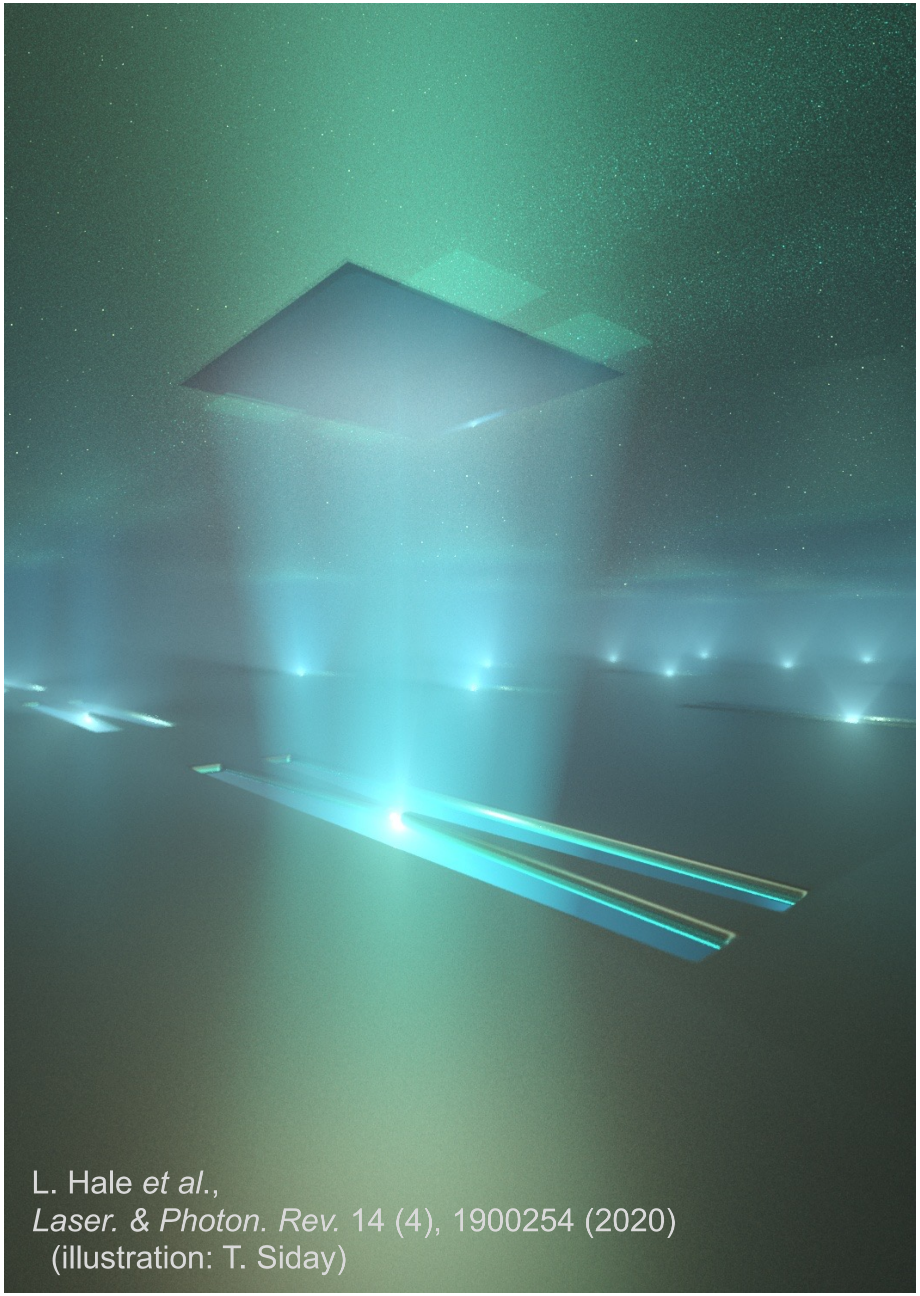
THz near-field Imaging and Spectroscopy:

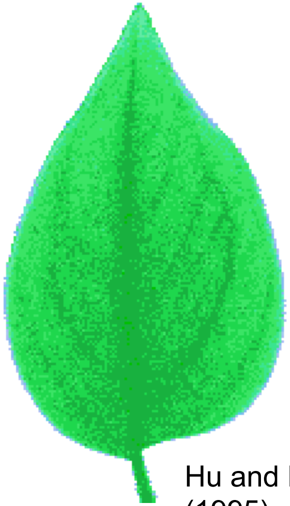
Fundamentals, Technology and Current Trends

Oleg Mitrofanov
UCL


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

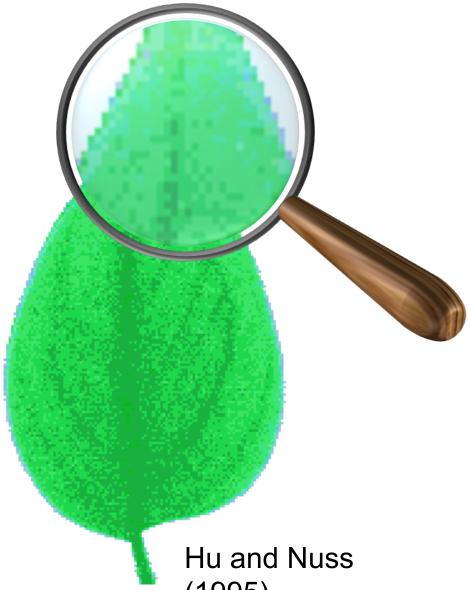
Winter College on Optics (ICTP)
Terahertz Optics and Photonics
Trieste, Italy
Feb 6-17, 2023

THz Imaging



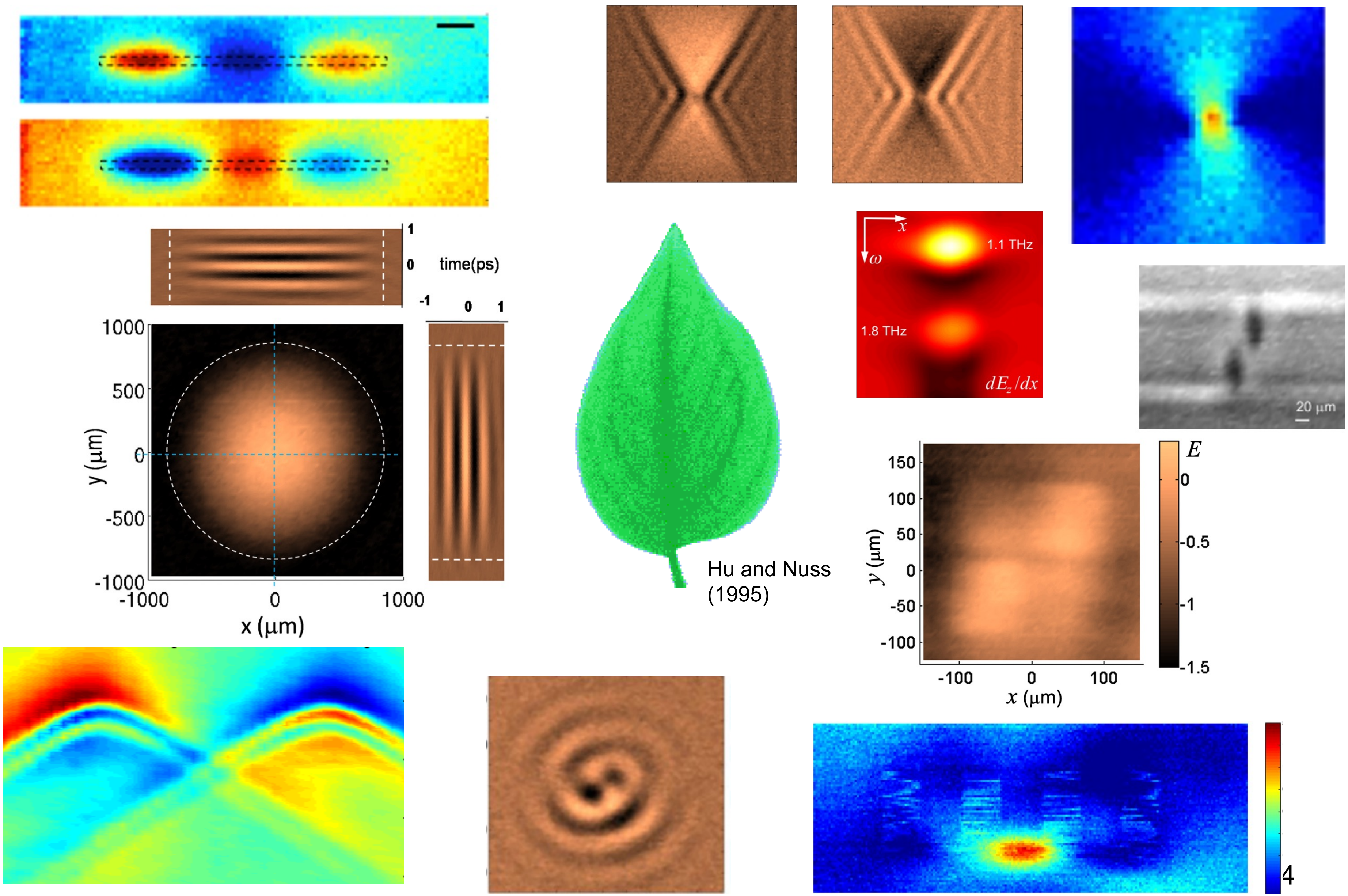
Hu and Nuss (1995)

THz Imaging – Spatial Resolution

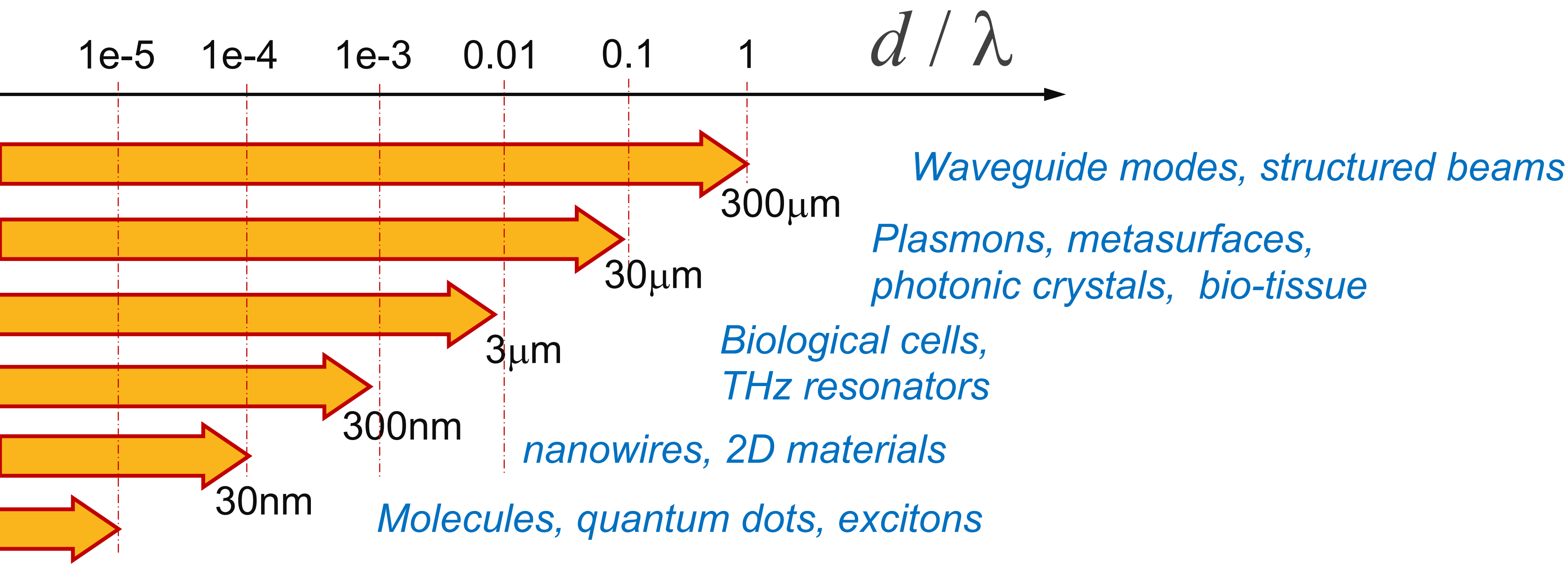


Hu and Nuss
(1995)

THz Imaging – Subwavelength Spatial Resolution

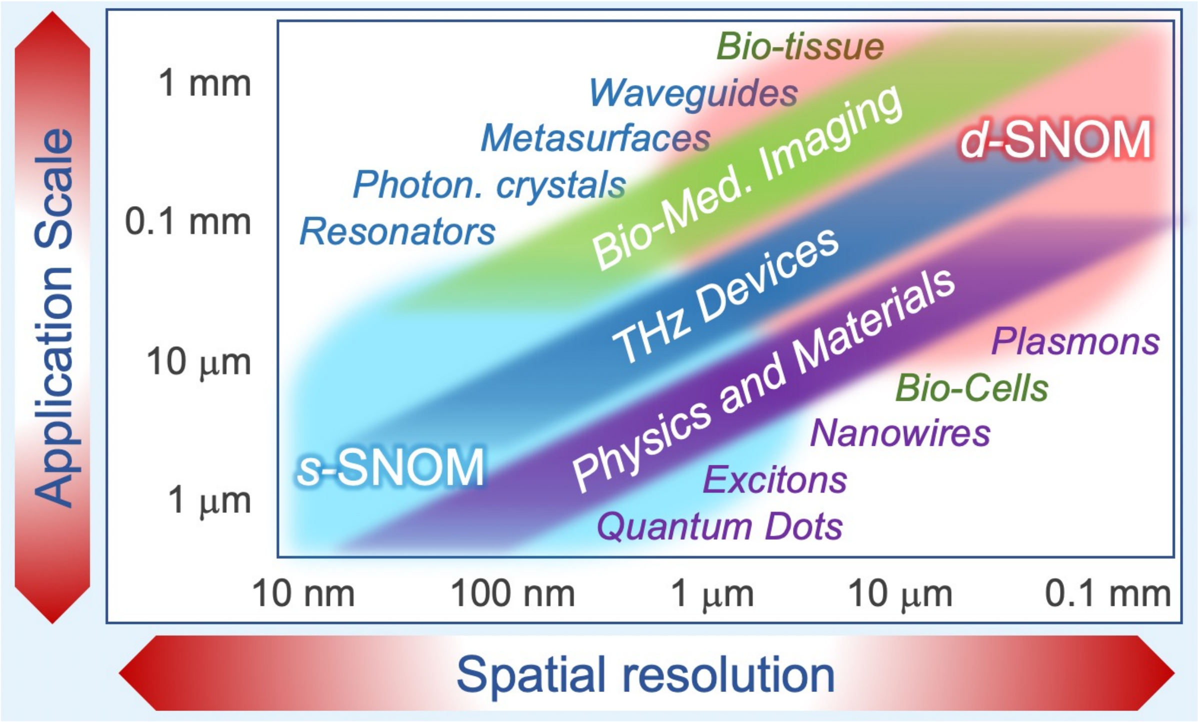


Wide range of subwavelength size systems

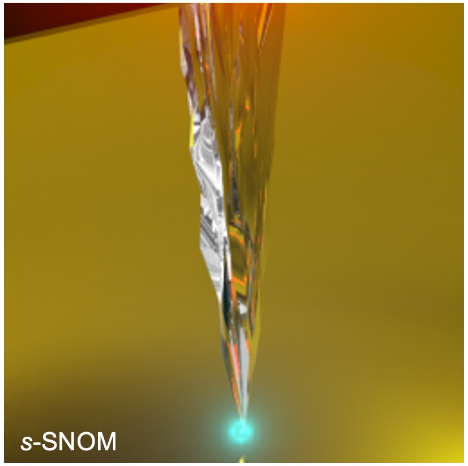


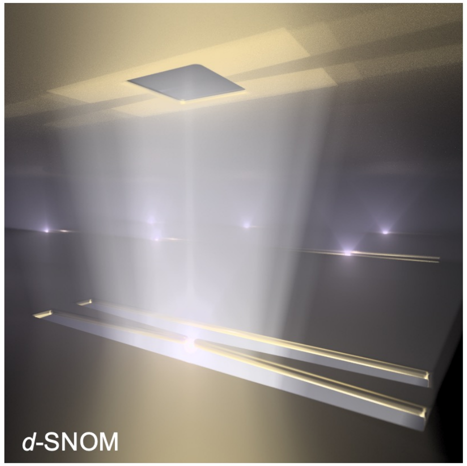
How do we enable THz imaging?

