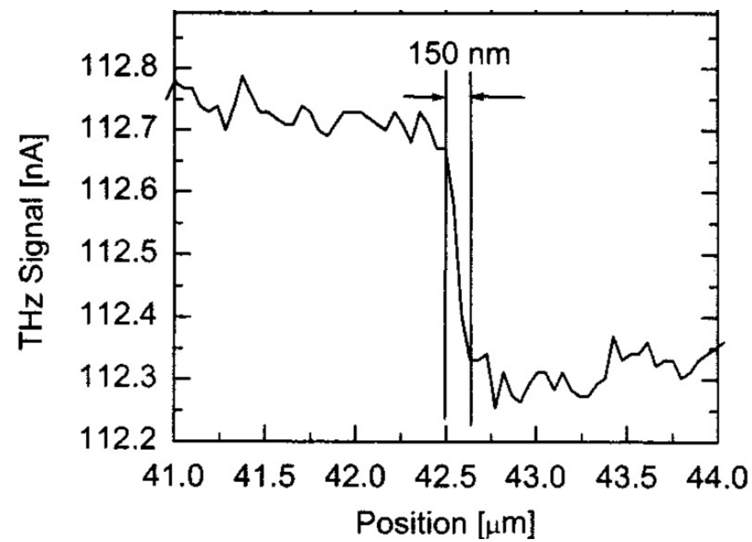


Van der Valk et al., APPL. PHYS. LETT. (2002)

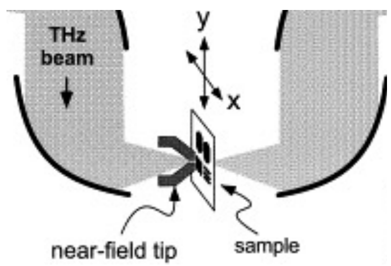
Early Development of THz Microscopes

Scattering Tip near-field microscopy (THz-TDS)

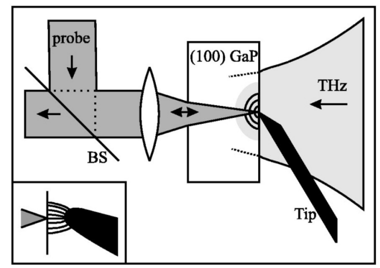




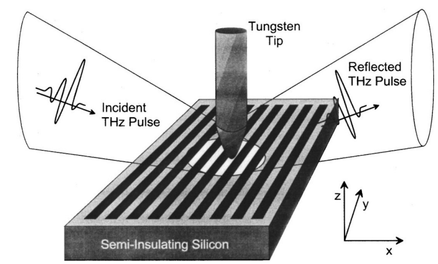
Chen et al., APPL. PHYS. LETT. 83, 3009 (2003)



Hunsche et al., 1998



Van der Valk et al., 2002



Chen et al., 2003

Near-field probes with integrated THz detectors

Use of patterns instead of apertures

Sub-wavelength THz generation

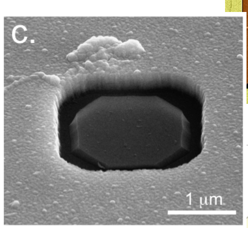
EO materials/ultrathin crystals

High-E THz sources

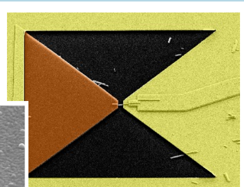
High Order Demodulation

Resonant Tip Probes

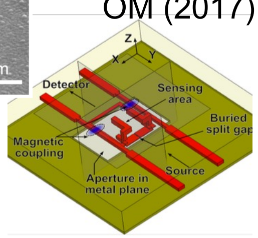
Self-mixing Detection



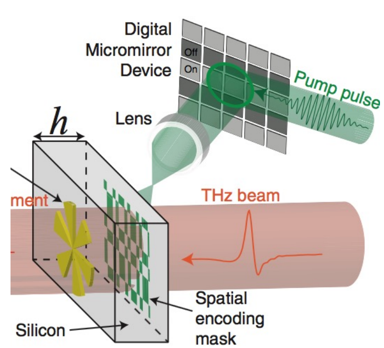
OM (2016)



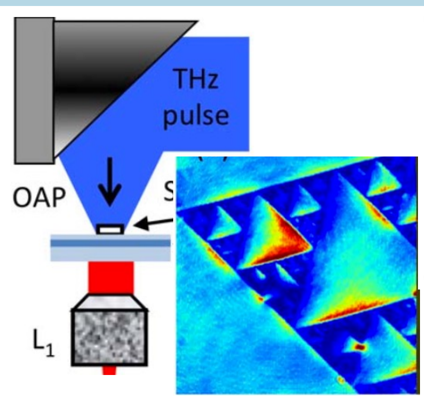
OM (2017)



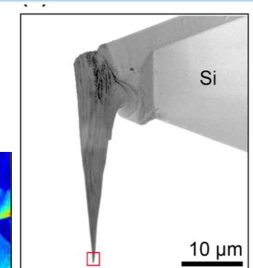
Grzyb (2016)



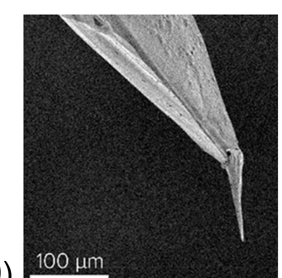
Stantchev (2016)



Blanchard & Tanaka (2016)



Maissen (2019)



Siday (2020)

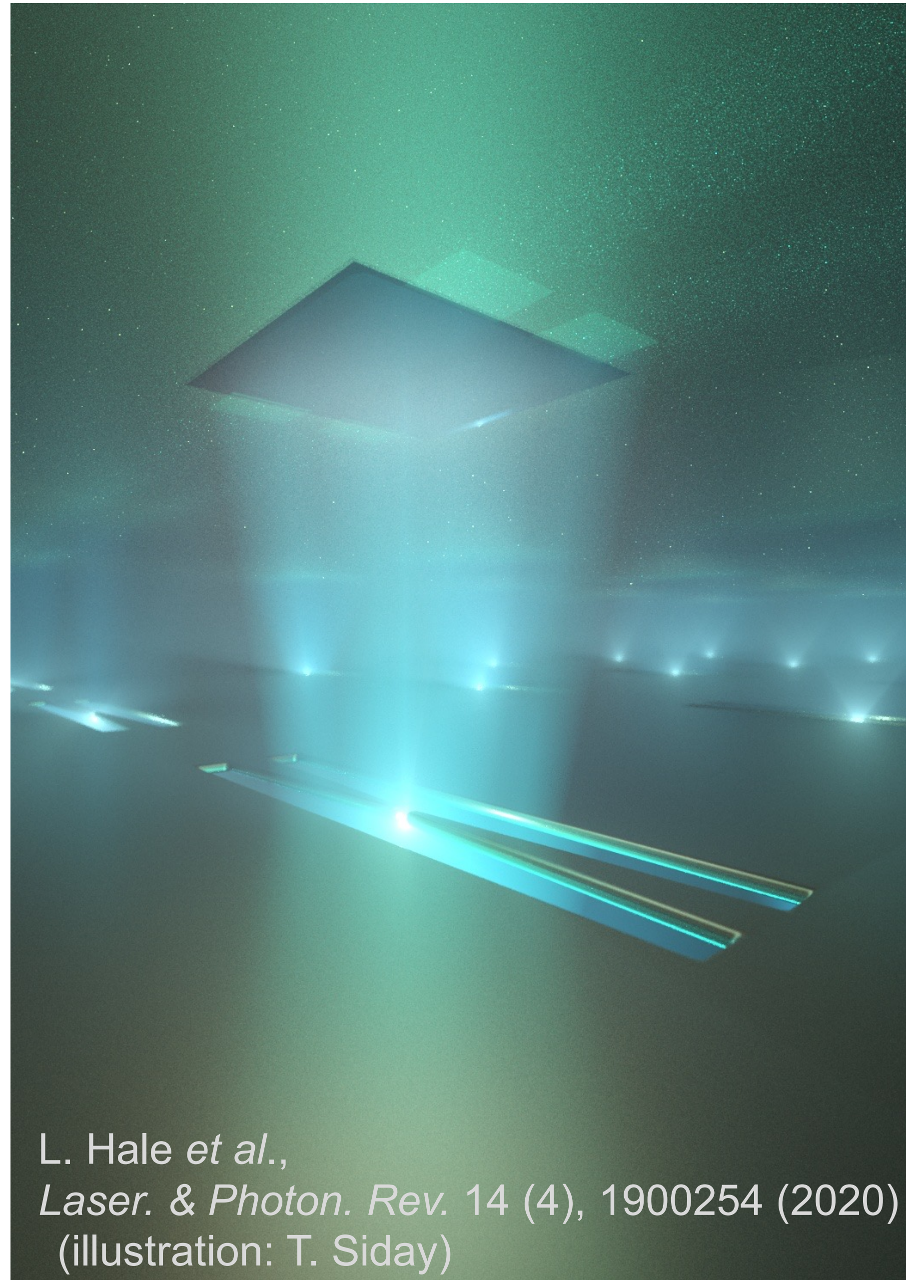
Aperture-type THz Microscopy

Principle

Practical Limitations

Enabling Technology Advances

Applications



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

Schematic

Far-field:

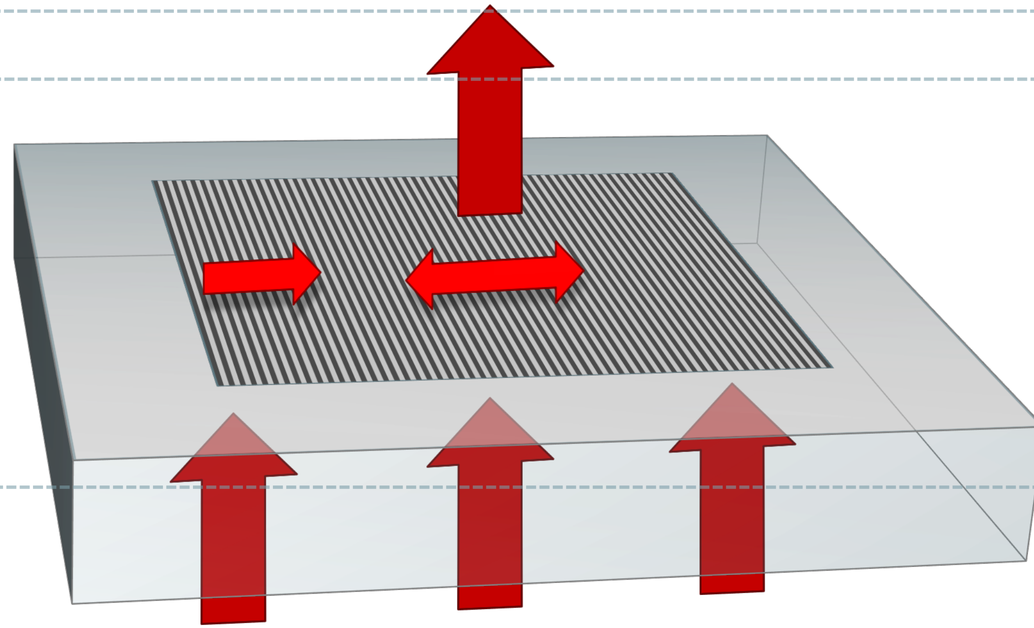
Transmitted wave

Diffracted wave

Near-field

Resonant surface plasmons

Surface waves excited
at edges (non-resonant)



Incident THz wave

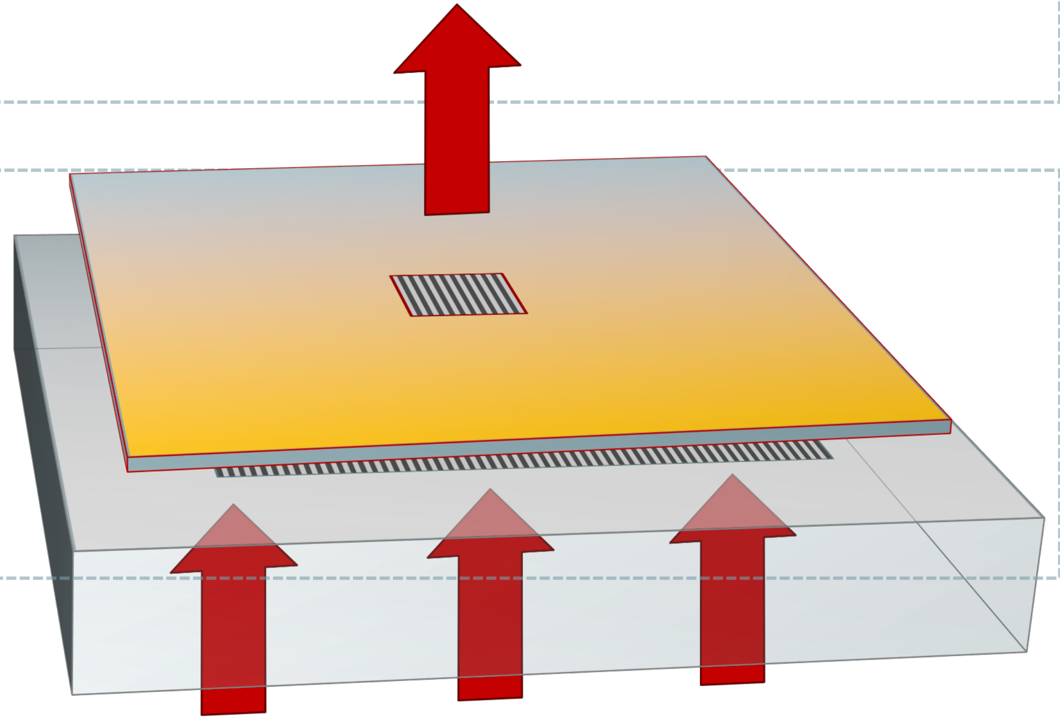
Schematic – Collection Mode

Localized fields are sampled and transferred to **Far-field:**

Near-field

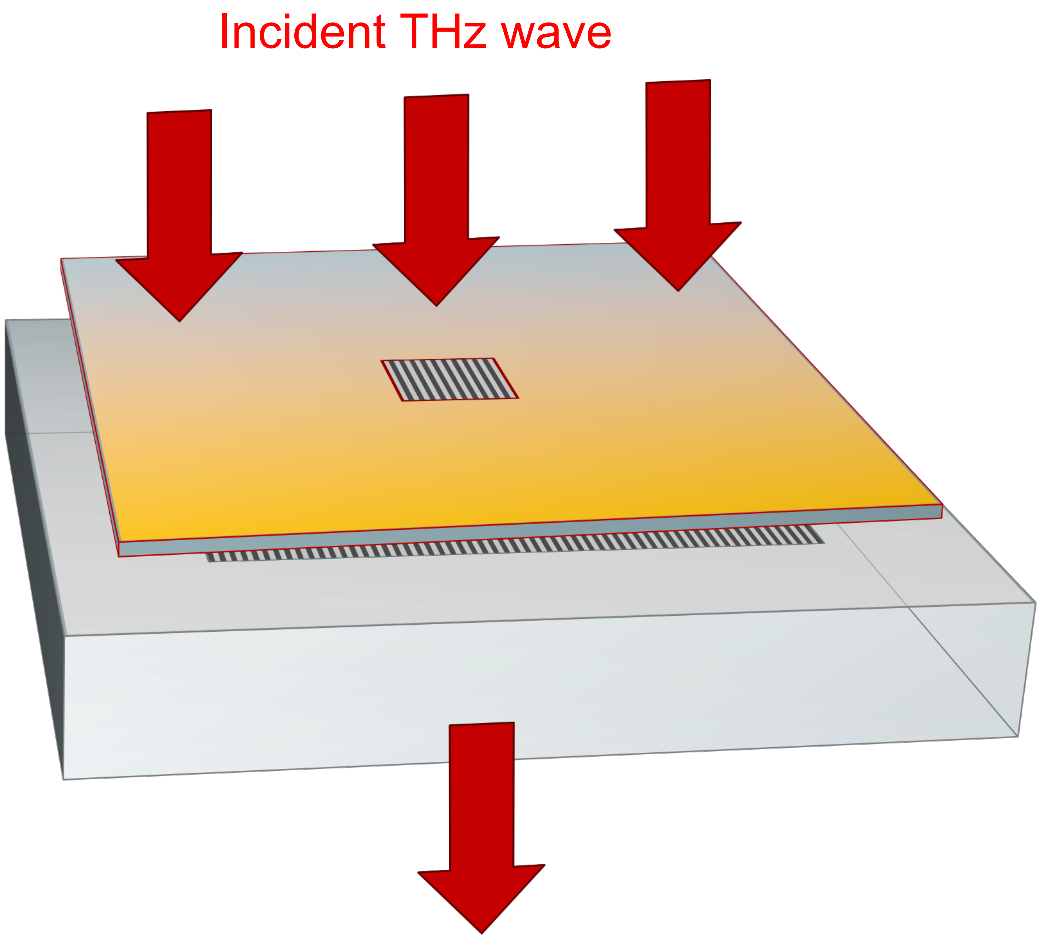
Resonant surface plasmons

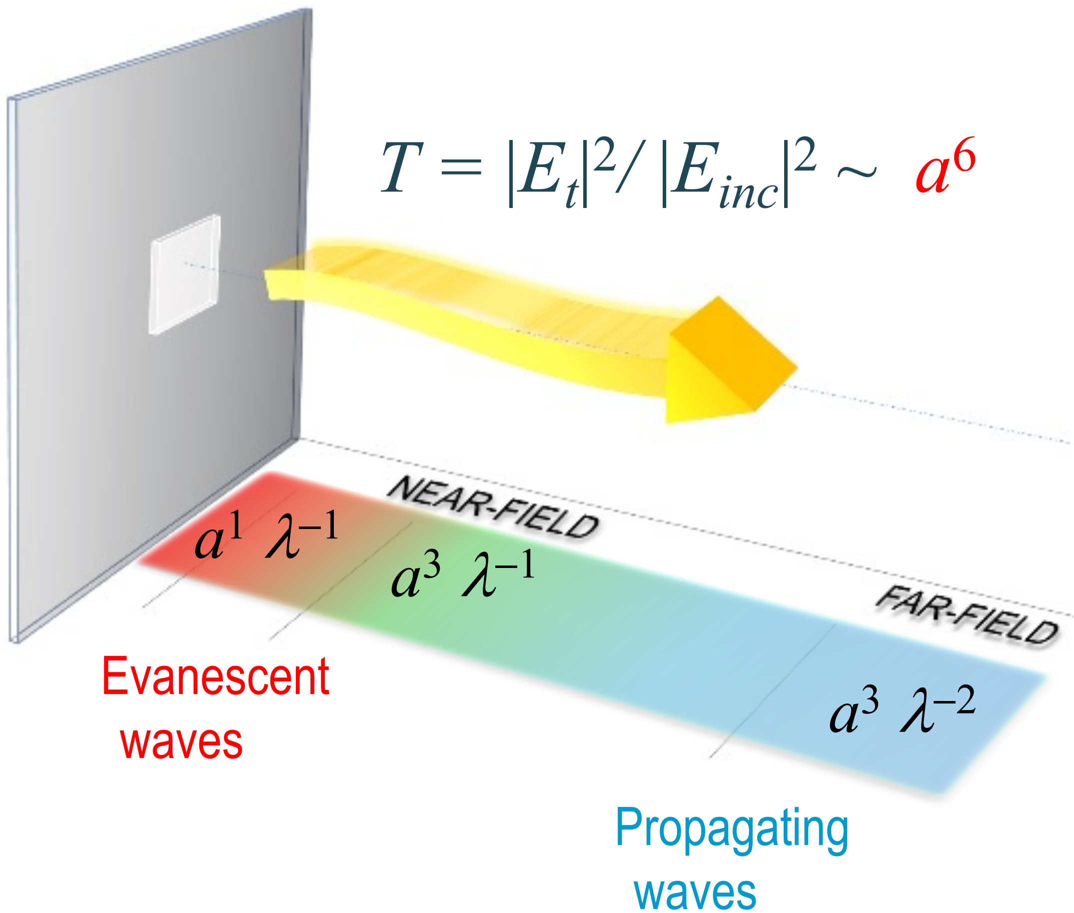
Surface waves excited
at edges (non-resonant)



Incident THz wave

Schematic – Illumination Mode

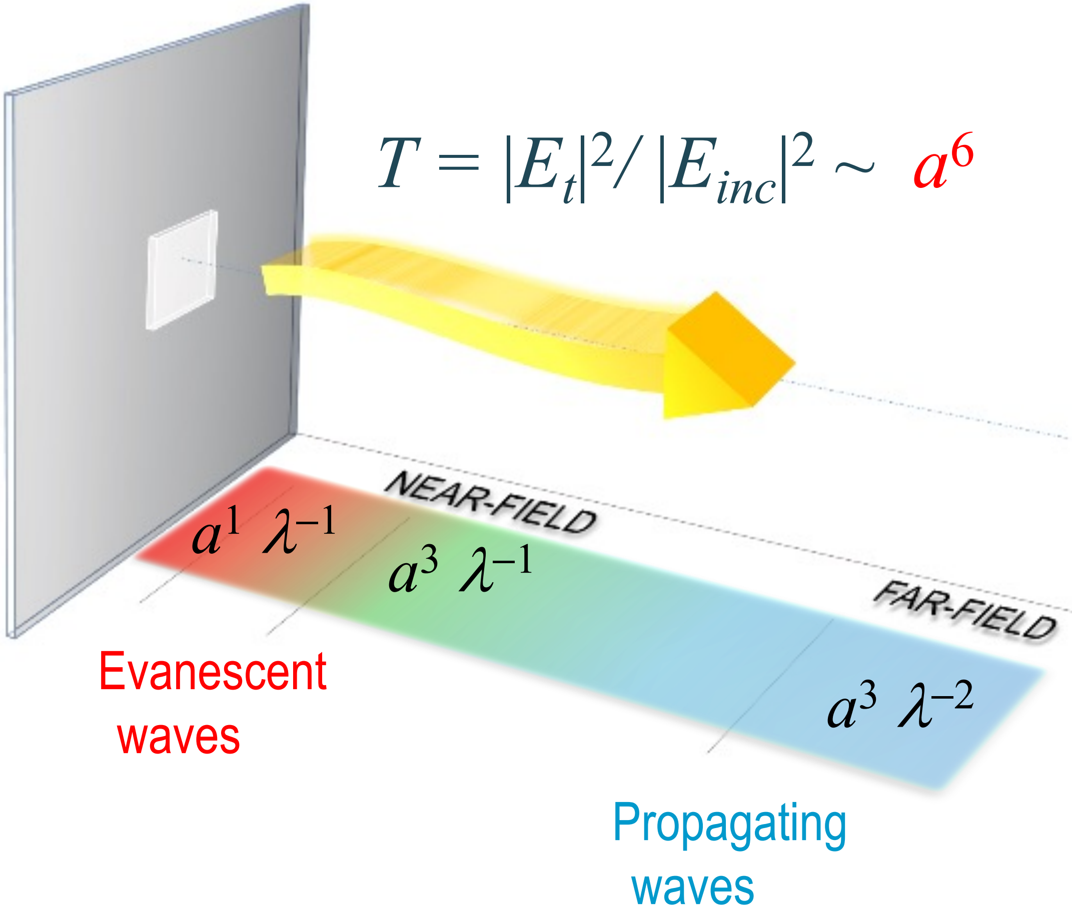


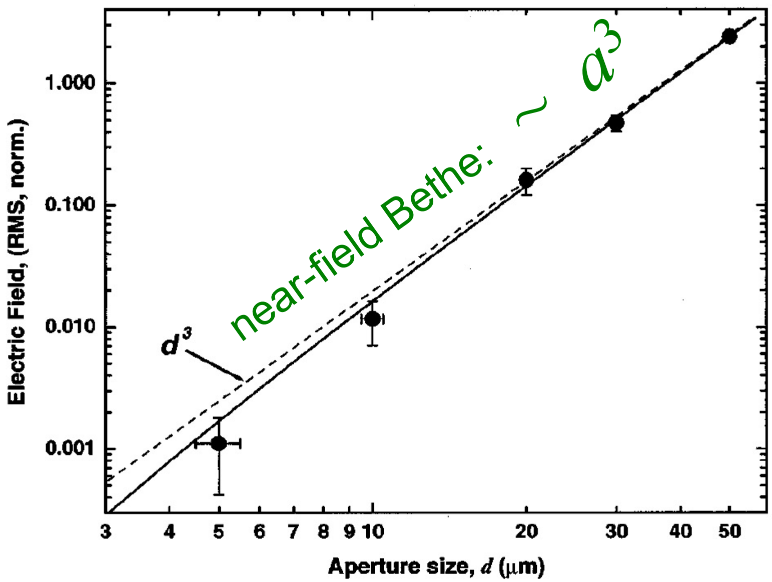


H. A. Bethe Phys. Rev. 66, 163 (1944)

Wave Transmission through Subwavelength Apertures

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





OM et al., APL **79,** 907 (2001)

