PART 2

THz near-field Imaging and Spectroscopy:
Fundamentals, Technology and Current Trends

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L. Hale et al.,
(illustration: T. Siday)
Fundamentals of THz near-field microscopy

Examples:
  Microscopy and Spectroscopy of THz resonators
  Imaging of THz surface plasmon waves
  Image interpretation

Technology:
  Subwavelength aperture and Scattering tip probes
  Improving sensitivity in THz microscopy

Current Trends in THz microscopy methods
Surface plasmon waves – THz-a-SNOM

THz surface plasmon waves

How are SPP waves excited?
Why are they detected?
Excitation of THz surface plasmon waves

Metallic edge discontinuity

$E_z$
$E_x$

$k$
$E_{inc}$
Excitation of THz surface plasmon waves

Metallic edge discontinuity

$E_z$ $E_x$ $E_{inc}$

$E_z(x)$ $E_z(k_x)$

$\omega$ $k_x$
Generation of surface waves at metallic edges

Bow-tie antenna

Image area: 1.4 mm X 1.4mm

Mueckstein et al., J.of IRMMW 32, 1031 (2011)
Generation of surface waves at metallic edges

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Bow-tie antenna

Image area: 1.4 mm X 1.4mm

Distinctive signature of surface wave:

$E_{\text{inc}}$

Mueckstein et al., J. of IRMMW 32, 1031 (2011)
Consecutive images (“frames”) ~0.13 picosecond apart

Mueckstein et al., J.of IRMMW 32, 1031 (2011)
Detection of surface waves

\[ k \]

\[ E_{\text{inc}} \]

\[ E_x \]

\[ E_z \]
Detection of surface waves

Direct detection Near-field Probe: Electro-optic crystal
Detection of surface waves

Direct detection Near-field Probe: Electro-optic crystal

Blanchard & Tanaka (2016)
Detection of surface waves

Direct detection Near-field Probe:

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

Bhattacharya and Rivas,
APL Photonics 1, 086103 (2016)
Detection of surface waves

Direct detection Near-field Probe:

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Bhattacharya and Rivas,
APL Photonics 1, 086103 (2016)
Detection of surface waves

Direct detection Near-field Probe: Aperture with THz detector

Mueckstein et al., J.of IRMMW 32, 1031 (2011)
Detection of surface waves

Scattering Near-field Probe

$k$

$E_z$

$E_x$

$E_{inc}$

$k$
What is detected in THz NF microscopy?

Aperture Near-field Probe?
Surface plasmon resonances
Conductive carbon fibres:
6.5 $\mu$m diameter, 50-250 $\mu$m long
THz Surface plasmons – Mapping with Aperture

\[ E \]
THz Surface plasmons – Mapping with Aperture

Symmetry changes:
from anti-symmetric to symmetric

\[ E_{det} = \frac{dE_z}{dx} \alpha \]
Surface plasmon resonances
What is the property or quantity of interest?
THz surface plasmon resonances

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

OM, Todorov, et al., Optics Express 26 (6), 7437 (2018)
THz surface plasmon resonances

SEM

20µm

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

graphene


Optics Express 26 (6), 7437 (2018)
THz surface plasmon resonances

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

OM, Todorov, et al., Optics Express 26 (6), 7437 (2018)
What is detected in THz NF microscopy?

$E$ - field

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

*IEEE Trans. THz S&T* 6, 382 (2016)
What is detected in THz NF microscopy?

**$E$ - field**

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

**$\varepsilon$ - dielectric constant (and $E$ - field ?)**


X. Chen et al. *ACS Photonics* 7, 687 (2020)
Multiple signal contributions – s-SNOM

\[ l : 10 \mu \text{m} (1000 \text{ cm}^{-1}) \]

Wang et al., *Nano Lett.* 2019, 19, 4620−4626
Multiple signal contributions – s-SNOM

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

** CW excitation (QCL)  
\[ \lambda = 10 \, \mu m \ (1000 \, cm^{-1}) \]
Surface plasmon waves – s-SNOM

$E$ – field

$\varepsilon$ – dielectric constant

Antenna resonance is superimposed over the material contrast

Wang et al., Nano Lett. 2019, 19, 4620–4626
Wang et al., *Nano Lett.* 2019, 19, 4620–4626
s-SNOM – nano-FTIR

