FIZINIŲ IR TECHNOLOGIJOS MOKSLŲ CENTRAS

THz-TDS techniques and devices

hermes

HERMES PROJECT 25-29

Funded by the European Union

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2026 July

CENTER FOR PHYSICAL SCIENCES AND TECHNOLOGY

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Outline

- Terahertz Excitation Spectroscopy (TES)
  - ✓ For investigating hot carrier dynamics
- Optical pump – THz probe (OPTP)
  - ✓ For picosecond carrier lifetime measurements
- Terahertz Time – Domain Spectroscopy (THz-TDS)
  - ✓ For terahertz transmission/reflection measurements

Terahertz waves in EM spectrum

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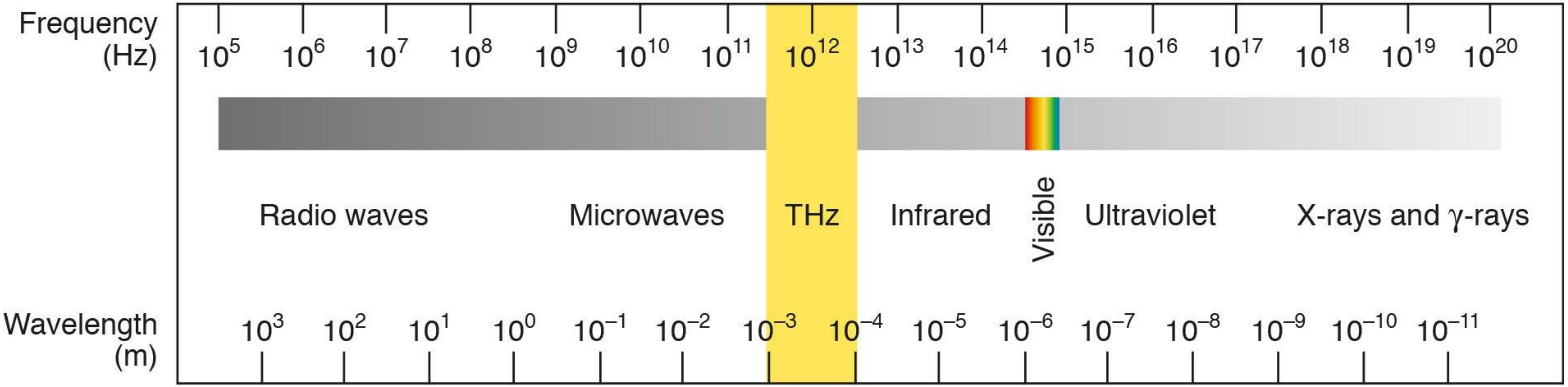
f = 100 GHz – 10 THz

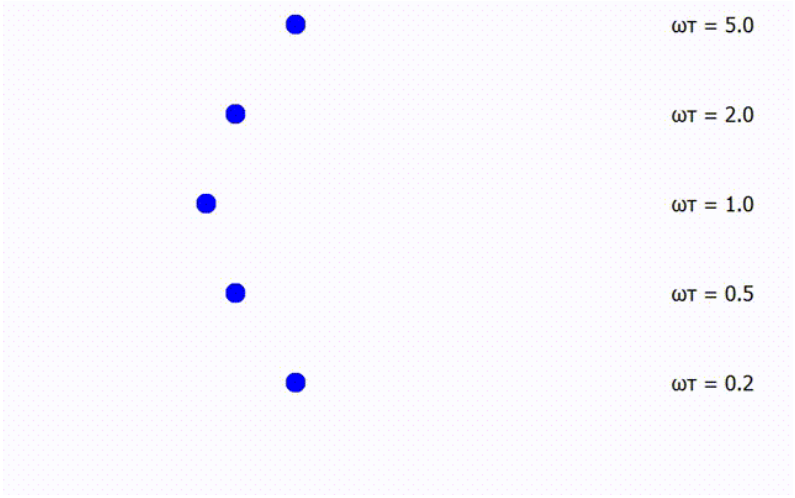
λ = 3 mm – 30 μm

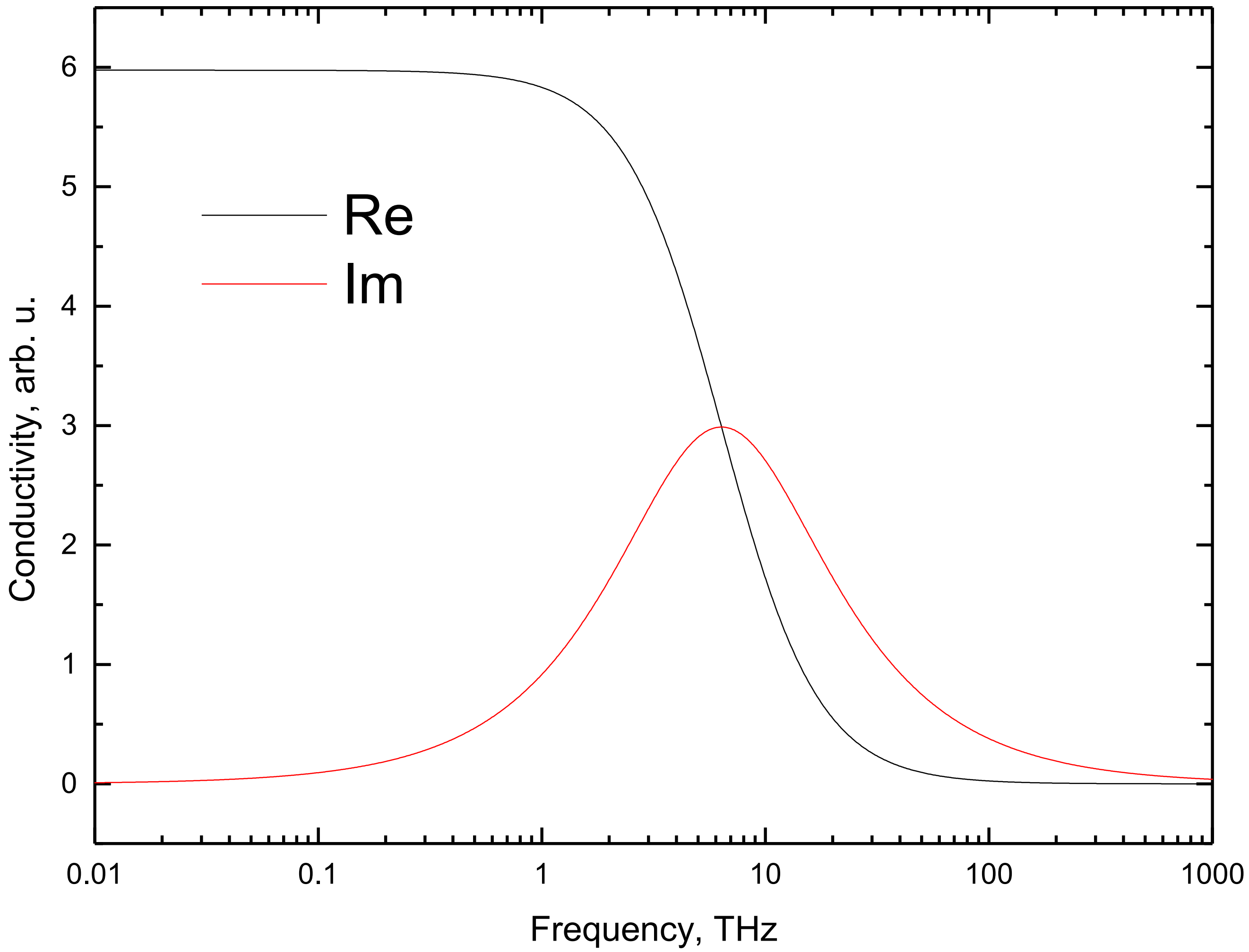
hν = 0.41 meV – 41 meV



- Transistors too slow
- Antennas are tiny
- Metals do not conduct well
- Thermal energy at room temperature is 25.6 meV or 6.19 THz
- THz LEDs/Lasers dominated by noise

Metal conductivity at THz frequencies



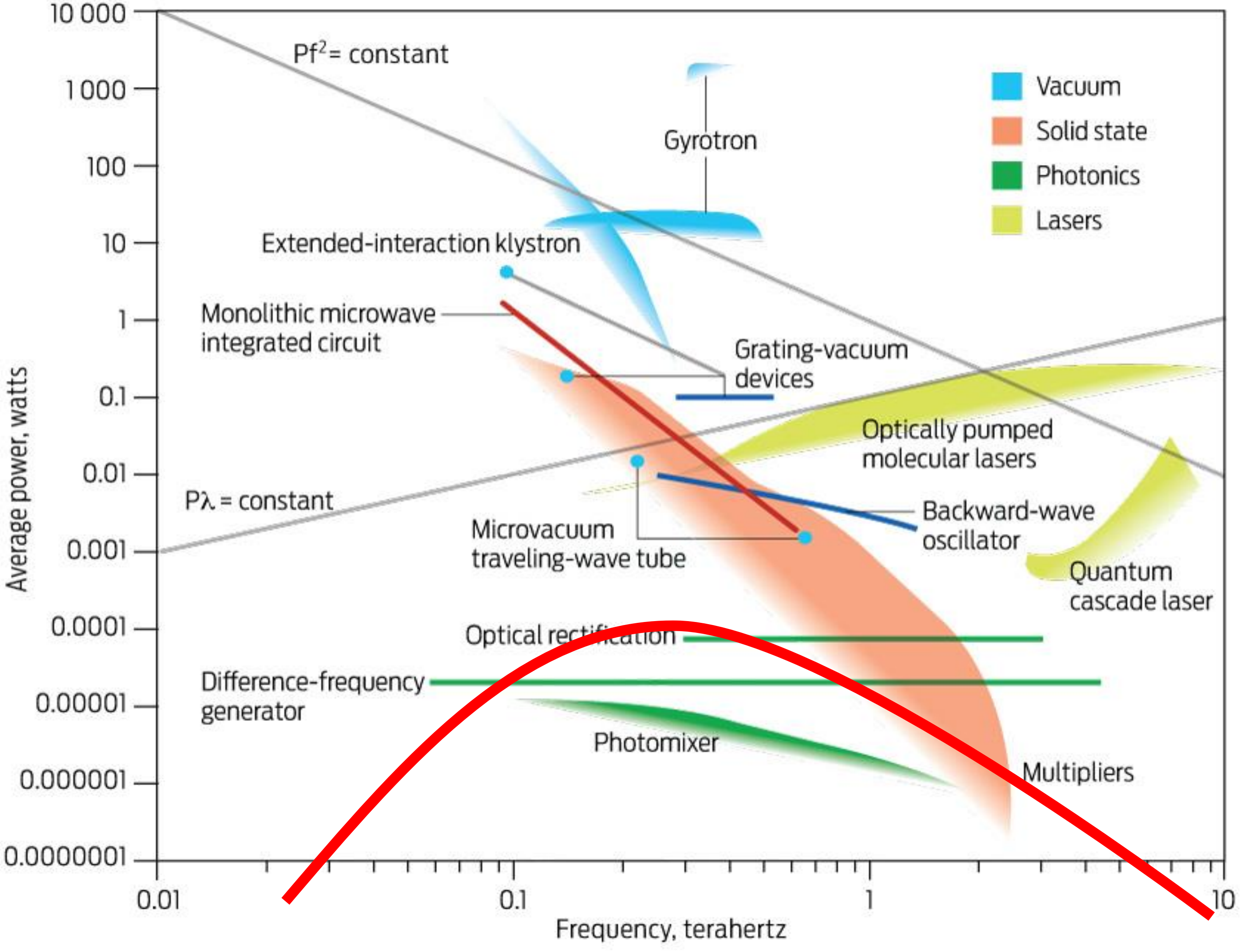


$$L_K = \left(\frac{m_e}{ne^2}\right)\left(\frac{l}{A}\right)$$

Kinetic inductance:

- finite electron velocity
- parasitic capacitance/inductance
- heating
- poor impedance matching

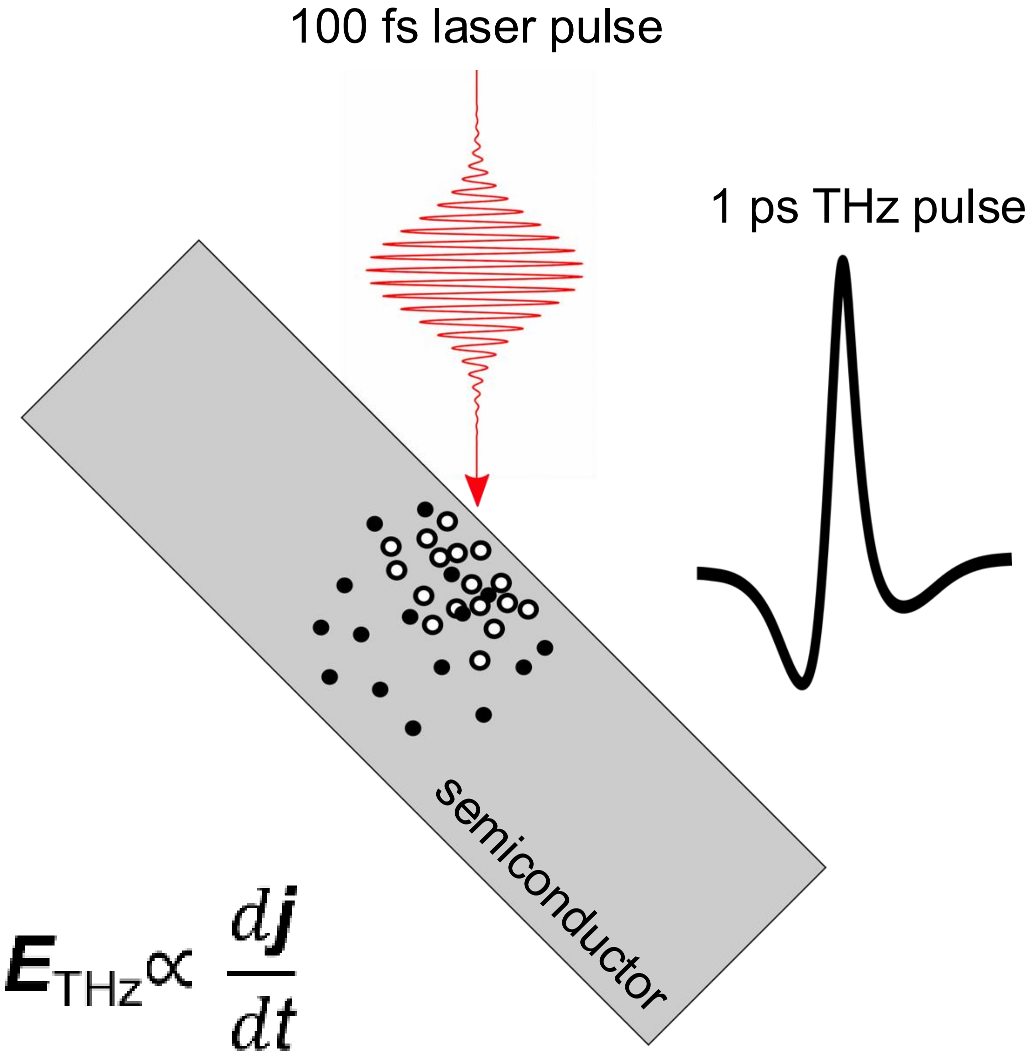
THz radiation generation methods



THz emission from semiconductors after femtosecond laser excitation:

- Simple to implement
- Extremely wide spectrum
- Works at Room Temperature
- Sensitive coherent detection gives good signal-to-noise ratios

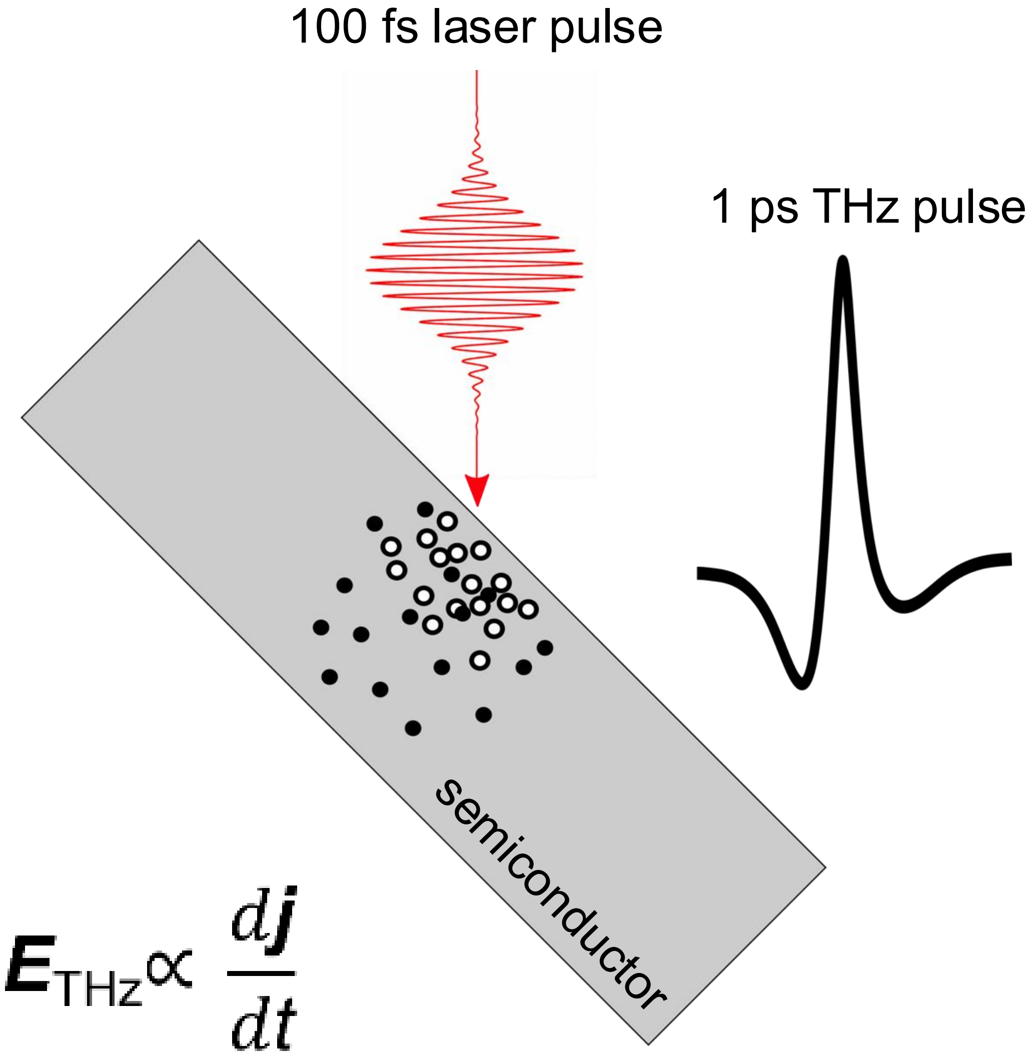
Terahertz pulse emission



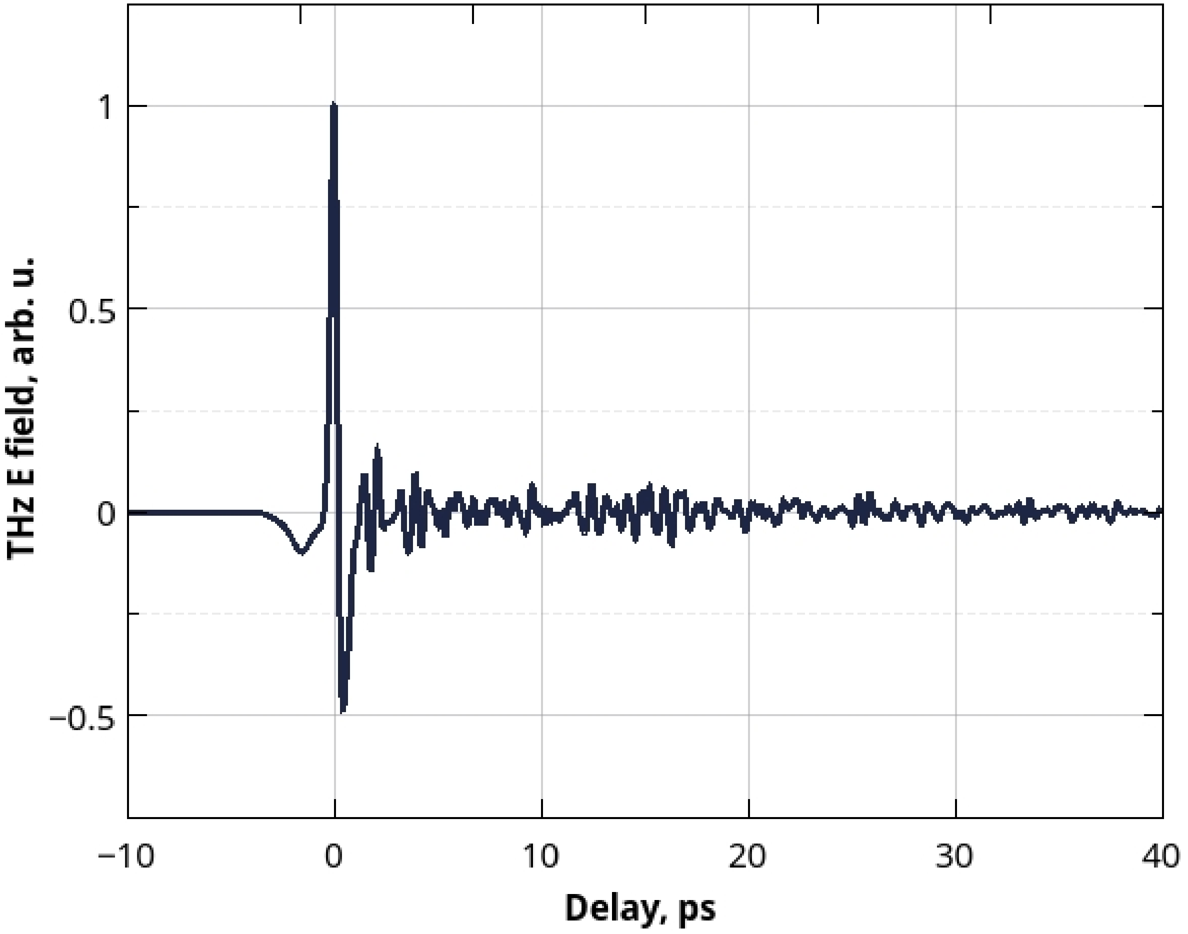
$$\boldsymbol{E}_{\mathrm{THz}} \propto \frac{d\boldsymbol{j}}{dt}$$

Time after pulse	Main process
0–100 fs	photon absorption, electron–hole pair generation
10–100 fs	carrier-carrier scattering, hot carrier thermalization
0.1–10 ps	carrier cooling by phonon emission
fs–ps	drift/diffusion currents, THz emission
ps–ns+	trapping, recombination, heat diffusion

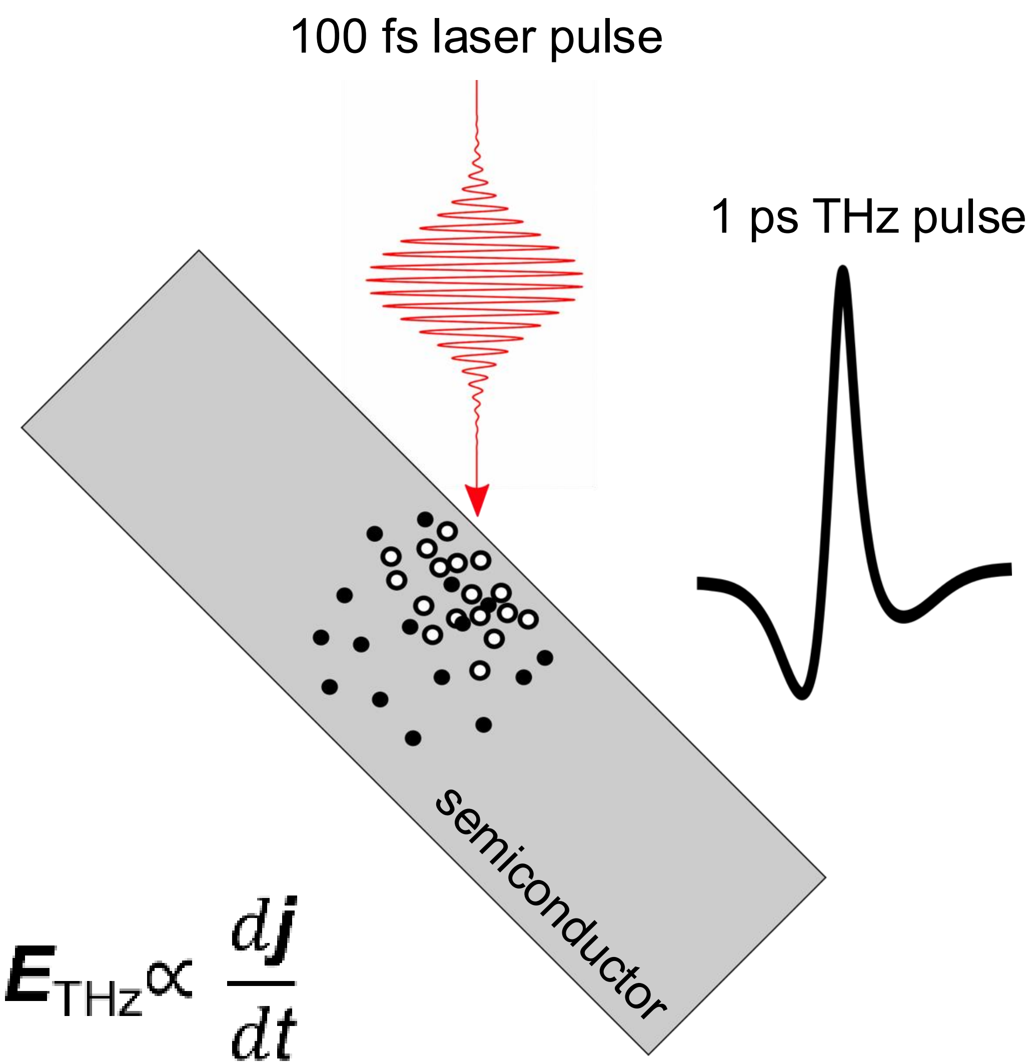
Terahertz pulse emission



$$\boldsymbol{E}_{\mathrm{THz}} \propto \frac{d\boldsymbol{j}}{dt}$$



Terahertz pulse emission



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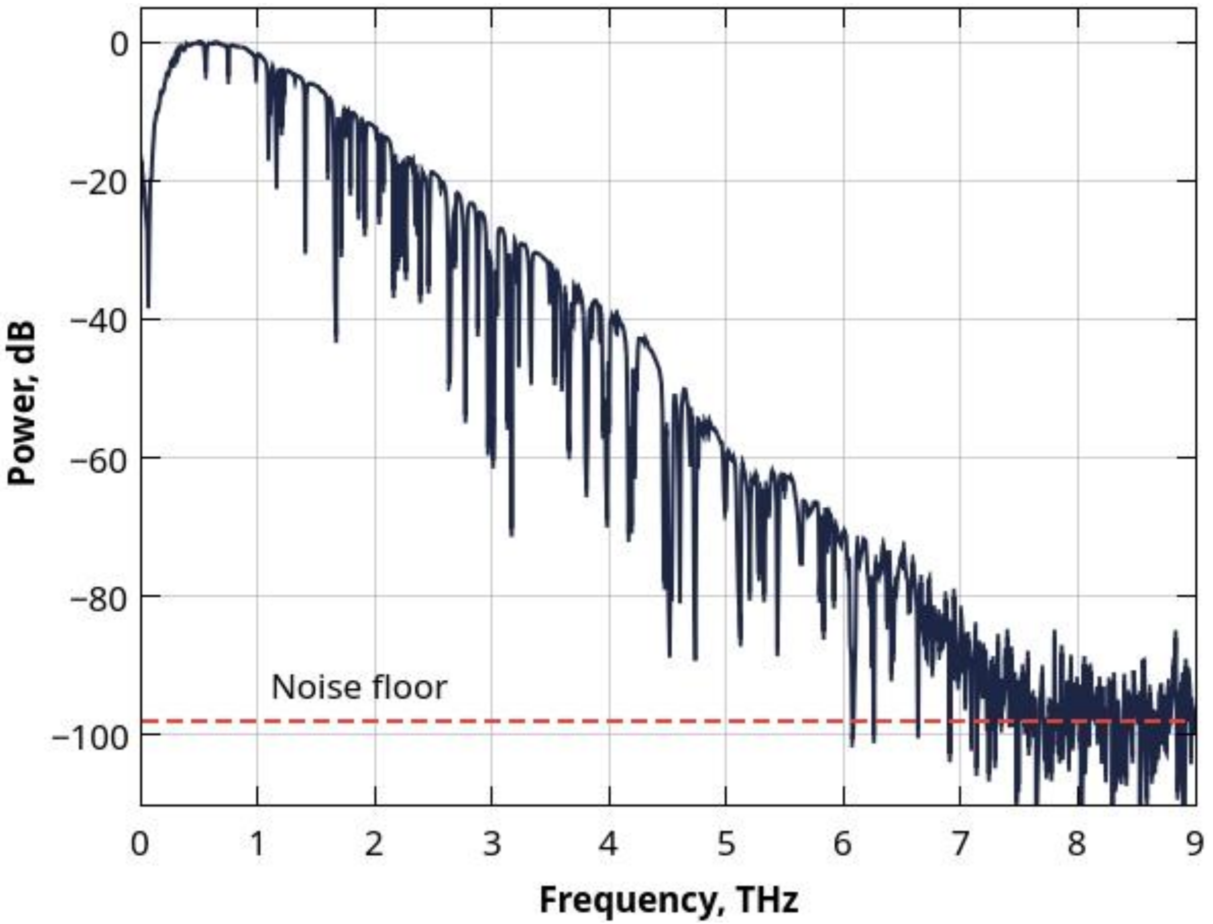
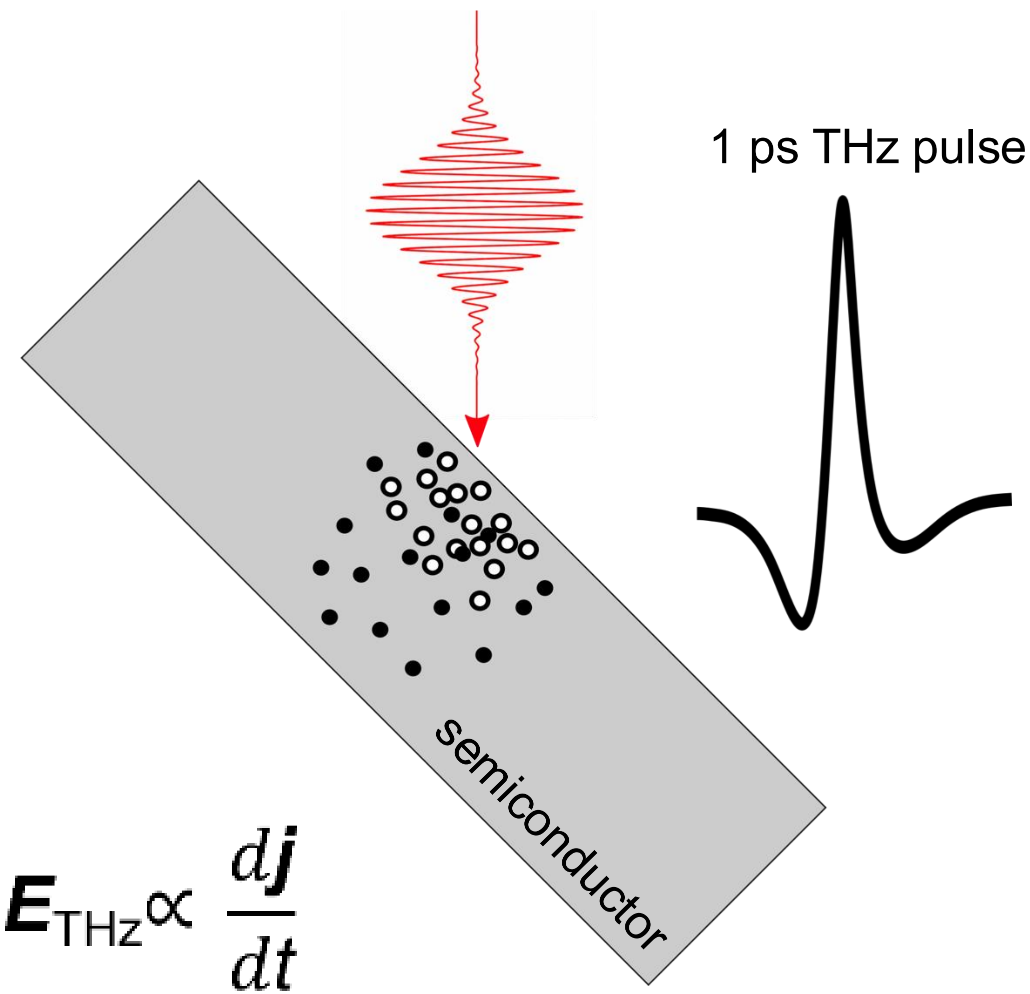