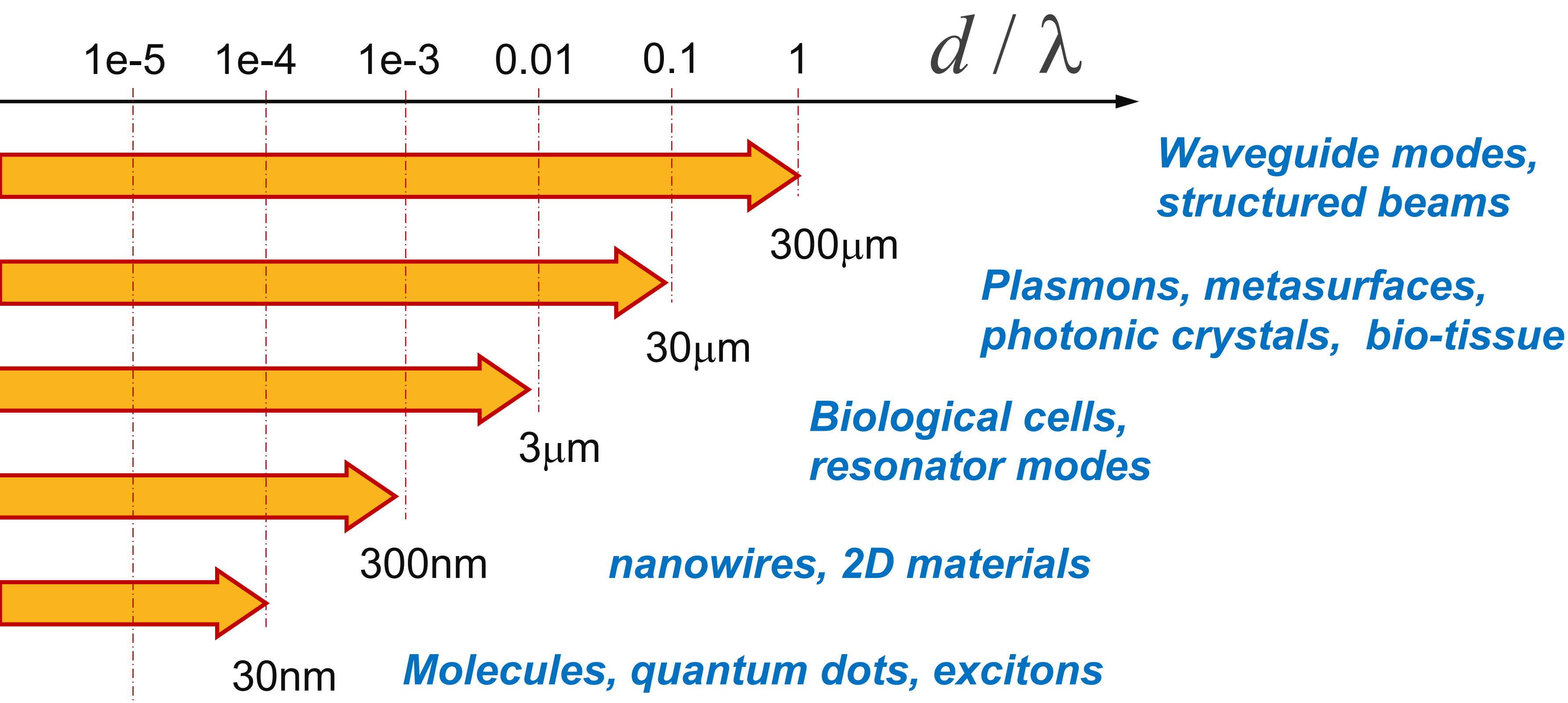
H. A. Bethe Phys. Rev. 66, 163 (1944)

Improving resolution by factor of 2 comes with power transmission penalty of almost 2 orders of magnitude

Aperture-type Probes Limitation

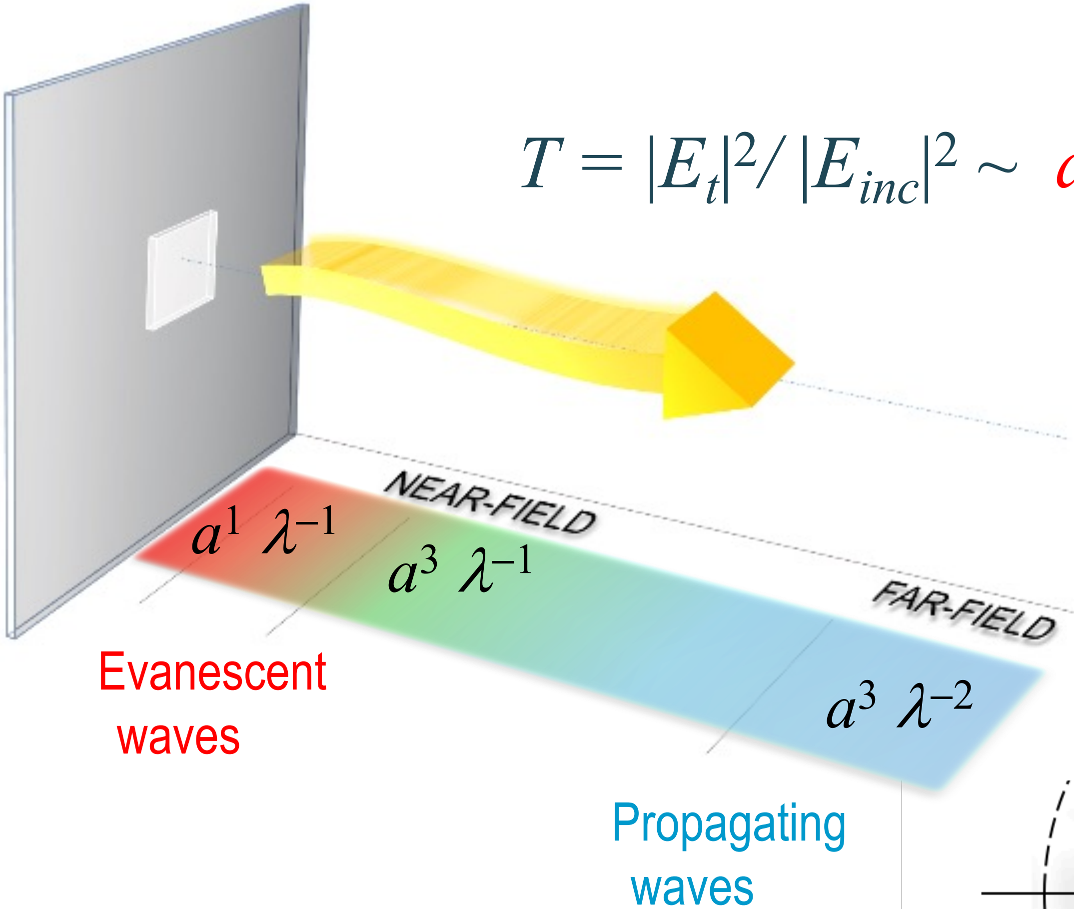
$$d = \frac{\lambda}{2n\sin\alpha}$$

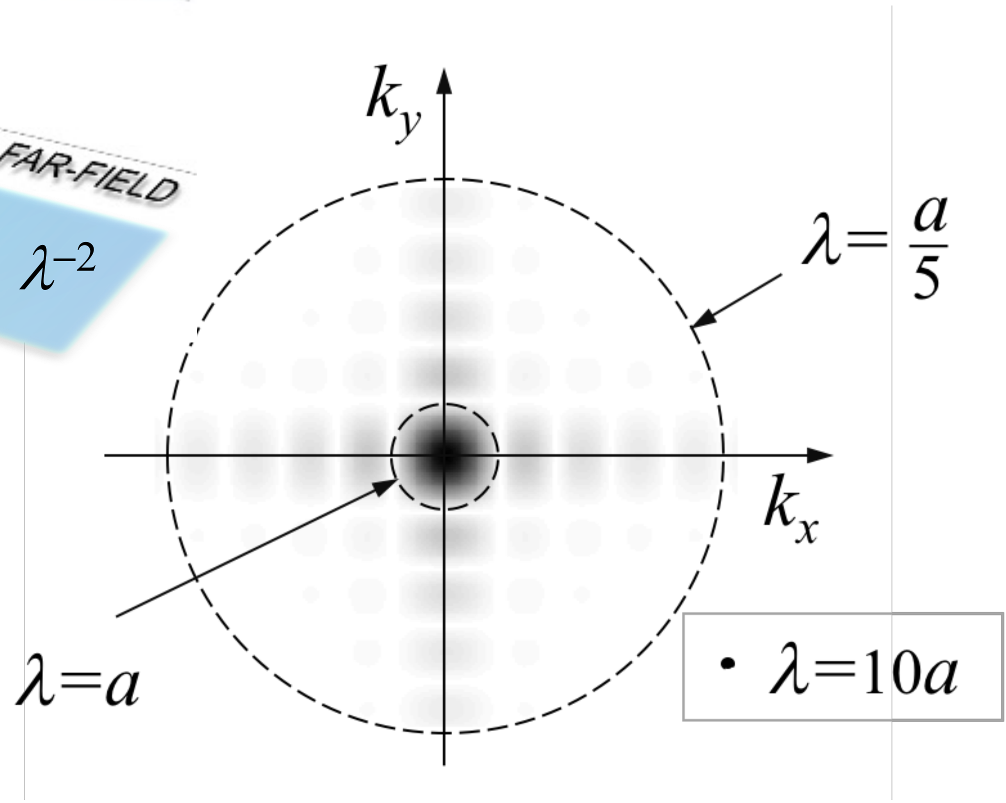
Ernst Abbe (c. 1873)



Near-field Detection

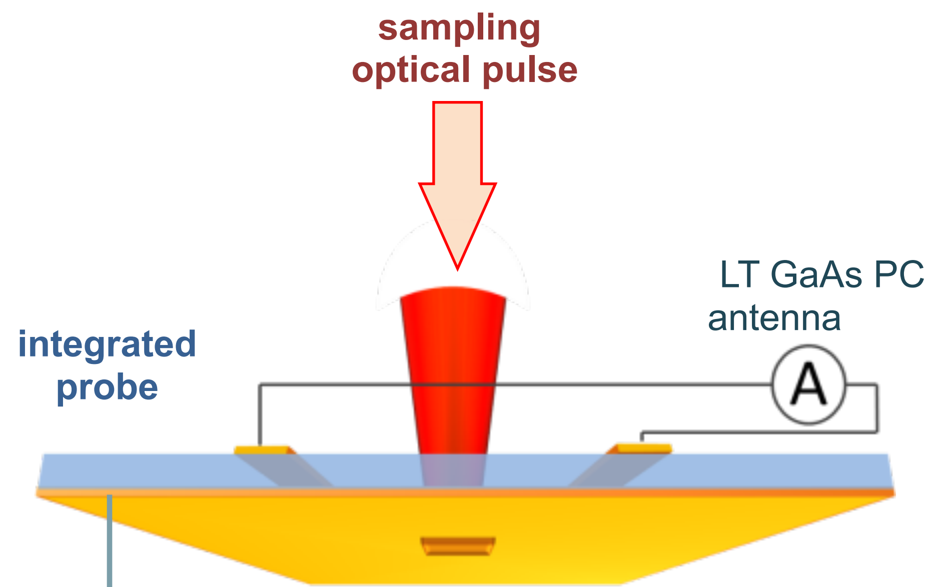
$$T = |E_t|^2 / |E_{inc}|^2 \sim a^6$$

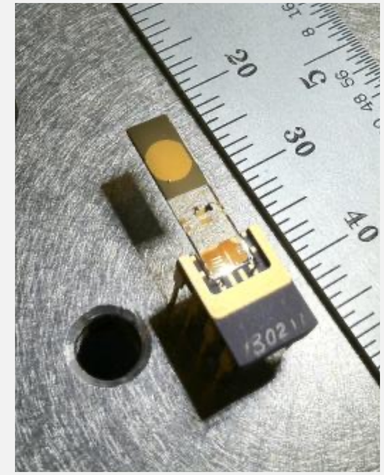


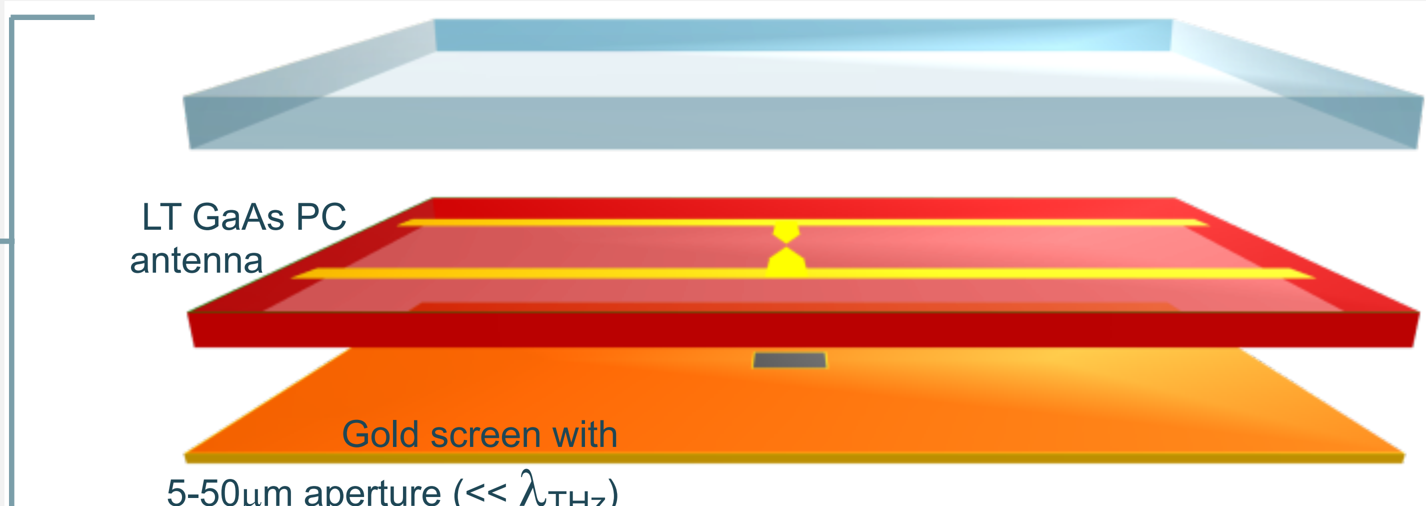


OM et al., APL **77**, 3496 (2000),
APL **79,** 907 (2001)

Aperture-type THz microscopy

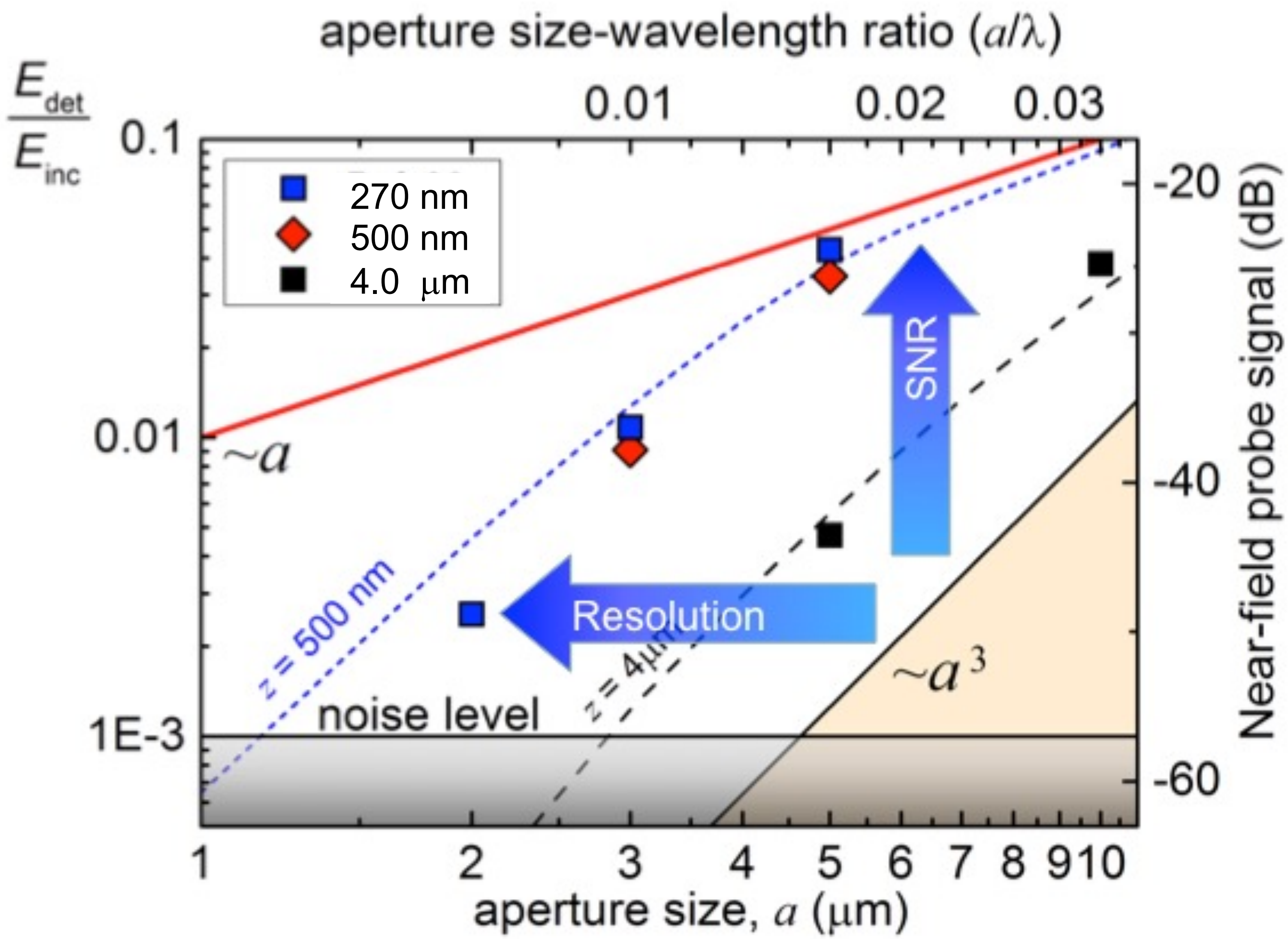






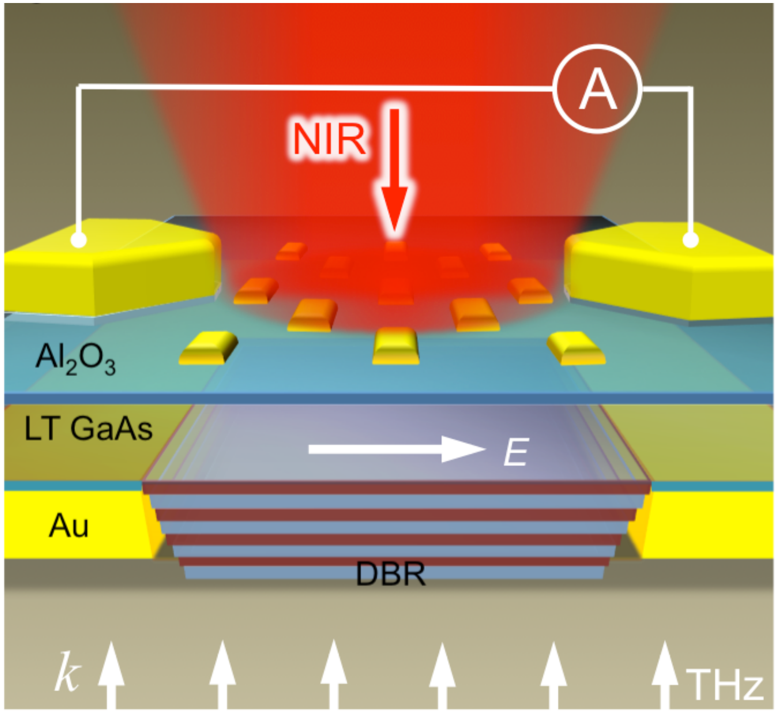
OM et al., APL. **77**, 3496 (2000)

Near-field Detection

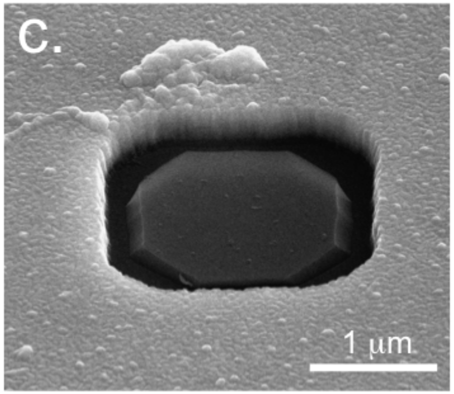


OM *et al. THz Sci. and Technology, IEEE Trans*. (2016)

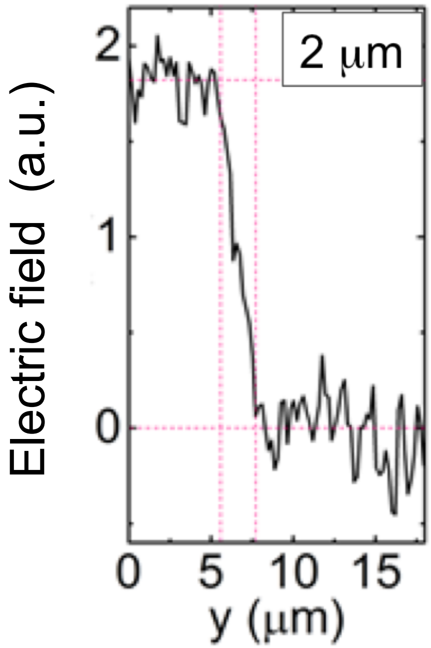
Near-field Probes with Integrated Detectors

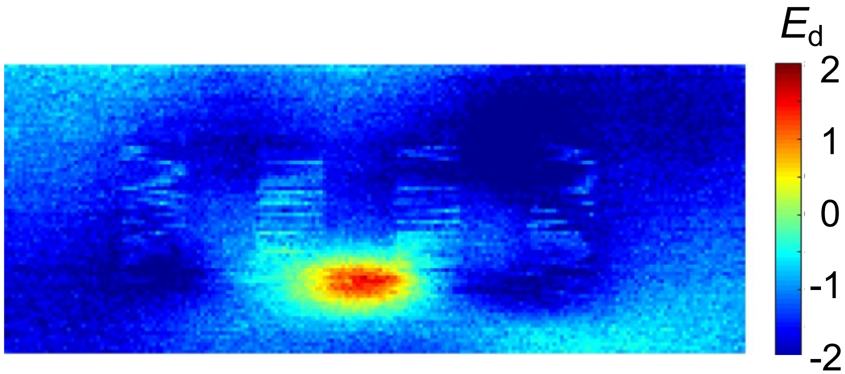


OM *et al.*, *ACS Photonics* (2015)



Resolution Test:
2 μm aperture



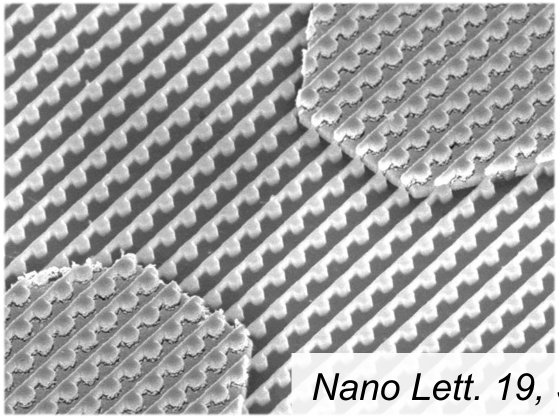


OM et al., *Appl Phys Lett.* 2017

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

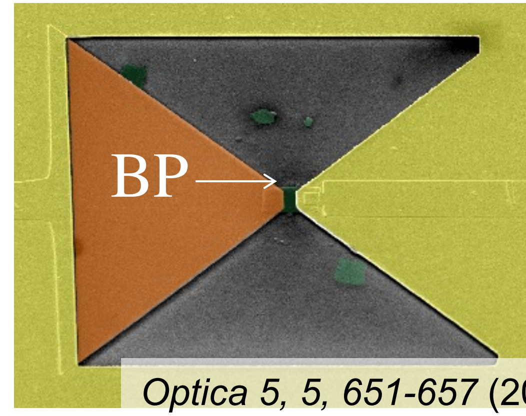
Nano-scale THz Detectors

Ultrathin Photoconductive Metasurfaces (THz-TDS)



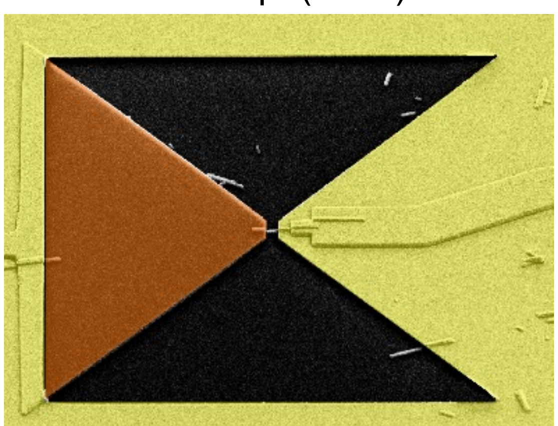
Nano Lett. 19, 5, 2888 (2019)

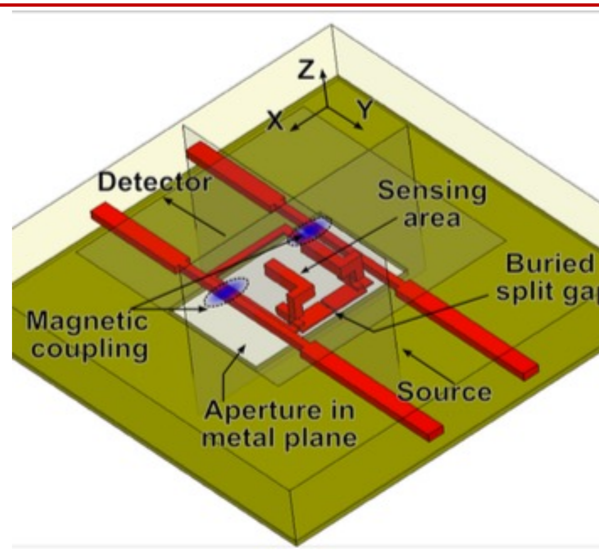
FET-based 2D materials



Optica 5, 5, 651-657 (2018)

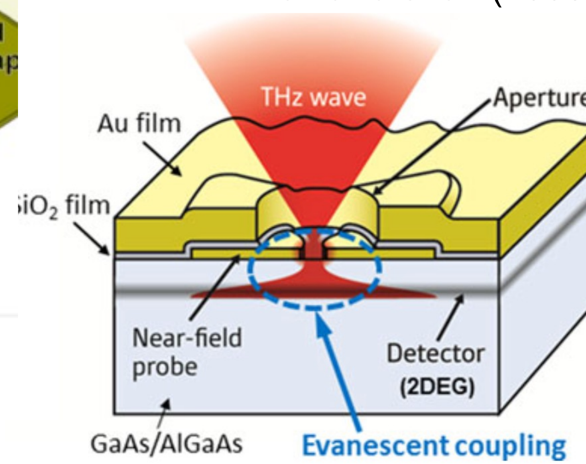
InAs nanowire detectors
OM et al. Sci. Rep. (2017)



