Current THz Research and Perspective

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ImPhys Image to insight Insight in imaging Department of Imaging Physics — Optics Research Group

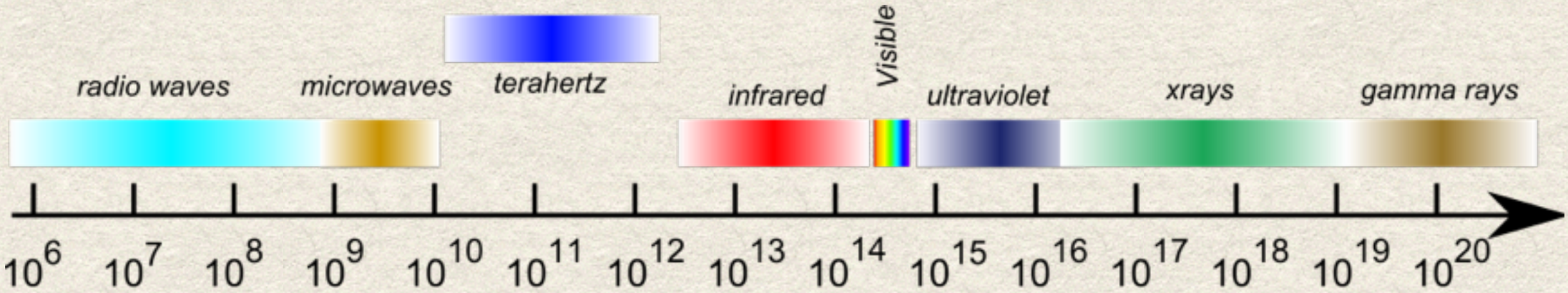
TUDelft

History of Terahertz

Start in 1920's as Far Infrared, *Terahertz* appeared in 1974 in Spectroscopy using Michelson Interferometer
Chief drivers of terahertz technology were for a long time Astronomers and Spectroscopist (1/2 of the luminous power is emitted at submillimeter wavelengths in our Milky way Galaxy)

More in P. H. Siegel, "Terahertz Technology," IEEE Trans. MTT, vol. MlT-50, no. 3, March 2002

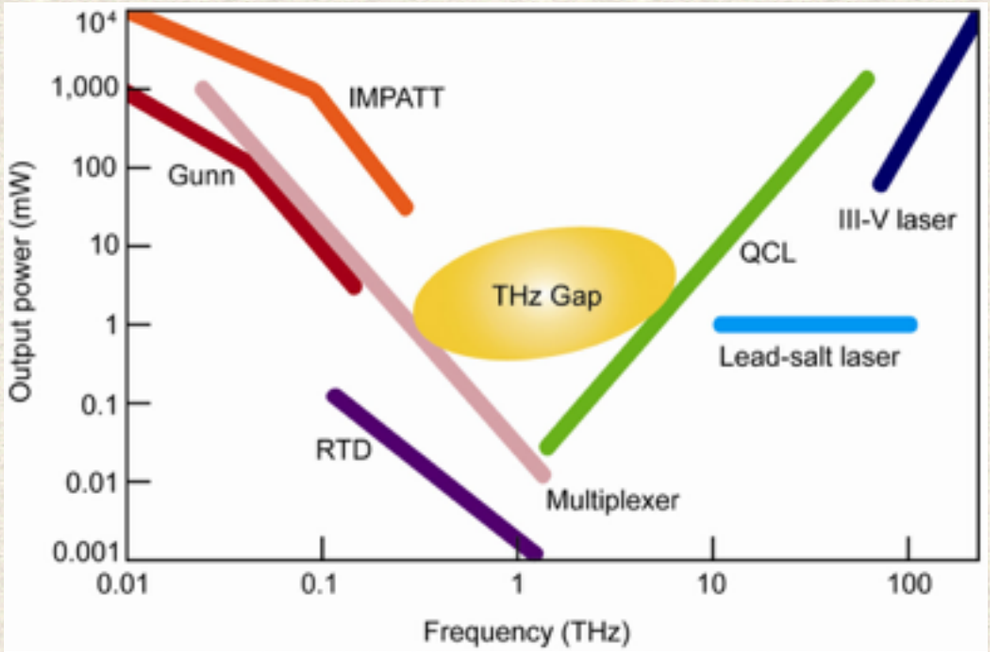
Naming of Terahertz science



The terahertz gap : 300 GHz to 10 THz or 30 μm to 1 mm or 10 cm-1 to 333 cm-1

- Different name for same range:
  - Far-infrared
  - Sub-millimeter
  - Terahertz
  - T-rays

Several communities, one gap



Is the gap still here?

THz source status 2006

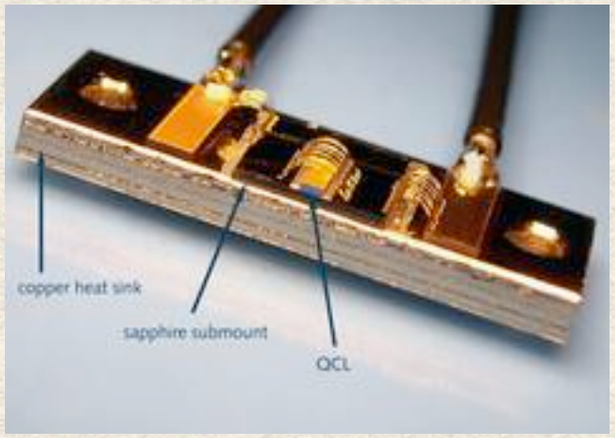
	Direct Laser		Laser-Enabled			Electronic	
	Optically Pumped Terahertz Laser	Quantum Cascade Laser	Terahertz Parametric Oscillator	Photomixing	Time-Domain System	Backward Wave Oscillator	Direct Multiplied Sources
Average Power	>100 mW[1]	mW @ 4K (Liquid He)	10's of nW	10 nW	~1 μW	mW	mW to μW (decreasing w/ increasing υ)
Usable Range	0.3 to 10 THz	2 to 10 THz	1 to 3 THz	0.3 to 10 THz	~0.1 to 10 THz	0.1 to 1.5 THz	0.1 to 1.5 THz
Tunability	Discrete Lines[2]	10 GHz	1 to 3 THz	0.3 to 10 THz	N/A	20% of υ_0	~10% to 15% of υ_0
Output Type	CW or Pulsed	CW or Pulsed	Pulsed	CW	Pulsed	CW or Pulsed	CW
Commercially Available	•				•		•

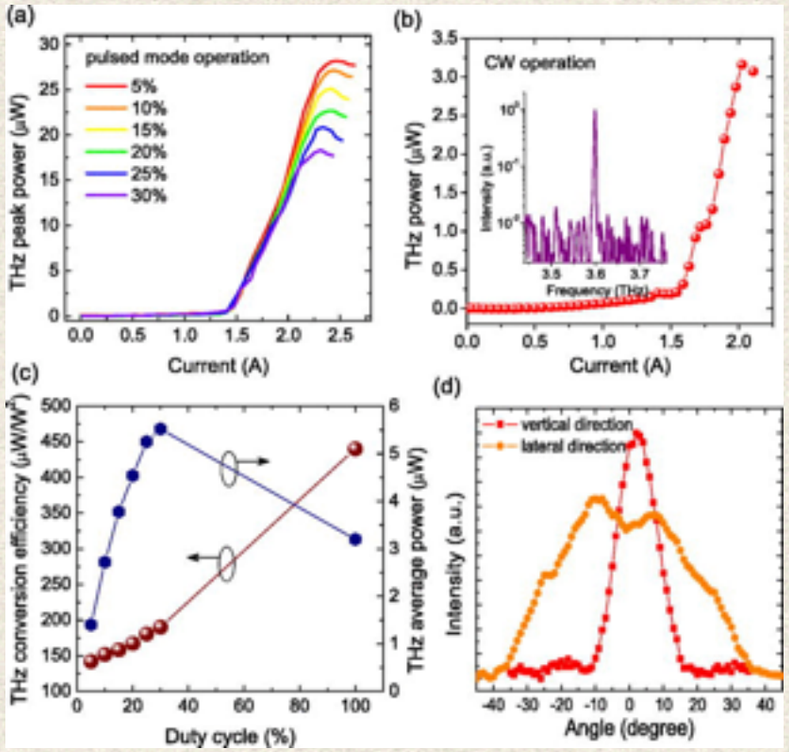
1. More than 1 W can be obtained at select frequencies.
2. Can be converted to tunable output using a Schottky-based sideband generator.

Photonics Spectra 2006

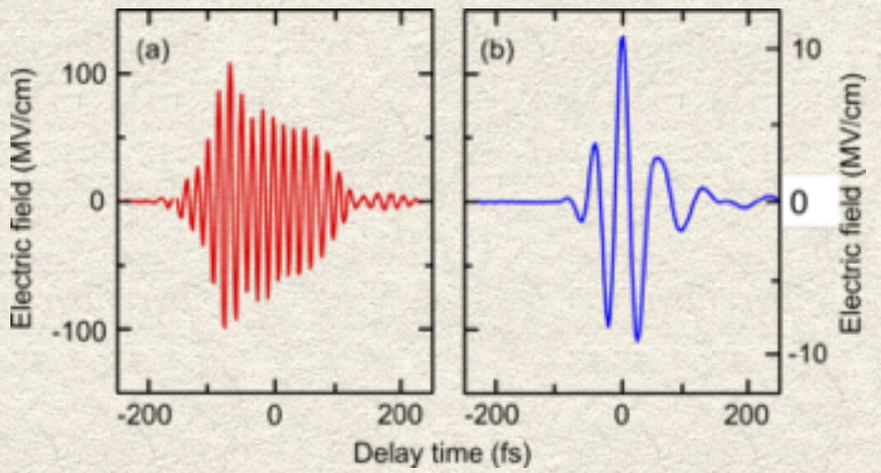
Is the gap still there today?