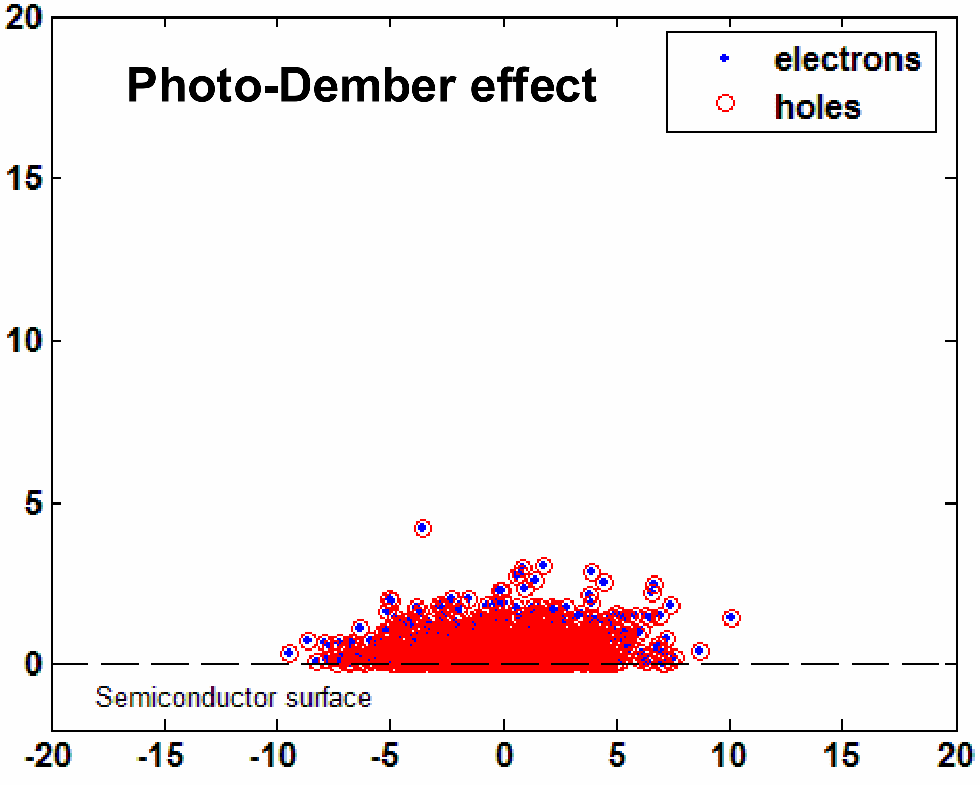
Terahertz pulse emission (diffusion)



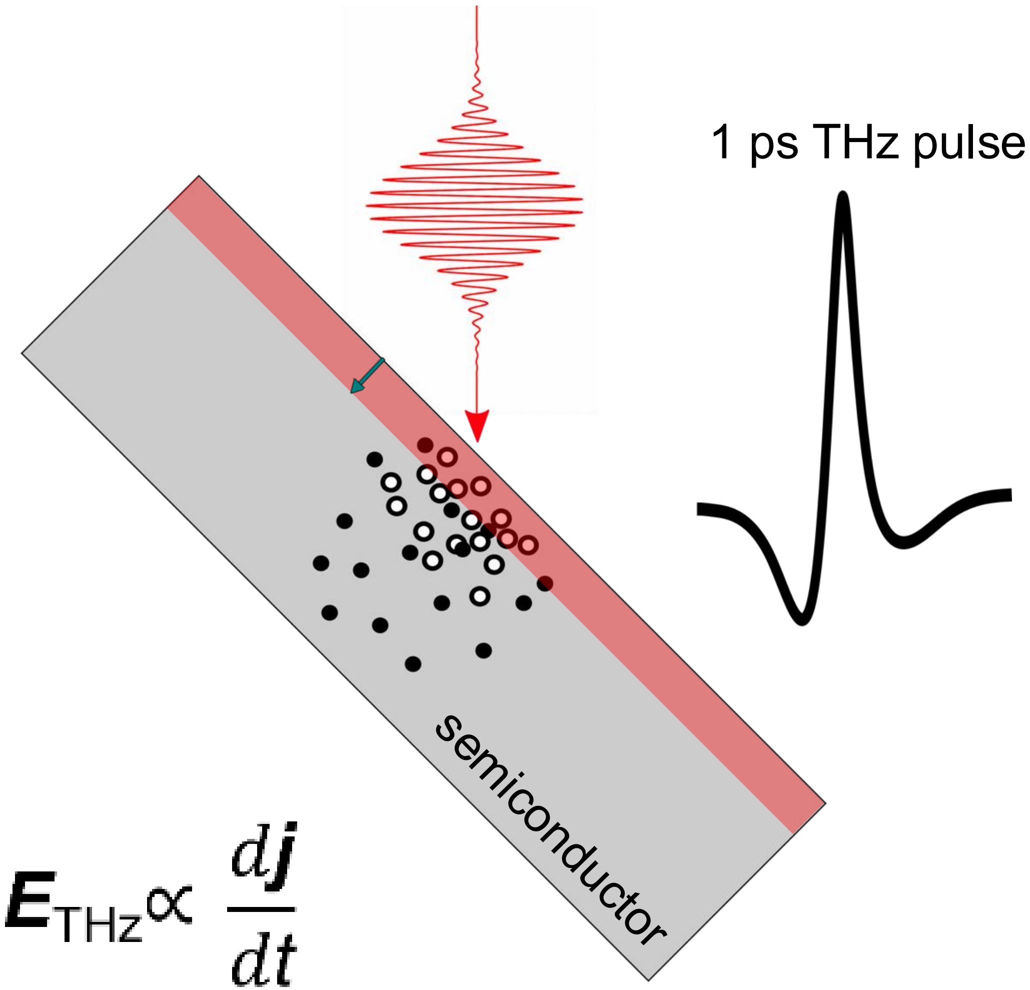
$$\boldsymbol{E}_{\mathrm{THz}} \propto \frac{d\boldsymbol{j}}{dt}$$

$$J_{diff} = qD\frac{dn}{dx} \qquad D \sim \mu\frac{k_B T_c}{q}$$

- Proportional to carrier concentration gradient

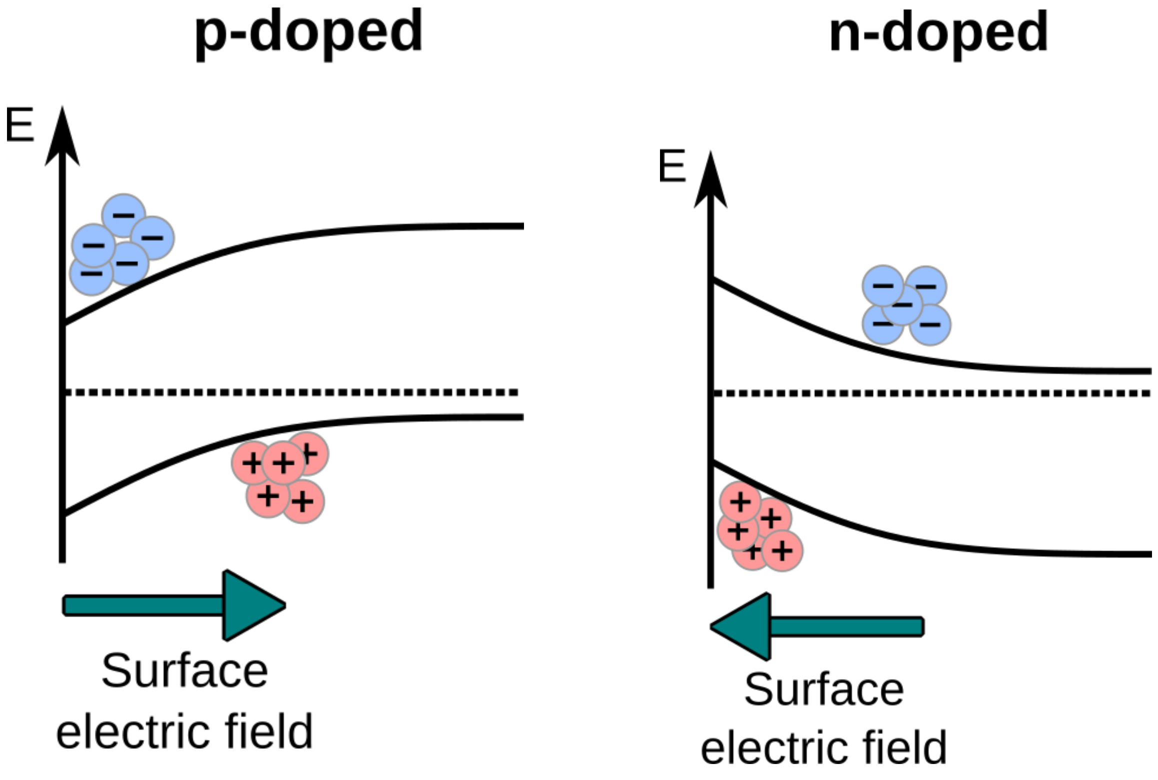


Terahertz pulse emission (drift)

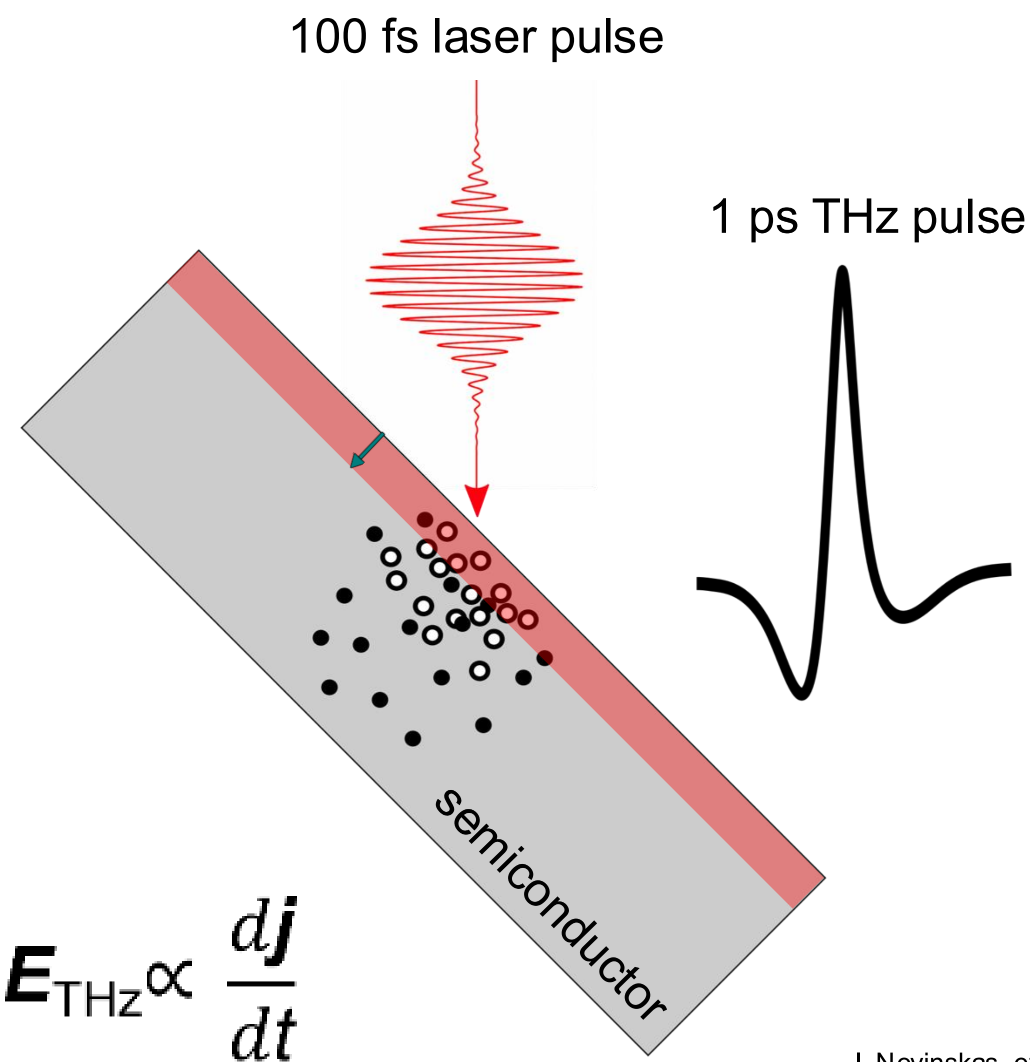


$$\boldsymbol{E}_{\mathrm{THz}} \propto \frac{d\boldsymbol{j}}{dt}$$

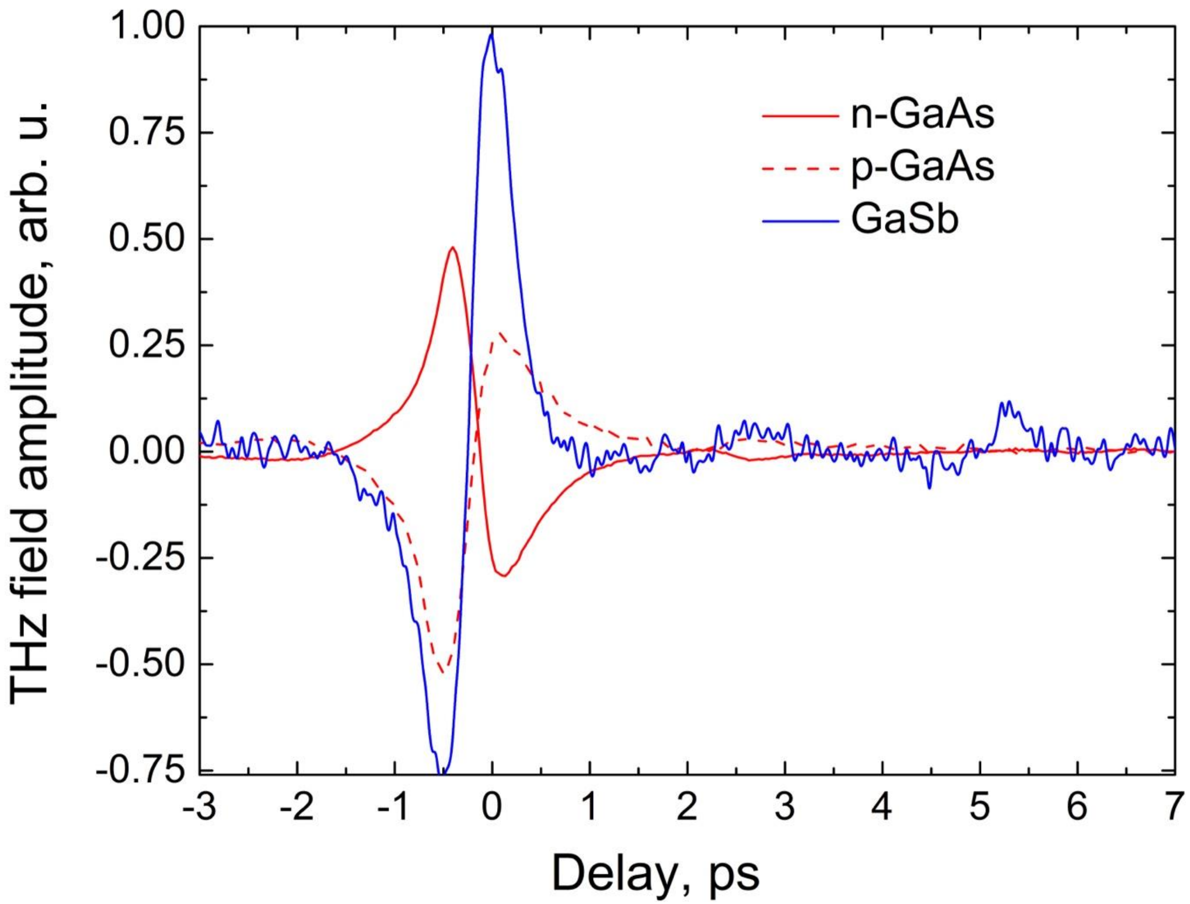
$$J_{\mathrm{drift}} = qn\mu E$$



Terahertz pulse emission (drift)

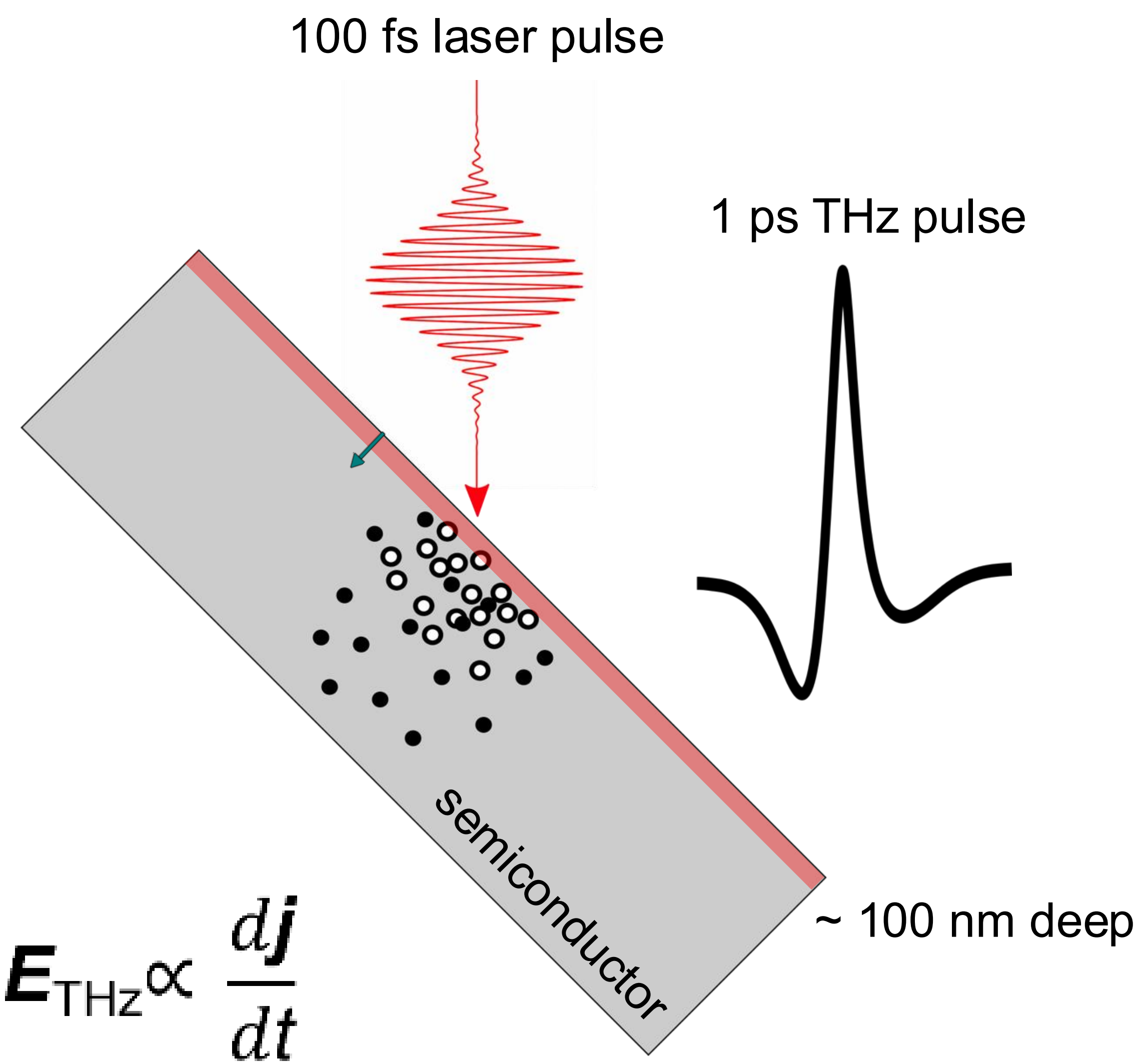


$$\boldsymbol{E}_{\mathrm{THz}} \propto \frac{d\boldsymbol{j}}{dt}$$



I. Nevinskas, et al., “Magnetic field enhanced terahertz pulse emission from a femtosecond laser excited GaSb epitaxial layer,” Electronics Letters, vol. 52, no. 19, pp. 1627–1629, 2016. DOI: 10.1049/el.2016.2216

Terahertz pulse emission (drift)



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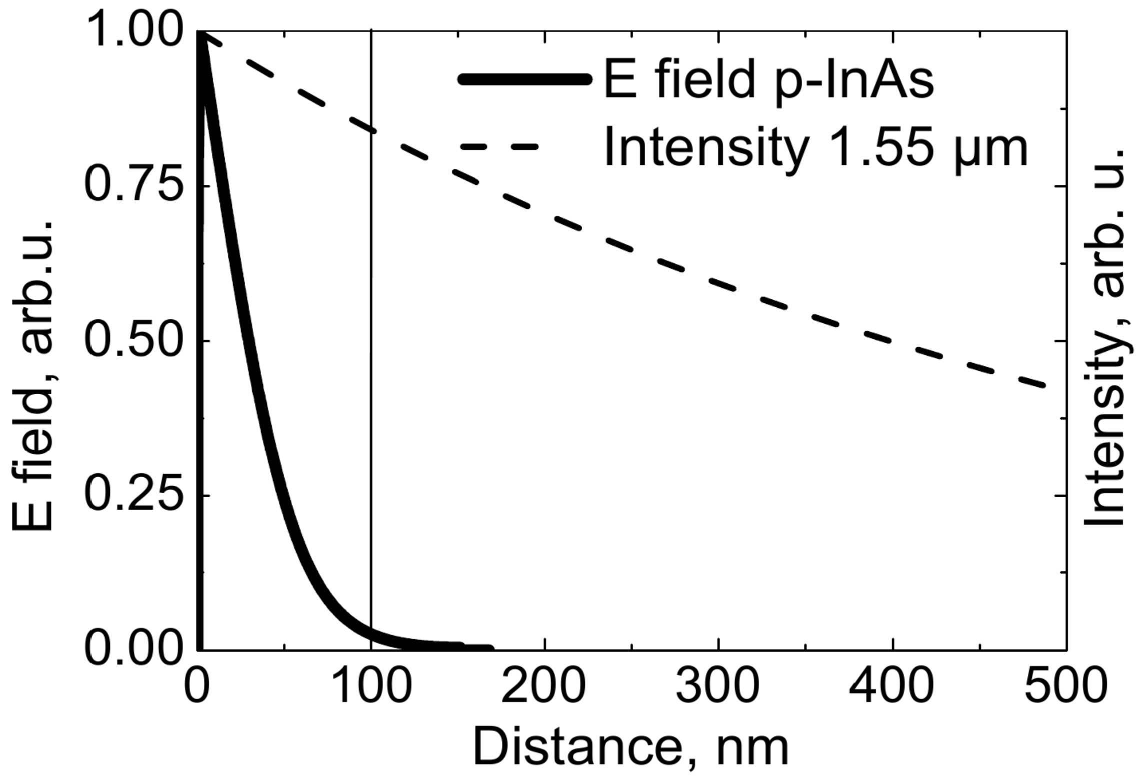
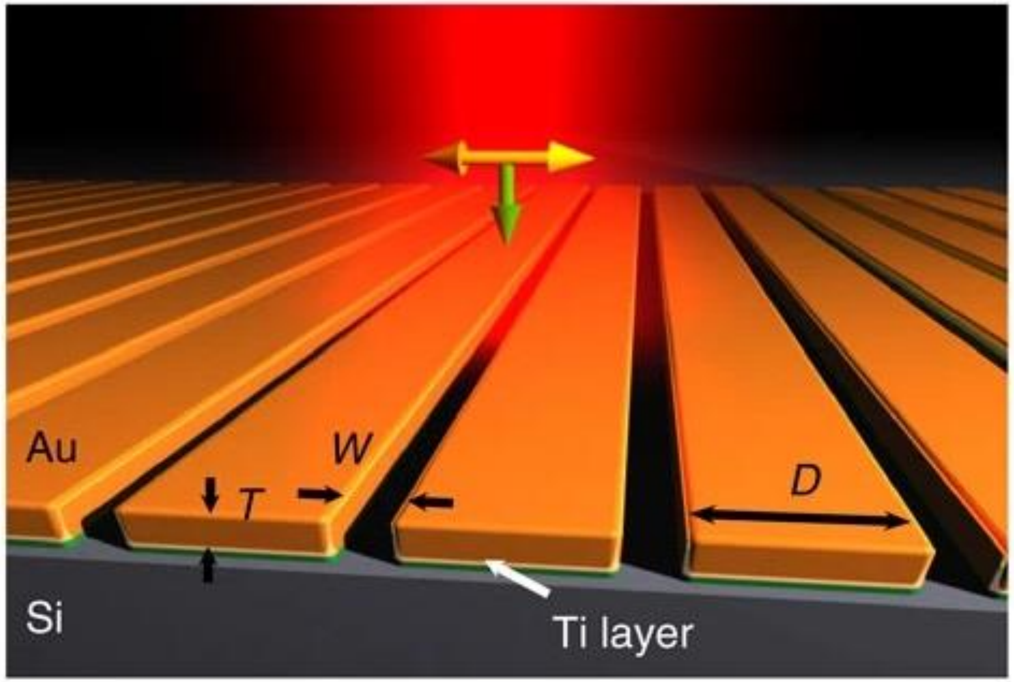
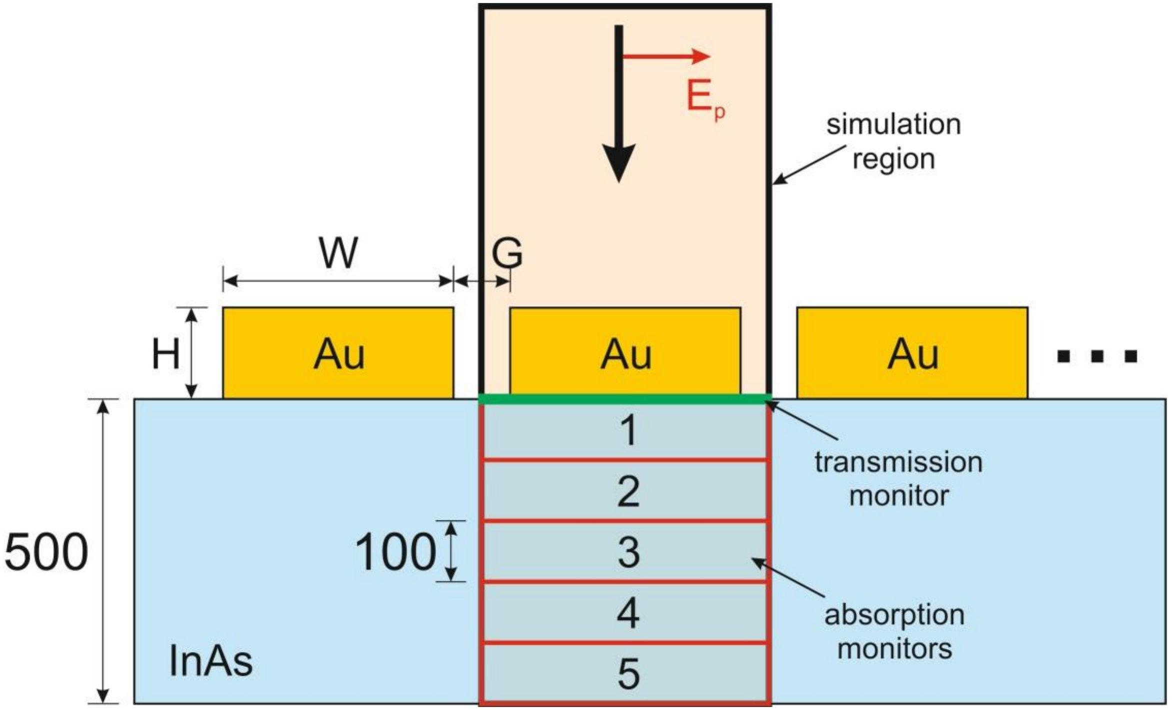