THz Near-Field Microscopy Application Space



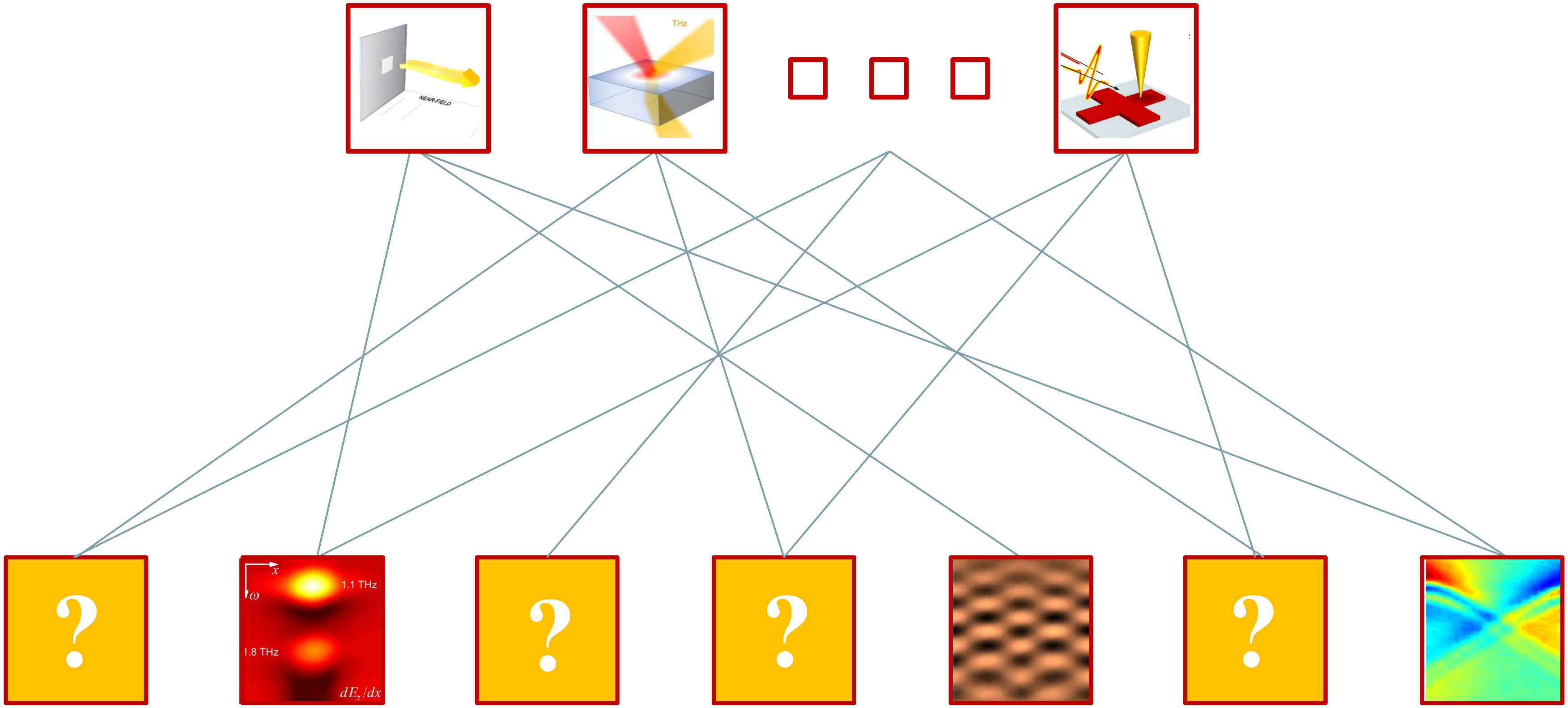
Boland et al. THz Roadmap (2023)





Graphics: Tom Siday

THz near-field Microscopy Approaches



THz near-field microscopy applications

Right instrument for a given problem

Appropriate problems for a given instrument

Tutorial Topics

Fundamentals of THz near-field microscopy

Examples:

- Microscopy and Spectroscopy of THz resonators
- Imaging of THz surface plasmon waves

Image interpretation

Technology:

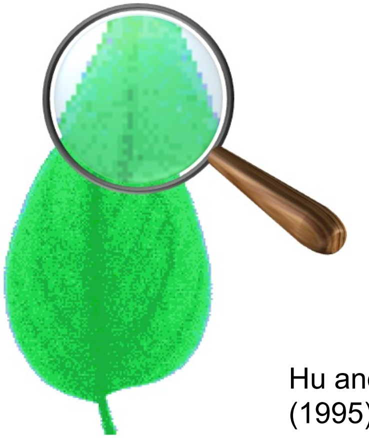
- Subwavelength aperture and Scattering tip probes
- Improving sensitivity in THz microscopy

Current Trends in THz microscopy methods

Spatial Resolution

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

Ernst Abbe (c. 1873)



Hu and Nuss
(1995)

Spatial Resolution

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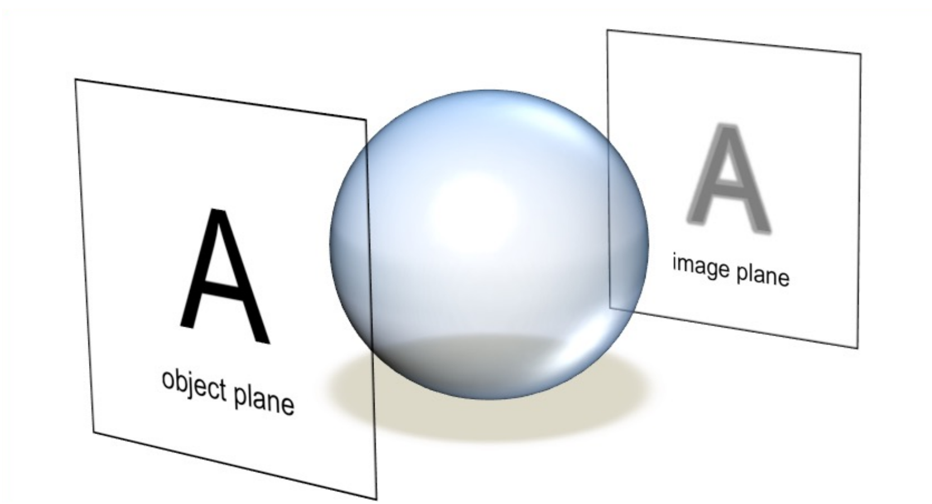
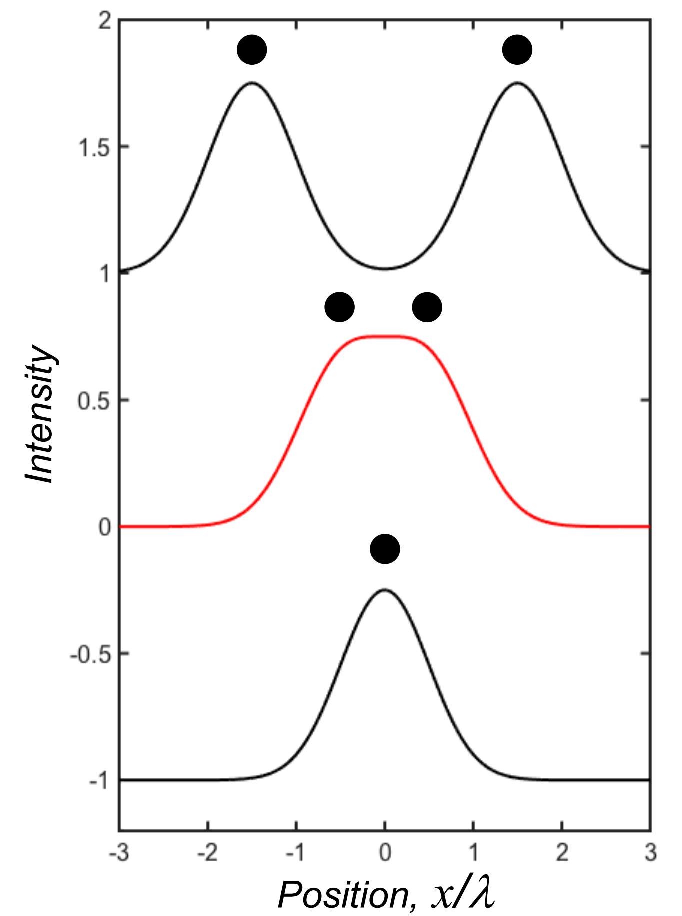
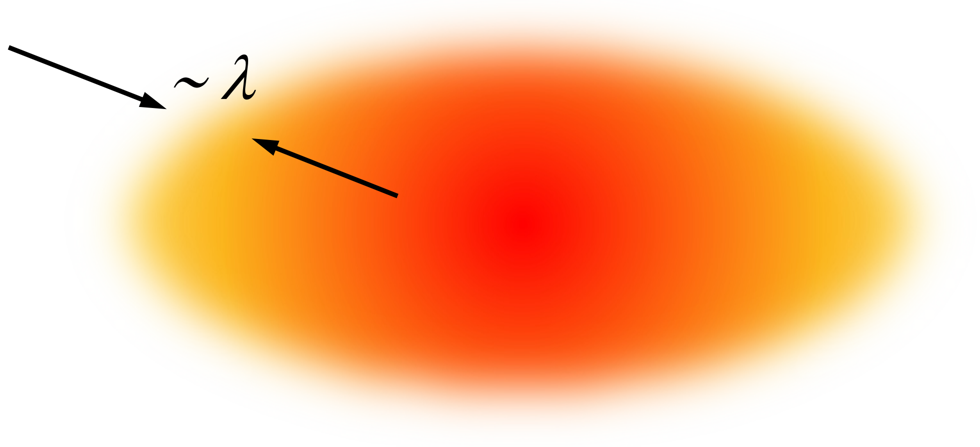
Ernst Abbe (c. 1873)



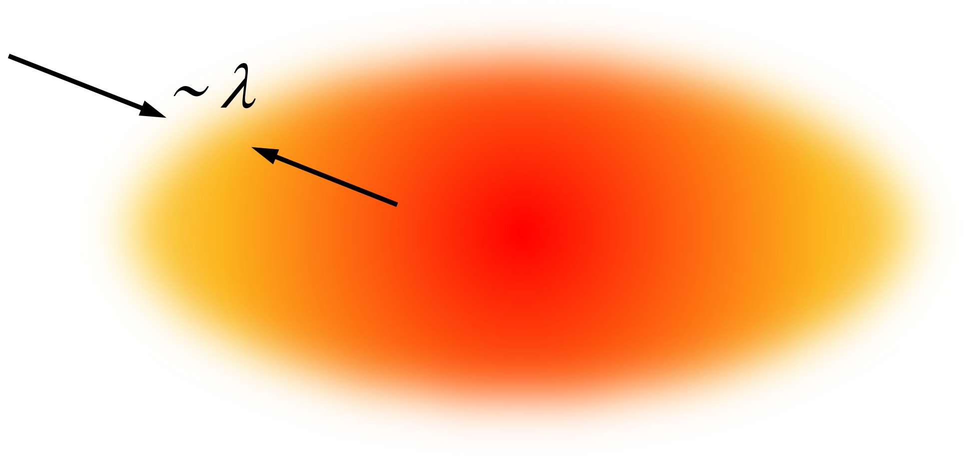
Far-Field – propagating waves:
point-spread function
limits resolving two points

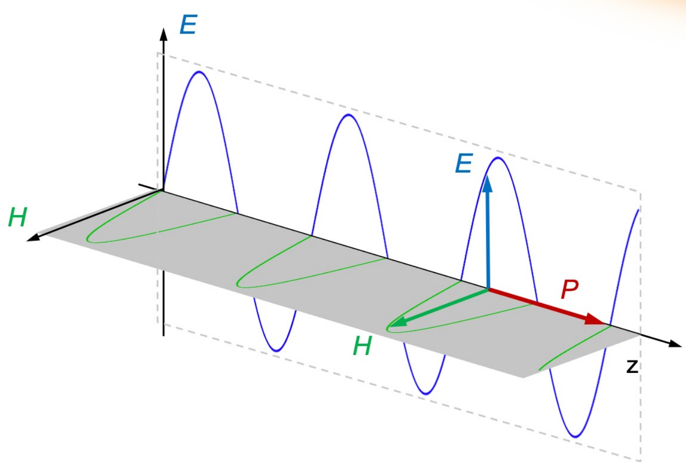


Spatial Resolution

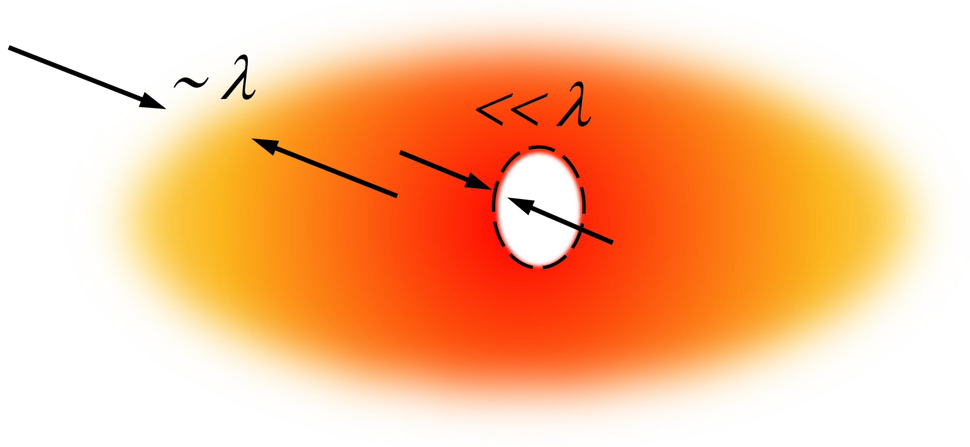


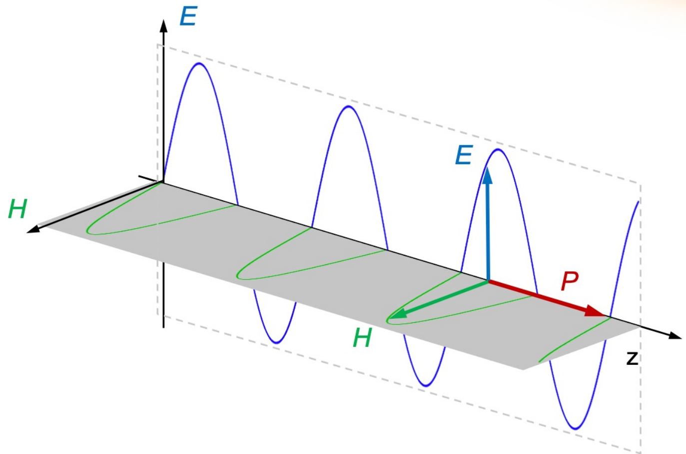
Spatial Resolution



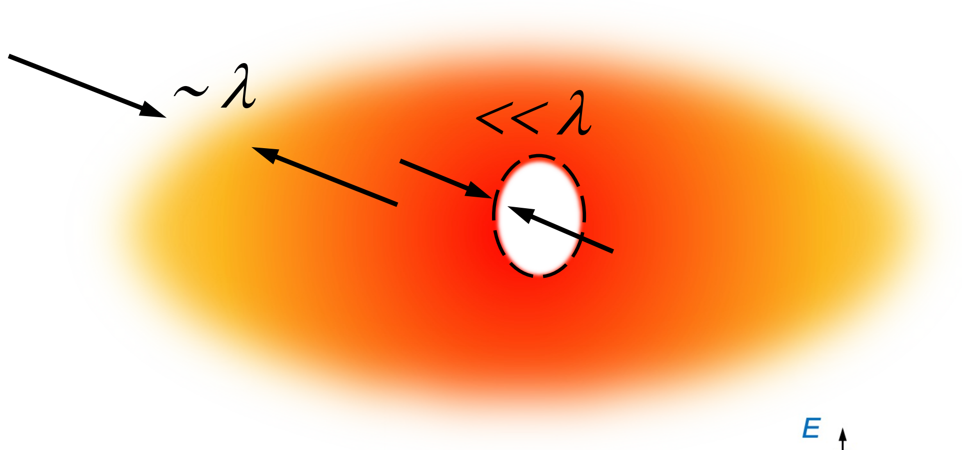


Spatial Resolution

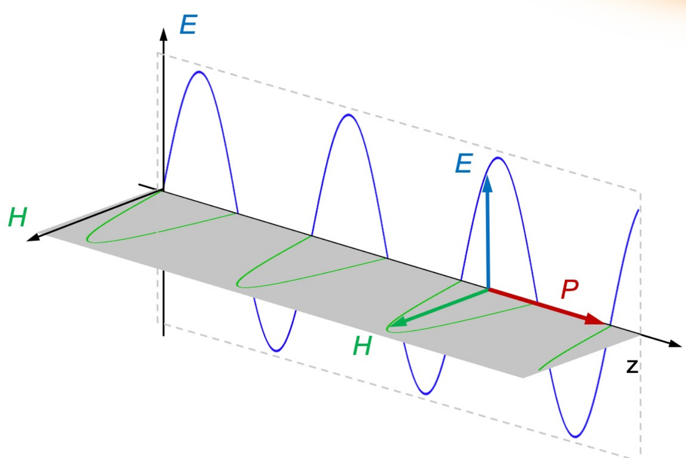


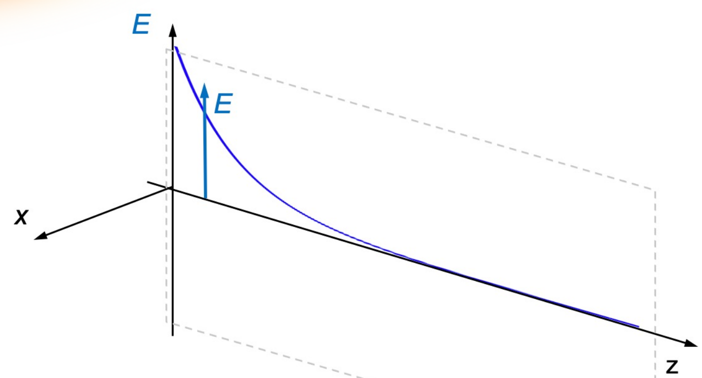


Spatial Resolution



Induced charges and Polarization



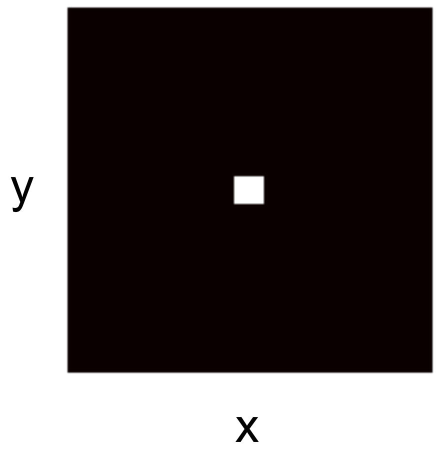


$$E_T(z,t) = E_T^{(0)} e^{i(kz-\omega t)}$$

Evanescent waves allow EM wave confinement on subwavelength scale

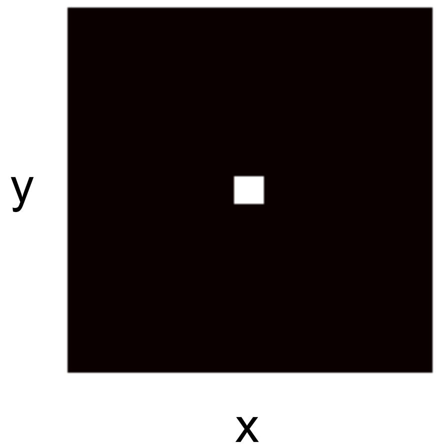
How to include Evanescent Waves into analysis framework?

