Terahertz near-field microscopy: Science, Technology, and Insights

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IRMMW-THz 2017
42nd International Conference on Infrared, Millimeter and Terahertz Waves
27 AUGUST - 1 SEPTEMBER 2017 | Cancún, México

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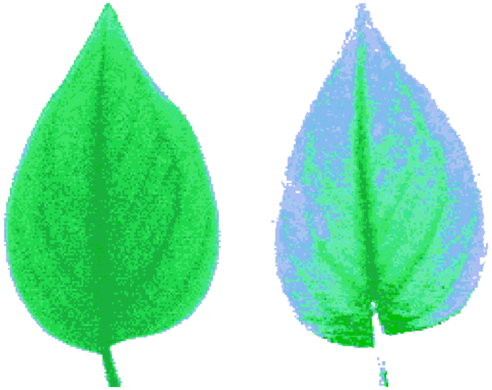
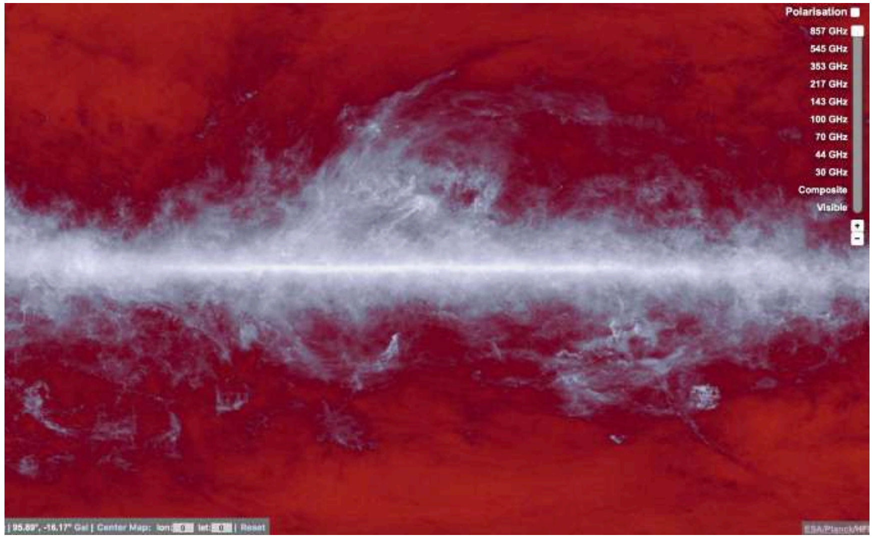
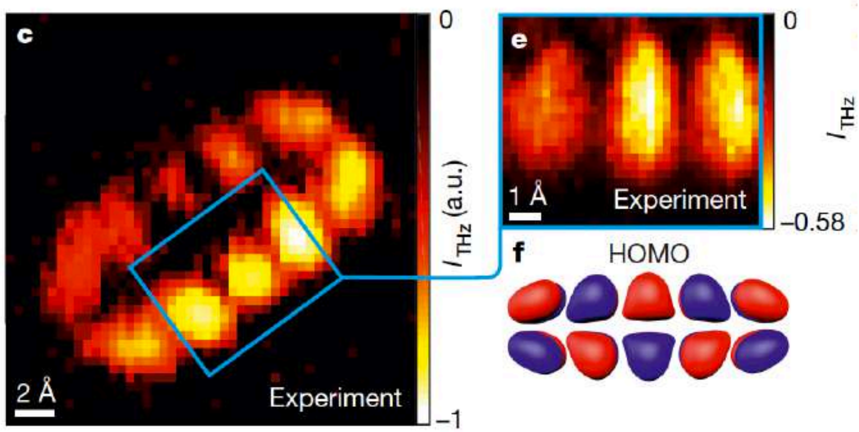
Terahertz Imaging



Hu and Nuss (1995)



Cosmic Microwave Background Map @ 0.857THz ESA/Plank (2015)



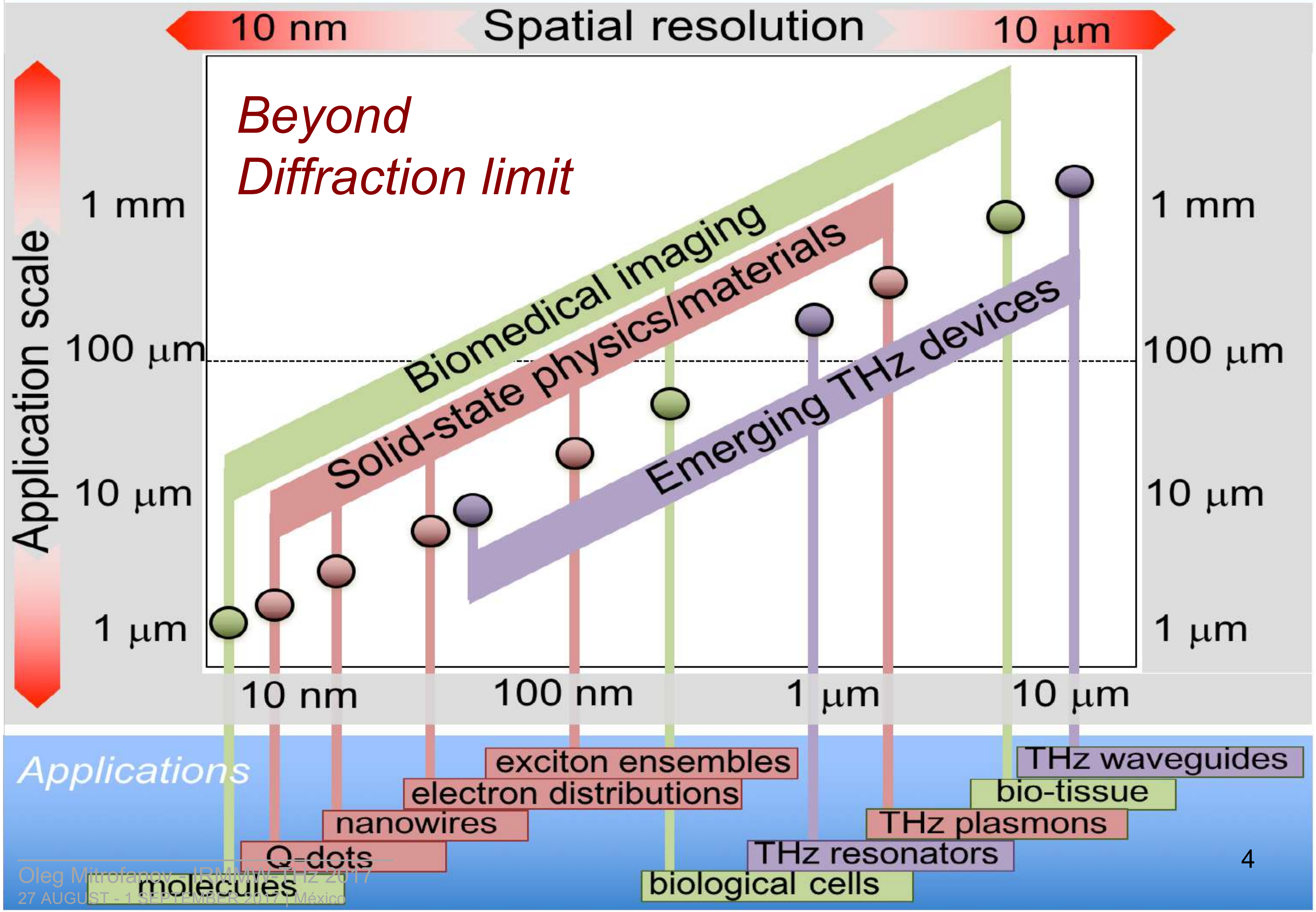
T. Cocker, D. Peller, P. Yu, J. Repp & R. Huber, Nature (2016)

Spatial Resolution Limit

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

Ernst Abbe (c. 1873)

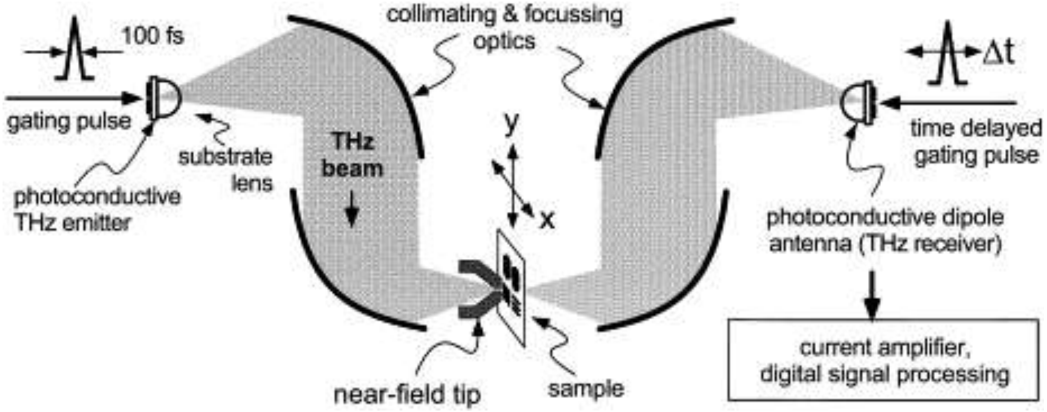
THz Near-field Imaging Technology and Applications

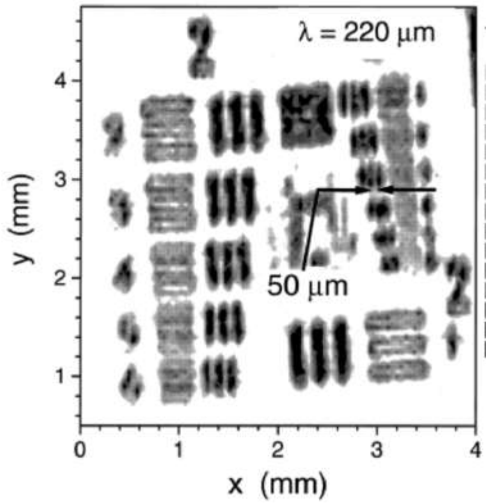


Breaking the diffraction limit in the THz range

$$\frac{\lambda}{r} = 1 - 100{,}000$$

Early development of THz microscopes

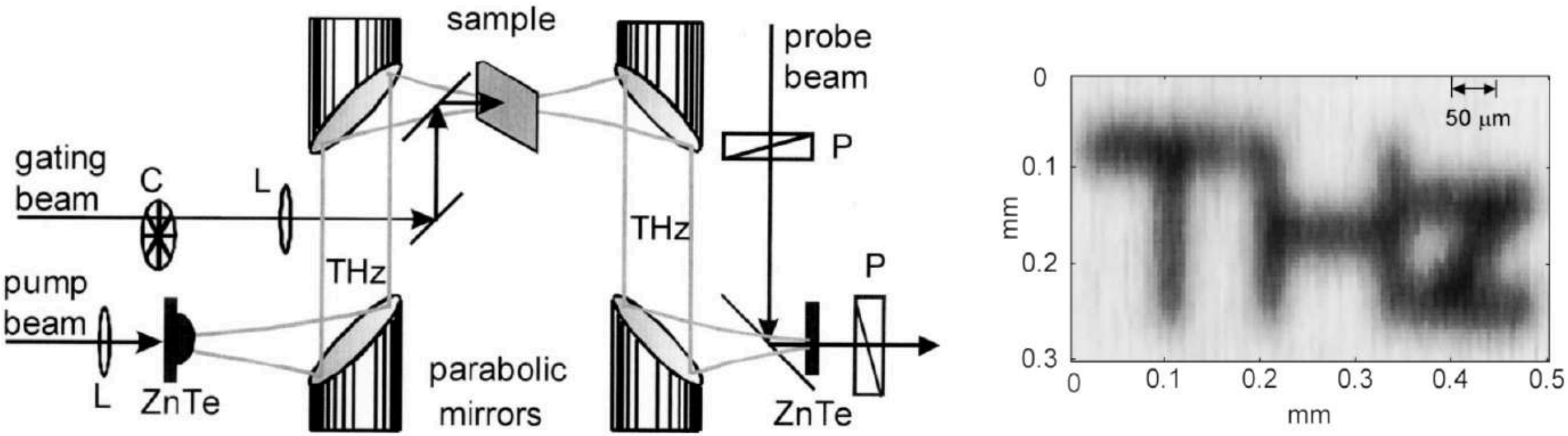




Hunsche et al. *OPTICS COMM* (1998)

Early development of THz microscopes

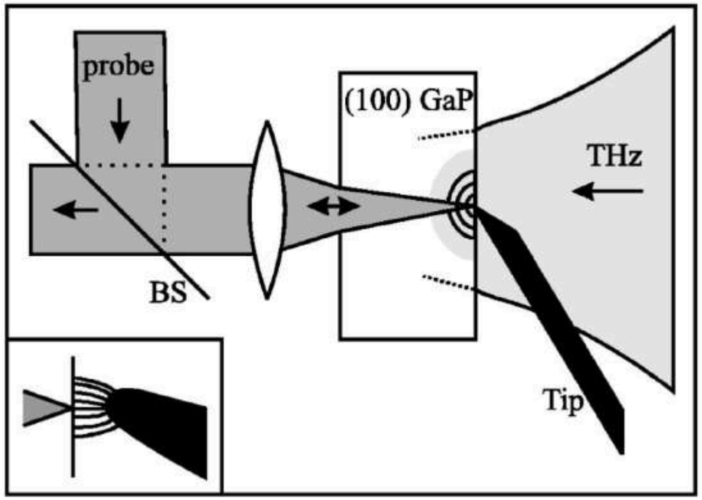
Near-field THz source modulation - 'Dynamic Aperture' (THz-TDS)



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

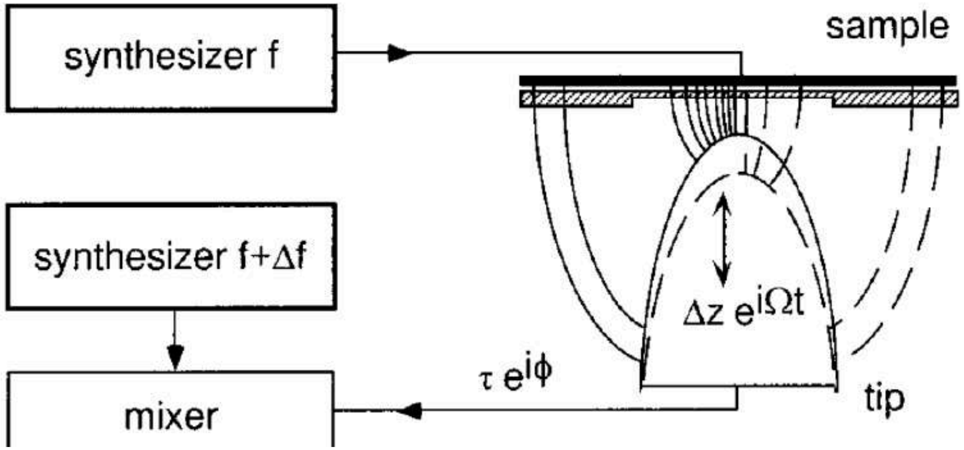
Early development of THz microscopes

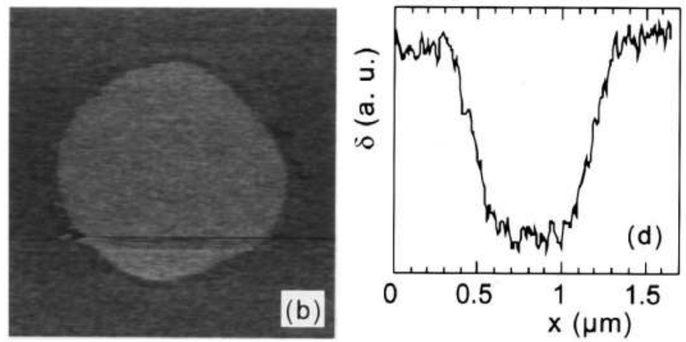
Electro-optic near-field probes (THz-TDS)



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

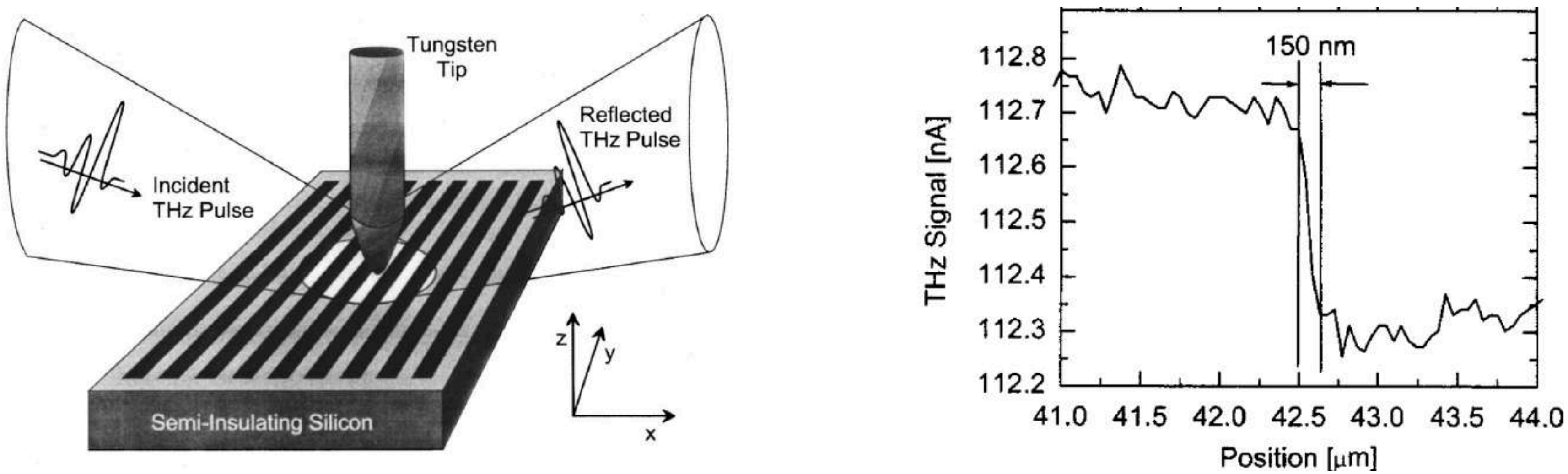
STM Tip - Microwave transmission (1 GHz)





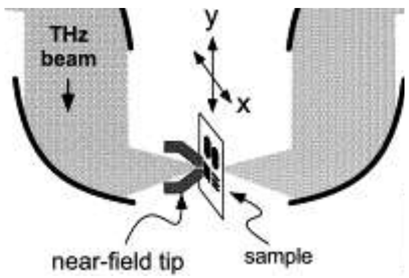
B. Knoll, F. Keilmann et al., APPL. PHYS. LETT. 70, 2667 (1997)

Scattering Tip near-field microscopy (THz-TDS)

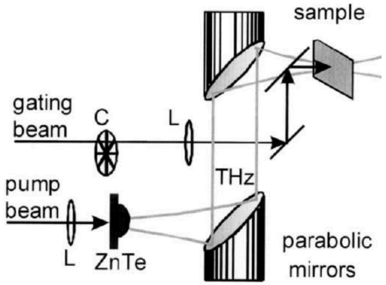


Chen et al., APPL. PHYS. LETT. 83, 3009 (2003)

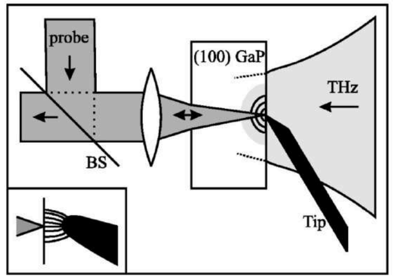
Progress in development of THz microscopy



