THz imaging and spectroscopy: The next wireless wave

Marion Matters, Giampiero Gerini, Lorenzo Tripodi

26th of October 2010

Content

- Background
- THz applications
- THz systems and technology
- Opportunities and limits of CMOS technology
- Conclusions

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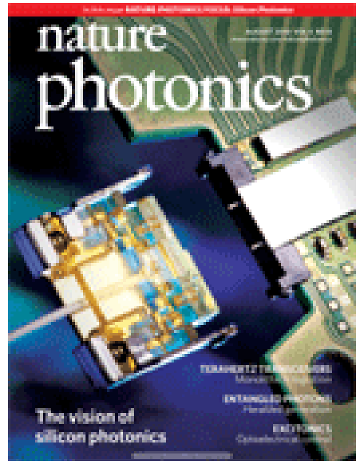
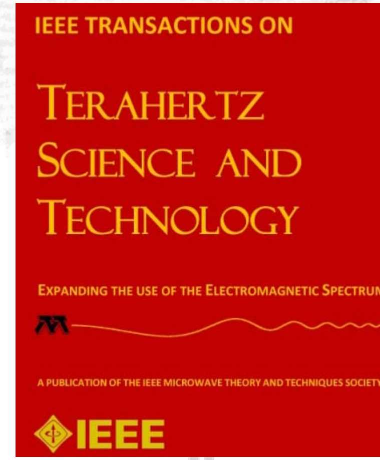
Growing interest in THz radiation

THz QCL 2002



THz QCL transceiver 2010



Expected fall 2011

- A section dedicated to THz technology is very often present in recent conferences on Microwaves and RF
- New IEEE transaction is expected in fall 2011

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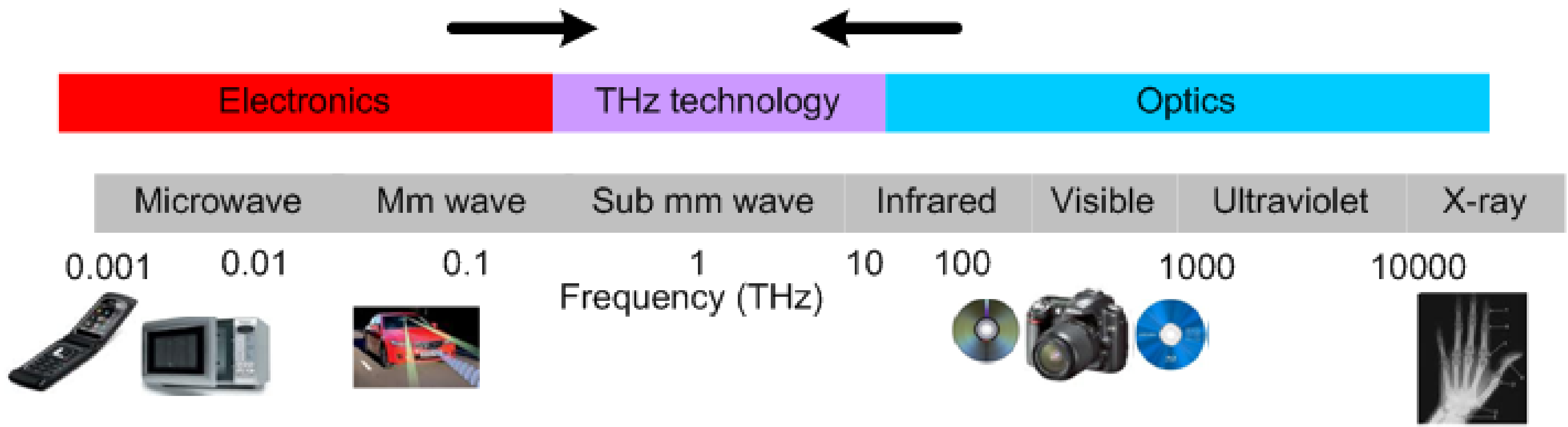
Background

1 THz = 1000 GHz



- THz radiation can penetrate through non-polar materials (e.g. plastics, wood, clothing)
- THz imaging has sub-mm resolution
- THz spectroscopy identifies specific materials (e.g. explosives)
- THz radiation is non-ionizing (and therefore safer than X-ray)
- THz radiation is strongly absorbed by metals and polar materials (e.g water)
- Enabler for extreme high data rate communication
- Applications in the THz range continue to increase rapidly

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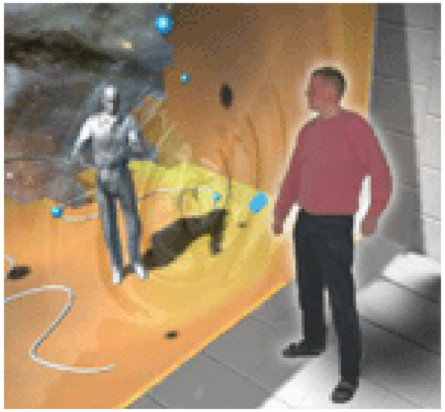
Application overview

Application type	Application sector/example
Imaging	Medical imaging, Airport security scans, baggage screening systems, Coating control of medication, Production quality control, Non-distructive inspection
Spectroscopy	Lab-on-chip, pharmaceutical drug distinction, Gas detection, explosive detection, food-inspection, Water detection in paper/wood/tissue, Astronomy
Communication	High-speed short range communication Ultra-broadband indoor pico-cells High speed computing
Nanoscopes	THz imaging of transistors or other semiconducting or conducting devices with a nano-meter resolution, providing information which can neither be provided by optical microscope nor by electron microscopes.

Imaging Applications

- **Security**: *Concealed object and substances detection*
- **Intelligent/interactive Spaces:** *activities monitoring*



- Acquisition time and dimensions:
  - People screening in public places (airports, stadiums, public buildings, etc.): acquisition time up to few seconds, no major limitations in dimensions.
  - Covert operations (police and army anti-terrorism/criminal operations): real time (video rate: 30-100 ms), preferably portable or anyway of reduced dimensions.