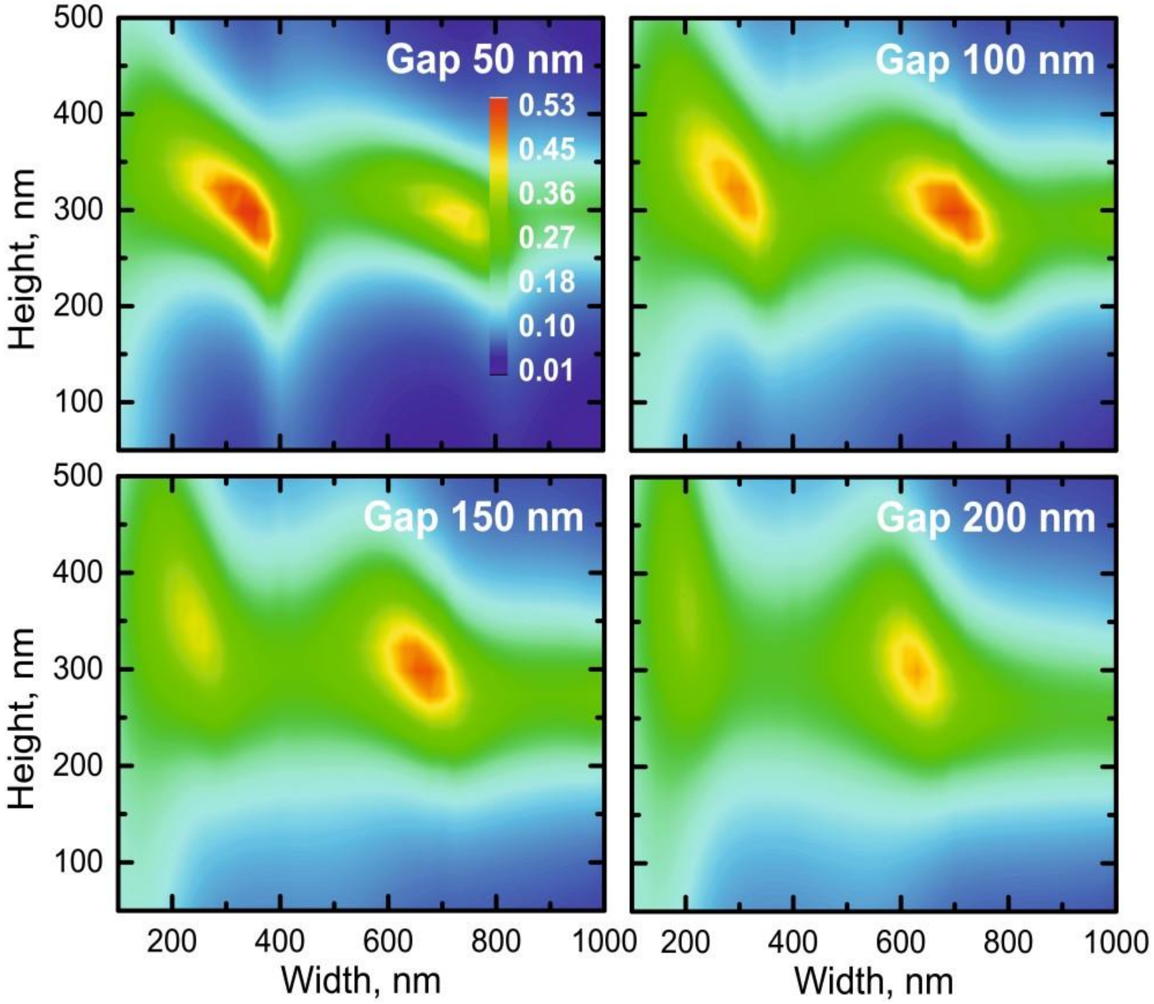
Plasmonic diffraction grating

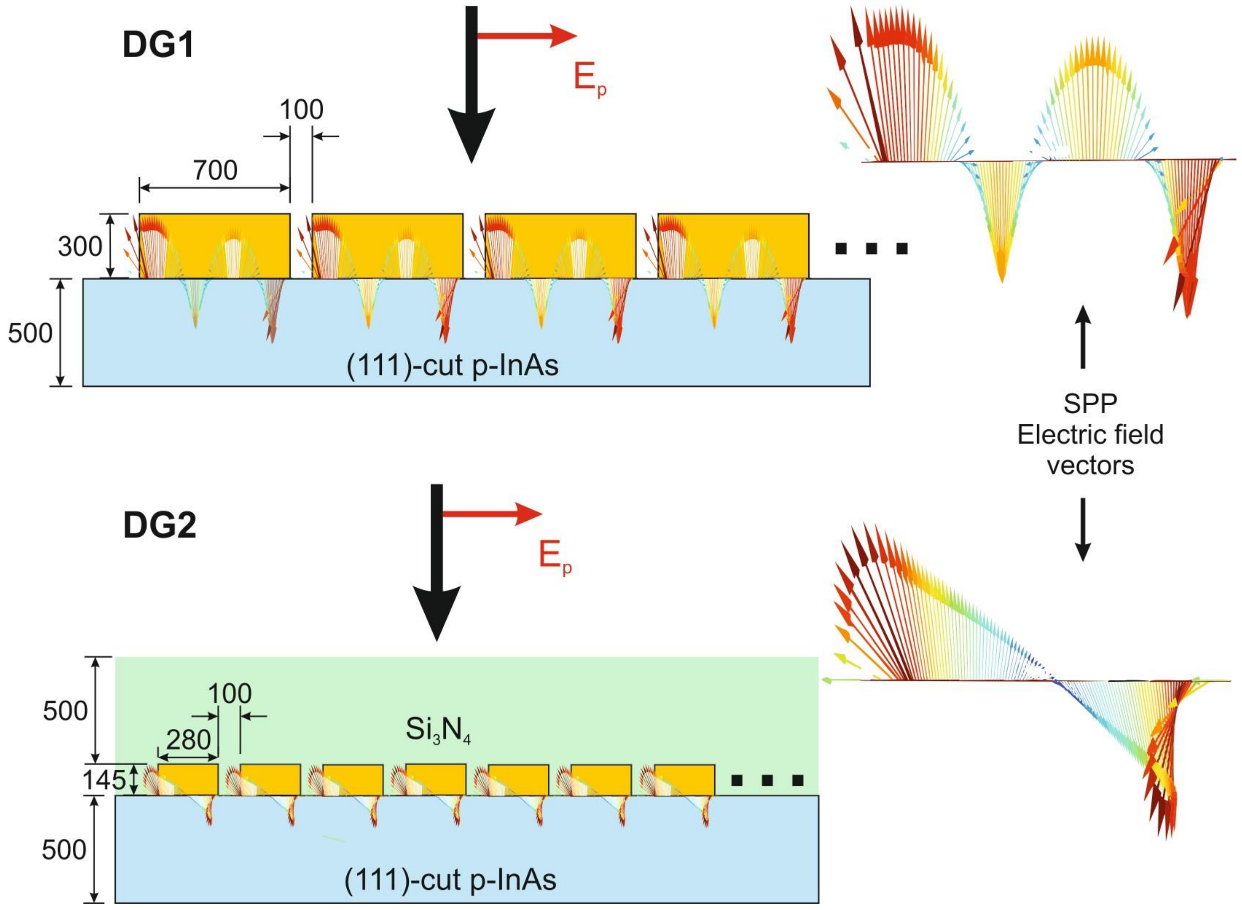




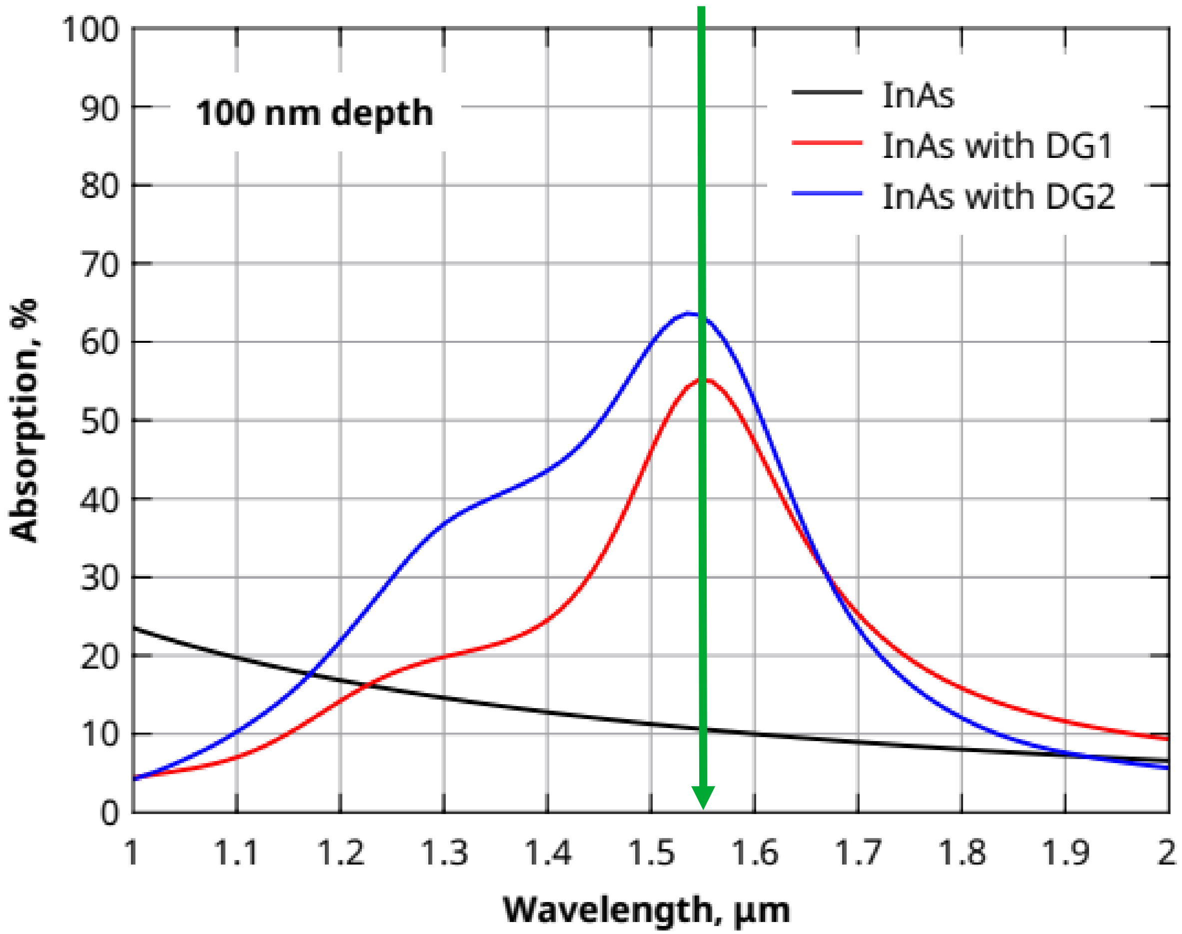
A. Sobhani et al., "Narrowband photodetection in the near-infrared with a plasmon-induced hot electron device," Nat Commun, vol. 4, no. 1, p. 1643, Mar. 2013, doi: 10.1038/ncomms2642.

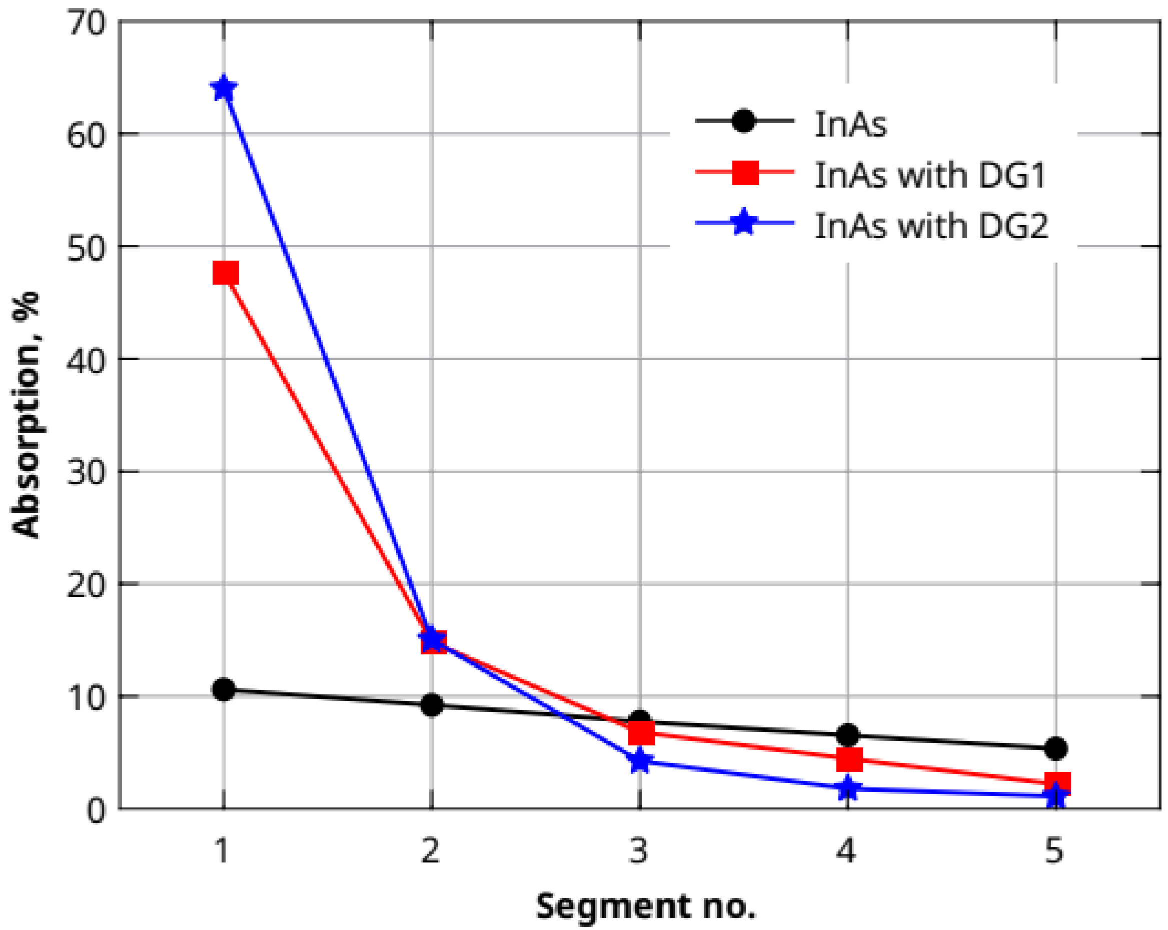
Plasmonic diffraction grating (sweeps)



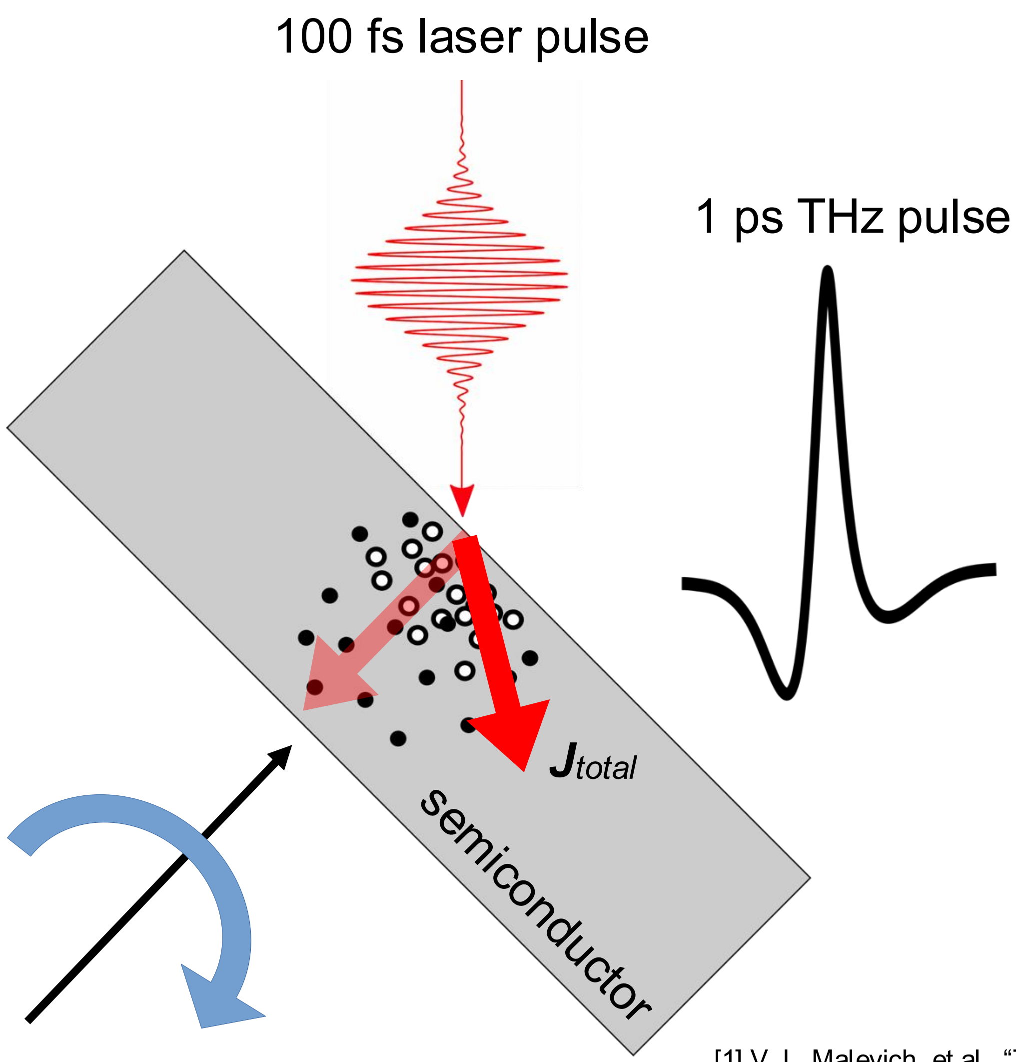


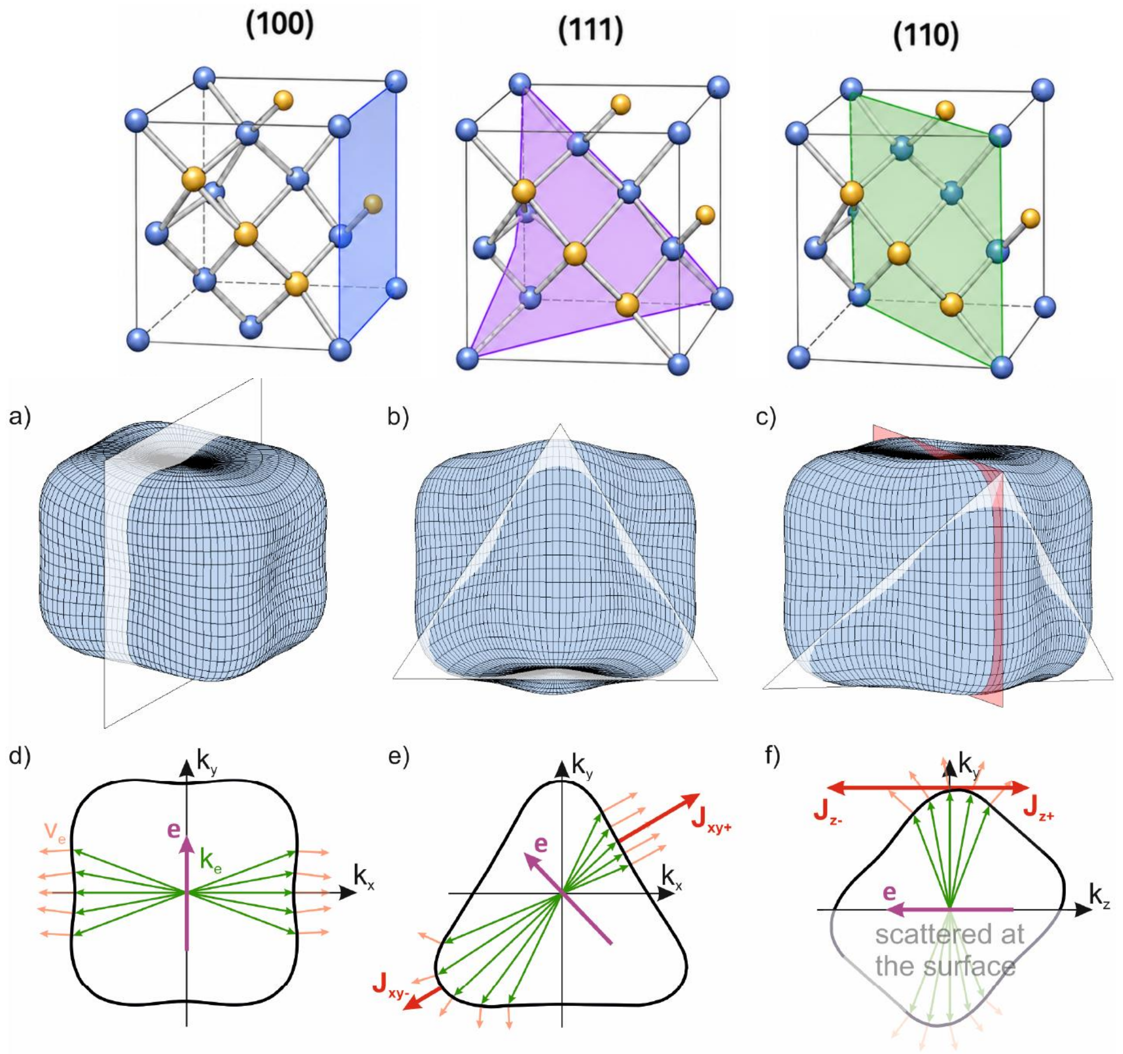
Plasmonic diffraction grating





Terahertz pulse emission (lateral photocurrent)

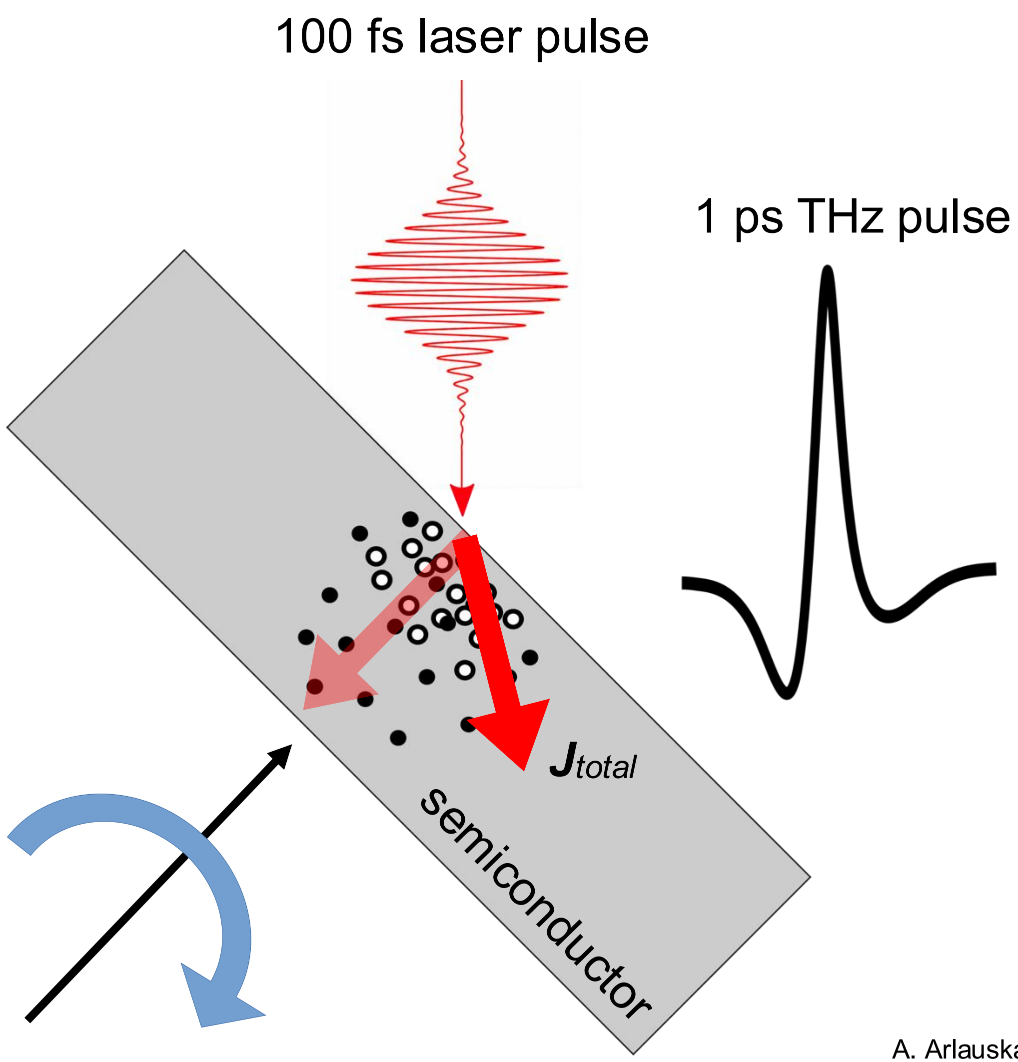




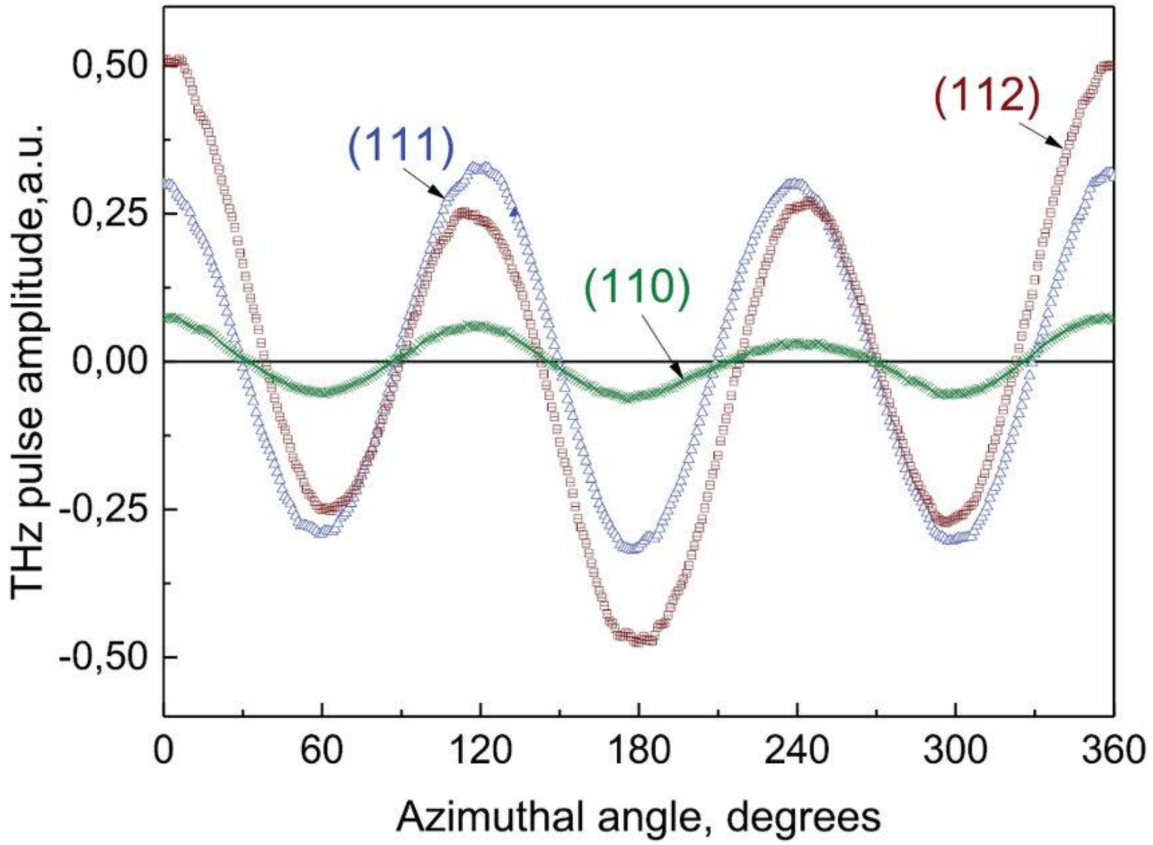
[1] V. L. Malevich, et al., “Terahertz emission from cubic semiconductor induced...,”. *JAP.* **112** (2012), DOI: 10.1063/1.4758181

[2] Y. V. Malevich, et al., Anisotropic picosecond photoconductivity...,” *JAP*, vol. 115, no. 7, p. 073103, Feb. 2014, DOI: 10.1063/1.4865961

Terahertz pulse emission (lateral photocurrent)



InSb



A. Arlauskas, L. Subačius, A. Krotkus, and V. L. Malevich, “Terahertz emission from InSb illuminated by femtosecond laser pulses,” J. Phys. D: Appl. Phys., vol. 50, no. 5, p. 055101, Jan. 2017, doi: 10.1088/1361-6463/aa4ed4.