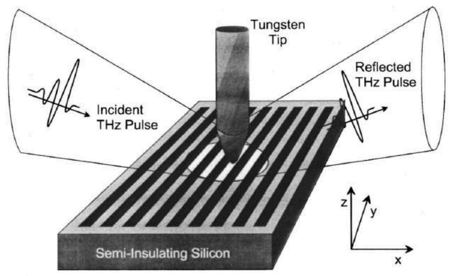
Hunsche et al., 1998



Chen et al., 2000



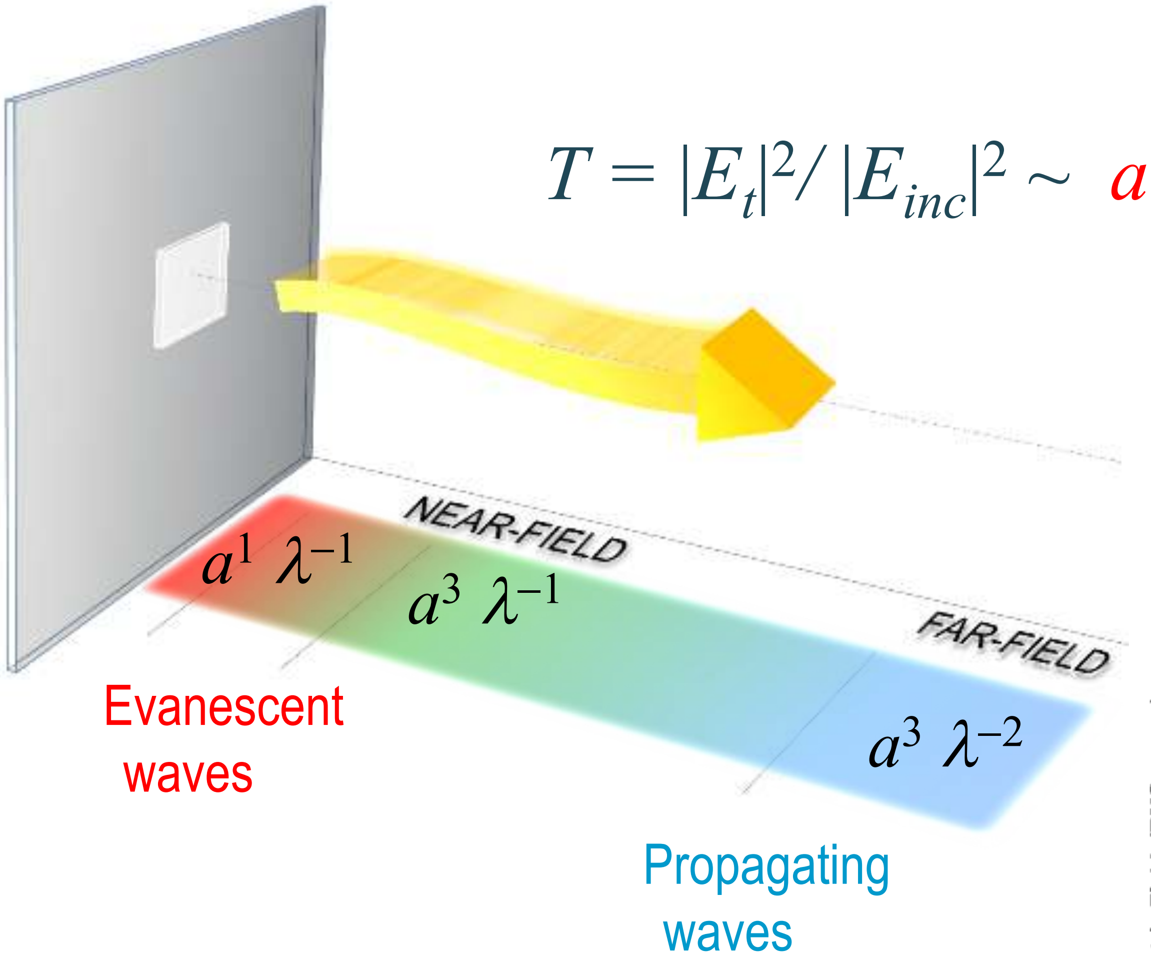
Van der Valk et al., 2002

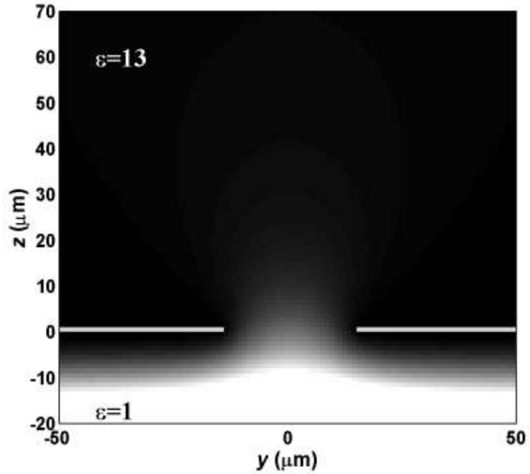


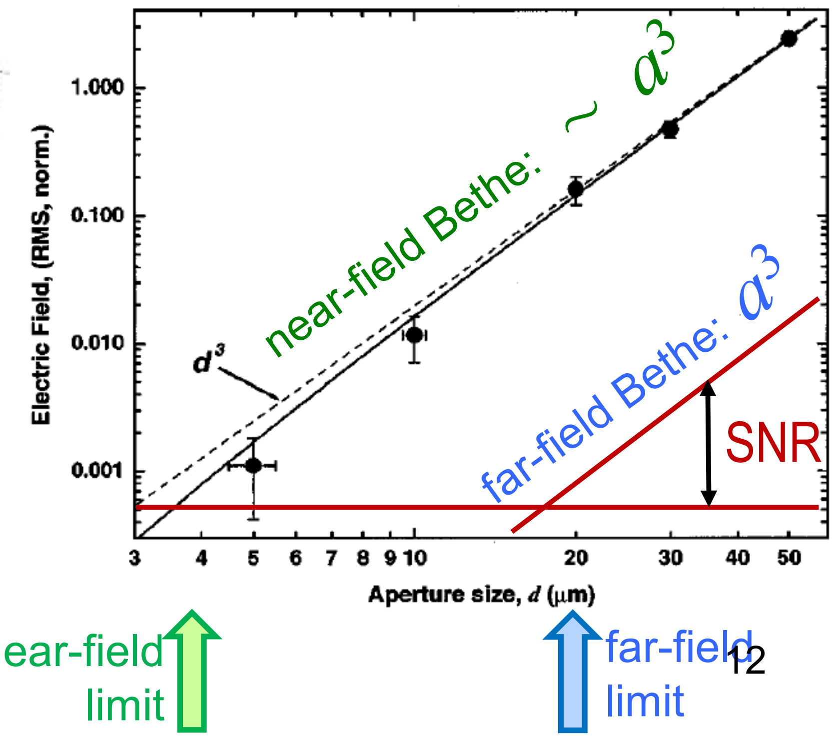
Chen et al., 2003

Wave transmission through subwavelength apertures

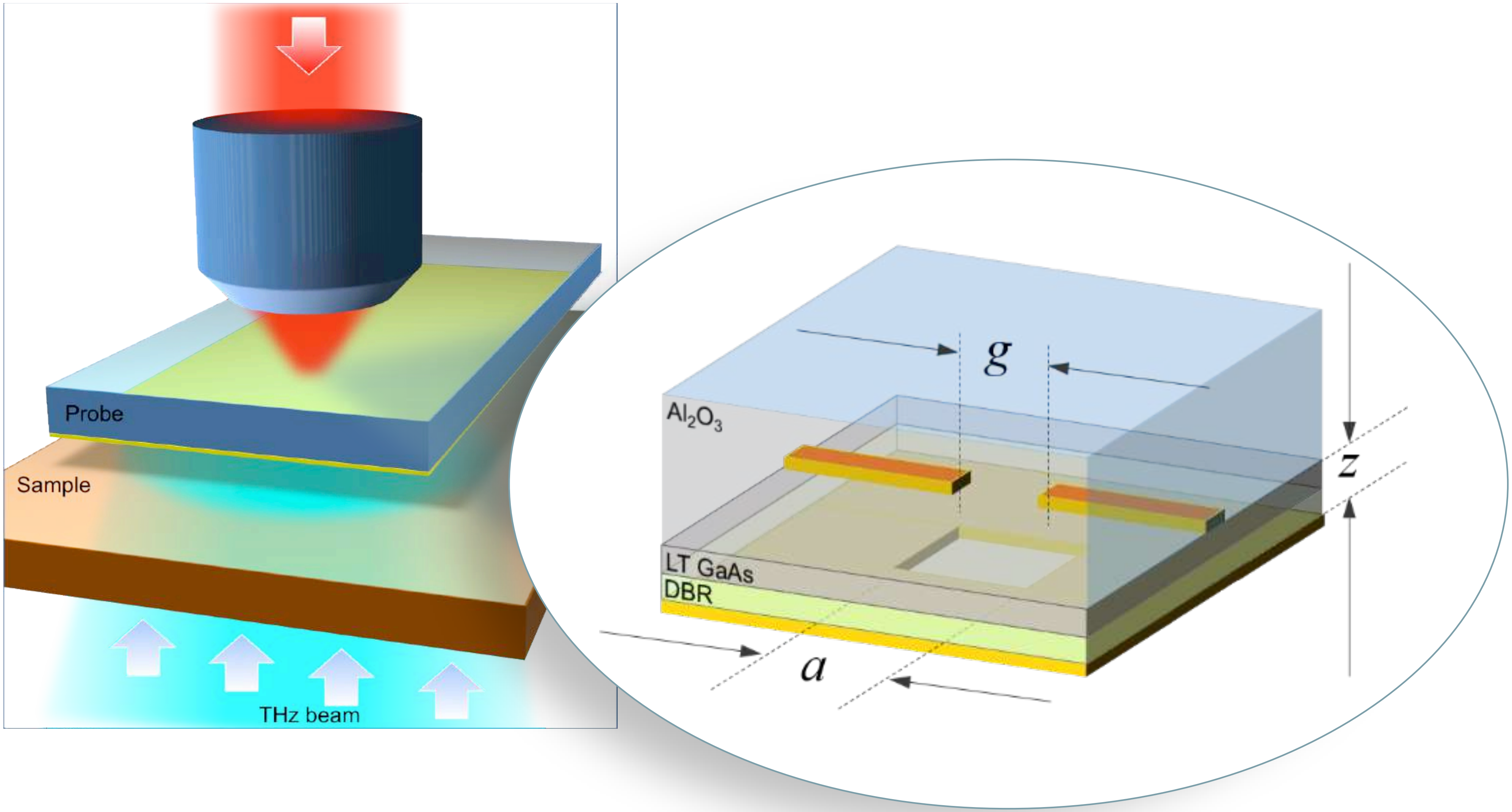
$$T = |E_t|^2 / |E_{inc}|^2 \sim a^6$$



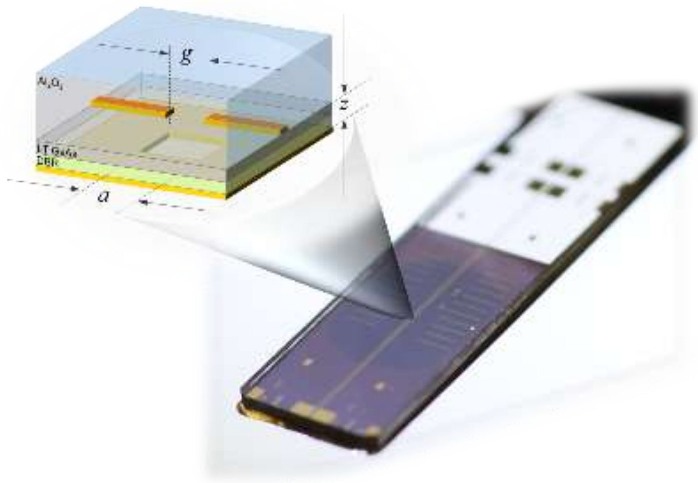


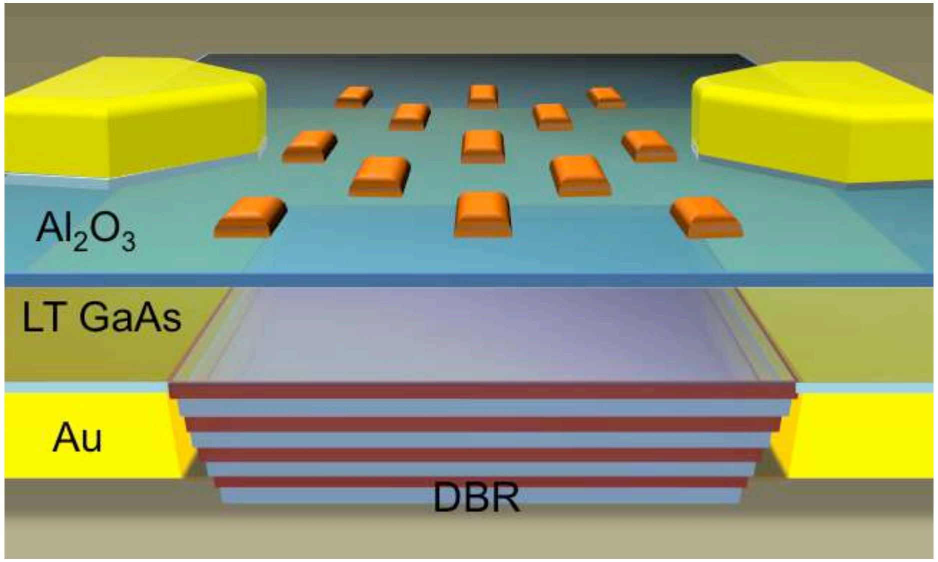


Mitrofanov et al.,
APL **77**, 3496 (2000), APL 79, 907 (2001)

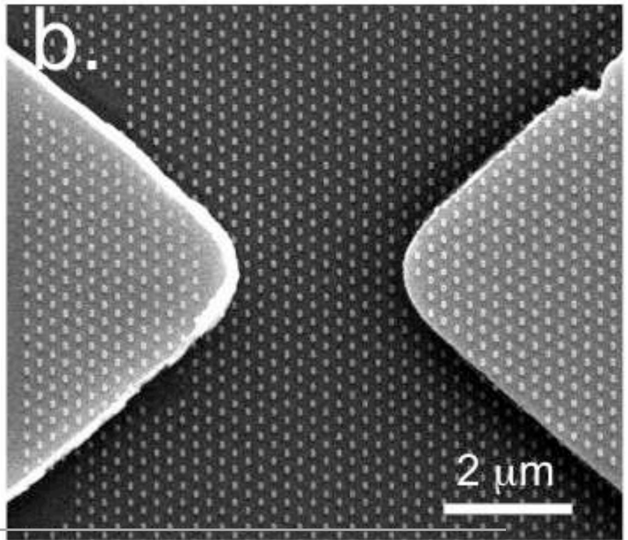

Probe
Sample
THz beam
g
Al_2O_3
z
LT GaAs
DBR
a

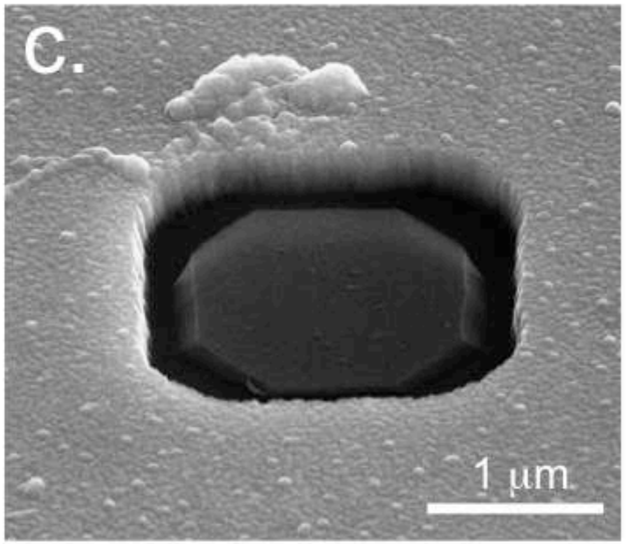
Aperture-type THz near-field probes

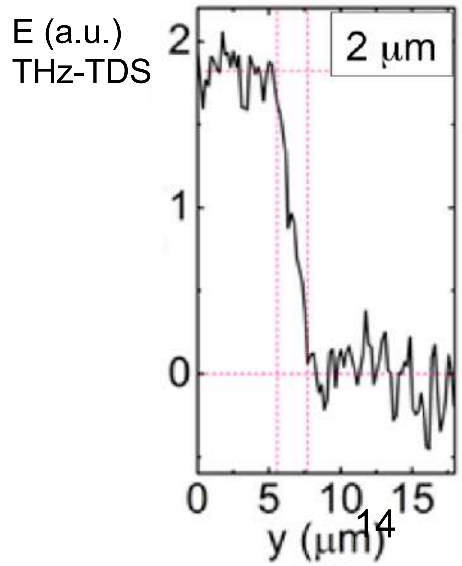




Spatial Resolution Test
2 μm aperture



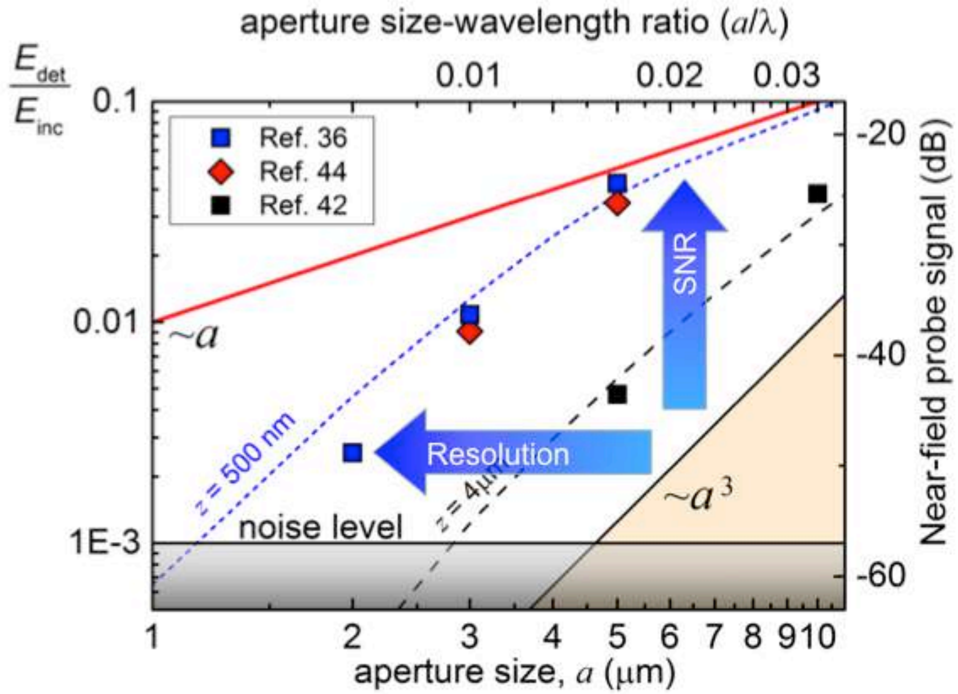




Mitrofanov *et al., ACS Photonics* (2015)

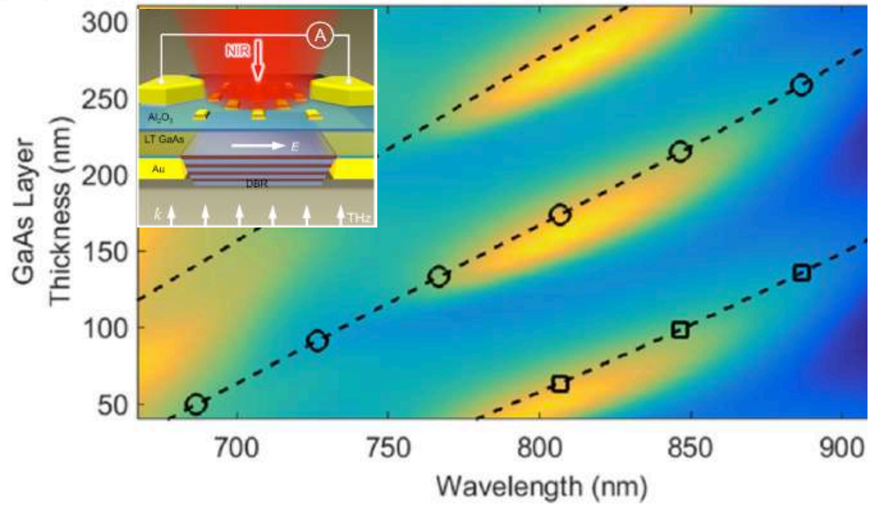
Mitrofanov *et al. THz Sci. and Technology, IEEE Trans*. (2016)

Aperture-type THz microscopy



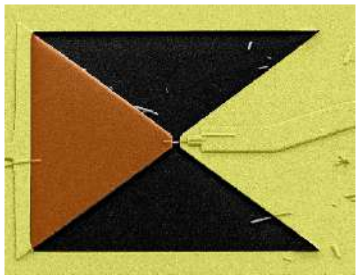
Ultrathin Photoconductive Detectors:

LT GaAs can be 50nm

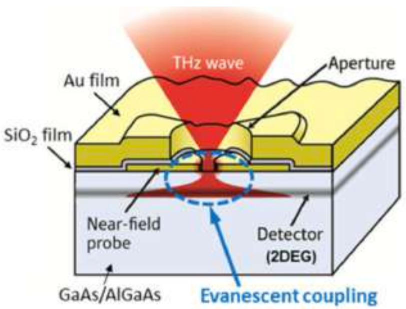


Thompson et al. Appl. Phys. Lett. (2017)

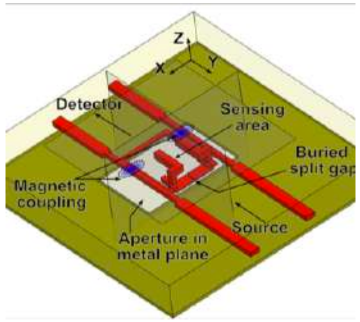
Nano-scale THz detectors:



InAs nanowire detectors
Mitrofanov et al. (2017)

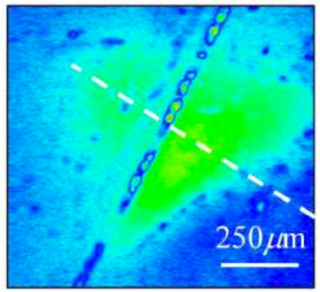


2DEG detectors
Kawano et al. (2008)



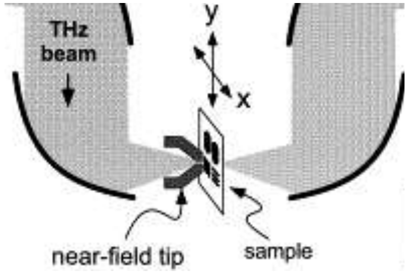
CMOS-based detectors
Grzyb et al. (2016)

Subwavelength THz sources

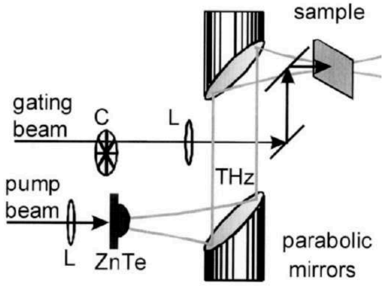


THz emission microscope
Serita et al. (2012)

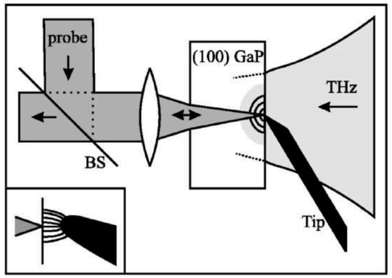
Progress in development of THz microscopy



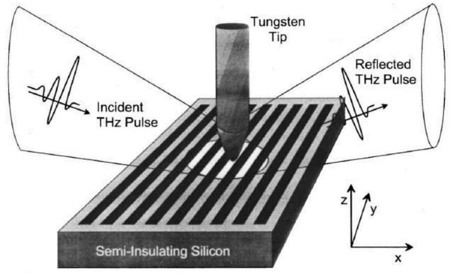
Hunsche et al., 1998



Chen et al., 2000

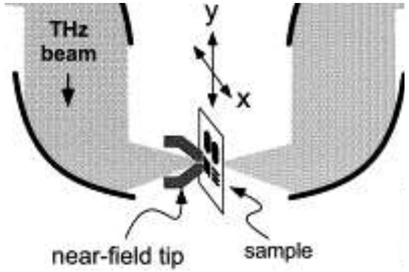


Van der Valk et al., 2002

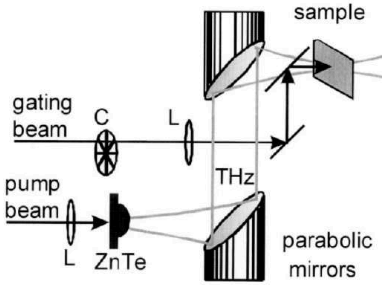


Chen et al., 2003

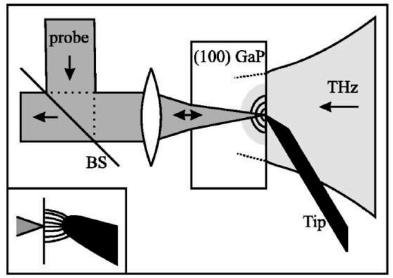
Progress in development of THz microscopy



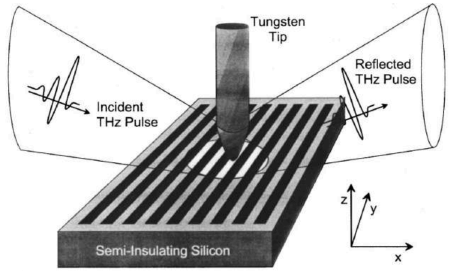
Hunsche et al., 1998



Chen et al., 2000



Van der Valk et al., 2002



Chen et al., 2003

Near-field probes with integrated THz detectors

Sub-wavelength THz generation

Use of patterns instead of apertures

Signal processing: adaptive imaging and compressive sensing

EO materials/ultrathin crystals

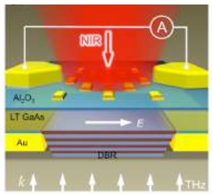
High-*E* THz sources

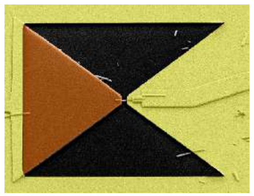
Spectral filtering

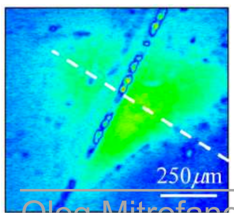
Higher order modulation techniques

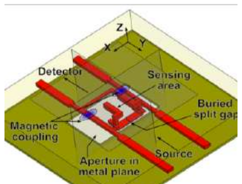
Surface plasmons

Detection of a THz driven tunneling current

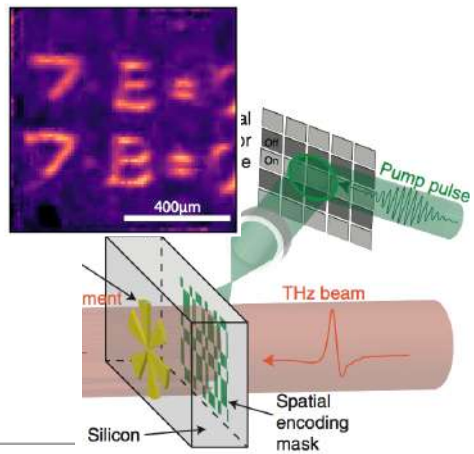




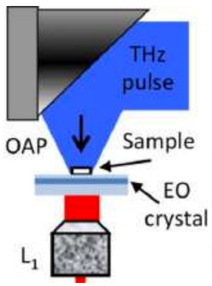


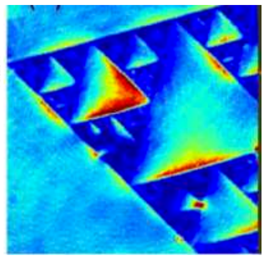


Serita (2012) Grzyb (2016)