- Novel sources:
  - Quantum Cascade Lasers: Room temperature, large power
  - High-field THz source >100 MV/cm and large bandwidth





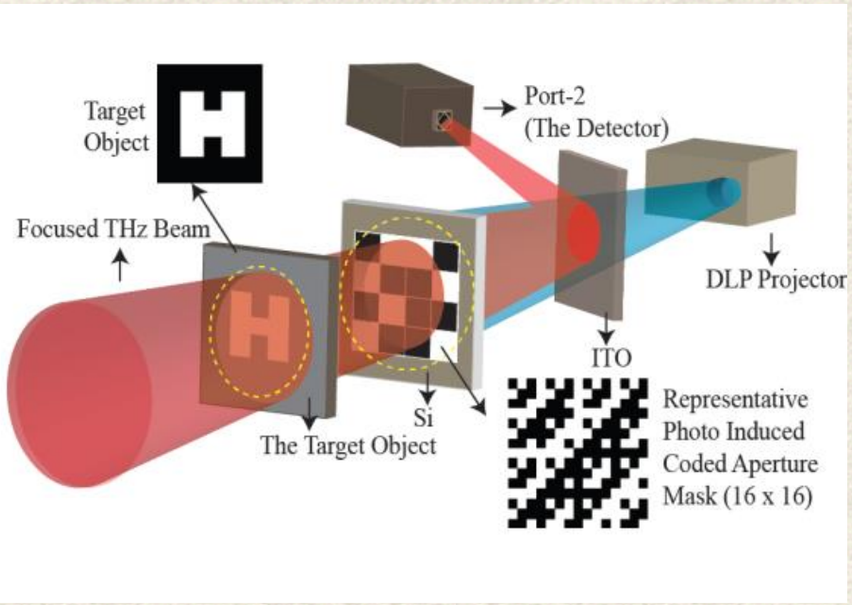
Q. Y. Lu, et al.. Continuous operation of a monolithic semiconductor terahertz source at room temperature. Applied Physics Letters, 104(22):–, 2014.

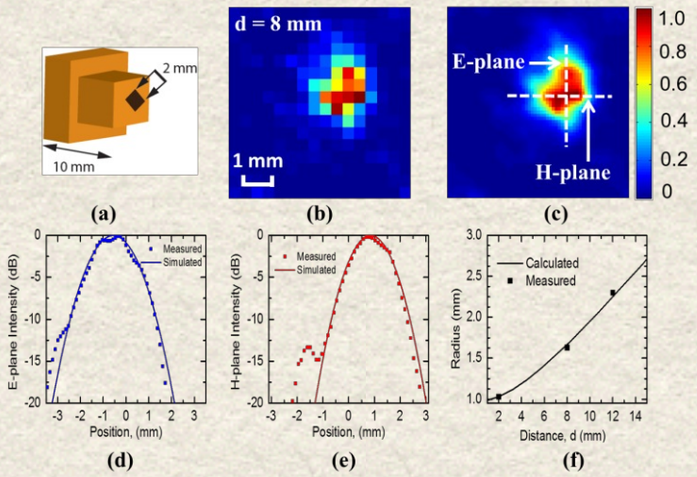


Optics Letters, Vol. 36, Issue 13, pp. 2399-2401 (2011)

Is the gap still there today?

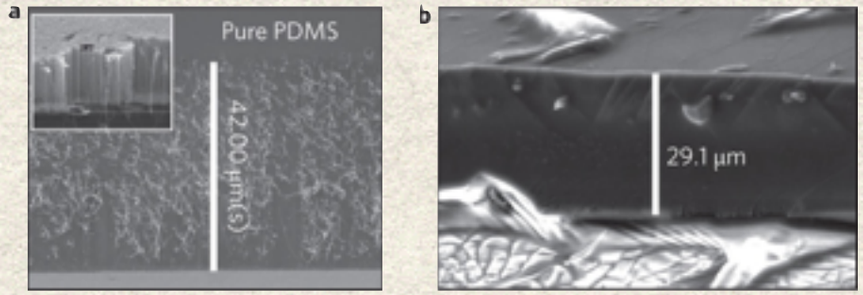
Fast imaging with single pixel

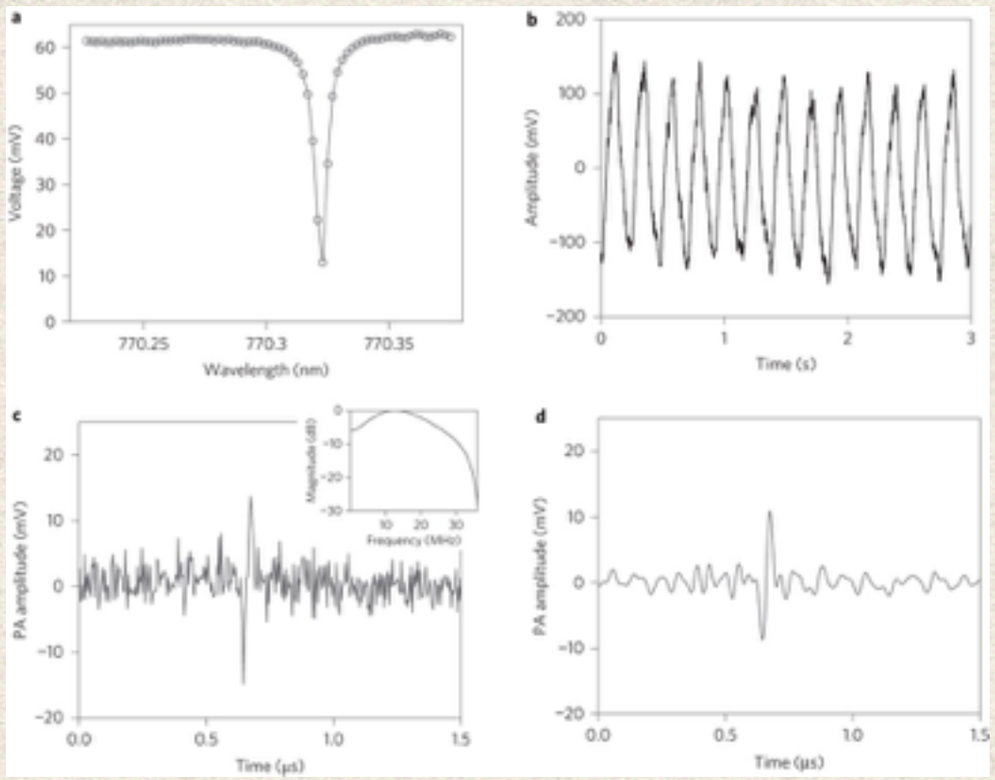




Proc. SPIE 9102, Terahertz Physics, Devices, and Systems VIII: Advanced Applications in Industry and Defense, 910207 (May 21, 2014)

Use of Carbo Nanotubes for acoustic detection



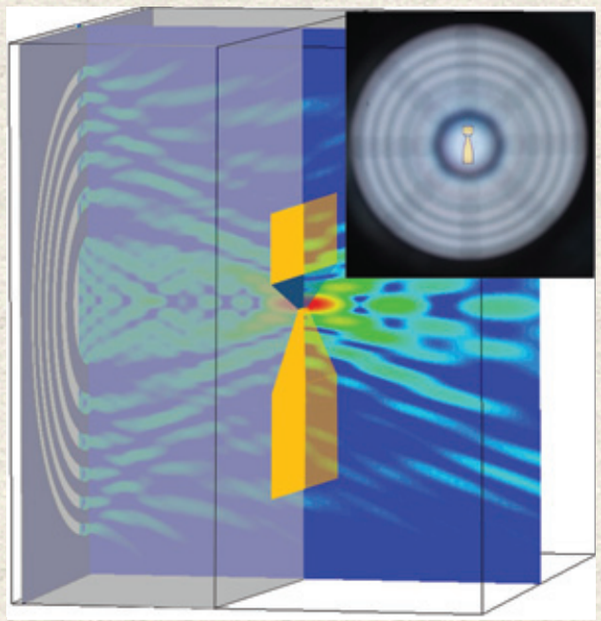


Nature Photonics **8**, 537–542 (2014)

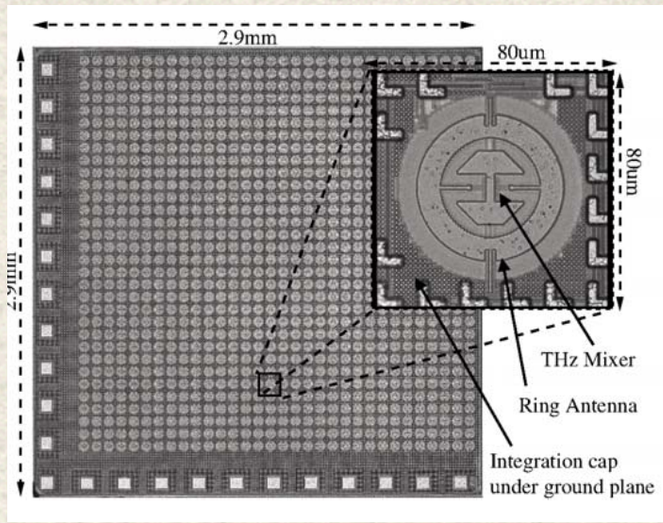
Detection: Antennas & cameras

Bolometers

64x64 pixels camera sub-THz



Electronics



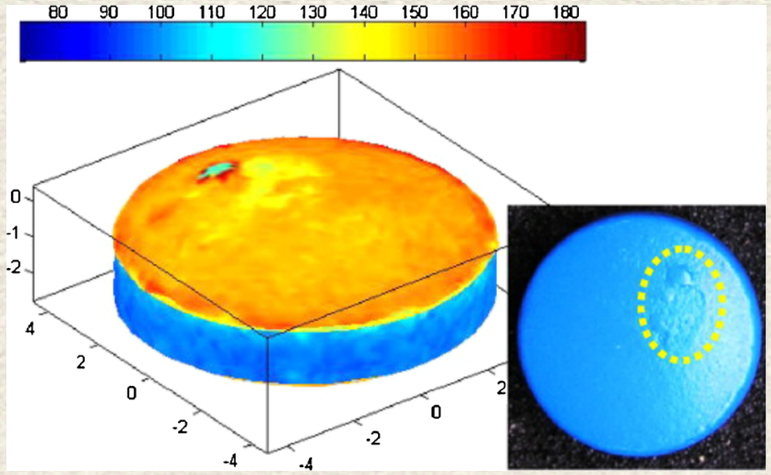
U. Pfeiffer and E. Ojefors. A 600-GHZ CMOS focal-plane array for terahertz imaging applications. In Solid-State Circuits Conference, 2008. ESSCIRC 2008. 34th European, pages 110–113, Sept 2008.