Terahertz pulse emission (lateral photocurrent)

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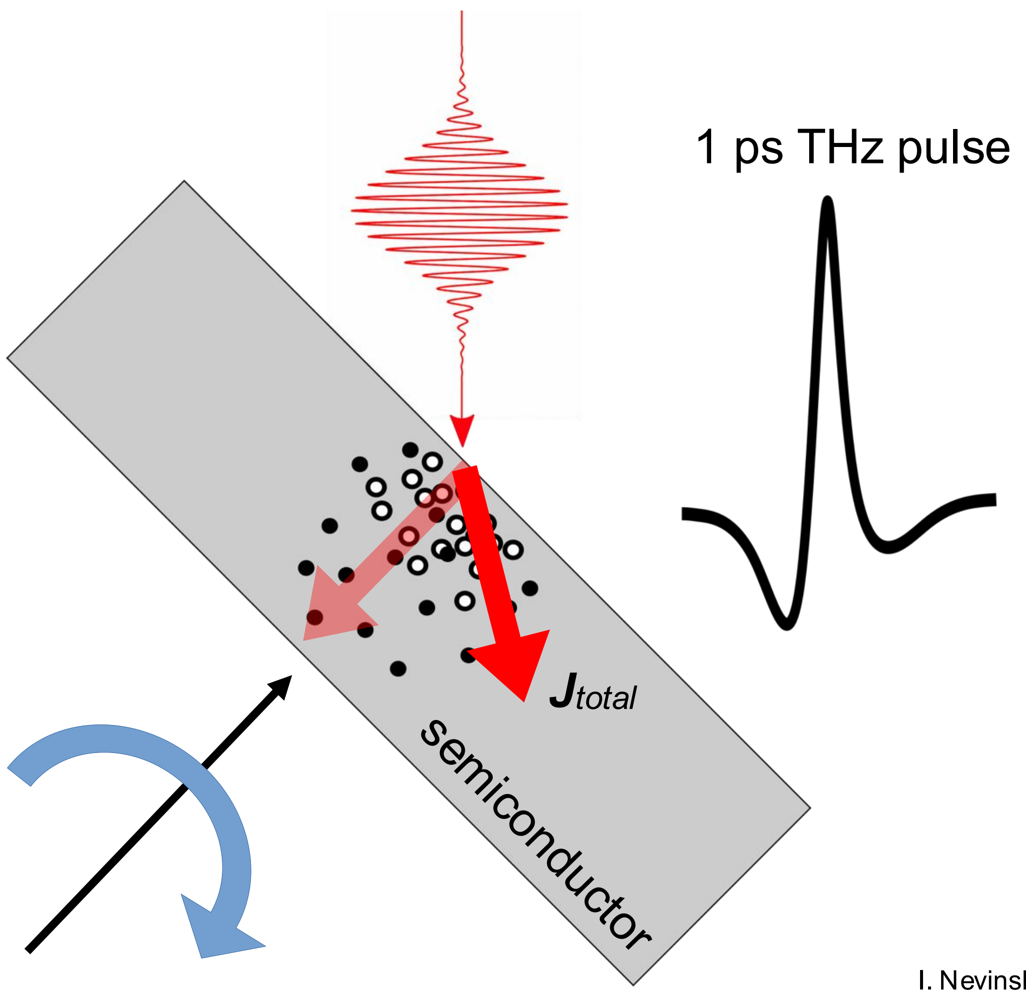
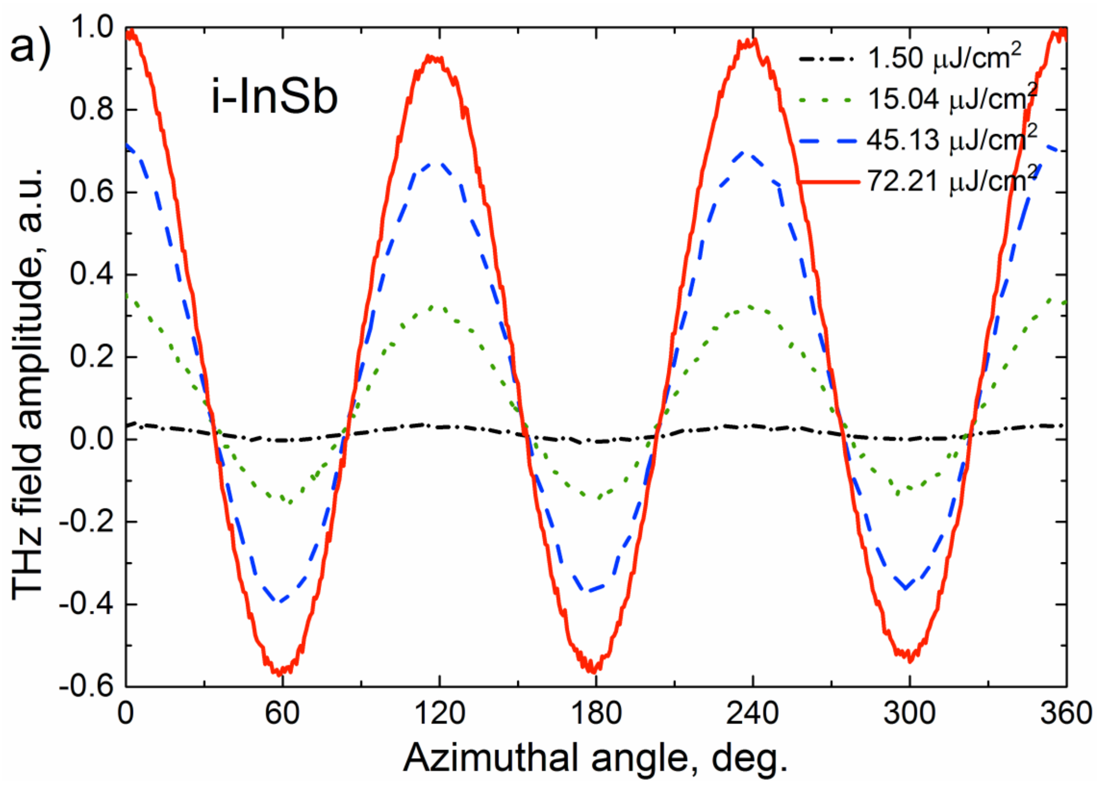
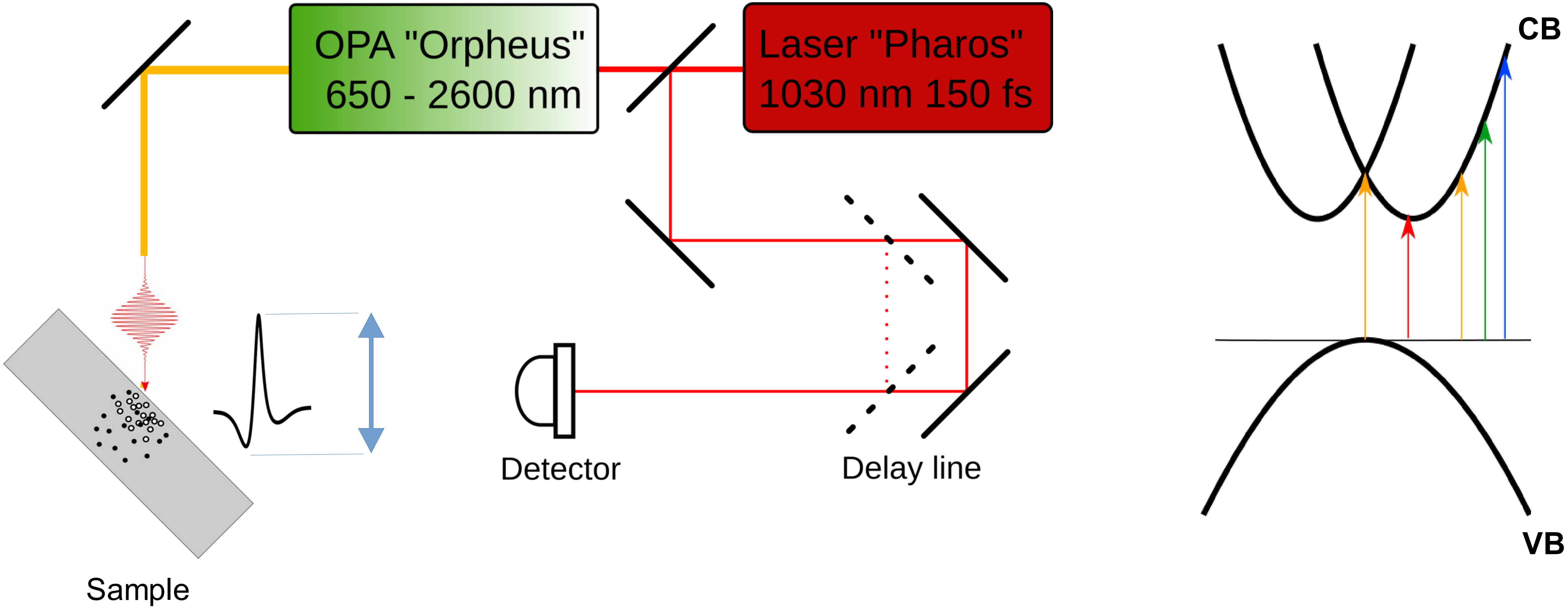


InSb

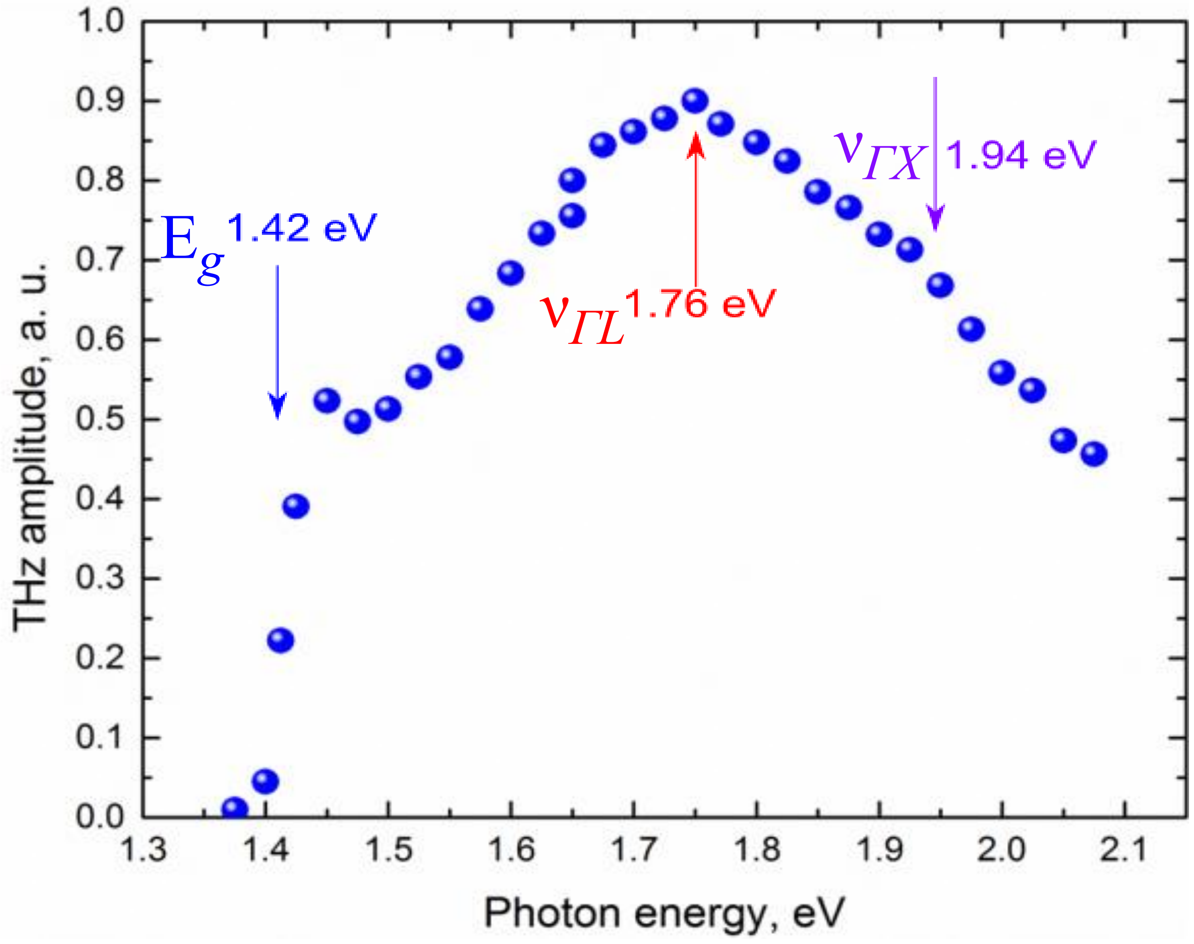


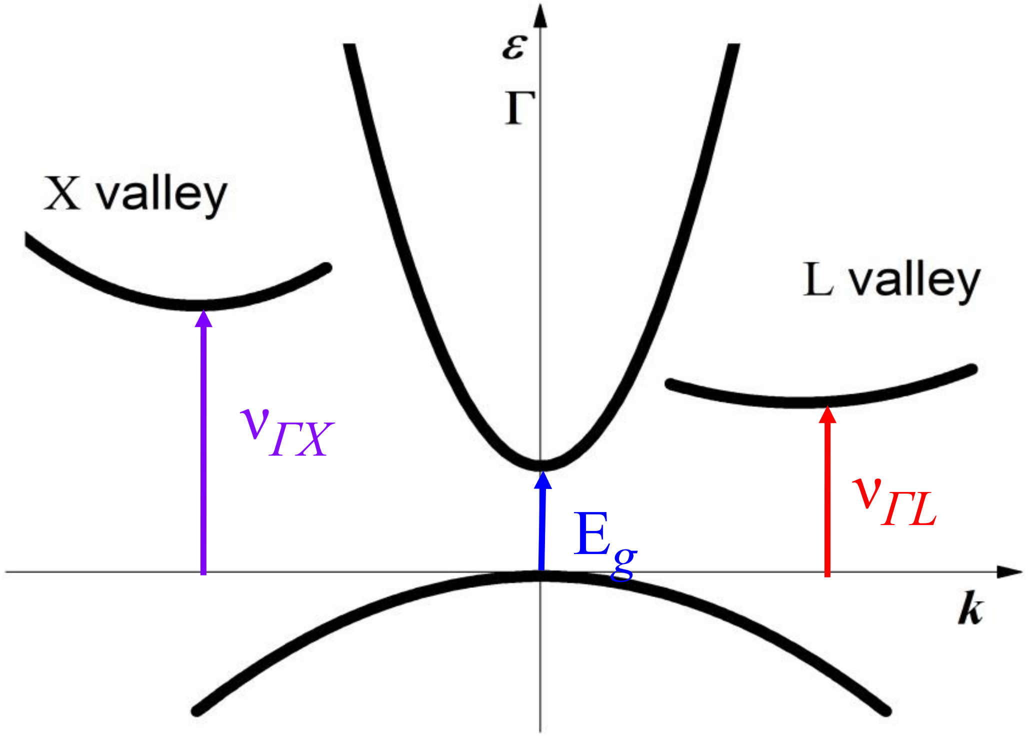
I. Nevinskas, K. Vizbaras, A. Trinkūnas, R. Butkutė, and A. Krotkus, "Terahertz pulse generation from (111)-cut InSb and InAs crystals when illuminated by 1.55-μm femtosecond laser pulses," Opt. Lett., OL, vol. 42, no. 13, pp. 2615–2618, Jul. 2017, doi: 10.1364/OL.42.002615.

Terahertz Excitation Spectroscopy (TES)



TES characterization (GaAs)

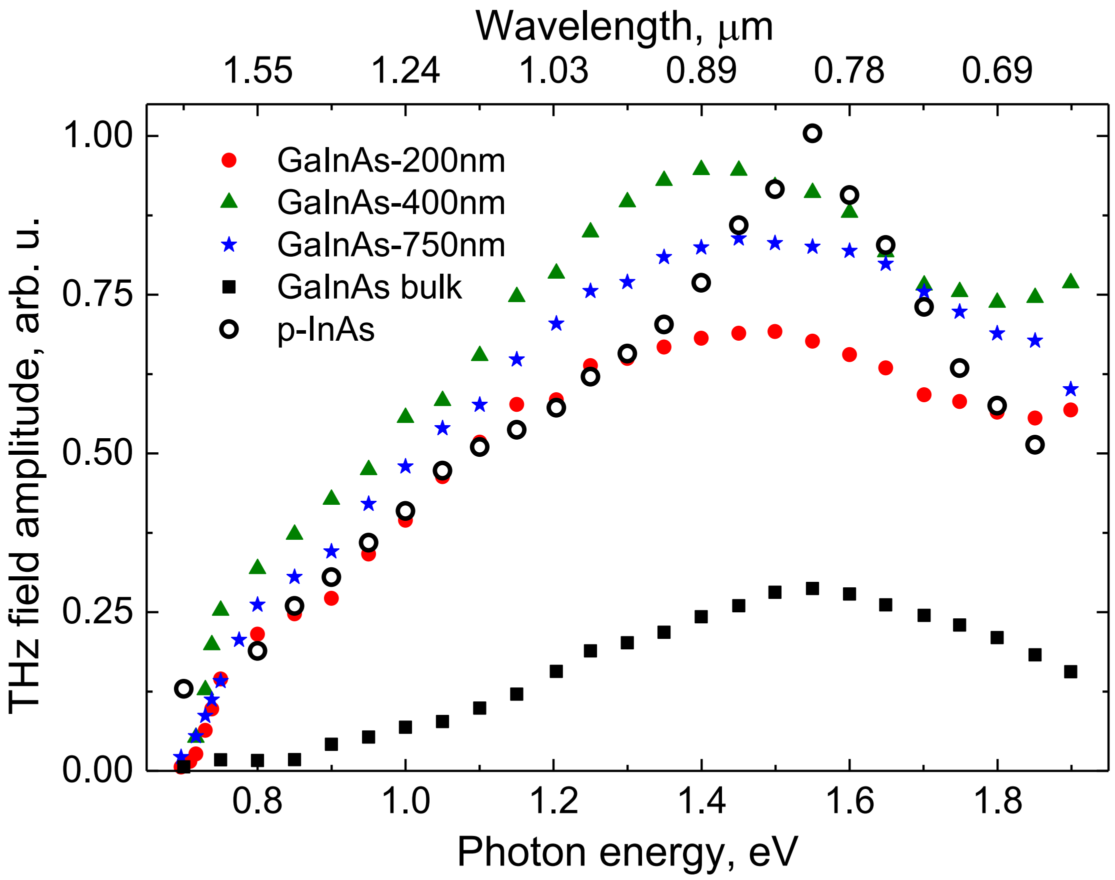




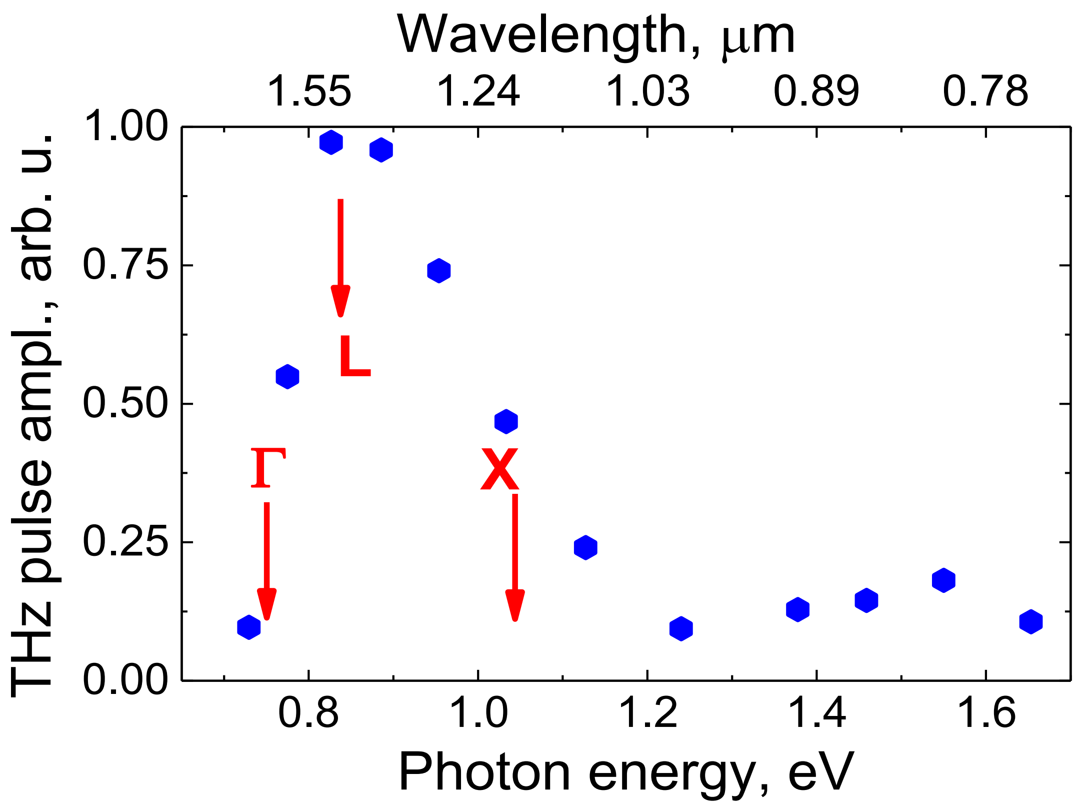
A. Arlauskas, A. Krotkus, THz excitation spectra of AIIIBV semiconductors. *Semicond. Sci. Technol.* 27 (2012), DOI: 10.1088/0268-1242/27/11/115015;

TES characterization

- **GaInAs p-i-n junction**



- **GaSb**



TES characterization

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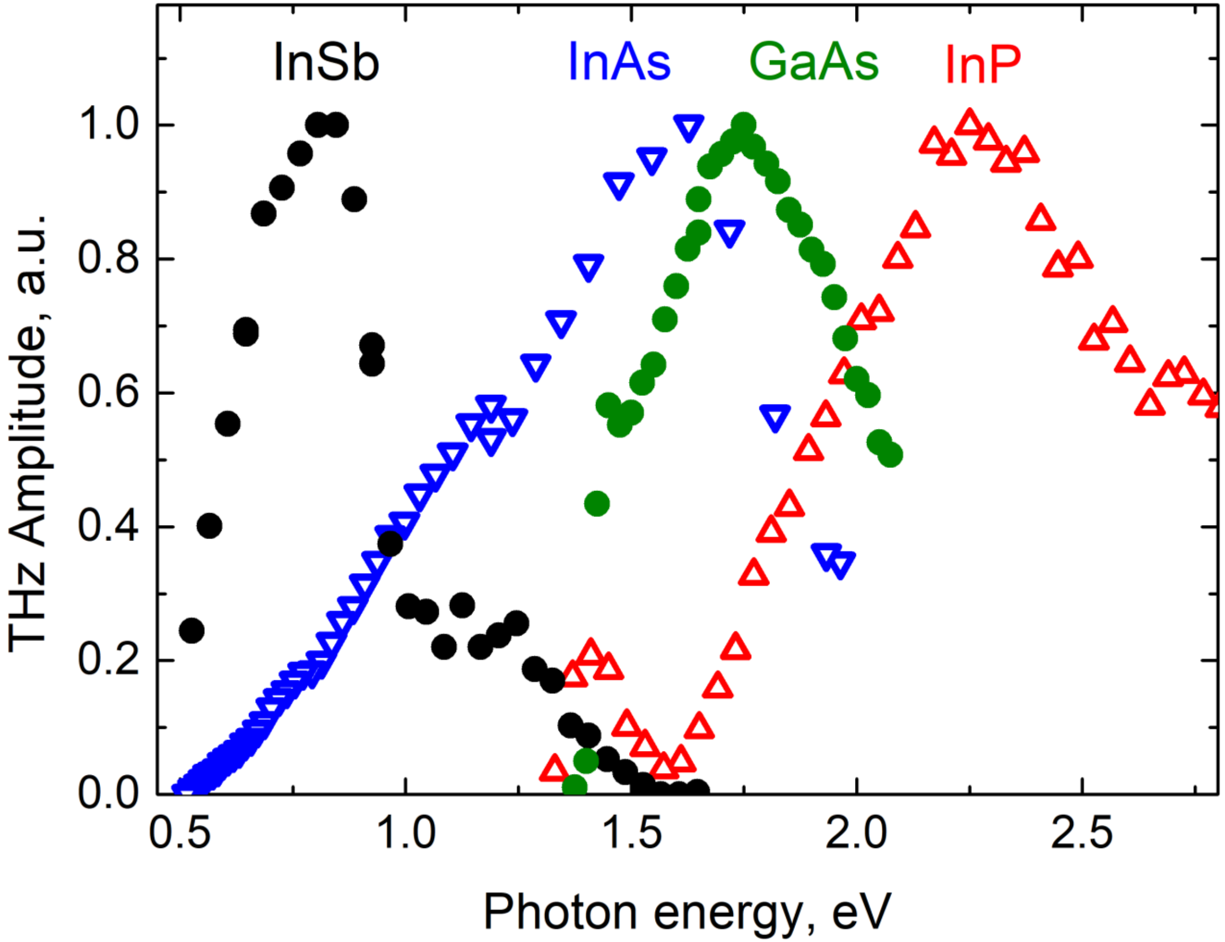
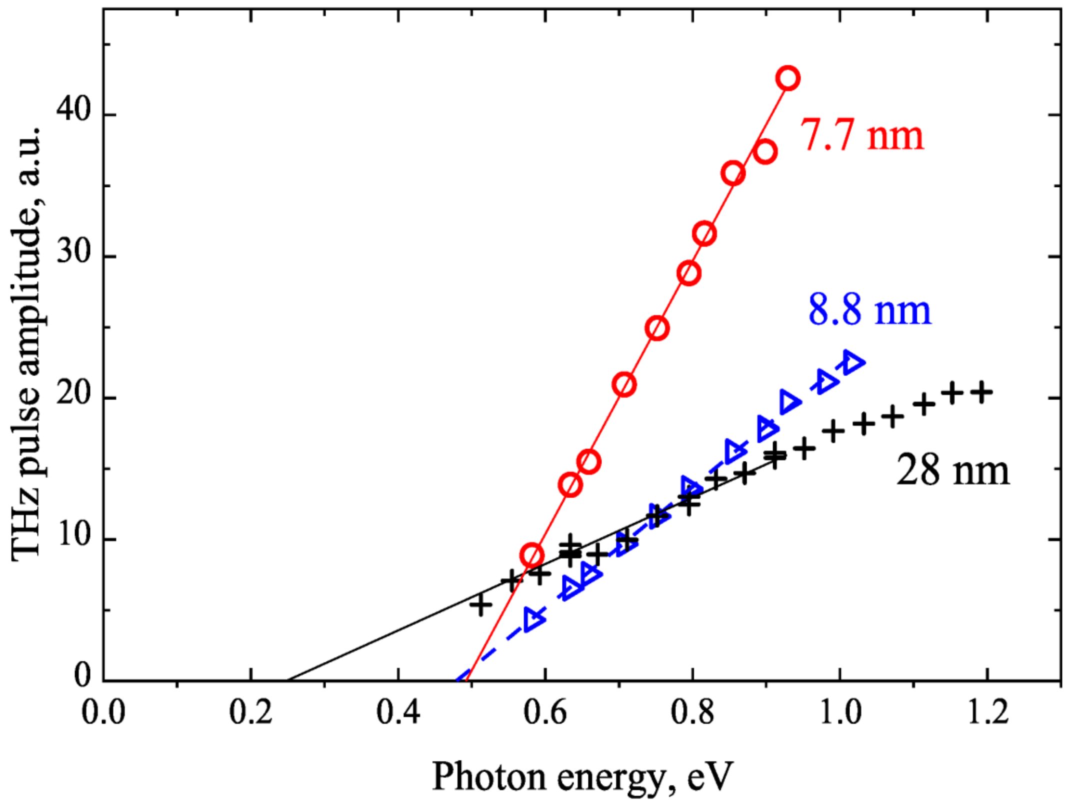