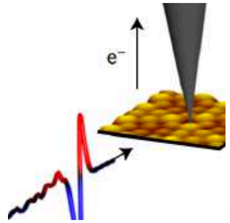
Rayko et al., 2016

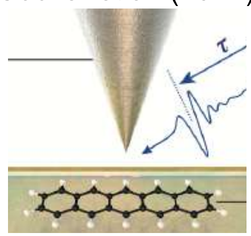




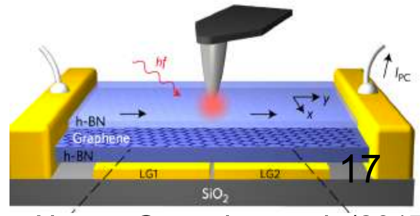
Blanchard & Tanaka, 2016

Cocker et al. (2017)



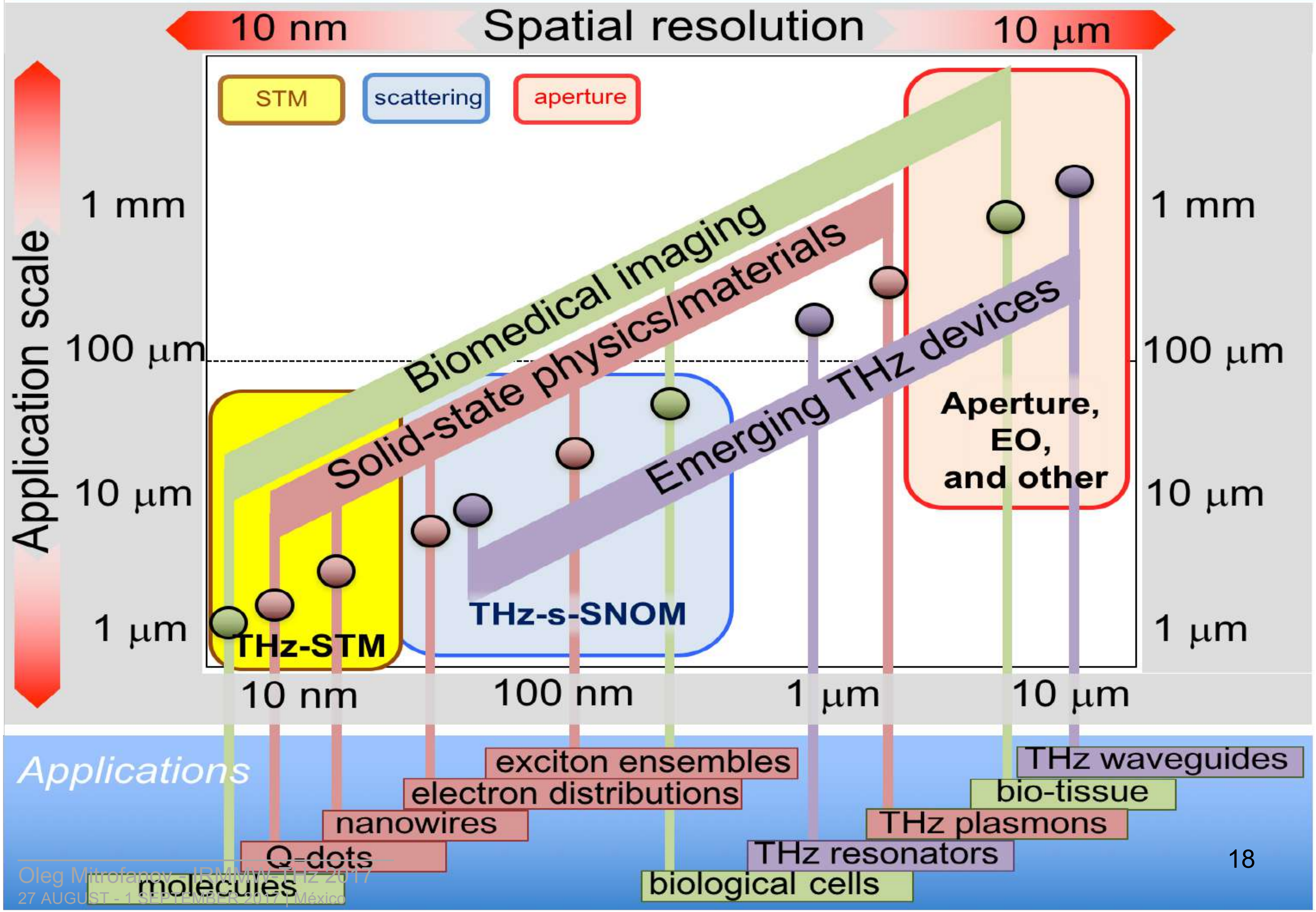


Jelik et al. (2017)



Alonso-Gonzalez et al. (2017)

THz Near-field Imaging Technology and Applications



Near-field studies at IRMMW-THz 42

10:30 - 12:00

Near Field Imaging and Spectroscopy I

Location: Cozumel Room
Chairperson: Fritz Keilmann, Germany;

Pres Time	Presentation title/Abstract title	Speakers/Authors	Pres
10:30	ADVANCES IN IR AND THZ SPECTROSCOPIC NANOIMAGING	Rainer Hillenbrand	WA1.1
11:00	IMAGING SINGLE NANOPARTICLES USING LASER TERAHERTZ EMISSION NANOSCOPY	Pernille Klarskov	WA1.2
11:15	SEMICONDUCTOR THZ NANOSCOPY OF SUBLIMINAL SURFACE DYNAMICS	Geunchang Choi	WA1.3
11:30	THZ NEAR-FIELD MICROSCOPES: OPTIMUM OPERATION CONDITIONS	Haewook Han	WA1.4
11:45	GUIDED TERAHERTZ PULSED REFLECTOMETRY SIMULATION WITH NEAR FIELD PROBE	Jean-Paul Guillet	WA1.5

16:00 - 17:30

Near Field Imaging and Spectroscopy II

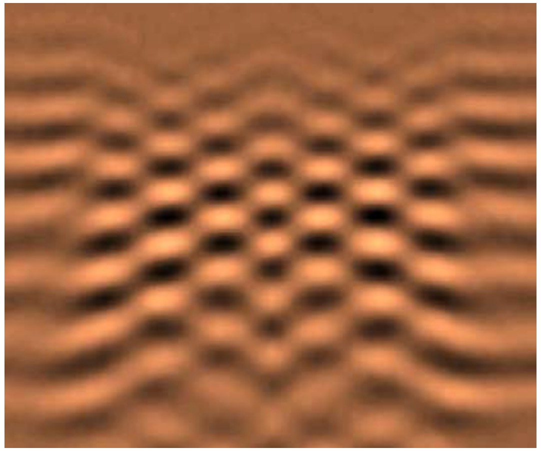
Location: Cozumel Room
Chairperson: Rainer Hillenbrand;

Pres Time	Presentation title/Abstract title	Speakers/Authors	Pres
16:00	NEAR-FIELD NANOSCOPY OF CURRENT-INDUCED EXCESS NOISE IN GRAPHENE	Kuan-Ting Lin	WC1.1
16:15	NEAR-FIELD MICROSCOPY WITH PHASE SENSITIVE COHERENT DETECTION EMPLOYING QUANTUM CASCADE LASERS	Oleg Mitrofanov	WC1.2
16:30	ANALYZING NANOSCALE OPTICAL AND THERMAL PROPERTIES IN NANOPOROUS GRAPHENE BY NEAR-FIELD INFRARED MICROSCOPY	Takuya Okamoto	WC1.3
16:45	INTEGRATED PROBES FOR NEAR FIELD THZ MICROSCOPY	Naser Qureshi	WC1.4
17:00	RESONANT SCATTERING PROBES IN THE TERAHERTZ RANGE	Thomas Siday	WC1.5

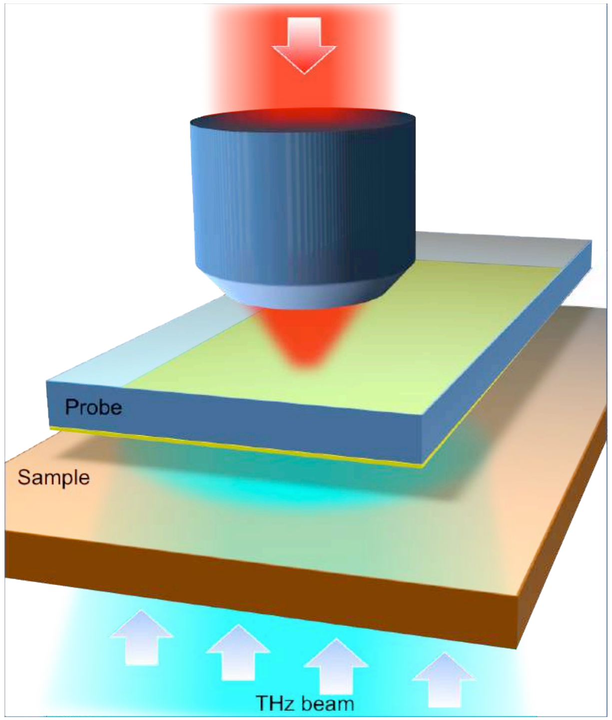
Applications of aperture-type THz near-field microscopy

Applications of aperture-type THz near-field microscopy

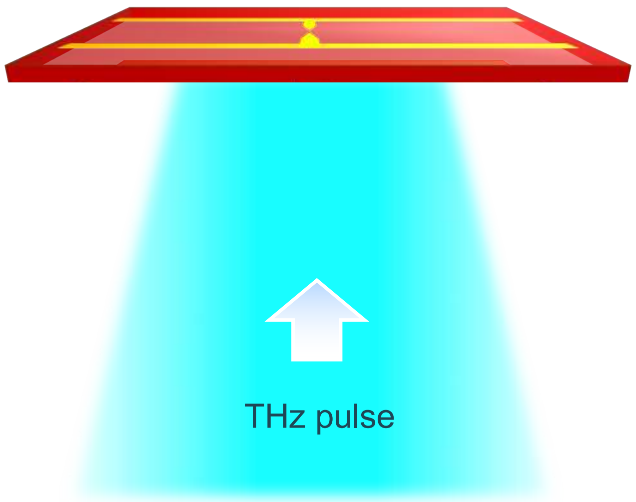
THz surface waves

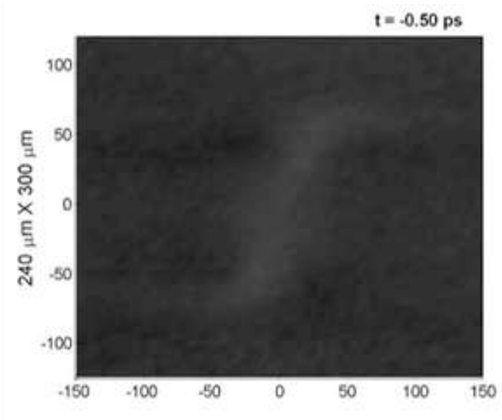


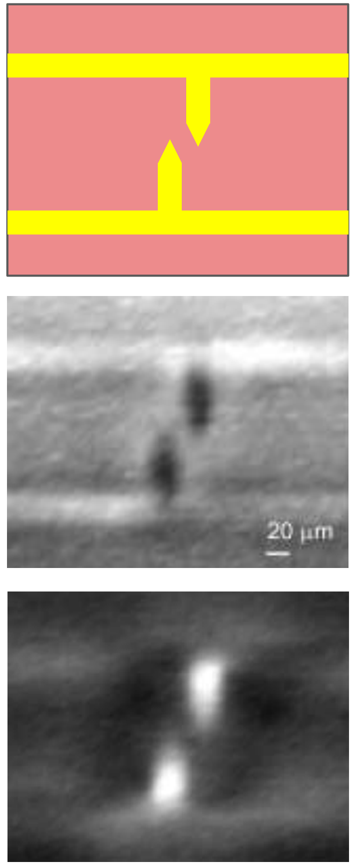
THz surface wave observation



$E(x,y,\ t)$ - ?

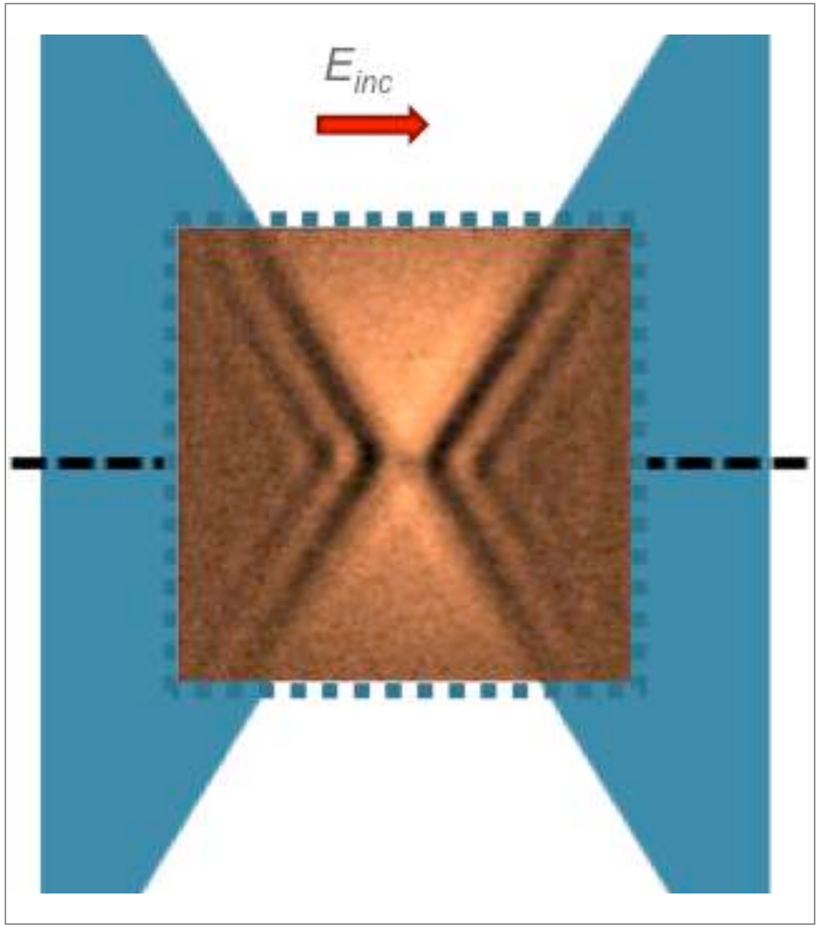


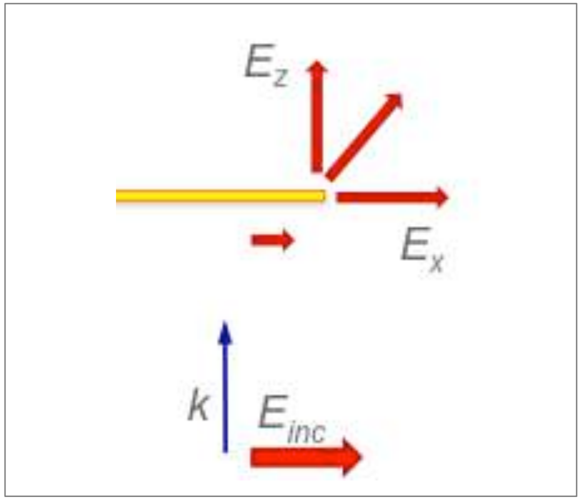


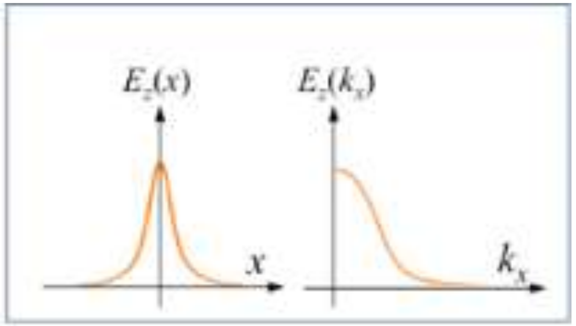


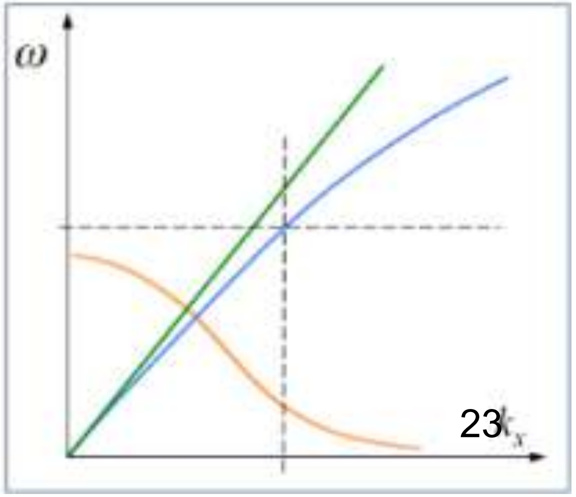
Mitrofanov et al.
J. STQE **103**, 600 (2001)

Excitation of surface plasmon waves near metallic edges



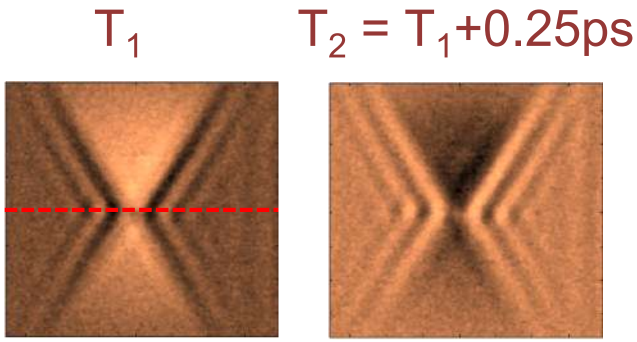


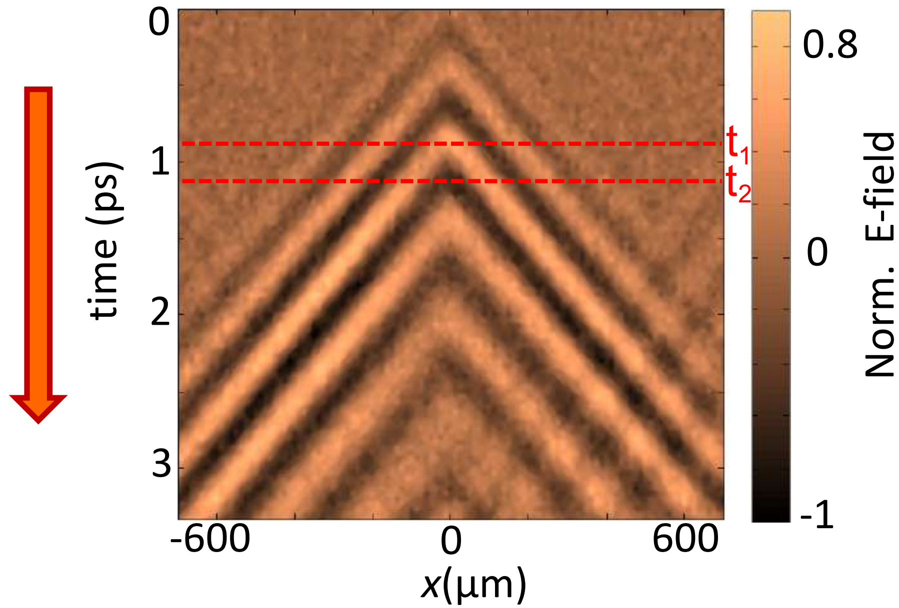


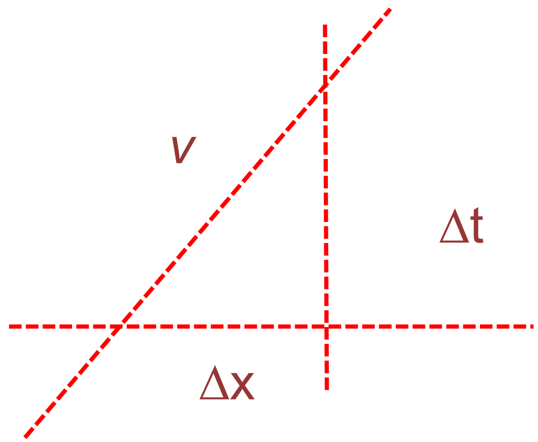


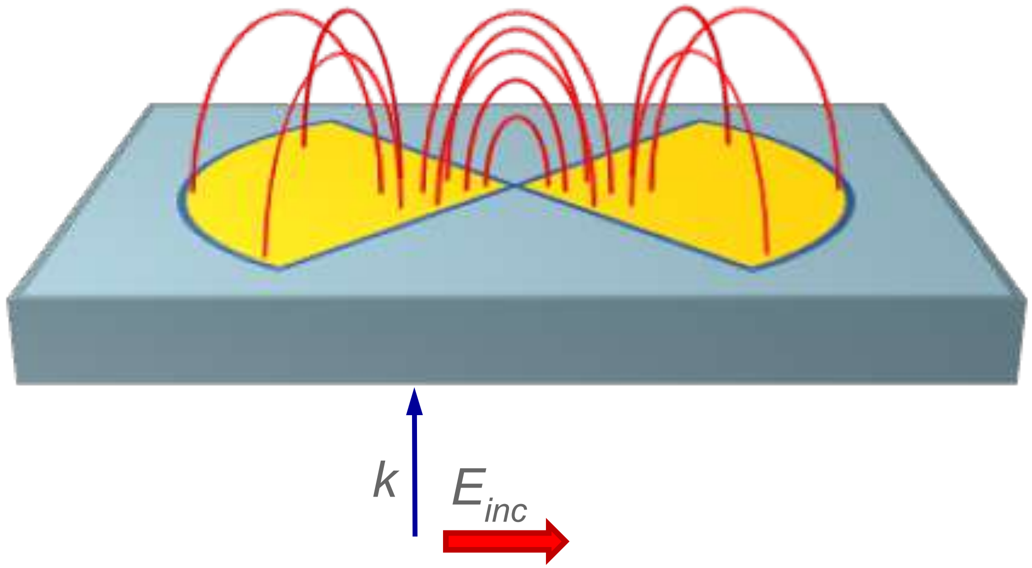
Mueckstein *et al.*, J.of IRMMW 32, 1031 (2011)