THz Detection of Explosives

- **Many common explosives have characteristic features ("fingerprints") between 0.5 and 3.0 THz.**

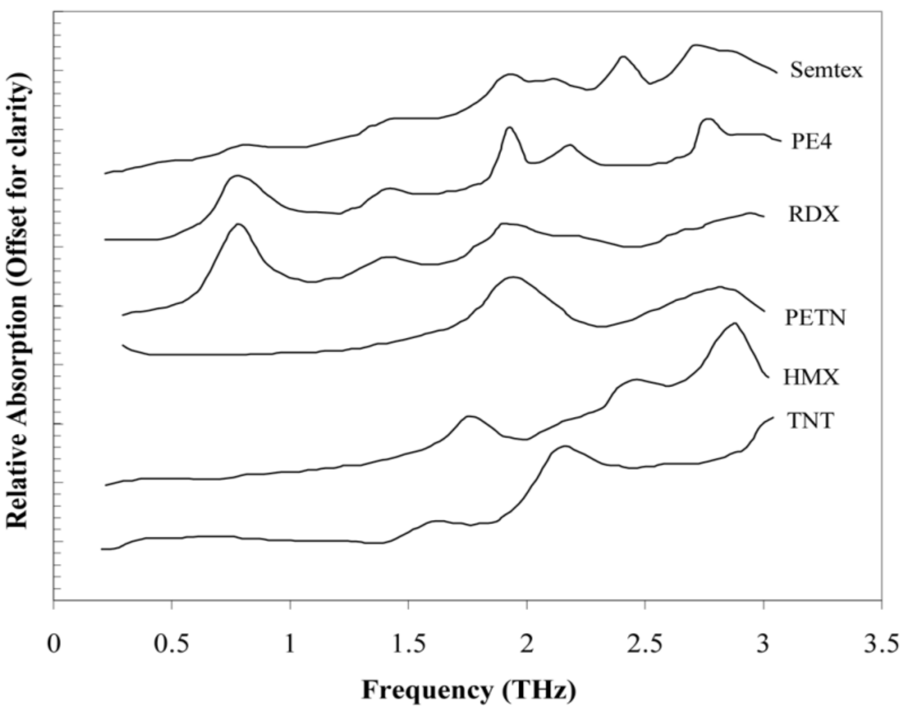
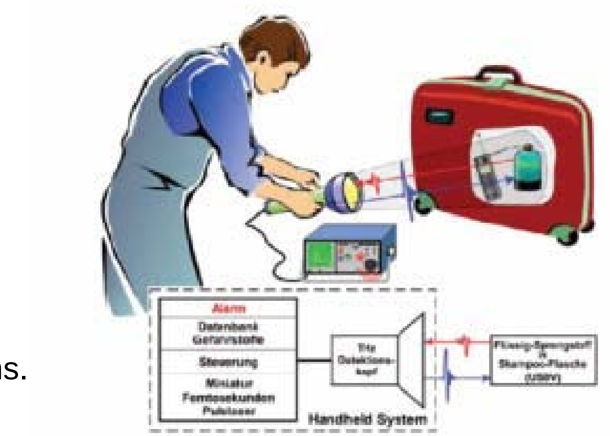
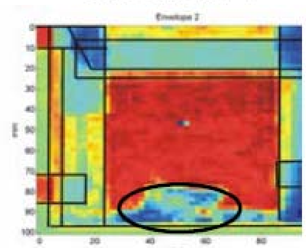


image a letter



"anthrax"?



R. Appleby, H. B. Wallace, "Standoff Detection of Weapons and Contraband in the 100 GHz to 1 THz Region", IEEE Trans. on AP, Vol. 55, No. 11, Nov. 2007

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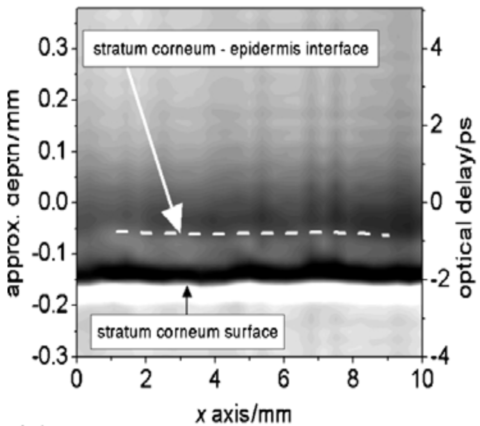
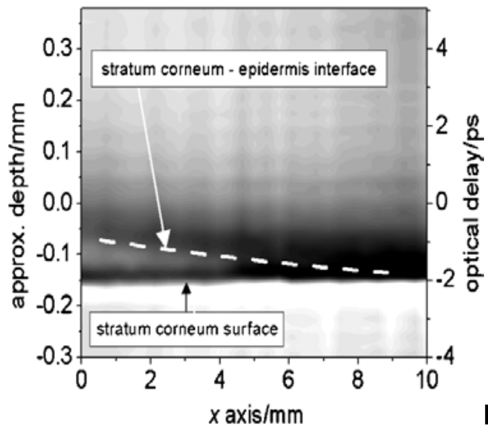
THz Resolution for the analysis of skin disorders

- Spatial resolution: ~ 200 μm
- Depth resolution in the skin: ~ 40 μm
- Penetration depth: ~ 1 mm