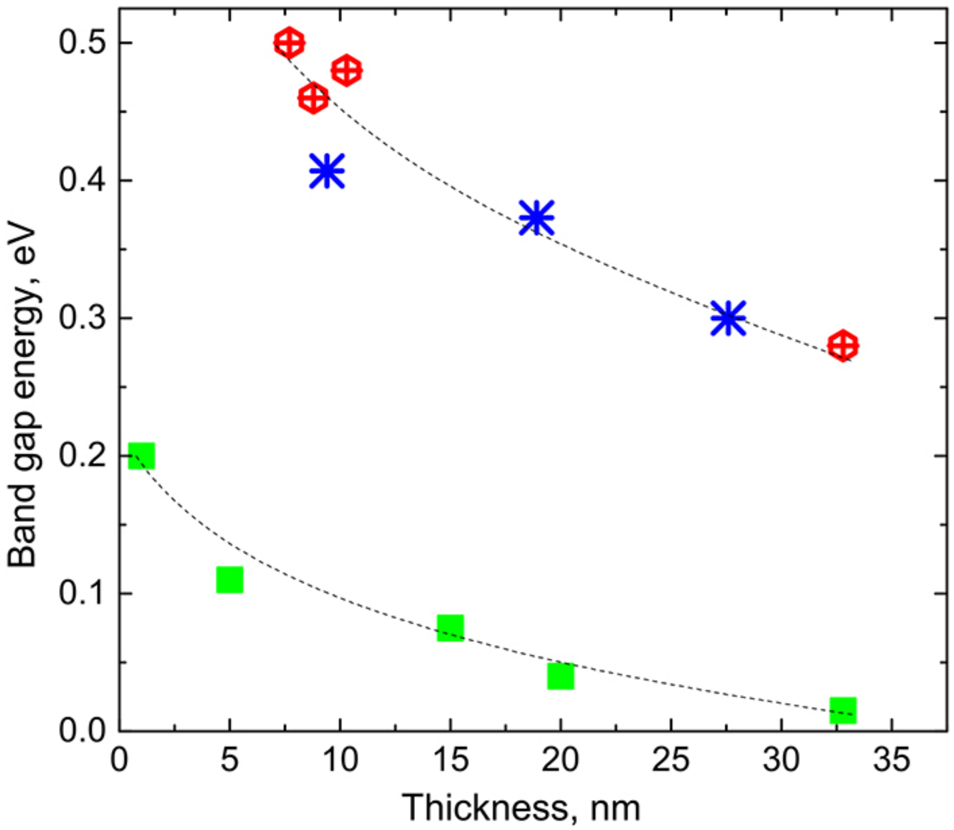
R. Adomavičius et al, Spectral dependencies of terahertz emission from InAs and InSb. *Appl. Phys. Lett.* 87, 1–3 (2005);

A. Krotkus, I. Nevinskas, R. Norkus, "Semiconductor Characterization by Terahertz Excitation Spectroscopy", Materials, 16, 2859 (2023), DOI: 10.3390/ma16072859

TES characterization (2D materials)

Bismuth on silicon substrate

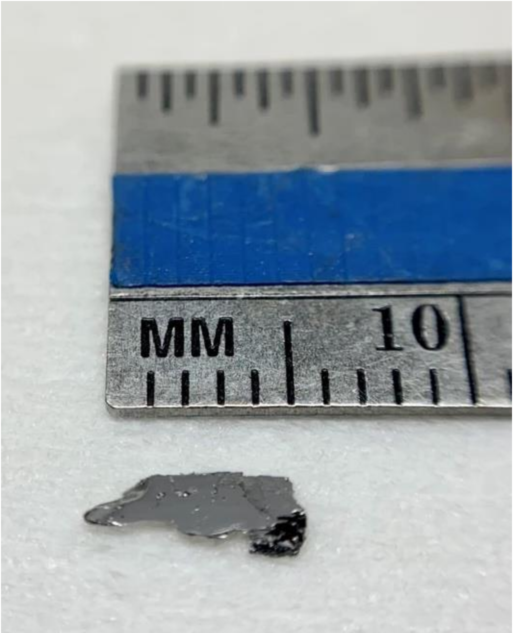




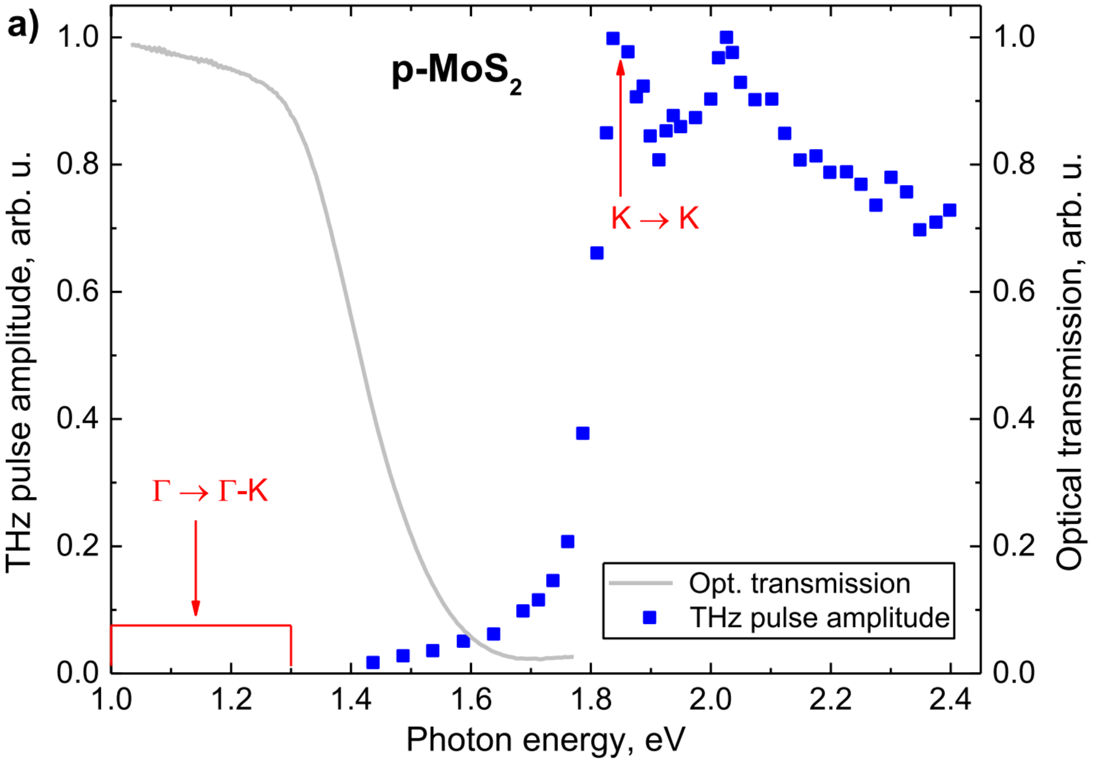
I. Nevinskas, S. Stanionytė, J. Devenson, and A. Krotkus, “Direct bandgap dependence of bismuth films on their thickness,” Journal of Applied Physics, vol. 132, no. 5, 2022. DOI: 10.1063/5.0095477

TES characterization (nm flakes)

- **Transition Metal Dichalcogenides (TMD)**



10-50 μm thick



I. Nevinskas et al., "Terahertz pulse emission from photoexcited bulk crystals of transition metal dichalcogenides," J. Phys. D: Appl. Phys., vol. 54, no. 11, p. 115105, Jan. 2021, doi: 10.1088/1361-6463/abcc26.

TES characterization (nm flakes)

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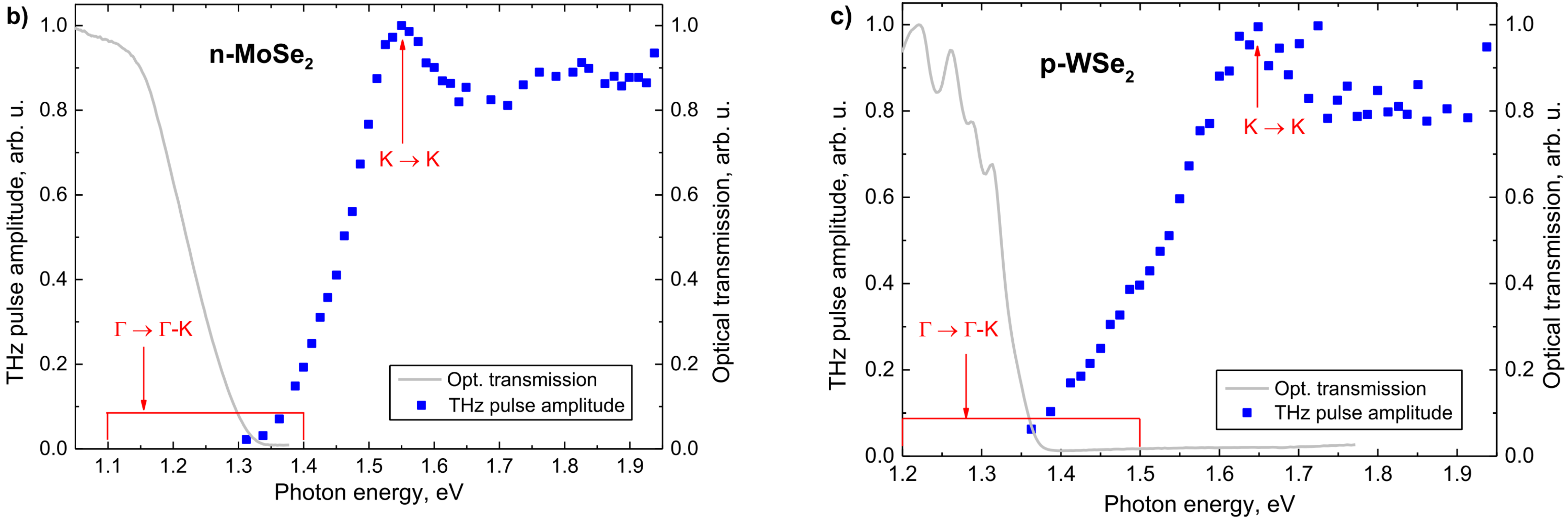
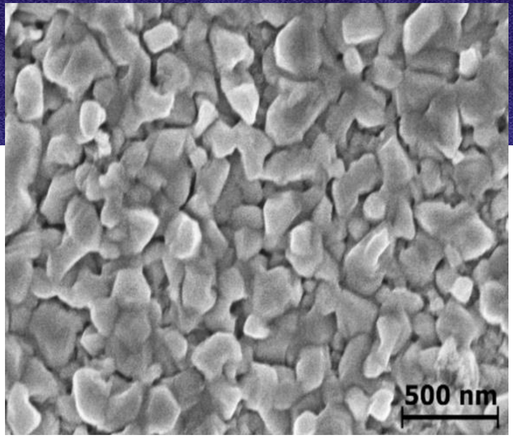
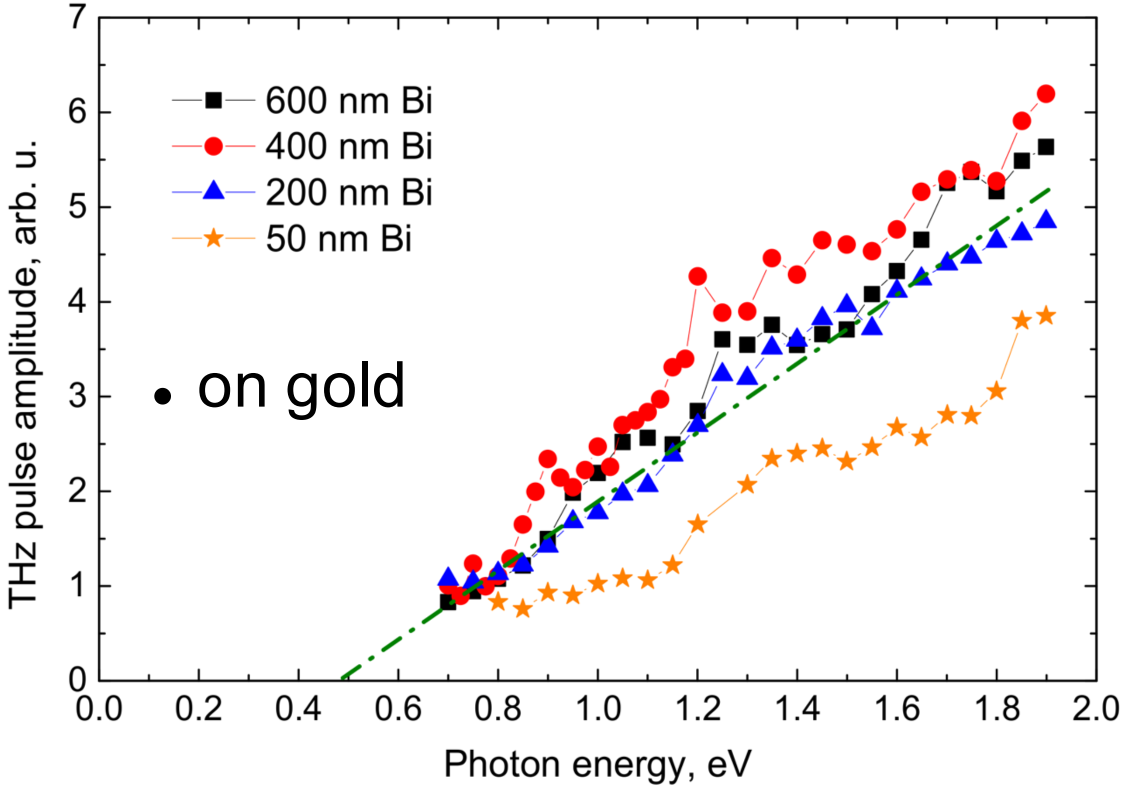


I. Nevinskas et al., "Terahertz pulse emission from photoexcited bulk crystals of transition metal dichalcogenides," J. Phys. D: Appl. Phys., vol. 54, no. 11, p. 115105, Jan. 2021, doi: 10.1088/1361-6463/abcc26.

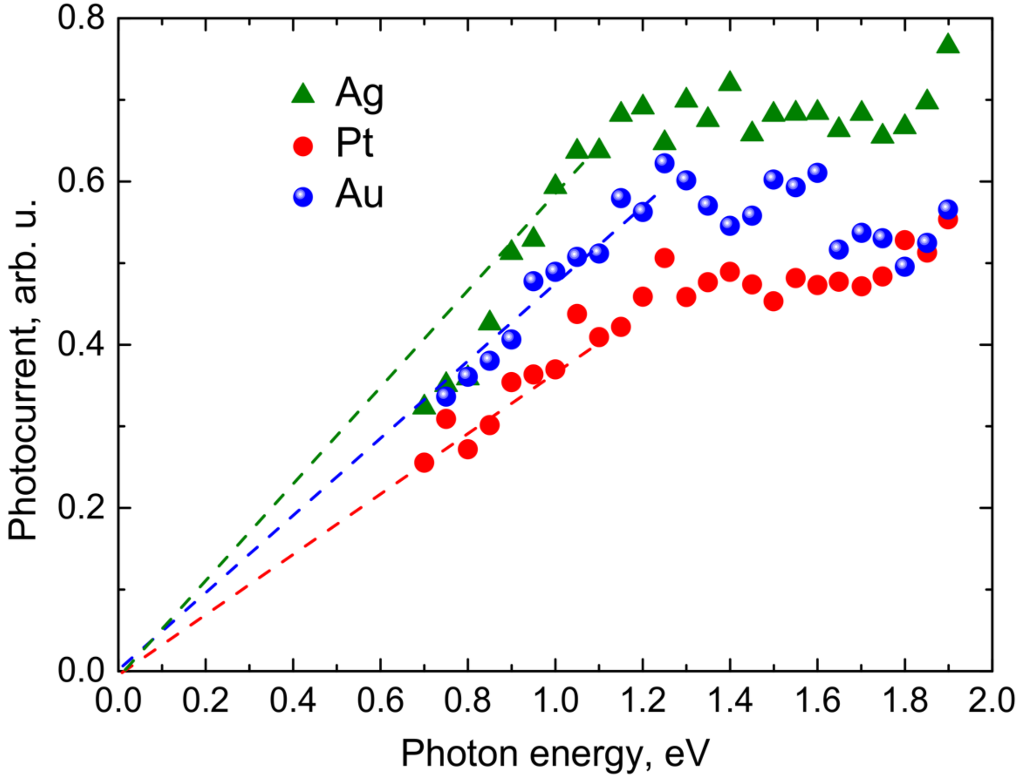
TES characterization

- **Electrodeposited bismuth on metals**
  - (Seebeck effect)





- on gold



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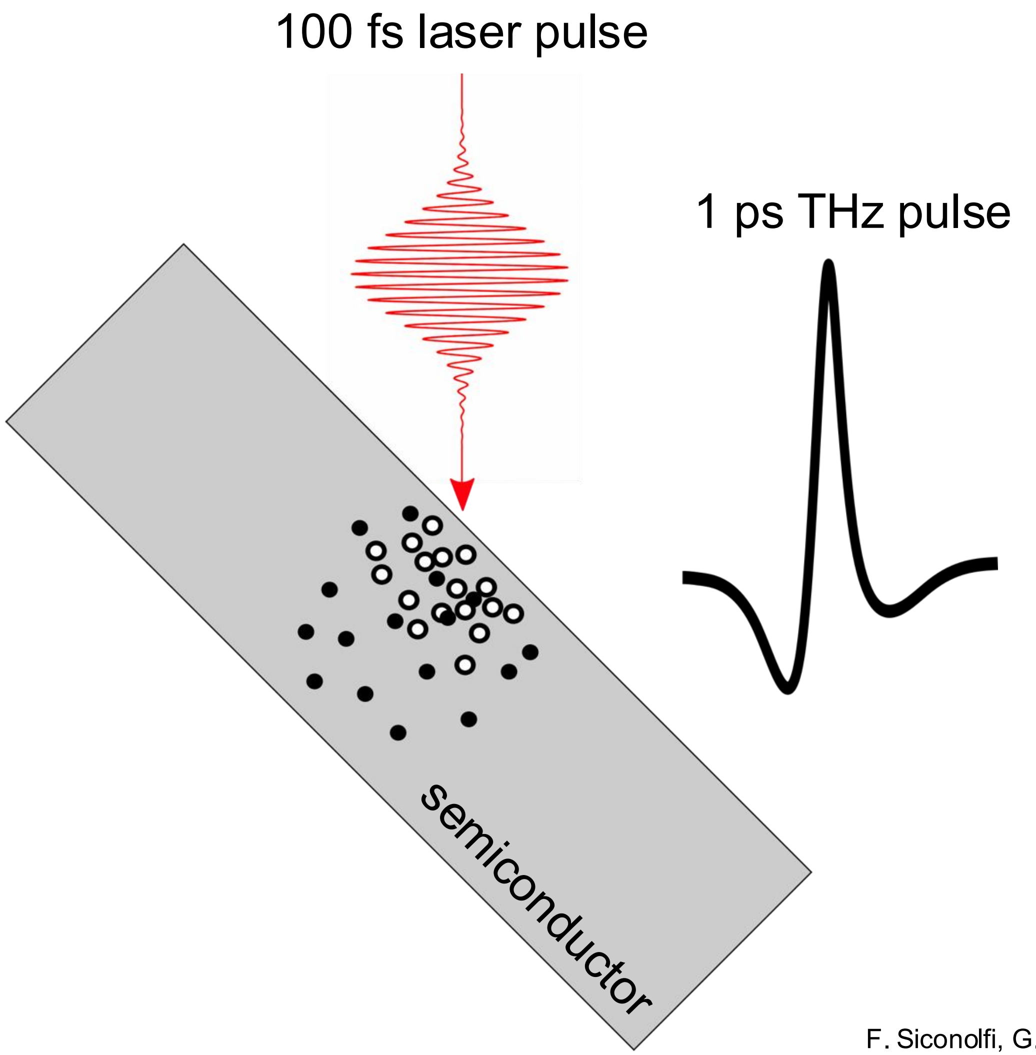
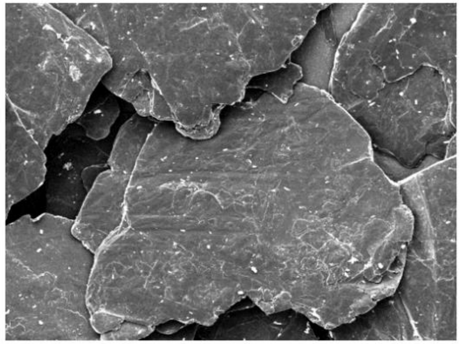
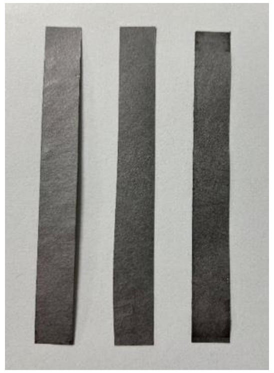
TES characterization (2D materials)

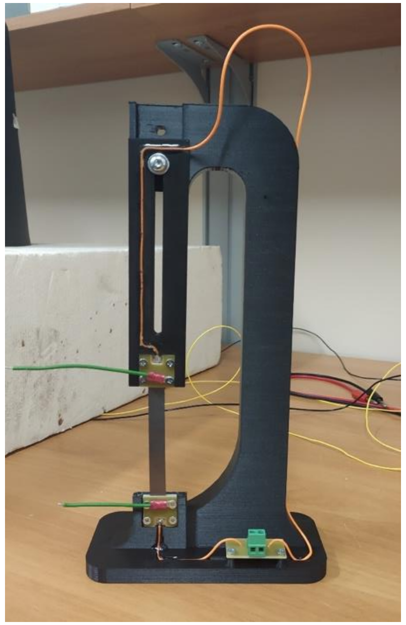




SEM image of GNP flakes

GNP-strips
(1 cm x 10 cm x ~100 μm)



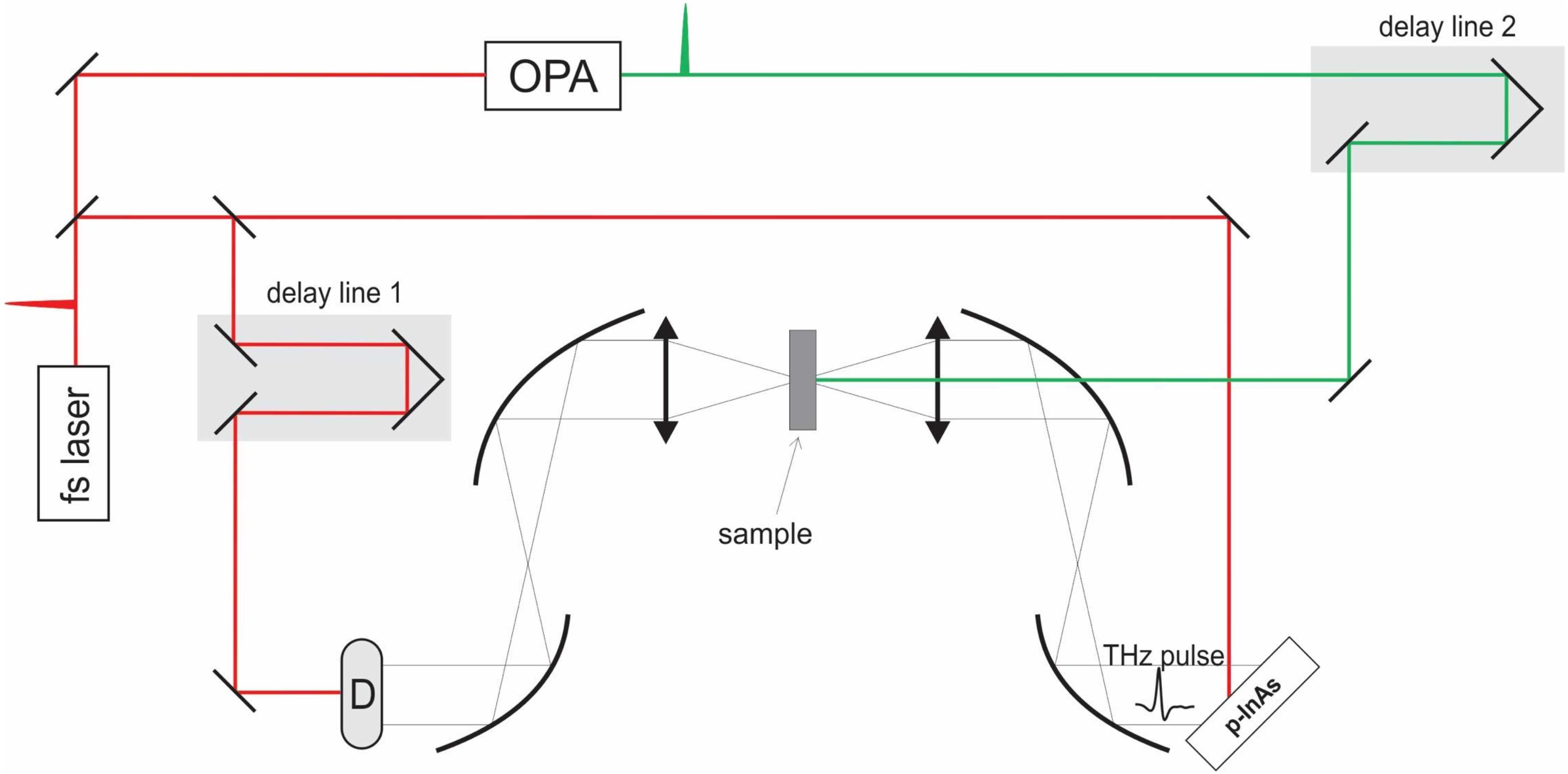


- **THz emission from GNP-strips under strain conditions**
  - Electrical properties change and so does the THz pulse emission

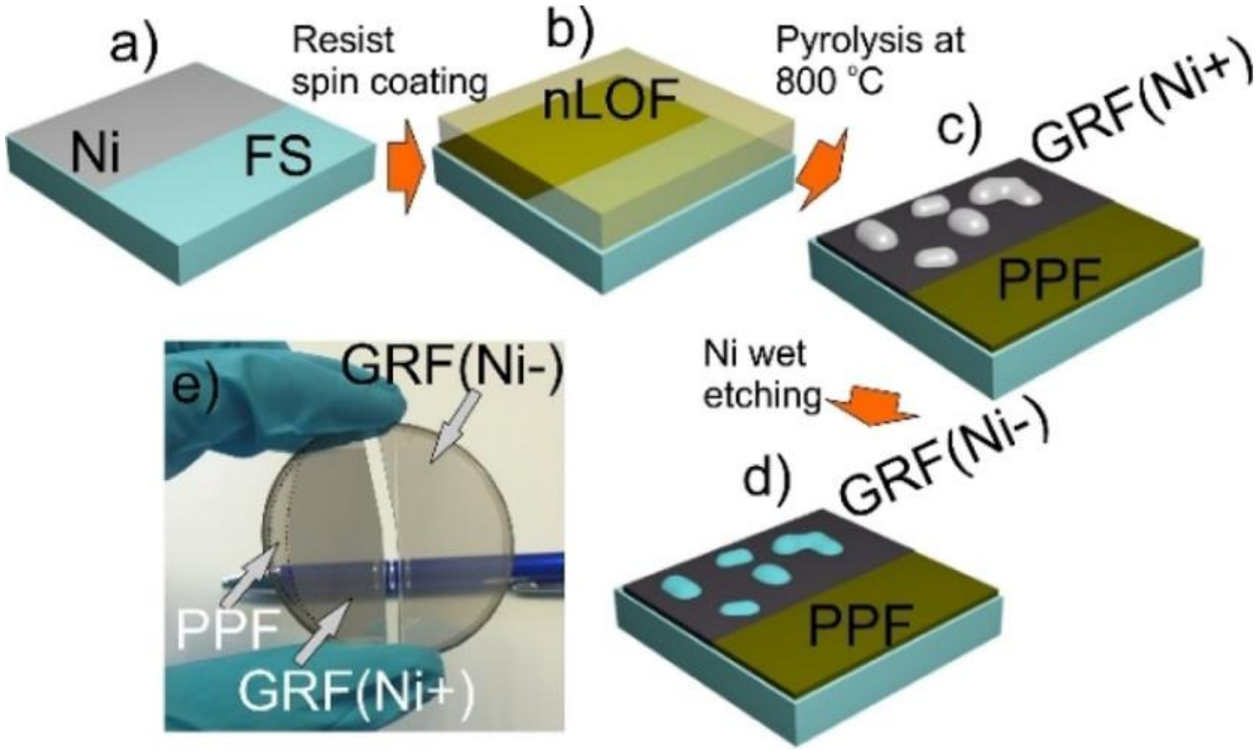
F. Siconolfi, G. Cavaliere, S. Sibilia, F. Cristiano, G. Giovinco, and A. Maffucci, "Industrial-Grade Graphene Films as Distributed Temperature Sensors," Sensors, vol. 25, no. 10, p. 3227, Jan. 2025, doi: 10.3390/s25103227.