ELECTRONICS LETTERS 11th September 2014 Vol.50 No.19 p1332

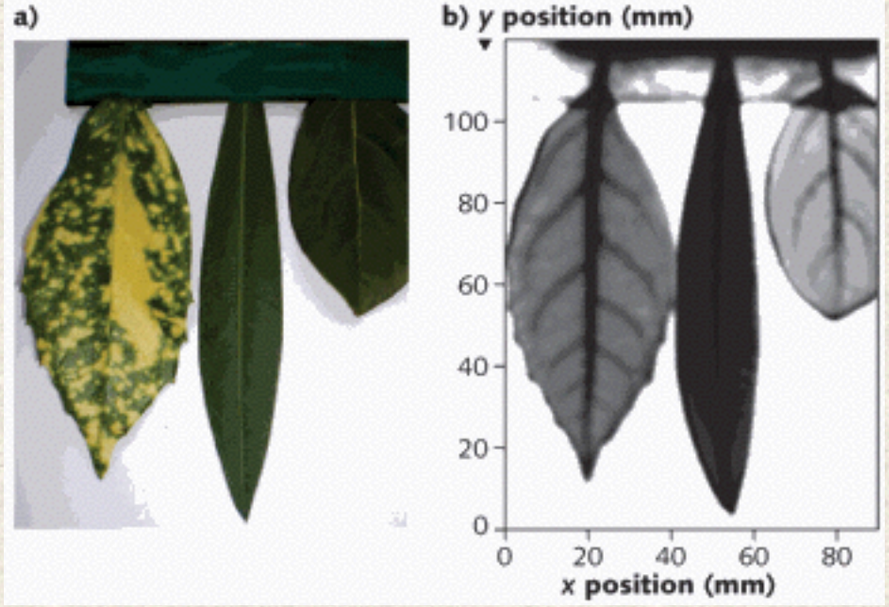
Technics	vs	Use
• Imaging		• Medical
• Tomography		• Security
• Spectroscopy		• Non destructive testing
• Transmission		• Communication

THz Imaging / Tomography

- Terahertz goes through paper, plastic, board ceramic
- Nice tool for non destructive testing
- Should be robust to be inserted for online monitoring
- Problem with Water (liquid) and atmospheric absorbtion



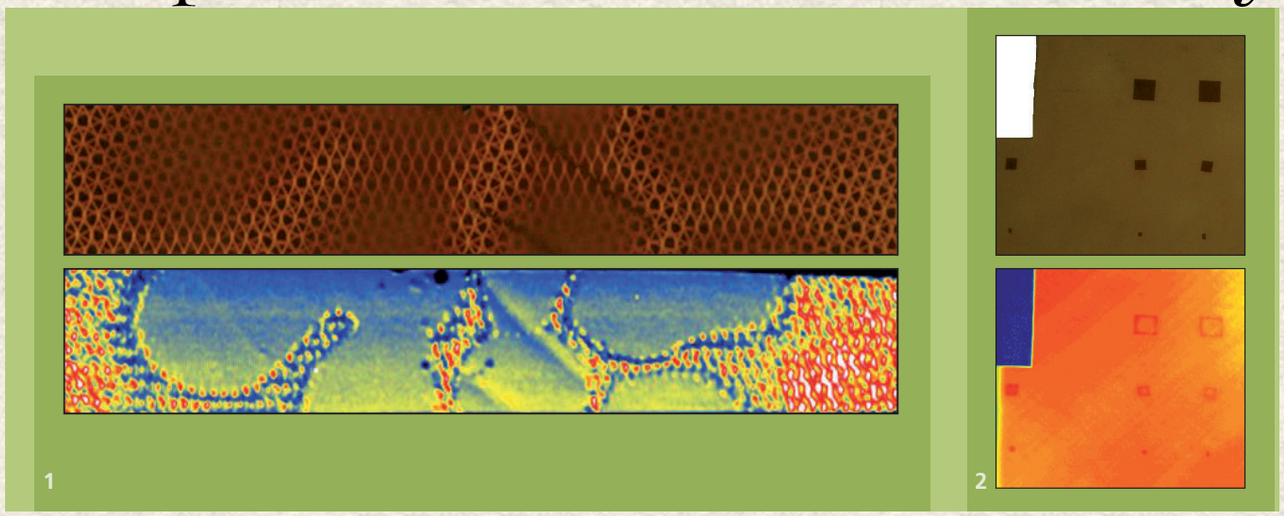
J. Guillet,Review of terahertz tomography techniques. Journal of Infrared, Millimeter, and Terahertz Waves, 35(4):382–411, 2014.



F. Schuster et al., "A Broadband Terahertz Imager in a Low-cost CMOS Technology," Int. Solid-State Circuits Conf.

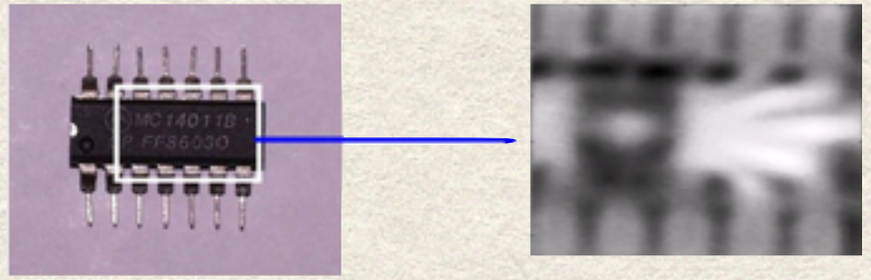
THz Imaging: non destructive testing

Composite for the aeronautic industry

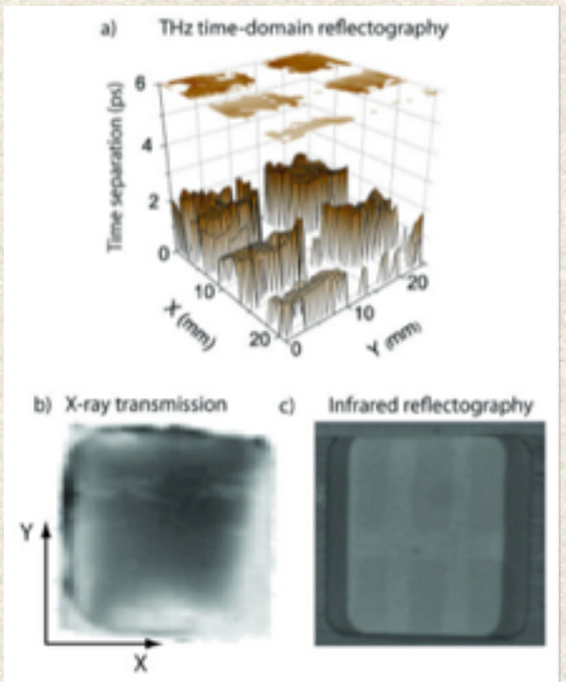


EU Project - Fraunhofer institute

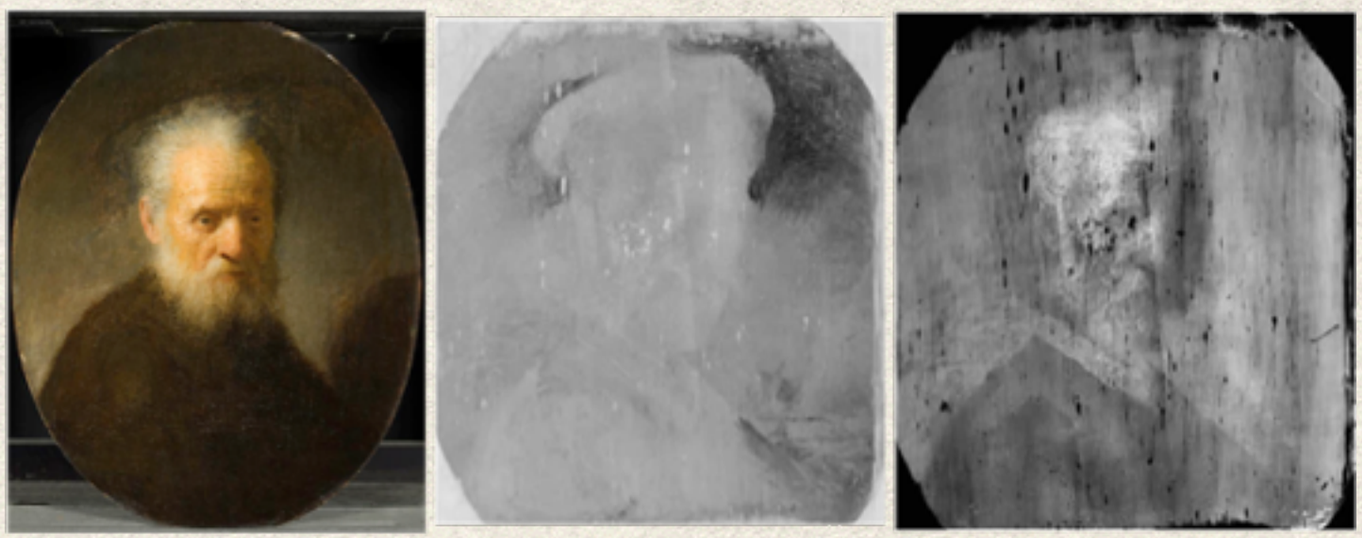
Chip inspection



X.C. Zhang, Rensselaer Polytechnic Institute



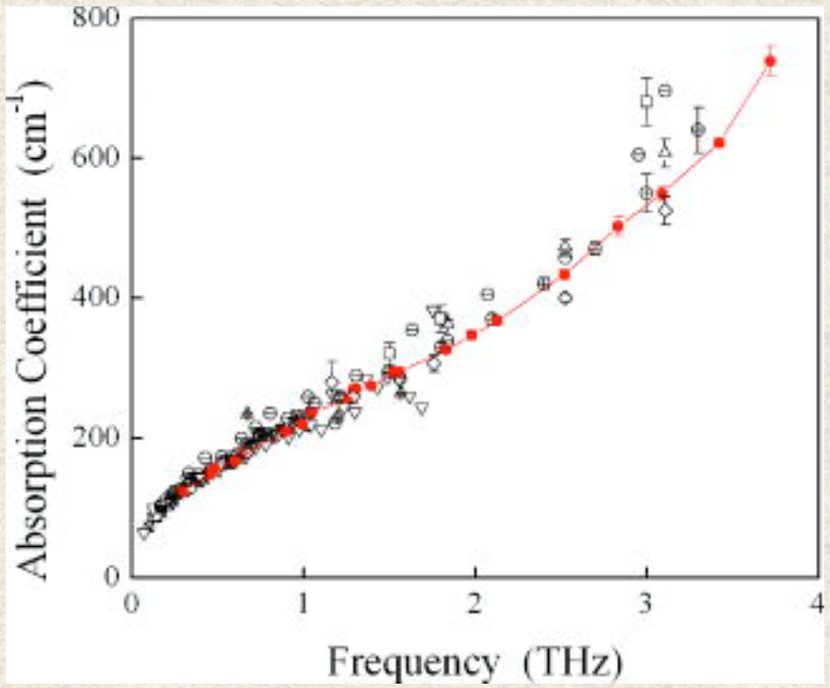
With use of X-ray at European Synchrotron Radiation Facility



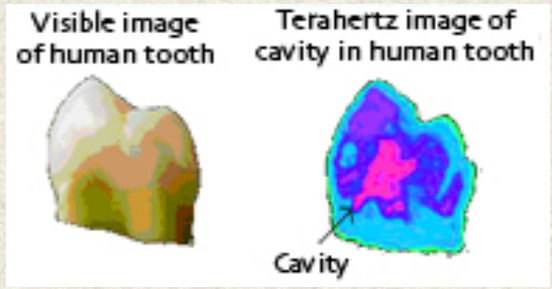
A. J. L. Adam, P. C. M. Planken, S. Meloni, and J. Dik. Terahertz imaging of hidden paint layers on canvas. Opt. Express, 17(5):3407–3416, 2009.