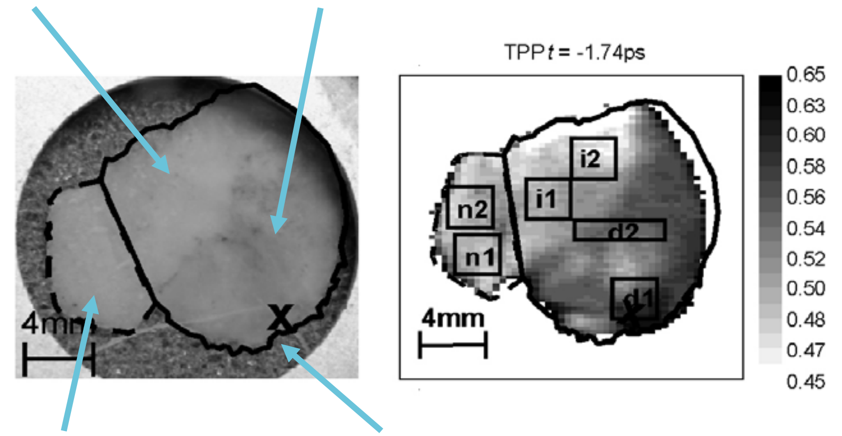


central portion of the volunteer's palm



edge of the volunteer's hand

inflammation diseased tissue



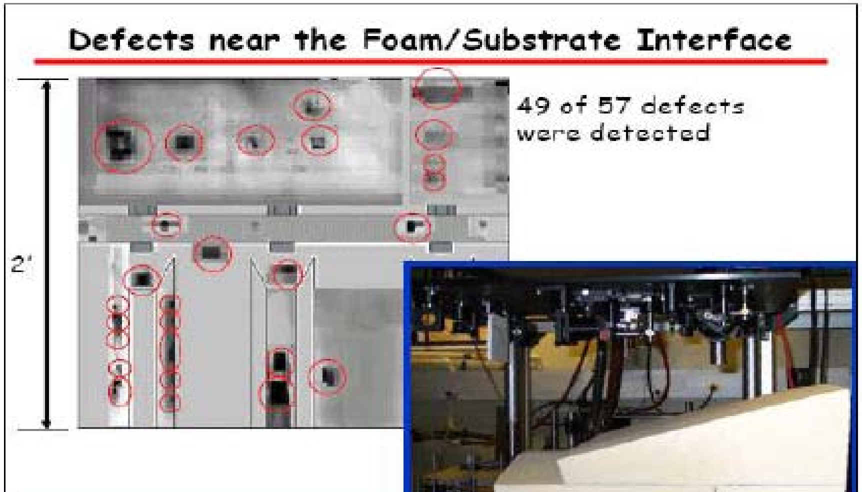
normal tissue location of the suture

visible image THz image

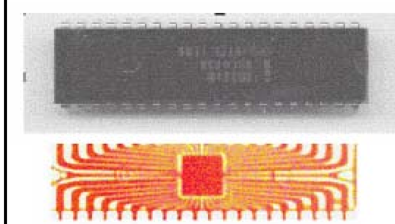
Ruth M. Woodward et al., "Terahertz pulse imaging in reflection geometry of human skin cancer and skin tissue", Physics in Medicine and Biology, 2002

- The ability to observe both the SC-epidermal junction and the hydration of the SC, as well as the identification of cancer biomarkers has shown useful applications both for cosmetic and pharmaceutical industry and also for medial imaging (e.g. skin cancer detection).

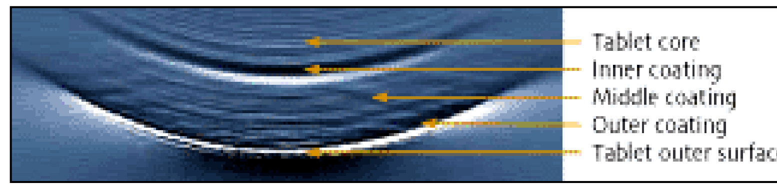
Non Destructive Evaluation (NDE)



NASA THz NDE of Shuttle cryotank



THz imaging of CMOS chip (Rice University)



(picture courtesy of TeraView)

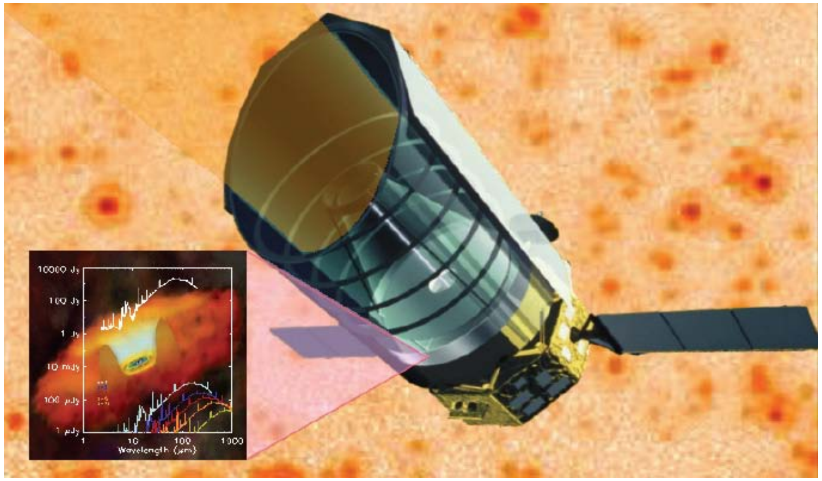
Terahertz as an NDE Tool:

- Excellent ***transmission*** through non metallic materials
    - Coatings, insulation, polymers, ceramics
- Excellent spatial resolution versus μwave/mm
- Significantly less scattering versus visible/IR
- Species-specific ***spectral absorption*** of THz energy
- Non-ionizing $\rightarrow$ not harmful to body
- Potential for compact/efficient imaging system

Space Science and Radio-astronomy

Next generation satellite **SPICA**
proposed by the Japanese Space Agency

with European instrument **SAFARI:**
(Top Priority for Space in NL)