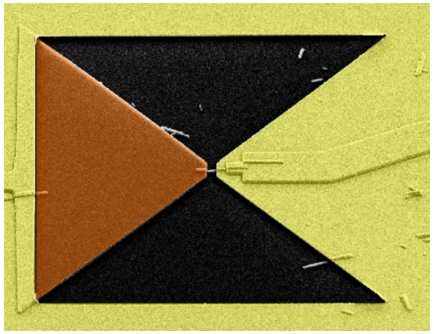


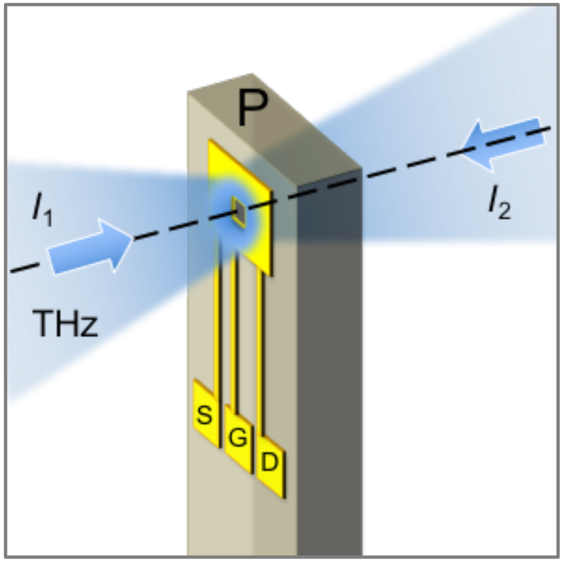
CMOS-based detectors
Grzyb et al. (2016)

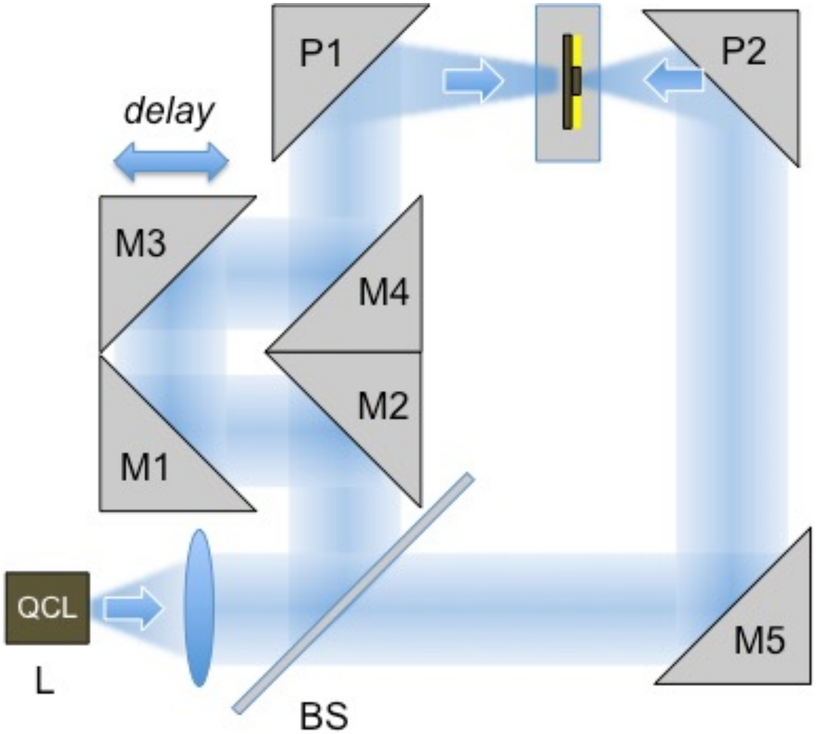
2DEG detectors
Kawano et al. (2008)



Coherent Aperture-type THz microscopy with QCLs

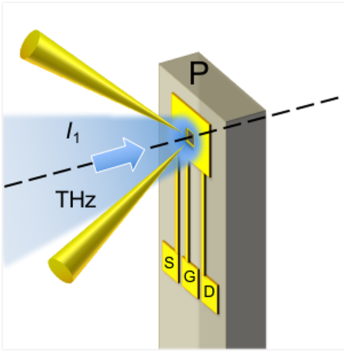






OM et al., *Scientific Reports 7, 44240* (2017)

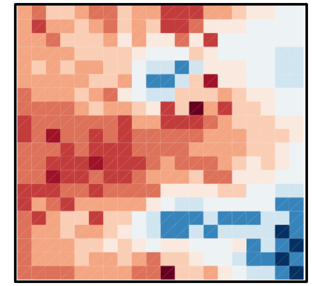
Phase Mapping and Sensitivity Gain

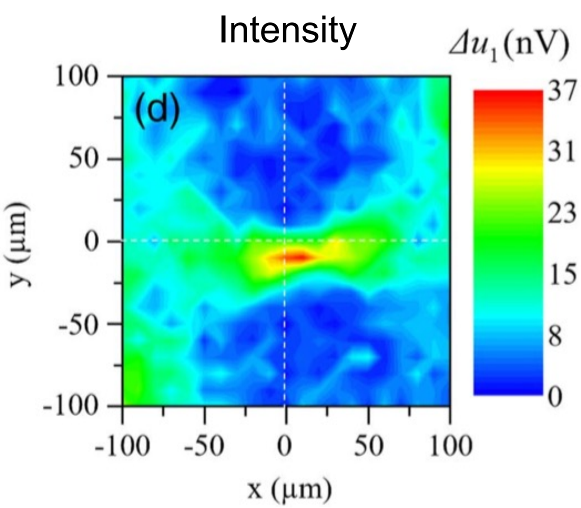


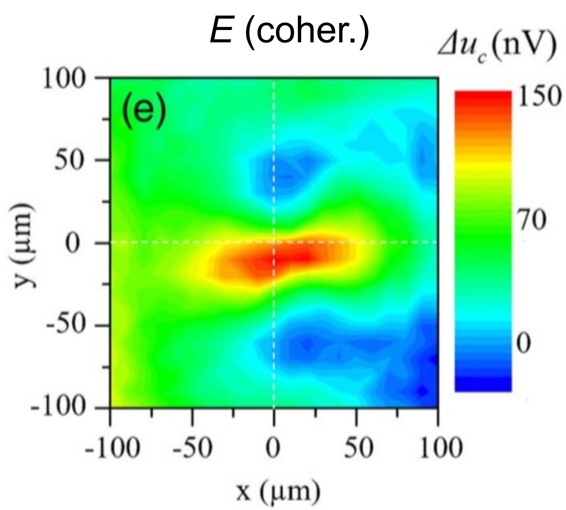
Phase Information

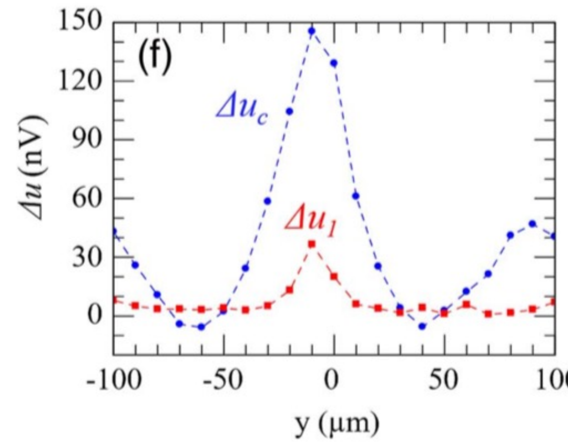
Sensitivity Gain

Phase





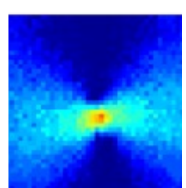




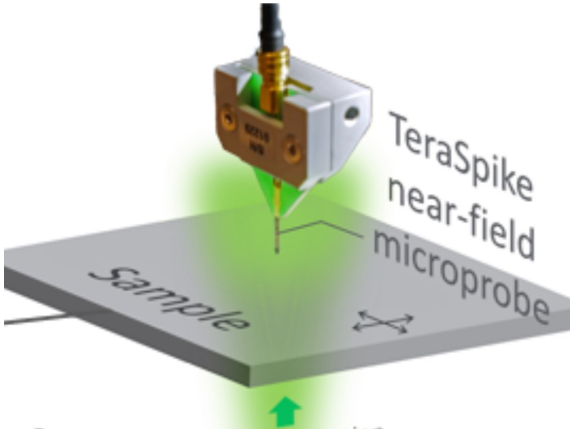
Optica 5, 5, 651-657 (2018)

Consistent with
THz-TDS NF microscopy:

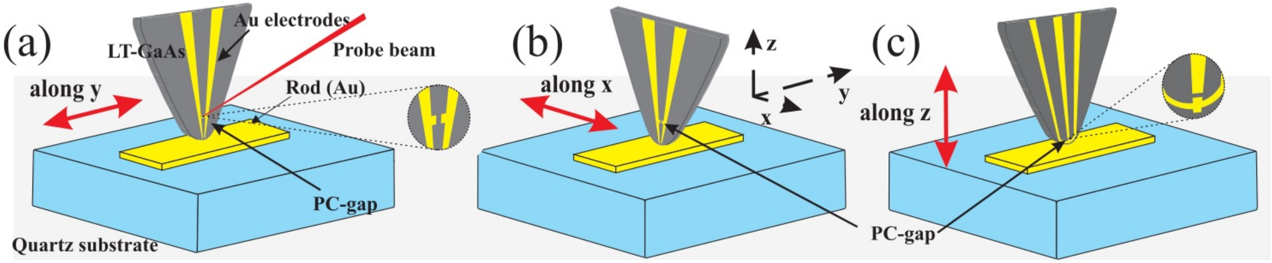
Optics Express 20(6), 6197 (2012)

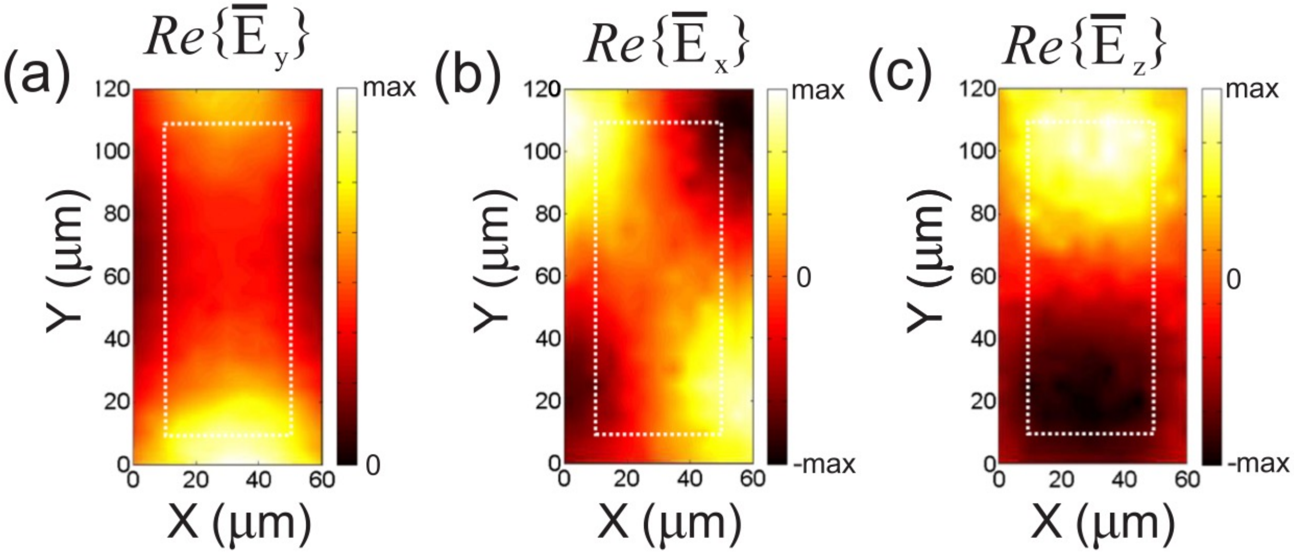


Local THz Probes

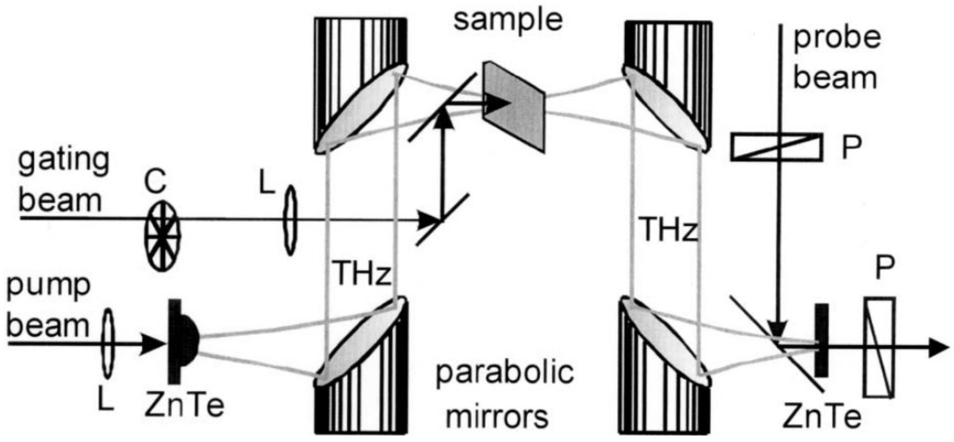


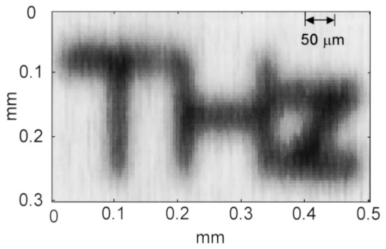
Commercial Tera-Spike probe from Protemics
www.protemics.com





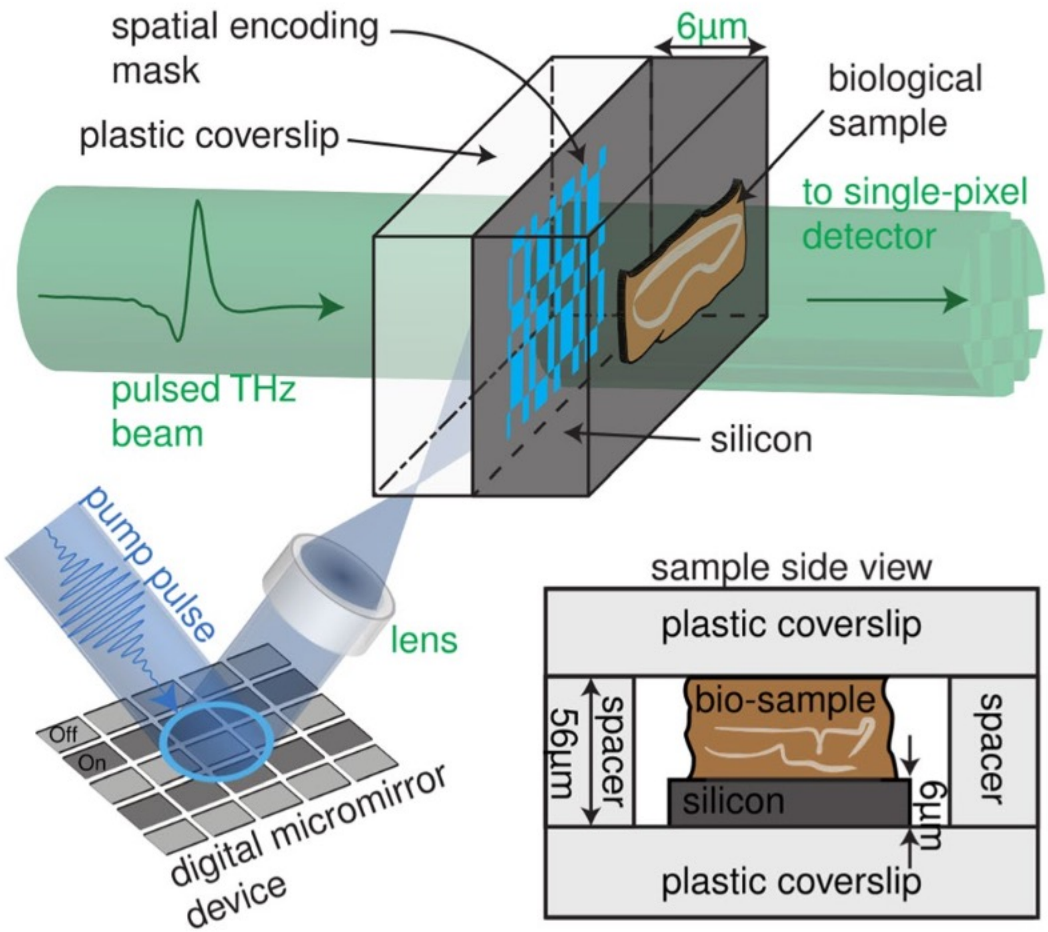
Bhattacharya and Rivas,
APL Photonics 1, 086103 (2016)





Chen et al. *OPTICS LETTERS* 25 (2000)

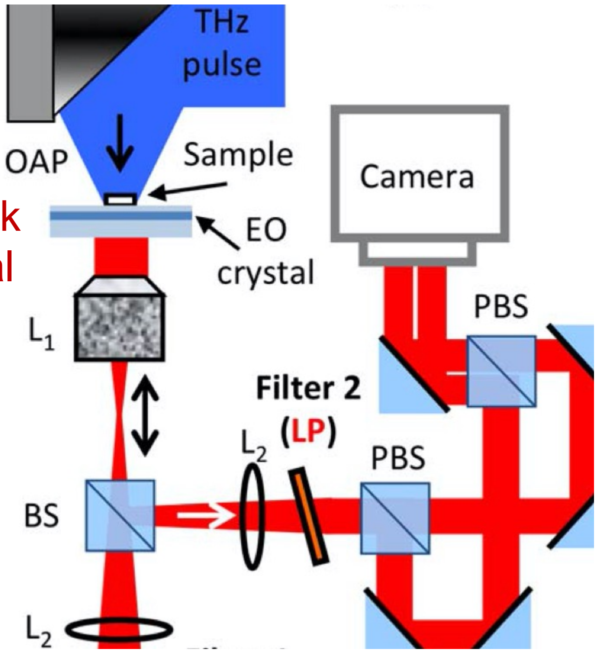
Local (near-field) THz Wave Modulation, Generation and Detection

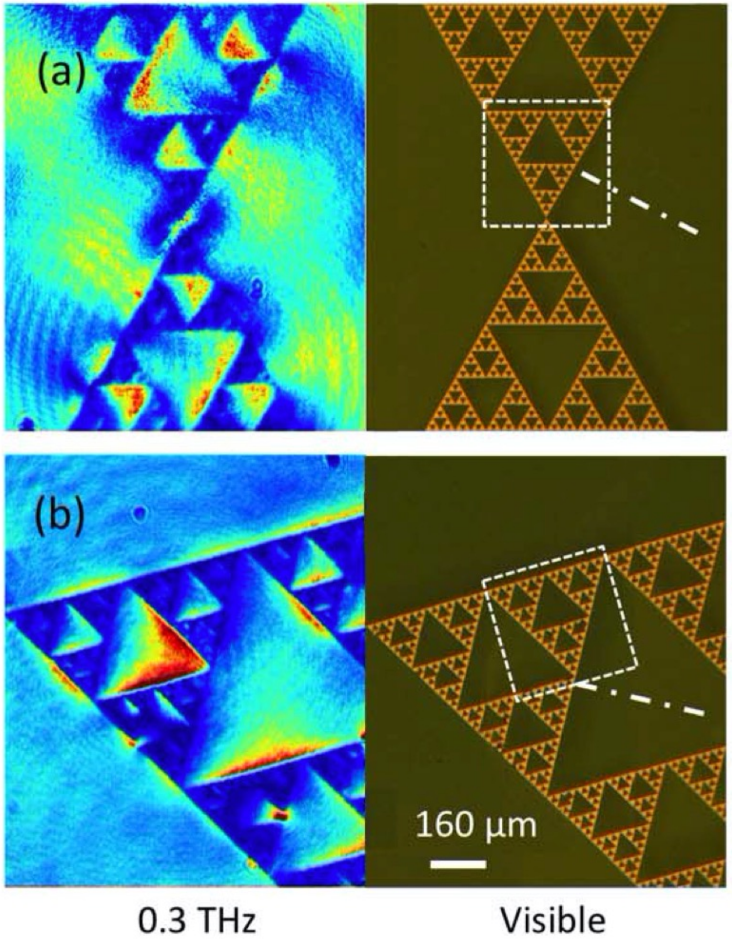


Stantchev et al., *Sci. Reports* 8, 6924 (2018)

Near-field Detection – Electro-Optic Imaging

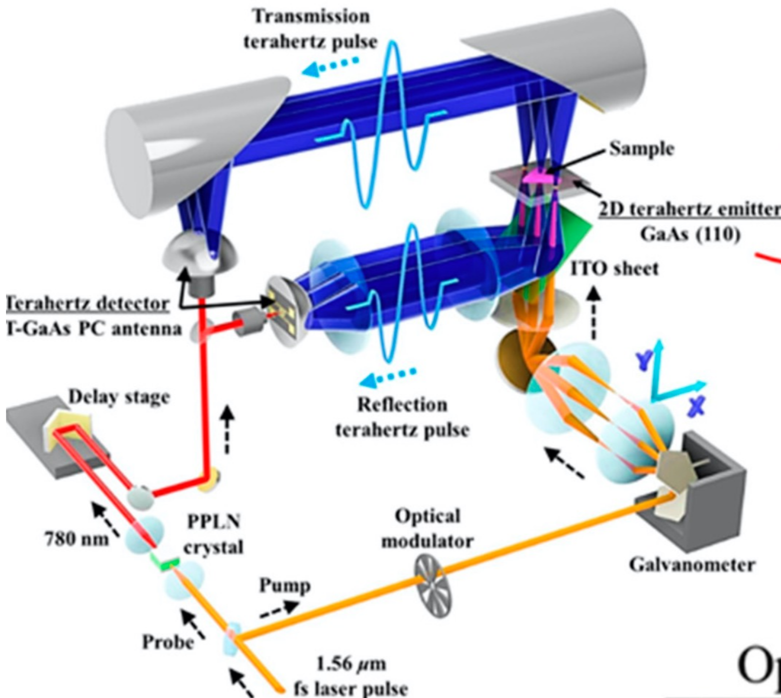
10 μm thick
EO Crystal

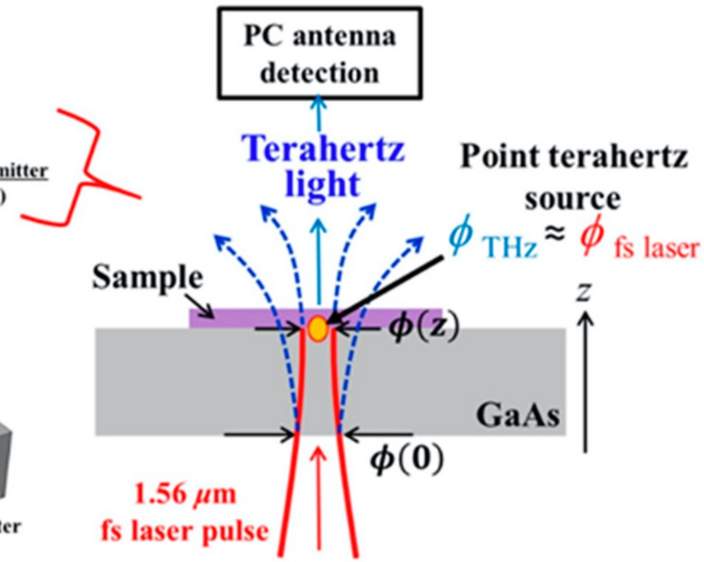




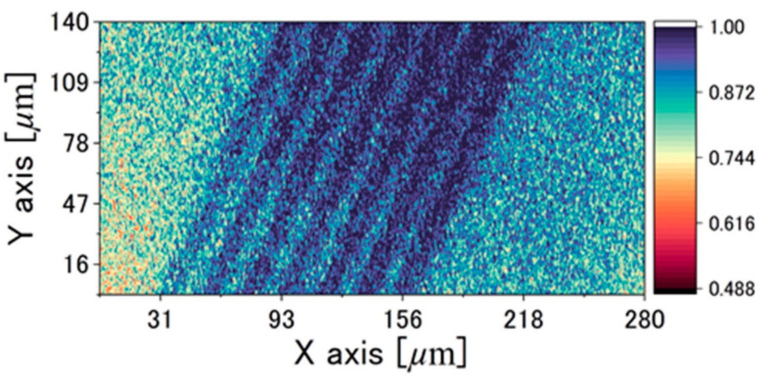
Blanchard & Tanaka
Optics Lett. 41, 4645 (2016)