Angular spectrum representation of EM fields



Spatial distribution

$$E(k_x, k_y) = \frac{1}{4\pi^2} \iint_{xy} E(x, y) e^{-i\left[k_x x + k_y y\right]} dx dy$$



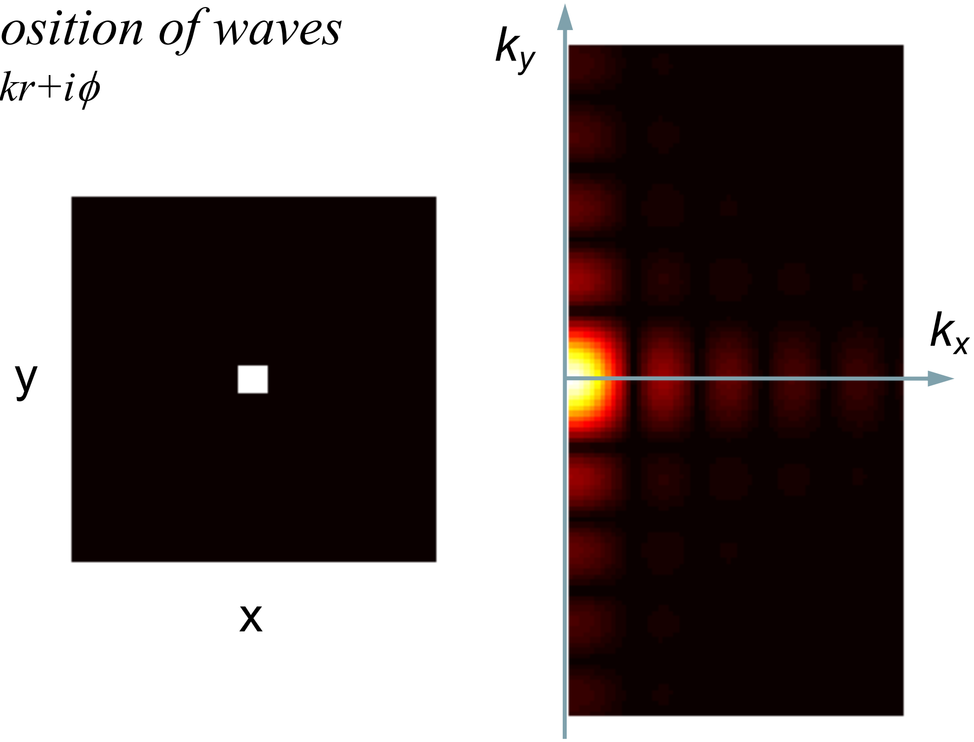
Spatial distribution

2D Fourier transform

$$E(k_x, k_y) = \frac{1}{4\pi^2} \iint_{xy} E(x,y) e^{-i[k_x x + k_y y]} dxdy$$

E(x,y) is a superposition of waves

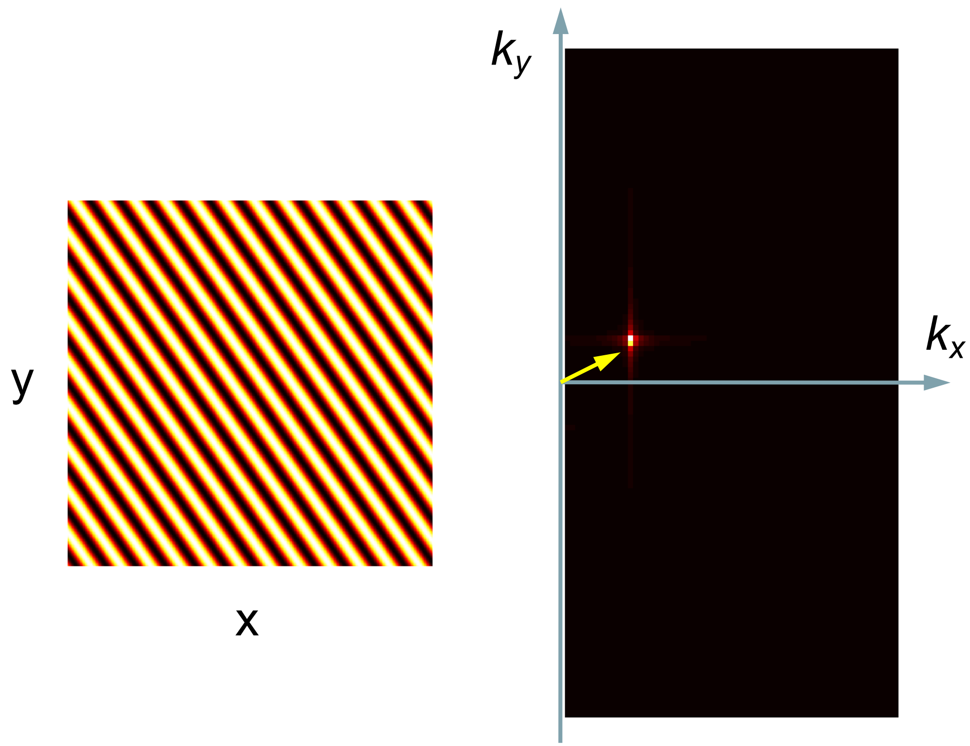
$$E(k)\ e^{ikr+i\phi}$$



Spatial distribution ⟷ *k-space distribution*

Fourier Transform

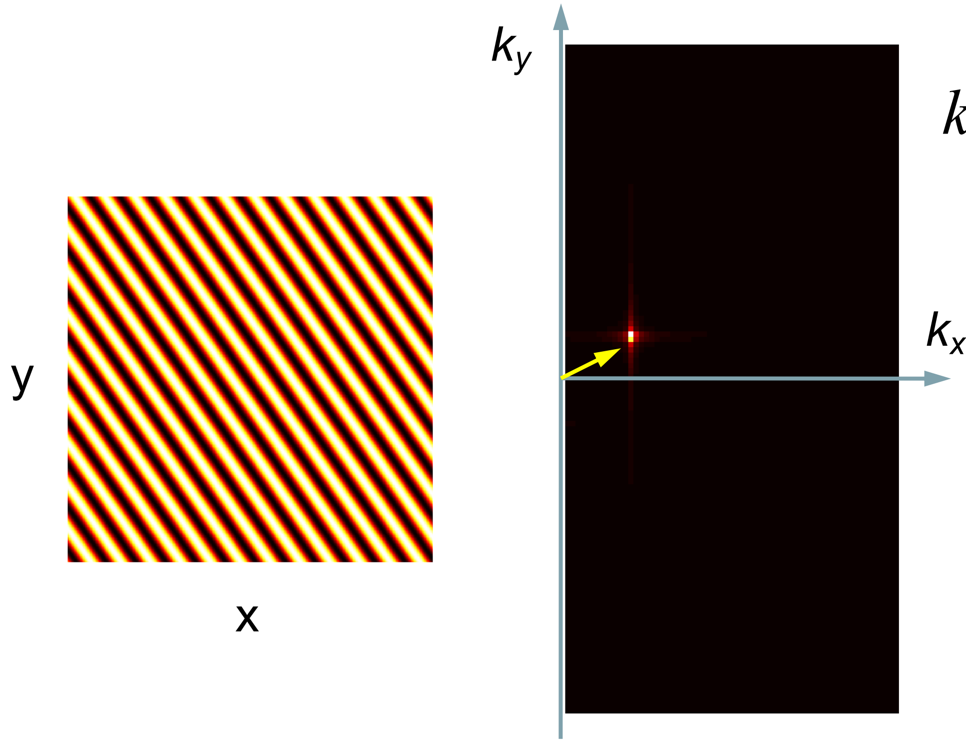
2D Fourier transform



Spatial distribution ⟷ *k-space distribution*

Fourier Transform

2D Fourier transform

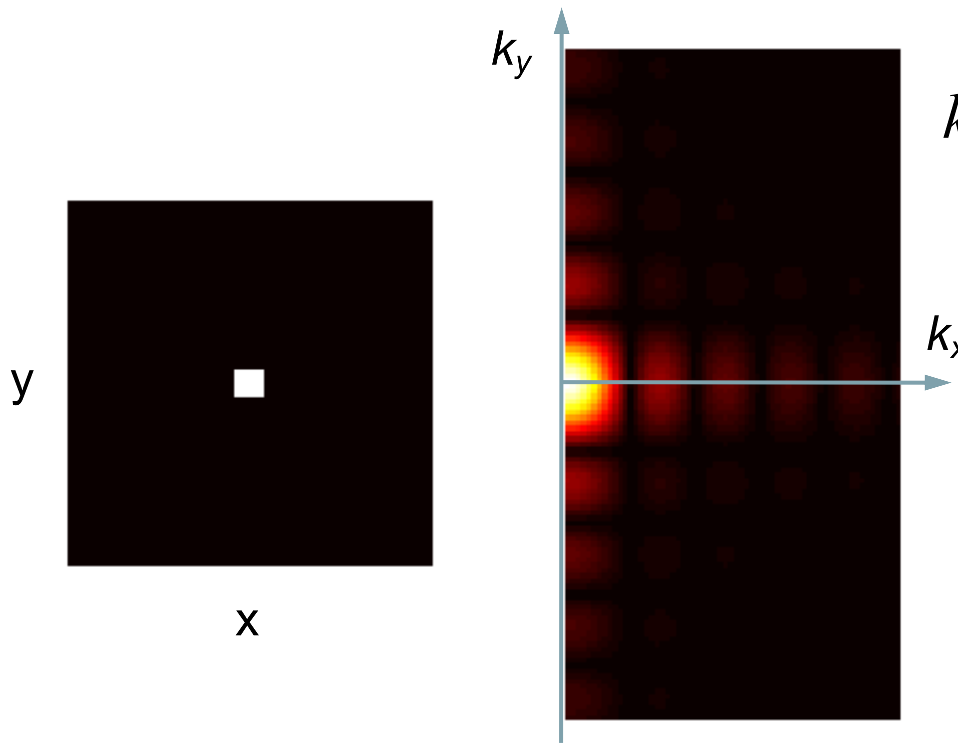


$$k_x^{\,2} + k_y^{\,2} = k_0^{\,2}$$

Spatial distribution ⟷ *k-space distribution*

Fourier Transform

2D Fourier transform



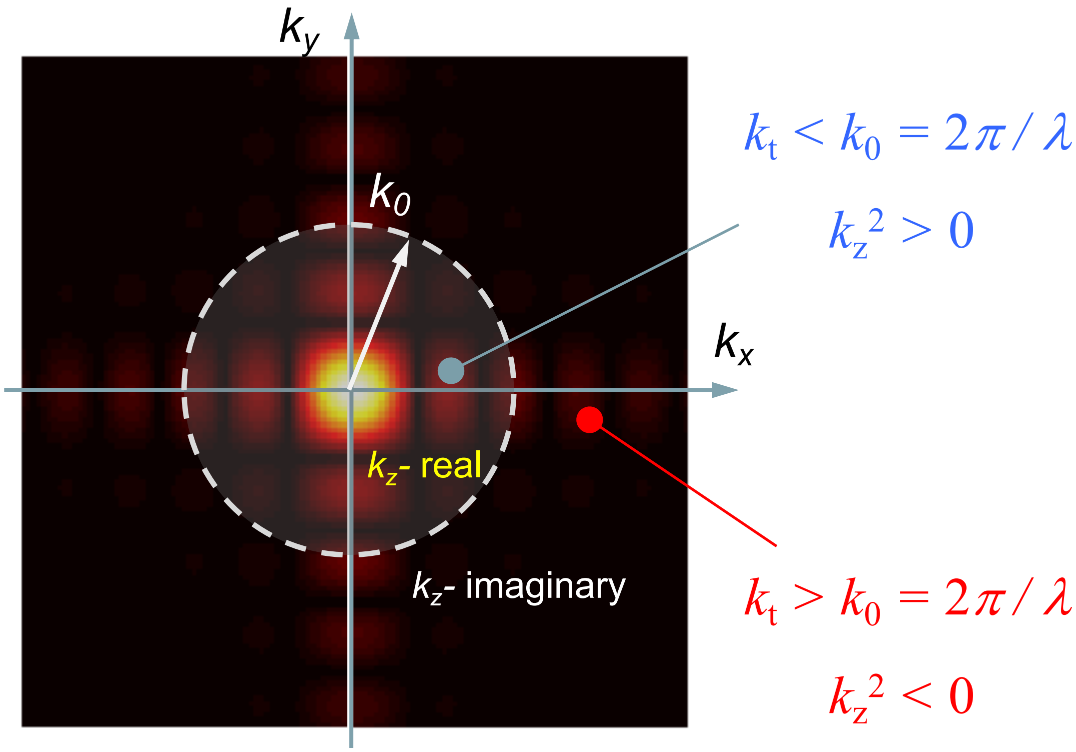
$$k_x^2 + k_y^2 + k_z^2 = \\ = k_0^2$$

Spatial distribution ⟷ *k-space distribution*

Fourier Transform

Angular spectrum representation of EM fields

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

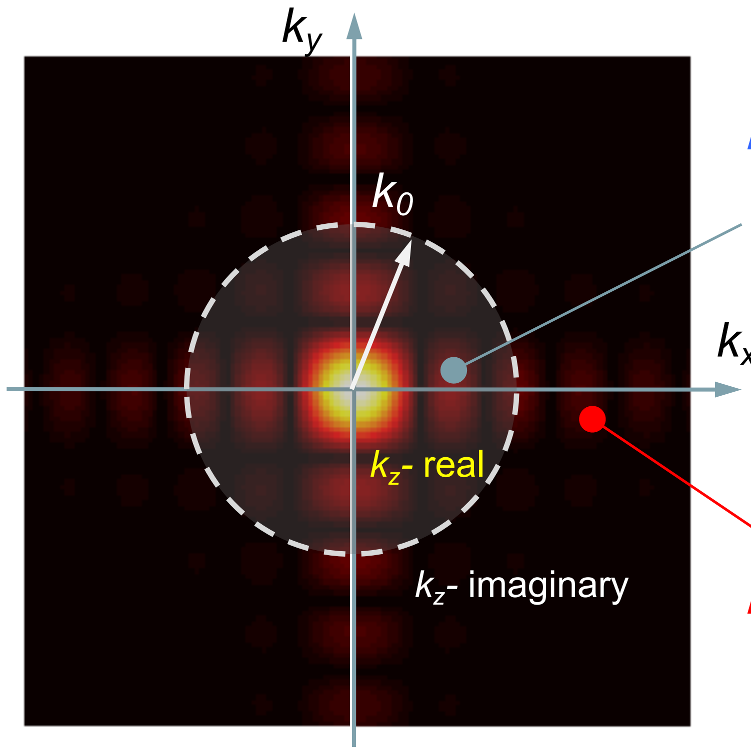


Any subwavelength field distribution contains imaginary k_z components – evanescent waves, localized near objects and interfaces

Angular spectrum representation of EM fields

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

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



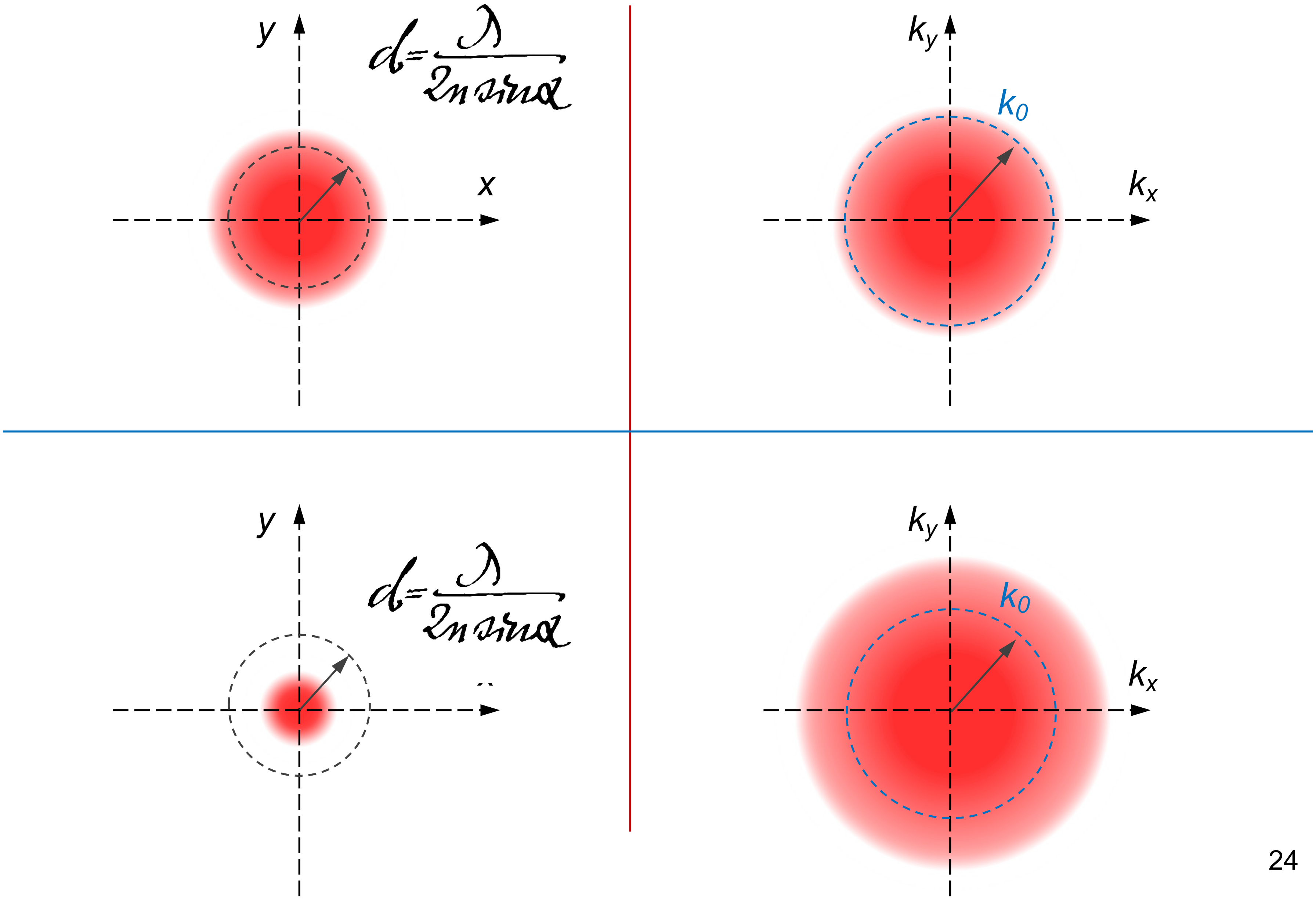
$$k_t < k_0 = 2\pi/\lambda$$

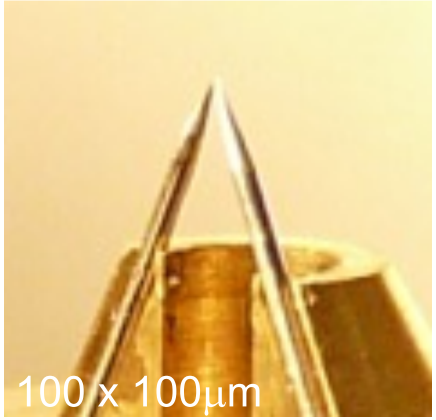
$$k_z^2 > 0$$

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

$$k_z^2 < 0$$

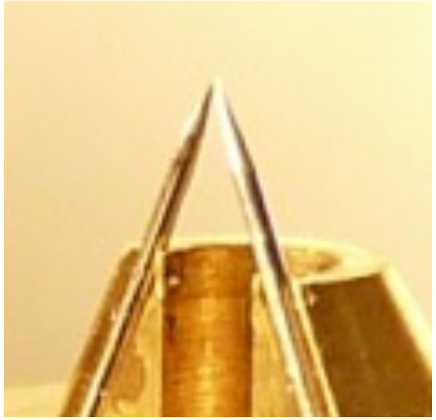
Any subwavelength field distribution contains imaginary k_z components – evanescent waves, localized near objects and interfaces


y
x
k_y
k_0
k_x
y
k_y
k_0
k_x



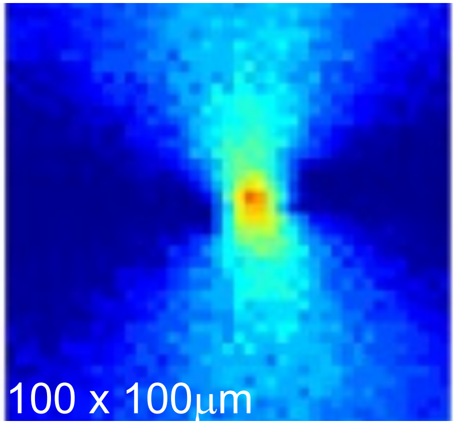
Opt. Express **20**, 6197 (2012)