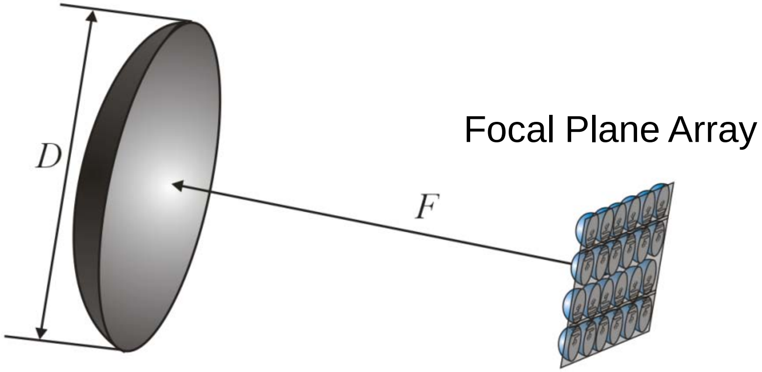


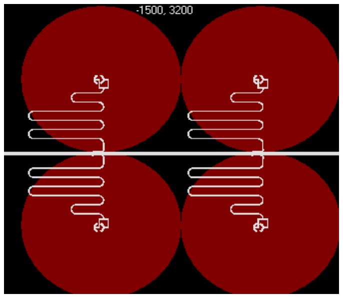
- **Number of pixels**
  (~6000)

- **Sensitivity**
  (NEP < $2{\cdot}10^{-19}$ W/√Hz)

- **Bandwidth**
  (Wavelength coverage: 30-210 μm
  (Frequency: 1.4-10 THz)

  Band A:30-57 μm
  Band B:57-106 μm
  Band C:106-210 μm)





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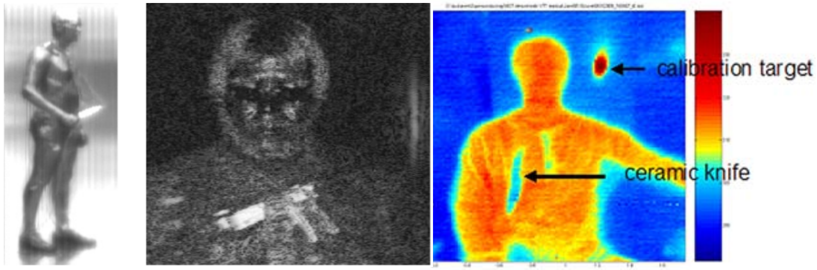
Imaging: Radiometry versus Radar

- **Radiometer**

– Measure the thermal electromagnetic emission by a certain scene under observation.

– For the image reconstruction it is important to have a high temperature resolution. Only the amplitude of the signal is used and not the phase.

– Passive:
  - No need for power generation;
  - Limitations in absence of natural illumination;
  - Problems with attenuation introduced by clothes and other packaging materials at mm/sub-mm frequencies.



– Active:
  - Power generation and EM effects;
  - Reflectivity of objects is strongly dependent on the angle of incidence of the illuminating power (specular effects and unpredictable brightness).

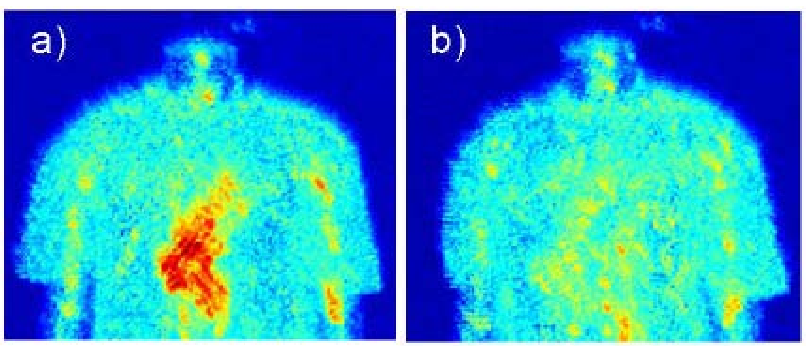
Imaging: Radiometry versus Radar

- **Radar**

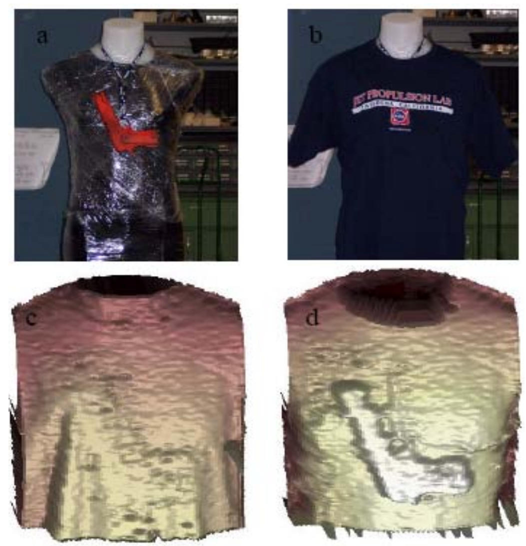
  – Both amplitude and phase information are used. This allows also to obtain range information (depth).

  – The image is reconstructed form the range data and is independent of the amount power that is reflected. This eliminates the problem of the specular brightness ambiguity.

  – Only active (Tx and Rx)



Active radiometric measurements:
a) frontal; b) rotated of 20 degrees.