Temporal mapping of surface plasmon waves

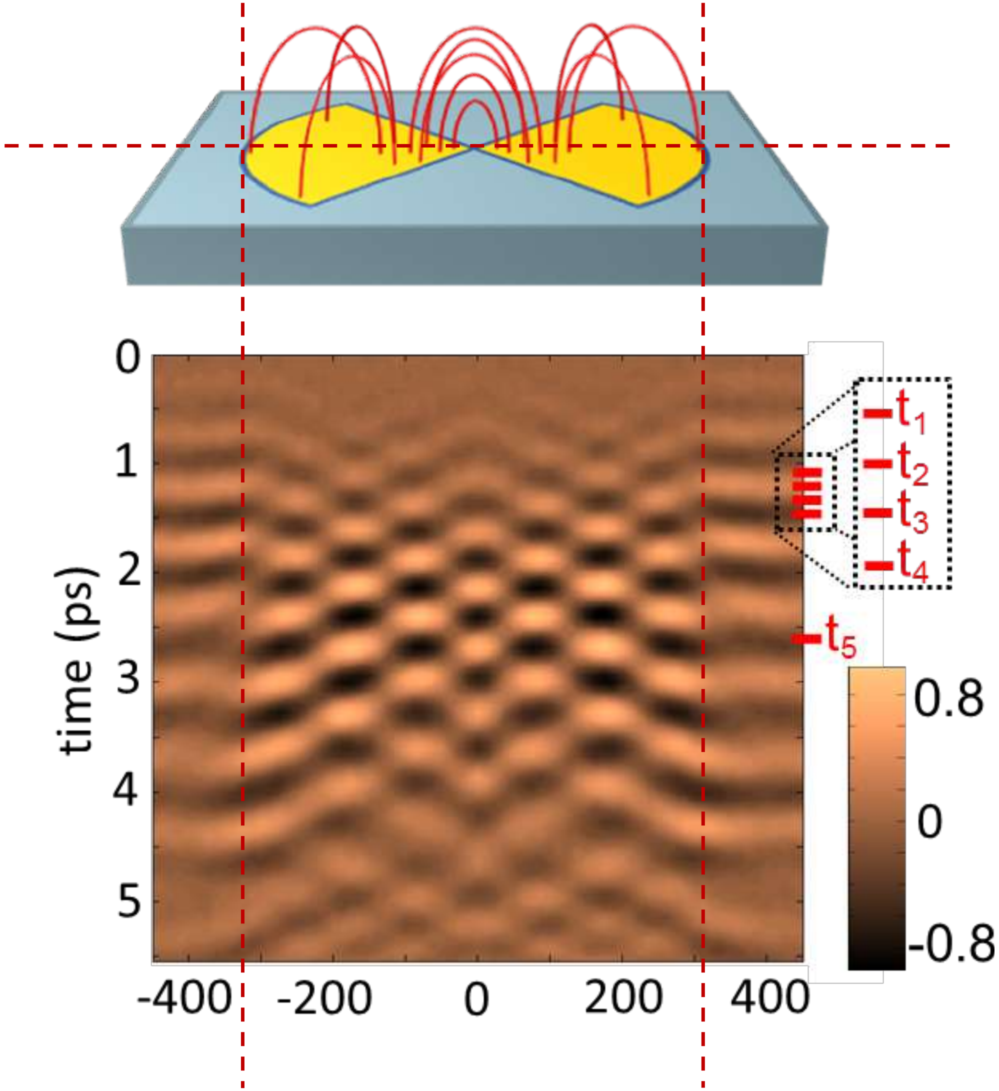


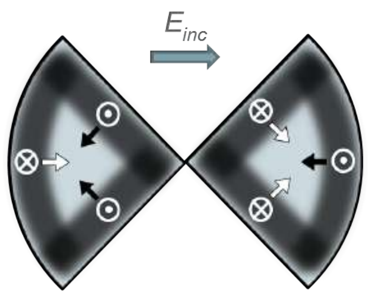


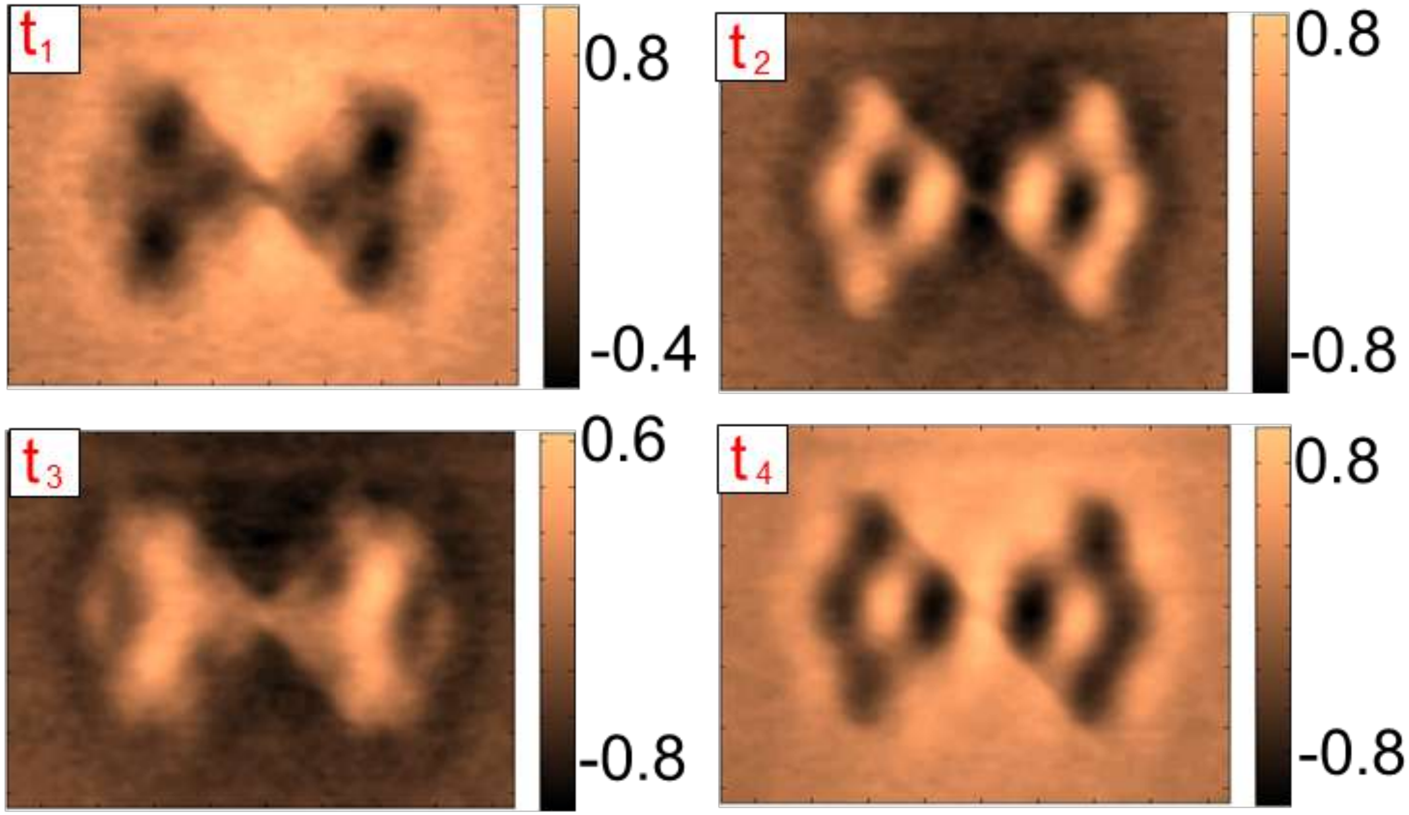



k
E_{inc}

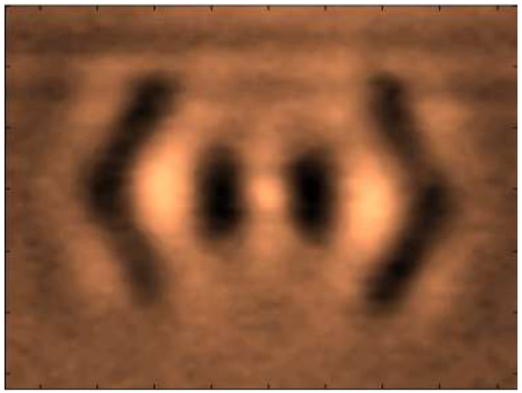
Resonance on the bow-tie surface





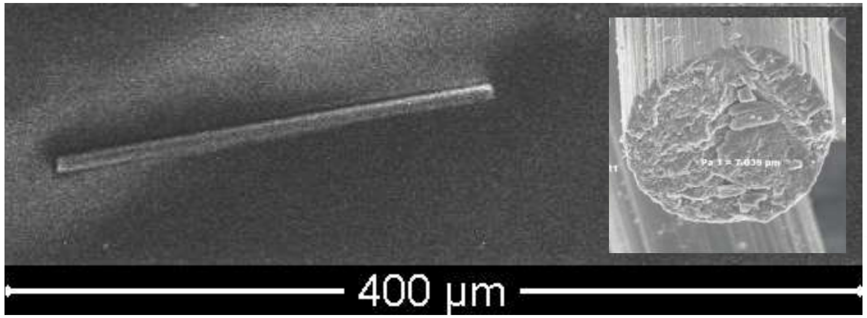


Consecutive images
Δt = 0.13 ps

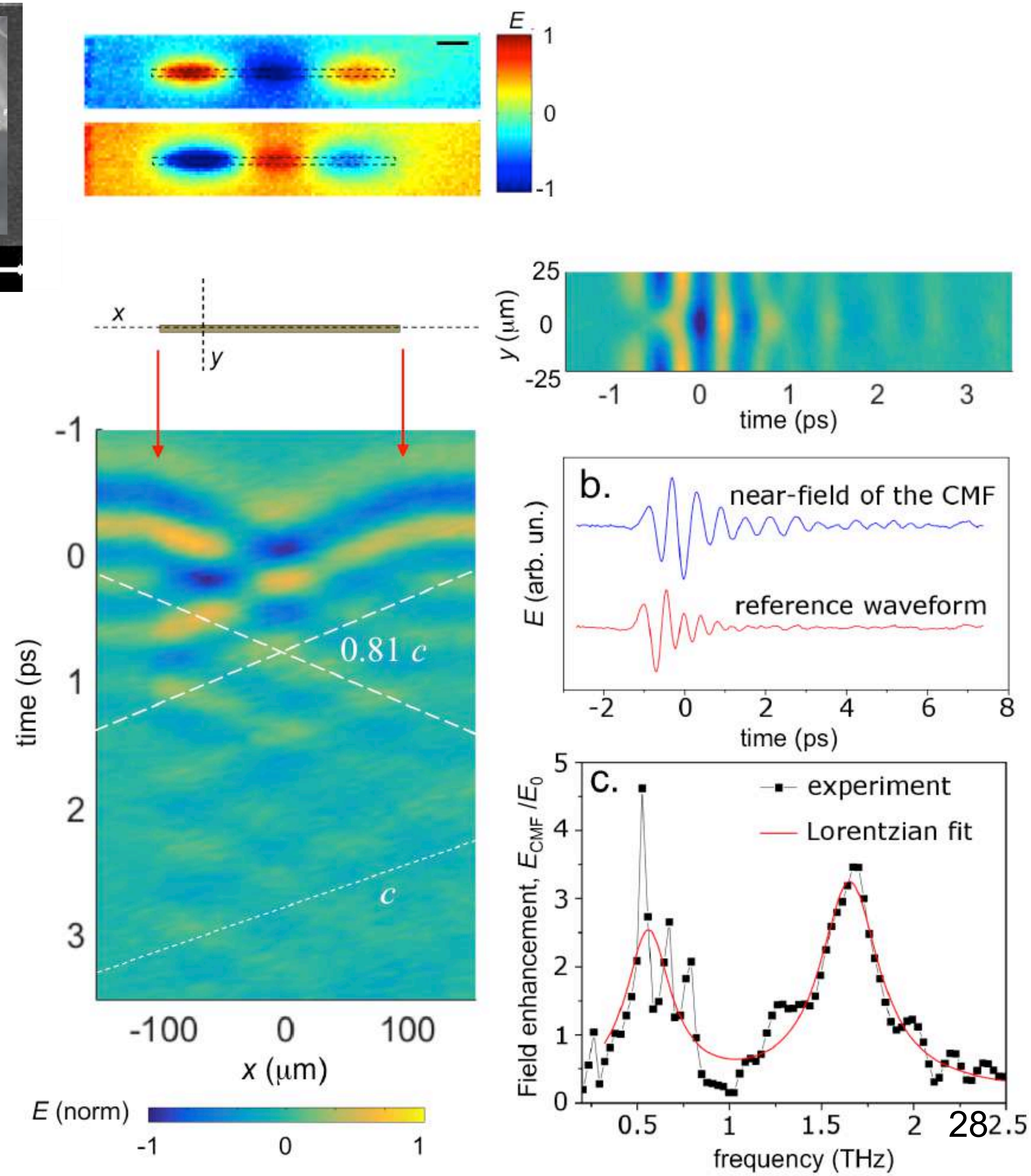


$t_5 = t_1 + 1.5$ ps

Plasmonic excitations in THz Resonators



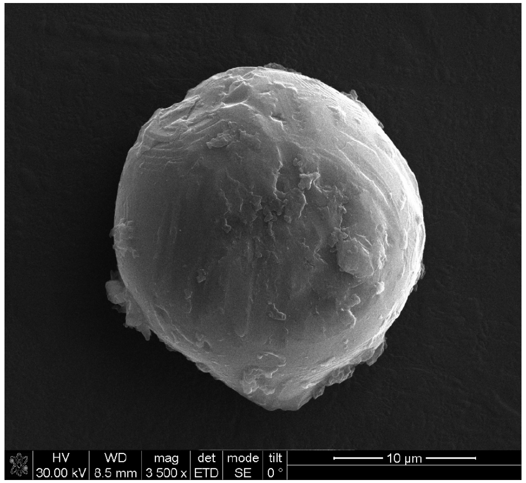
Conductive carbon fibres:
6.5 μm diameter, 50-250 μm long



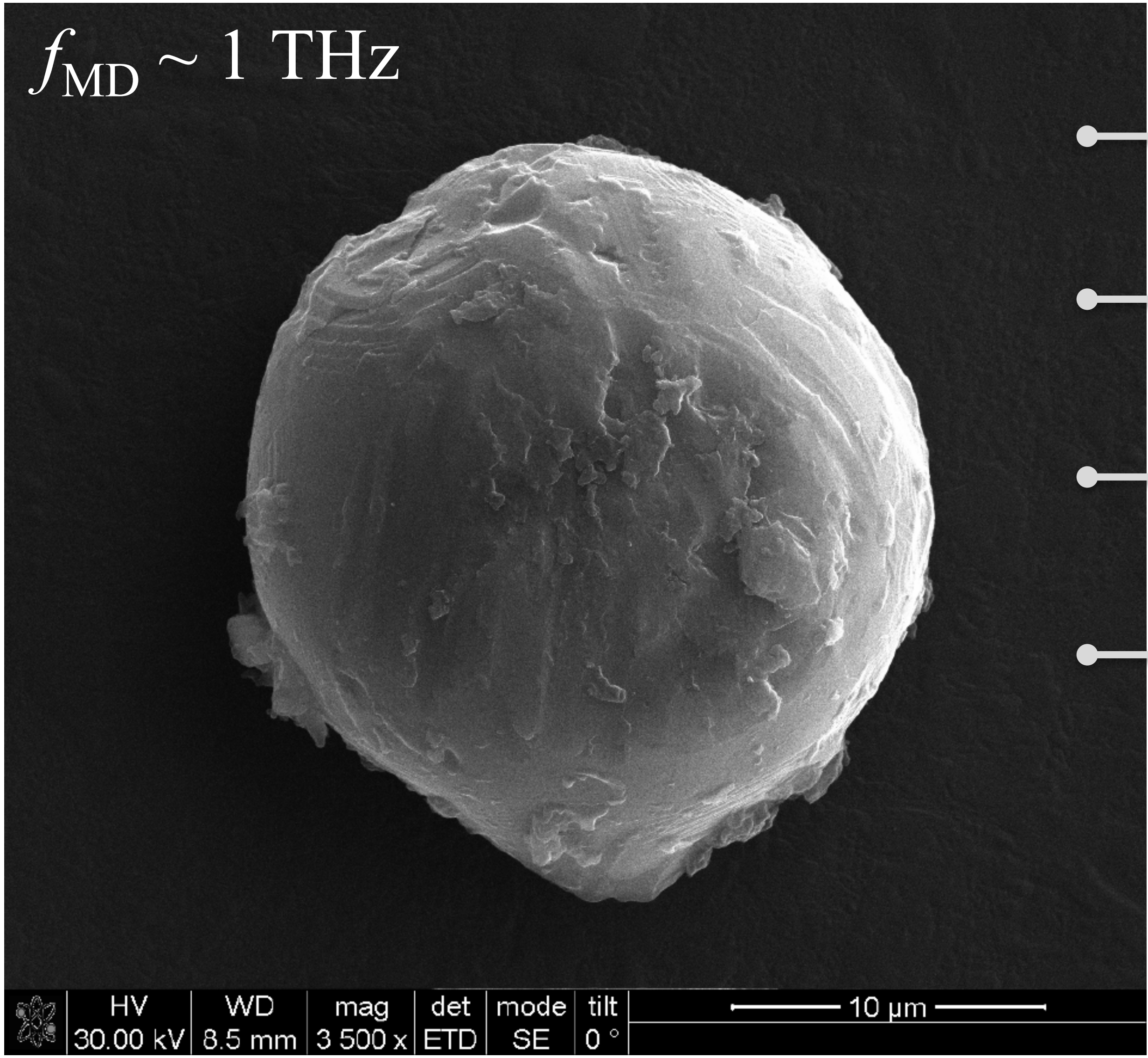
IEEE Trans. THz S&T 6, 382 (2016)

Applications of aperture-type THz near-field microscopy

Dielectric Resonators



Dielectric subwavelength resonators



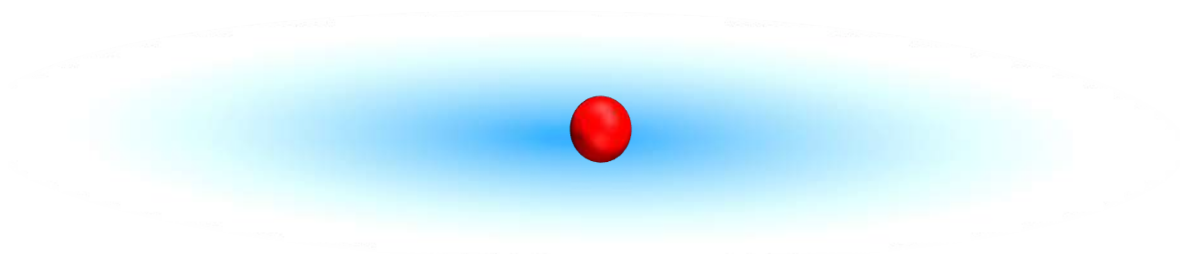
TiO_2 *microsphere:*
~20 μm diameter

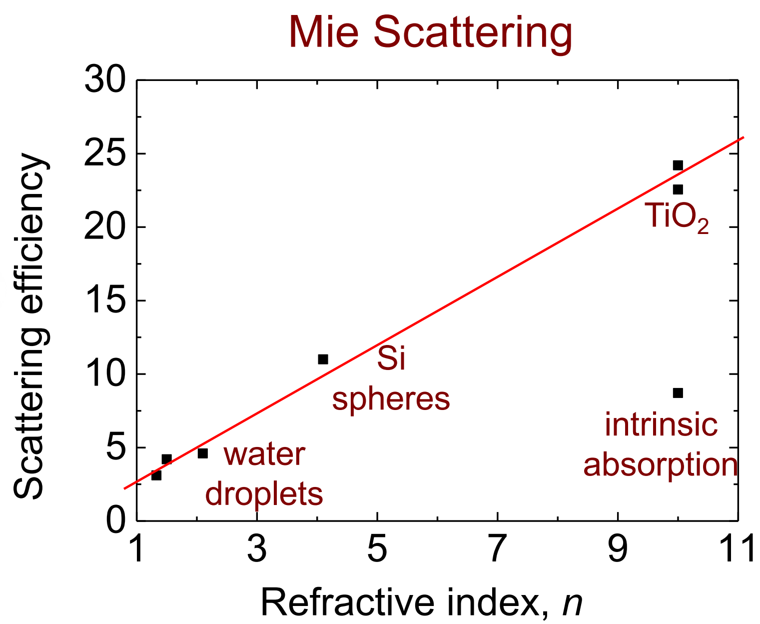
- $\varepsilon \sim 70 - 150$
- $d \sim \lambda / 10$
- $\varepsilon_o , \varepsilon_e$ – ?
- $Im(\varepsilon)$ – ?

How to investigate such resonators?

Sub-wavelength size
of TiO_2 resonators

$$d \sim \lambda/n$$



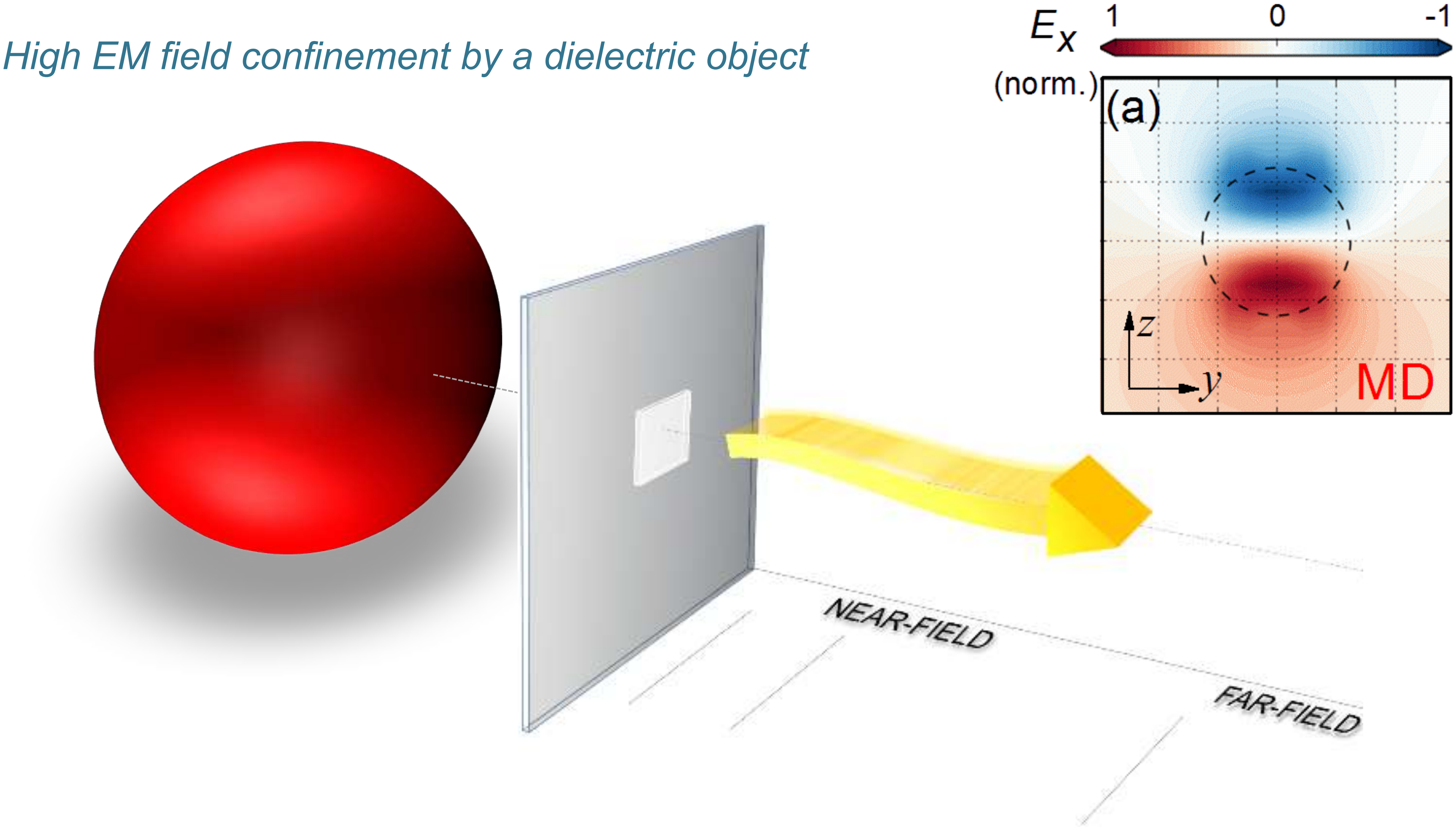


Far-field total extinction
by a single TiO_2 sphere
(est. for typical THz-TDS) : 0.1-1.0%

Scattering efficiency increases with n,
However total scattered power reduces due
to the physical cross-section scaling with n^{-2}

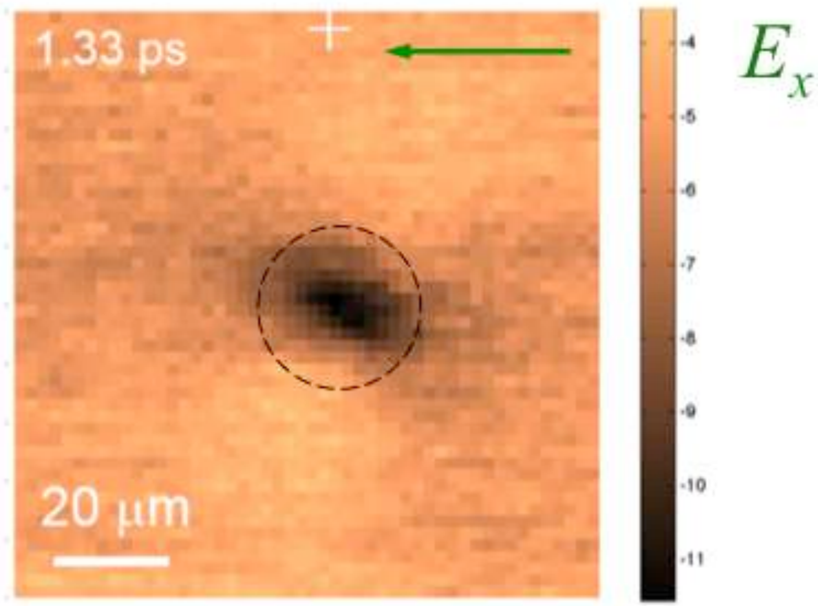
Effect on sub-wavelength aperture transmission