THz Field Confinement

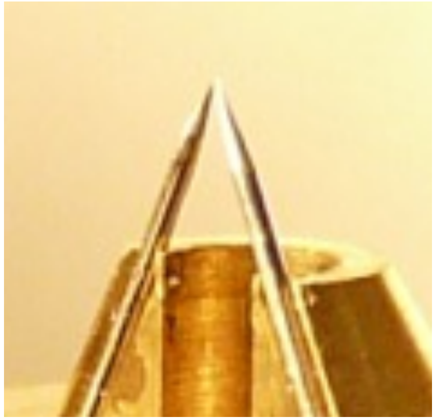


$\lambda \sim 200\ \mu m$

$d < 10\ \mu m$

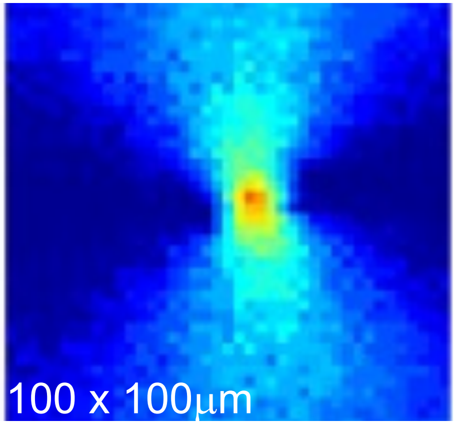


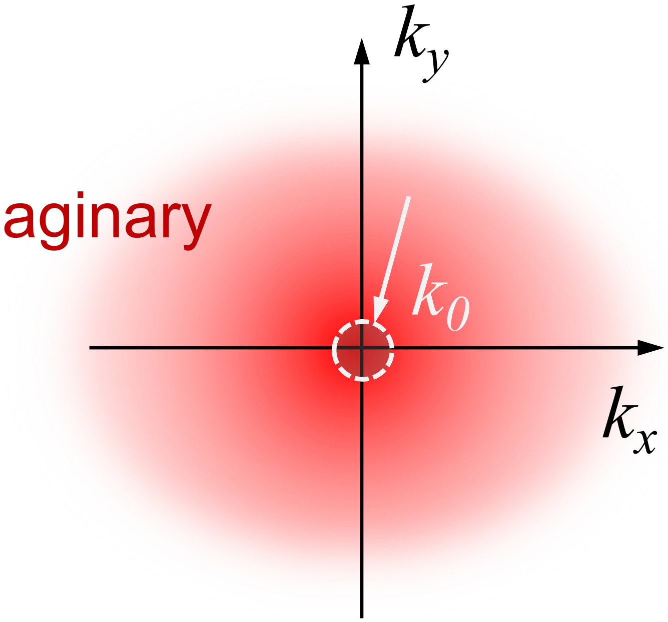
Opt. Express **20**, 6197 (2012)



$\lambda \sim 200\ \mu m$

$d < 10\ \mu m$





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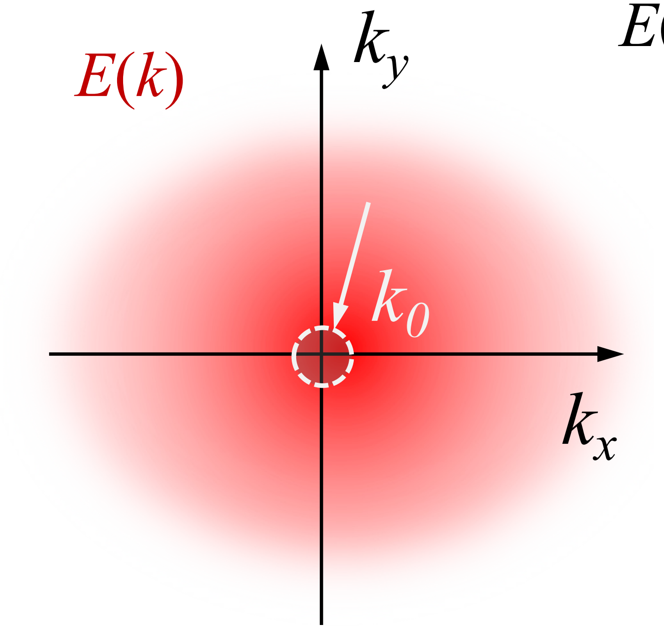
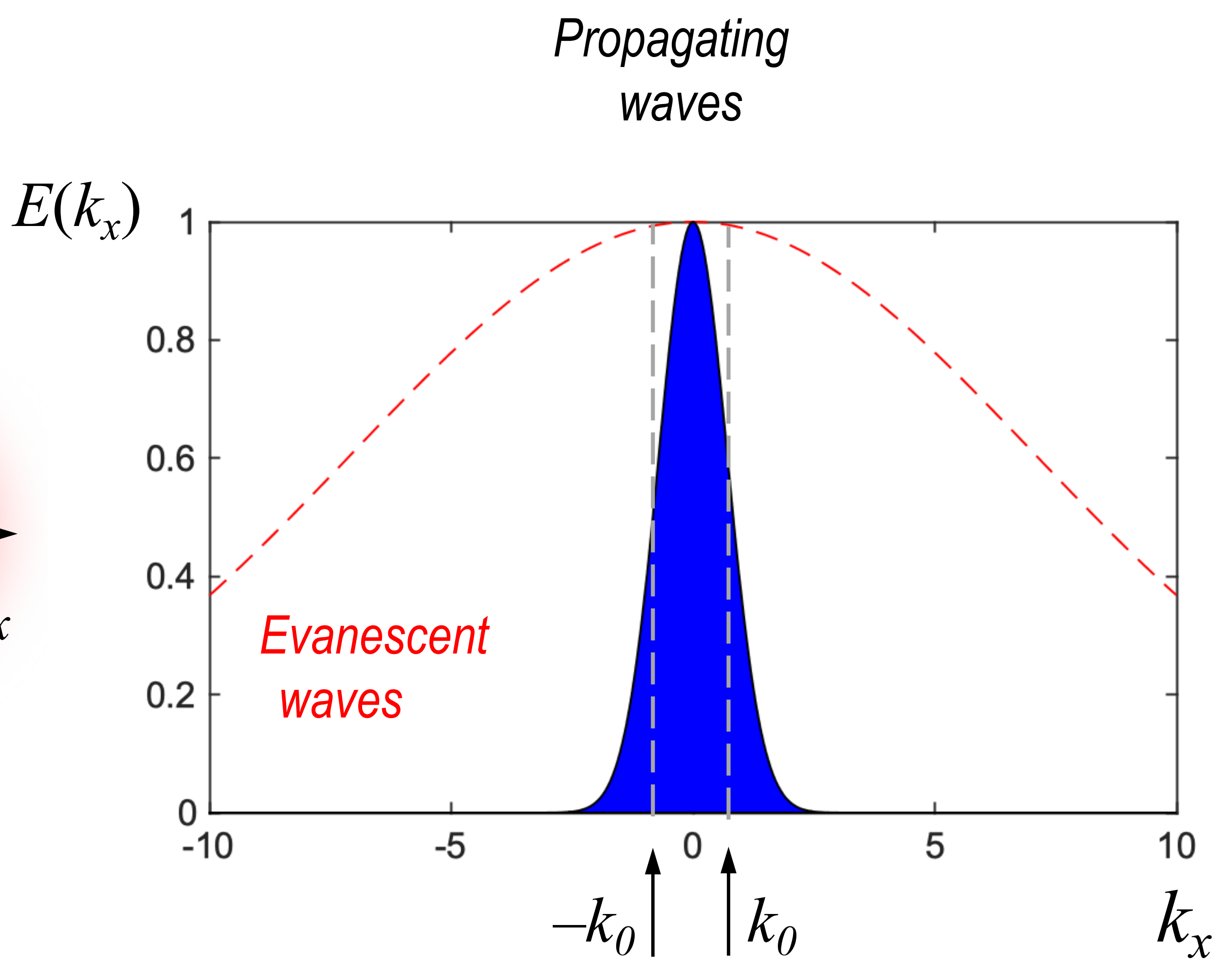
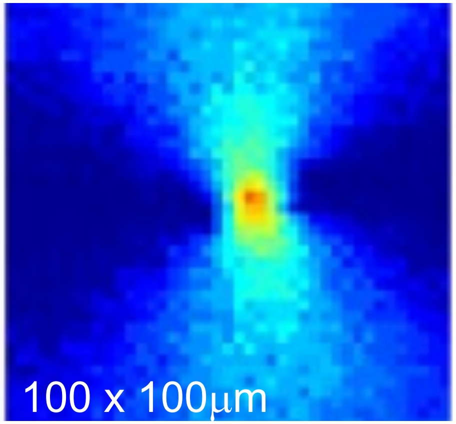
Representation in k-space





THz Field Confinement



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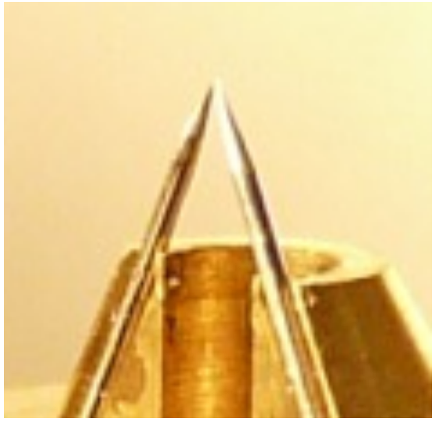

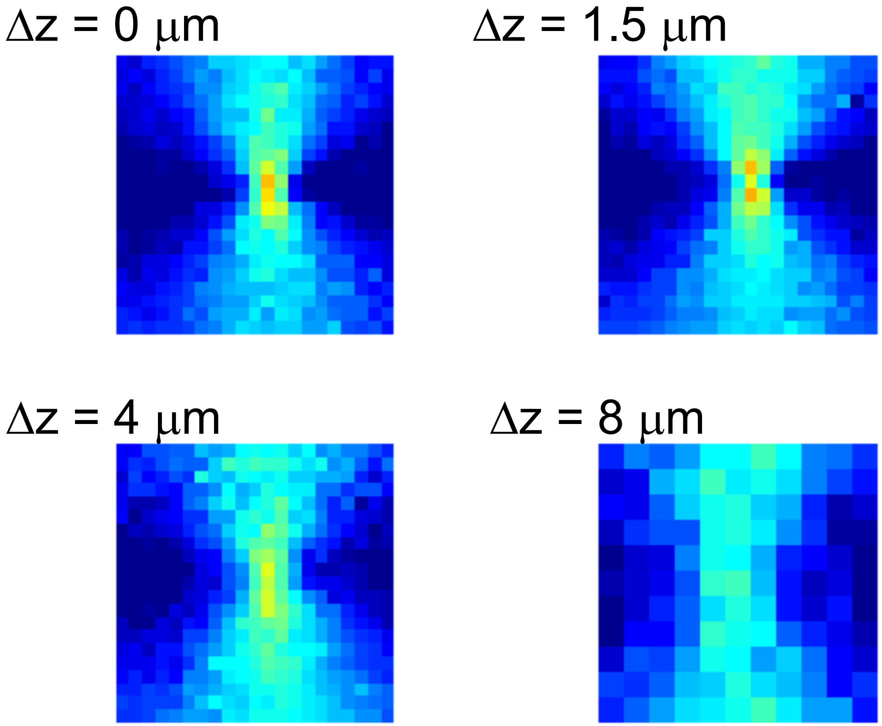

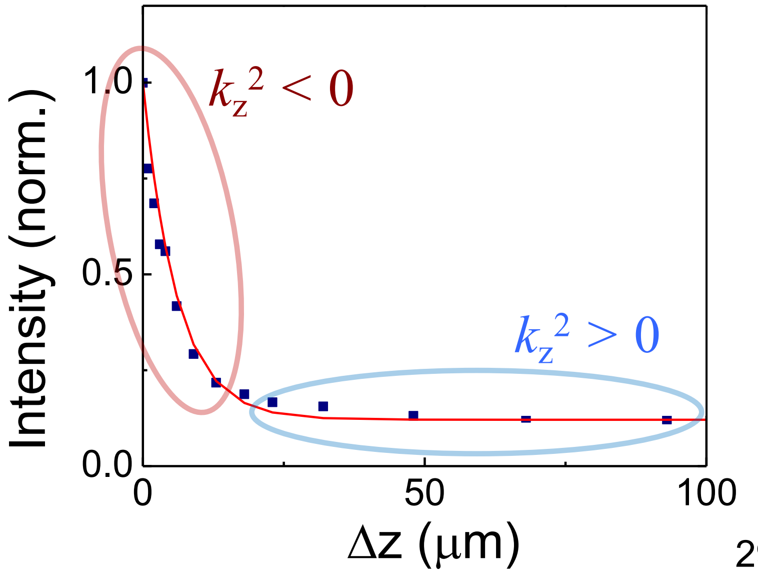

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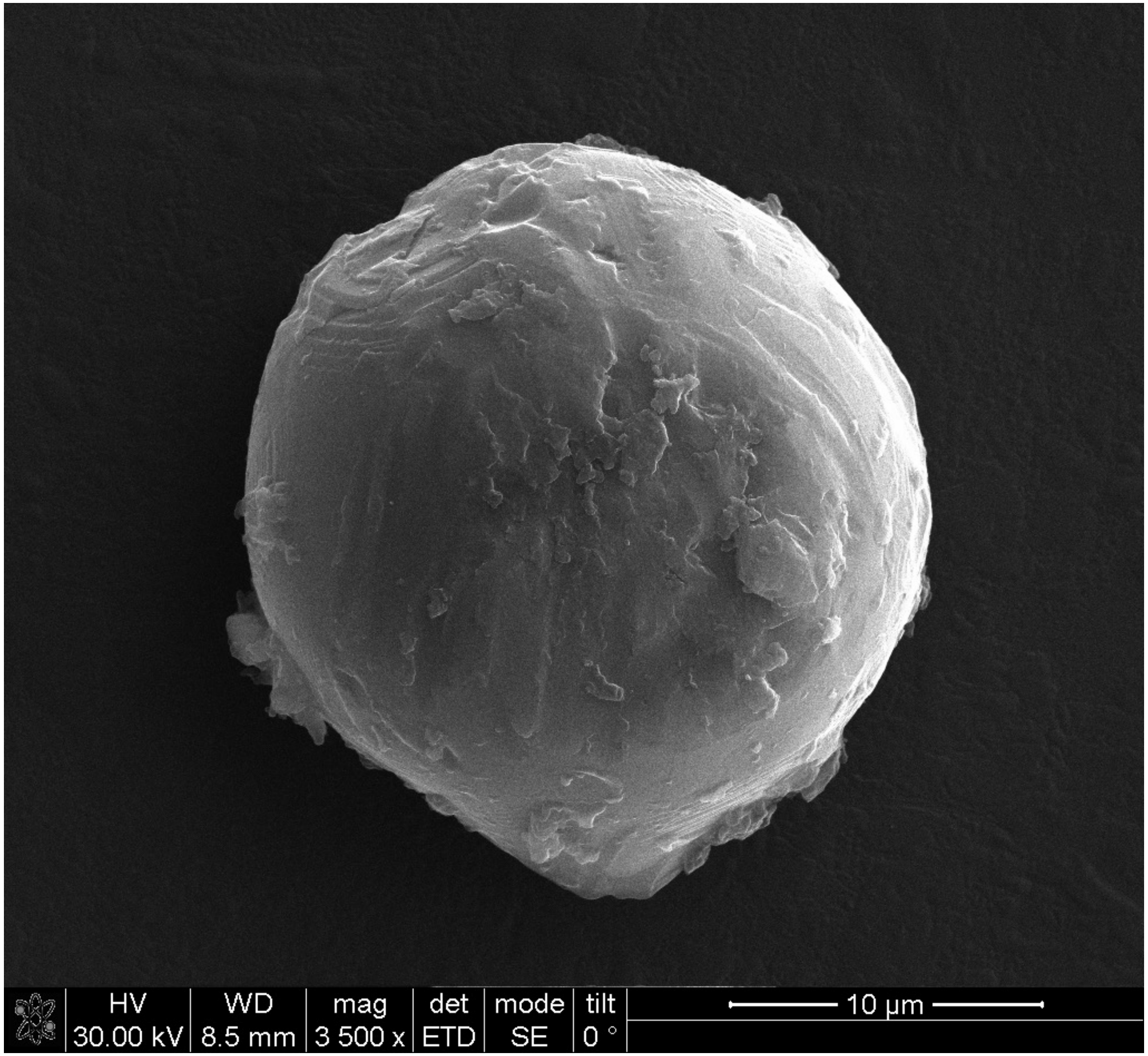
High permittivity Dielectric Resonator



TiO$_2$ sphere:

$d \sim 20$ µm $\qquad \lambda_{MD} \sim 300$µm

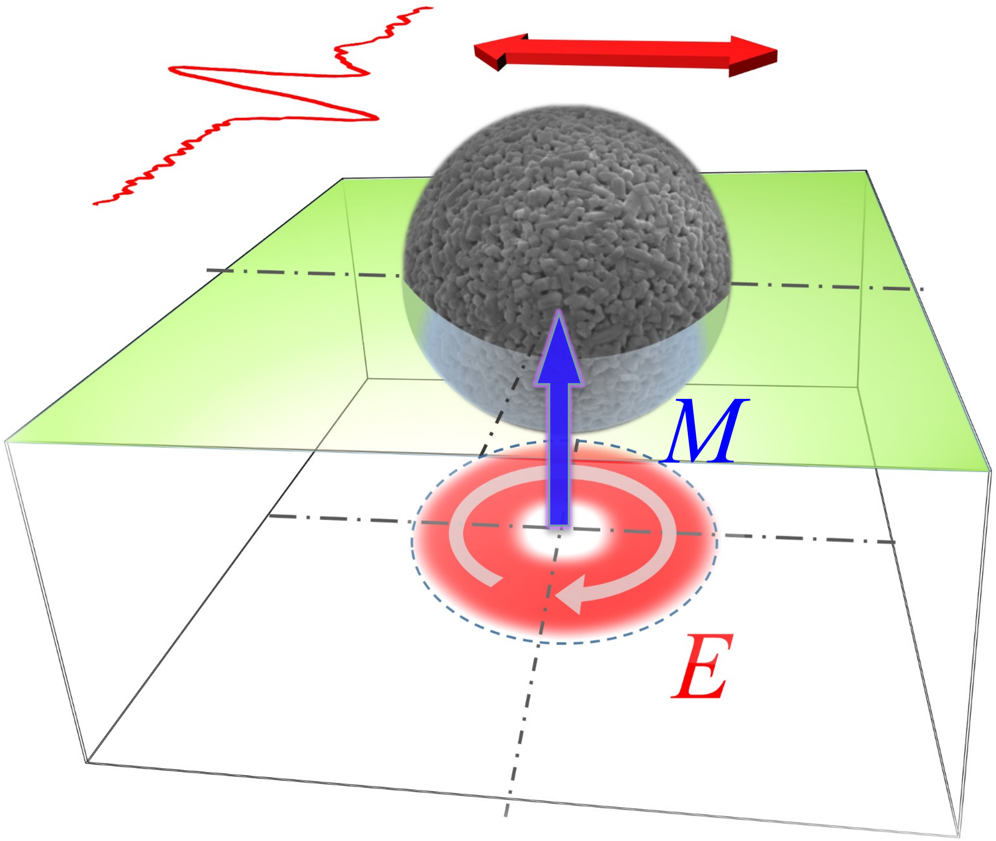
$d / \lambda \sim 0.07$

Mie resonances in TiO_2 spheres

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

$d \sim 20\ \mu m$

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

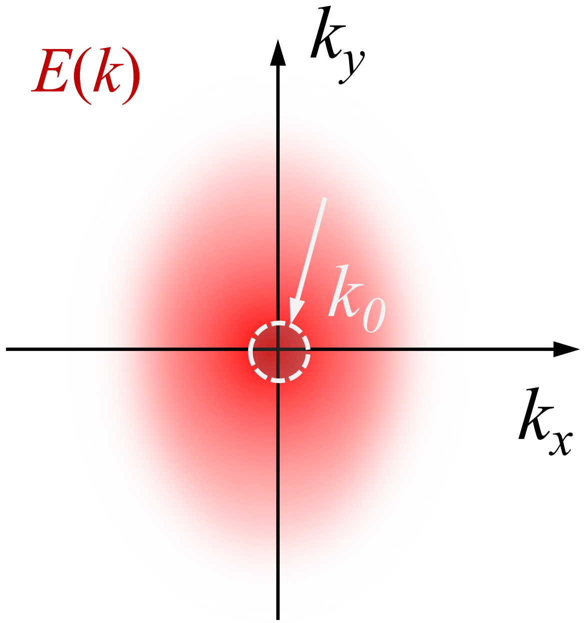


$d / \lambda \sim 0.07$

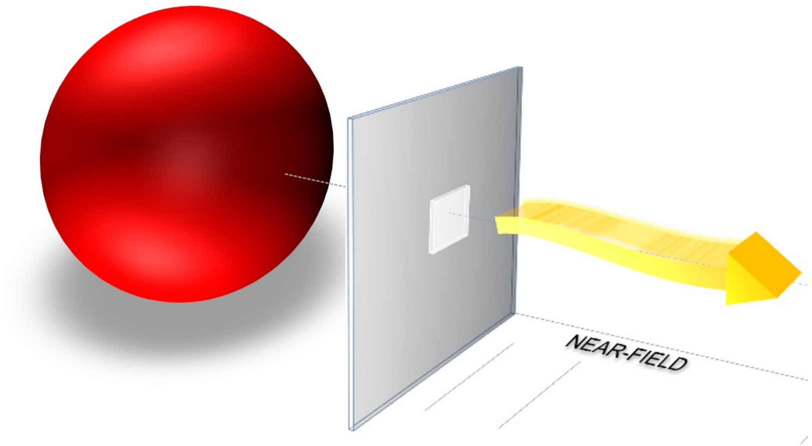
$k_t >> k_0$

Optics Express, 22, 23034 (2014)