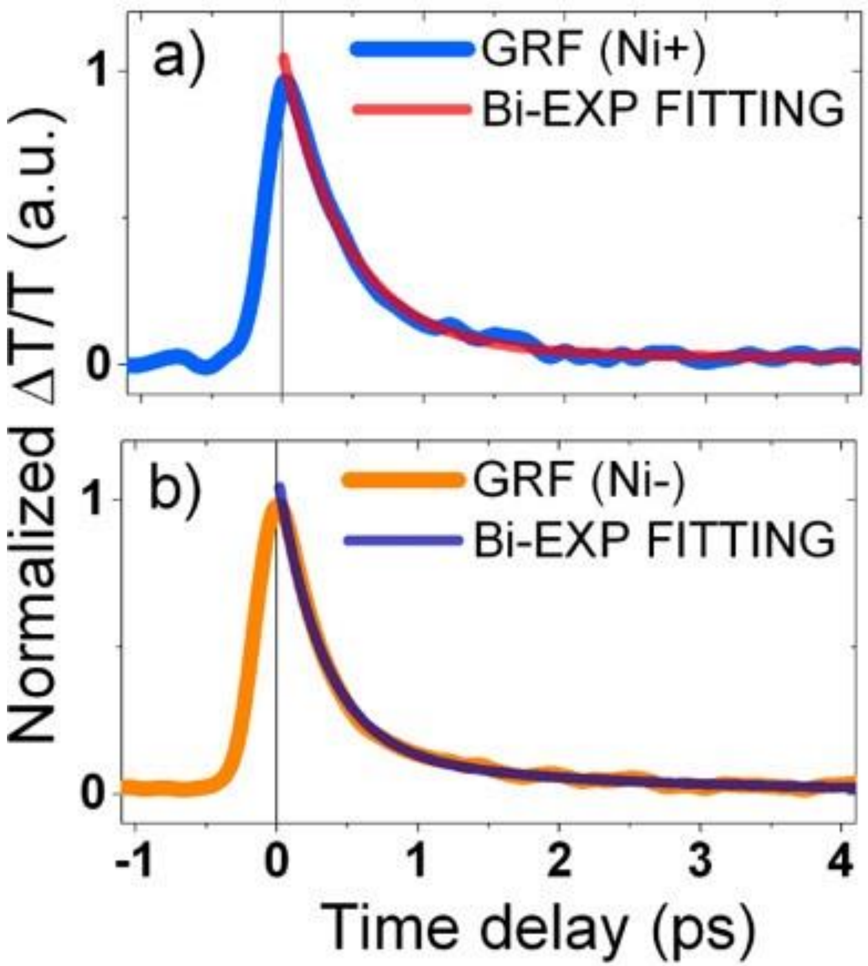
Optical pump – THz probe

λ from 640 to 2500 nm



Optical pump – THz probe

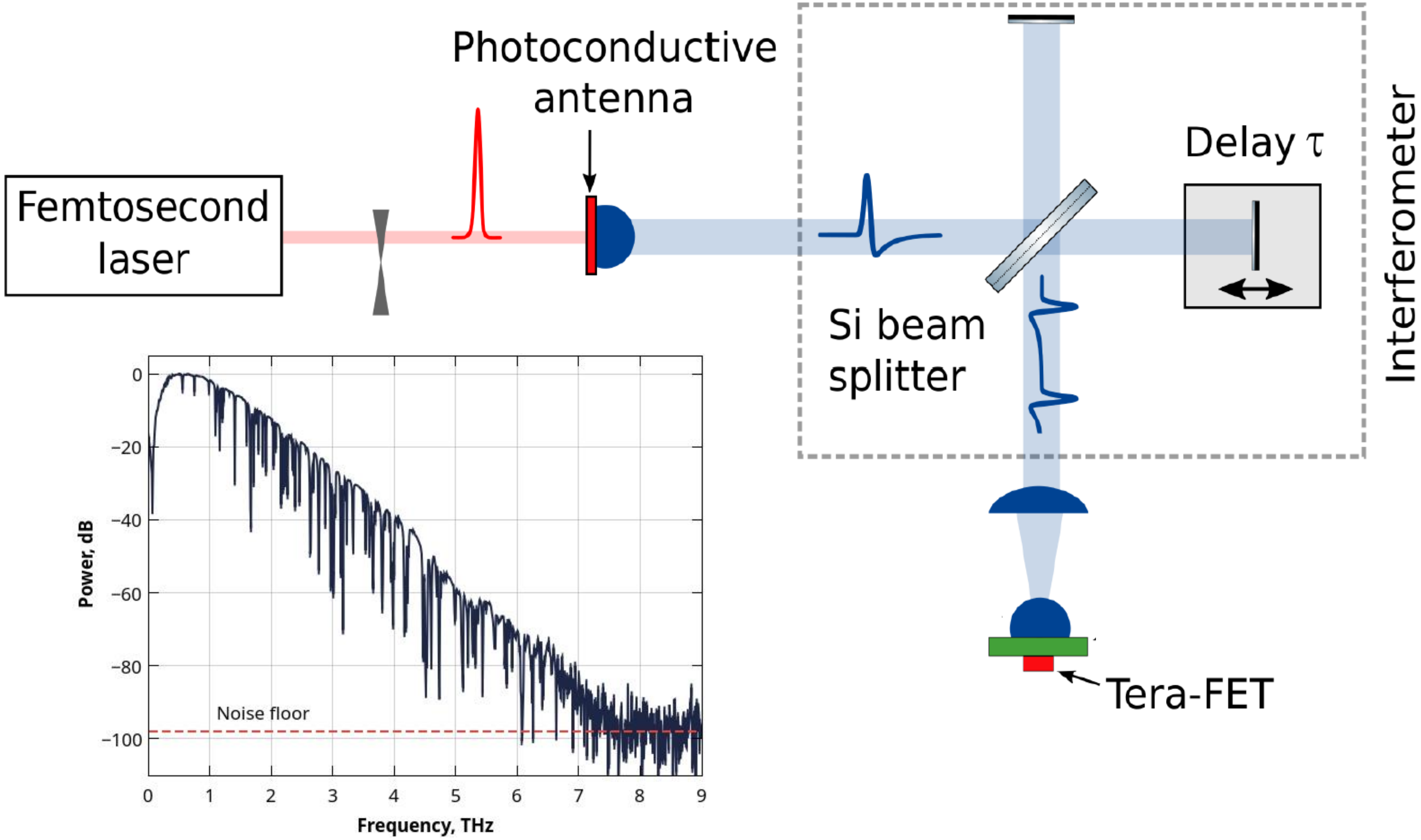


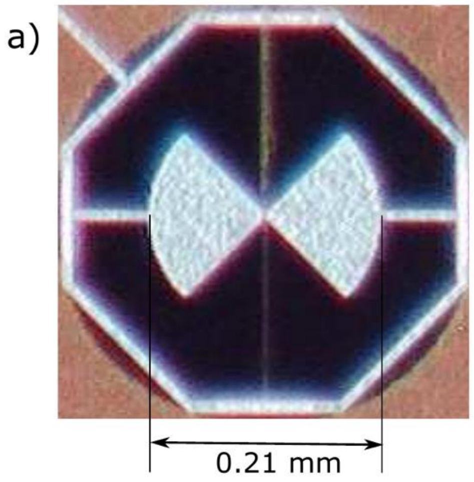


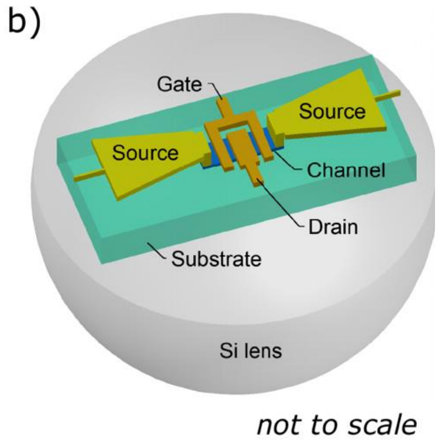
~ 50 nm thick graphitic films

M. Baah et al., "Electrical, Transport, and Optical Properties of Multifunctional Graphitic Films Synthesized on Dielectric Surfaces by Nickel Nanolayer-Assisted Pyrolysis," ACS Appl. Mater. Interfaces, vol. 12, no. 5, pp. 6226–6233, Feb. 2020, doi: 10.1021/acsami.9b18906.

THz pulse autocorrelation





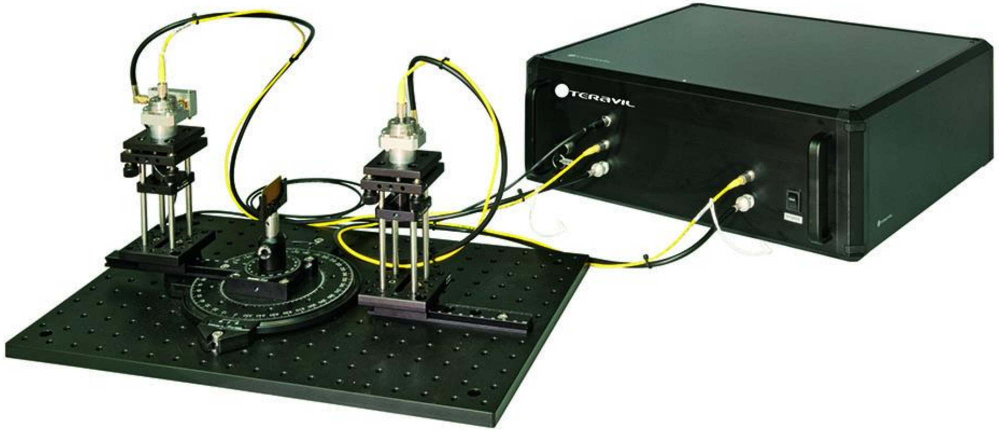


K. Ikamas, I. Nevinskas, A. Krotkus, and A. Lisauskas, “Silicon Field Effect Transistor as the Nonlinear Detector for Terahertz Autocorellators,” Sensors, vol. 18, no. 11, Art. no. 11, Nov. 2018, doi: 10.3390/s18113735.

Real-Time Terahertz Spectrometers

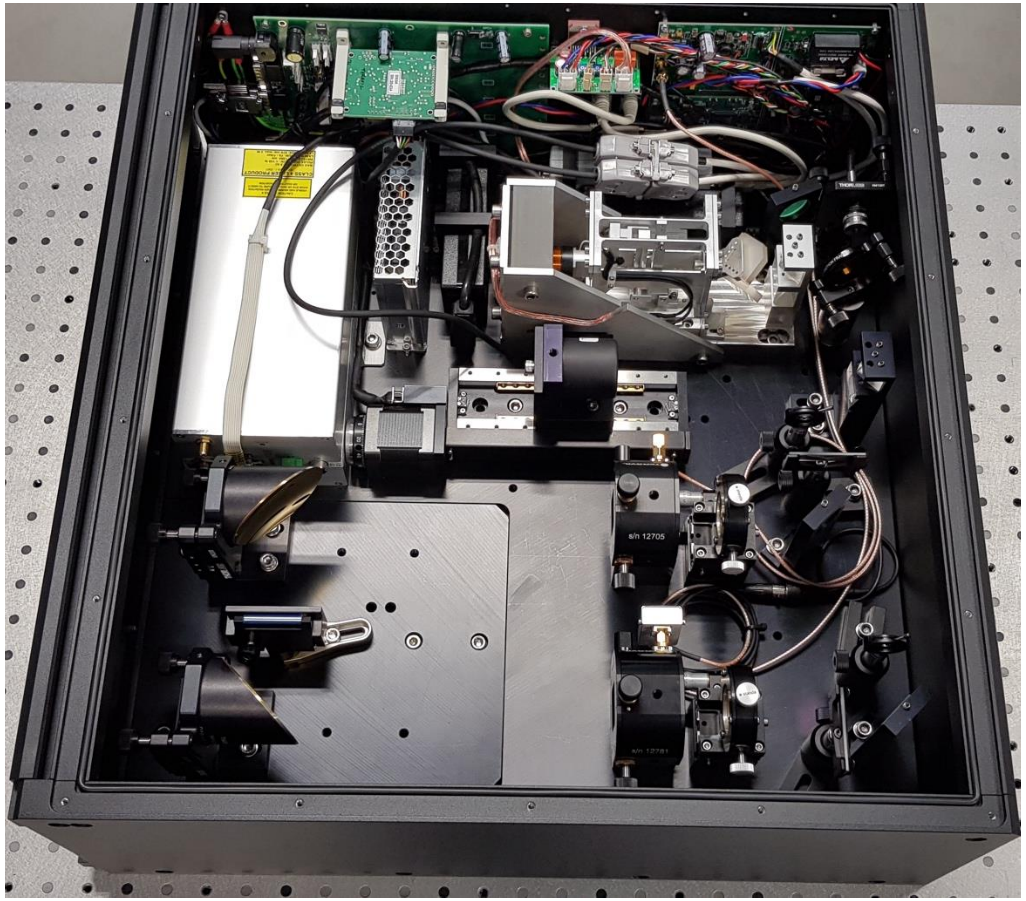
T-SPEC series

T-FIBER series

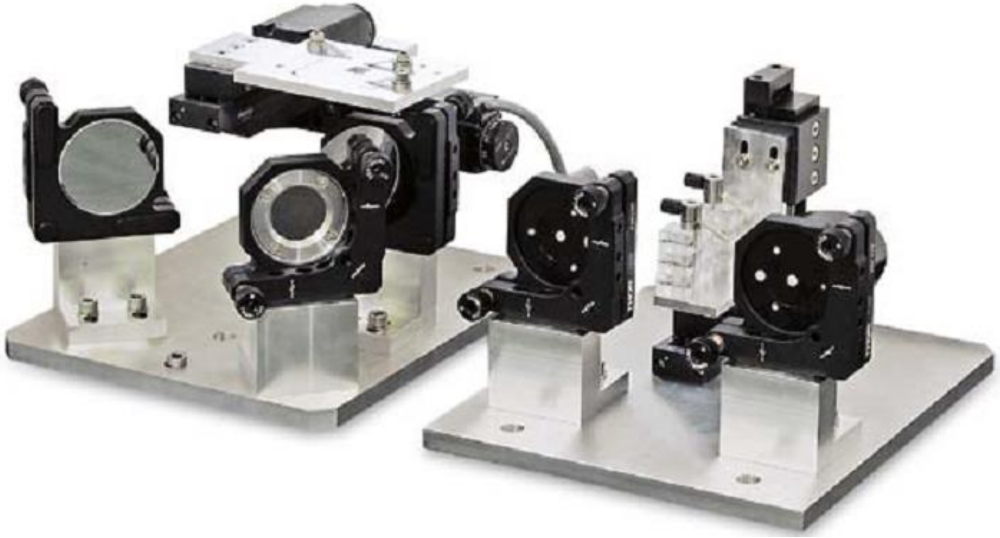


For more information: **www.teravil.lt**

Real-Time Terahertz Spectrometer



Reflection module

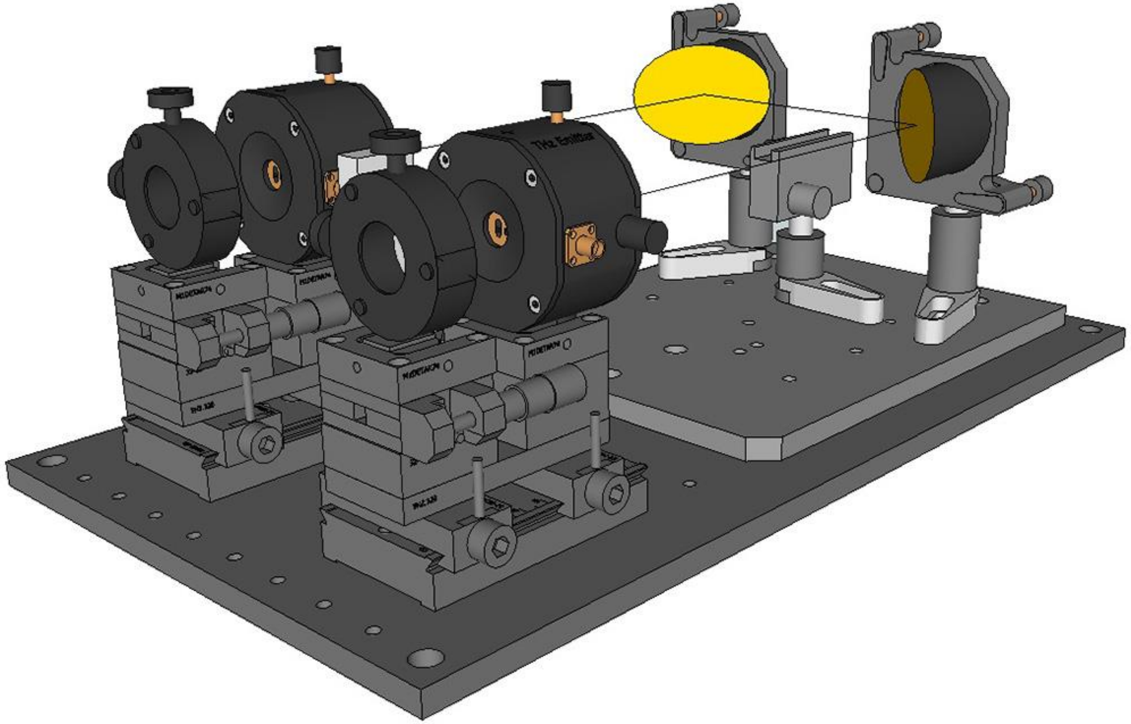


Transmission module

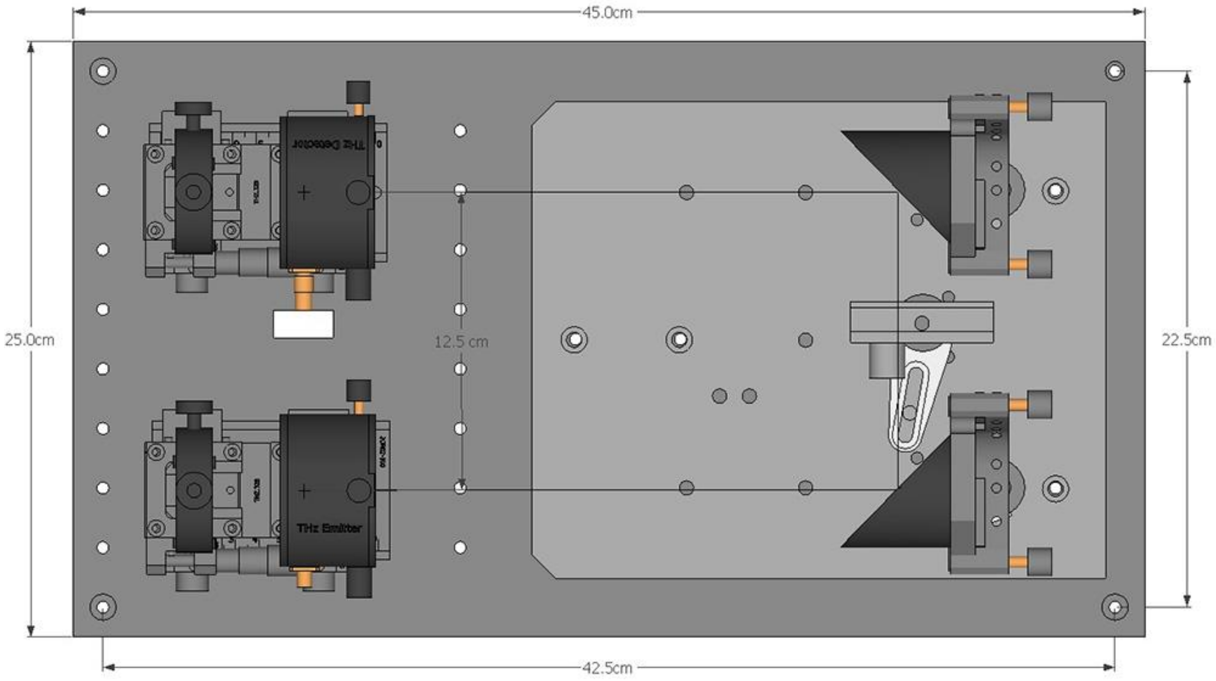
For more information: **www.teravil.lt**

Thz-TDS transmission

Side view



Top view

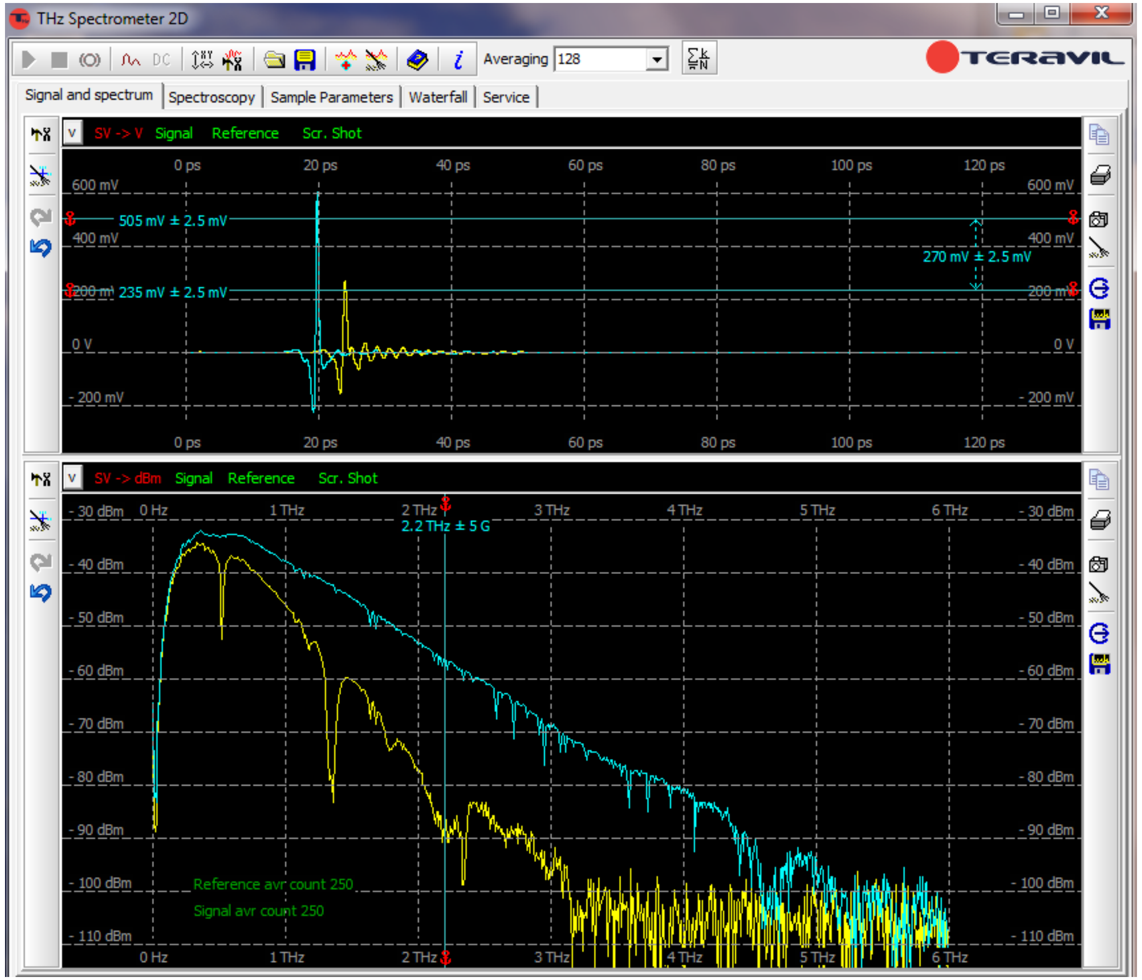


For more information: **www.teravil.lt**

Real-Time Terahertz Spectrometer

Specifications

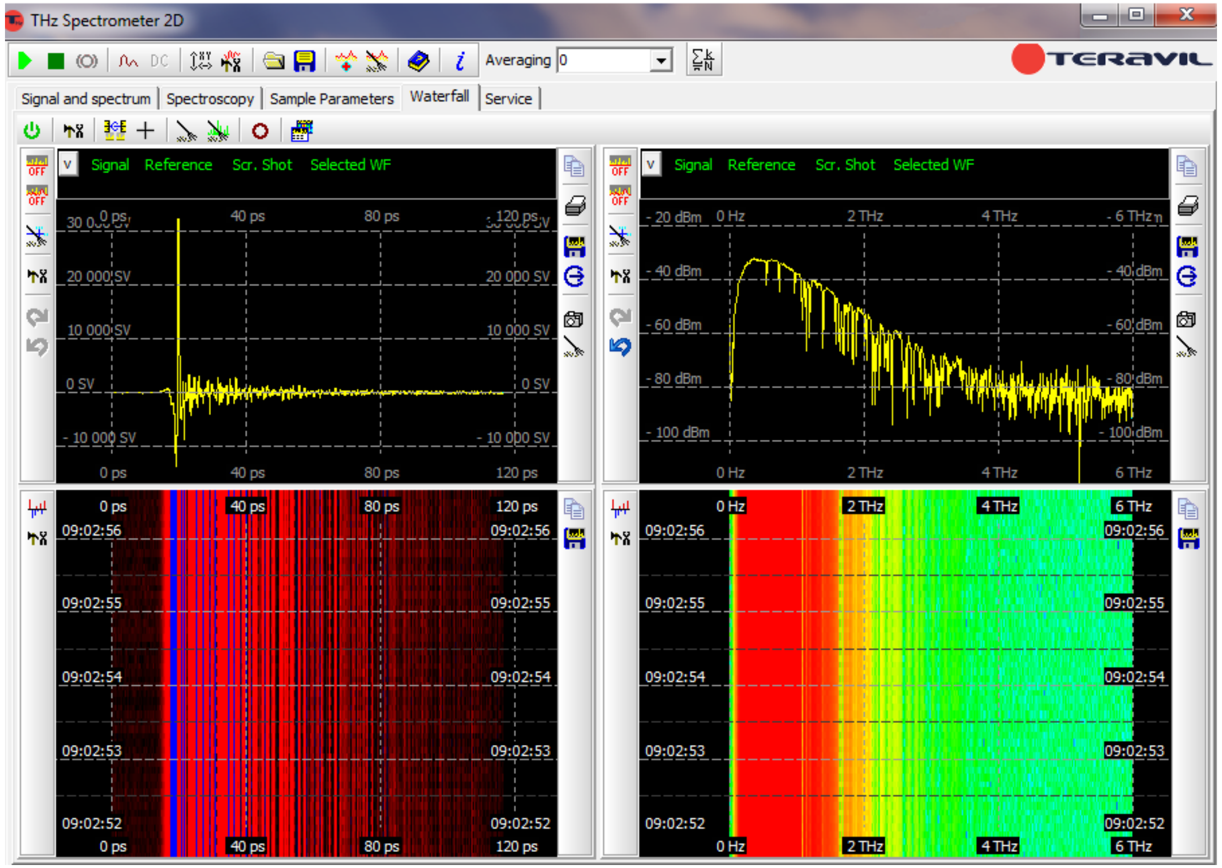
Model	T-SPEC 800	T-SPEC 1000
General specifications		
Spectral range	>4.5 THz	>3.5 THz
Dynamic range	>90 dB @ 0.4 THz	>70 dB @ 0.4 THz
Acquisition rate	10 scans/s	
Spectral resolution:		
fast scan	8.6 GHz	
combined mode (fast + slow)	~1 GHz	
Scan range:		
fast scan	116 ps	
combined mode (fast + slow)	928 ps	
Beam diameter on the sample	~ 2 mm @ 0.4 THz	
Configurations	Transmission / normal reflection	
Computer interface	USB 2.0	
Dimensions	560 × 520 × 202 mm	
Pump Laser		
Pump laser	Integrated ELMO with second harmonic module	Integrated FF50
Laser output type	Free space	
Wavelength	780 nm	1064 nm
Pulse duration	<100 fs	<160 fs
Output power	>80 mW	>60 mW
Pulse repetition rate	100 MHz	30 MHz