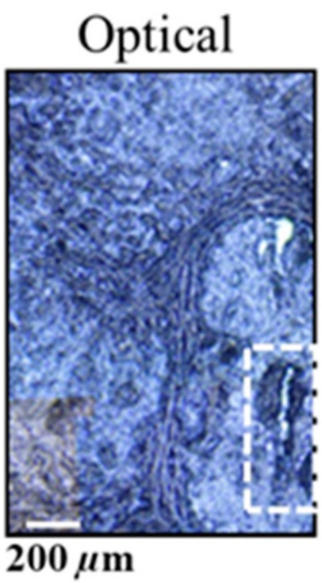
THz Near-field Emission

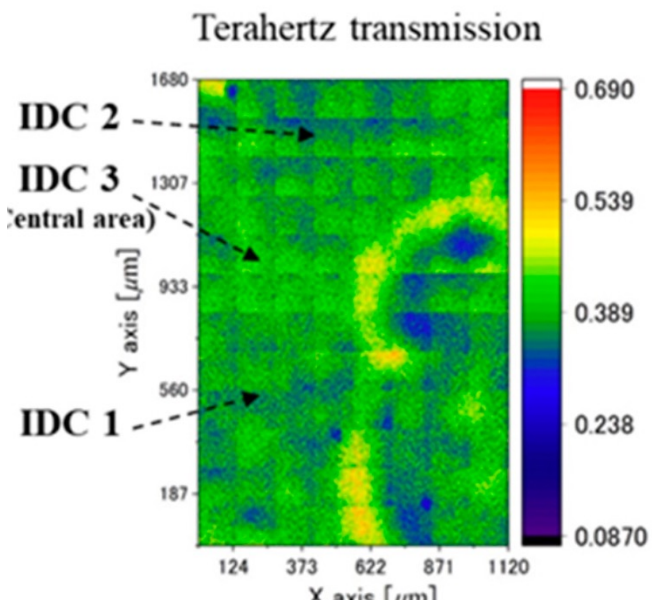




K. Okada et al. *Photonics, 8, 151* (2021)



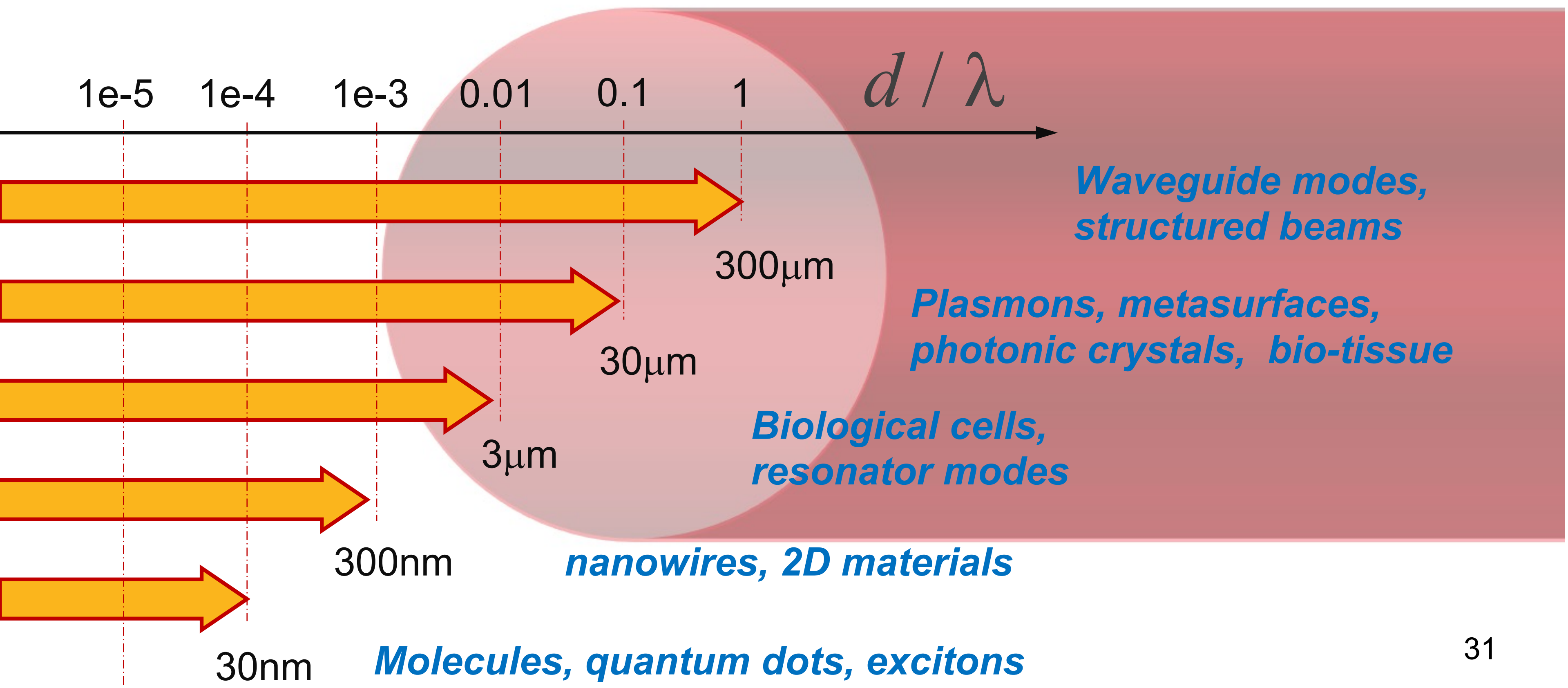




Aperture-type THz Microscopy Application Range

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

Ernst Abbe (c. 1873)



Scattering Tip THz Nanoscopy

Principle

Practical Limitations

Enabling Technology Advances

Applications

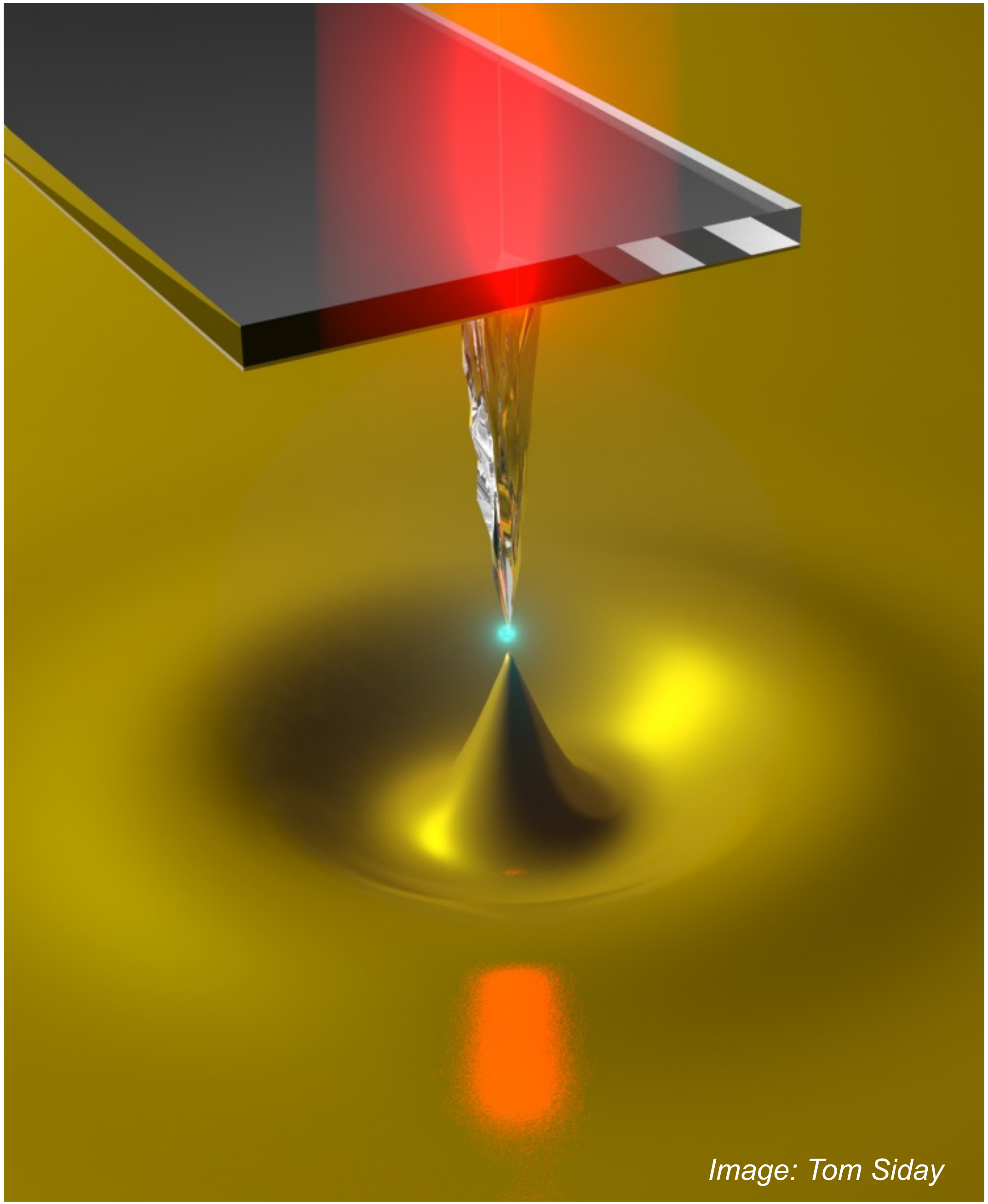
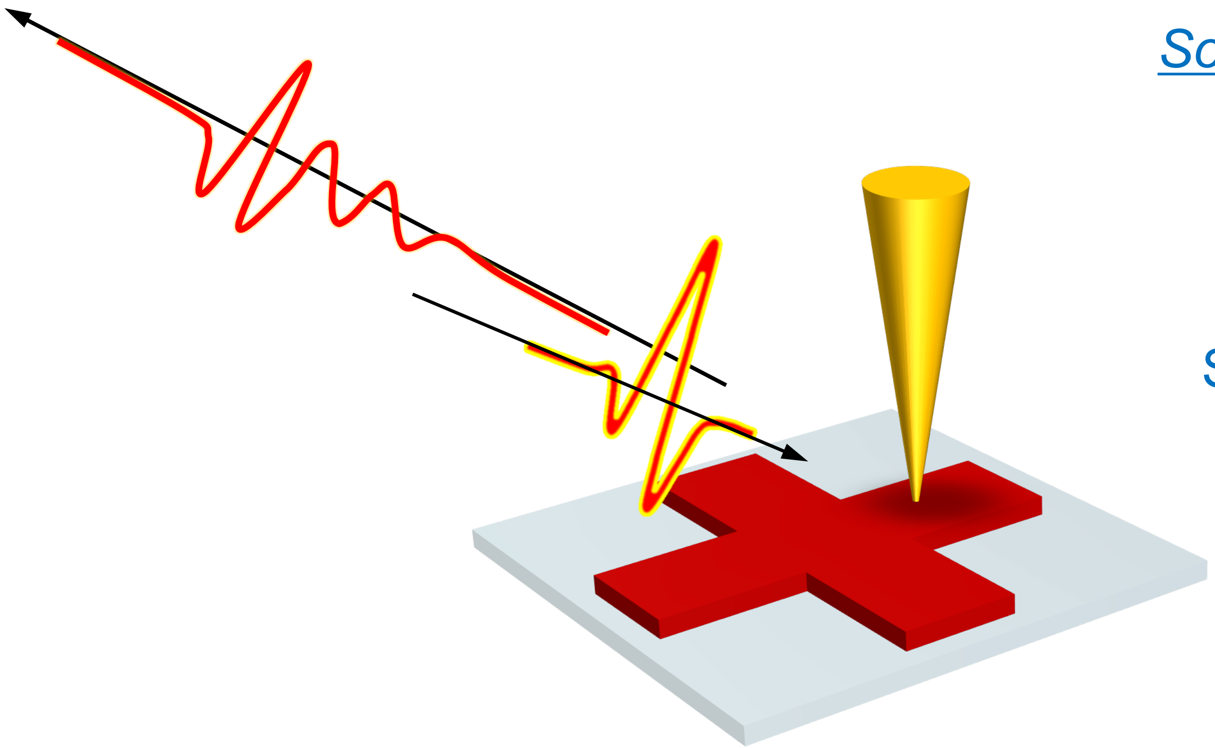


Image: Tom Siday

Challenges:

Image Interpretation

Weak THz Scattering from Probe Tip



Solutions:

Scattering Enhancement

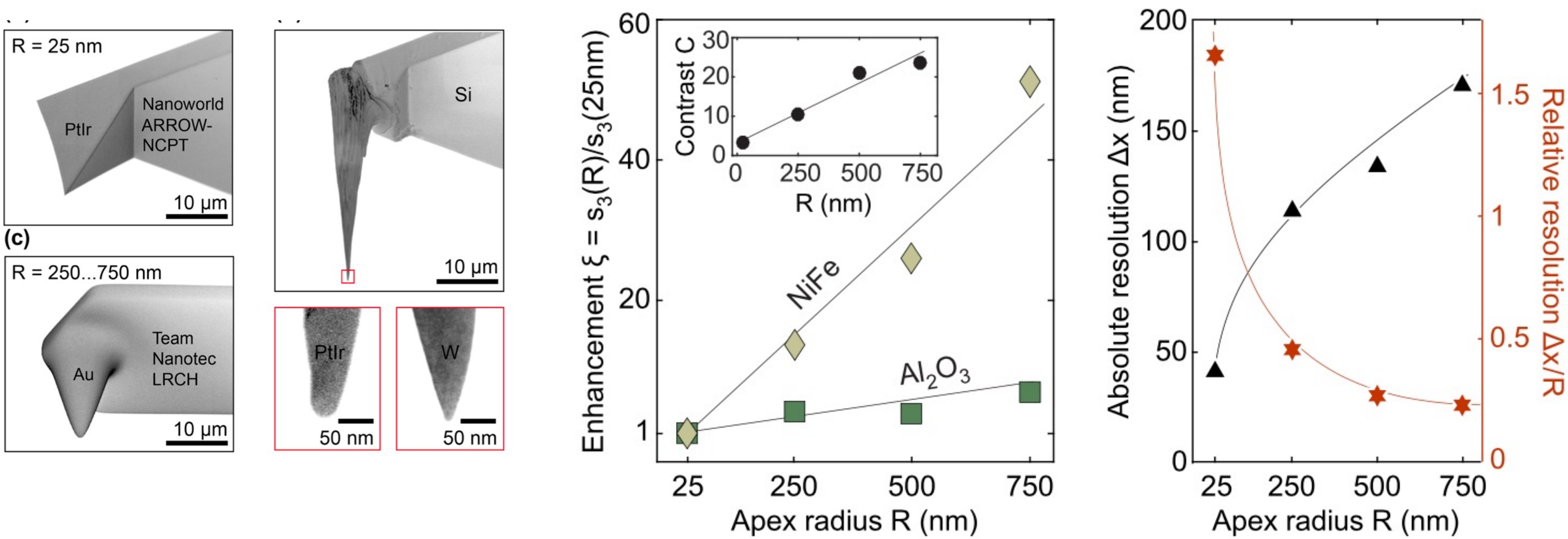
Sensitive Detection

Detailed Introduction: Invited talk by Mengkun Liu (CLEO 2021 SW2K.7)

Two Main Factors affecting the Scattering efficiency:

Tip apex size

Tip shaft length

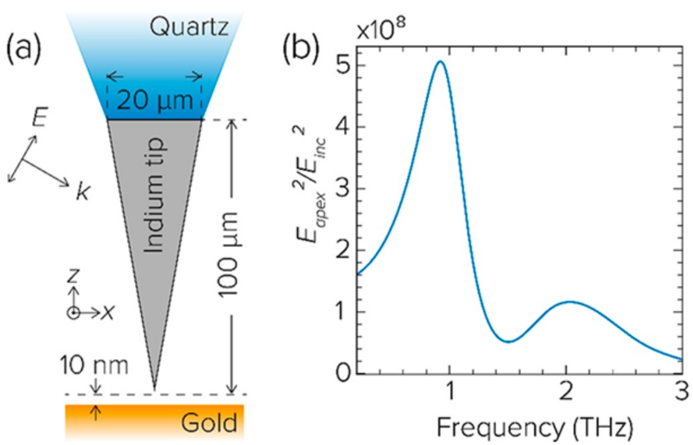


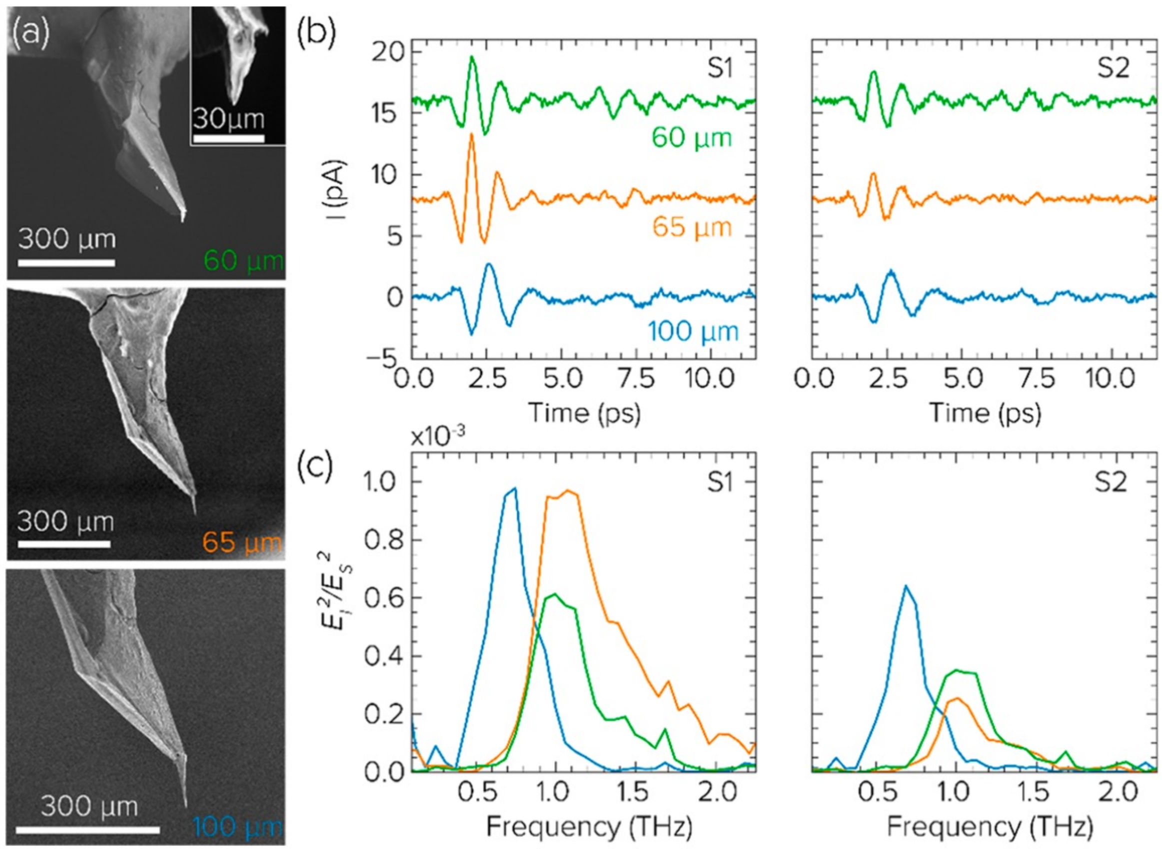
C. Maissen et al.,
ACS Photonics 6, 1279 (2019)

Two Main Factors affecting the Scattering efficiency:

Tip apex size

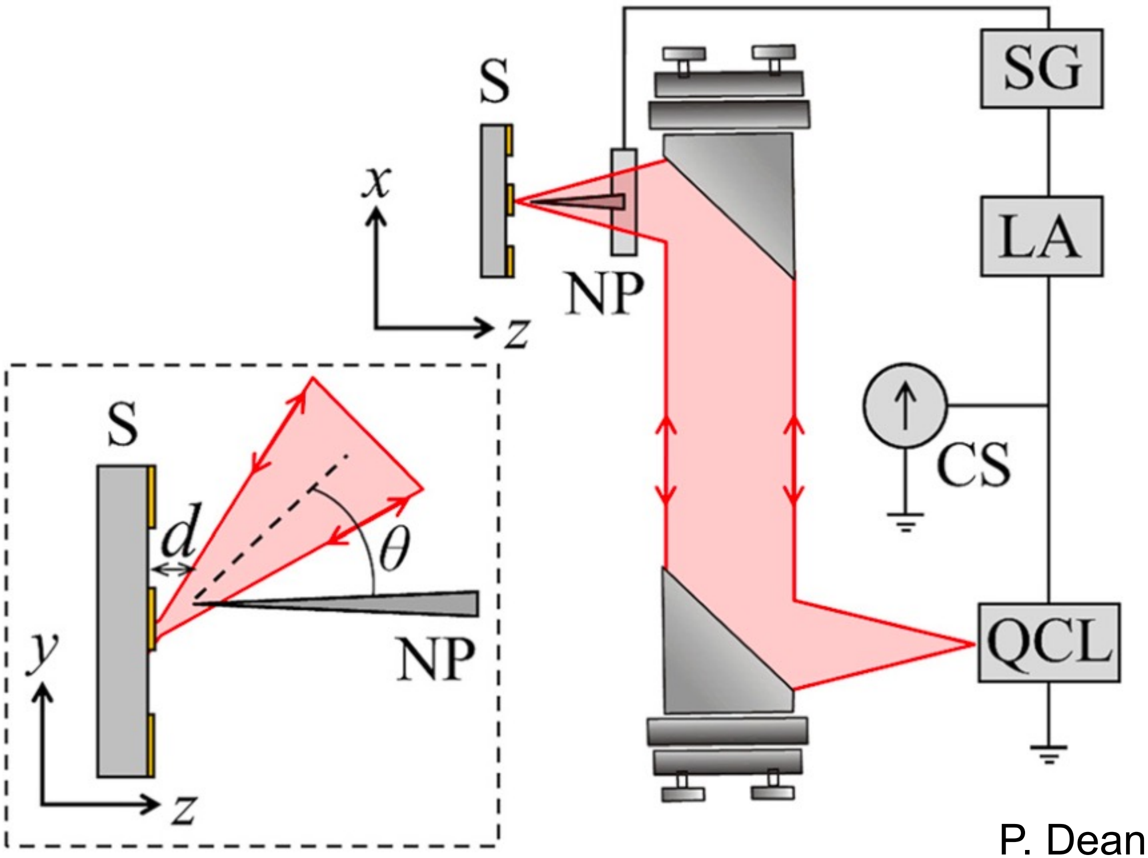
Tip shaft length





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:

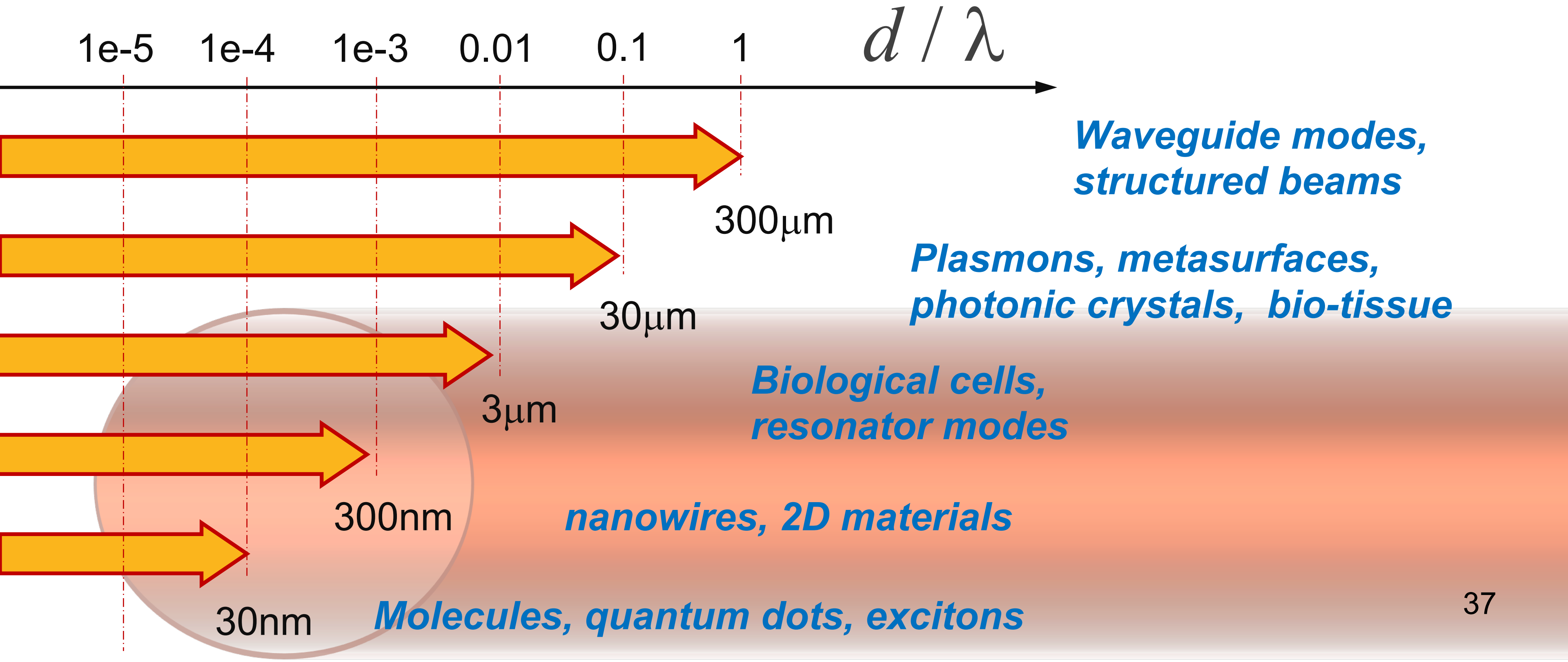
Riccardo Degl'Innocenti (ACS Photonics 2017) – Tunning fork Probe

Miriam Vitiello (OpEx 2018) - Neaspec

THz s-SNOM Application Range

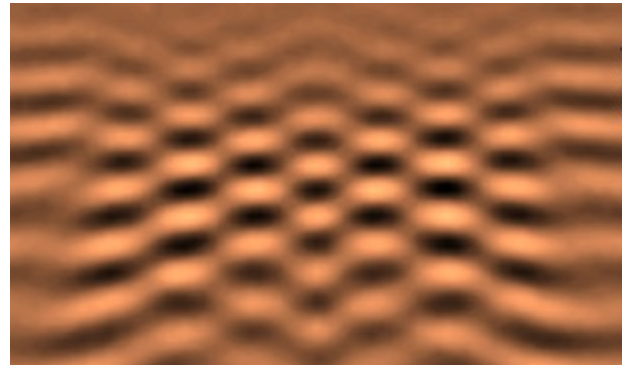
$$d = \frac{\lambda}{2n \sin \alpha}$$

Ernst Abbe (c. 1873)