Resonance Mode representation in k-space



NF probing using subwavelength aperture



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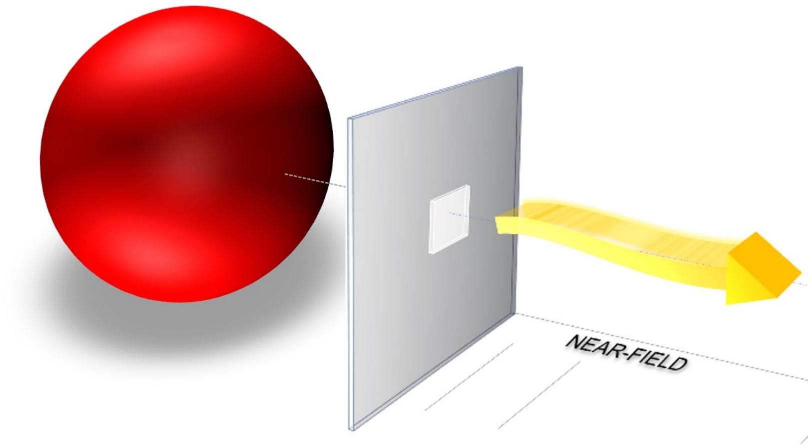

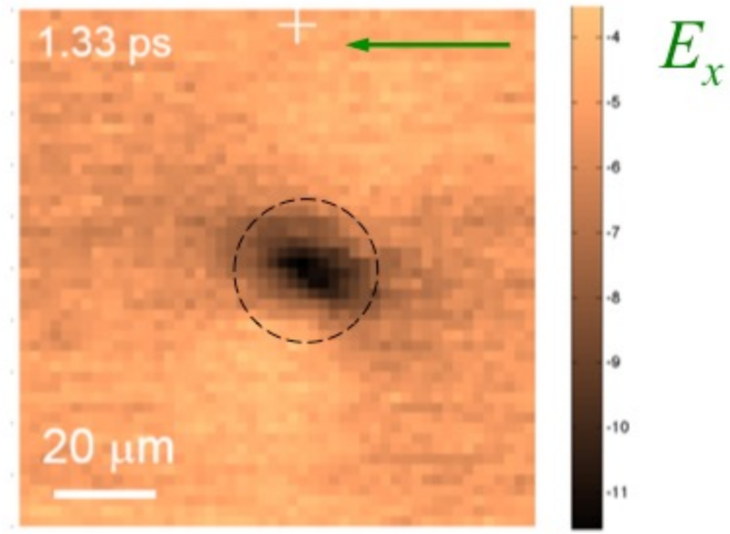

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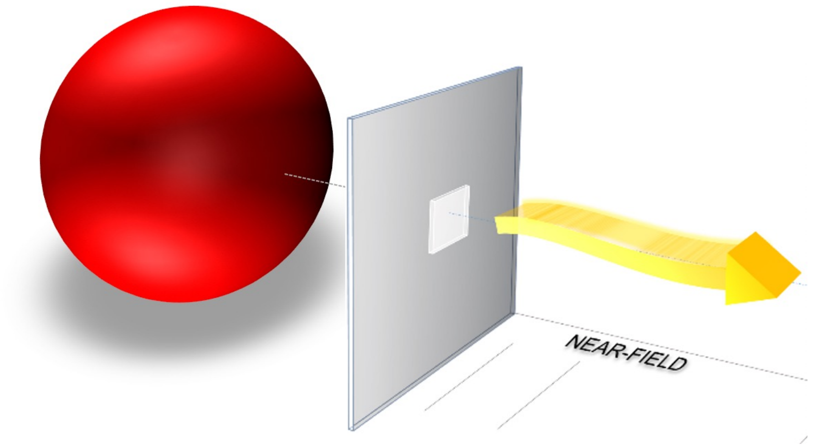
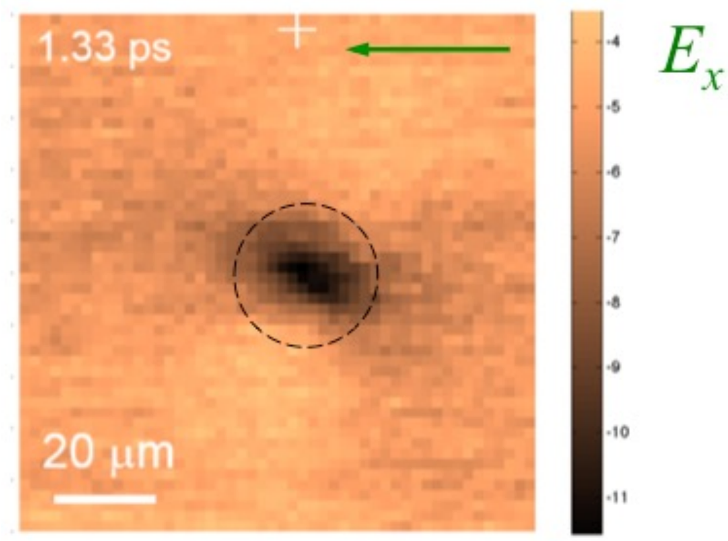
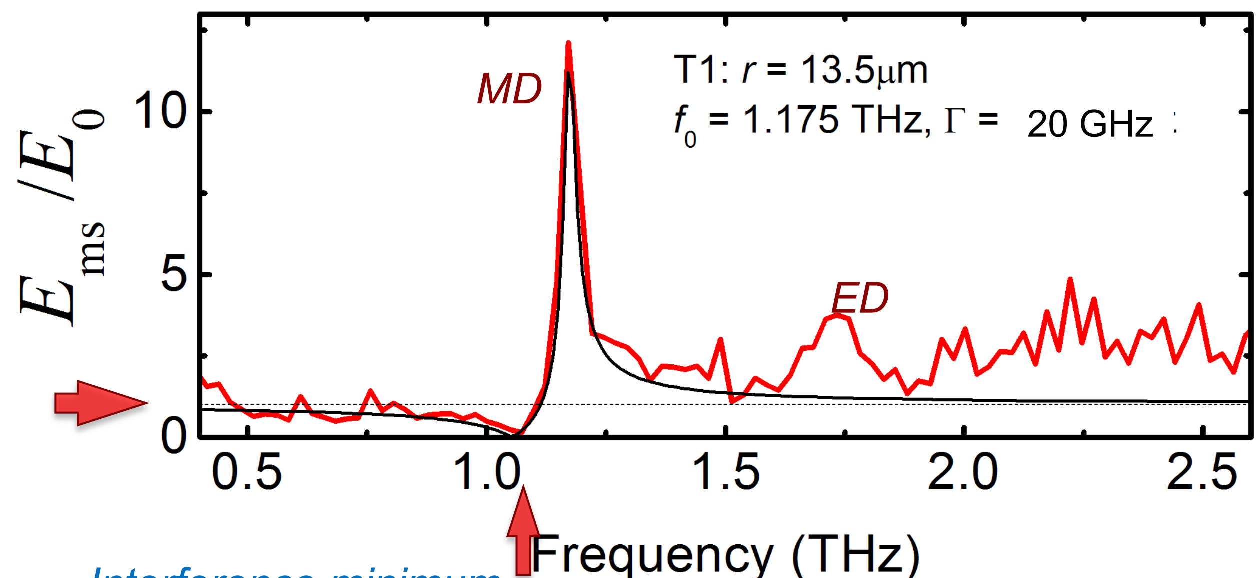




Enhancement factor and width to quantify the resonator

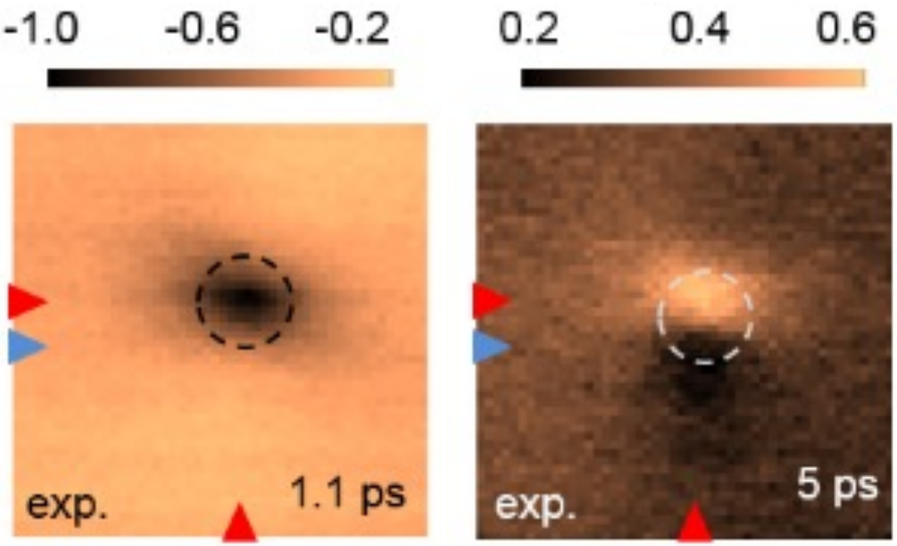


No effect on transmission away from resonance

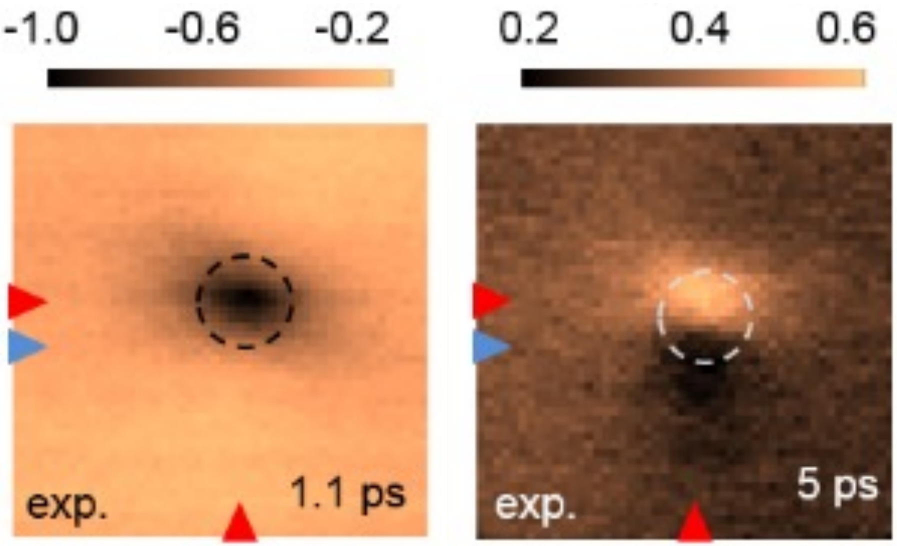
Interference minimum (Fano line-shape)

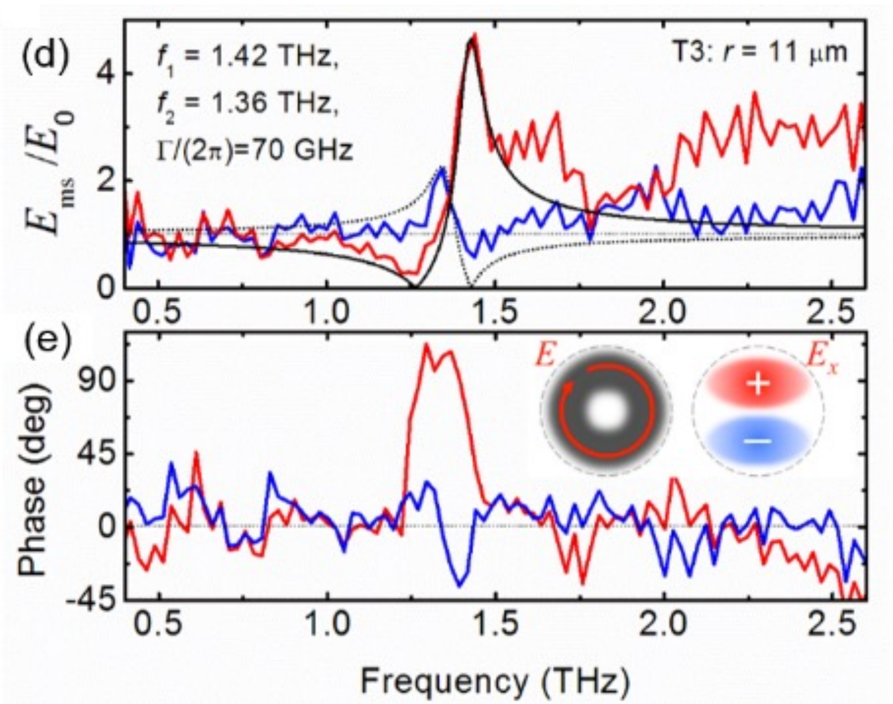
Optics Express, 22, 23034 (2014)