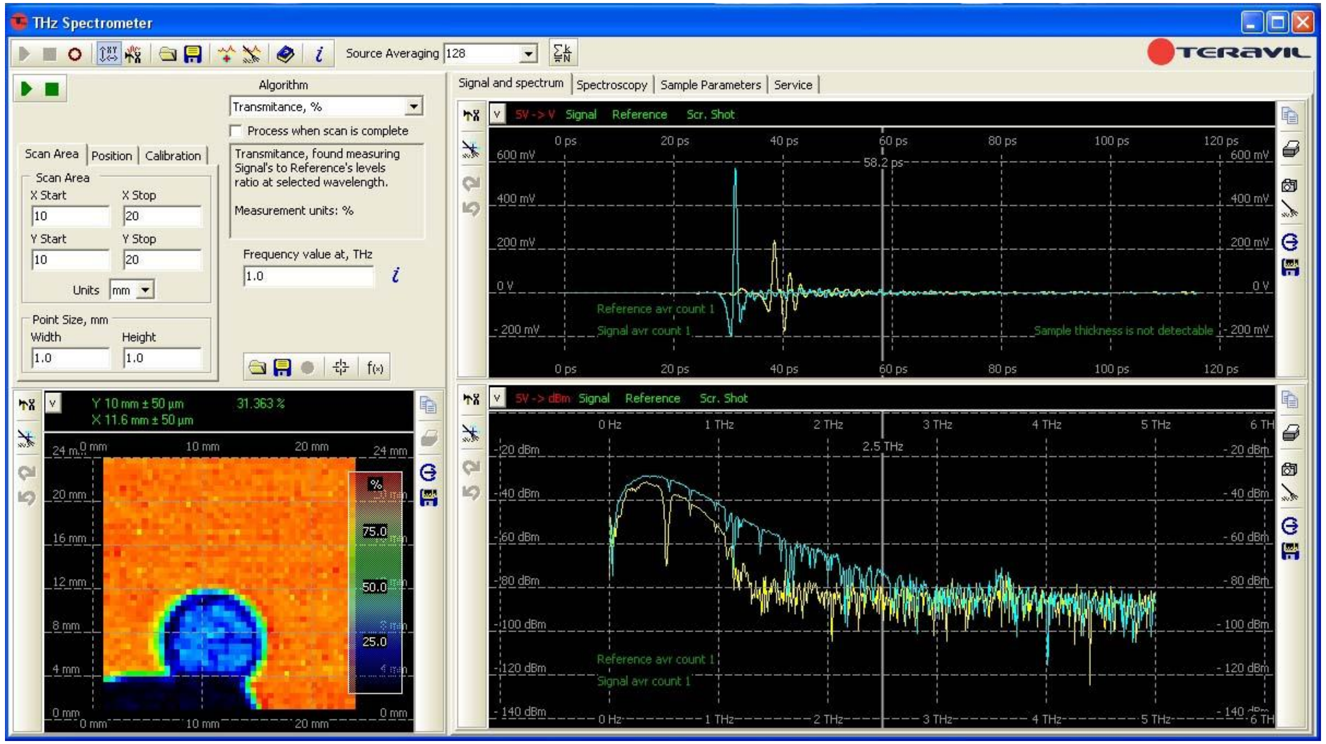
For more information: **www.teravil.lt**

Real-Time Terahertz Spectrometer

- **Waterfall function**

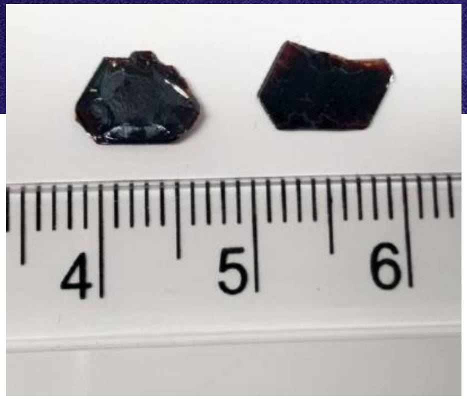


- **Raster scan imaging**

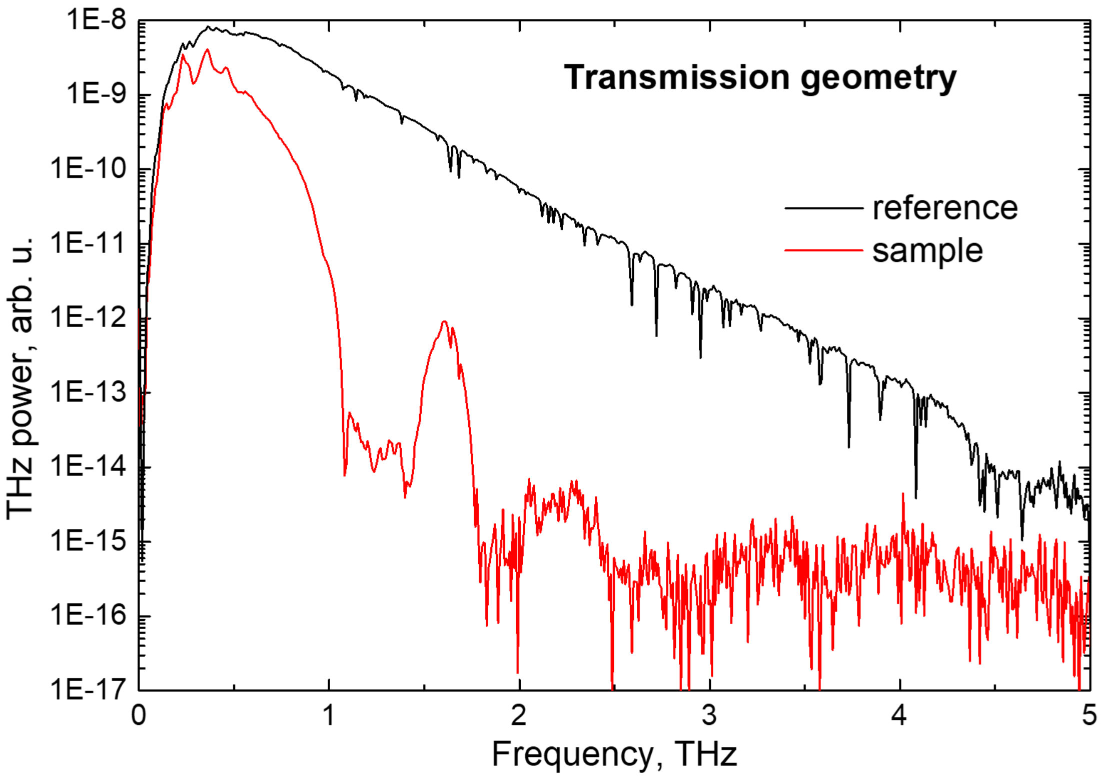


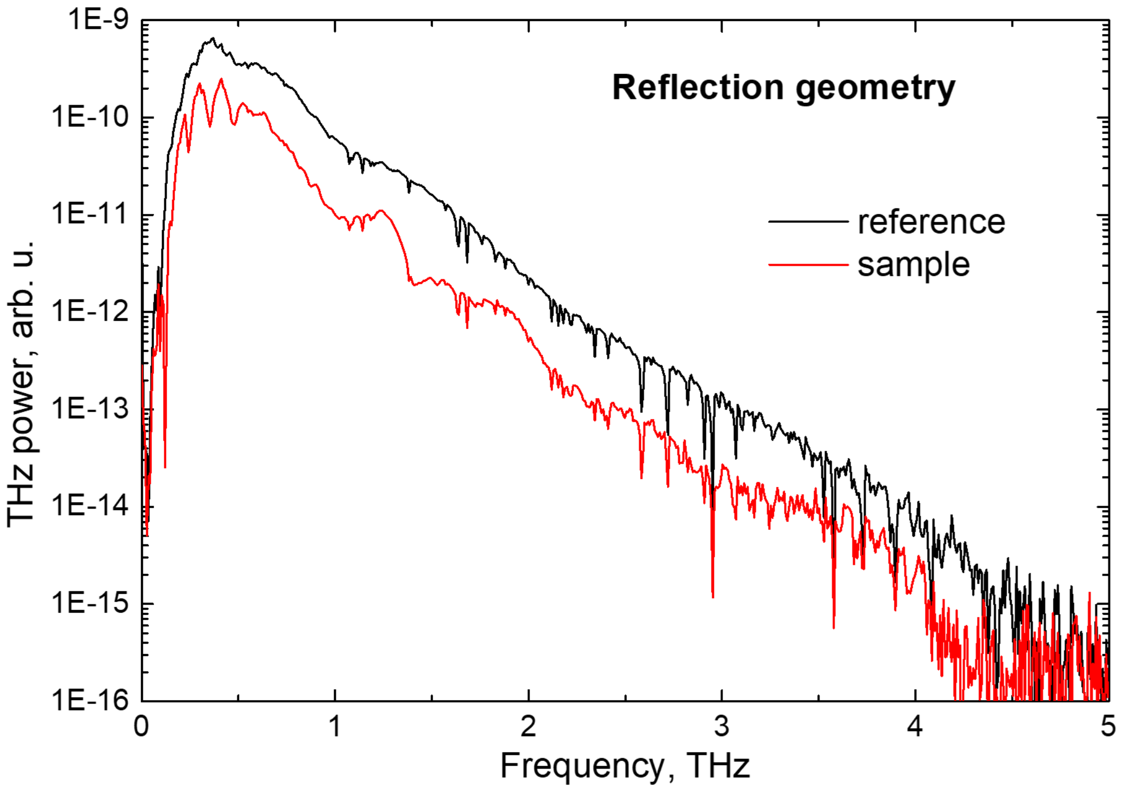
For more information: **www.teravil.lt**

THz-TDS (transmission)



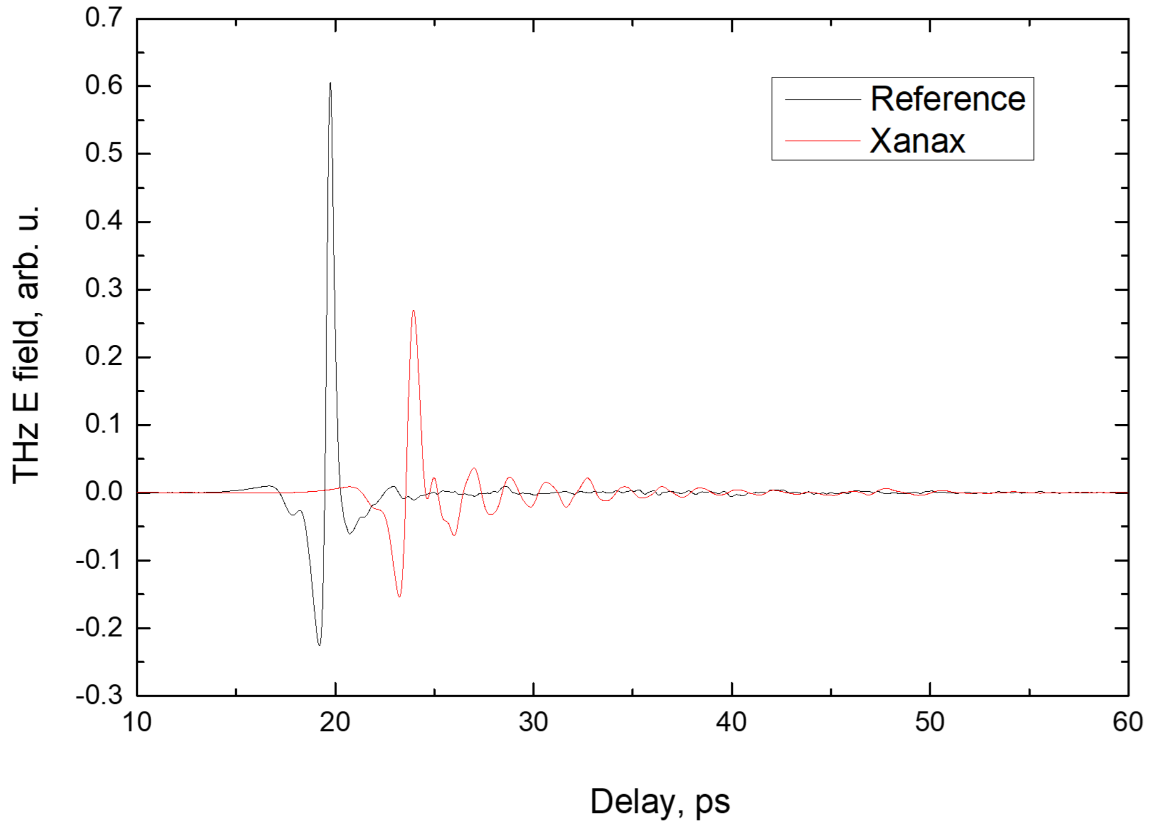
- $Cs_3Bi_2Br_9$ + $CuBr_2$ perovskite

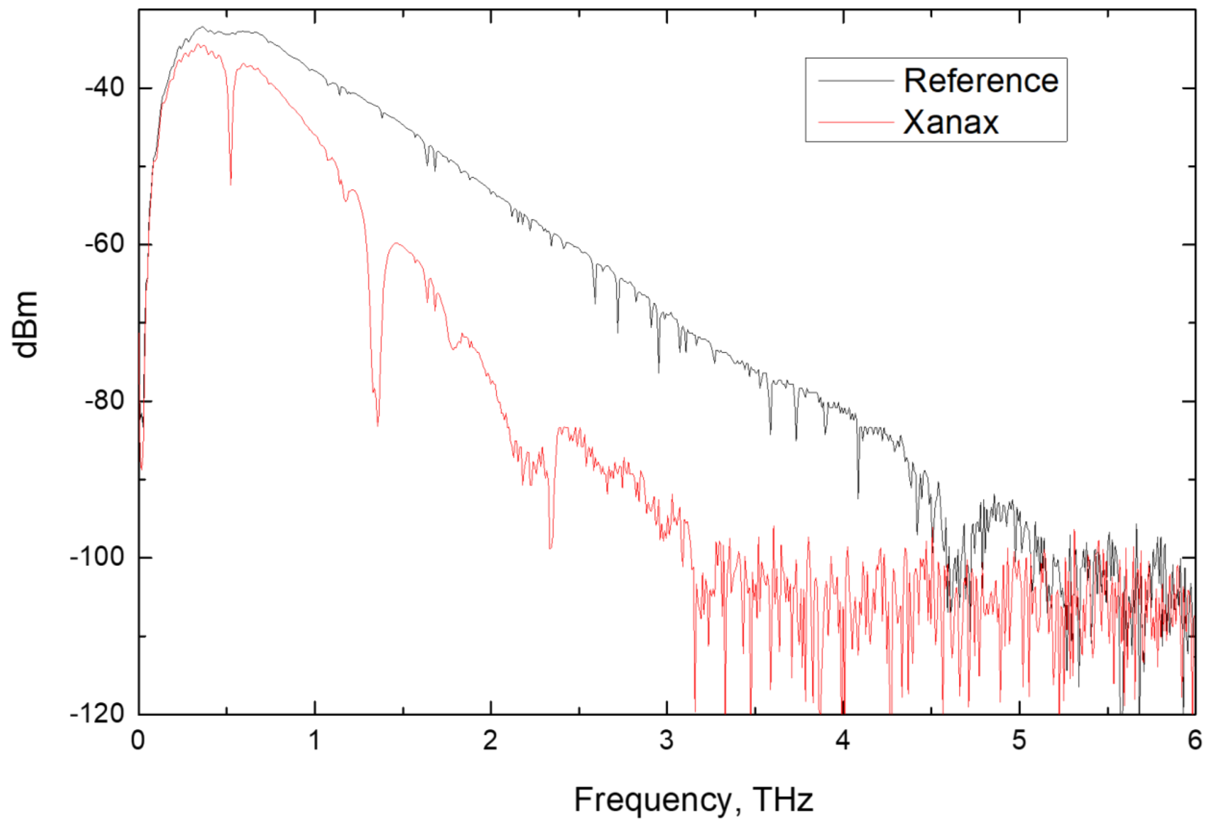




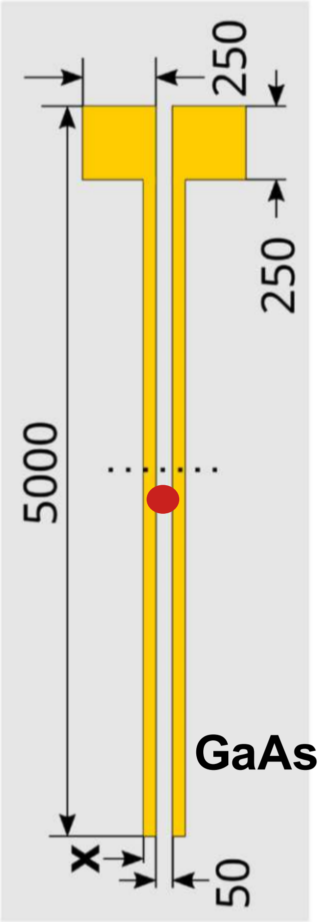
THz-TDS (transmission)

- **XANAX tablet (Lactose and Alprazolam)**





Photoconductive antenna

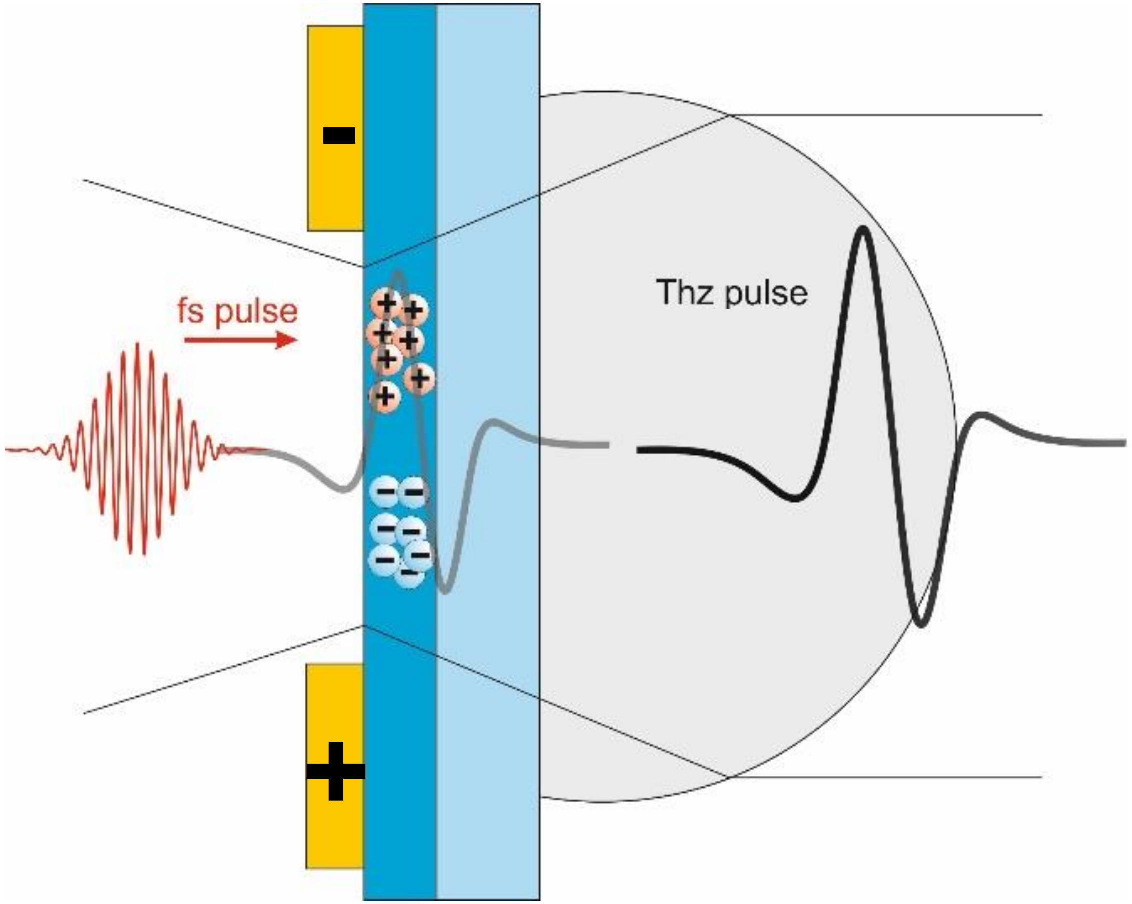


µm

For more information: **www.teravil.lt**

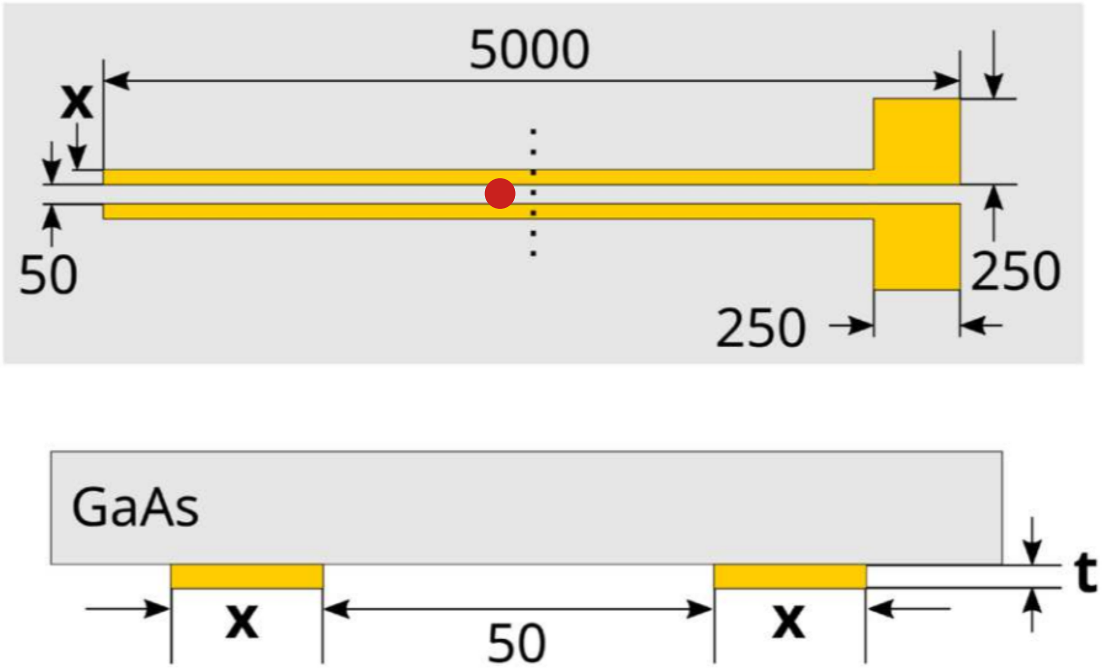
Photoconductive antenna

- Apply bias for THz emission
- Connect amperemeter for THz detection

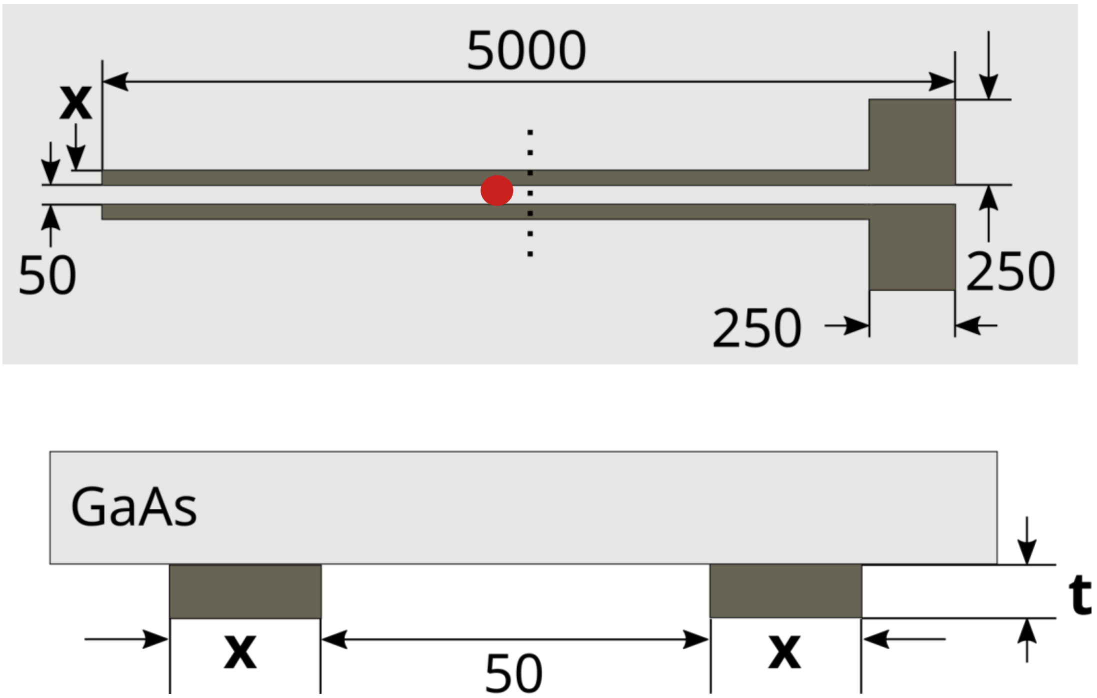


Photoconductive antenna

AuGe / Ni / Au
140 / 25 / 40 nm



Ti 1 μm



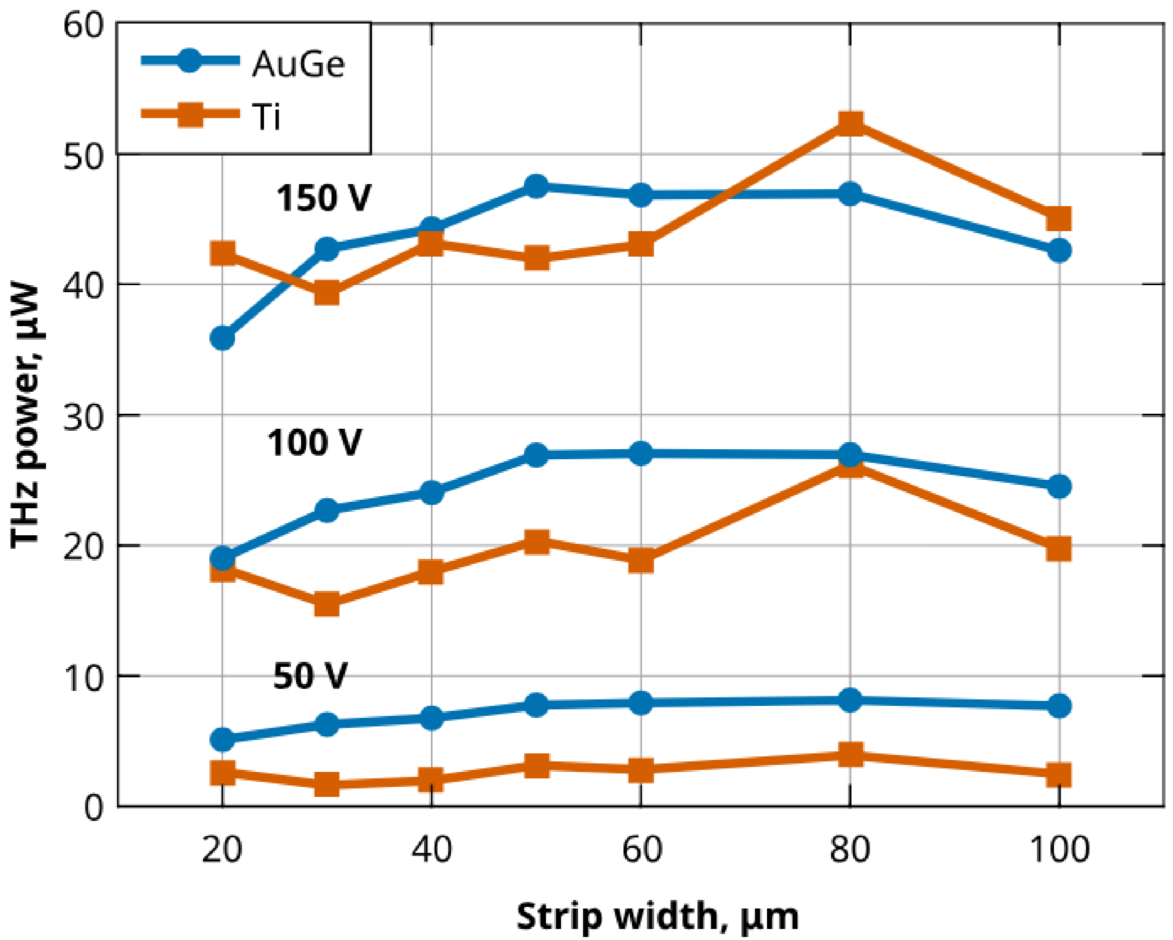
I. Nevinskas et al., “Systematic investigation of stripline width and contact metal effects on terahertz photoconductive antenna performance,” Phys. Scr., vol. 101, no. 10, p. 105503, Mar. 2026, doi: 10.1088/1402-4896/ae4836.