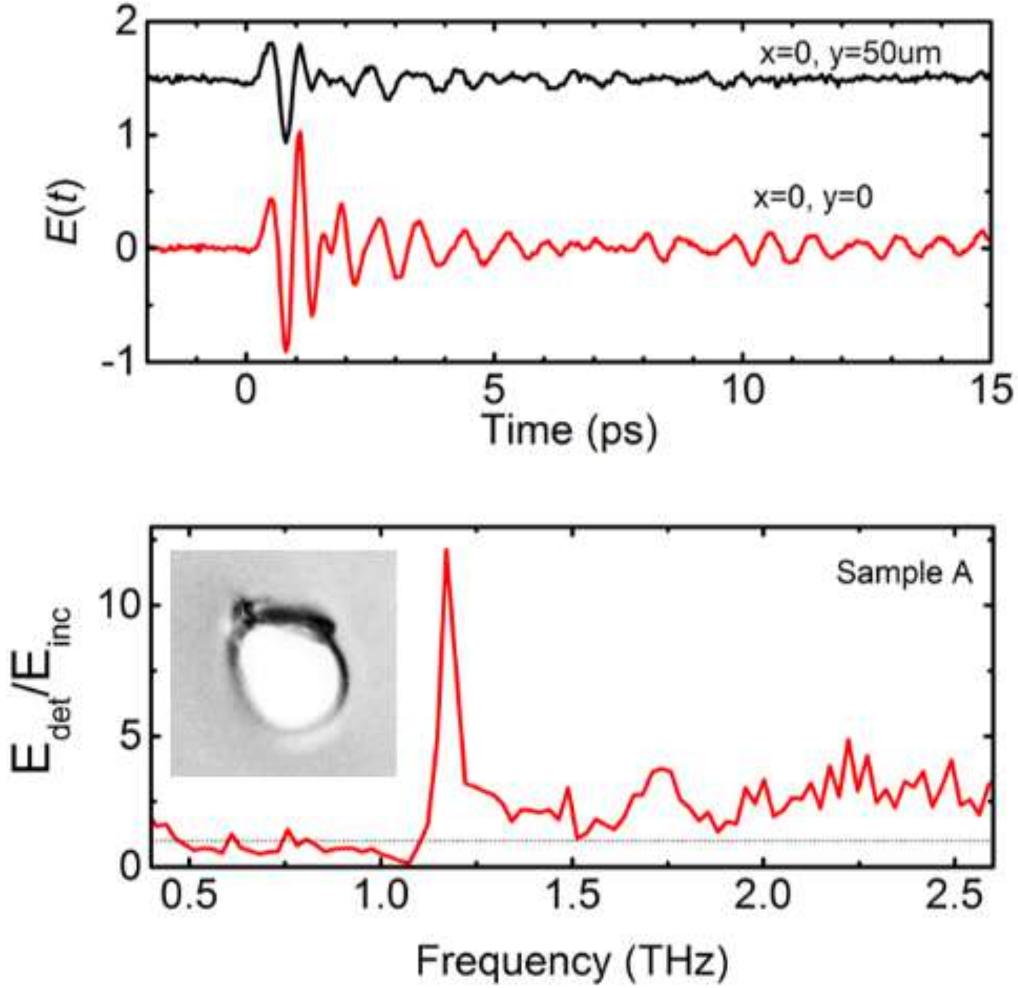
High EM field confinement by a dielectric object



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

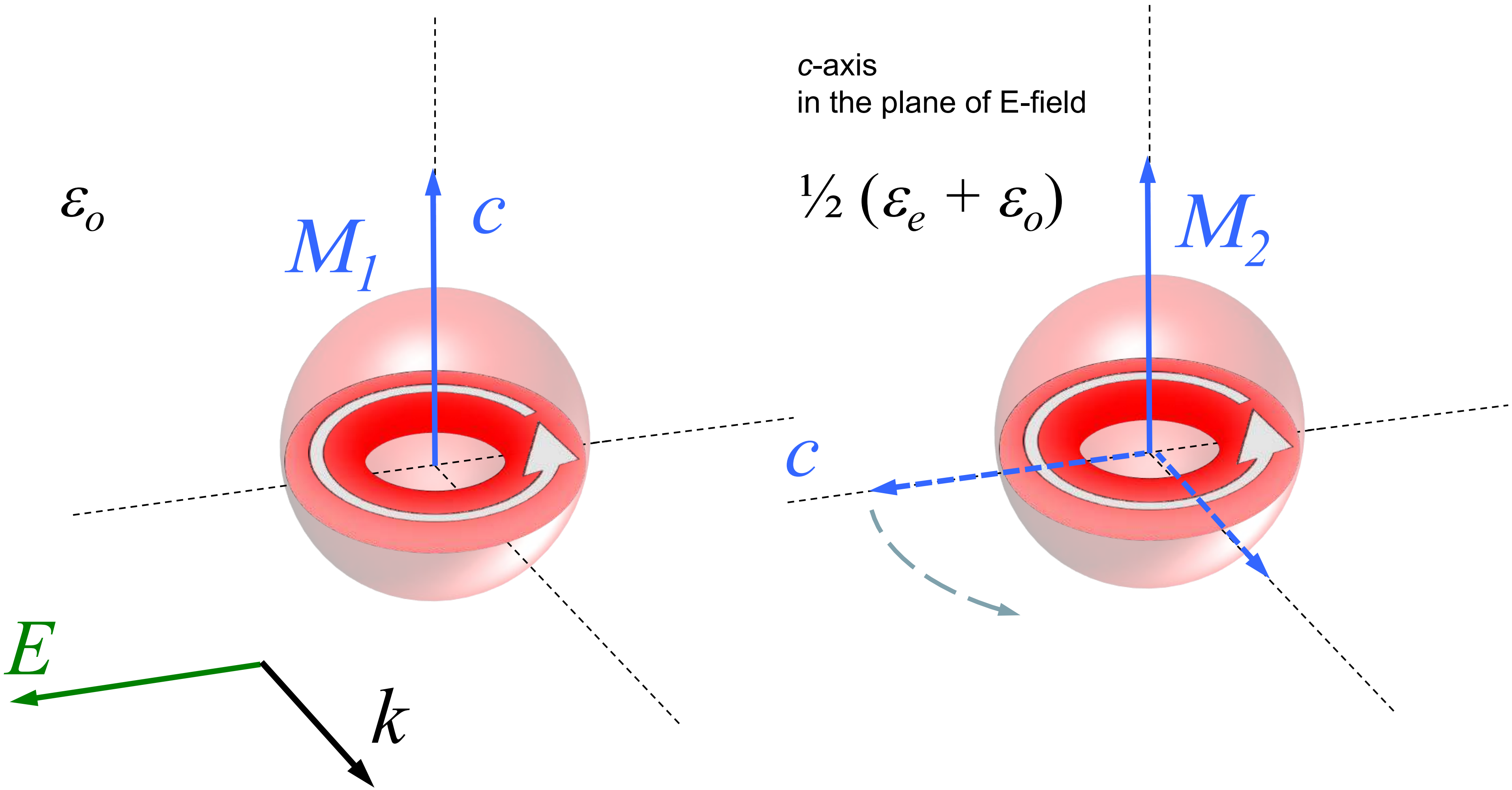
Optics Express, 22, 23034 (2014)



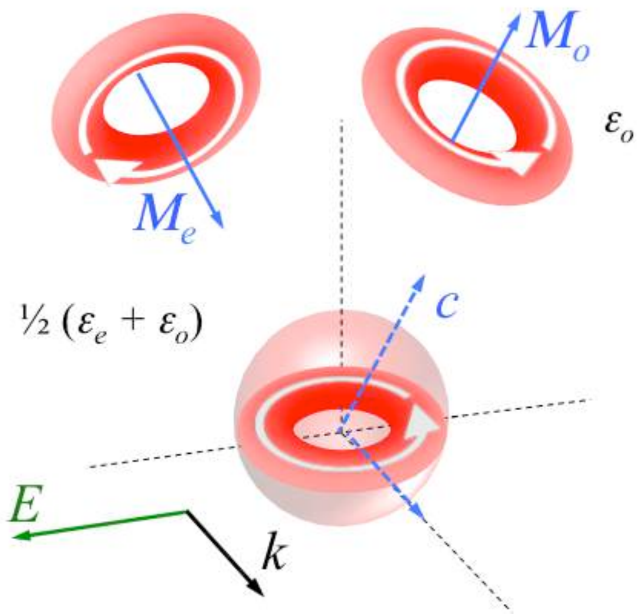


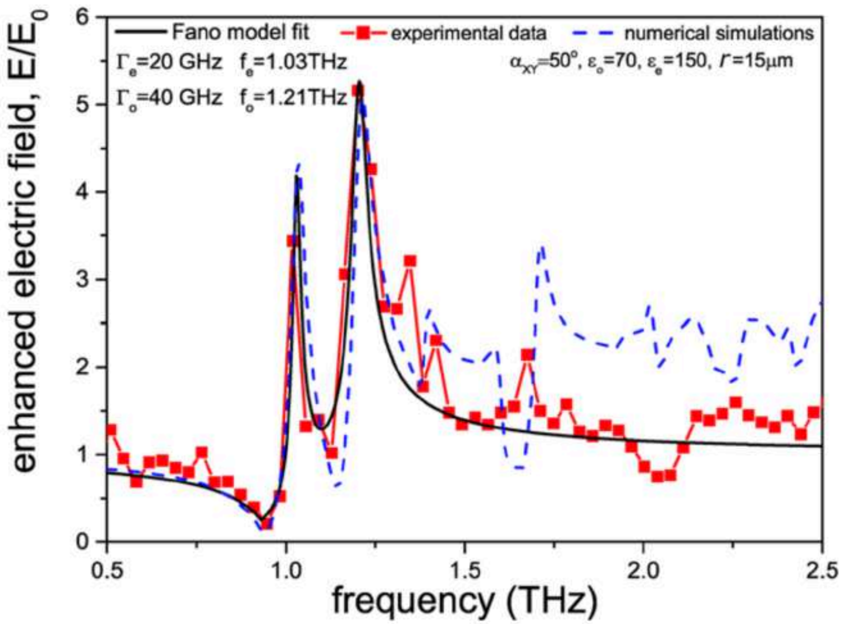
Mitrofanov et al., Optics Express, 22, 23034 (2014)

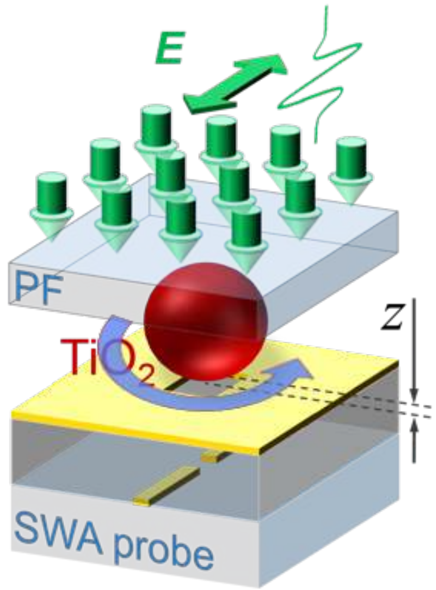
TiO_2: $\varepsilon_e = \sim 150$; $\varepsilon_o = \sim 70$

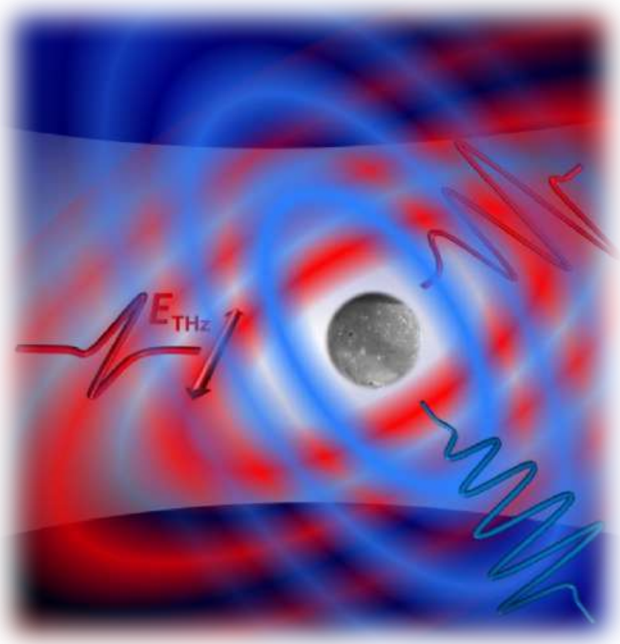


Anisotropic dielectric THz resonators:



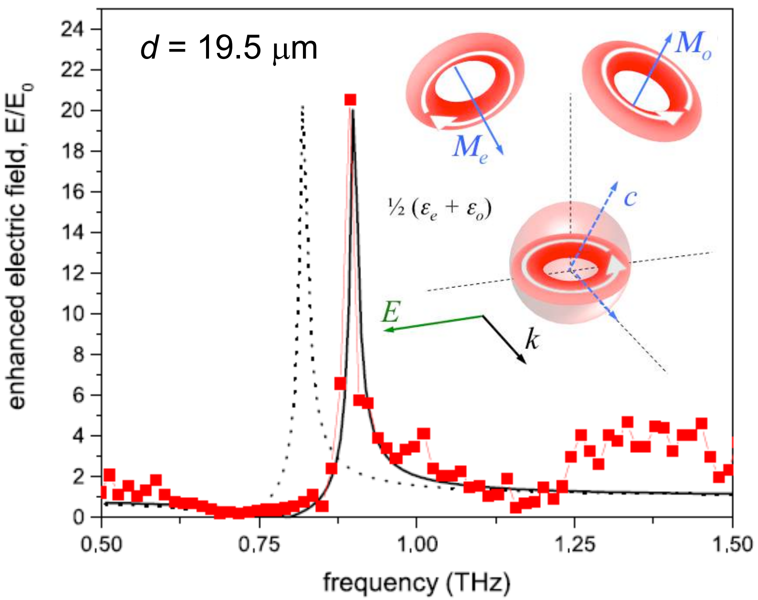






I. Khromova et al., *Laser and Photon. Reviews* (*2016*)

Narrow linewidth TiO_2 Resonators



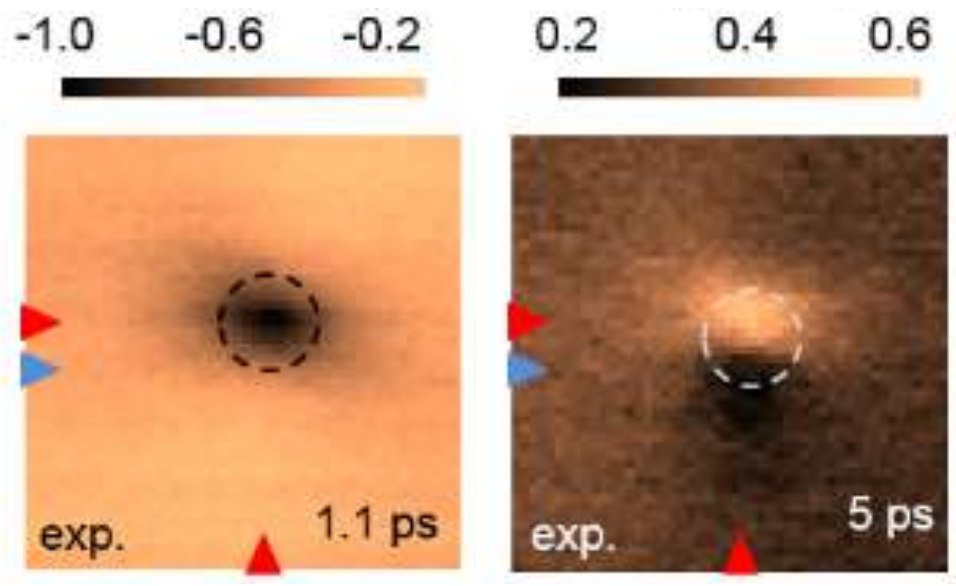
Near-field measurement enables precise characterization of TiO_2 anisotropic properties at THz frequencies in sub-wavelength size micro-spheres.

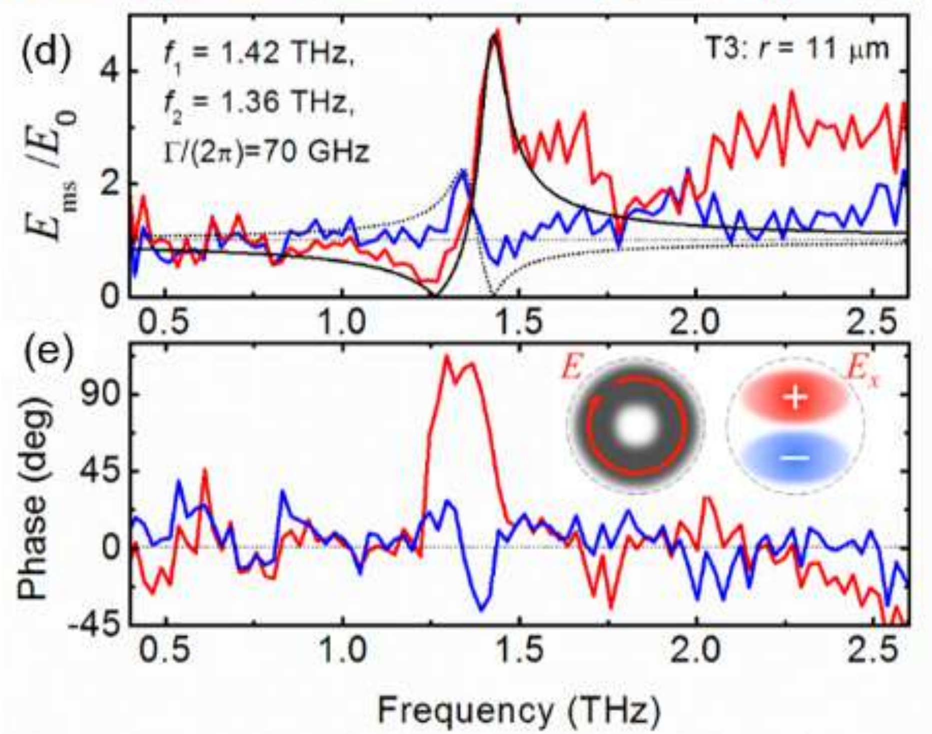
THz magnetic dipole resonances are characterized without broadening due to ensemble size variation.

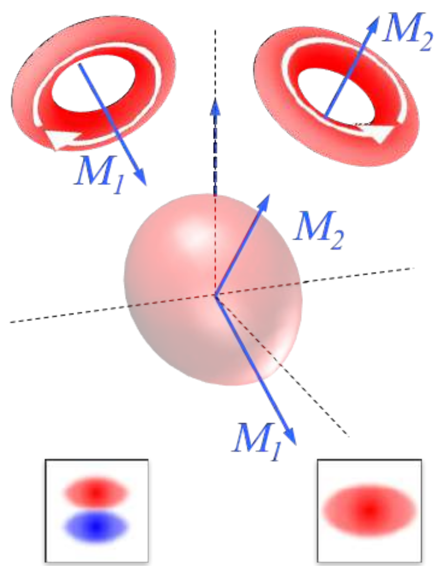
The resonance linewidth of ~10 GHz is observed confirming the potential of TiO_2 as a material for all-dielectric THz metamaterials.

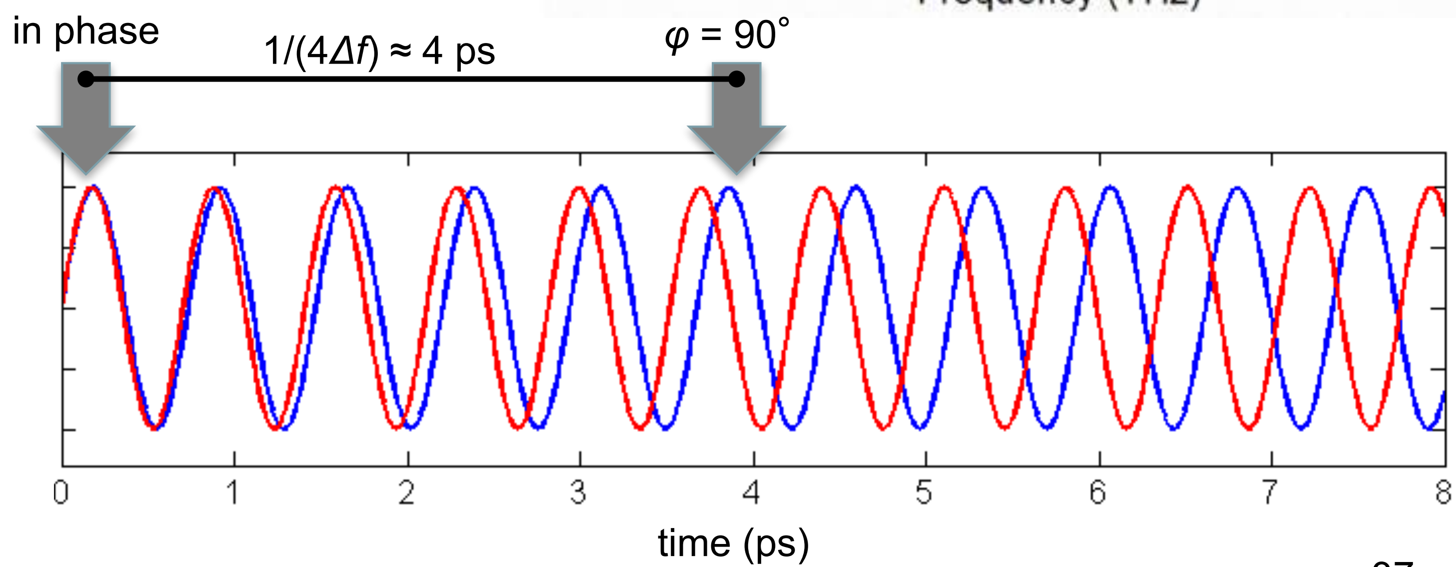
I. Khromova et al., *Laser and Photon. Reviews* (*2016*)

Non-sphericity





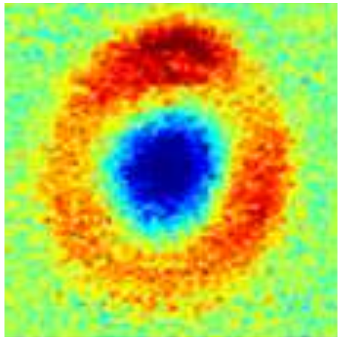




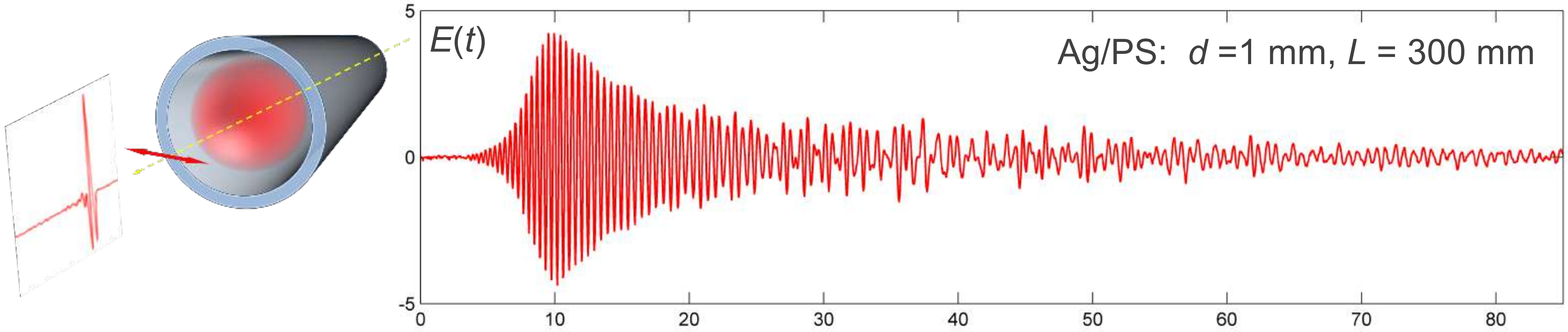
Optics Express, 22, 23034 (2014)