Medical Terahertz Imaging

Water is a killer

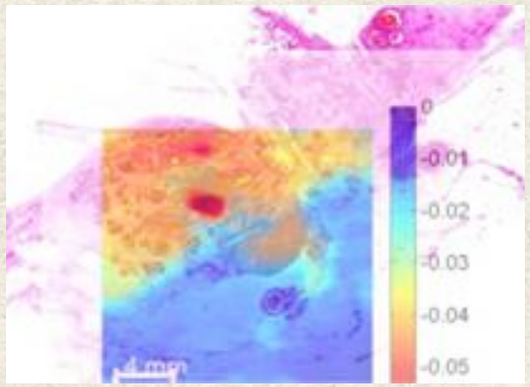


Tooth cavities

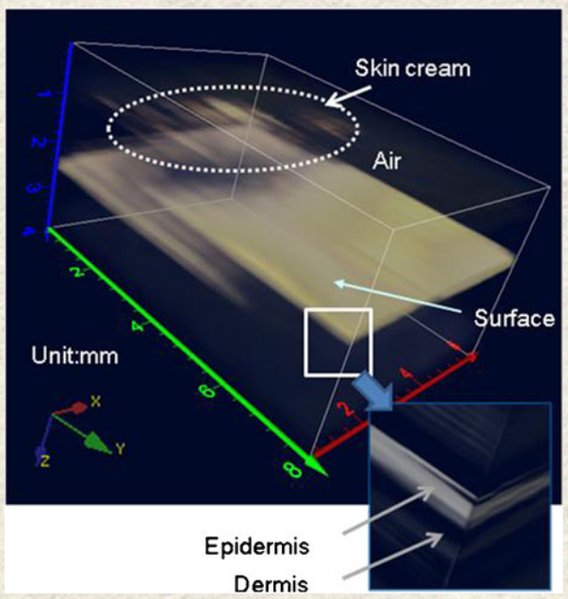


Teraview®

Histology of Breast cancer cell



Teraview®

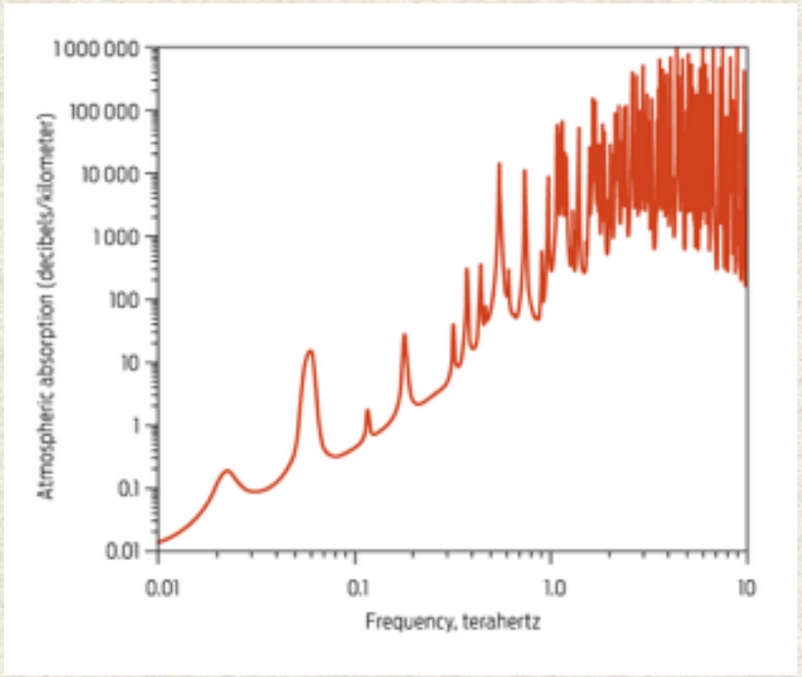


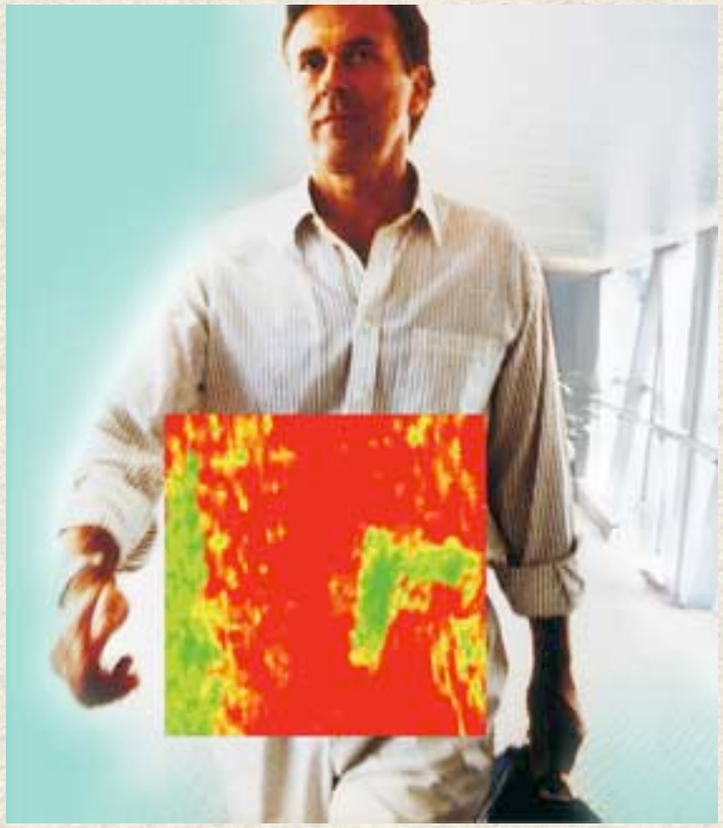
Three-dimensional image of porcine skin

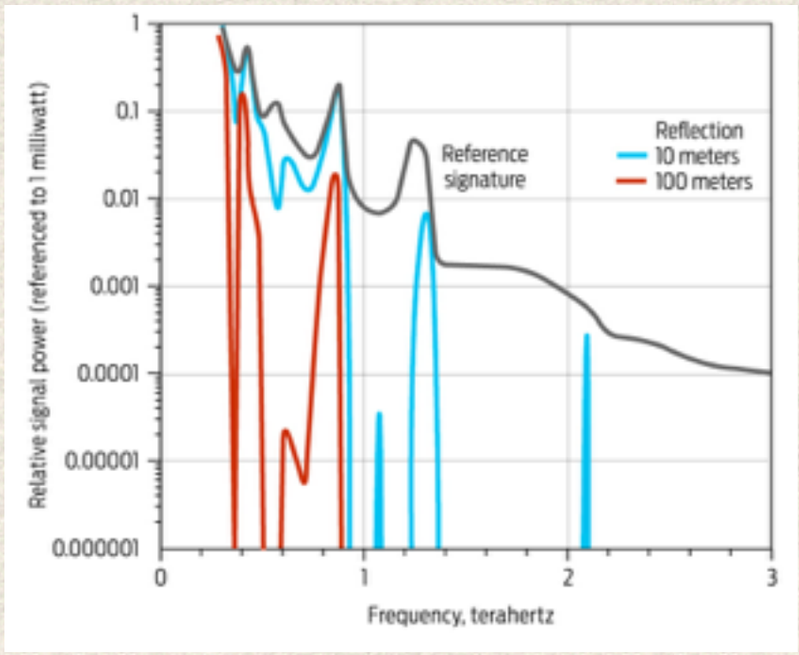
J Infrared Milli Terahz Waves (2014) 35:118–130