Subwavelength Structure

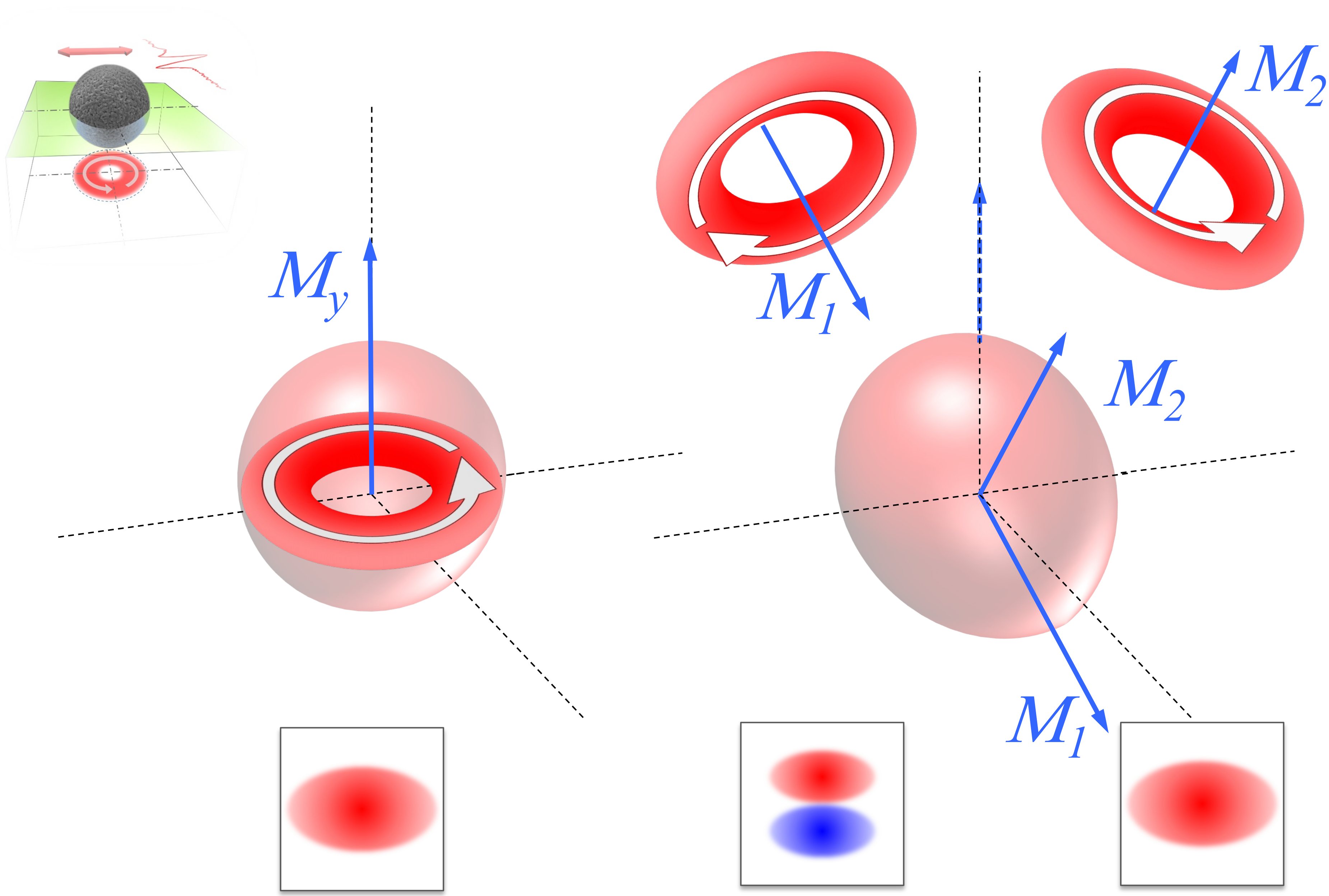


Near-field structure in time-domain

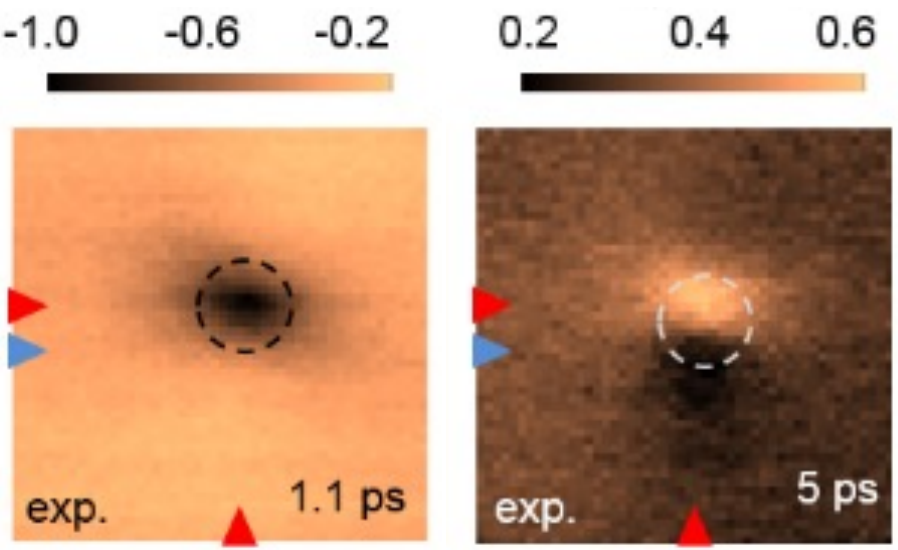


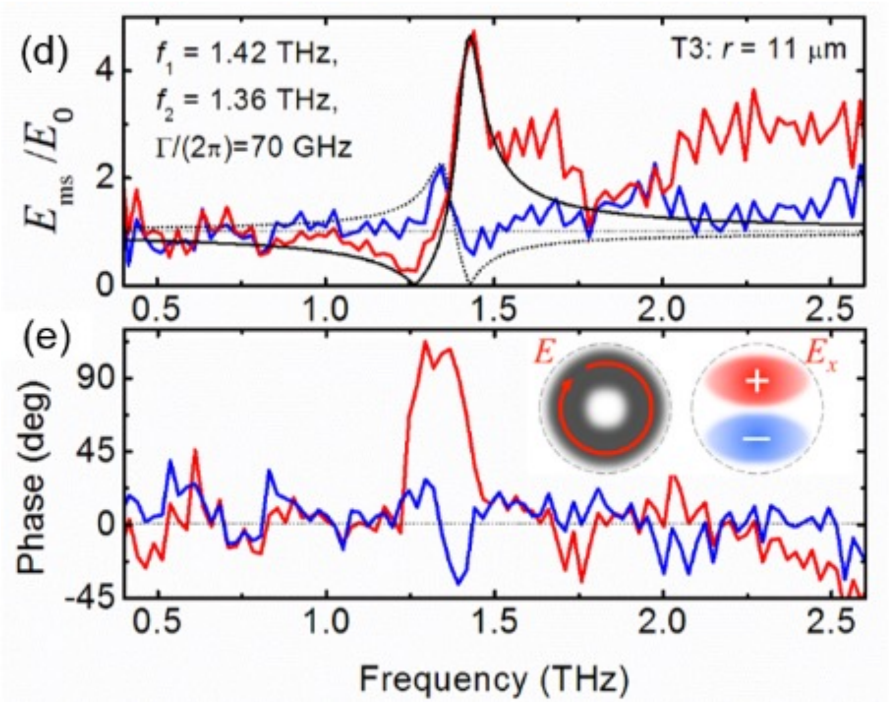


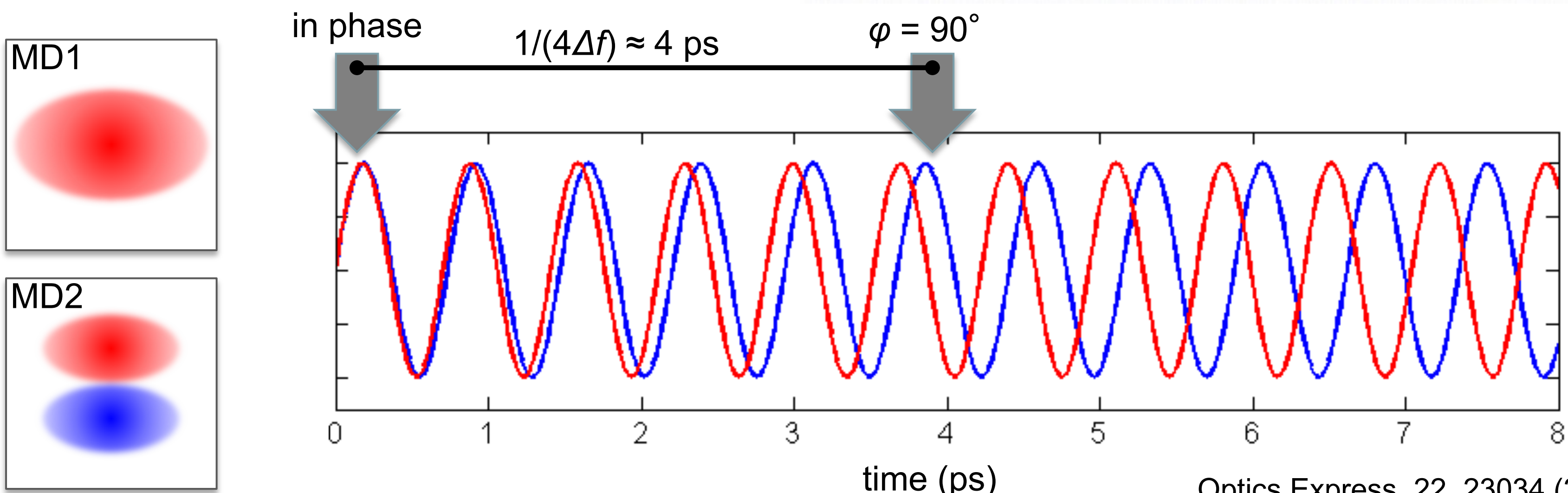
Resonator non-sphericity



Resonator non-sphericity





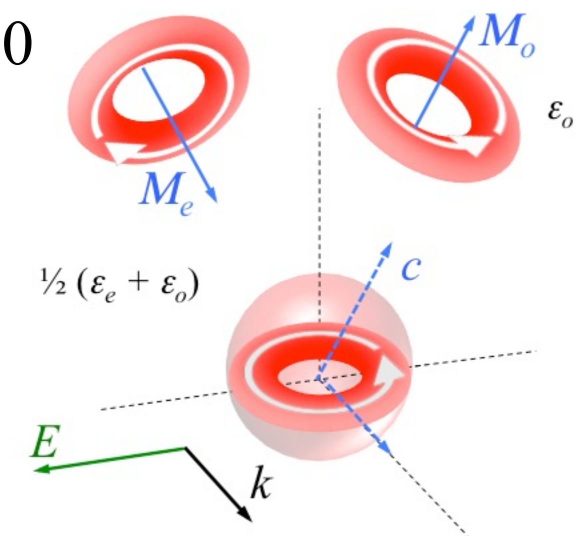


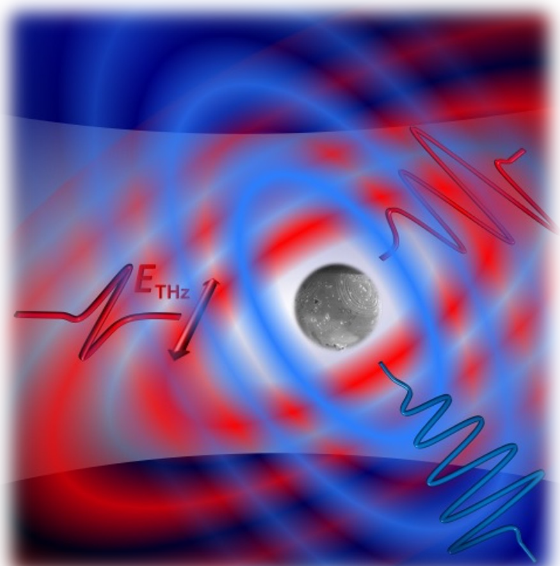
Optics Express, 22, 23034 (2014)

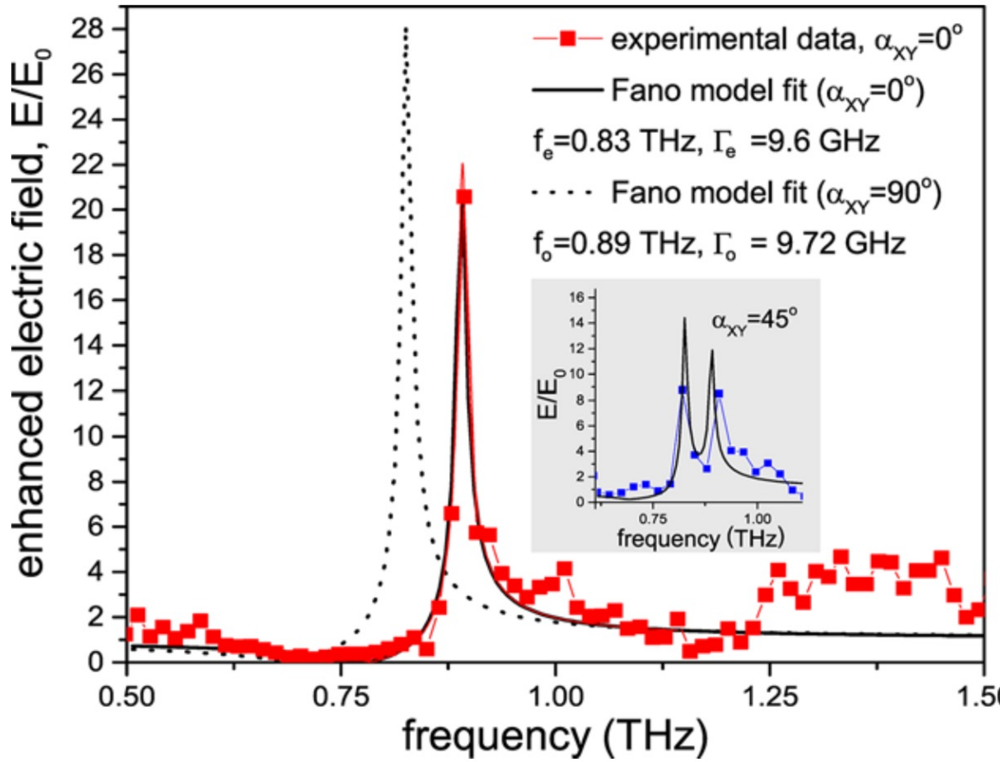
Single crystal TiO_2:

$\varepsilon_e = \sim 150$;

$\varepsilon_o = \sim 70$







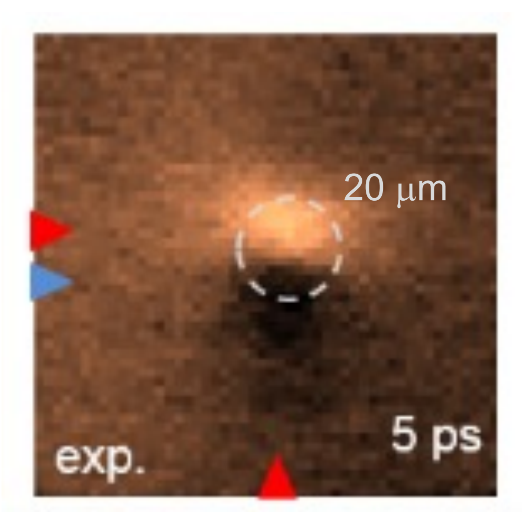
Near-field spectroscopy allows 'seeing' two modes

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

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

Ernst Abbe (c. 1873)

Hu and Nuss (1995)



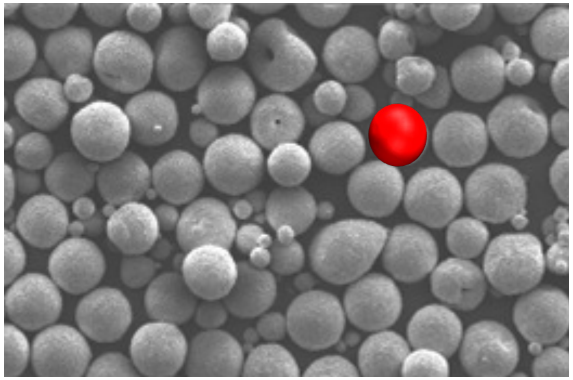
Subwavelength resolution reveals additional structure in the fields

Can near-field microscopy improve sensitivity?

Probing of single resonator – Scattering view

Sub-wavelength size
of TiO_2 resonators

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

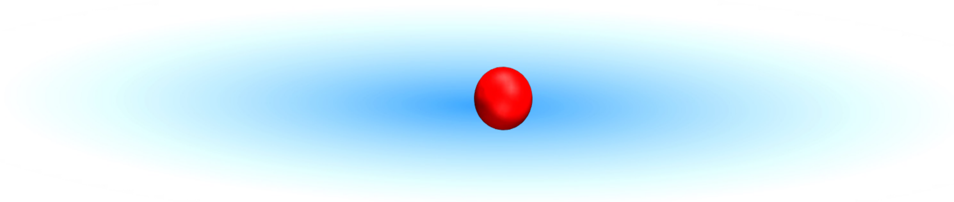


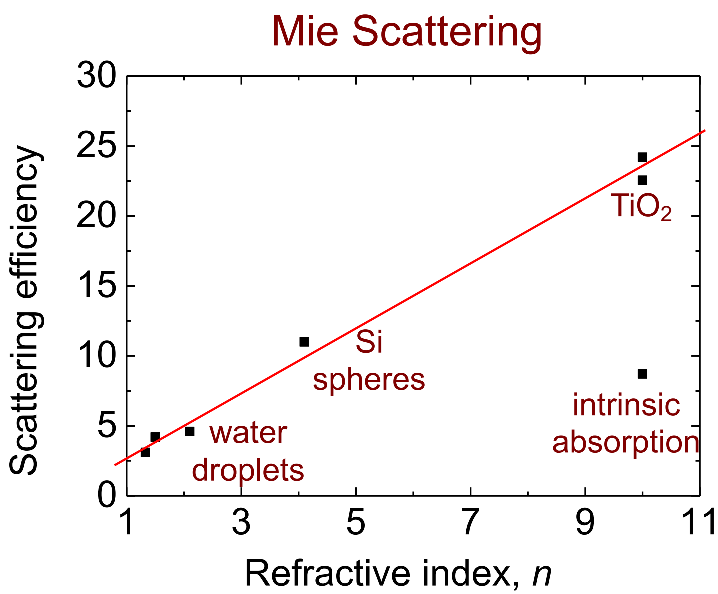
What is far-field effect
due to single resonator?

Probing of single resonator – Scattering view

Sub-wavelength size of TiO_2 resonators

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





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

Far-field total extinction by a single TiO_2 sphere

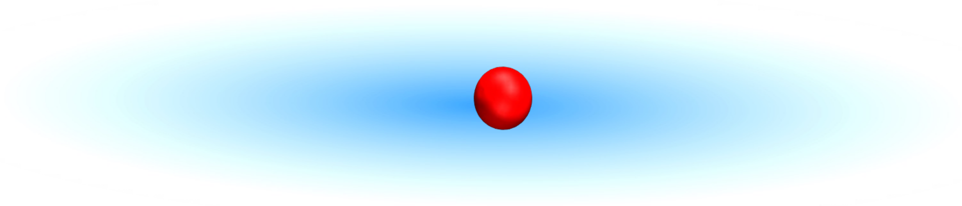
0.1-1.0%

(*est. for typical THz-TDS*)

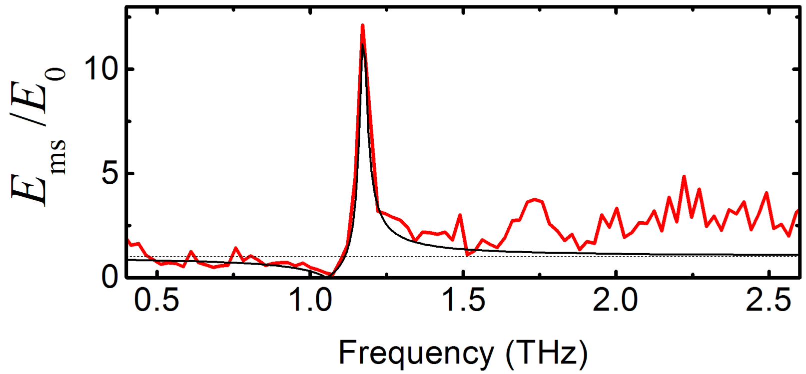
Probing of single resonator – Scattering view

Sub-wavelength size
of TiO_2 resonators

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



Near-field:

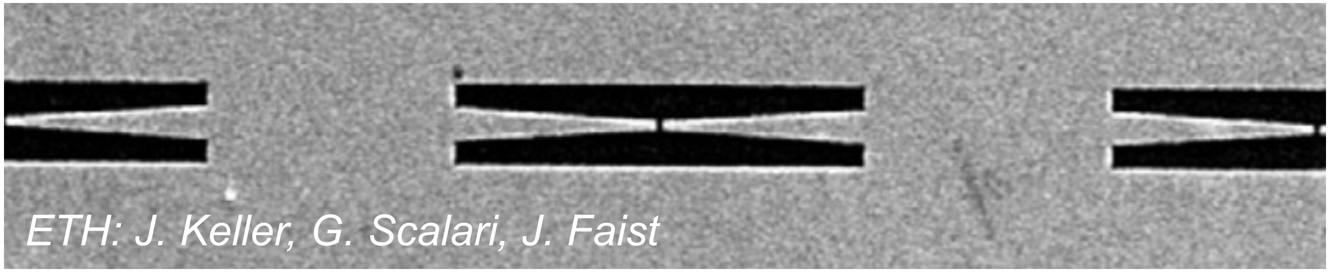


Far-field total extinction by a single TiO_2 sphere

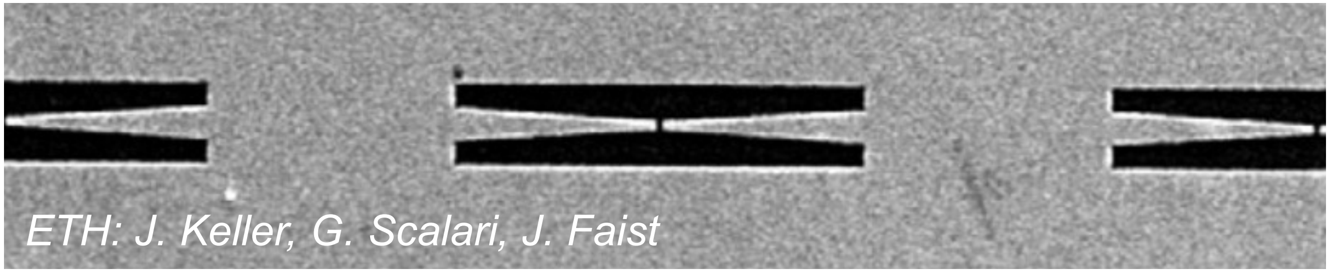
0.1-1.0%

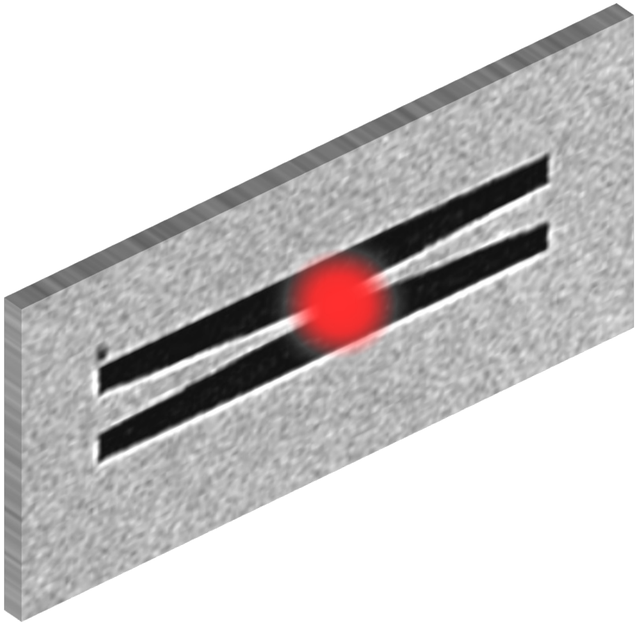
(*est. for typical THz-TDS*)