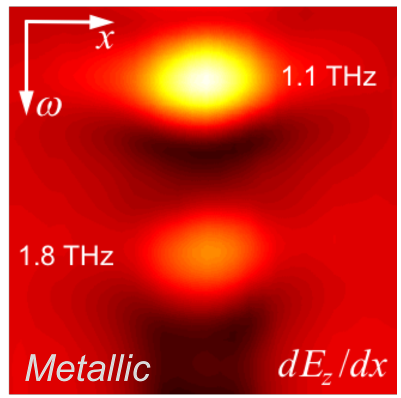


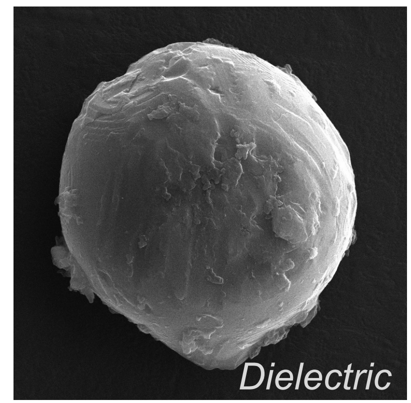
THz sub-wavelength Imaging Applications

Surface waves / Plasmons

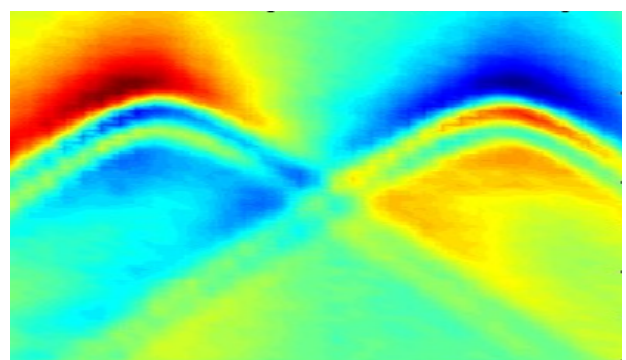


THz Subwavelength Resonators

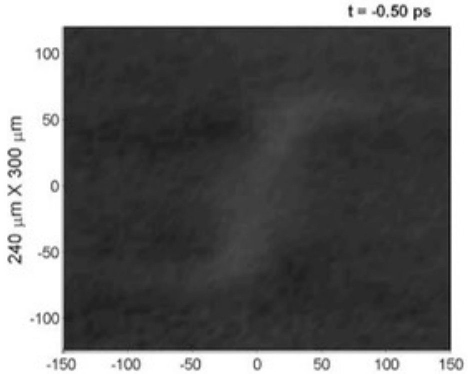


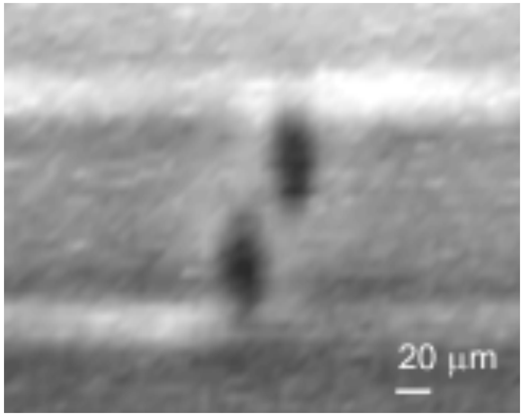


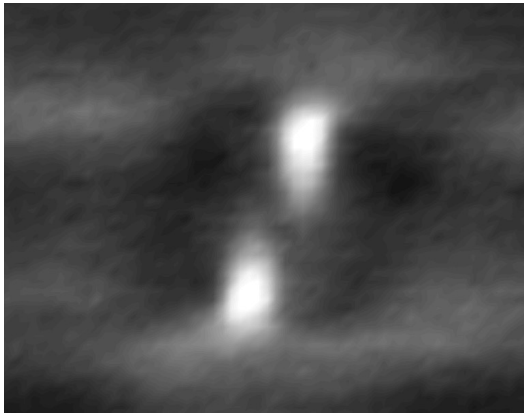
THz Emission



THz Surface Plasmon Waves

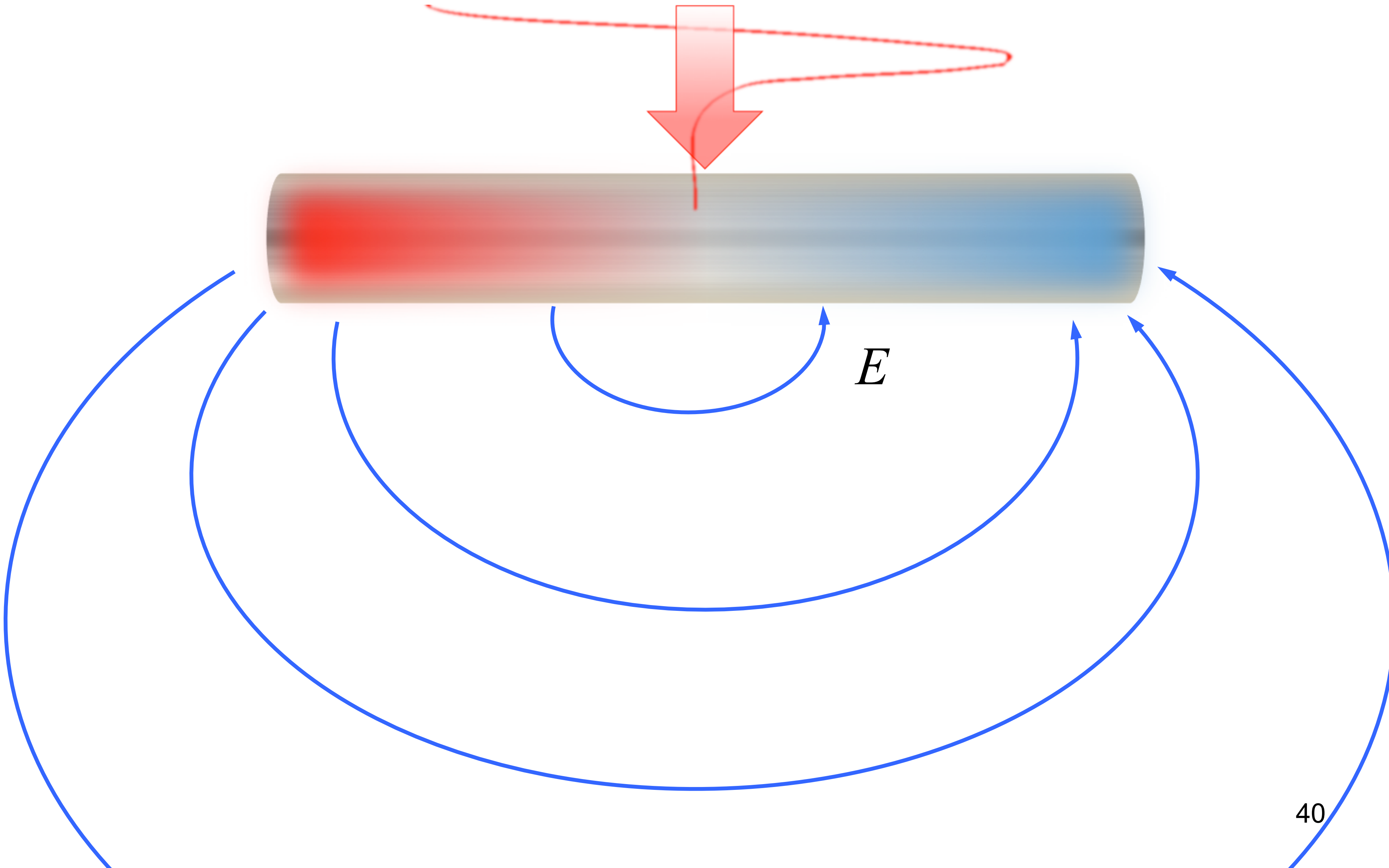




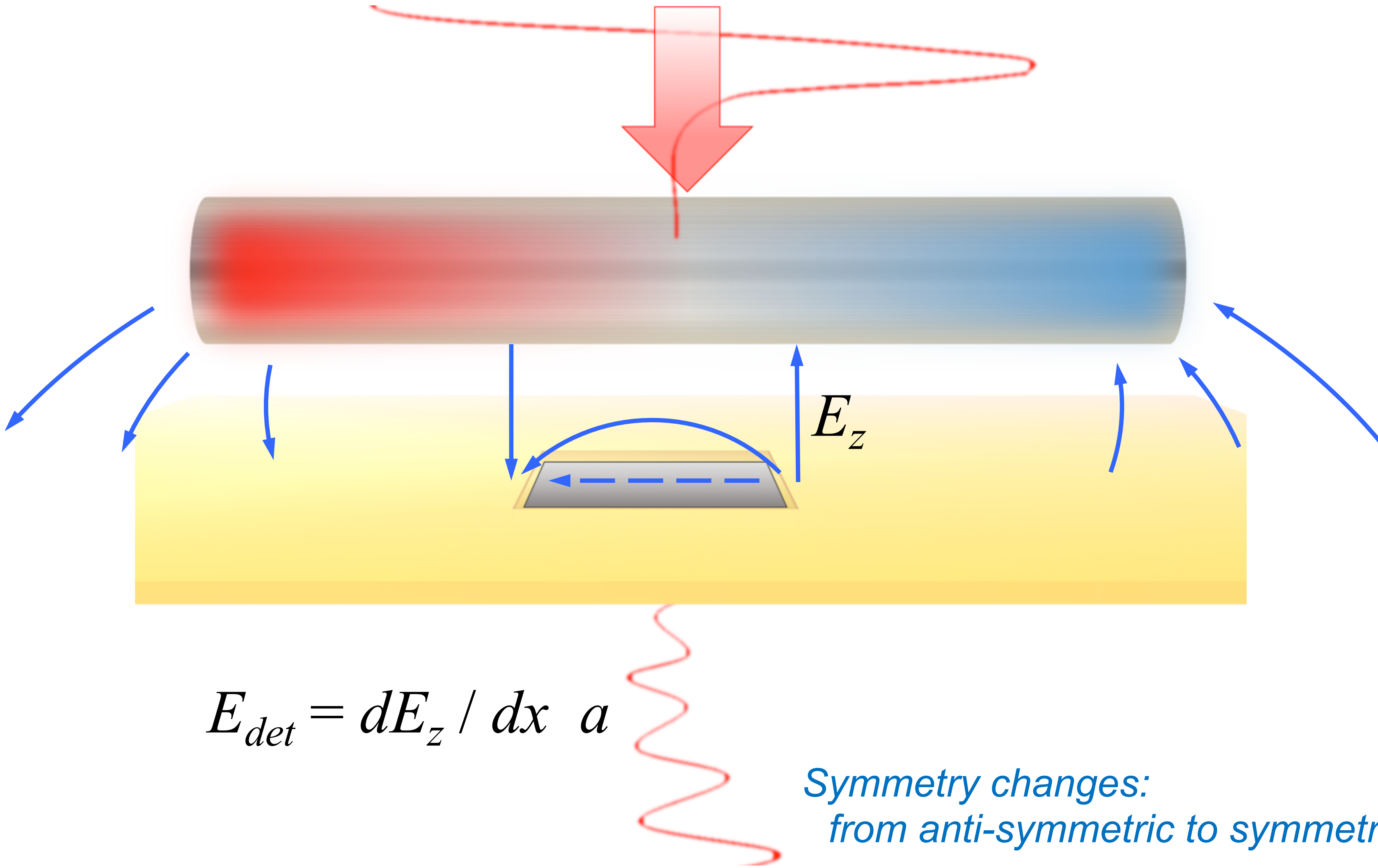


Mitrofanov et al.*J. STQE* **103**, 600 (2001)

THz Surface Plasmon Waves – Mapping with Aperture



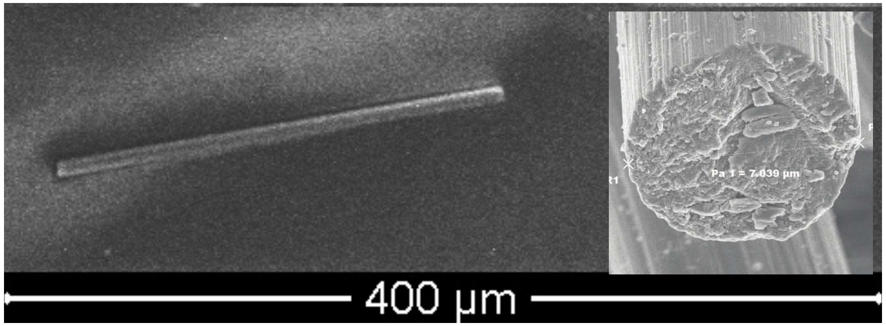
THz Surface Plasmon Waves – Mapping with Aperture



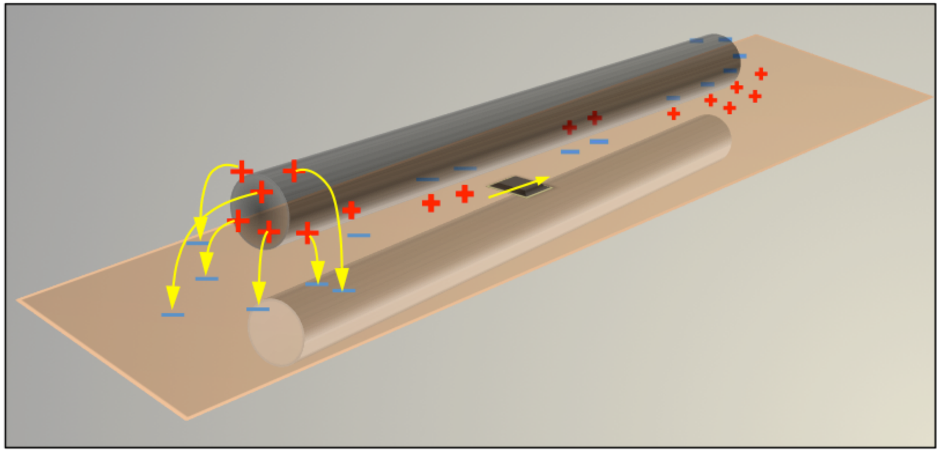
$$E_{det} = dE_z / dx \;\; a$$

Symmetry changes:
from anti-symmetric to symmetric

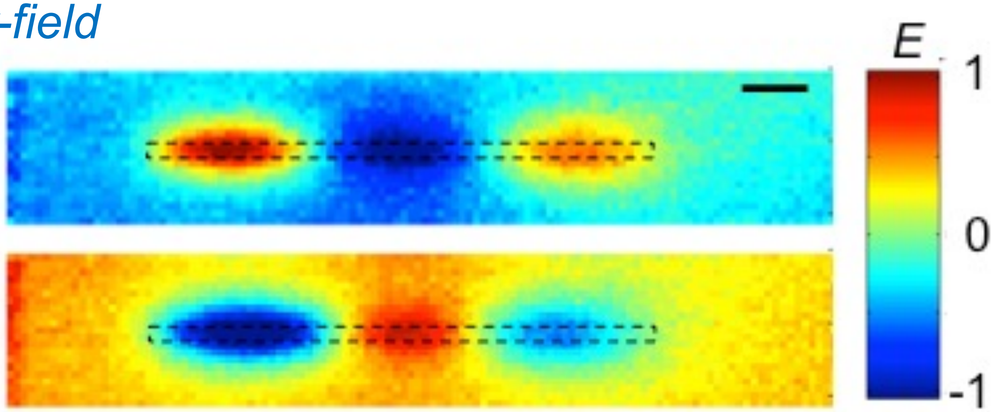
THz Surface Plasmon Waves – Mapping with Aperture



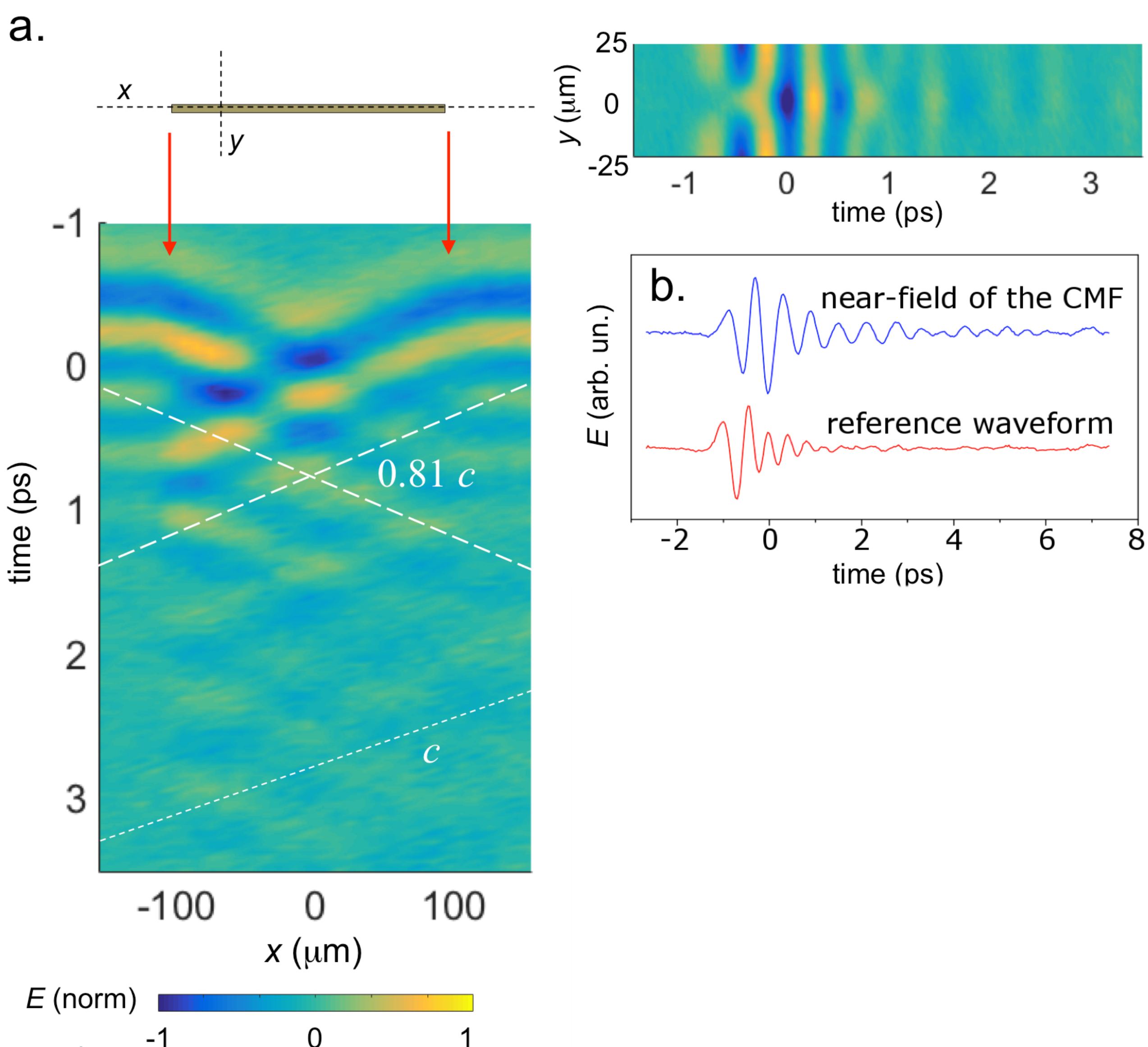
Conductive carbon fibres:
6.5 μm diameter, 50-250 μm long



THz near-field Images



THz Surface Plasmon Waves – Mapping with Aperture



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

THz Surface Plasmon Waves - Graphene

Far-field:

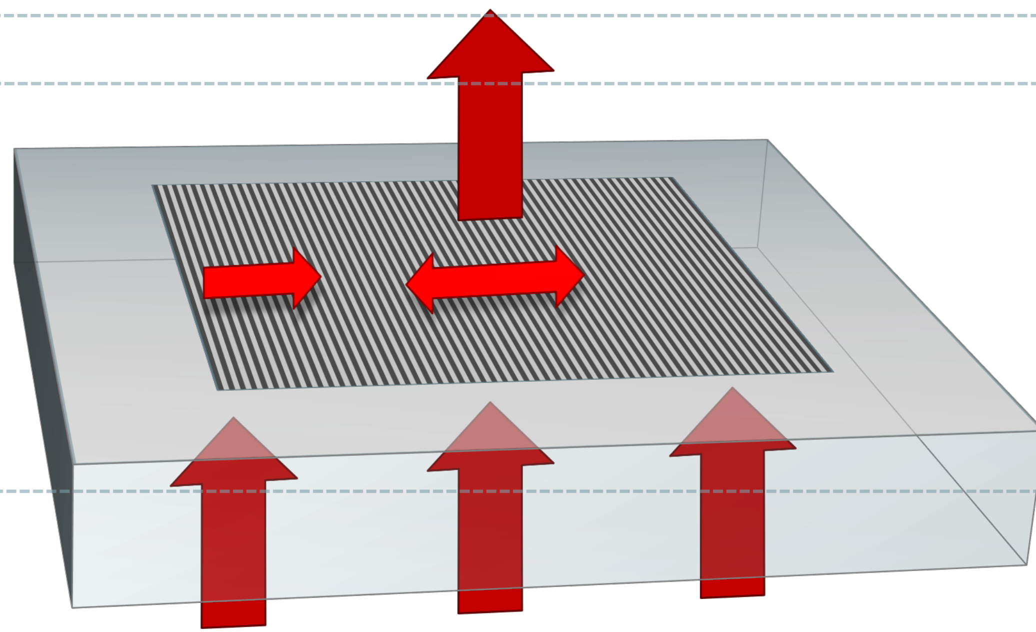
Transmitted wave

Diffracted wave

Near-field

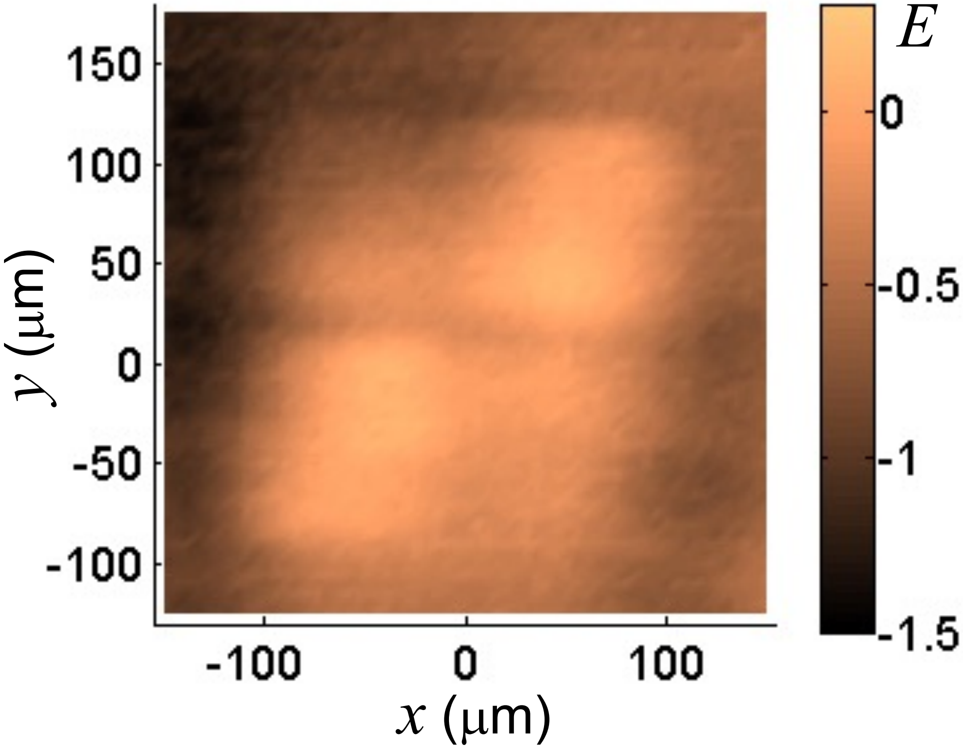
Resonant surface plasmons

Surface waves excited
at edges (non-resonant)



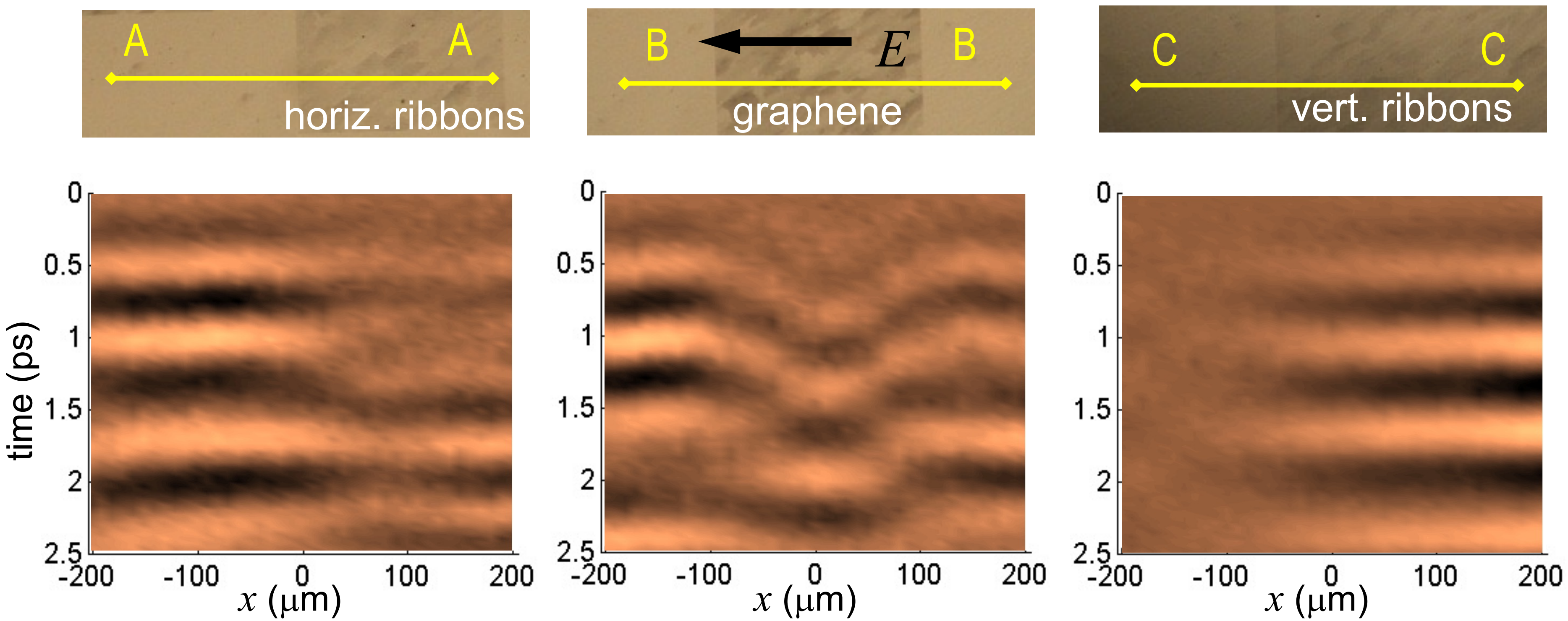
Incident THz wave

Transmission contrast due to Graphene



OM *et al.*,
Appl. Phys. Lett. 103, 111105 (2013)