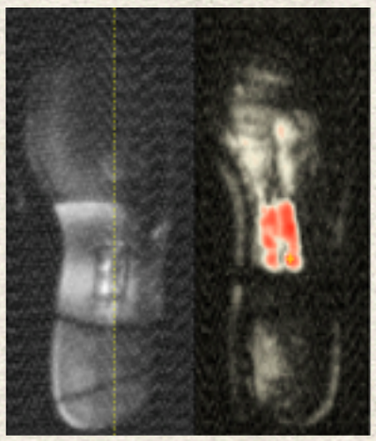
Imaging:Security - Screening

Atmospheric absorption





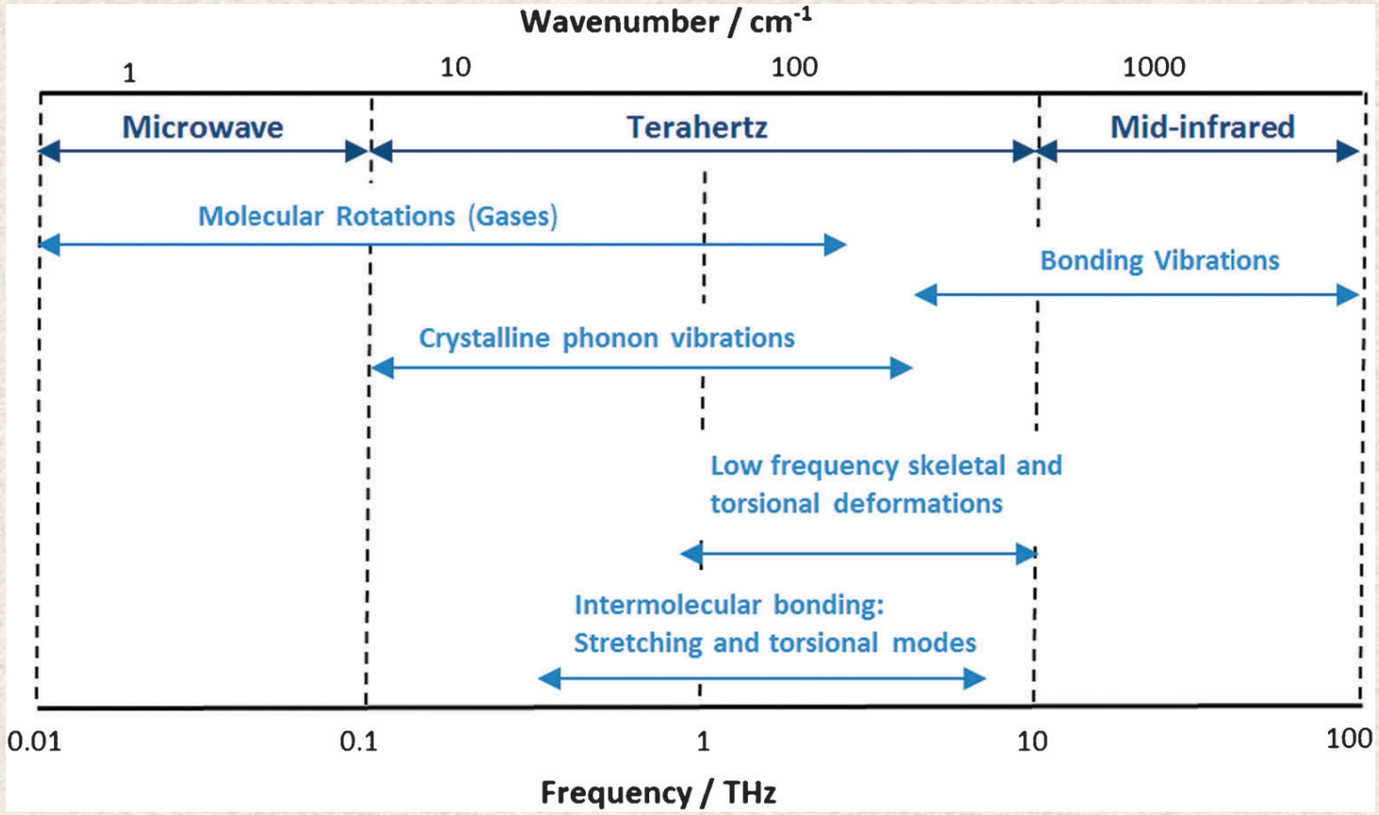




Razor blase on a shoe

Michael C. Kemp, Explosives Detection by Terahertz Spectroscopy—A Bridge Too Far?
IEEE transactions on THz Science and Technology, Vol. 1, n°1, Sep. 2011

THz Spectroscopy



- No need to direct access (compared to Raman/IR)

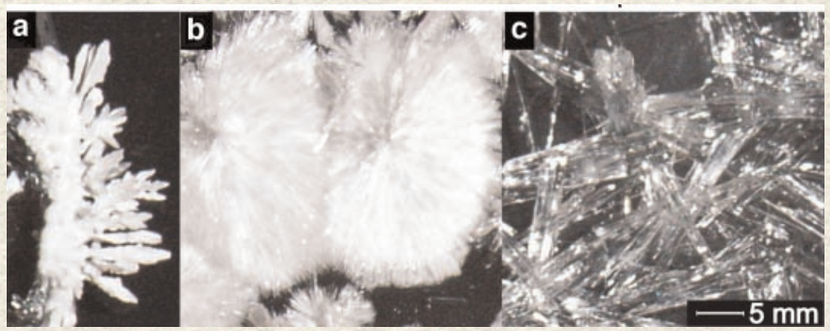
A. I. McIntosh, Terahertz spectroscopy: a powerful new tool for the chemical sciences? Chem. Soc. Rev., 41:2072–2082, 2012.

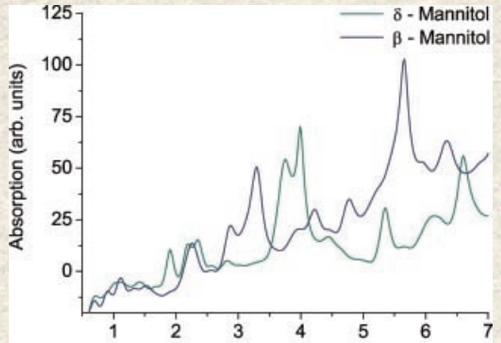
- Fingerprinting and chemical identification
- Studies of biomolecules in the solid state
- Studies of biomolecules in aqueous solution
- Studies of liquid dynamic
- Solid state transformations

THz Spectroscopy: Solid states transformation

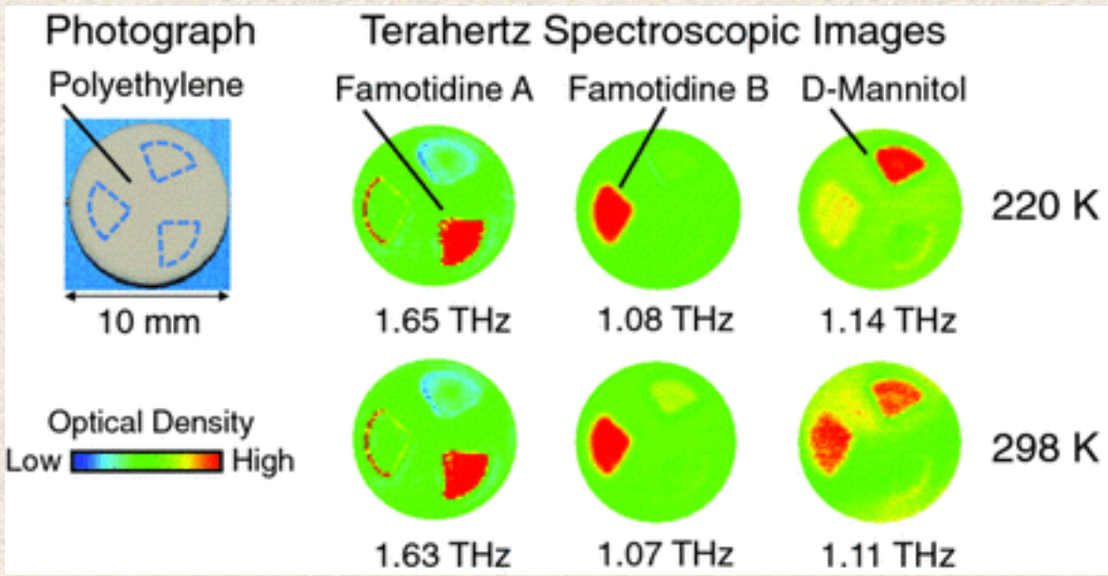
- Vibrational modes can distinguish polymorphs