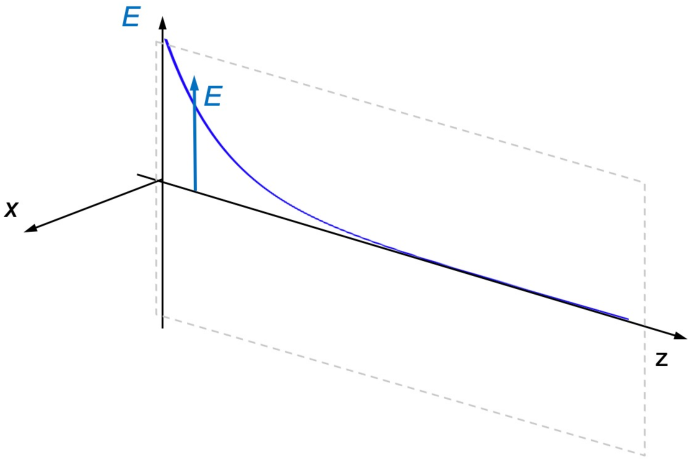
Single resonator sensitivity – Plasmonic resonator

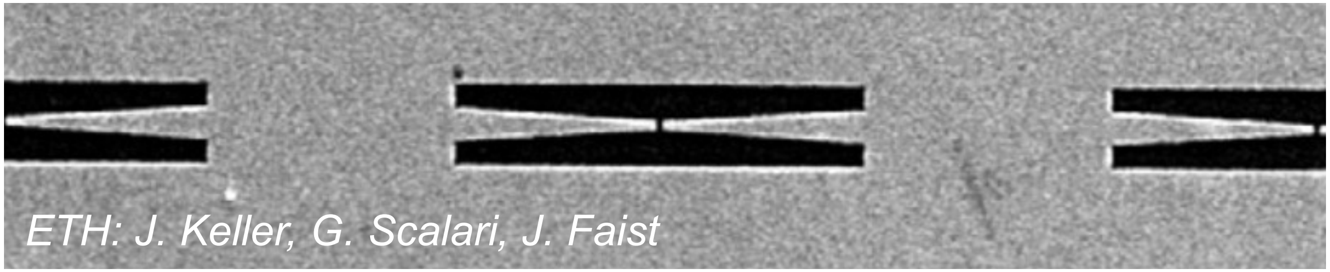


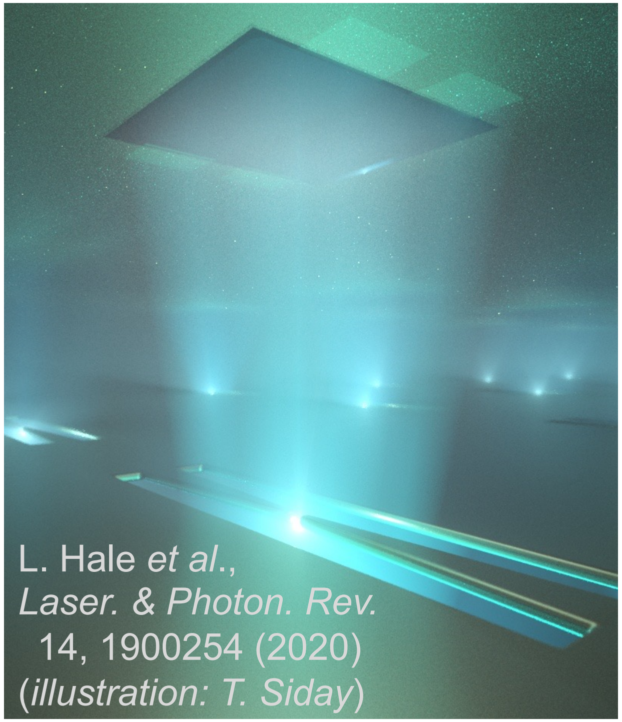
Single resonator sensitivity – Plasmonic resonator

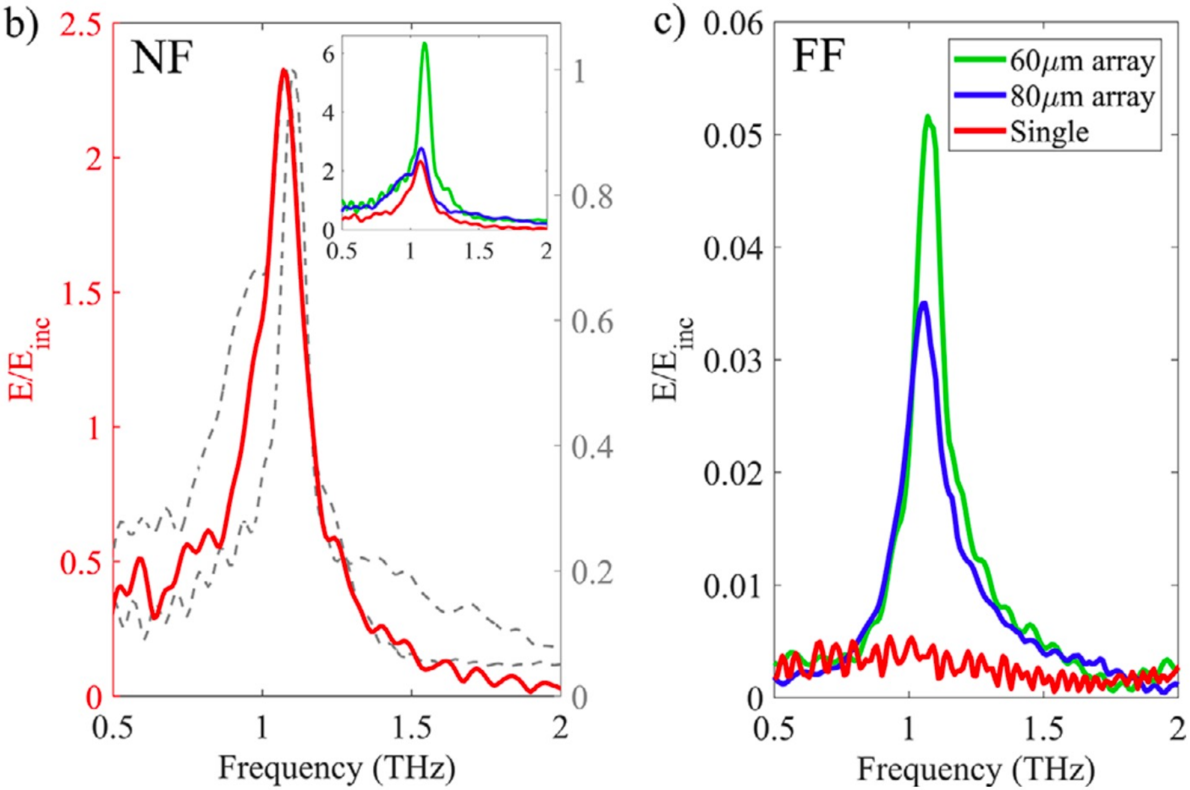




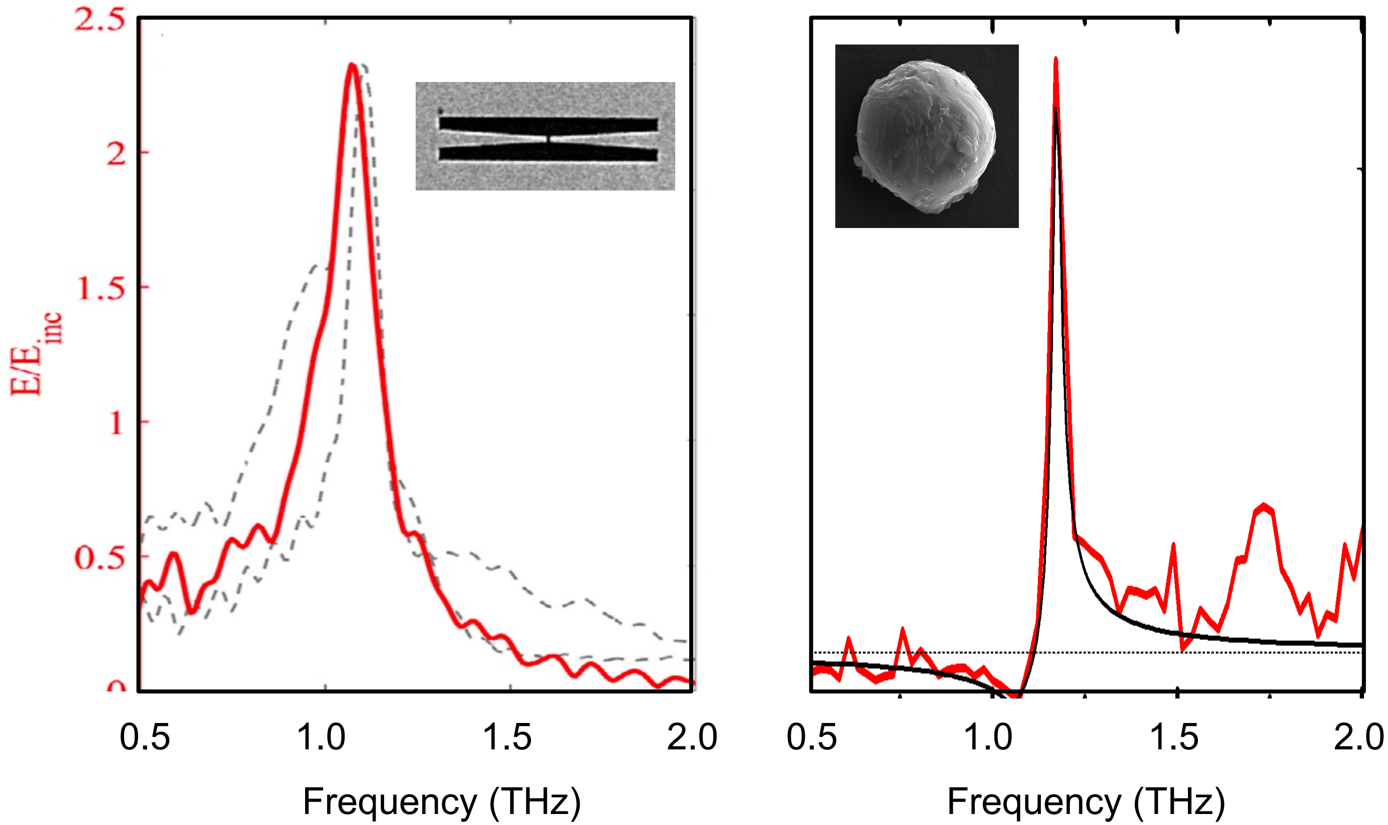



ETH: J. Keller, G. Scalari, J. Faist

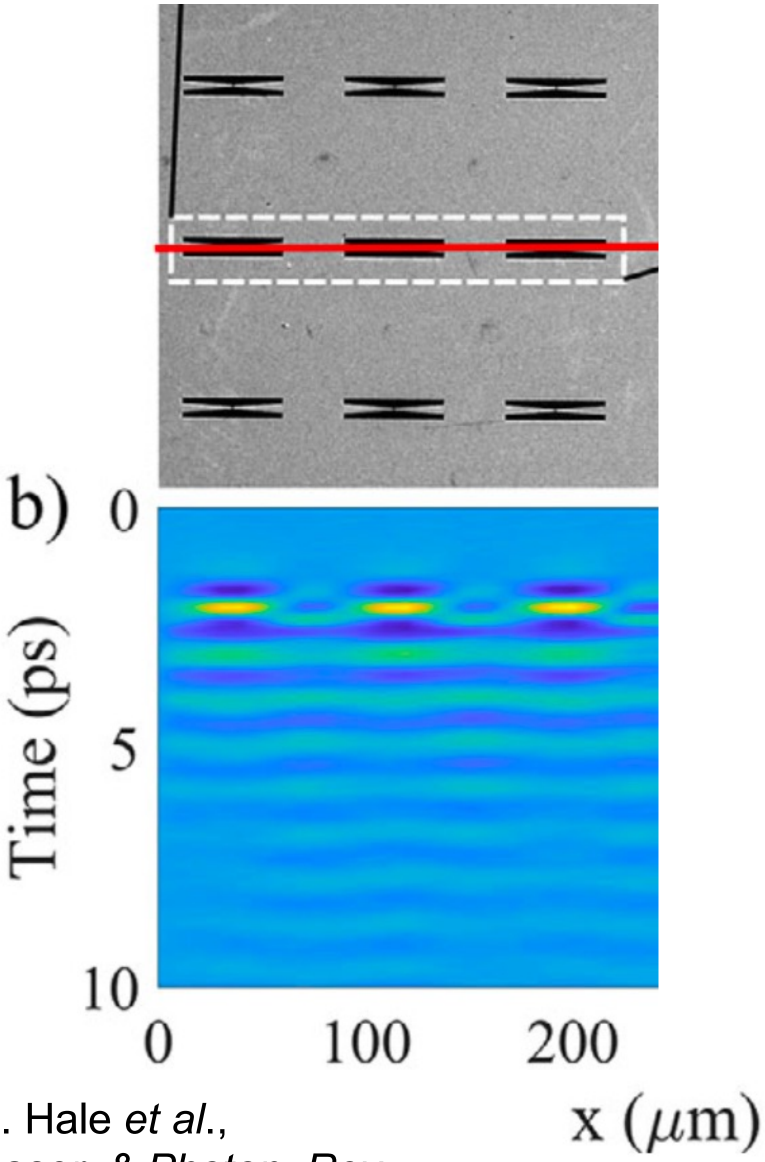

L. Hale et al.,
Laser. & Photon. Rev.
14, 1900254 (2020)
(illustration: T. Siday)


b)
NF
E/E_inc
Frequency (THz)
c)
FF
60μm array
80μm array
Single
E/E_inc
Frequency (THz)

What is detected in THz NF microscopy?

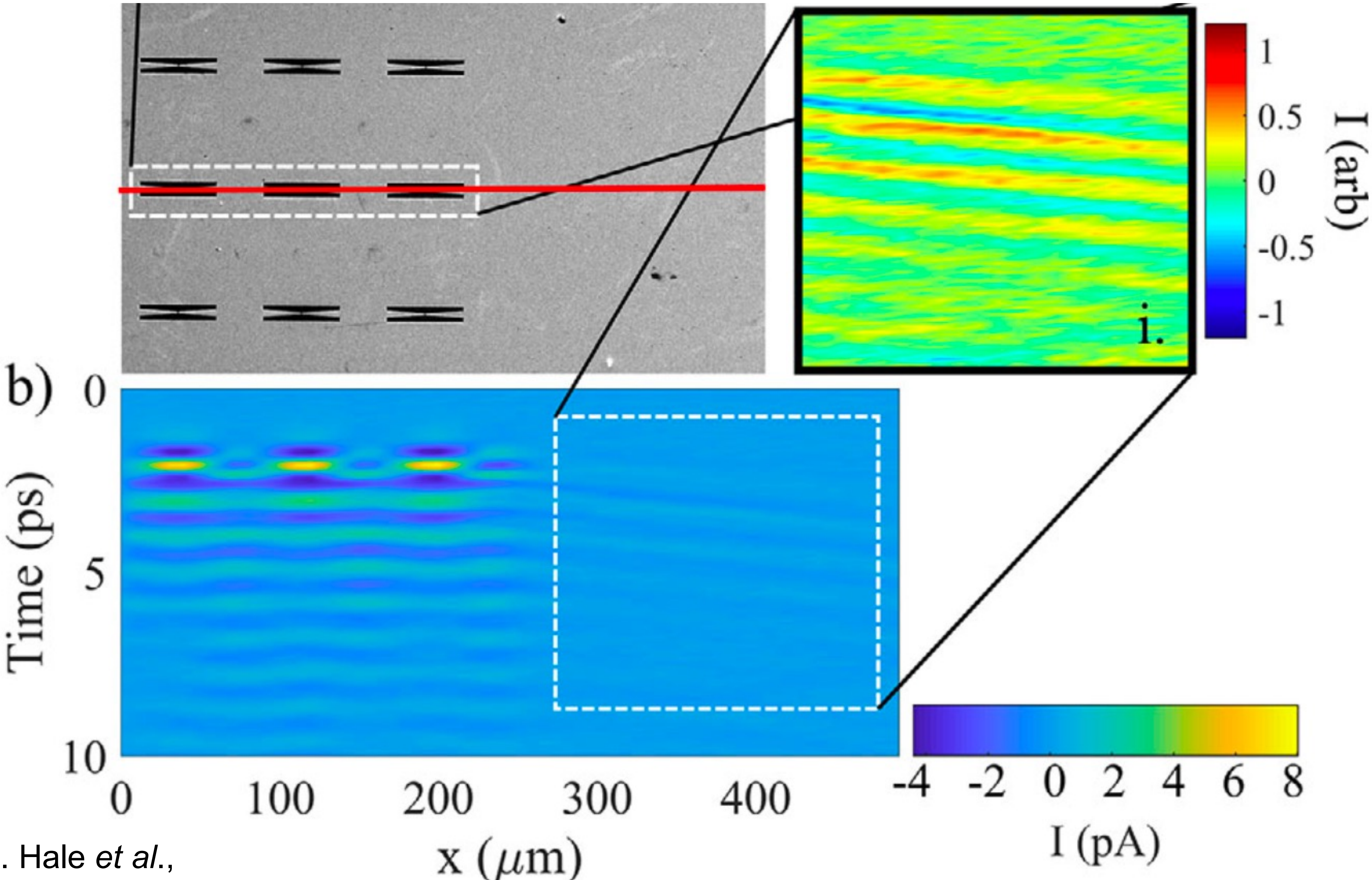


What are the waves detected on metallic surface?