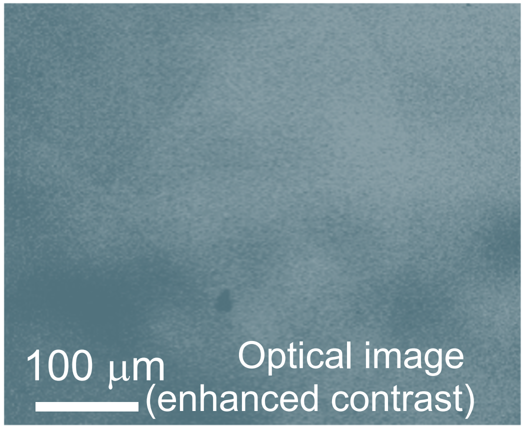
Imaging of Gr Ribbon Arrays

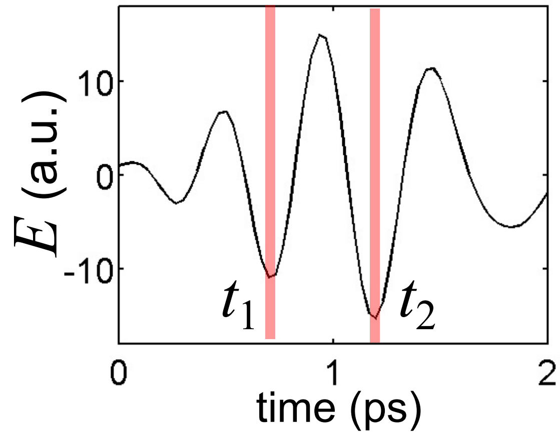


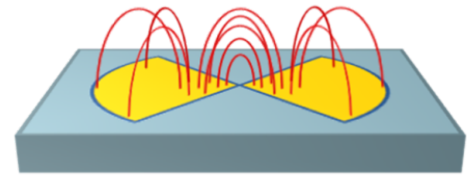
OM *et al.*,
Appl. Phys. Lett. 103, 111105 (2013)

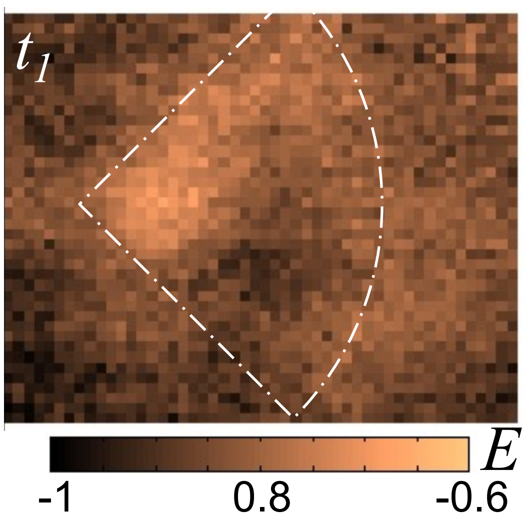
Surface Waves on Gr Bow-Tie Antenna

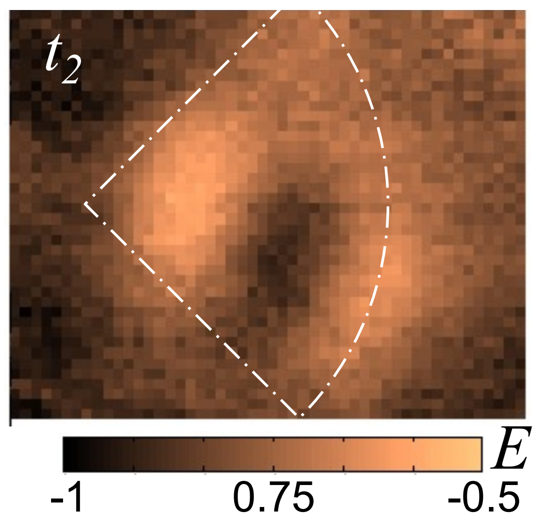
Epitaxial monolayer graphene - Gr on C-face SiC











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

Surface Waves on Gr Bow-Tie Antenna

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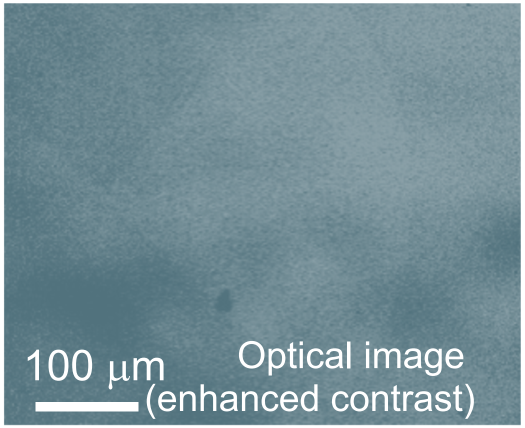
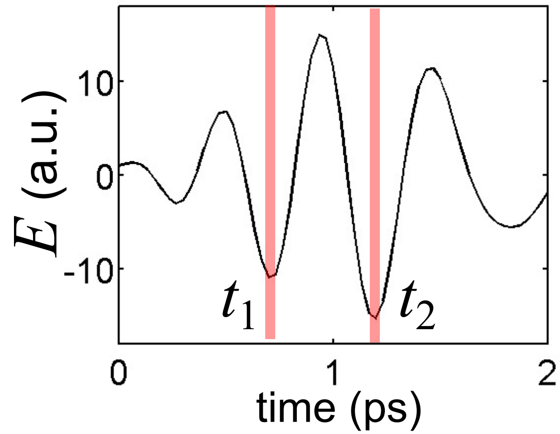
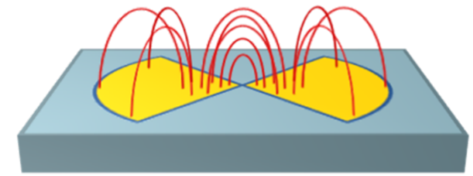
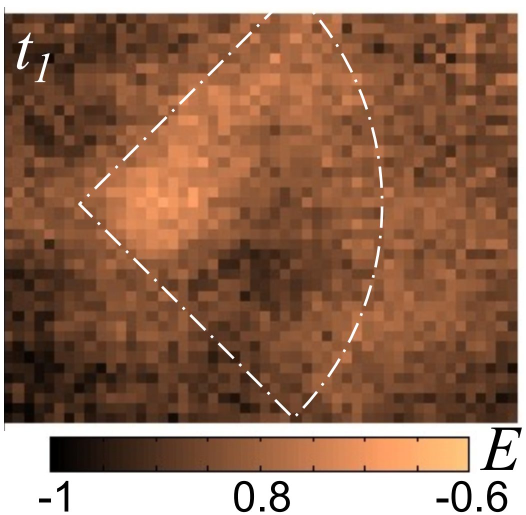
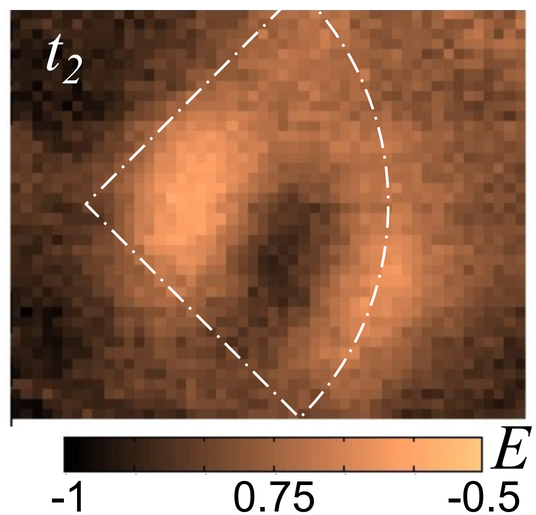


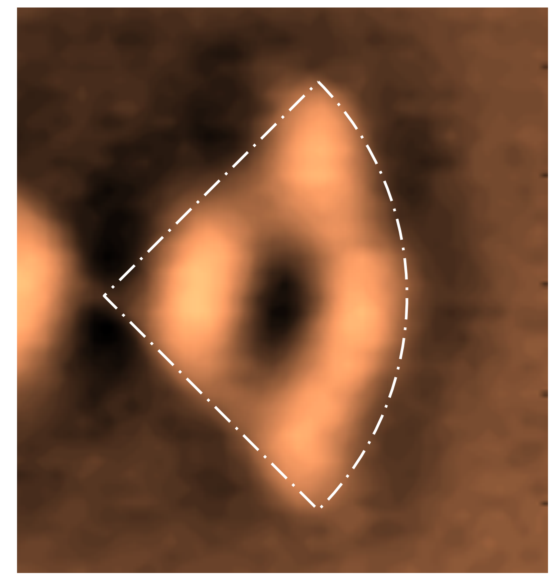








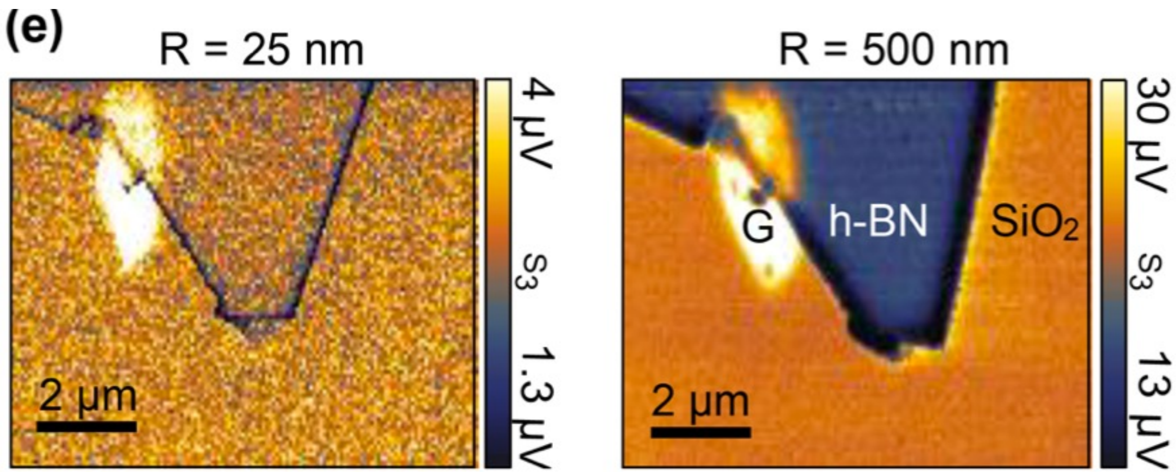
Metallic Bow-tie antenna



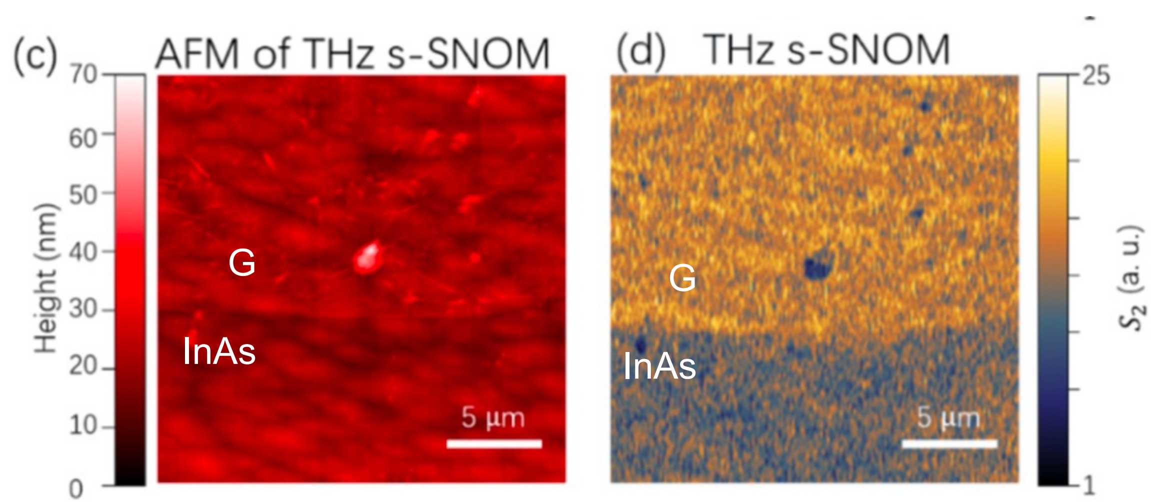
Mueckstein *et al.*,
J.of IRMMW 32, 1031 (2011)

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

THz s-SNOM Imaging of Graphene

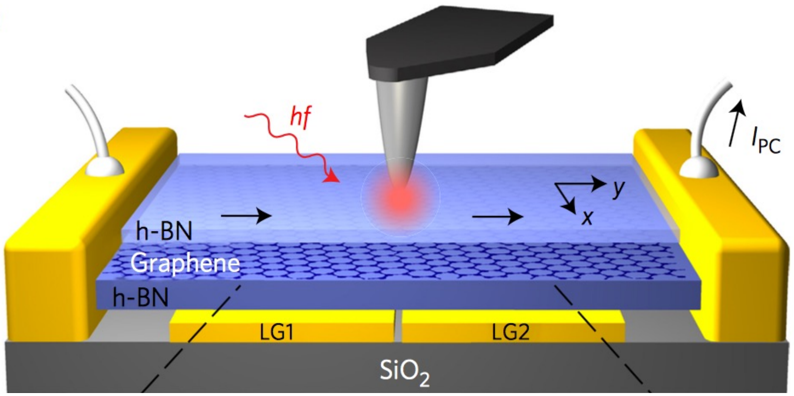


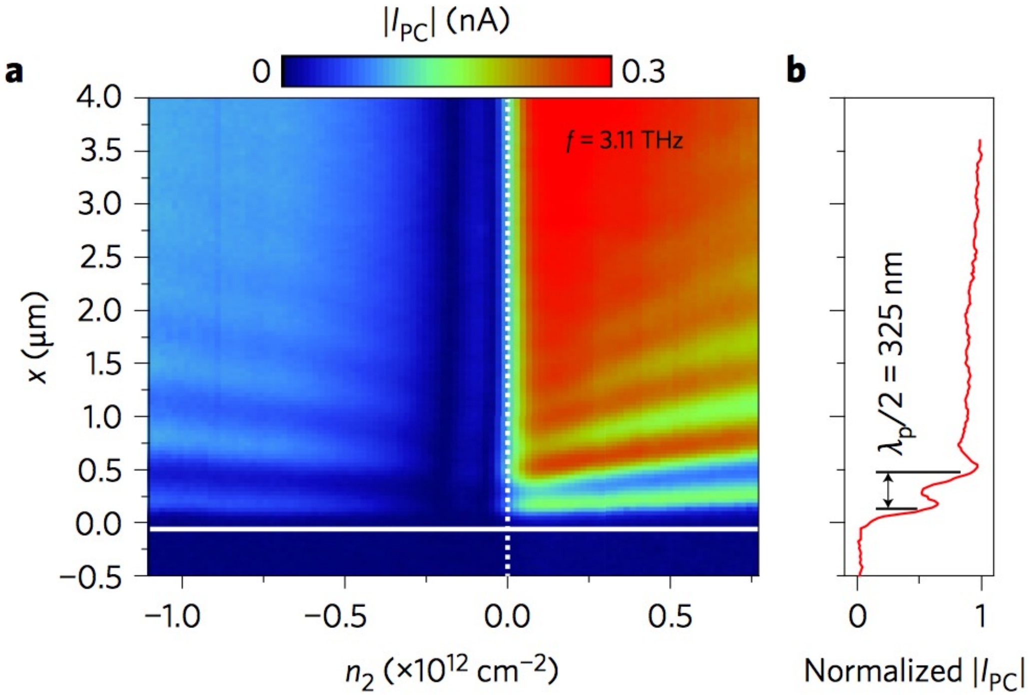
C. Maissen et al.,
ACS Photonics 6, 1279 (2019)



Z. Yao et al.,
OpEx 27, 13611 (2019)

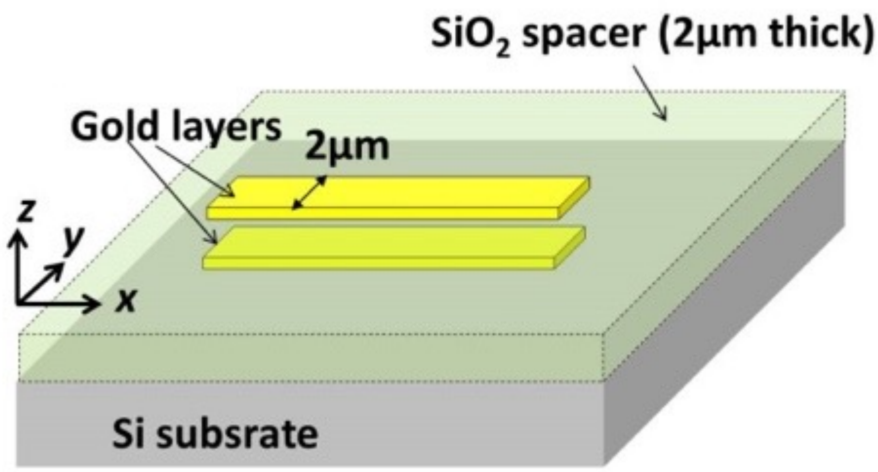
THz Surface Plasmon Waves – Acoustic Modes

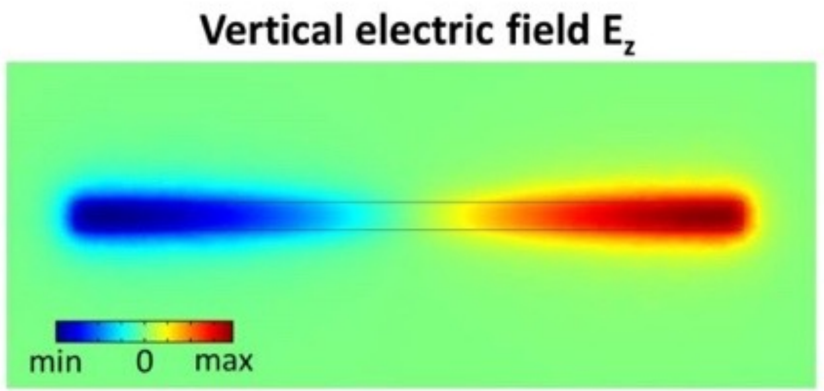


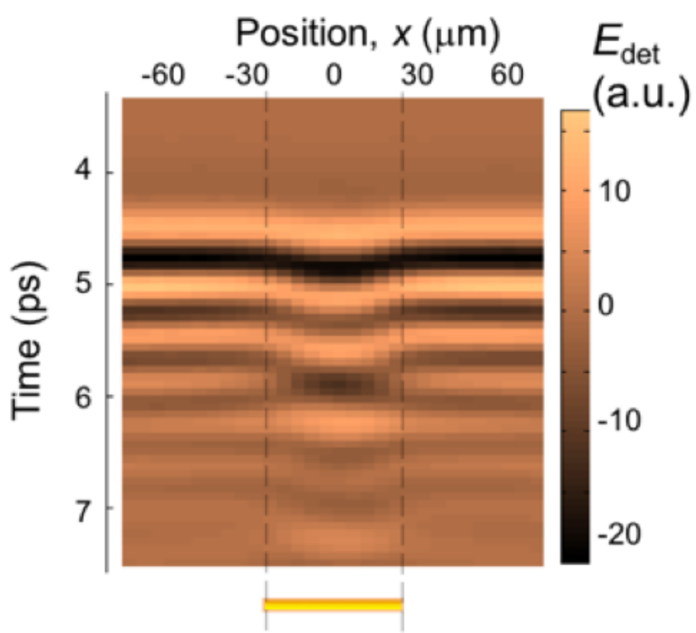


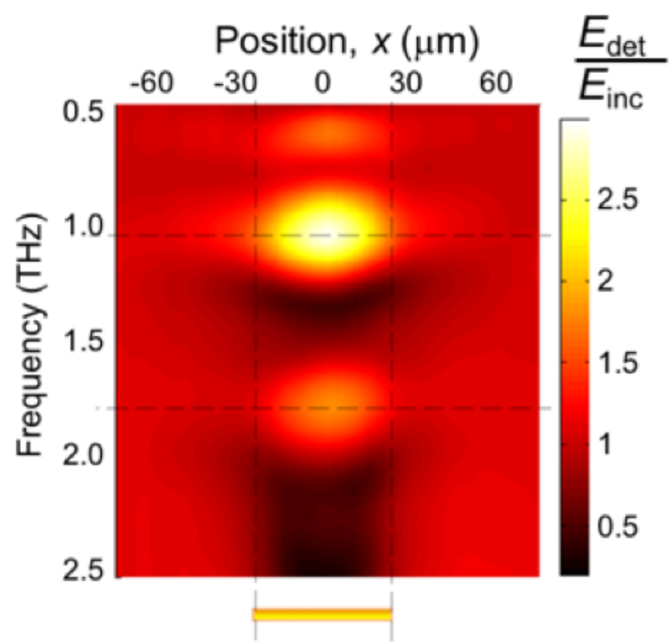
Alonso-Gonzalez et al. (2017)

Subwavelength Metallic Resonators



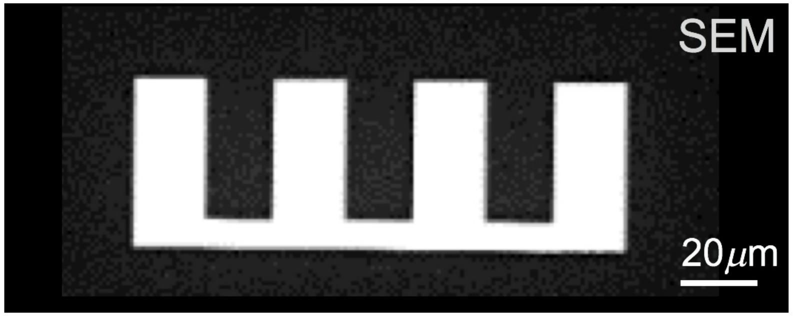


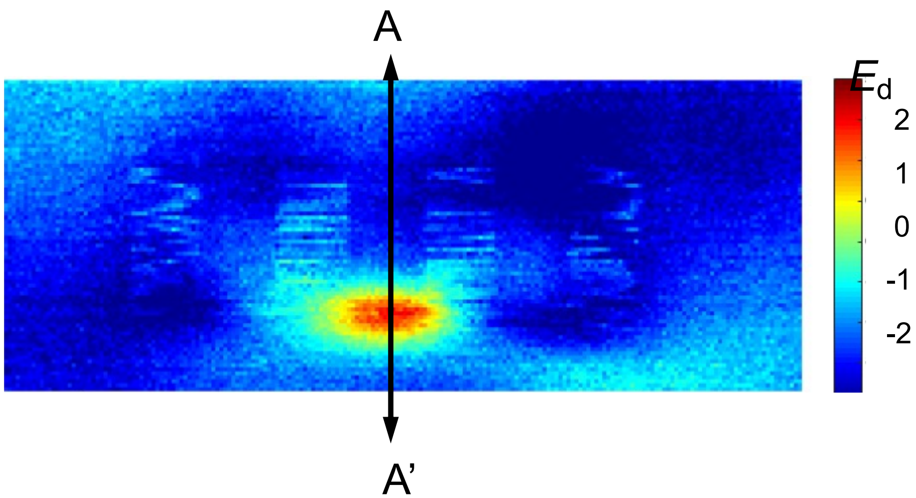


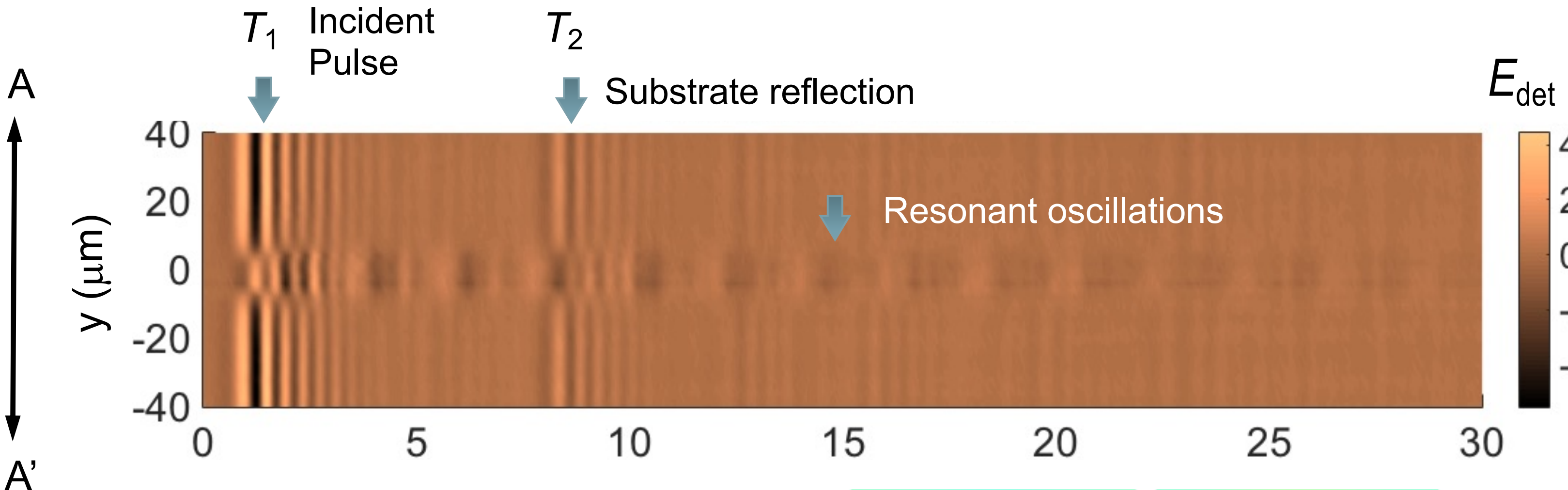


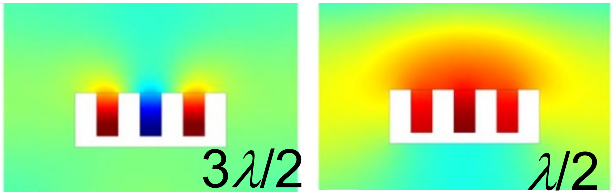
Mitrofanov, Todorov, et al., *Optics Express 26 (6), 7437* (*2018*)