Spectroscopy of polymorphs



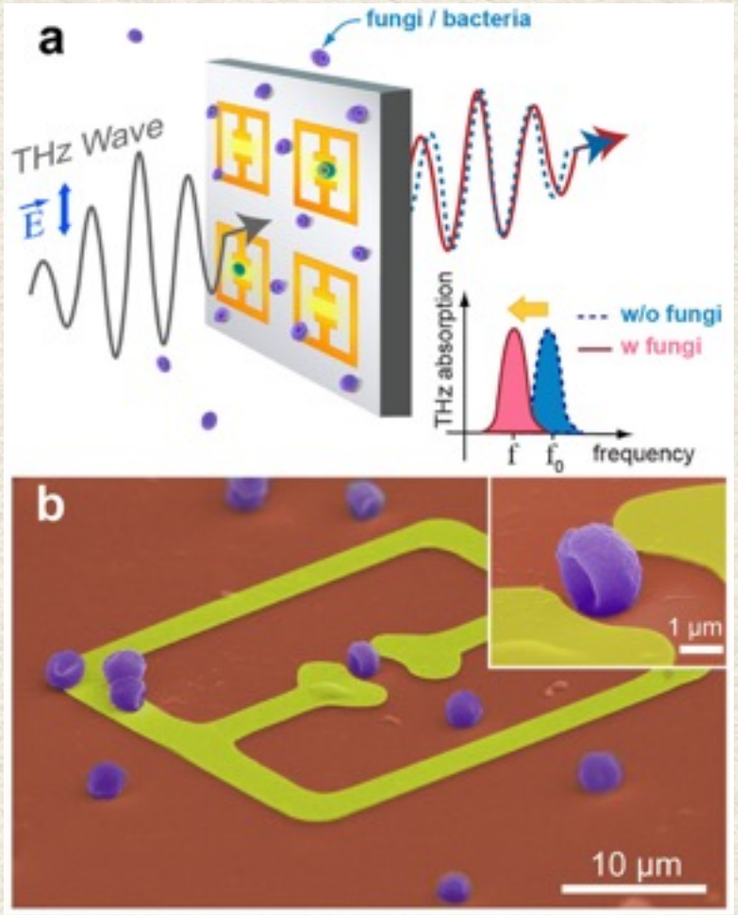


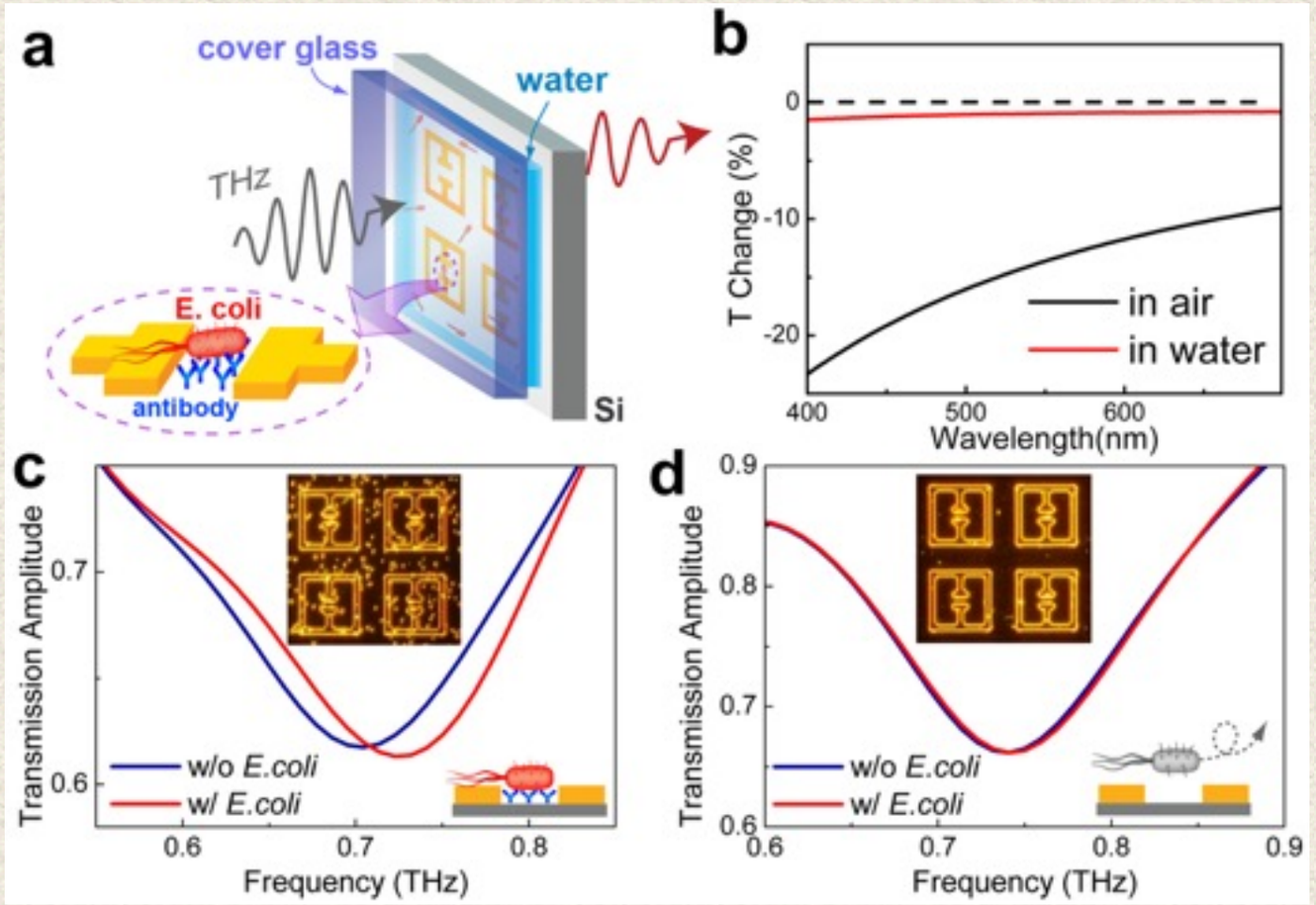
JOURNAL OF PHARMACEUTICAL SCIENCES, VOL. 99, NO. 2, FEBRUARY 2010



J. Electrochem. Soc. 2014 161(9): B171-B175;

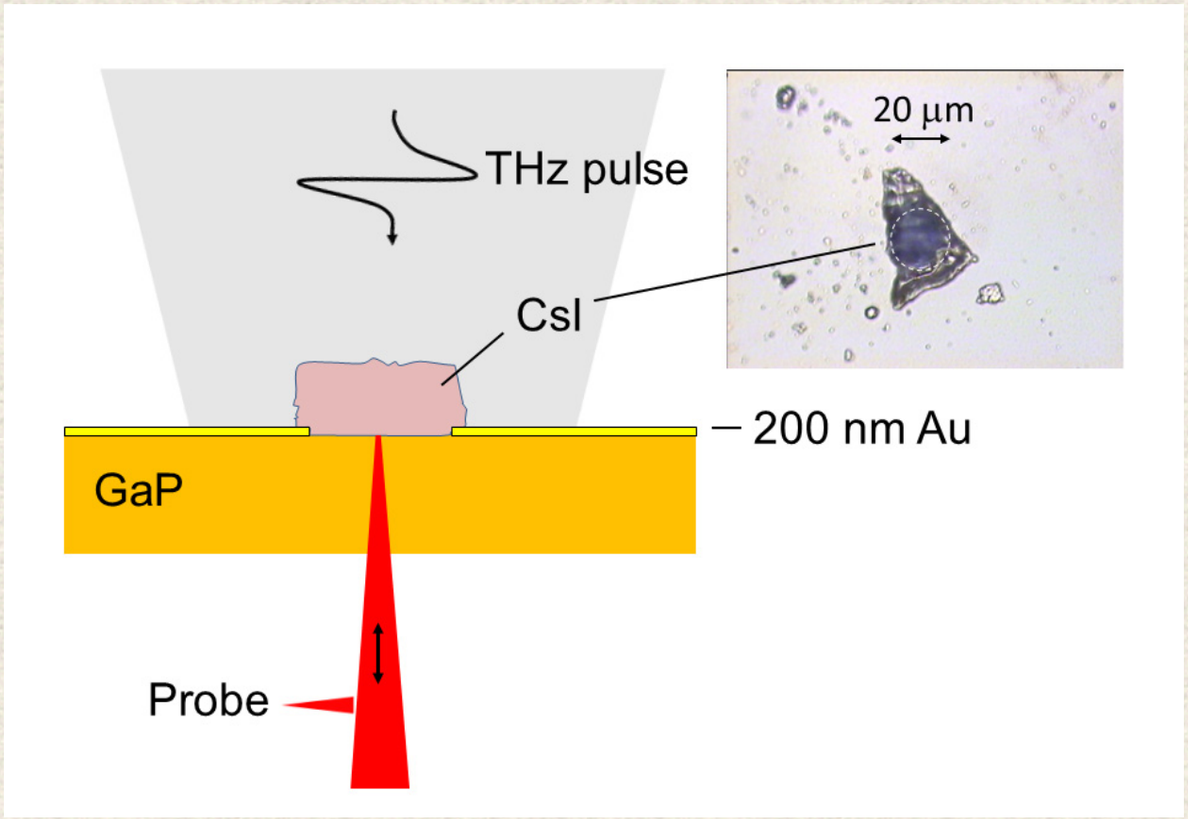
THz Spectroscopy: Detection of biological samples

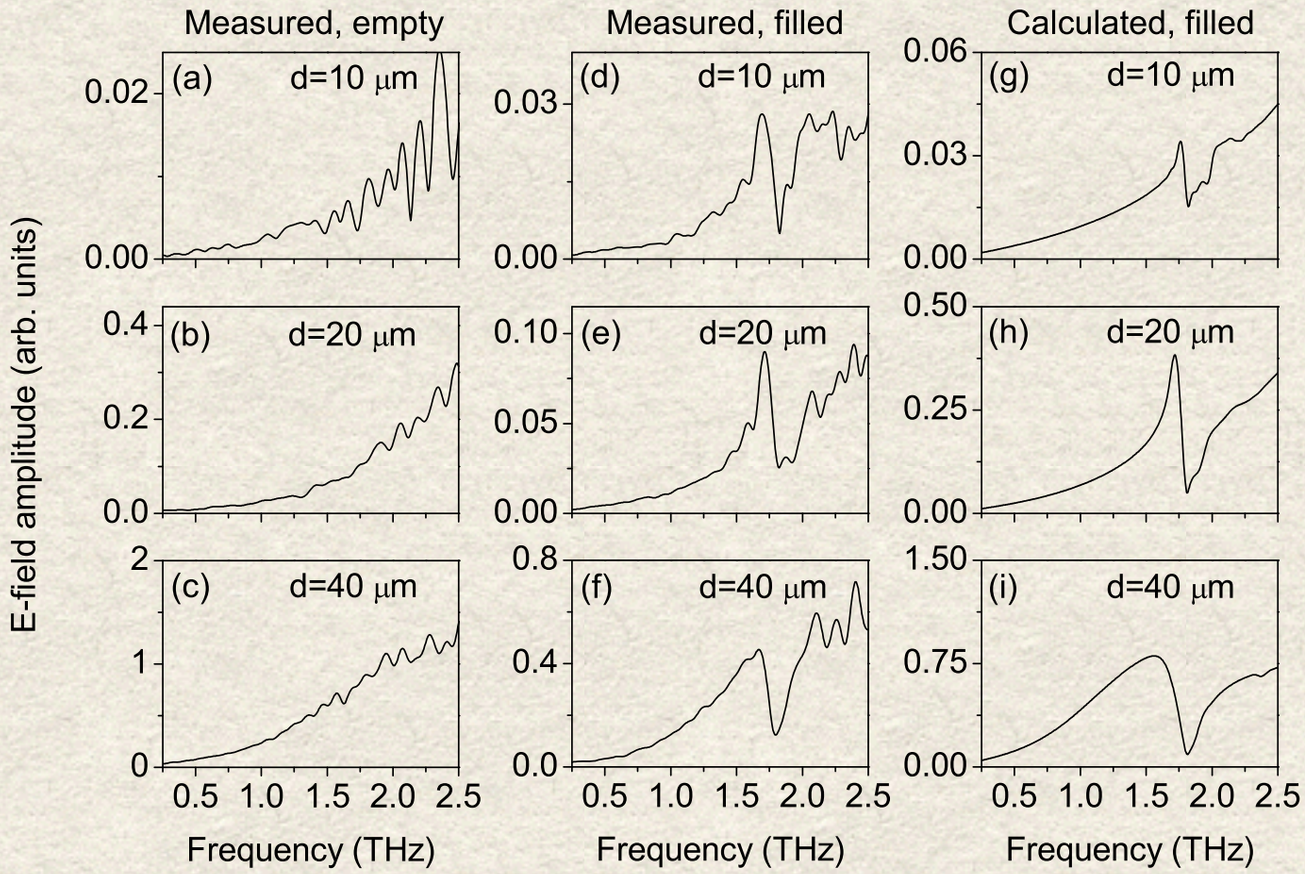




S.J.Park, Detection of microorganisms using terahertz metamaterials. Sci. Rep., *4*, 05 2014.

THz Near-field Spectroscopy





J. R. Knab and al.,Applied Physics Letters, 97(3), Jul 19 2010.
J. R. Knab et al.,Opt. Express, 21(1):1101–1112, Jan 2013.