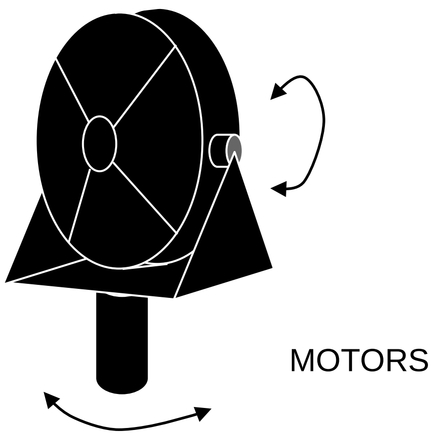


Radar measurements

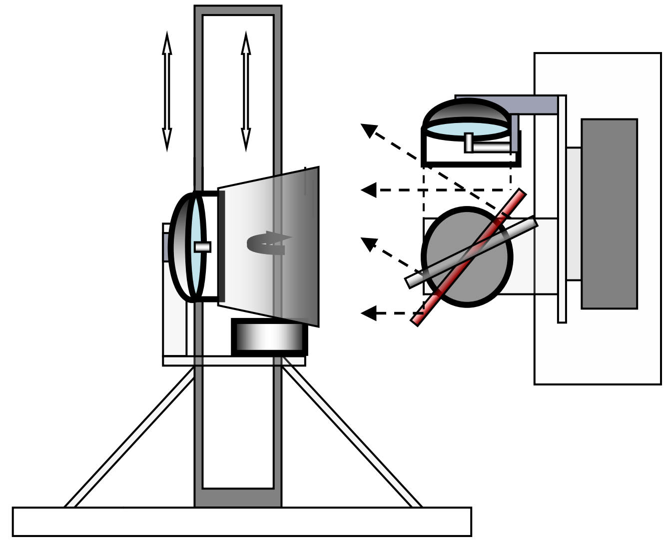
Bryllert, T.; Cooper, K.B.; Dengler, R.J.; Llombart, N.; Chattopadhyay, G.; Schlecht, E.; Gill, J.; Choonsup Lee; Skalare, A.; Mehdi, I.; Siegel, P.H.; , "A 600 GHz imaging radar for concealed objects detection," *Radar Conference, 2009 IEEE* , vol., no., pp.1-3, 4-8 May 2009

Imaging Systems

- Imaging with Mechanically Scanned Single-Element



Antenna scanned in two dimensional plane

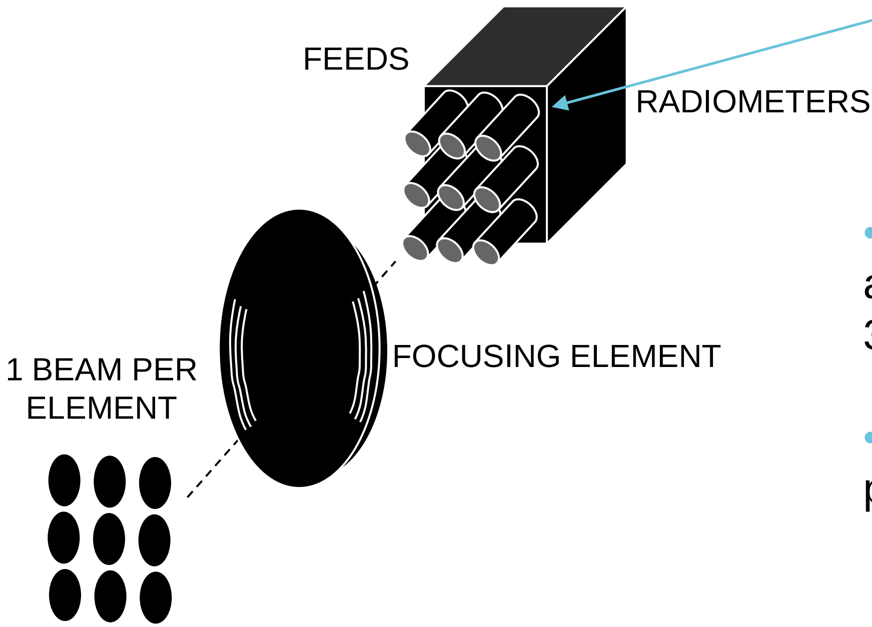


Antenna scanned vertically + rotating mirror for horizontal scanning

- Imaging area: 1x2 m
- Resolution: 1 cm^2
- Image acquisition time = $t * N_{pix} = 0.08 \times 10^{-3} * 2 \times 10^{4} = 1.6$ sec.
  - Mechanical problems
  - Too high for real-time applications

Imaging Systems

- Imaging with Focal Plane Arrays



Array of detectors located in the focal plane array of a focusing system

- Assuming an integration time of 0.08 ms, in a frame time of 30 ms, it is possible to take 375 partial images.

- In order to produce the final image of 2×10^4 pixels, each partial image should contain:

$$2 \times 10^4 / 375 \approx 54 \text{ pixels}$$

A focal plan array of 54 elements would be able to produce a real time image.

Key technical challenges

Radiation sources

Up-converters, tubes, lasers, optical down-converters

Detectors

Detectors for heterodyne or direct detection systems; room temperature and cryogenically cooled

Antennas

Integrated lens antennas, large focal plane arrays

Amplifiers

High frequency Low Noise Amplifiers (e.g. CMOS technology)