Wang et al., *Nano Lett.* 2019, 19, 4620–4626
Surface plasmon resonances – THz-s-SNOM

3.45 THz

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

L. Thomas, T. Hannotte, C. Santos et al., ACS Appl. Mater. Interfaces (2022)
What is detected in THz NF microscopy?
THz microscopy challenges

Graphics: Tom Siday
Aperture-type THz Near-Field Microscopy

How much light passes through a subwavelength aperture?
Aperture-type THz Near-Field Microscopy

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

\[ \lambda = \frac{a}{5} \]

\[ \lambda = a \]

\[ \lambda = 10a \]
Aperture-type THz Near-Field Microscopy

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

Most waves in spectrum have imaginary $k$, i.e. evanescent
Aperture-type THz Near-Field Microscopy

\[ T = \frac{|E_t|^2}{|E_{inc}|^2} \sim a^6 \]

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

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

\[ \lambda = \frac{a}{5} \]

\[ \lambda = a \]

\[ \lambda = 10a \]
Aperture-type THz Near-Field Microscopy

Evanescent waves

\[ a^3 \lambda^{-2} \]

Propagating waves

Graph showing the aperture size-wavelength ratio (\( a/\lambda \)) and near-field probe signal (dB) with curves for different aperture sizes: 270 nm, 500 nm, and 4.0 \( \mu \)m. The graph illustrates the relationship between the aperture size and the near-field probe signal, with an increase in aperture size leading to a decrease in the near-field probe signal.
Ultrathin Photoconductive Metasurfaces (THz-TDS)

Hale et al. Optics Lett. (2021)
Integrated THz Near-Field Detectors

Ultrathin Photoconductive Metasurfaces (THz-TDS)

FET-based 2D materials

InAs nanowire detectors

CMOS-based detectors
Grzyb et al. (2016)

2DEG detectors
Kawano et al. (2008)

Hale et al. Optics Lett. (2021)

Giordano et al. Optica (2018)
Scattering Probe: THz-s-SNOM
Enhancement of Scattering from the Probe

Two Main Factors affecting the Scattering efficiency:

Tip apex size

Tip shaft length

C. Maissen et al.,
ACS Photonics 6, 1279 (2019)
THz s-SNOM Imaging

C. Maissen et al.,
*ACS Photonics* 6, 1279 (2019)
**Enhancement of Scattering from the Probe**

*Two Main Factors affecting the Scattering efficiency:*

**Tip apex size**

**Tip shaft length**

T. Siday et al.
*ACS Photonics 7, 596 (2020)*
Self-mixing effect in QCLs

see also works:
Riccardo Degl’Innocenti (ACS Photonics 2017 …) – Tunning fork Probe
Miriam Vitiello (Optics Express 2018, … later work) – Neaspec

Research trends: Surface plasmons in novel materials

Previous THz s-SNOM studies on Bi$_2$Se$_3$


L. Hale et al. (under review)
As more THz near-field systems coming online, the growing library of THz near-field images will help identify appropriate instruments for phenomena of interest.

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

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

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

University College London

J. Reno, I. Brener, T. Harris, T.S. Luk and W. Pan

CINT, Sandia National Laboratories

L. Viti, M. C. Giordano, E. Dardanis, and M. S. Vitiello

CNR-Nano, Italy

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China Jiliang University and DTU, Denmark

J. Keller, G. Scalari and J. Faist

ETH-Zurich

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

Results/Graphs from other groups
First demonstration of aperture-type THz microscopy (50-80 μm resolution)

Modern aperture-type THz microscopy
2-5 μm resolution

Hunsche et al. 
OPTICS COMM (1998)
Acknowledgement


*University College London*

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I. Khromova (*U. Navarra*) P. Mounaix (*CNRS, Bordeaux*), P. Kuzel (Czech Acad. Sci.)
Applications in THz technology research: *Waveguides*

APL. 94, 171104 (2009)
Applications in THz technology research: Waveguides
Integrated THz Detector

Aperture-type THz microscopy probe with PC detector

Potential Cryogenic Applications Require:

Nanoscale detectors

Integrated readout electronics

OM et al., ACS Photonics (2015)

THz Surface Plasmon Waves

Surface Waves on Gr Bow-Tie Antenna

Epitaxial monolayer graphene - Gr on C-face SiC