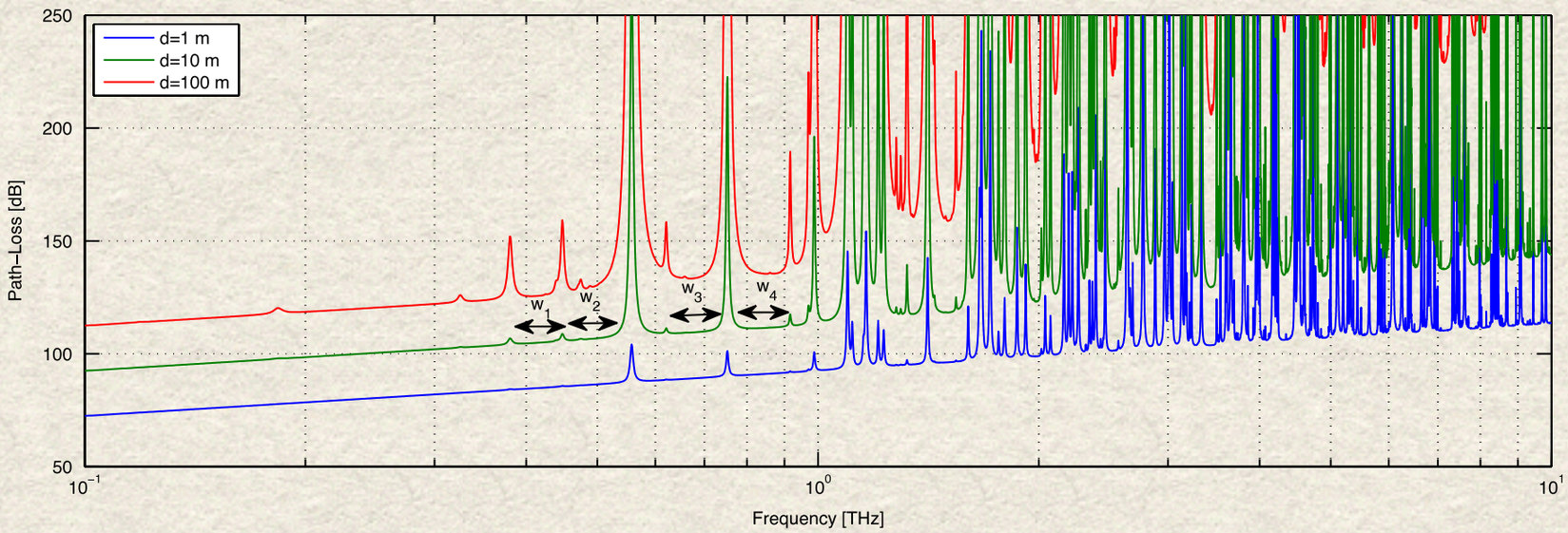
Next: move to liquid THz spectroscopy of small volumes

THz band: the next frontier for wireless communications

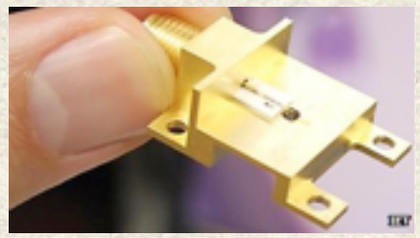
- Wireless technologies below 0.1 THz and above 10 THz are not able to support Tbps links.

- THz Band offers a much larger bandwidth

- Suffer from Path Loss



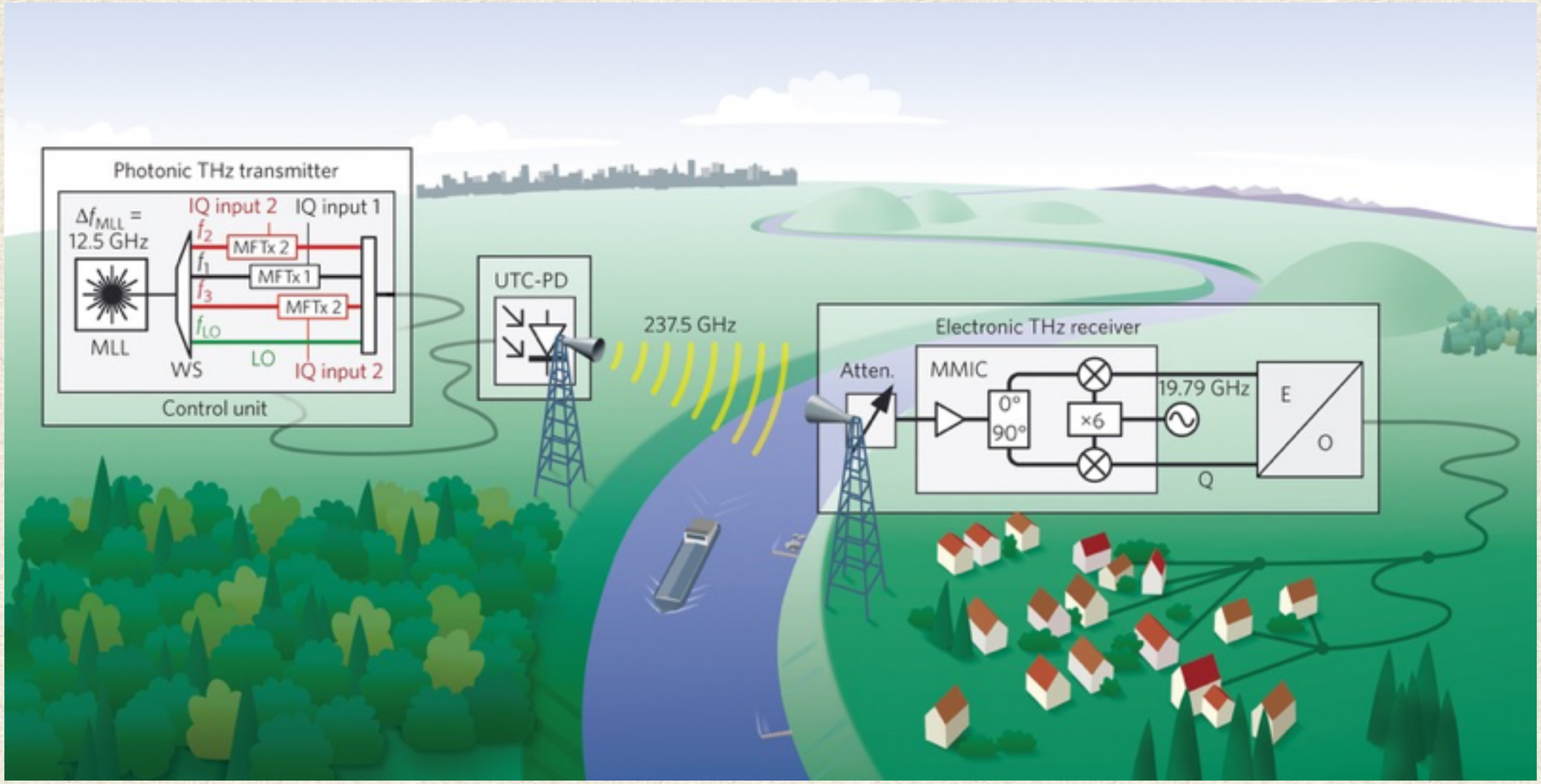
1.5Gb/s at a frequency of 300GHz.



K. Ishigaki
Electronics Letters(2012),48(10):582

I. F. Akyildiz, J. M. Jornet, and C. Han. Terahertz band: Next frontier for wireless communications. Physical Communication, 12(0):16 – 32,

Long distance calls?

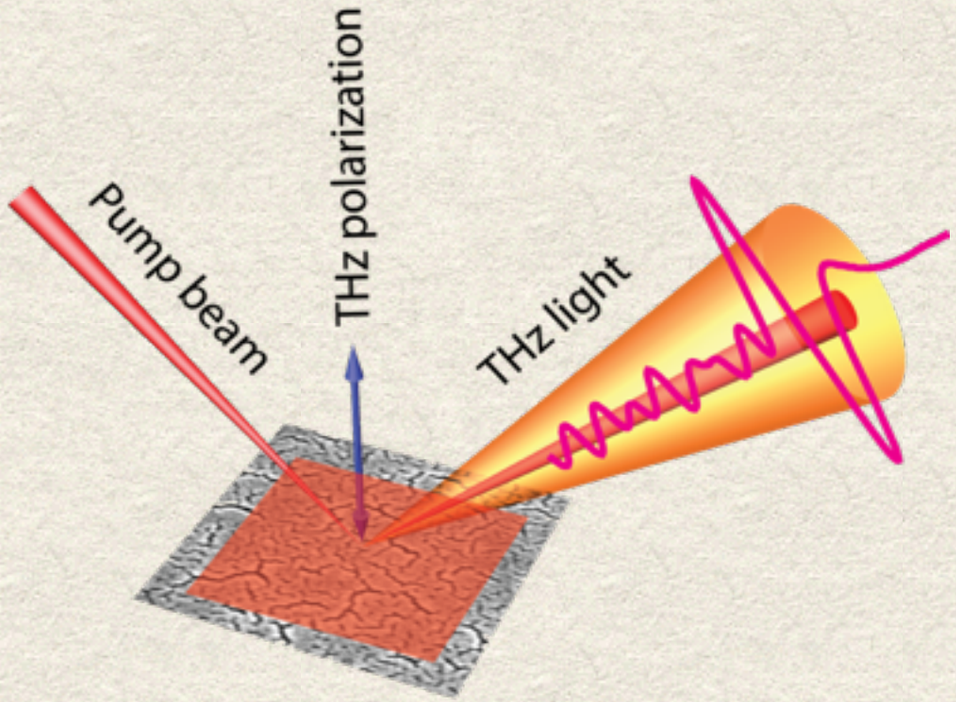


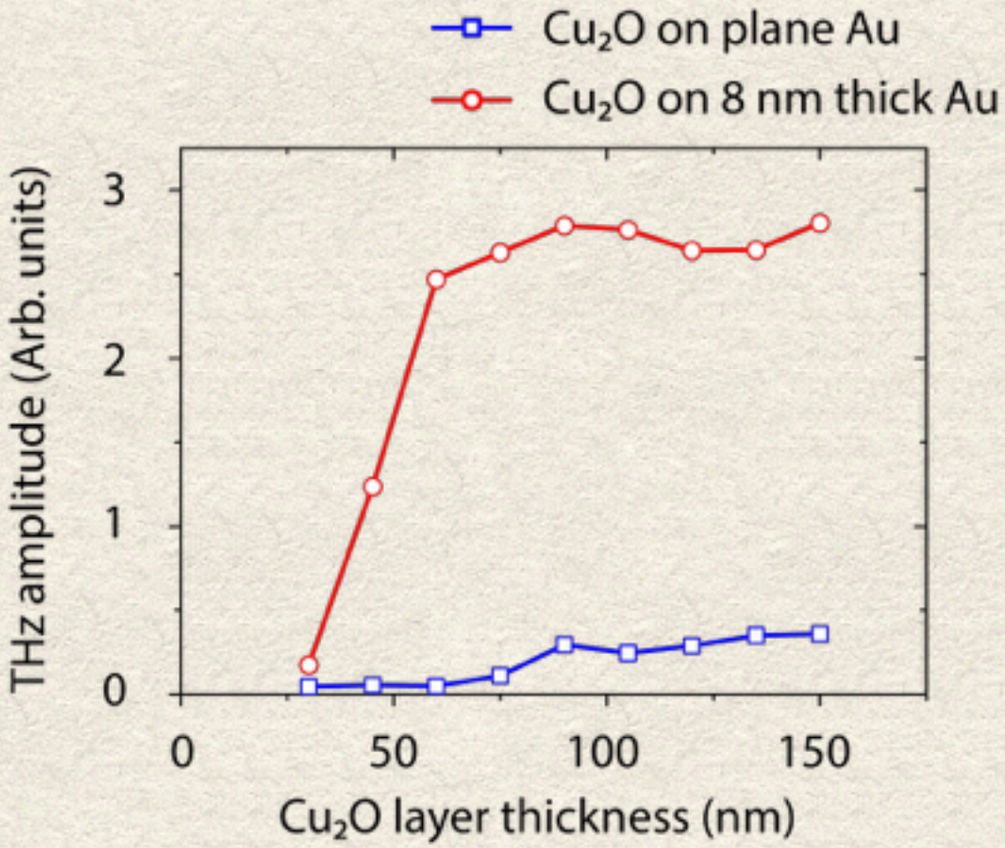
Carrier Frequency 237.5 THz
Data transfer over 20 m 100 Gbit/s