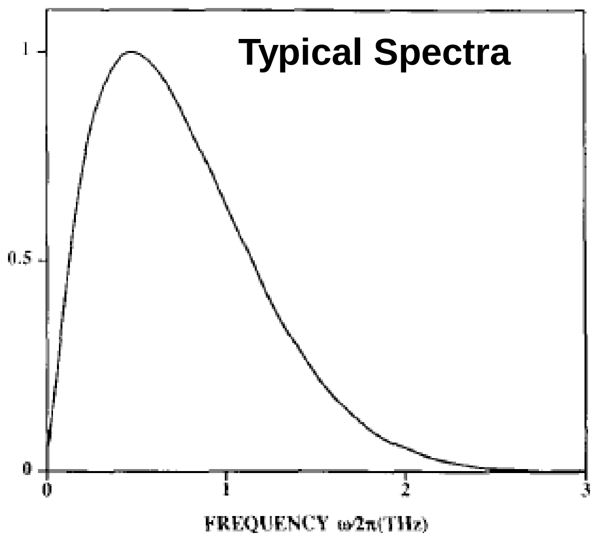
Waveguides

Antennas Used in Current Systems

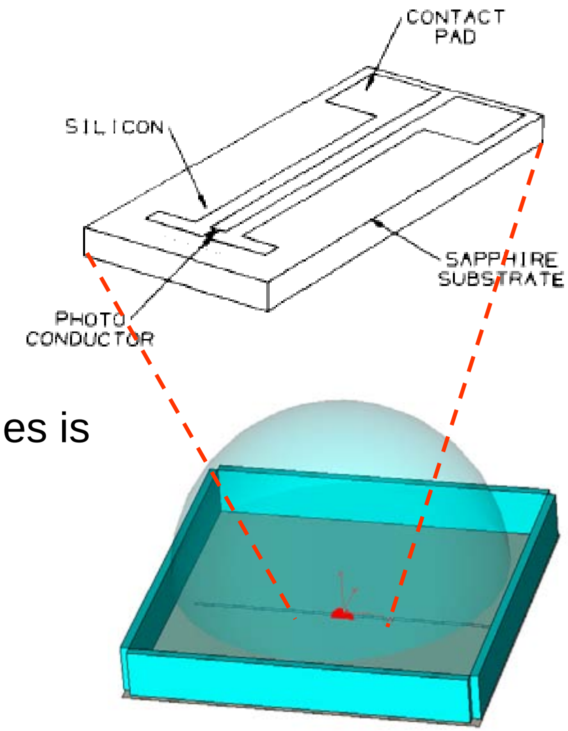
IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. 24, NO. 2, FEBRUARY 1988

Subpicosecond Photoconducting Dipole Antennas

PETER R. SMITH, DAVID H. AUSTON, MEMBER, IEEE, AND MARTIN C. NUSS



Impedance of short dipoles is quadratic with frequency

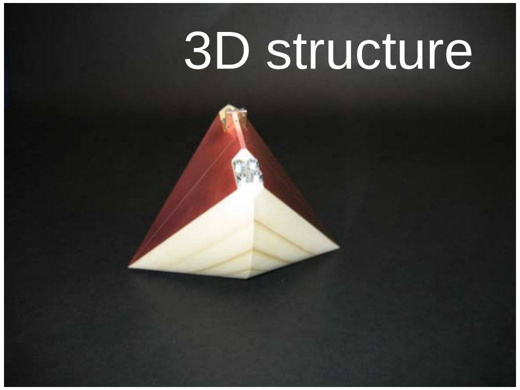


Over a decade BW efficiency lower than 10%

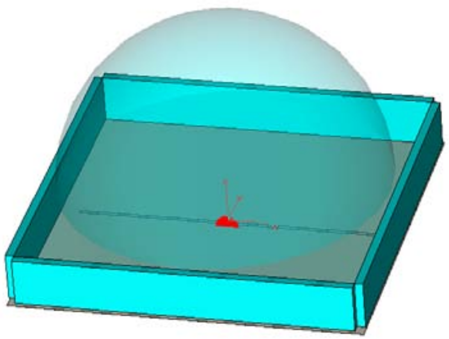
Picometrix claims 2 decades…… they use antennas in TX and RX..

Efficiency =1/10000

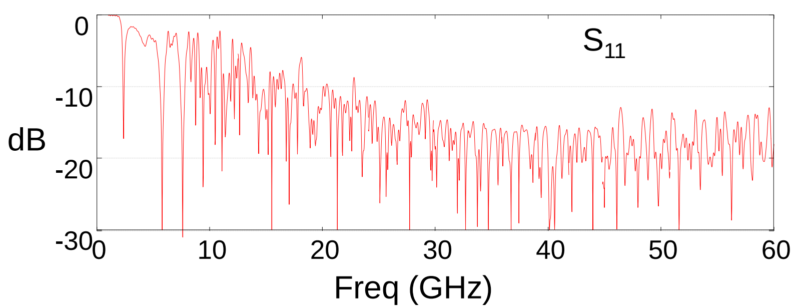
Toward Planar Integrated Technology

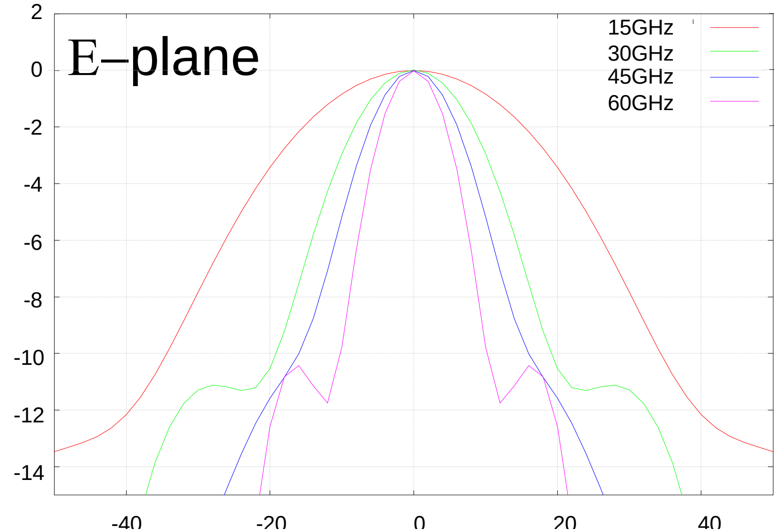


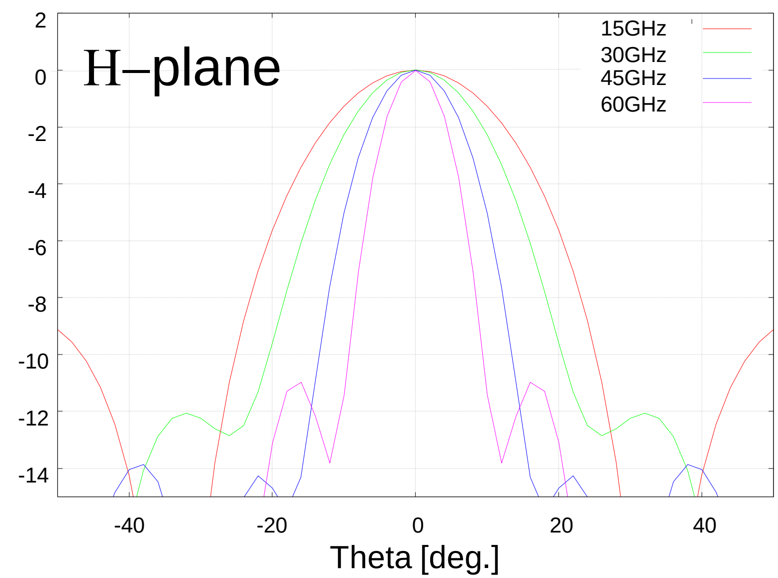
Original Ultra-wide-band leaky lens antenna (TNO-ESA patent)