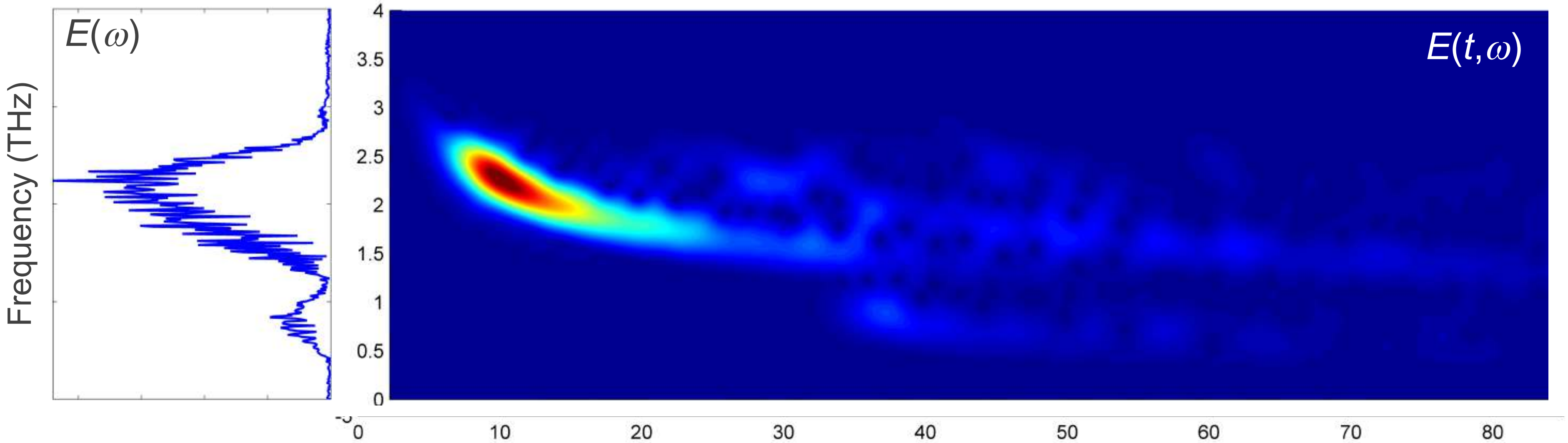
Applications of aperture-type THz near-field microscopy

THz Waveguides

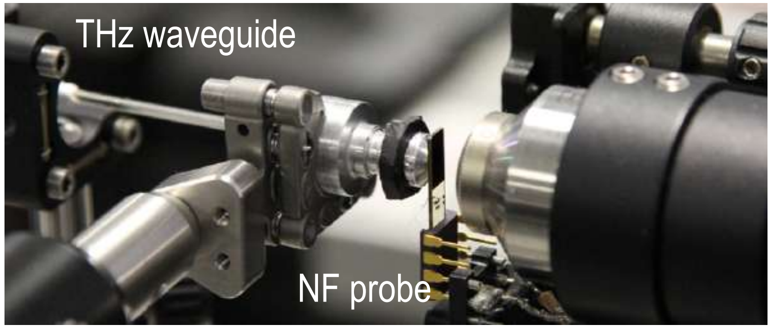


Applications: *Modes in Waveguides*

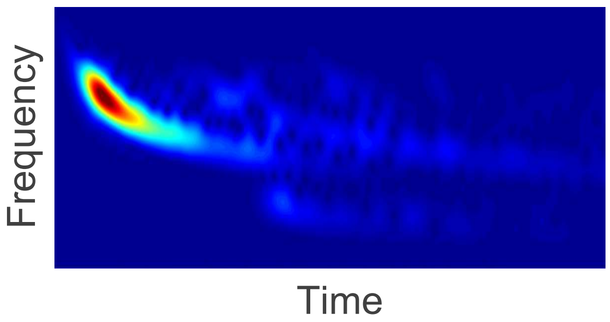




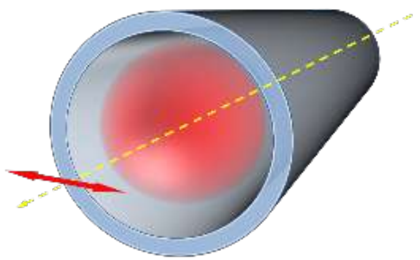
Navarro-Cia *et al.*, Opt. Express (2013)

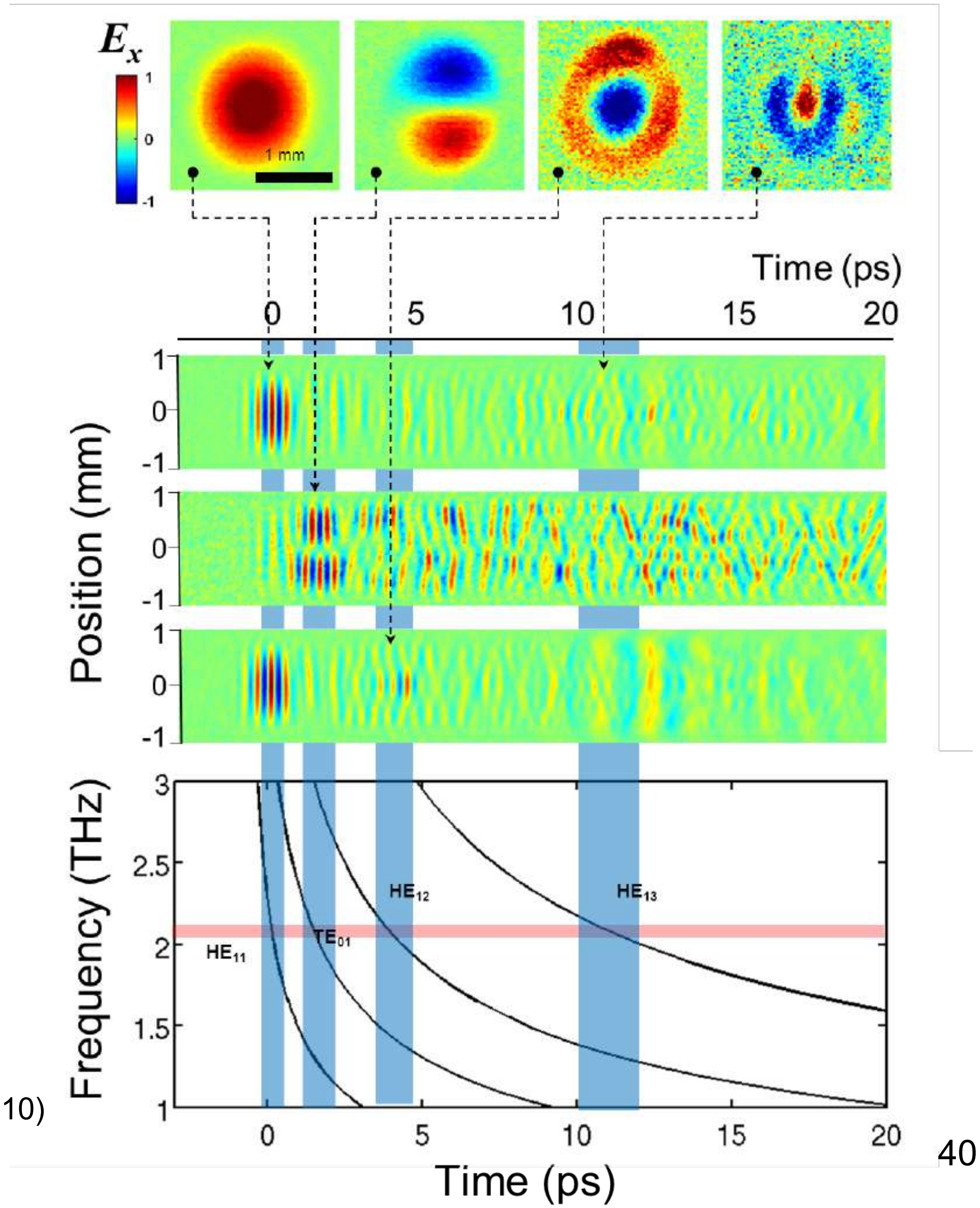


Applications in THz technology research: *Waveguides*



Selective mode excitation:





Enabling THz waveguide research:

Dispersion

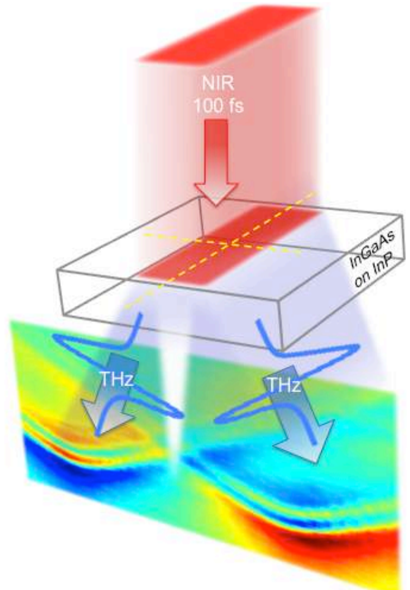
Loss

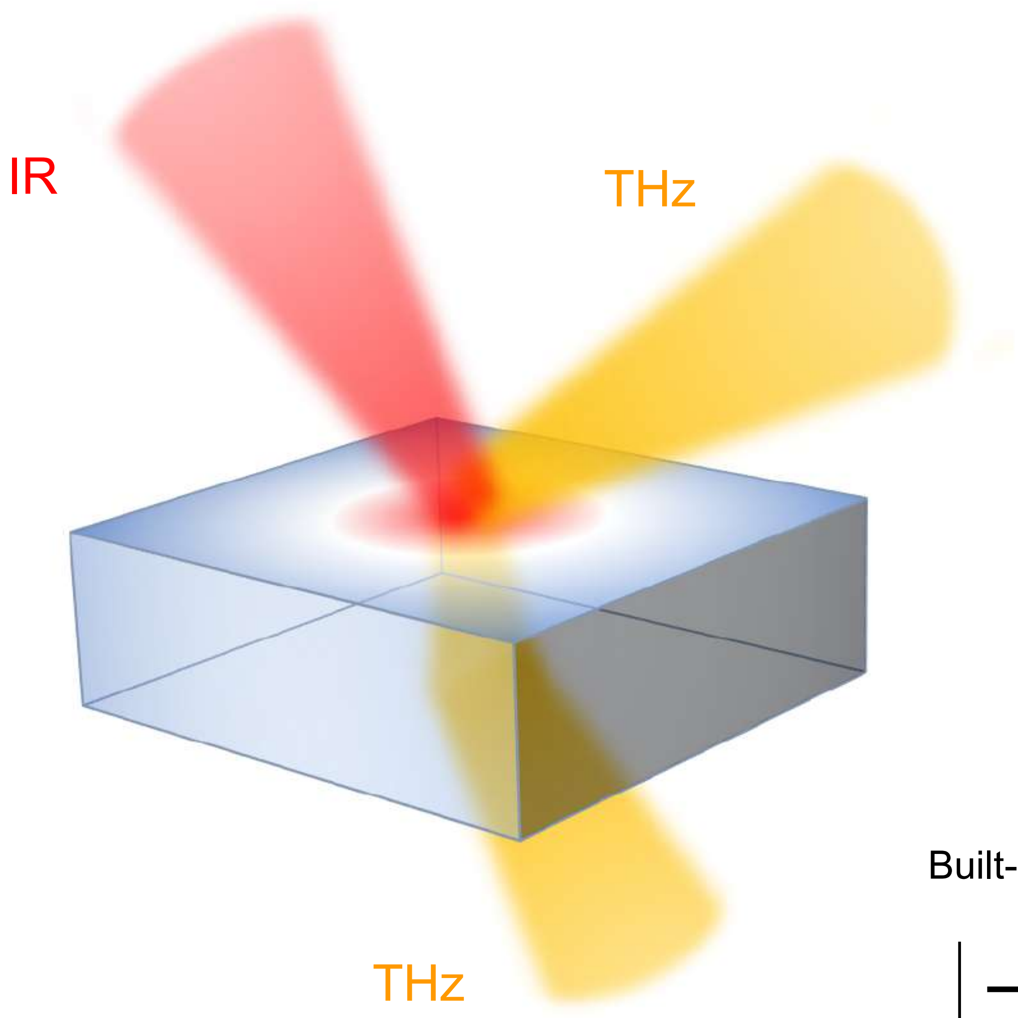
Mode Structure

Mitrofanov et al., Optics Express 18(3), 1898-1903 (2010)

Applications of aperture-type THz near-field microscopy

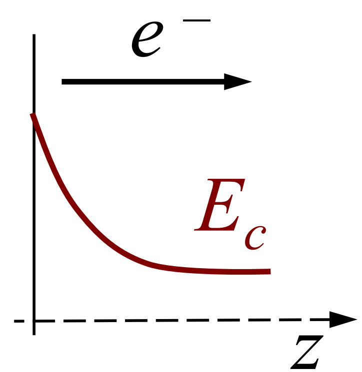
THz pulse generation
by transient currents



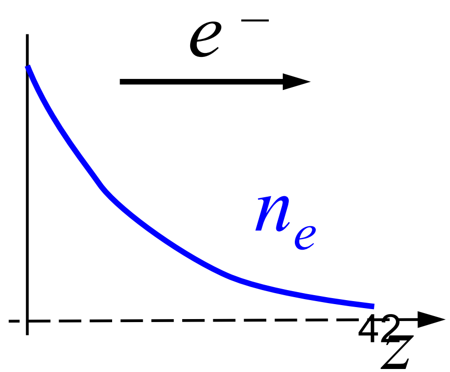


$$E \propto \frac{\partial I}{\partial t}$$

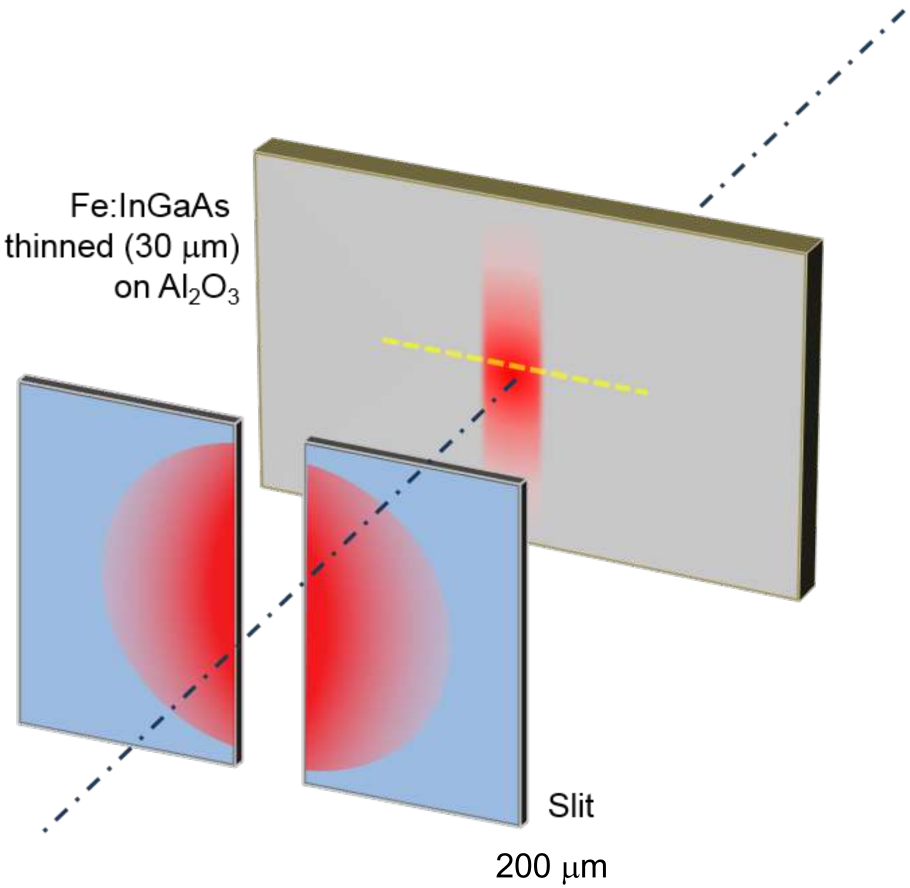
Built-in surface field

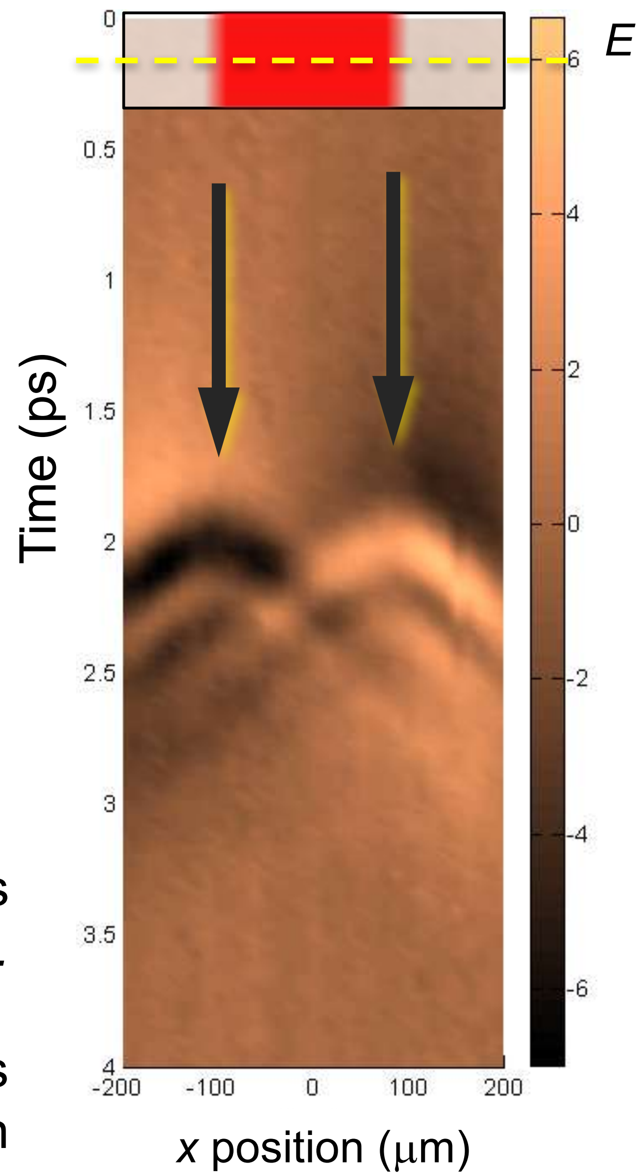


Carrier density gradient



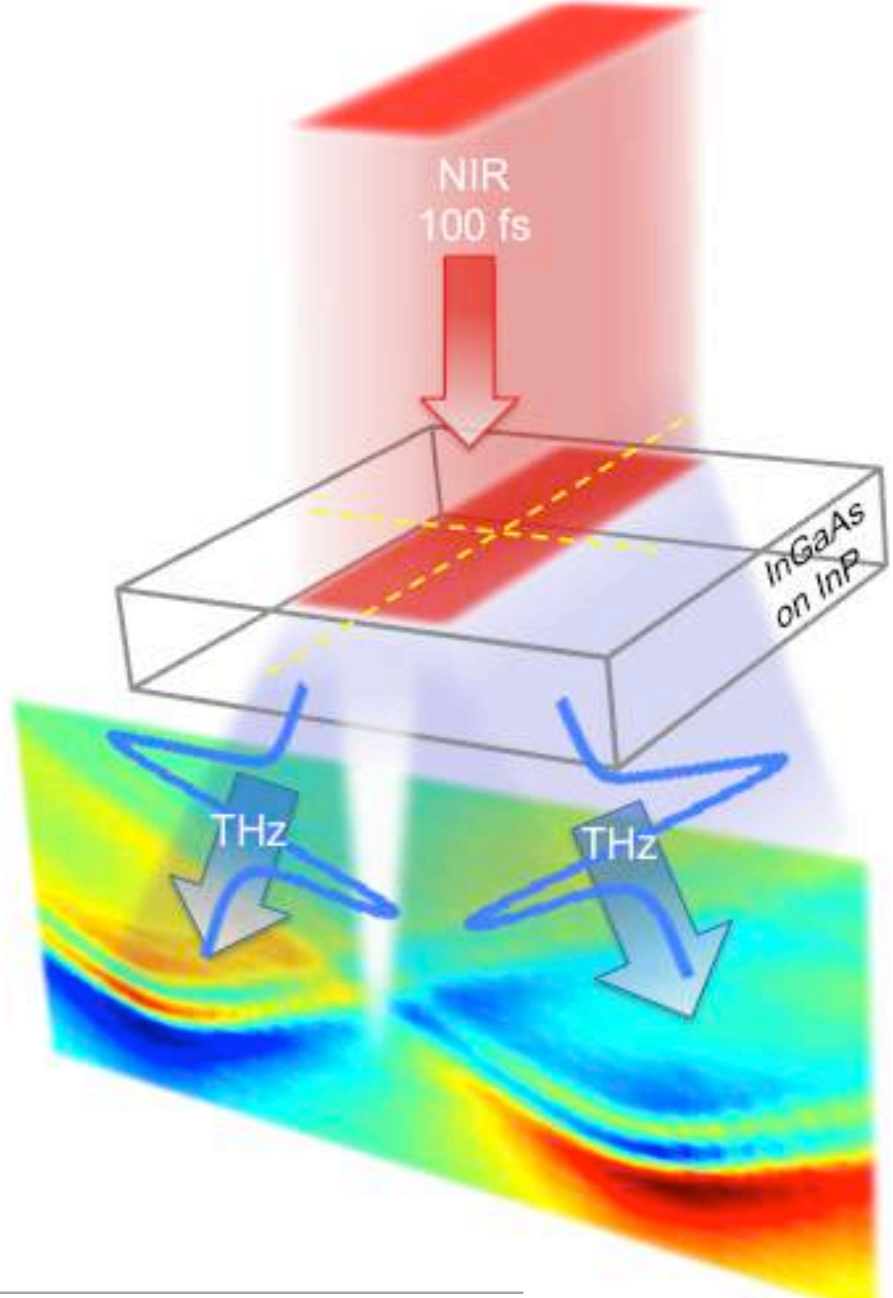
Emission of THz pulses



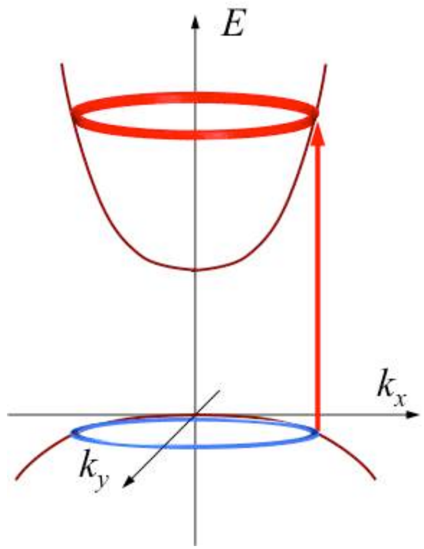


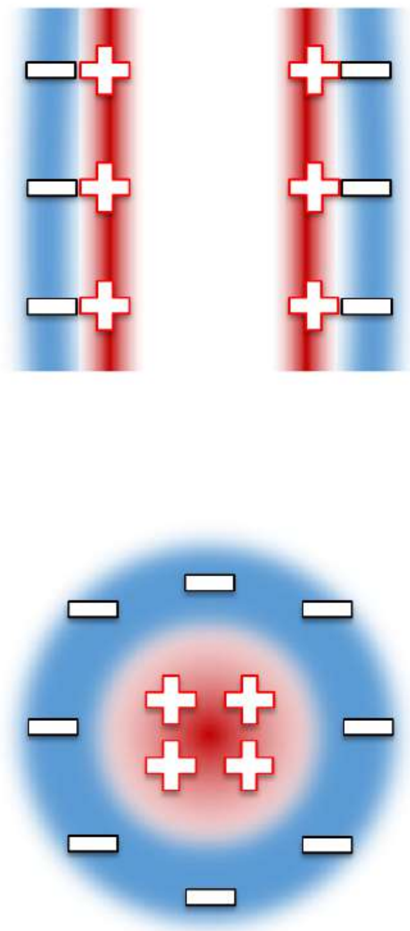
THz emission originates from two distinct points corresponding to the *Slit Edges.*