S. Koenig, and al. Wireless sub-Thz communication system with high data rate. Nat Photon, *7*(12):977–981, 12 2013.

Further enhancement? Plasmonics

Cu_2O on percolated gold

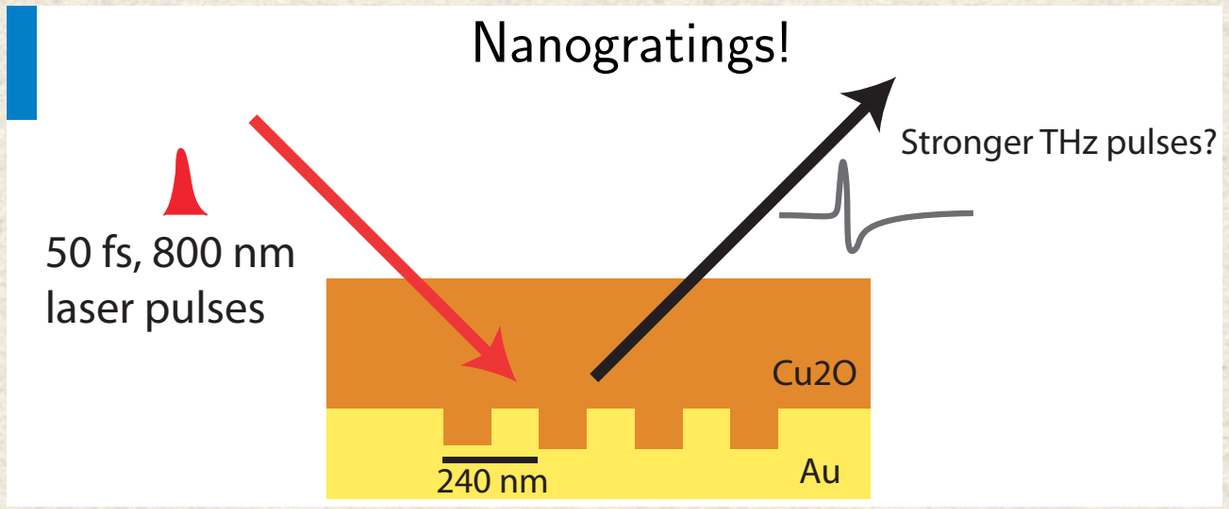


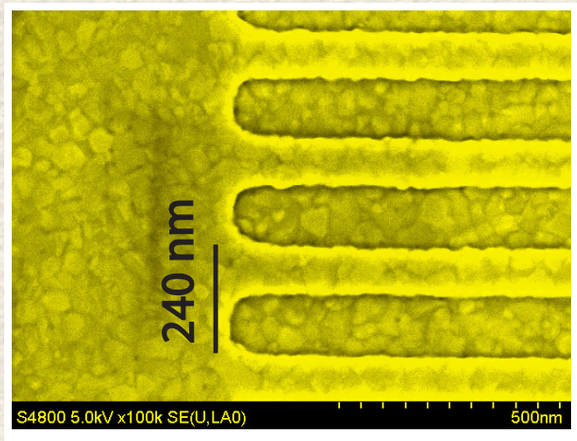


Nanostructured gold surface (localized surface plasmons)

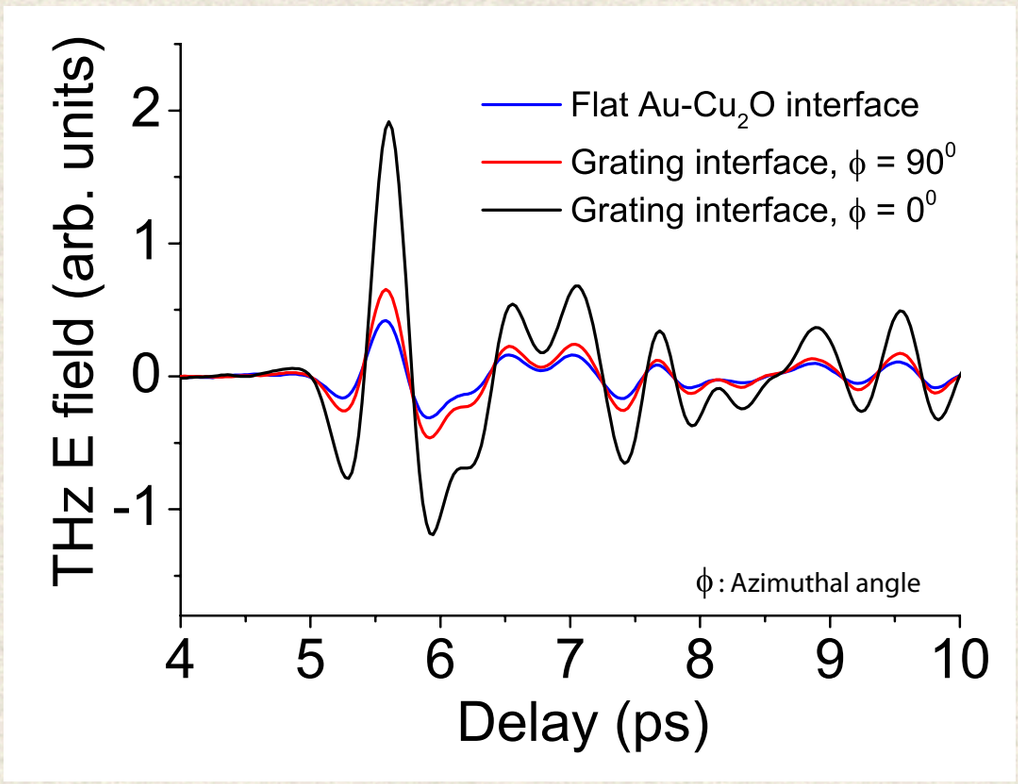
Optics Letters, Vol. 36, Issue 13, pp. 2572-2574 (2011)

800nm Plasmonics to improve THz generation



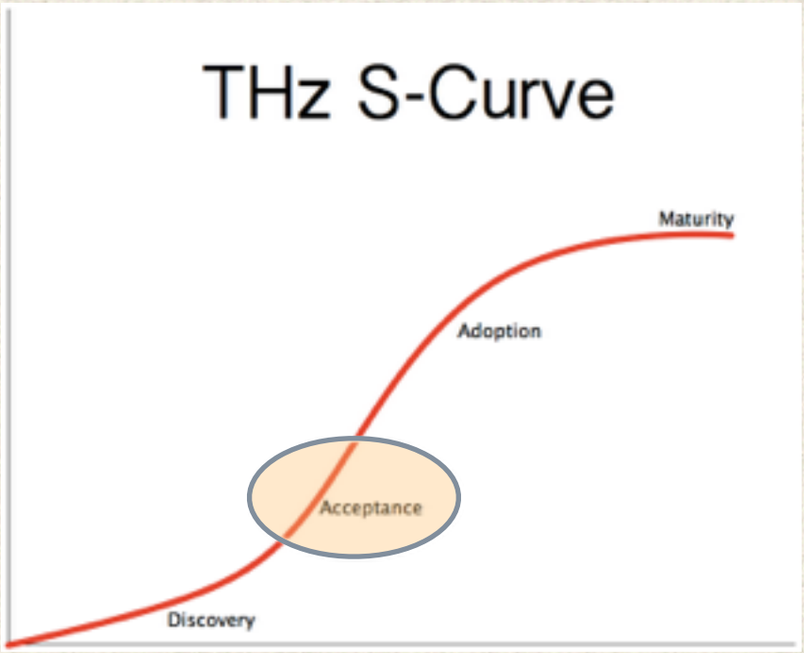


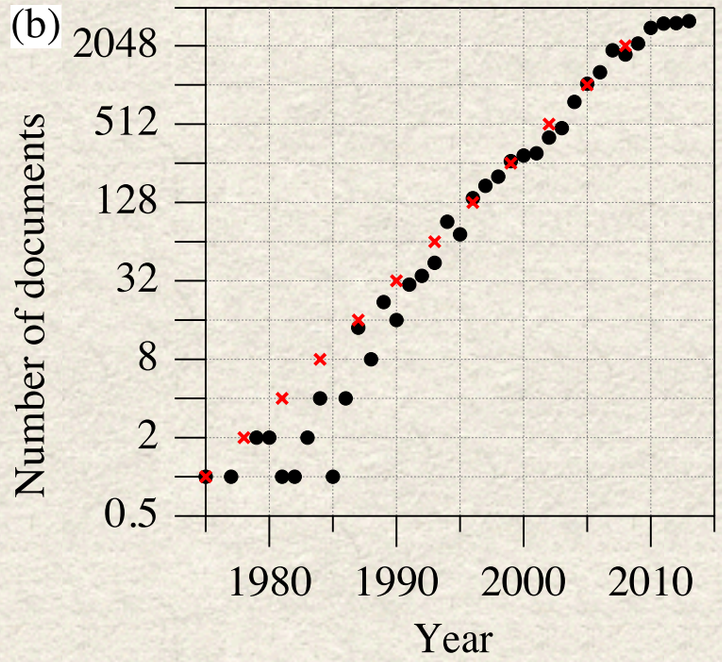
Gold Nanograting



THz generation

THz a bright future?





J. Phys. D: Appl. Phys. 47 (2014) 374001

THz makes cover and new journals are edited, conferences are flourishing

Company active in the field

Uncooled THz imager

Companies delivers competitive systems now!

THz in the Netherlands:

Neto (Antennas)
Gao (Astro)
Adam (TDS)
Siebbeles (Chemistry)

Gomez Rivas (Photonics)

Marion Matters (RF)

Engelkamp (Spectroscopy)

Baryshev (Detectors)

Main issues to THz use in industry

- Circumvent liquid Water
- Avoid atmospheric absorption
- Beat older technologies
  - only if cheaper or better
- Robust and easy to manipulate
- Find your niche