New concept: lens to be glued directly on PCB or integrated circuit

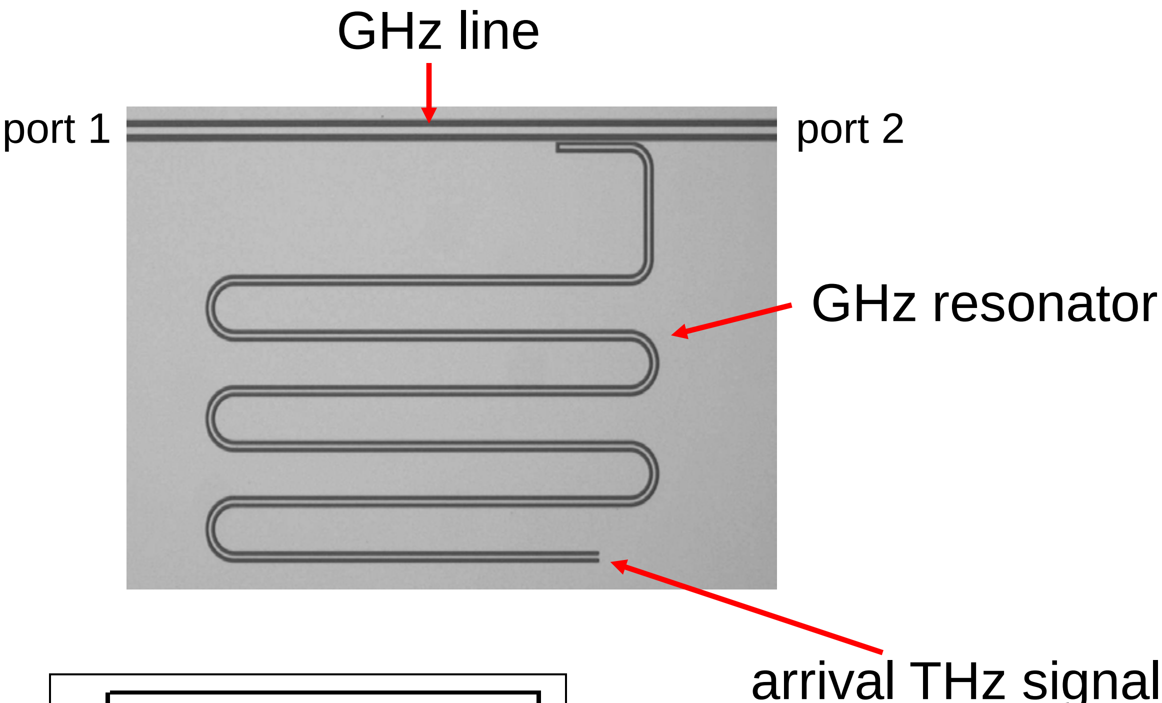




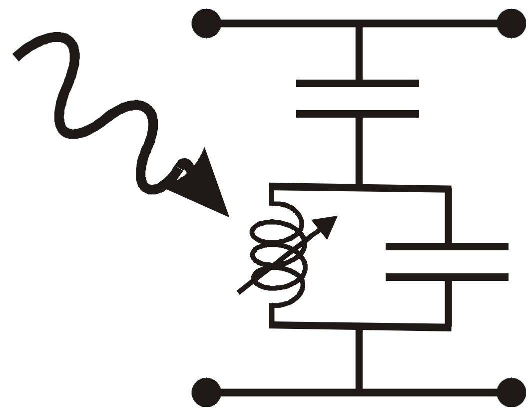


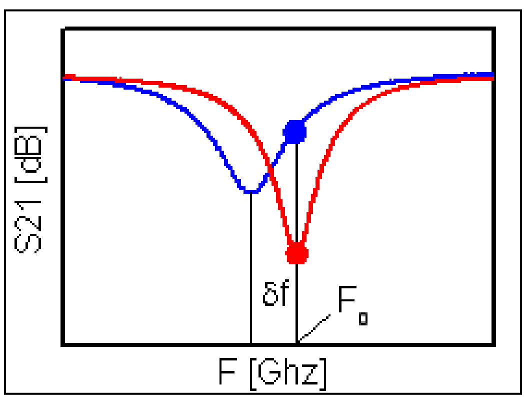
TNO - Patent Pending

SPICA Mission: KID working principle



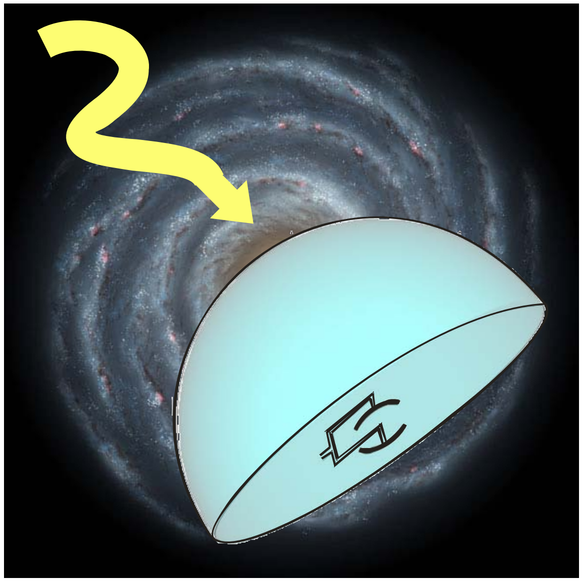
Superconducting material:
The received (THz) energy breaks Cooper pairs altering the resonator impedance