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

Surface plasmon waves – THz-a-SNOM



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

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

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J. Keller, G. Scalari and J. Faist

ETH-Zurich

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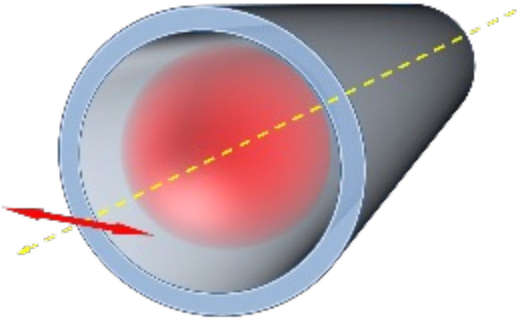
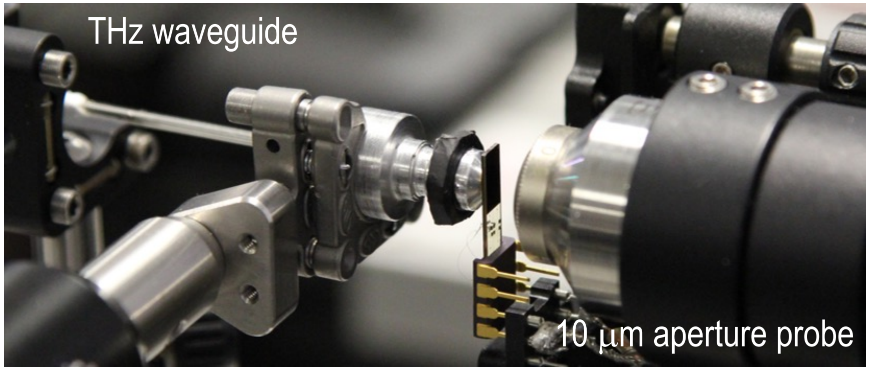
EPSRC Pioneering research and skills

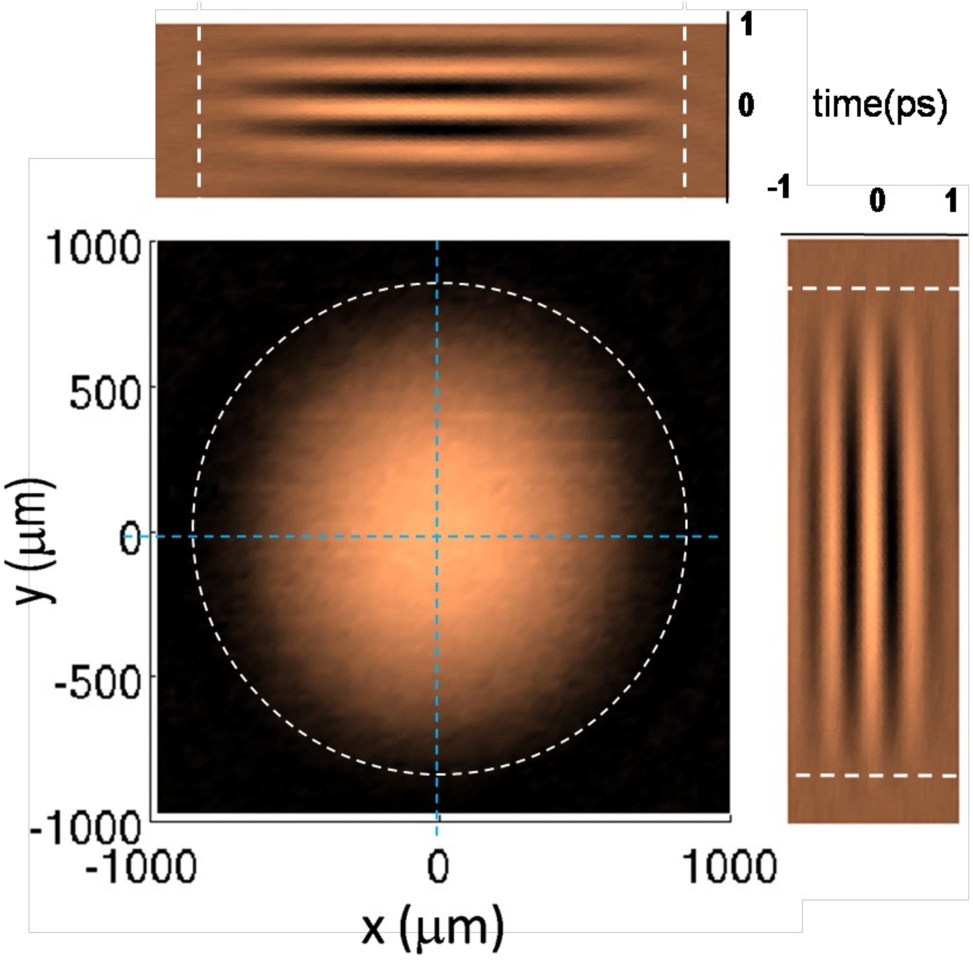
THE ROYAL SOCIETY

Results/Graphs from other groups

Applications in THz technology research: *Waveguides*

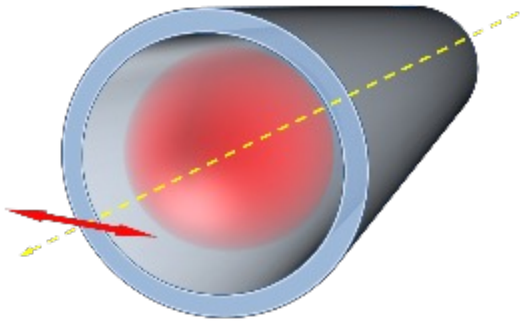


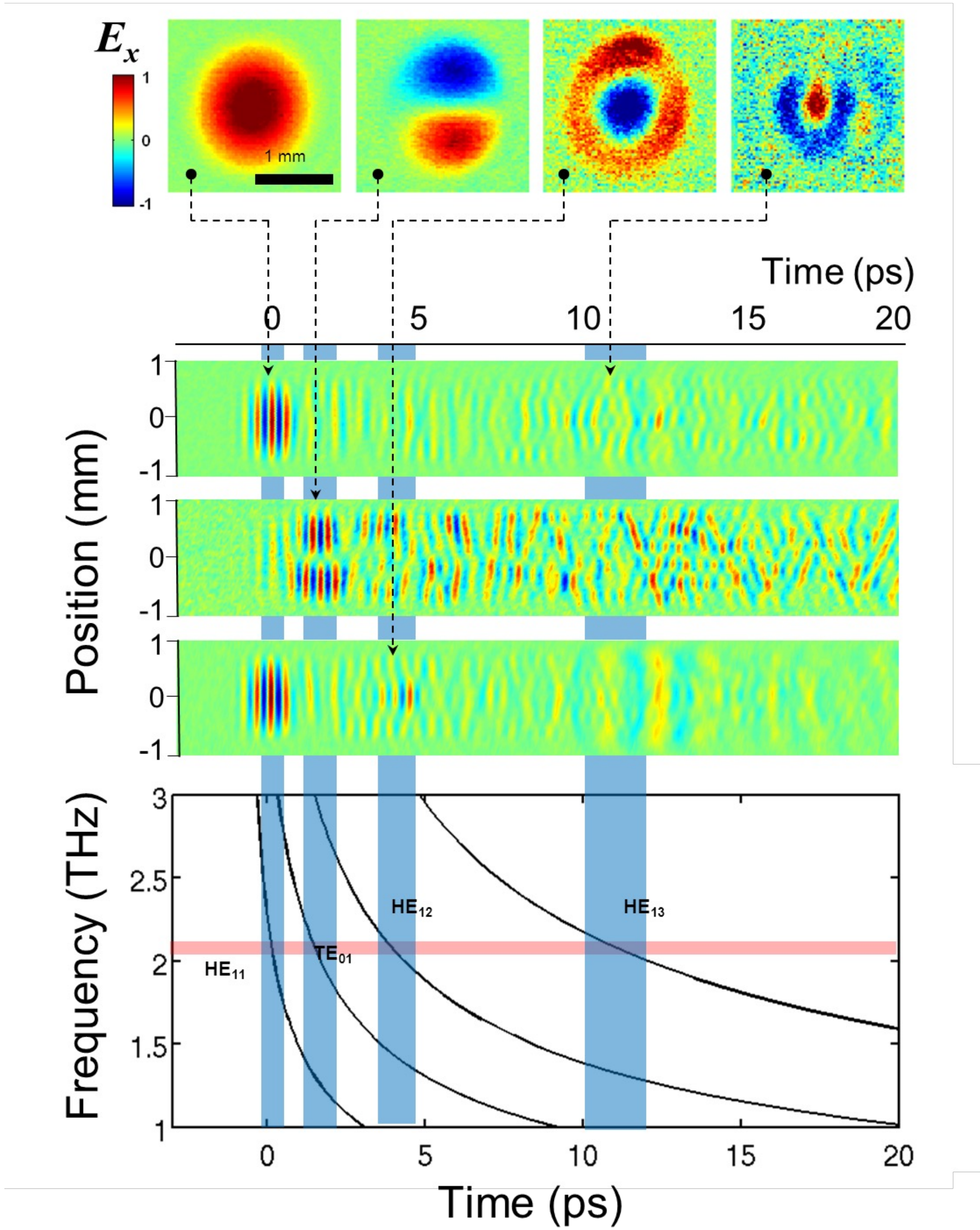




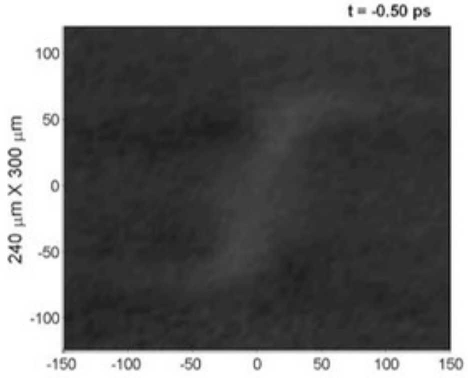
APL. **94**, 171104 (2009)

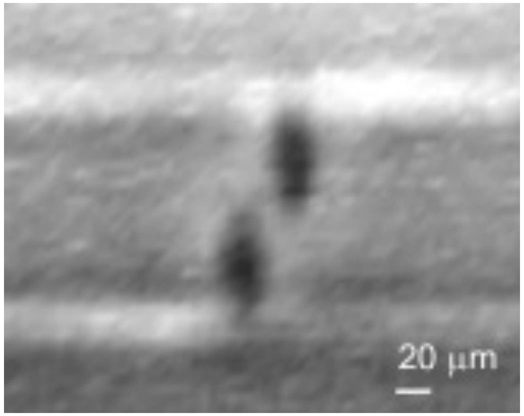
Applications in THz technology research: *Waveguides*

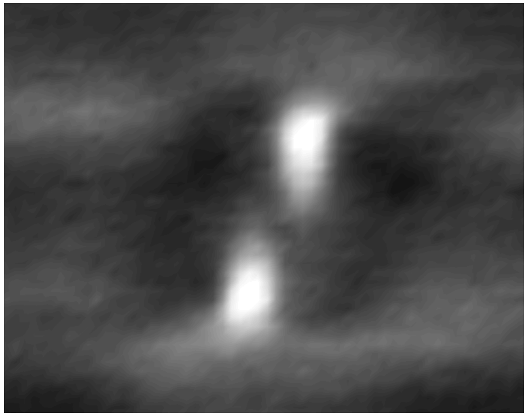




THz Surface Plasmon Waves

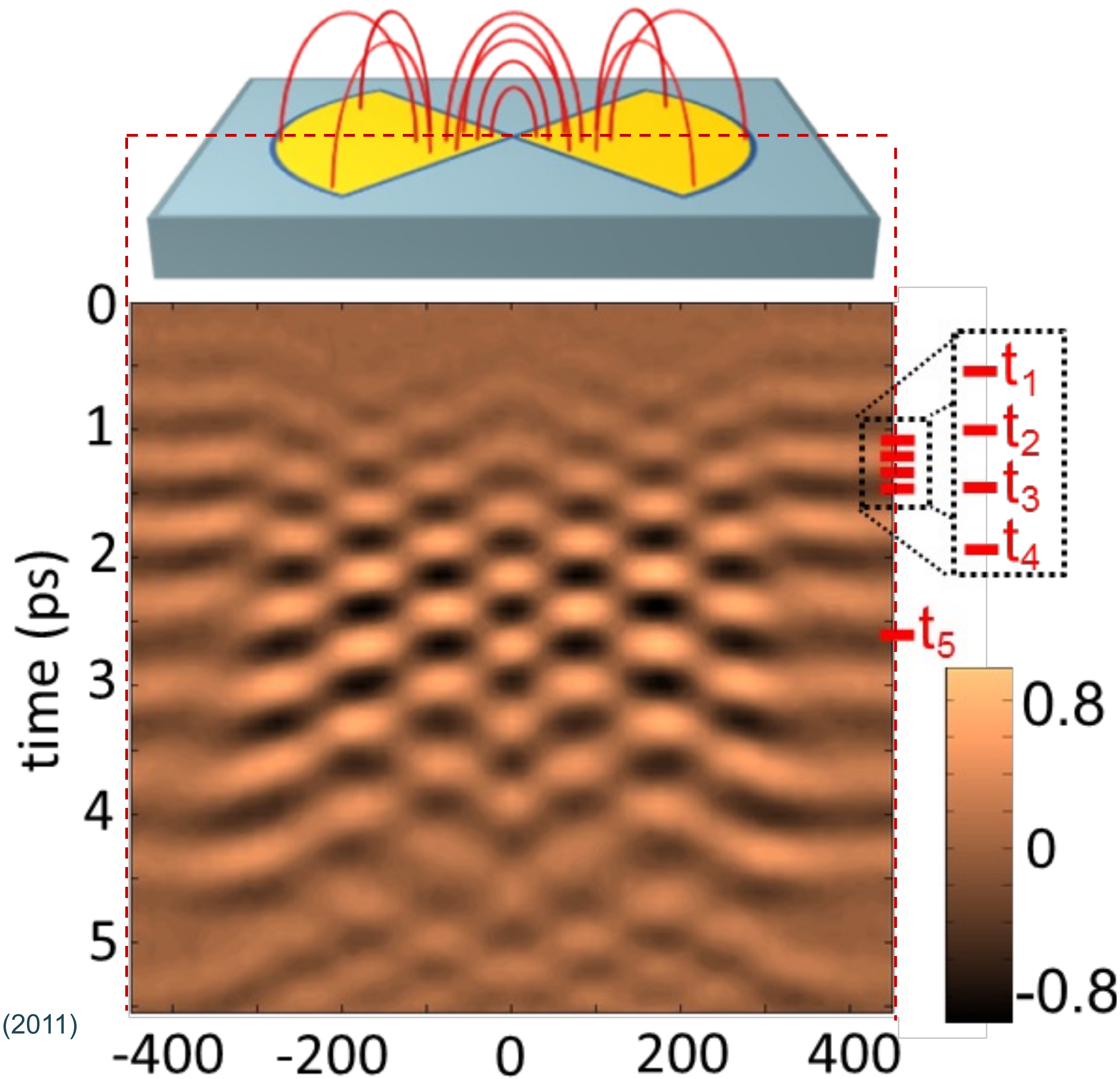






Mitrofanov et al.*J. STQE* **103**, 600 (2001)

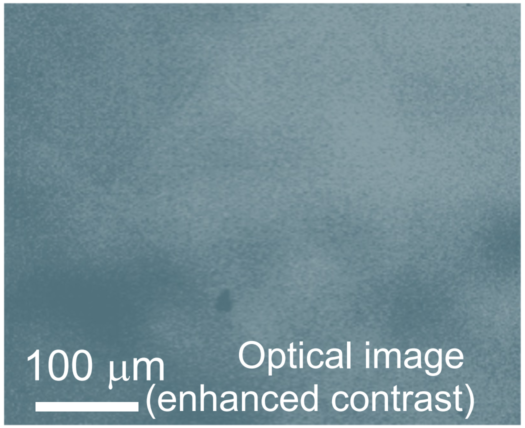
SPP resonance on the bow-tie surface

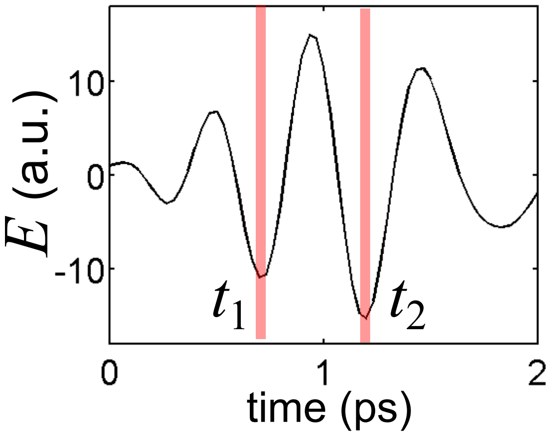


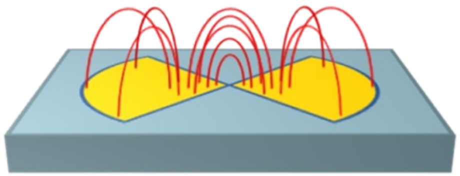
Mueckstein *et al.*,
J.of IRMMW 32, 1031 (2011)

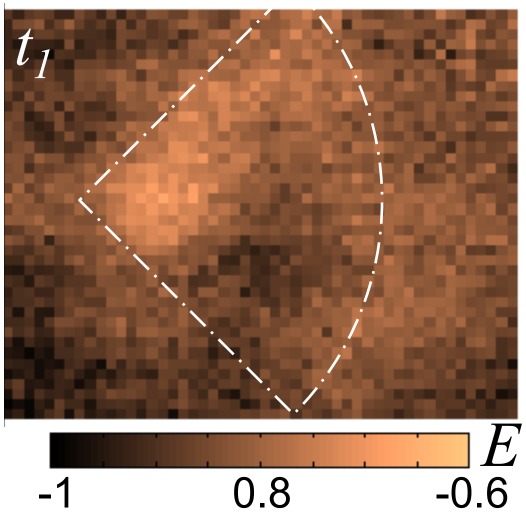
Surface Waves on Gr Bow-Tie Antenna

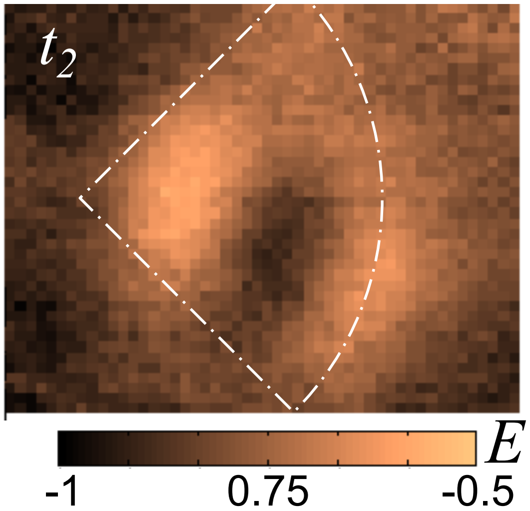
Epitaxial monolayer graphene - Gr on C-face SiC



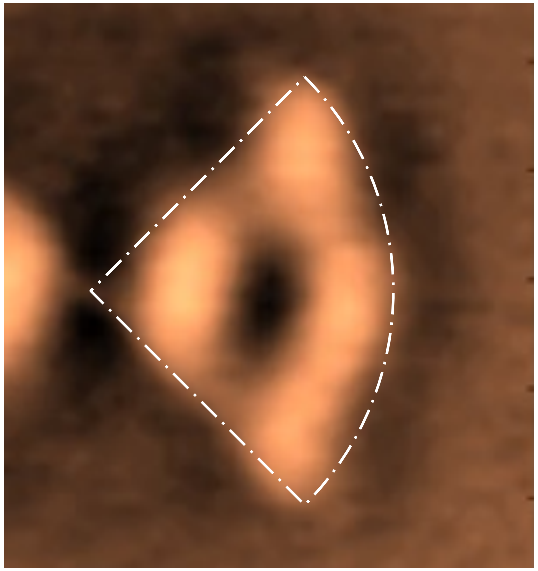








Metallic Bow-tie antenna



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

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