These two sources display opposite polarities leading to no far-field emission in forward direction



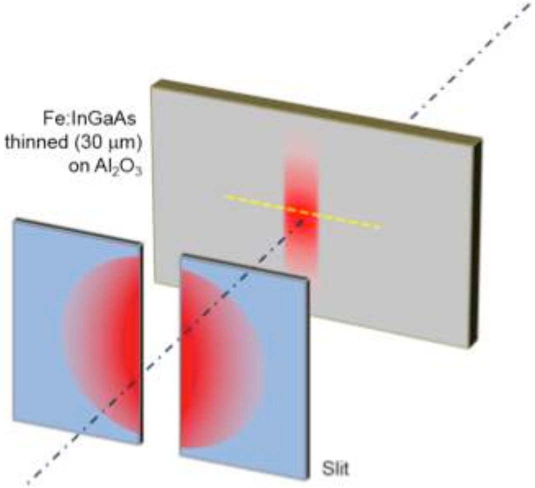
Transient Dipole Moment

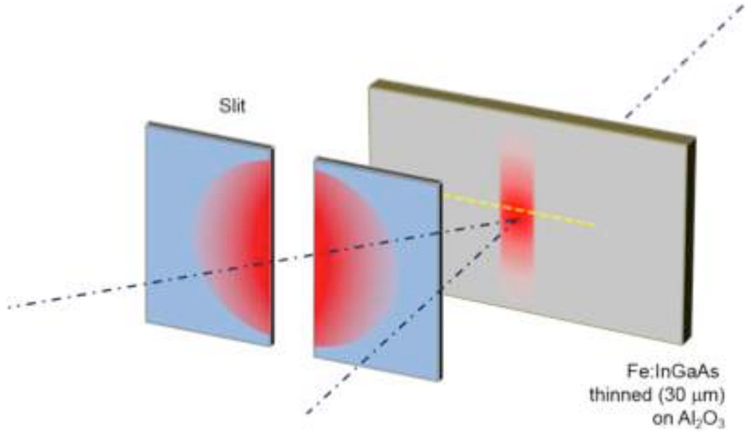




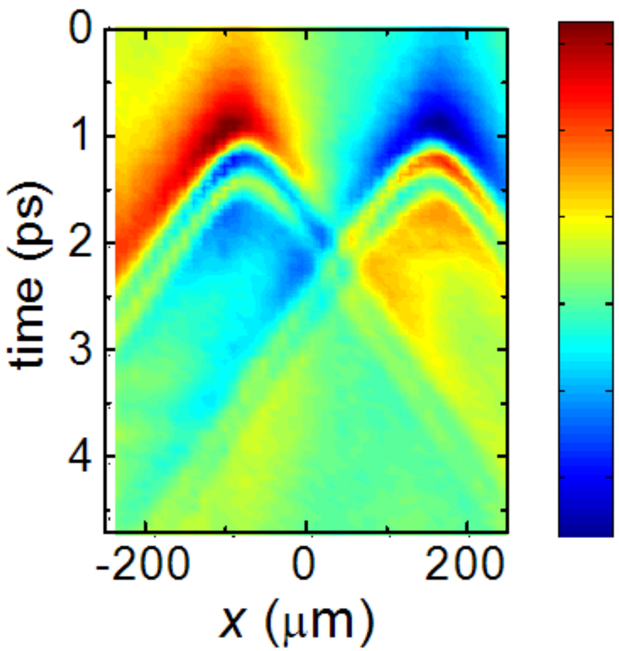
Mueckstein *et al.* THz Sci. and Technology, IEEE Trans. (2015)

Normal incidence *vs.* 45 degree incident angle

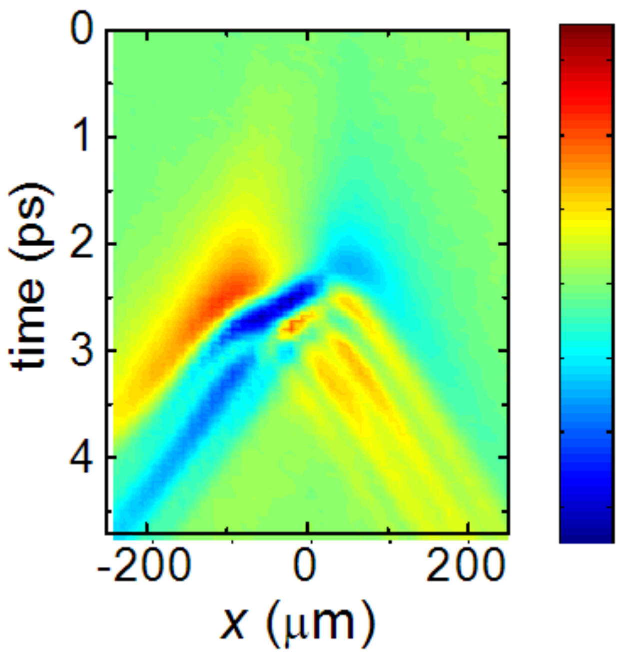




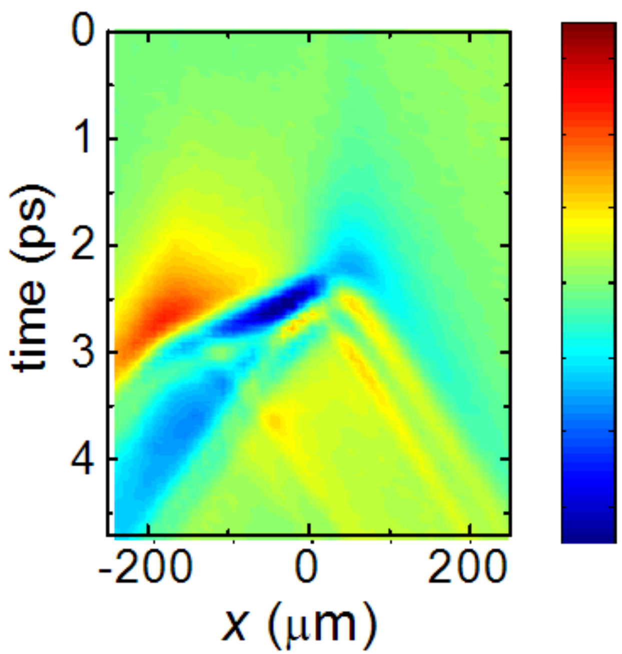
Normal incidence, 220 μm



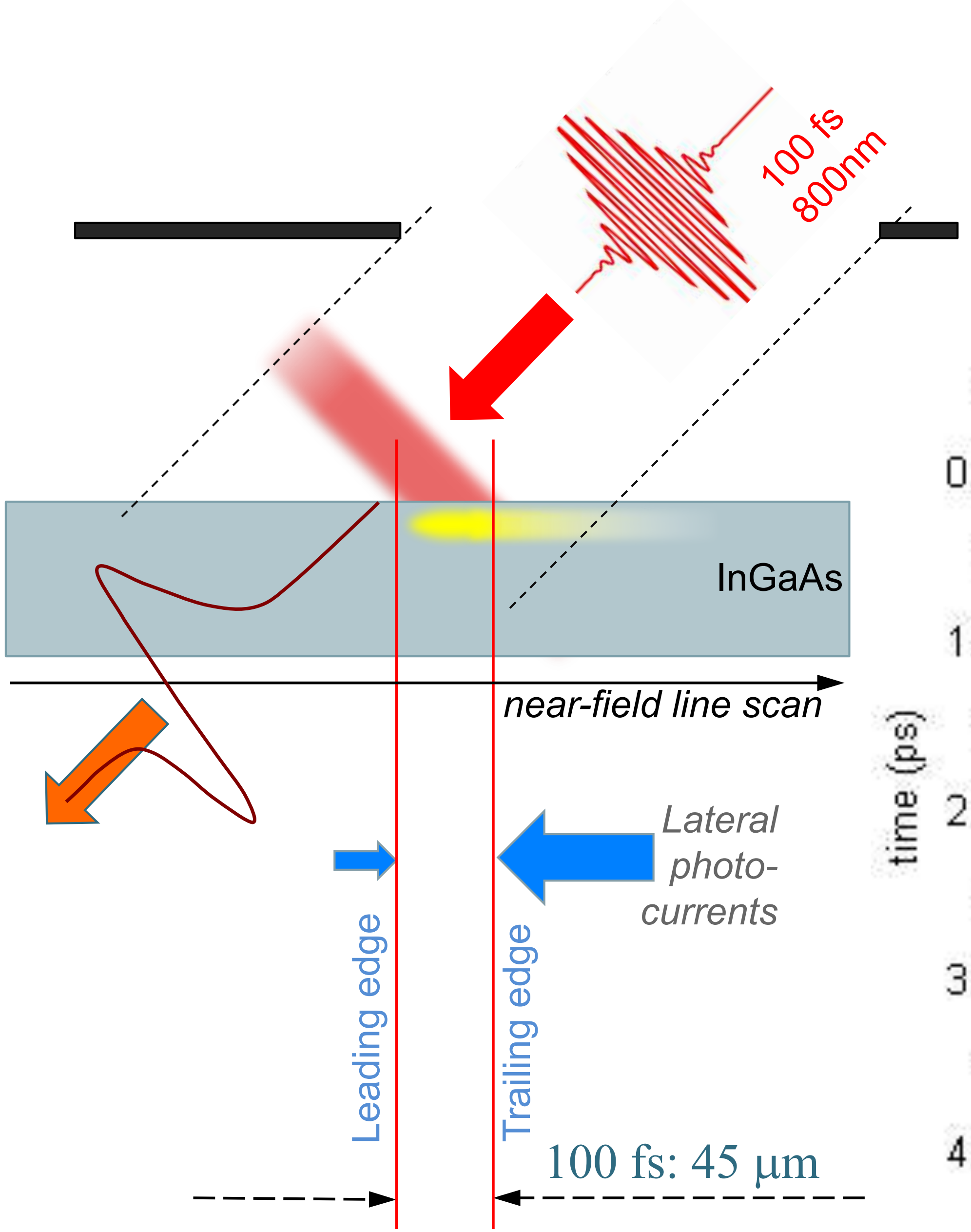
45 deg., 150 μm

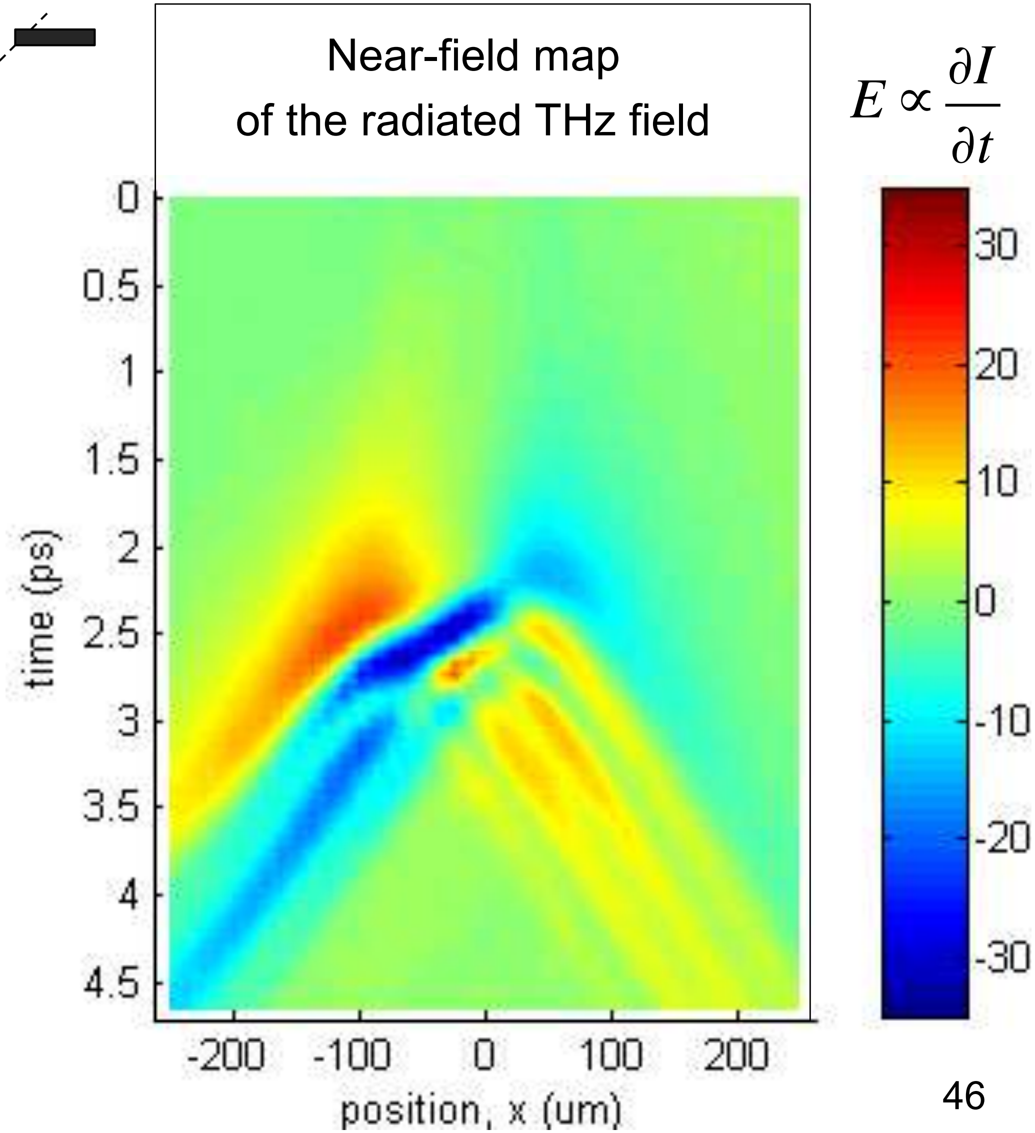


45 deg., 250 μm



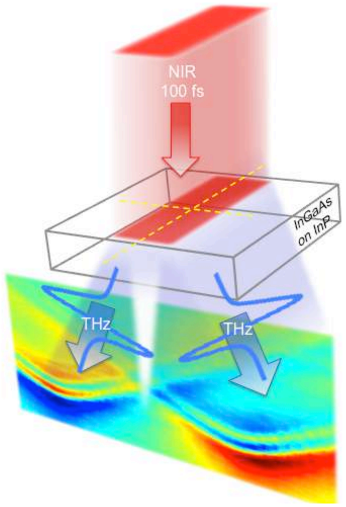
THz emission for the angle of incidence of 45 deg





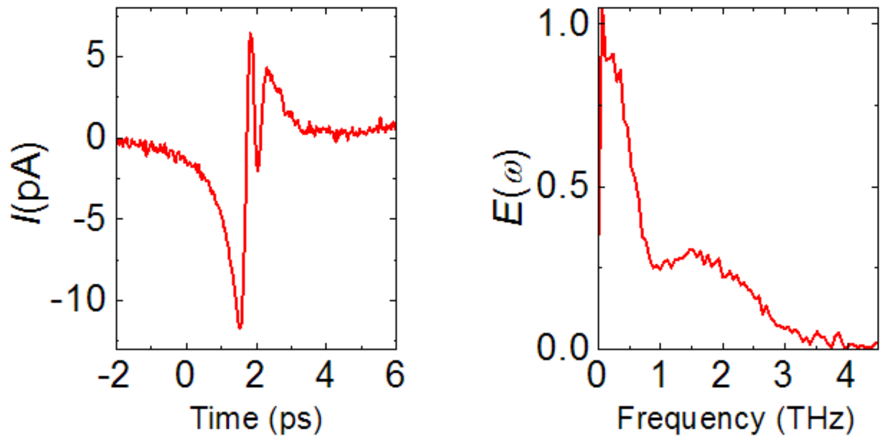
Mueckstein *et al.* THz Sci. and Technology, IEEE Trans. (2015)

Impact of near-field studies



Mueckstein *et al.* (2015)

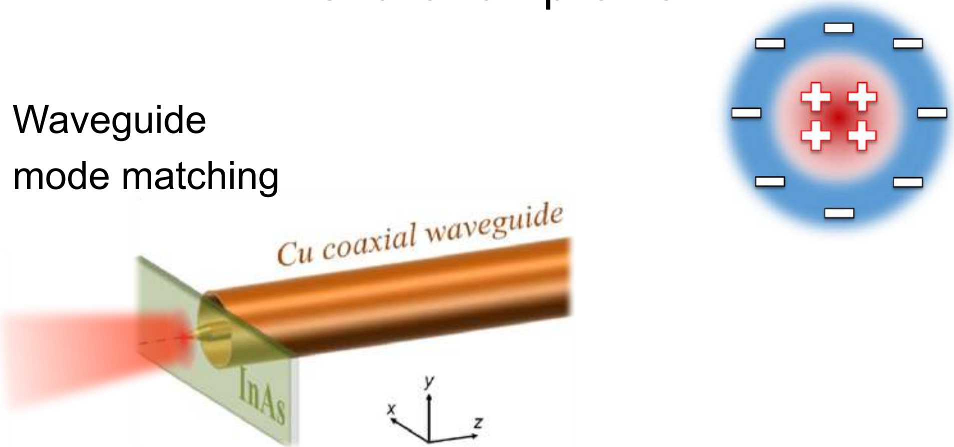
Physics of carrier dynmamics



Corzo-Garcia, Phys. Rev. B 94, 045301 (2016)

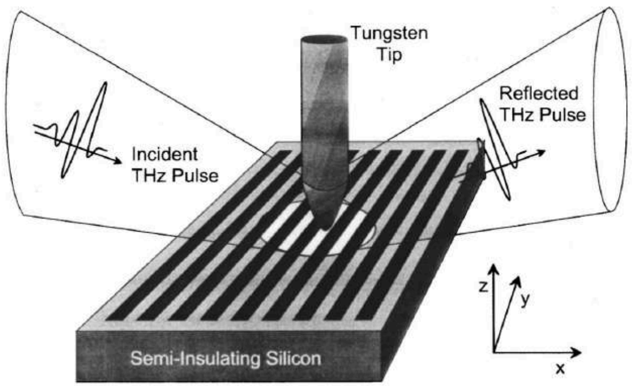
THz pulse generation through optical excitation profile

Waveguide
mode matching

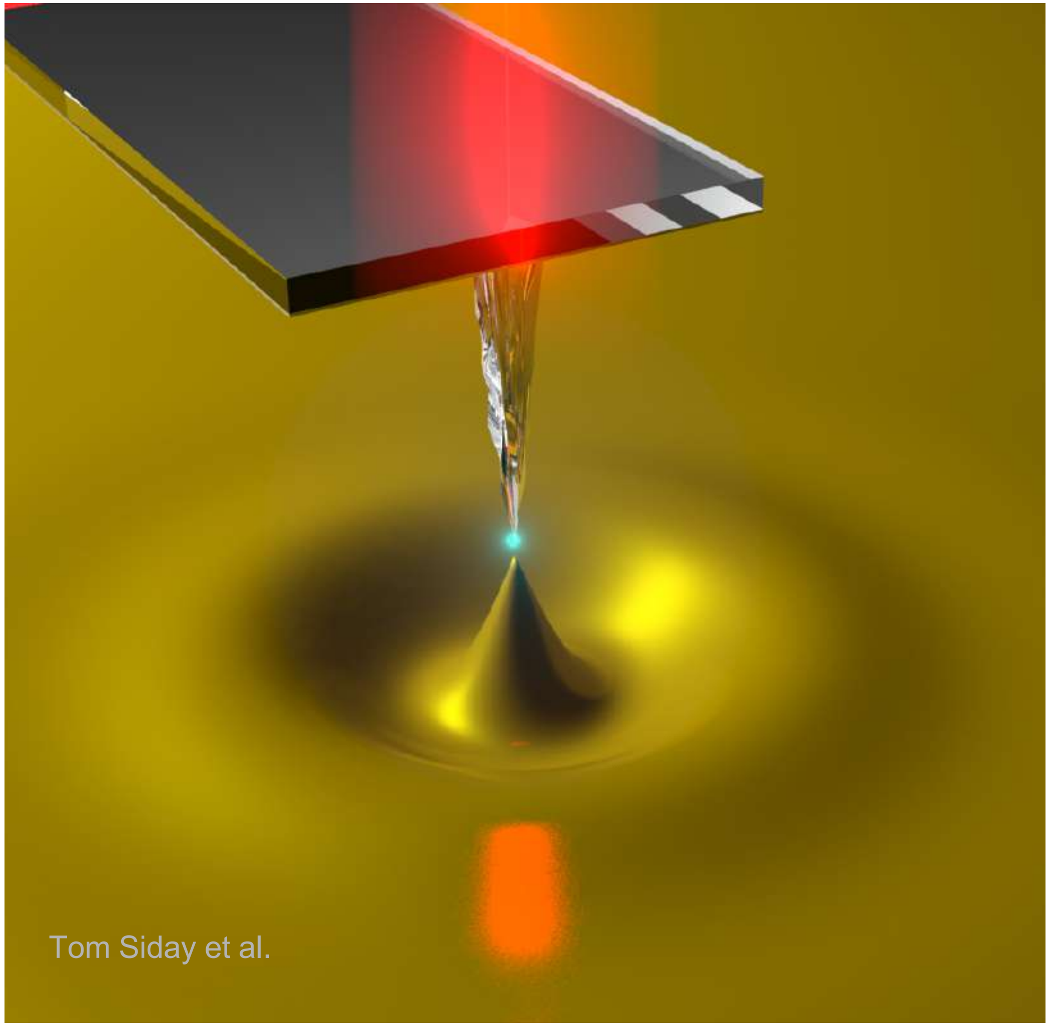


Navarro-Cia et al. Sci. Rep. 6:38926 (2016)

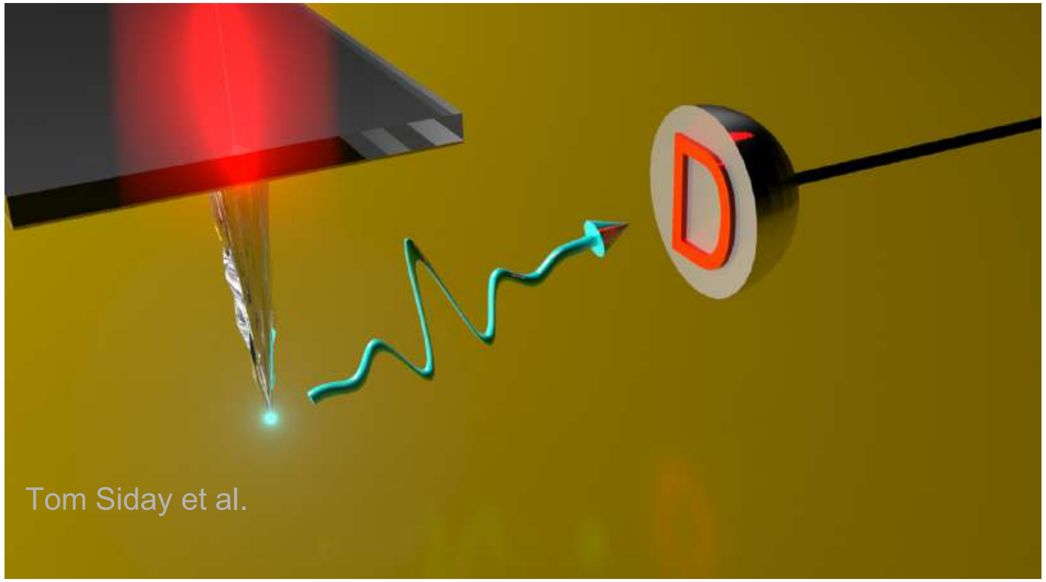
ACTIVE THz near-field probes

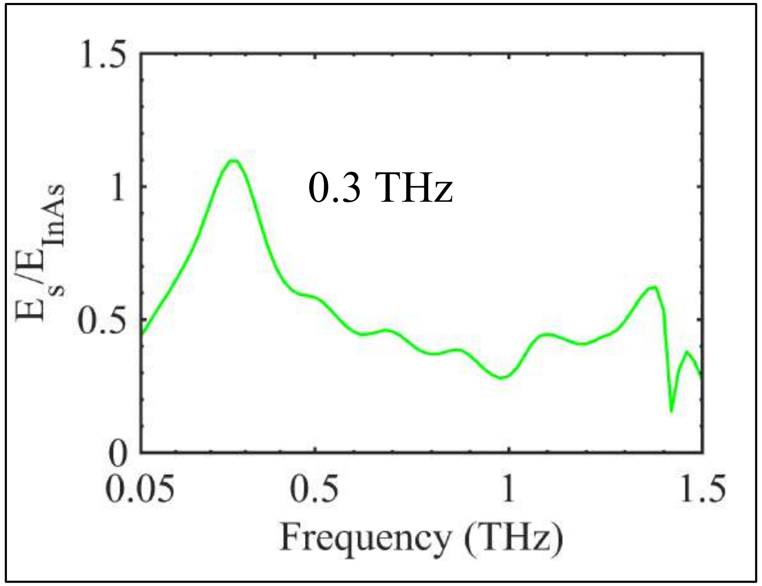


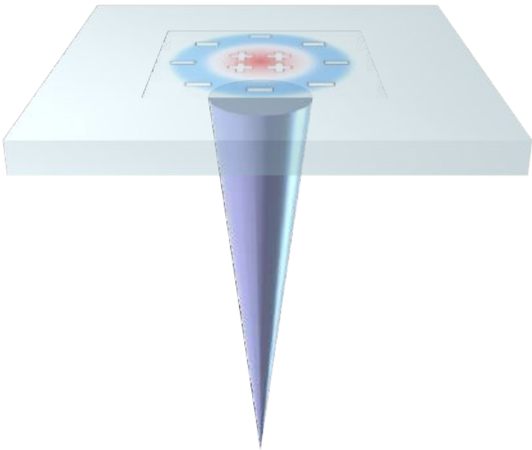
Chen et al., 2003



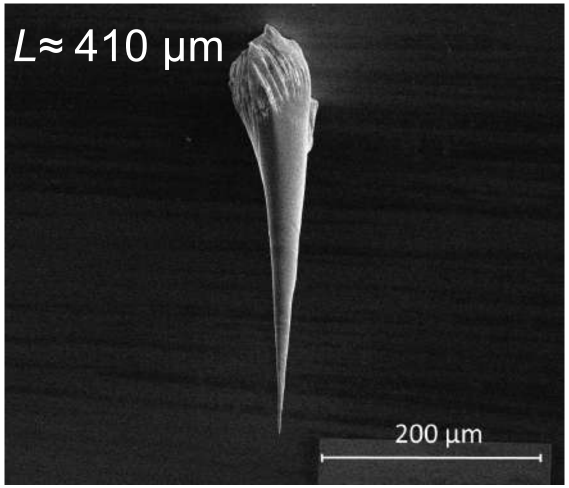
Tom Siday et al.