Subwavelength Metallic Resonators



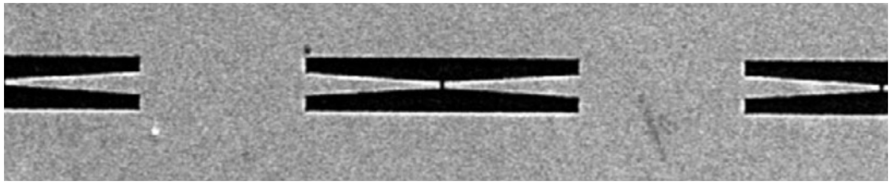


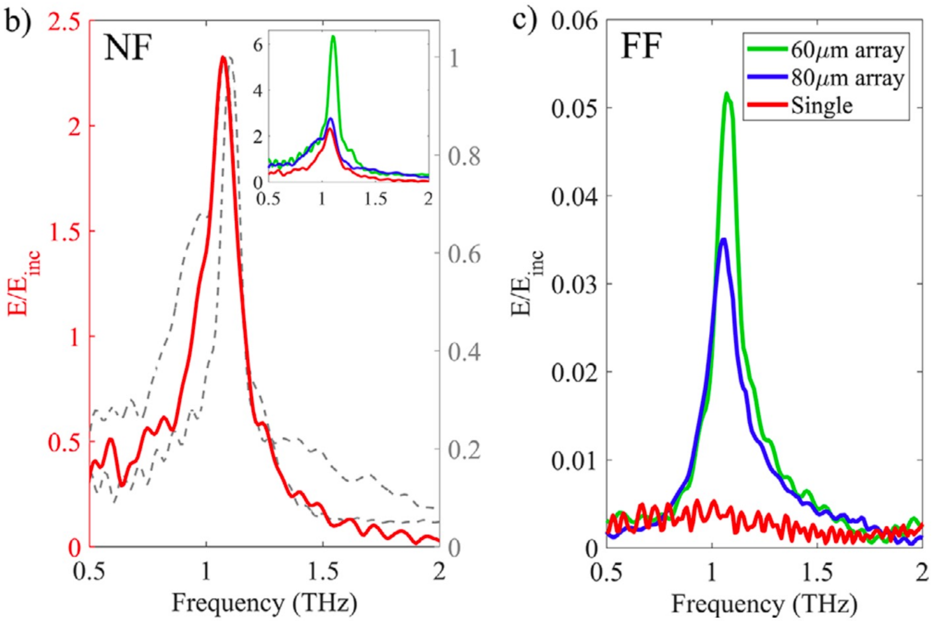


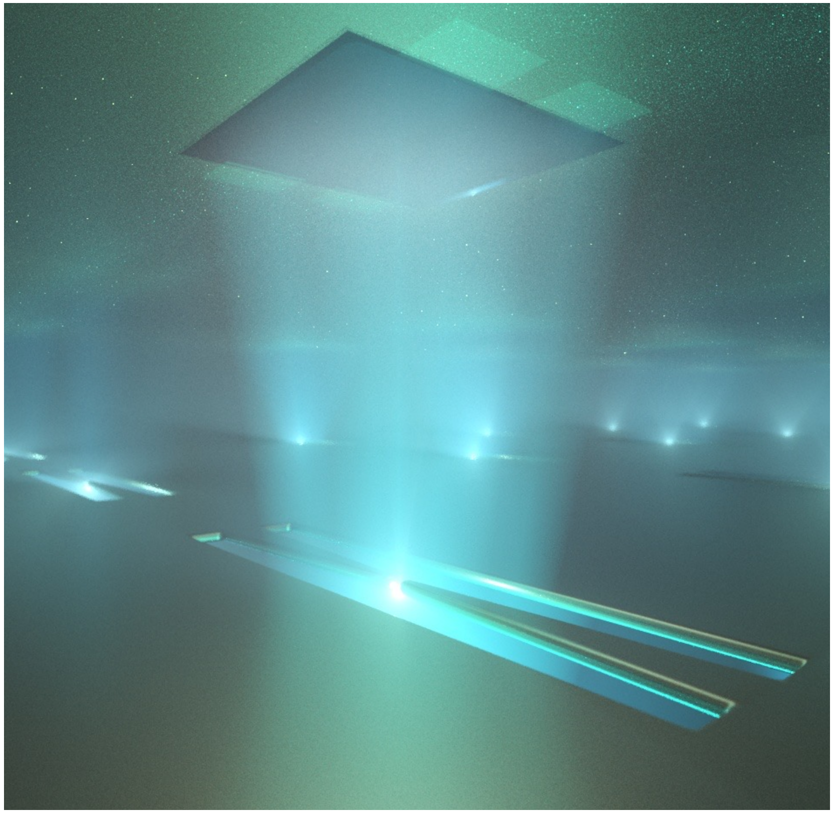


OM et al., *Appl. Phys. Lett.* 110 (6), 061109 (2017)

Single Resonator Sensitivity

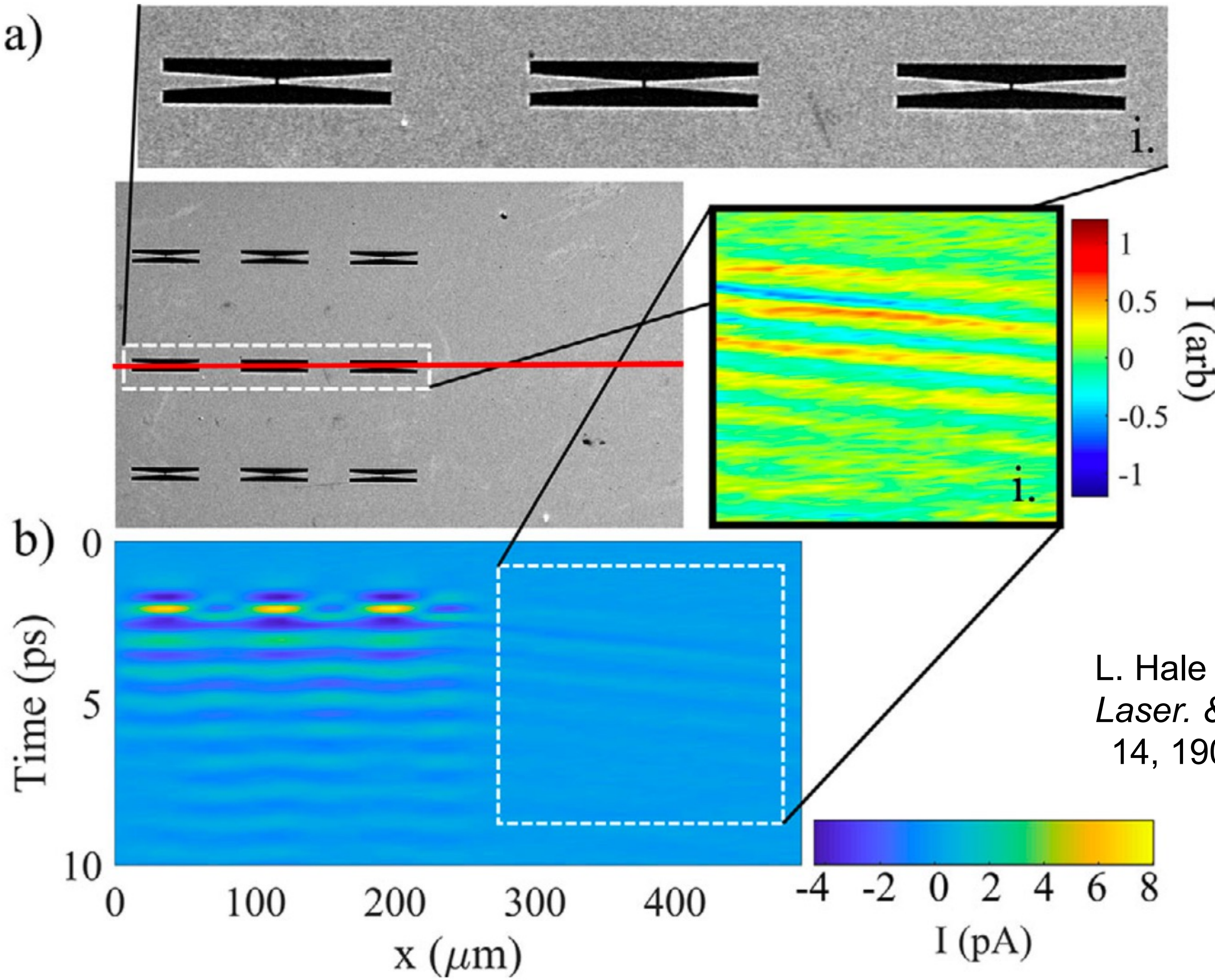






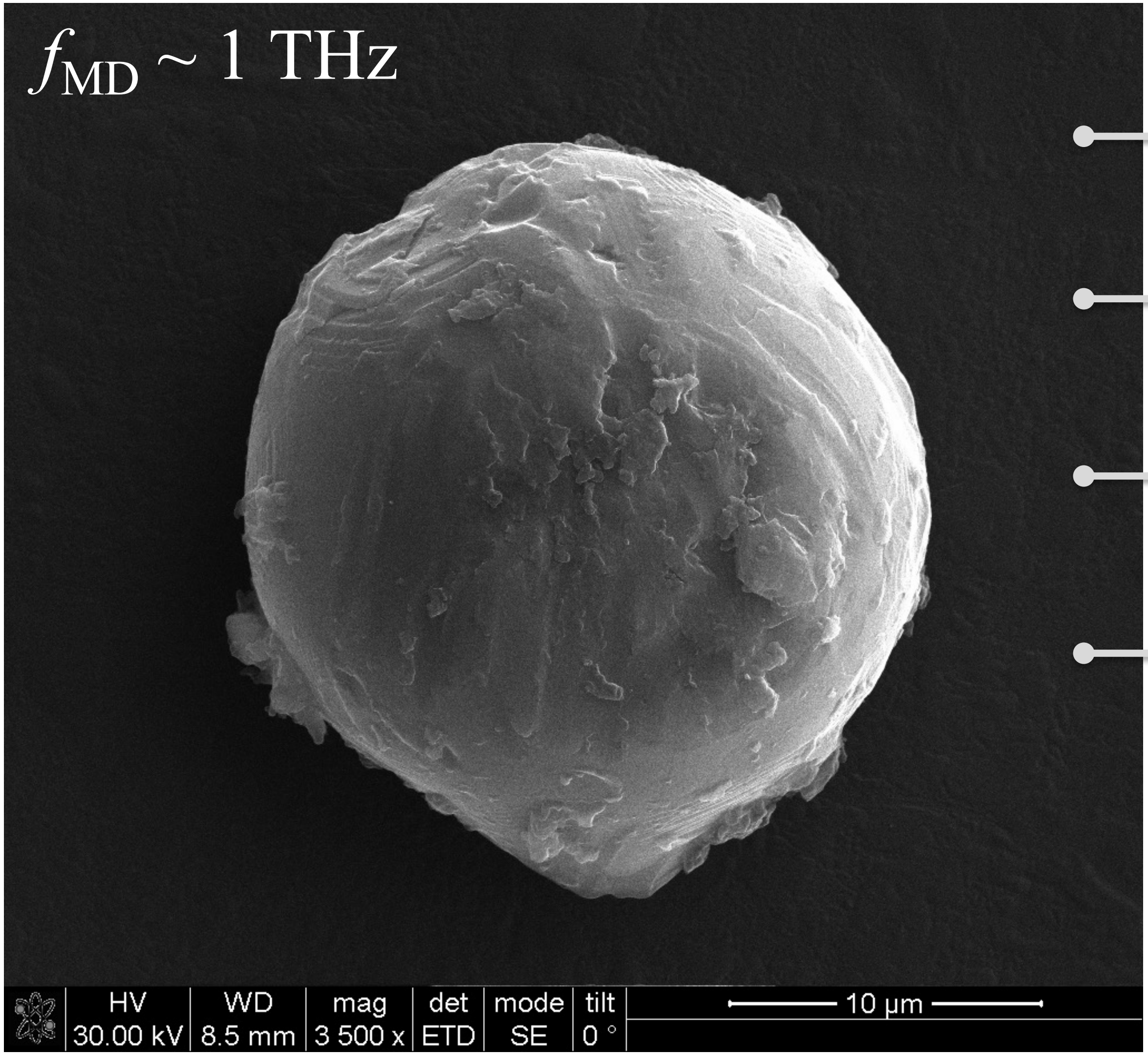
L. Hale *et al.*,
Laser. & Photon. Rev. 14 (4), 1900254 (2020)
(*illustration: T. Siday*)

Single Resonator Sensitivity



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

Dielectric Resonators



$\varepsilon \sim 70 - 150$

$d \sim \lambda/10$

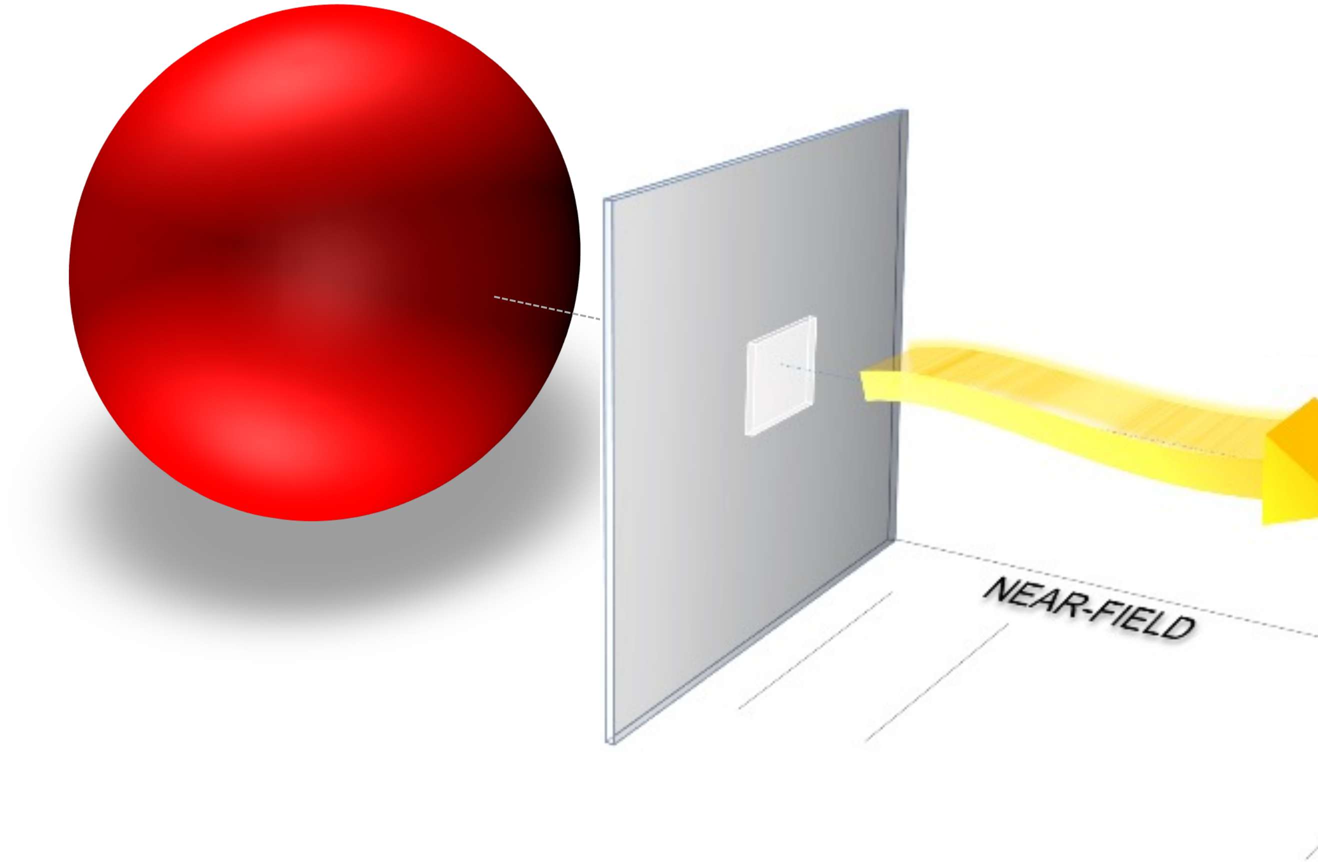
$\varepsilon_o, \varepsilon_e$ – ?

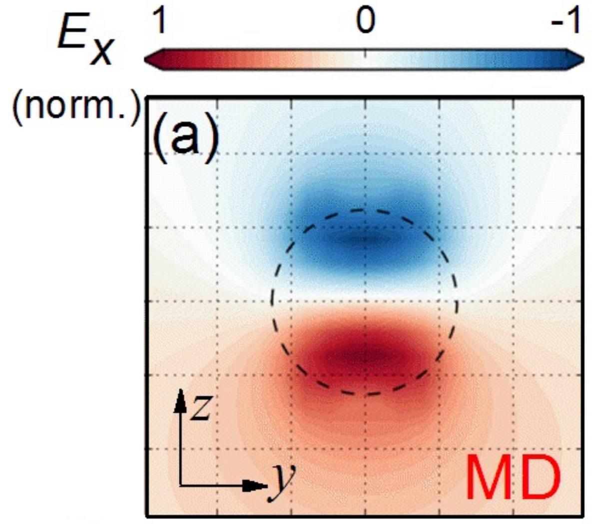
$Im(\varepsilon)$ – ?

Can NF microscopy probe such resonators?

TiO_2 microsphere:
~20 μm diameter

High EM field confinement by a dielectric object

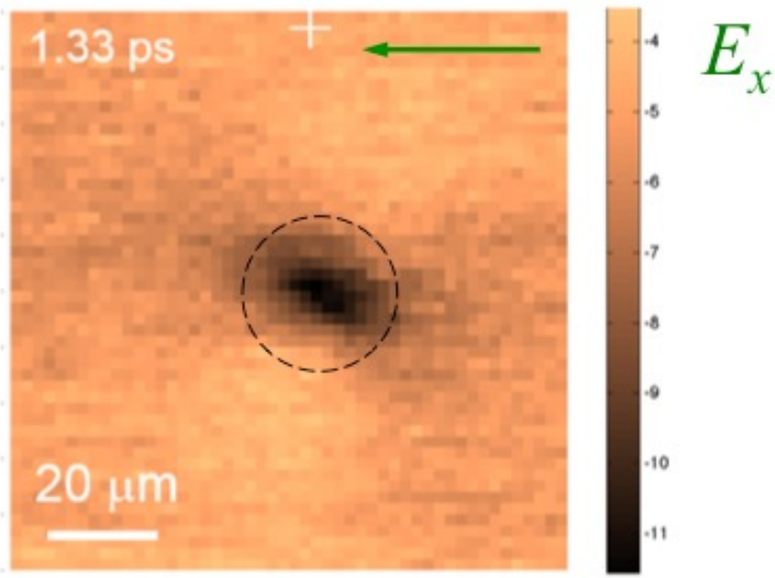


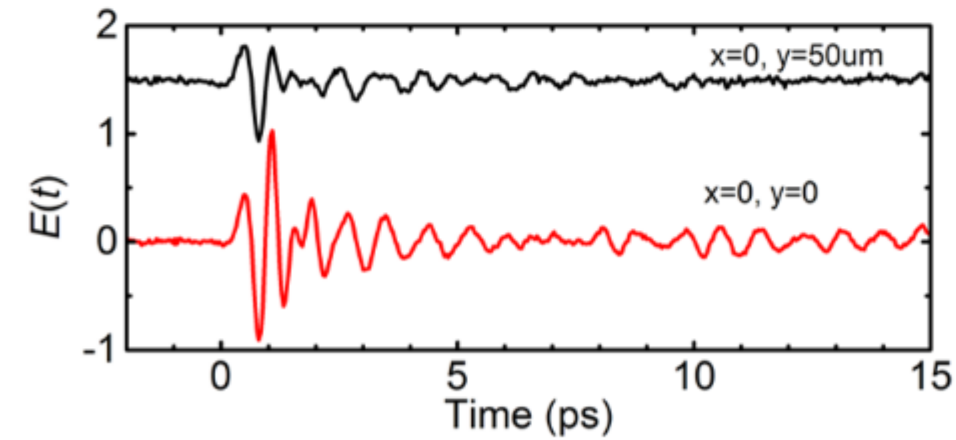


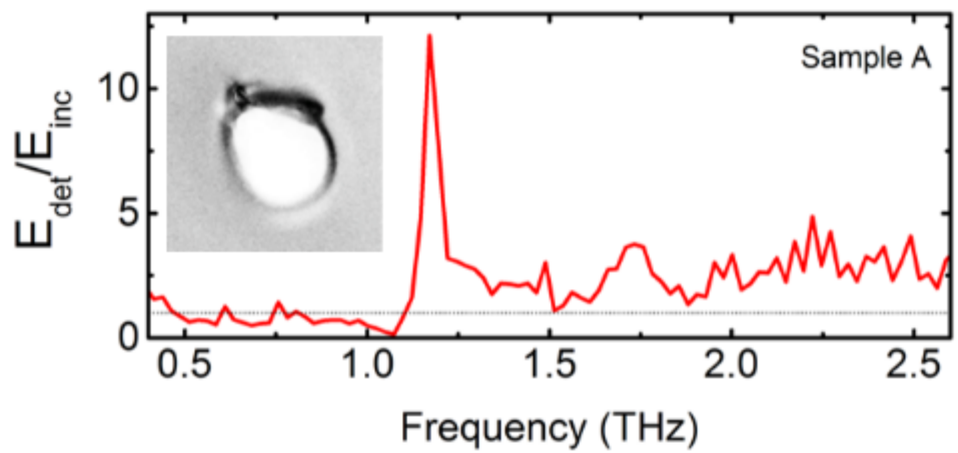
Enhanced transmission through aperture can be used to probe high-ε resonators

OM et al., *Optics Express*, 22, 23034 (2014)

Mie resonances in isotropic TiO_2 spheres

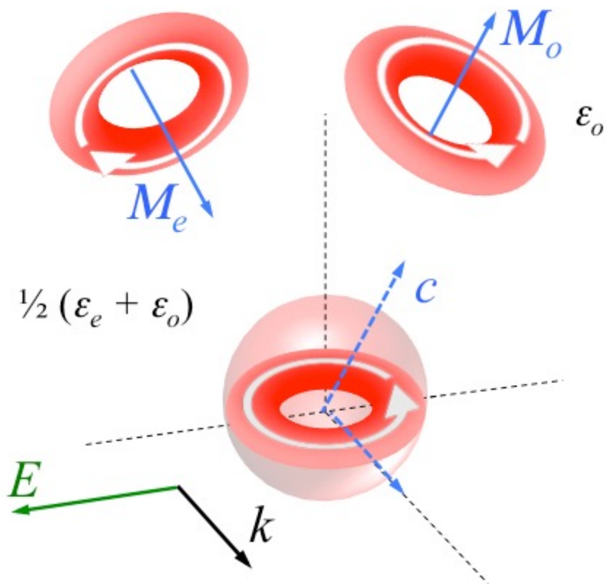


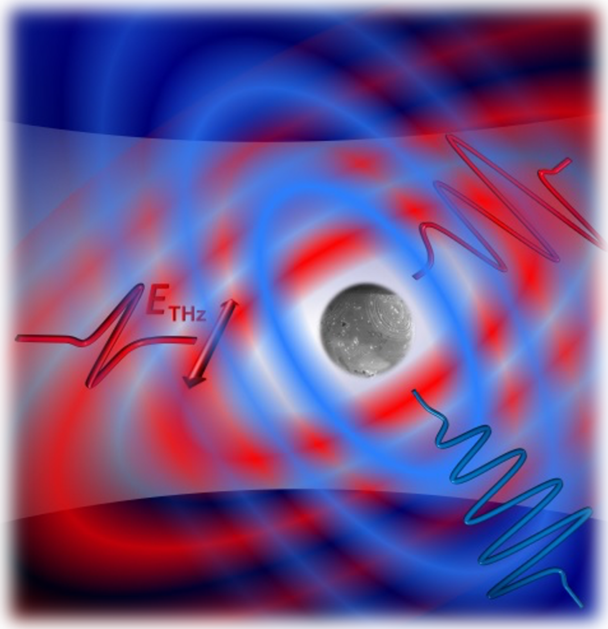


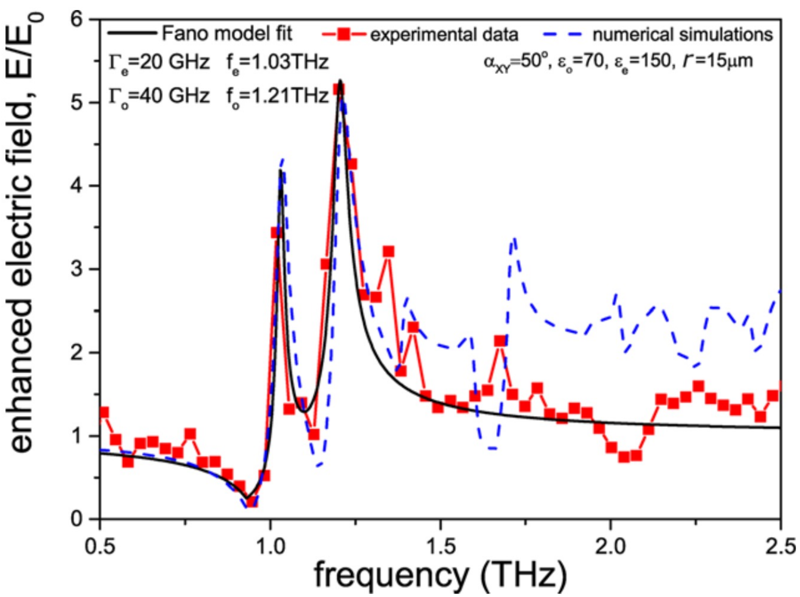


OM et al., *Optics Express*, 22, 23034 (2014)

Anisotropic Dielectric THz Resonators:

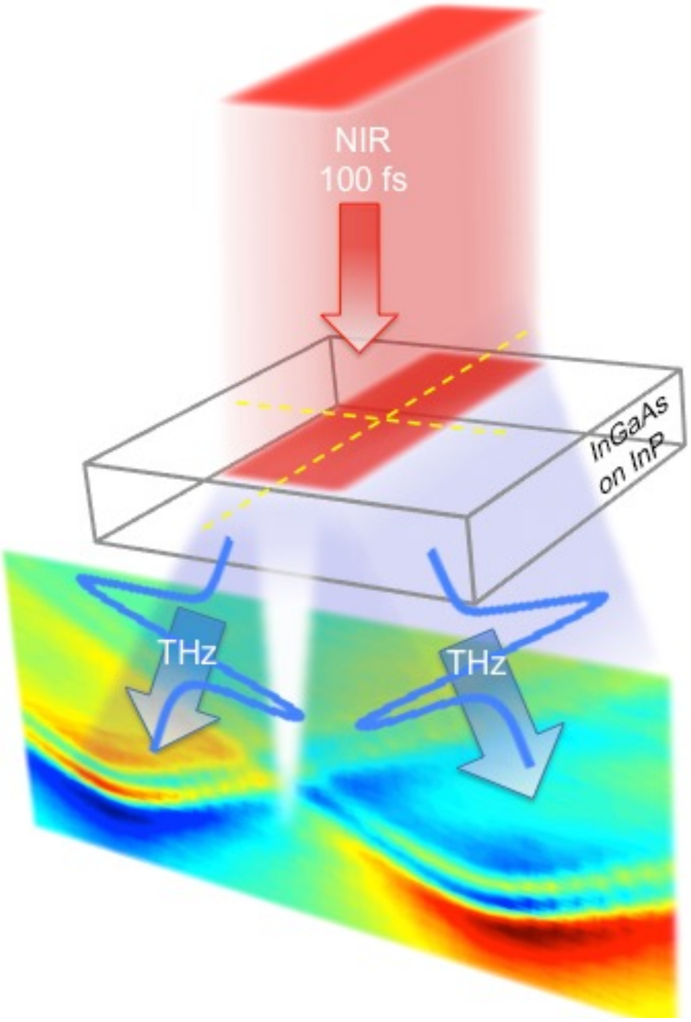




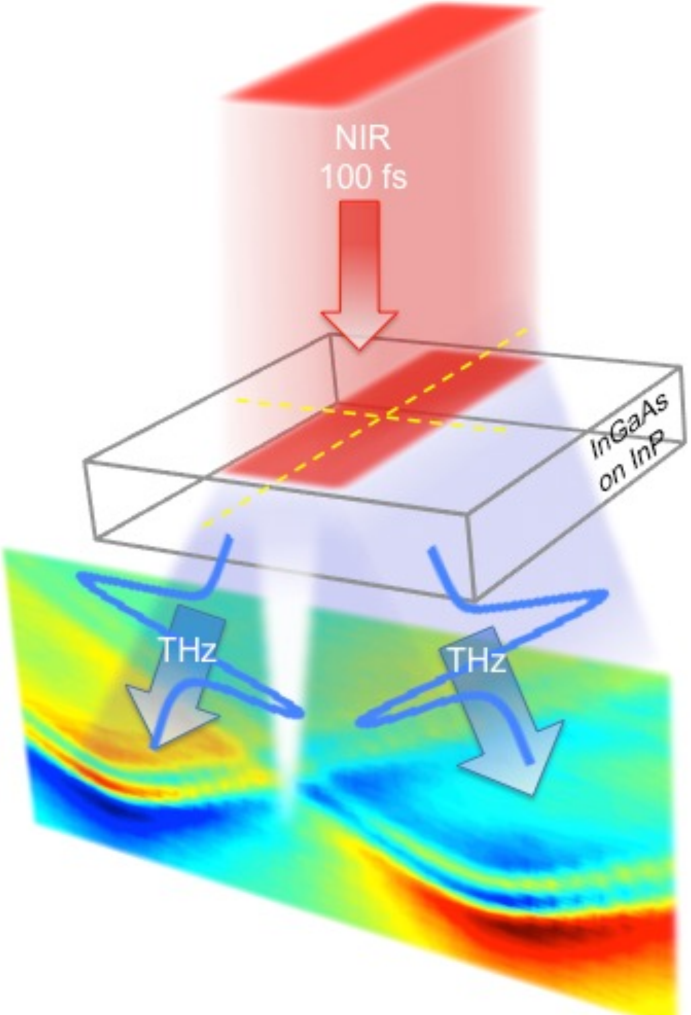


I. Khromova, et al.,
Laser & Photon. Rev. 10 (4), 681 *(2016)*

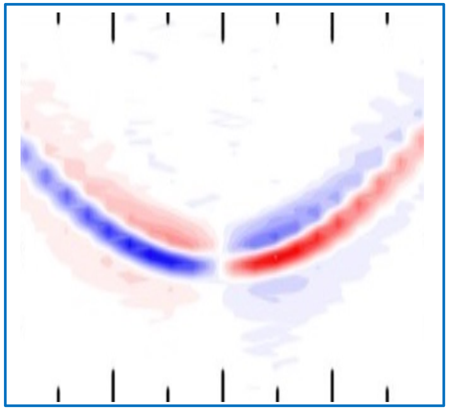
Near-field Mapping of THz Emission



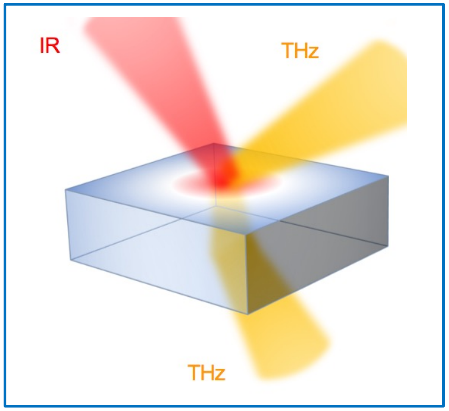
Near-field Mapping of THz Emission



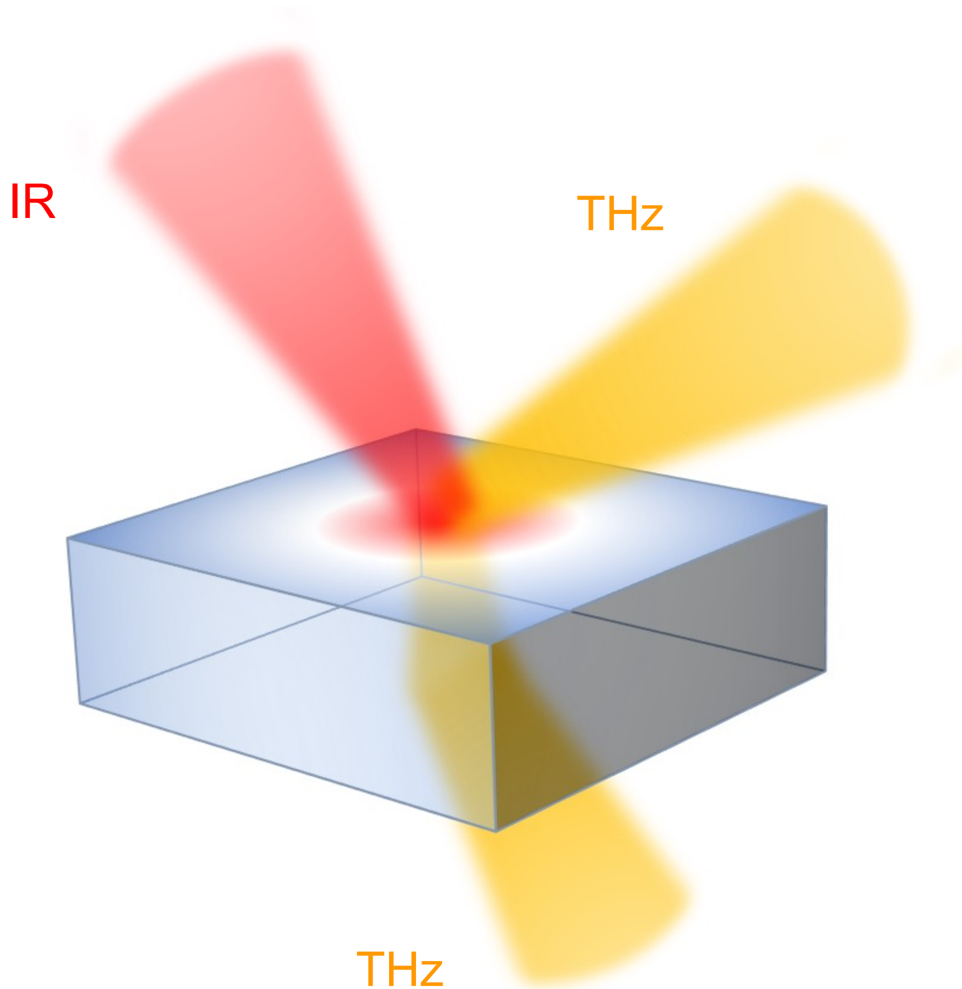
Engineering



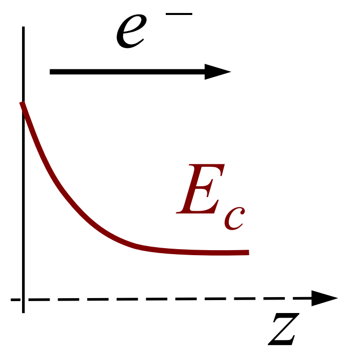
Physics



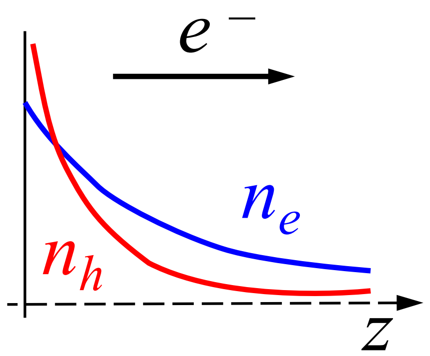
Sci. Rep. 6, 38926 (2016)



Built-in surface field



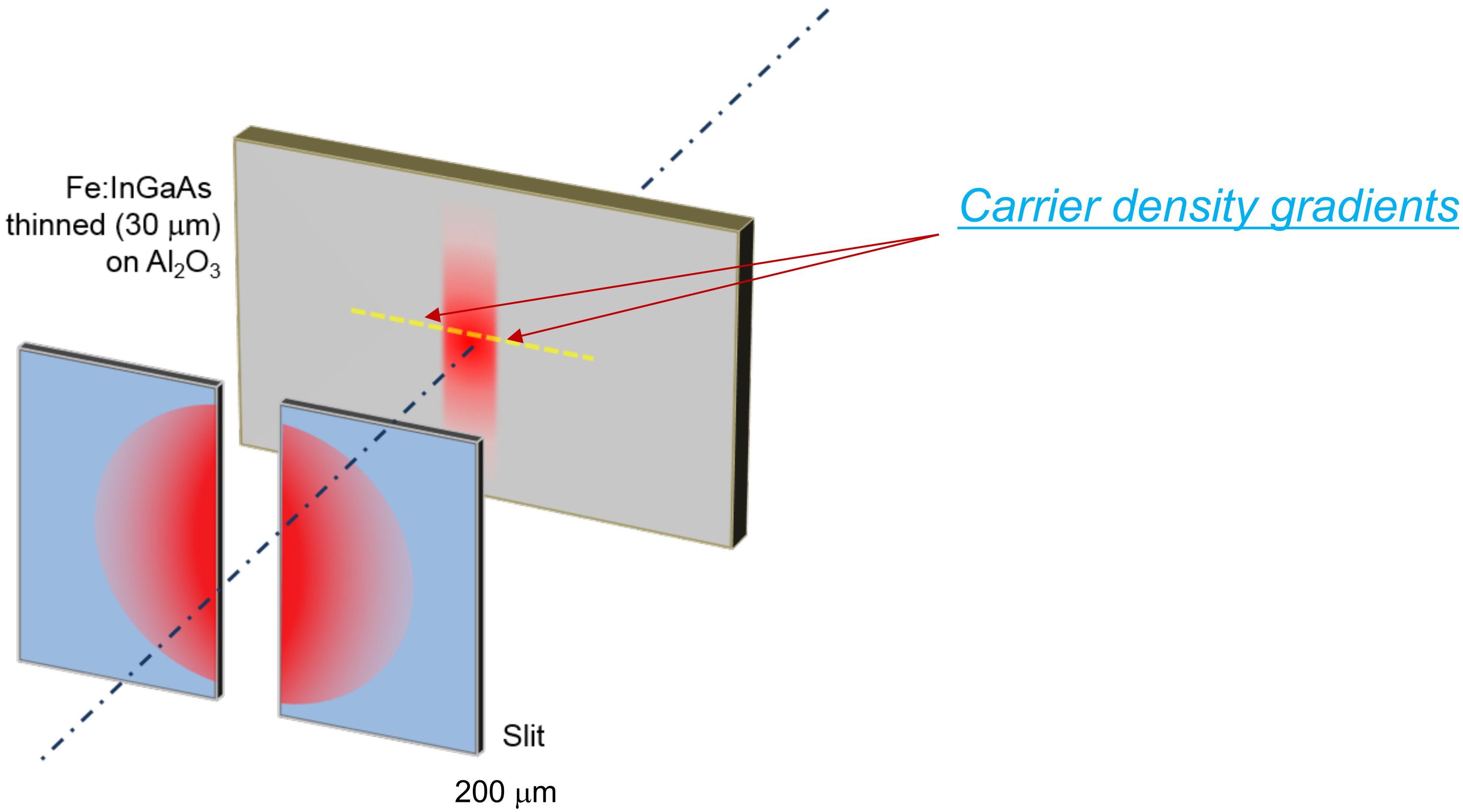
Carrier density gradient



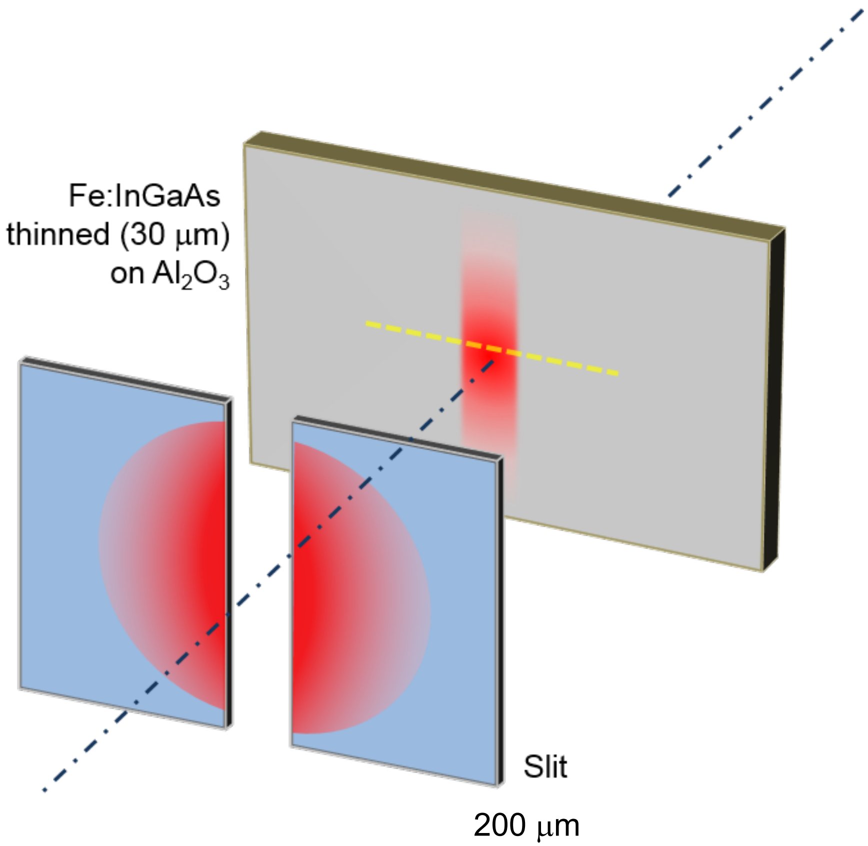
Bulk Optical Rectification

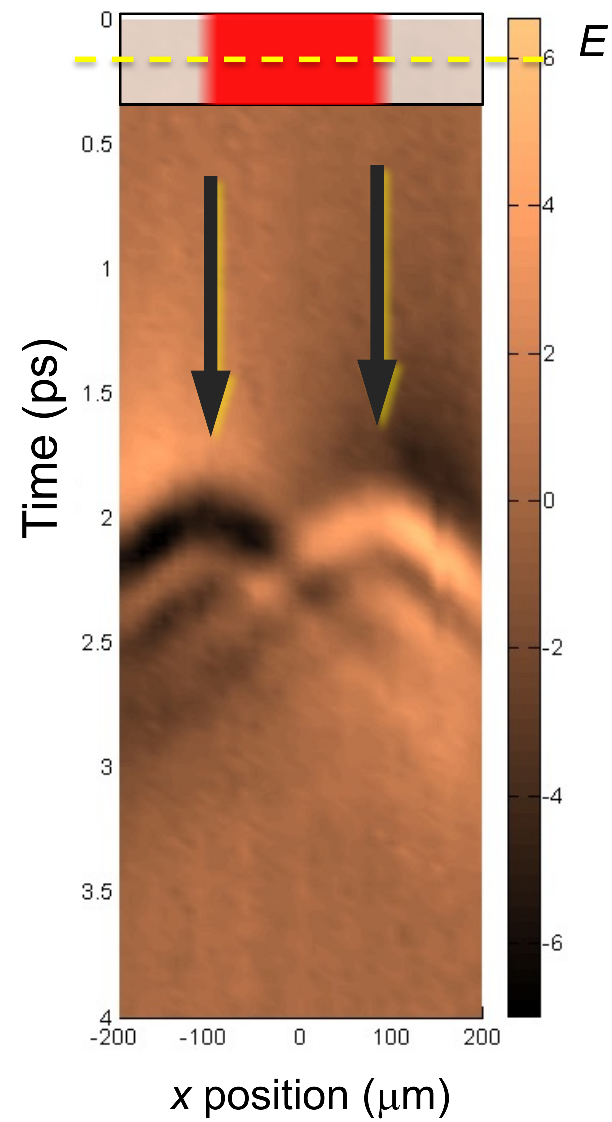
Surface Optical Rectification

THz Emission for Normal Incidence Photoexcitation



Spatial and Temporal Mapping of THz Emission

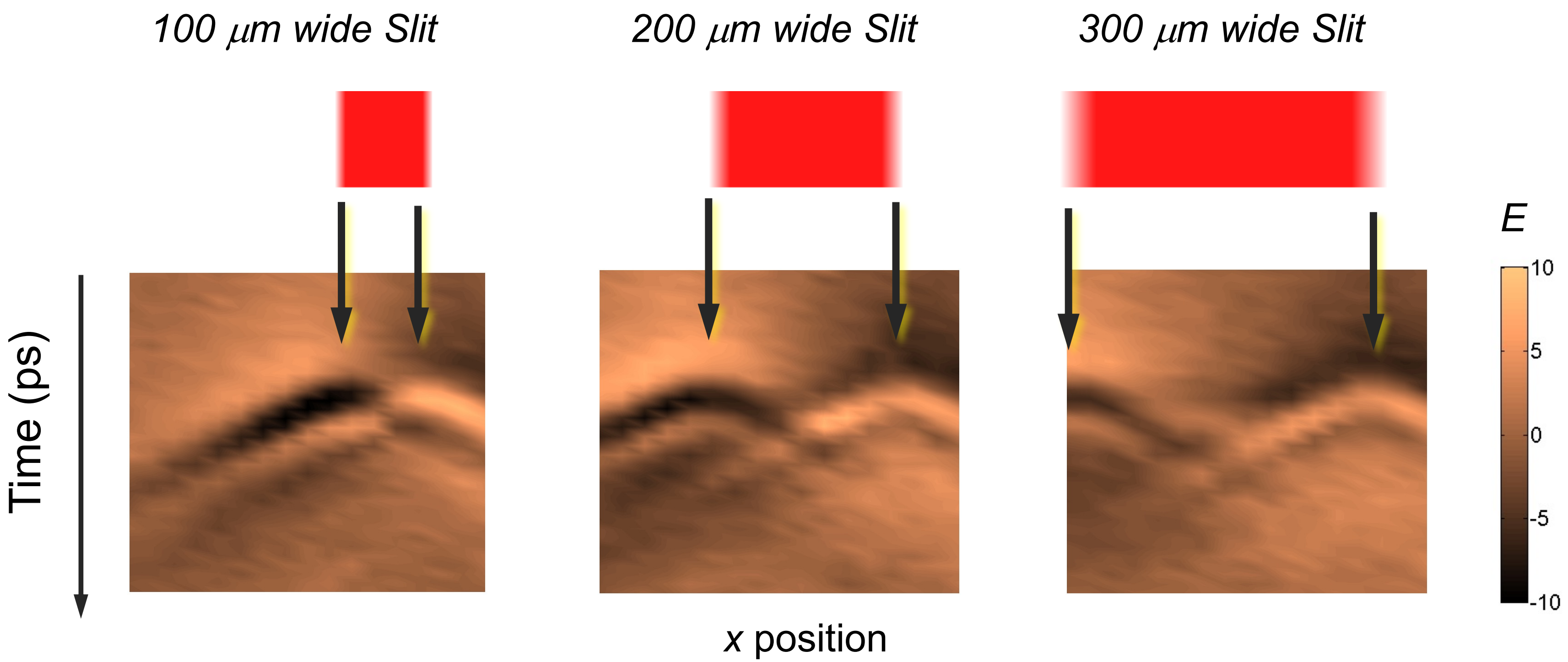




THz emission originates from two distinct points corresponding to the Slit Edges.

Mueckstein *et al.*
THz Sci. and Technology, IEEE Trans. 5 (2), 260 (2015)

Emission due to Charge Density Gradient

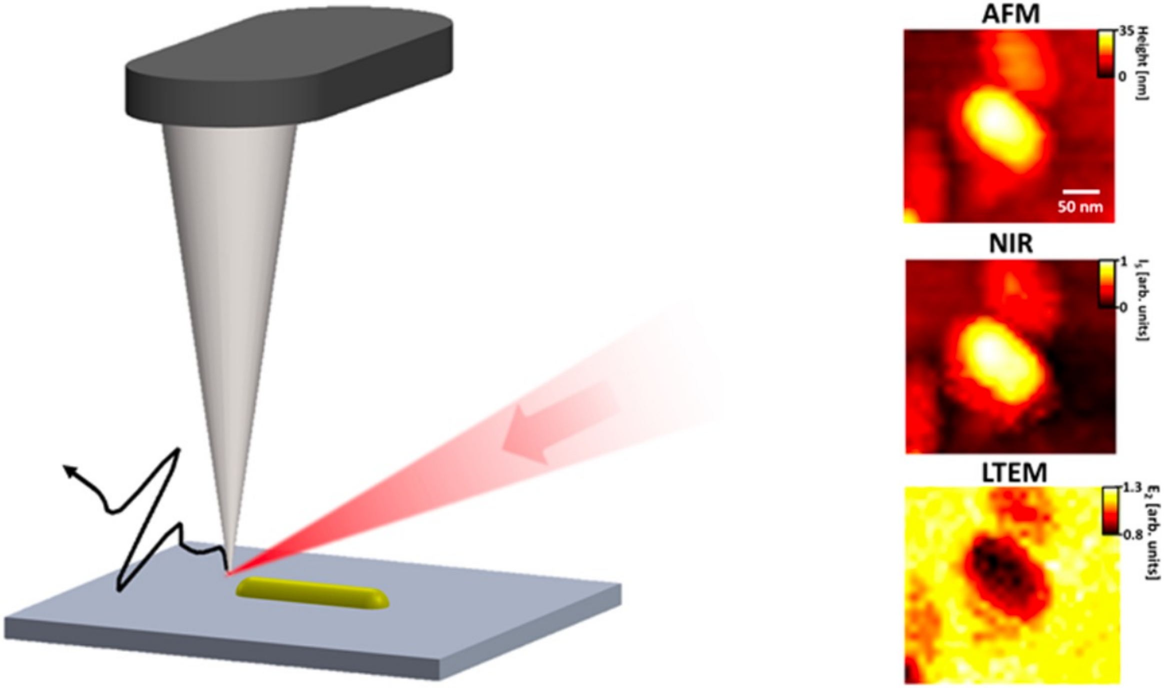


THz emission originates from two distinct points corresponding to the Slit Edges.

No emission from uniformly illuminated region of the semiconductor

Mueckstein *et al.*
THz Sci. and Technology, IEEE Trans. 5 (2), 260 (2015)

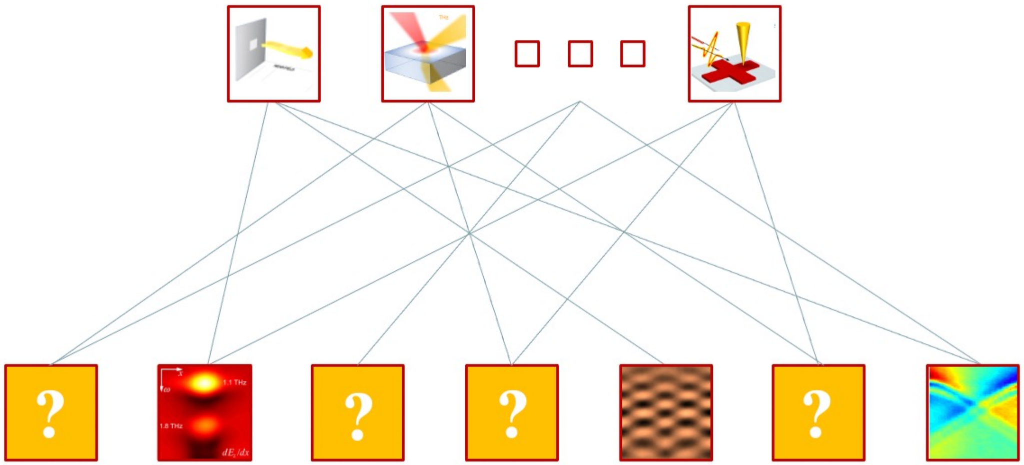
Nanoscale Mapping of THz Emission



P. Klarskov *et al. ACS Photonics* 4, 2676 (2017)

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.

After over 20 years, THz Near-Field Microscopy research
is just warming up, there is still so much to explore.

Acknowledgement

UCL

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.)

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