Photoconductive antenna (emitted power)

FIZINIŲ IR TECHNOLOGIJOS MOKSLŲ CENTRAS

→ Comparable THz emission power

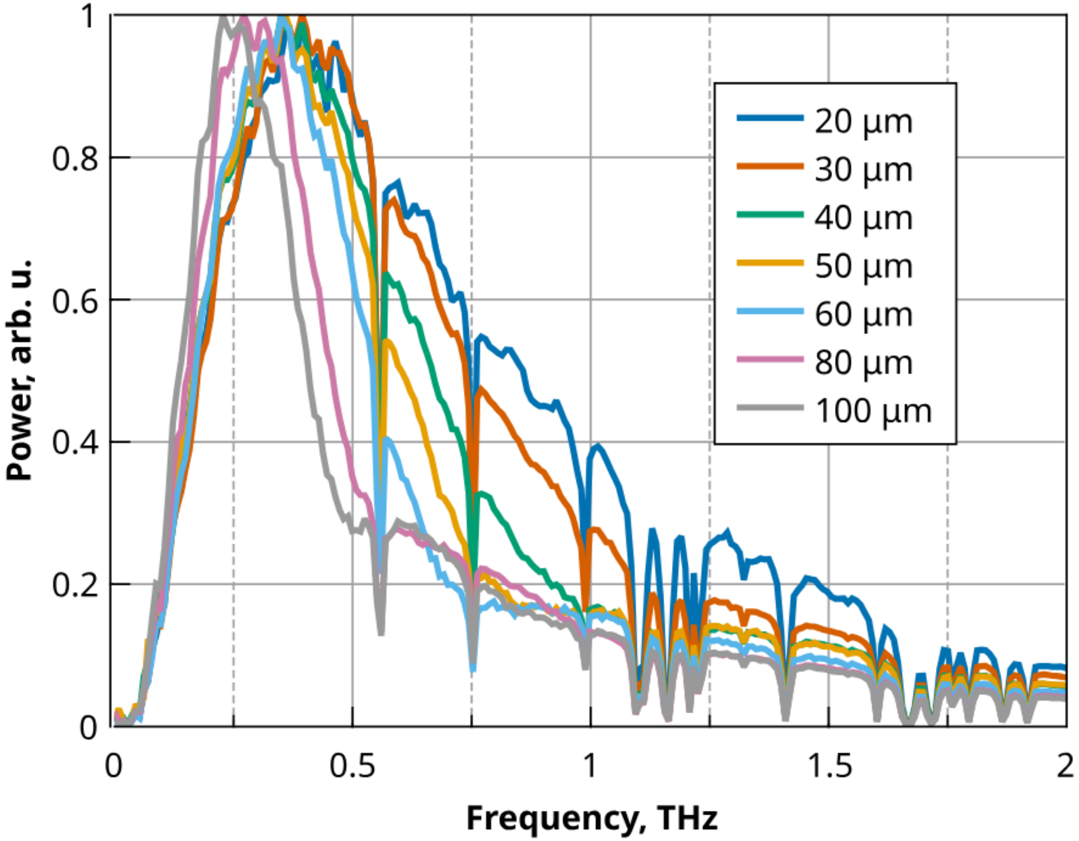
→ Ti has x20 lower conductivity than Au



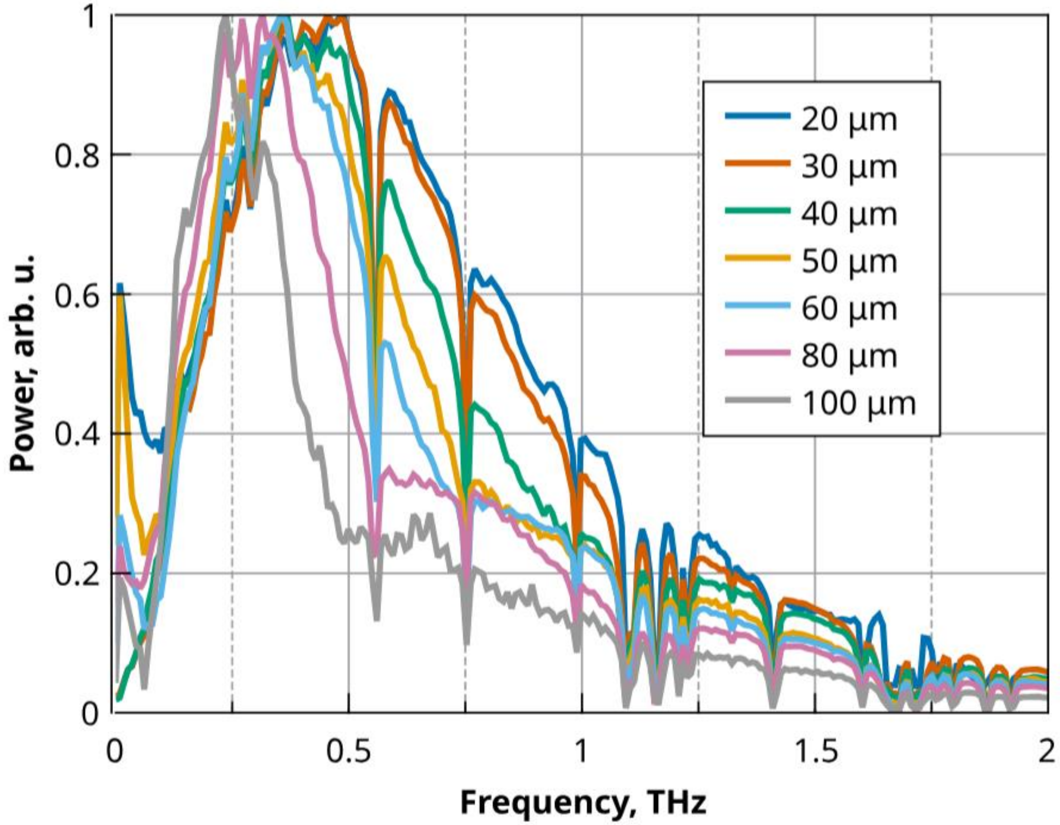
I. Nevinskas et al., "Systematic investigation of stripline width and contact metal effects on terahertz photoconductive antenna performance," Phys. Scr., vol. 101, no. 10, p. 105503, Mar. 2026, doi: 10.1088/1402-4896/ae4836.

Photoconductive antenna (spectra)

AuGe / Ni / Au
140 / 25 / 40 nm



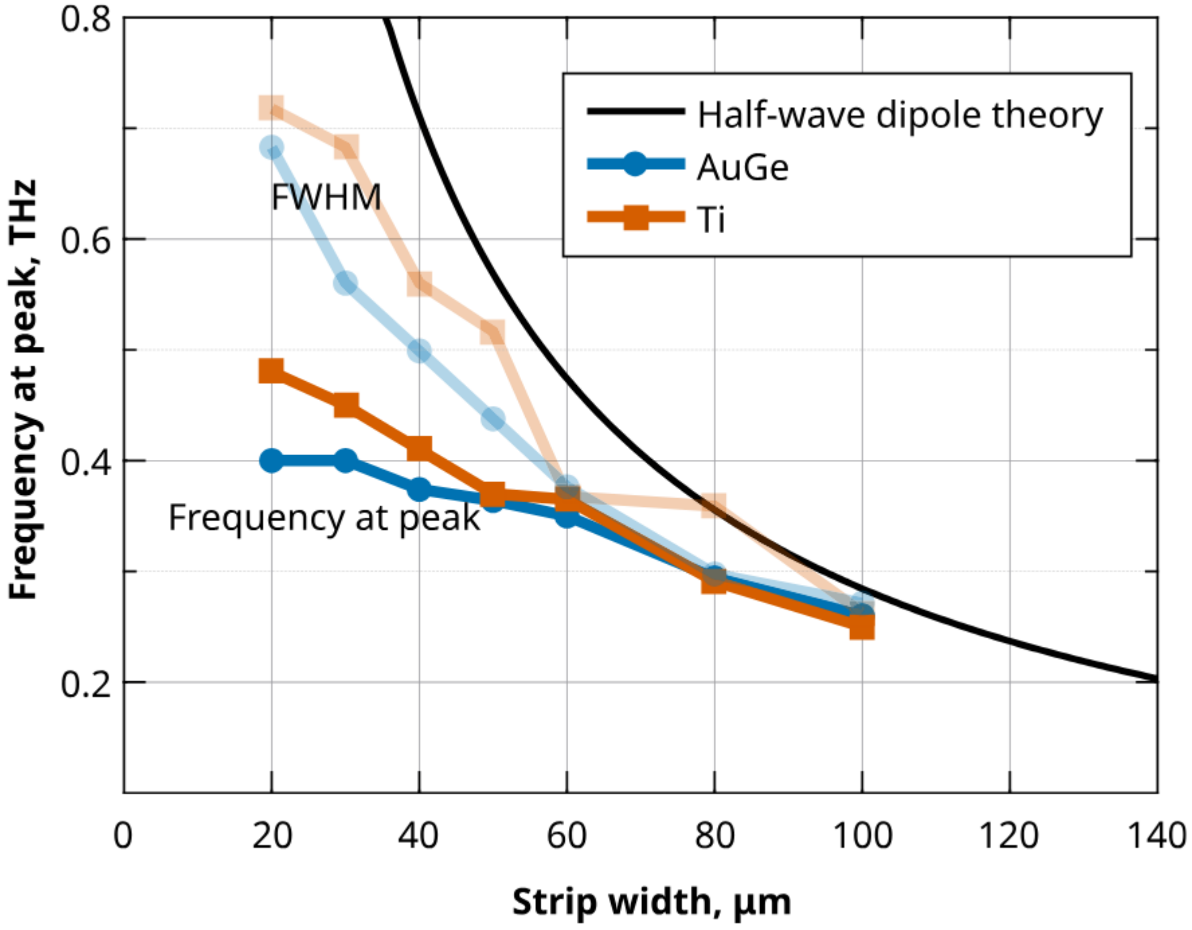
Ti 1 µm



I. Nevinskas et al., “Systematic investigation of stripline width and contact metal effects on terahertz photoconductive antenna performance,” Phys. Scr., vol. 101, no. 10, p. 105503, Mar. 2026, doi: 10.1088/1402-4896/ae4836.

Photoconductive antenna (spectra)

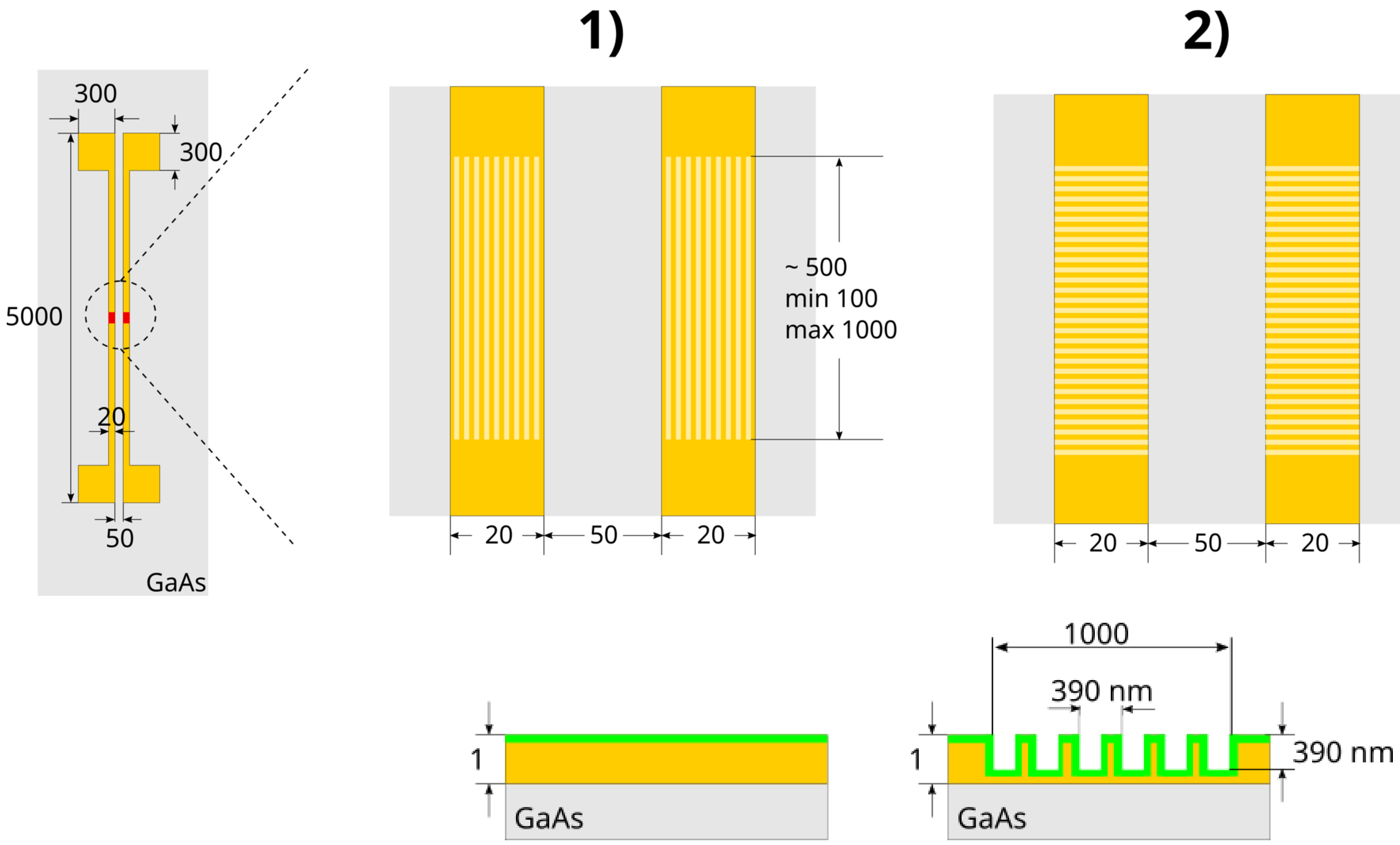
→ **Skin effect?**



I. Nevinskas et al., "Systematic investigation of stripline width and contact metal effects on terahertz photoconductive antenna performance," Phys. Scr., vol. 101, no. 10, p. 105503, Mar. 2026, doi: 10.1088/1402-4896/ae4836.

Photoconductive antenna (nanotexturization)

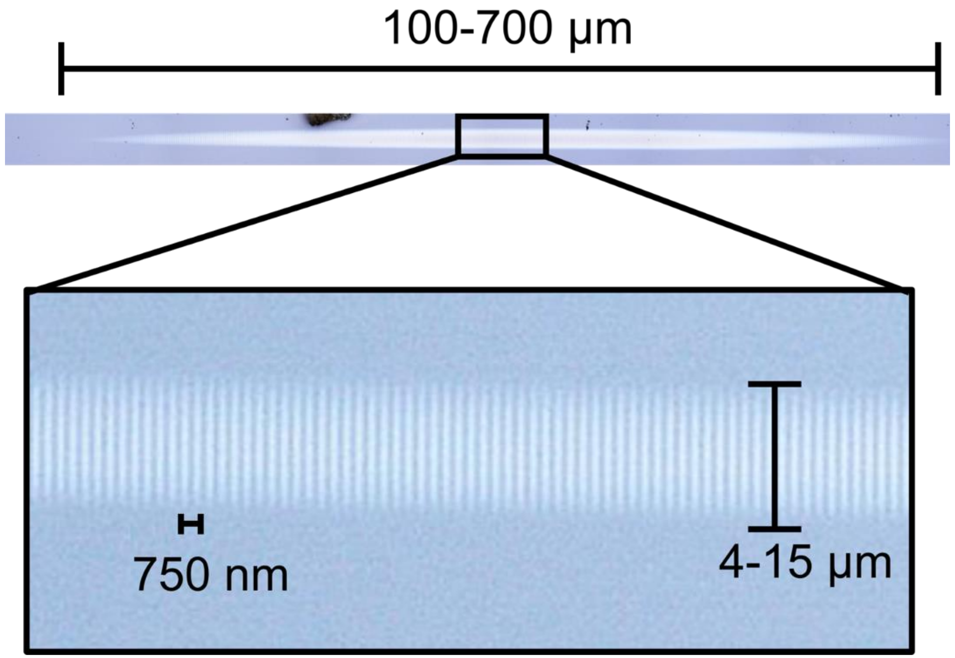
FIZINIŲ IR TECHNOLOGIJOS MOKSLŲ CENTRAS



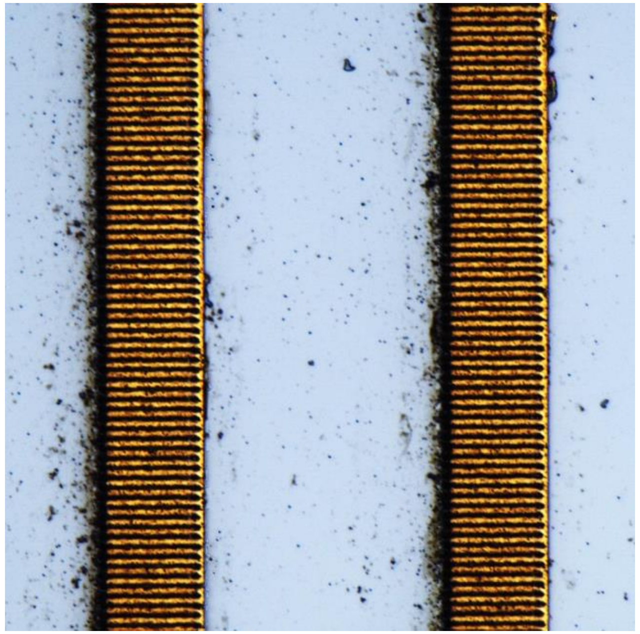
I. Nevinskas et al., "Systematic investigation of stripline width and contact metal effects on terahertz photoconductive antenna performance," Phys. Scr., vol. 101, no. 10, p. 105503, Mar. 2026, doi: 10.1088/1402-4896/ae4836.

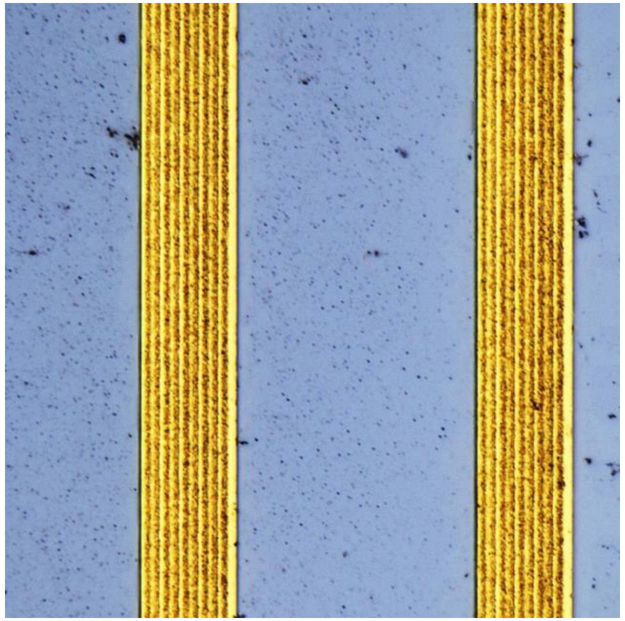
Laser nanotexturization

Interference ablation

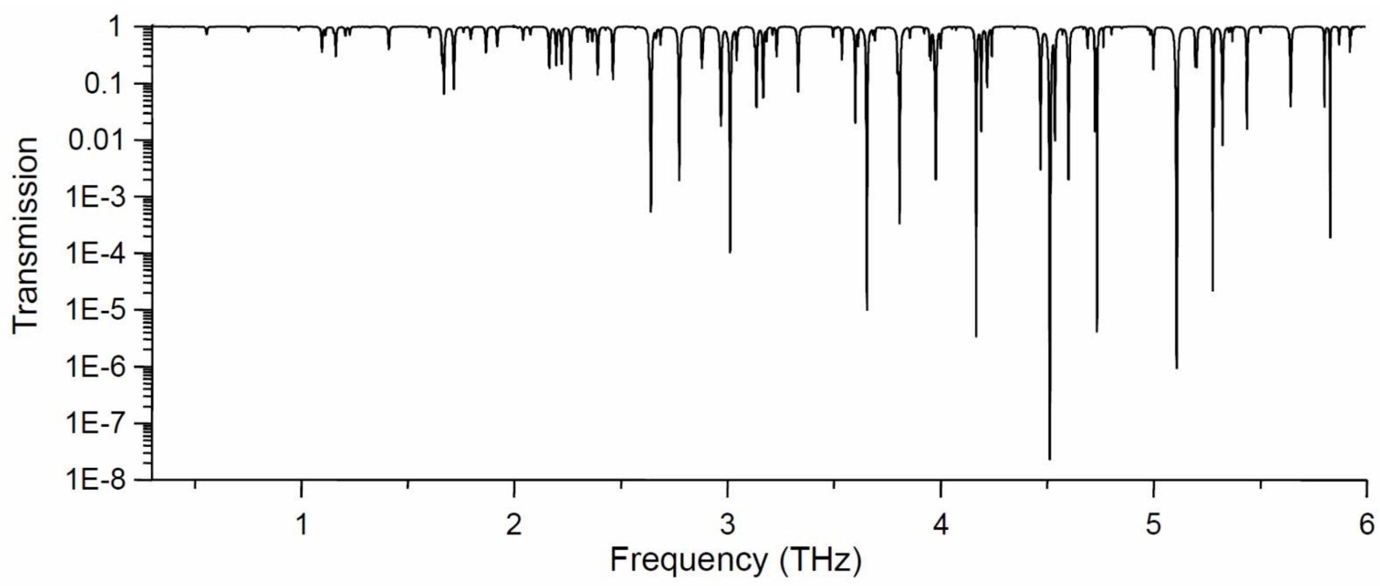


Focused beam scanning



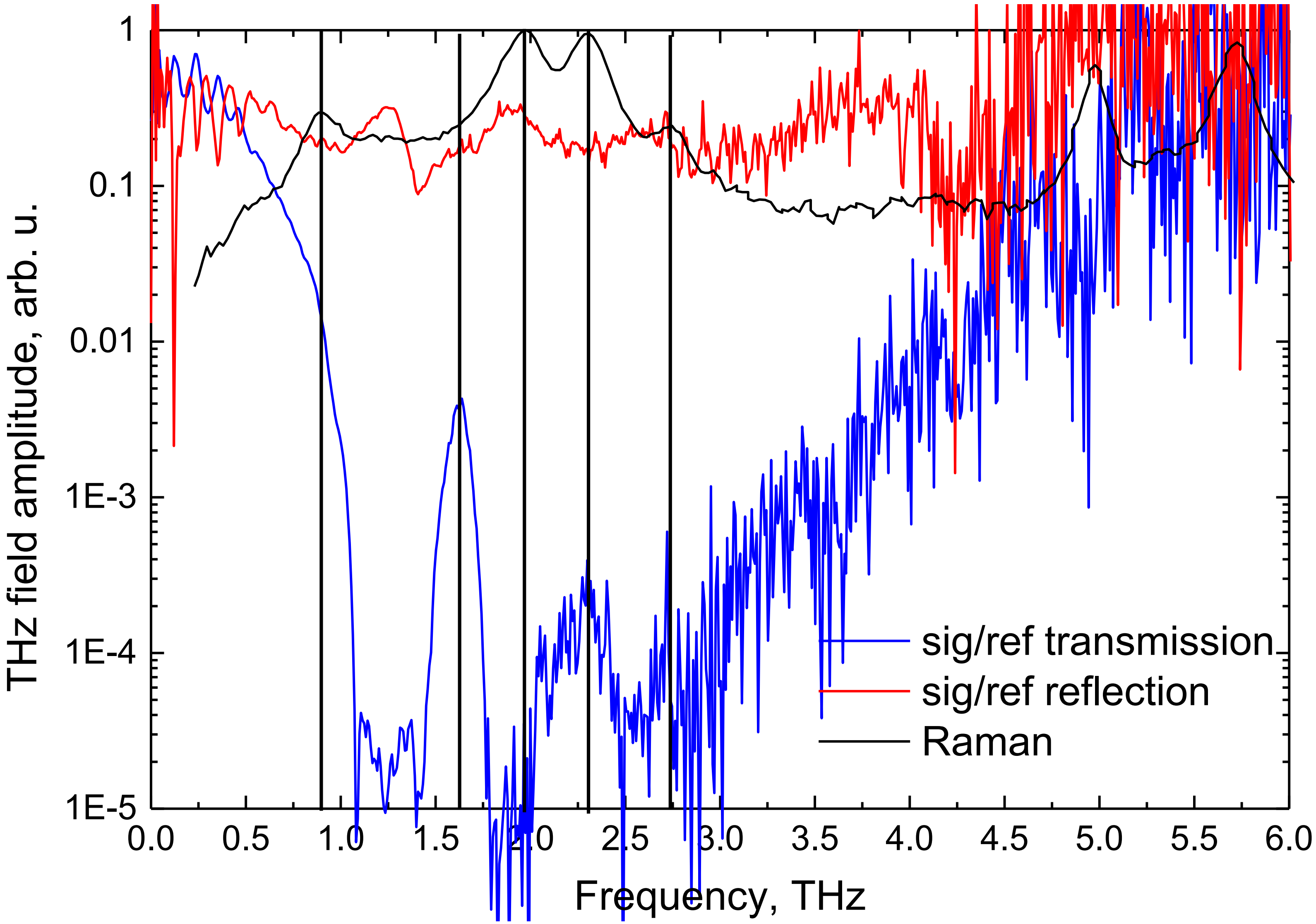


I. Nevinskas et al., “Systematic investigation of stripline width and contact metal effects on terahertz photoconductive antenna performance,” Phys. Scr., vol. 101, no. 10, p. 105503, Mar. 2026, doi: 10.1088/1402-4896/ae4836.

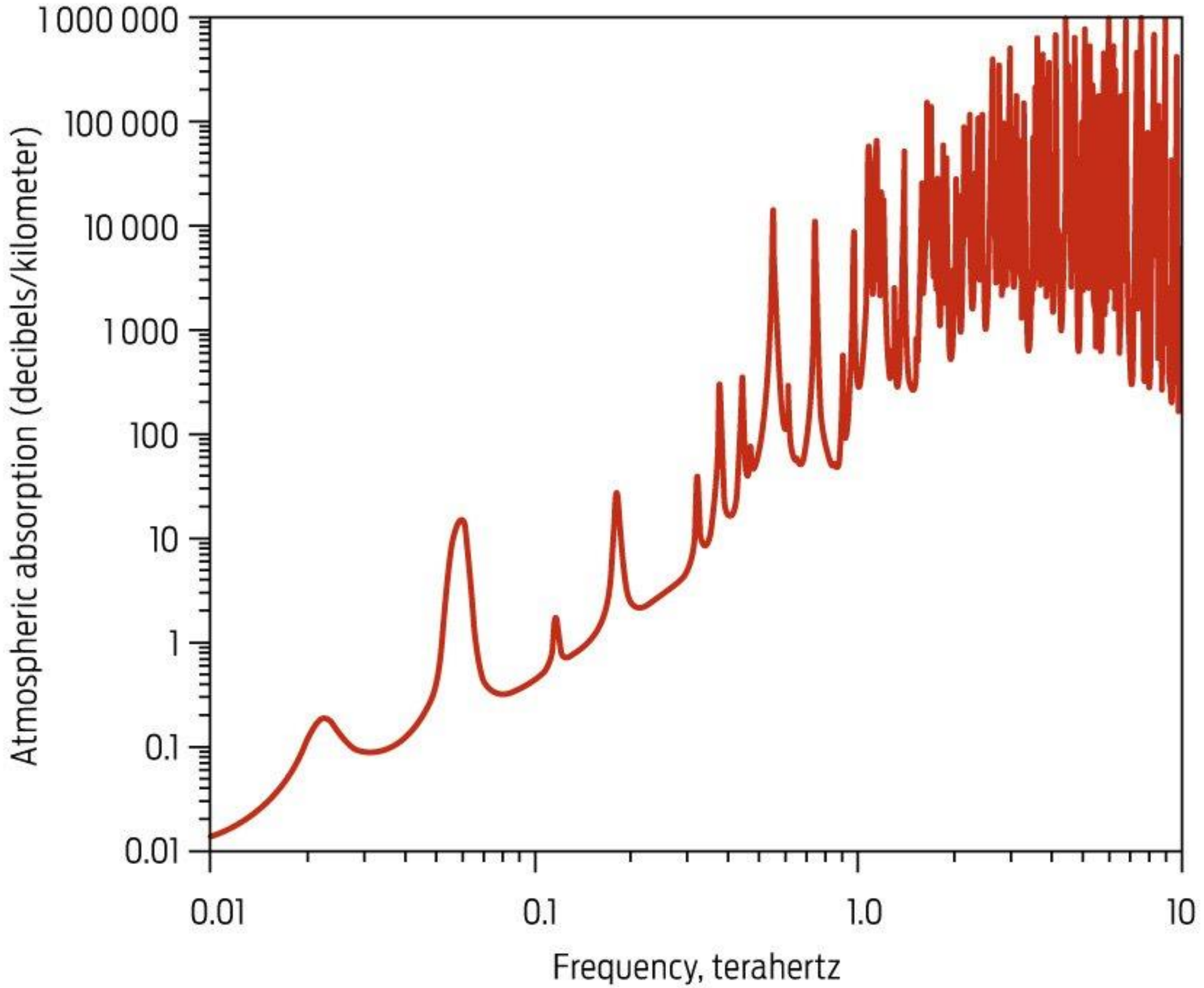

Transmission
1
0.1
0.01
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1
2
3
4
5
6
Frequency (THz)

THz radiation applications

Application	Main use	Key THz advantage
Spectroscopy	Material and molecular identification	Unique THz fingerprints
Semiconductors	Carrier lifetime, mobility, conductivity	Contact-free ultrafast probing
Non-destructive testing	Defects in composites, coatings, plastics	Penetrates non-metallic materials
Pharmaceuticals	Tablet coating, porosity, hydration	Non-contact quality control
Security	Concealed objects, explosives, powders	Penetrates packaging and clothing
Biomedical sensing	Skin, tissue, hydration, cancer margins	Sensitive to water and tissue structure
6G communication	Ultra-fast short-range wireless links	Very large bandwidth
Astronomy	Molecular lines and interstellar gases	Matches rotational/vibrational transitions
Cultural heritage	Hidden layers in art and manuscripts	Non-destructive imaging
Fundamental physics	Low-energy excitations in materials	Matches phonons, plasmons, magnons


1
0.1
0.01
1E-3
1E-4
1E-5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
THz field amplitude, arb. u.
Frequency, THz
sig/ref transmission
sig/ref reflection
Raman

Terahertz water absorption lines



H_2O