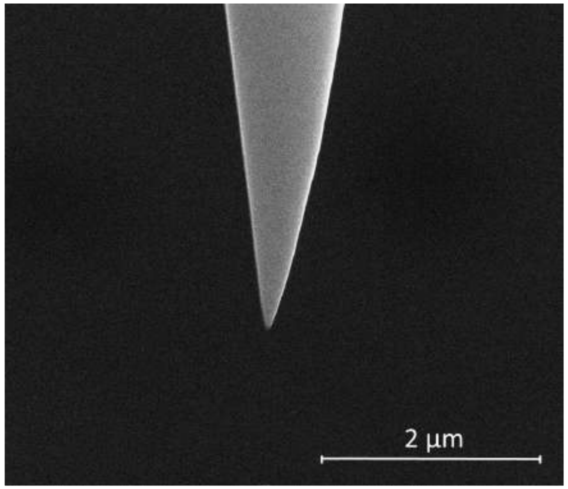


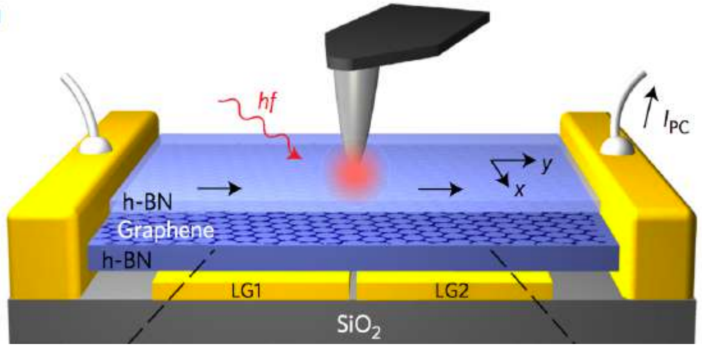


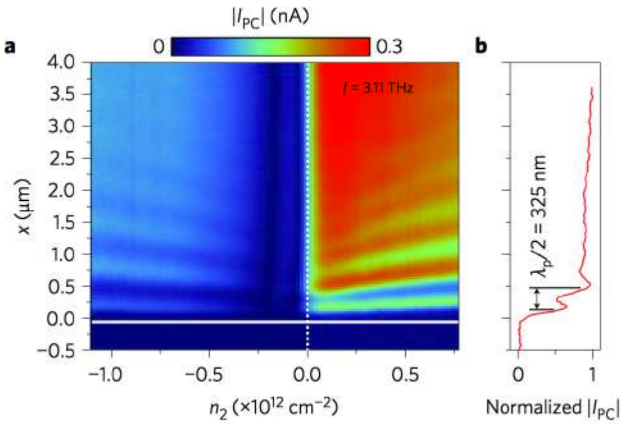


Tom Siday et al. (under review)
WC1.5 - *COZUMEL* at 17:00



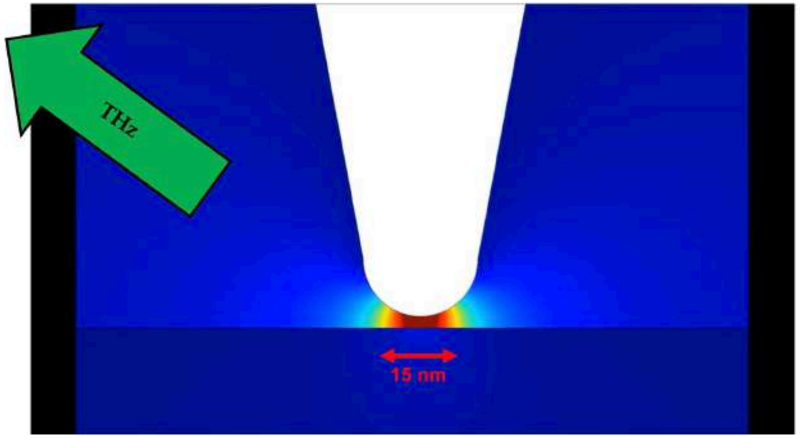






Alonso-Gonzalez et al. (2017)

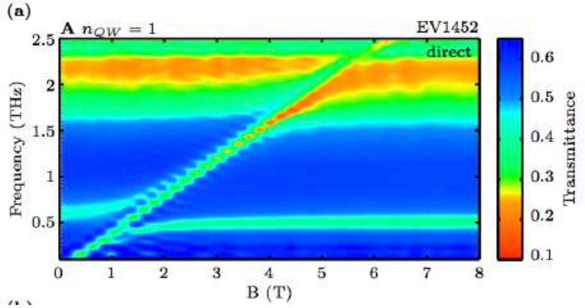
Rainer Hillenbrend - WC1.1 - *COZUMEL* at 10:30



Pernille Klarskov - WC1.2 - *COZUMEL* at 11:00

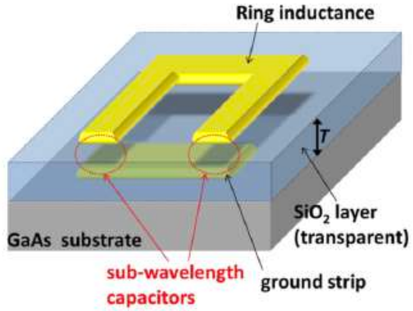
Exploiting sample-probe interaction

Light-matter coupling using resonators

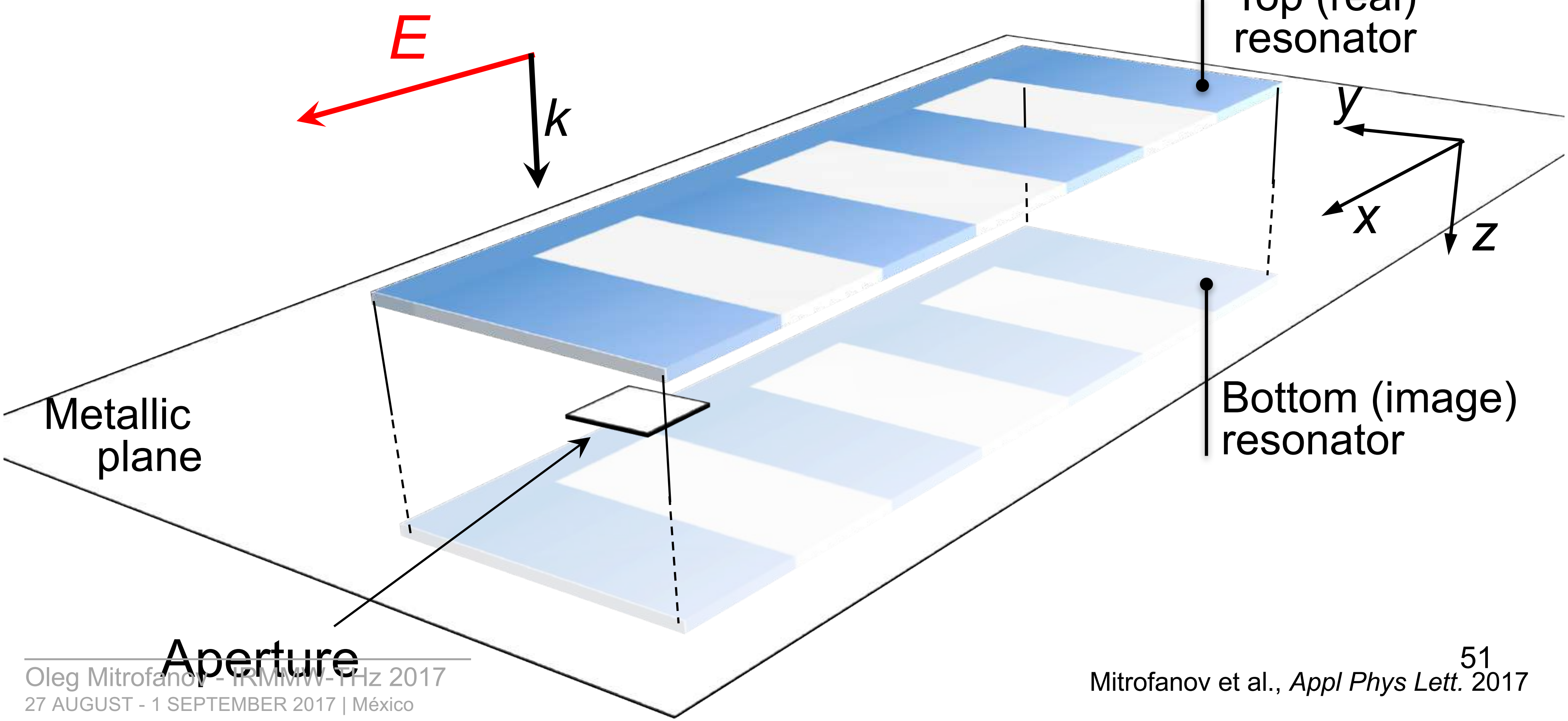


Maissen et al., *PRB* (2014)

Double metal resonators

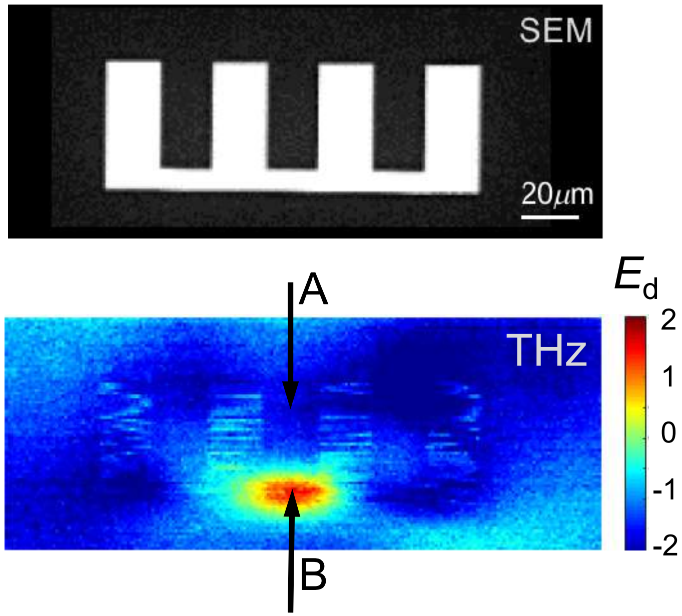


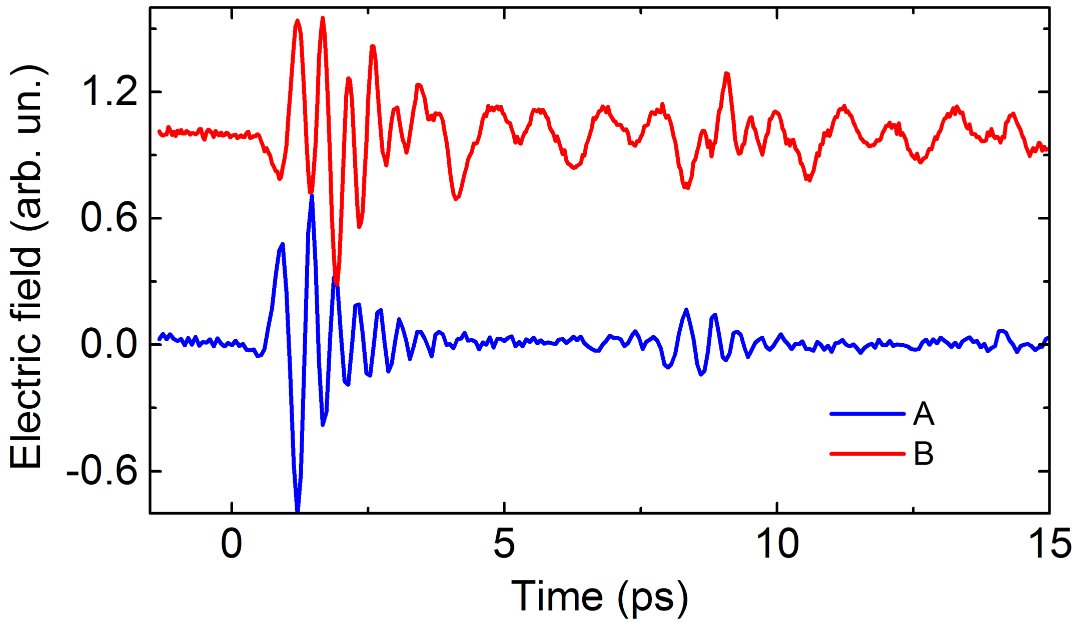
Y. Todorov et al.,
Op Ex. 23, 16838 (2015)



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

Detection of fields inside Double metal resonators

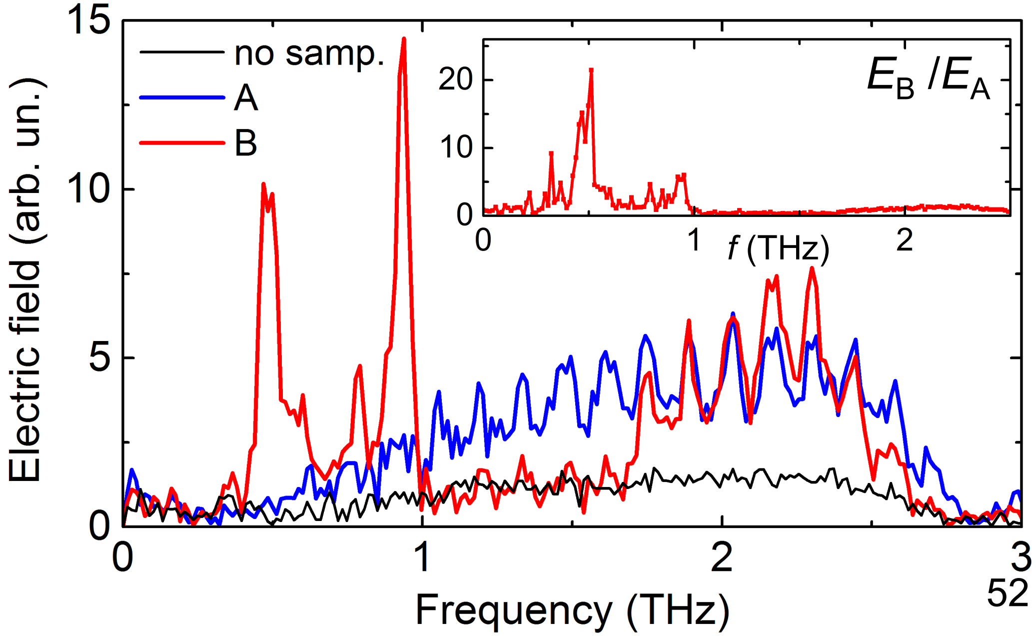




Detection of *internal* THz fields inside an individual Double-metal resonator by aperture-type probe

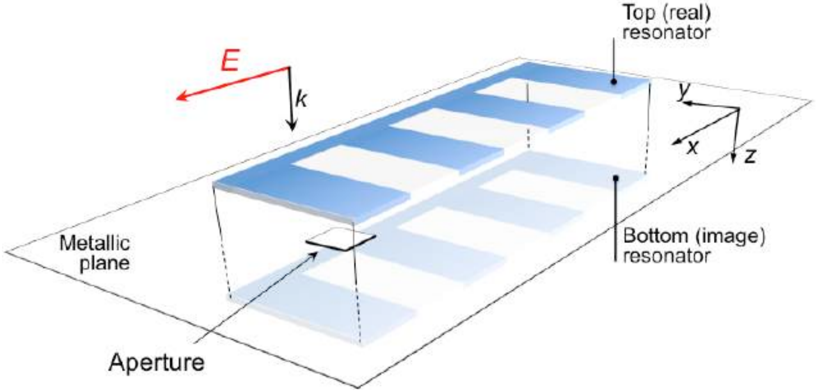
Full spectroscopic signature (enhancement and suppression)

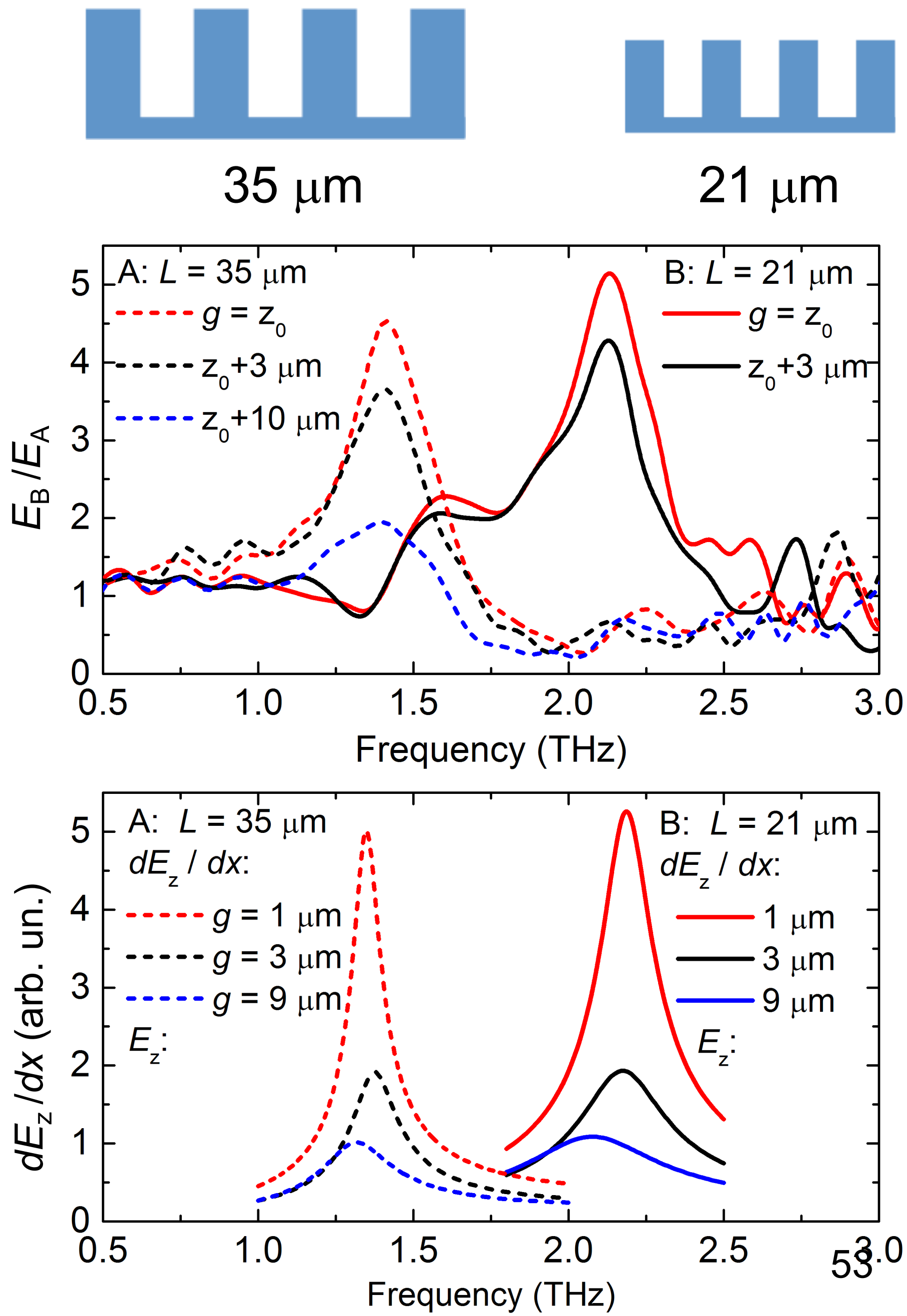
Resonance at ~0.5 THz (the enhancement is high ~20)



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

Interaction of the resonator with the probe





Internal THz fields inside individual Double-metal resonator be probed by aperture type THz near-field microscopy

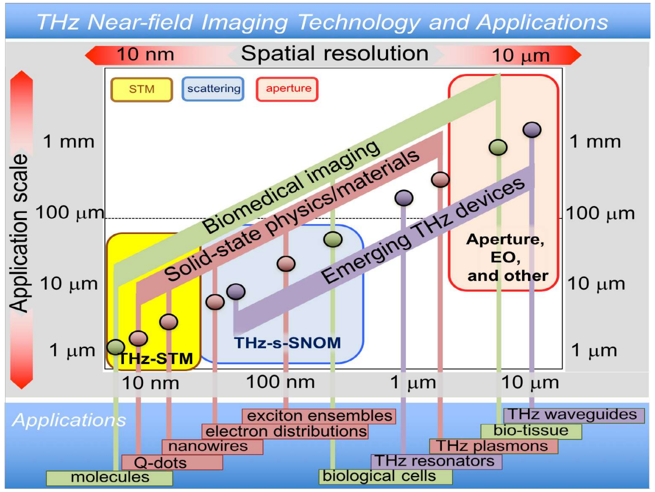
THz time domain spectroscopy

Field distribution (mode)

Tuning of the interaction and the resonant frequency is possible by size and the sample-probe separation

Summary

Imaging beyond the diffraction limit in the THz range enables a wide range of studies



No single near-field technology currently covers the entire range of applications

Technological limits have been broken repeatedly by novel THz devices and near-field techniques

Further development of the field of THz near-field microscopy will benefit from expanding the application spectrum, which sometimes leads to unexpected discoveries

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