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

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Hu and Nuss (1995)  
Cosmic Microwave Background Map @ 0.857THz ESA/Plank (2015)  
\[ d = \frac{\lambda}{2 \sin \alpha} \]

Ernst Abbe (c. 1873)
Beyond Diffraction limit

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

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)
Early development of THz microscopes

STM Tip - Microwave transmission (1 GHz)

B. Knoll, F. Keilmann et al., APPL. PHYS. LETT. 70, 2667 (1997)
Early development of THz microscopes

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

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

Evanescent waves

Propagating waves

Mitrofanov et al.,
Collection mode Aperture-type THz microscopy
Aperture-type THz near-field probes

Mitrofanov et al., ACS Photonics (2015)


Spatial Resolution Test
2 μm aperture

E (a.u.)
THz-TDS

2 μm
Aperture-type THz microscopy

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)

Ultrathin Photoconductive Detectors:
LT GaAs can be 50nm
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

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

Hunsche et al., 1998
Chen et al., 2000
Van der Valk et al., 2002
Chen et al., 2003

Rayko et al., 2016
Blanchard & Tanaka, 2016

Cocker et al. (2017)
Jelik et al. (2017)
Alonso-Gonzalez et al. (2017)
### Near Field Imaging and Spectroscopy I

**Location:** Cozumel Room  
**Chairperson:** Fritz Keilmann, Germany;

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

### Near Field Imaging and Spectroscopy II

**Location:** Cozumel Room  
**Chairperson:** Rainer Hillenbrand;

<table>
<thead>
<tr>
<th>Time</th>
<th>Presentation title/Abstract title</th>
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<th>Pres.</th>
</tr>
</thead>
<tbody>
<tr>
<td>16:00</td>
<td>NEAR-FIELD NANOSCOPY OF CURRENT-INDUCED EXCESS NOISE IN GRAPHENE</td>
<td>Kuan-Ting Lin</td>
<td>WC1.1</td>
</tr>
<tr>
<td>16:15</td>
<td>NEAR-FIELD MICROSCOPY WITH PHASE SENSITIVE COHERENT DETECTION EMPLOYING QUANTUM CAScade LASERS</td>
<td>Oleg Mitrofanov</td>
<td>WC1.2</td>
</tr>
<tr>
<td>16:30</td>
<td>ANALYZING NANOSCALE OPTICAL AND THERMAL PROPERTIES IN NANOPOrous GRAPHENE BY NEAR-FIELD INFRARED MICROSCOPY</td>
<td>Takuya Okamoto</td>
<td>WC1.3</td>
</tr>
<tr>
<td>16:45</td>
<td>INTEGRATED PROBES FOR NEAR FIELD THz MICROSCOPY</td>
<td>Naser Qureshi</td>
<td>WC1.4</td>
</tr>
<tr>
<td>17:00</td>
<td>RESONANT SCATTERING PROBES IN THE TERAHERTZ RANGE</td>
<td>Thomas Siday</td>
<td>WC1.5</td>
</tr>
</tbody>
</table>
Applications of aperture-type THz near-field microscopy
Applications of aperture-type THz near-field microscopy

THz surface waves
THz surface wave observation

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

THz pulse

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

\[ T_2 = T_1 + 0.25\text{ps} \]

\[ \Delta t \]

\[ \Delta x \]

\[ \nu \]

Opt. Express 19, 3212 (2011)
Surface waves on THz devices
Resonance on the bow-tie surface
Resonance build up

Consecutive images
$\Delta t = 0.13$ ps

$t_5 = t_1 + 1.5$ ps
Conductive carbon fibres:
6.5 µm diameter, 50-250 µm long

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

Plasmonic excitations in THz Resonators

Oleg Mitrofanov - IRMMW-THz 2017
27 AUGUST - 1 SEPTEMBER 2017 | México
Applications of aperture-type THz near-field microscopy

Dielectric Resonators
Dielectric subwavelength resonators

$f_{MD} \sim 1$ THz

$\varepsilon \sim 70 - 150$

$d \sim \lambda / 10$

$\varepsilon_o, \varepsilon_e - ?$

$\text{Im}(\varepsilon) - ?$

How to investigate such resonators?

$\text{TiO}_2$ microsphere:

$\sim 20$ µm diameter
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-\(\varepsilon\) resonators

Optics Express, 22, 23034 (2014)
Mie resonances in isotropic TiO$_2$ spheres

Mitrofanov et al., Optics Express, 22, 23034 (2014)
TiO$_2$: $\varepsilon_e \approx 150; \varepsilon_o \approx 70$

$M_1$ and $M_2$ are the magnetic moments, $E$ is the electric field, and $k$ is the wave vector.
Anisotropic dielectric THz resonators:

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

in phase

$1/(4\Delta f) \approx 4 \text{ ps}$

$\varphi = 90^\circ$

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27 AUGUST - 1 SEPTEMBER 2017 | México

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)

THz waveguide

NF probe

Ag/PS: $d = 1$ mm, $L = 300$ mm
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
Generation of THz pulses at semiconductor surfaces

\[ E \propto \frac{\partial I}{\partial t} \]

Built-in surface field

Carrier density gradient

Oleg Mitrofanov - IRMMW-THz 2017
27 August - 1 September 2017 | México
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.
Emission mechanism

Transient Dipole Moment

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

Leading edge

Trailing edge

InGaAs

near-field line scan

Lateral photo-currents

100 fs: 45 μm

100 fs: 800nm

Near-field map of the radiated THz field

\[ E \propto \frac{\partial I}{\partial t} \]

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27 AUGUST - 1 SEPTEMBER 2017 | México

Impact of near-field studies

Physics of carrier dynamics

Mueckstein et al. (2015)

THz pulse generation through optical excitation profile


Waveguide mode matching
ACTIVE THz near-field probes

Chen et al., 2003

Tom Siday et al.
THz generation and Resonant scattering

$L \approx 410 \mu m$

$E_s / E_{InAs}$

Frequency (THz)

0.3 THz

Tom Siday et al. (under review)

WC1.5 - COZUMEL at 17:00
Surface plasmon excitation and Local THz generation

Alonso-Gonzalez et al. (2017)

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

Rainer Hillenbrend - WC1.1 - COZUMEL at 10:30
Exploiting sample-probe interaction

Light-matter coupling using resonators

Maissen et al., PRB (2014)

Double metal resonators


Mitrofanov et al., Appl Phys Lett. 2017
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)
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
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.
Acknowledgement

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