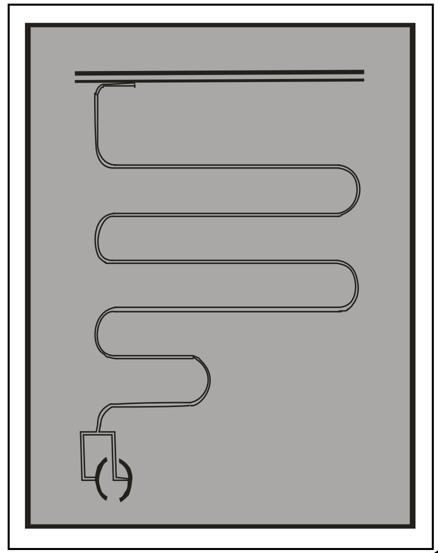


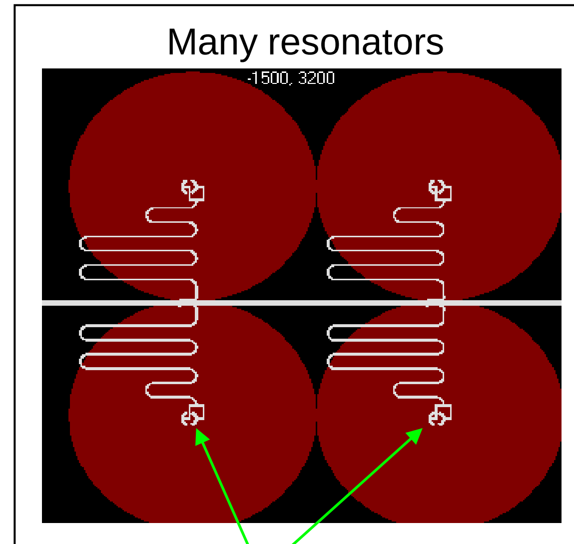


- Photon absorption changes impedance superconductor
- Read out Zs by resonant circuit
- S21 of structure has dip dependent on Zs

Focal Plane Array of Lens Antennas



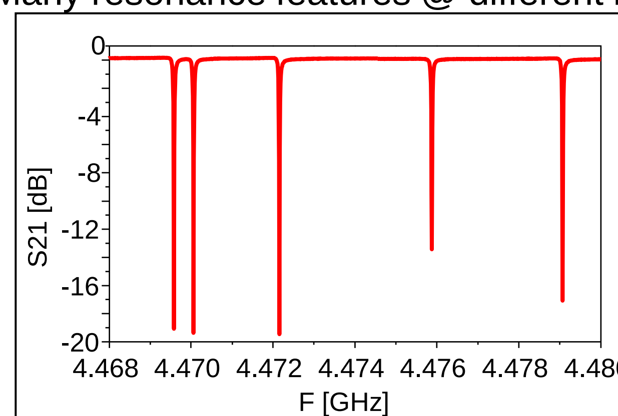




Imager elements: Antennas

Frequency multiplexing

Many resonance features @ different F



Extremely simple read out for arrays:

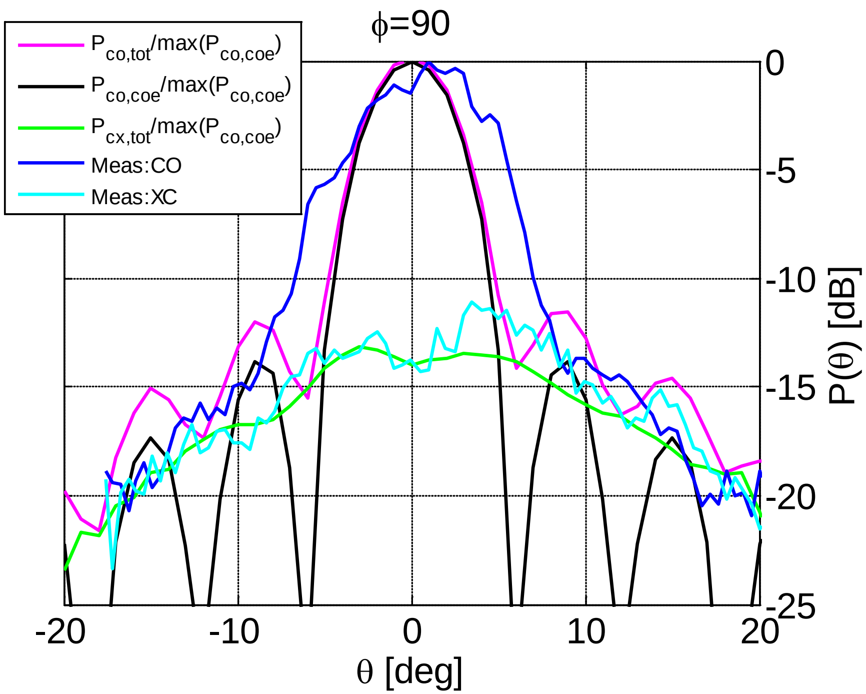
- Resonant frequency $\propto$ length of resonator
- Readout: different pixels at different modulation frequencies
- Thousands of pixels per single readout line/amplifier chain

TNO-SRON co-operation

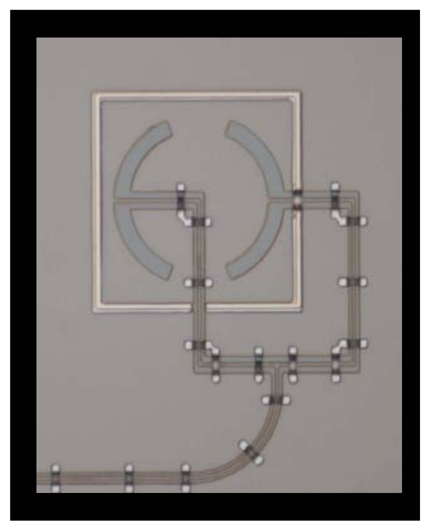
First Antenna Prototype

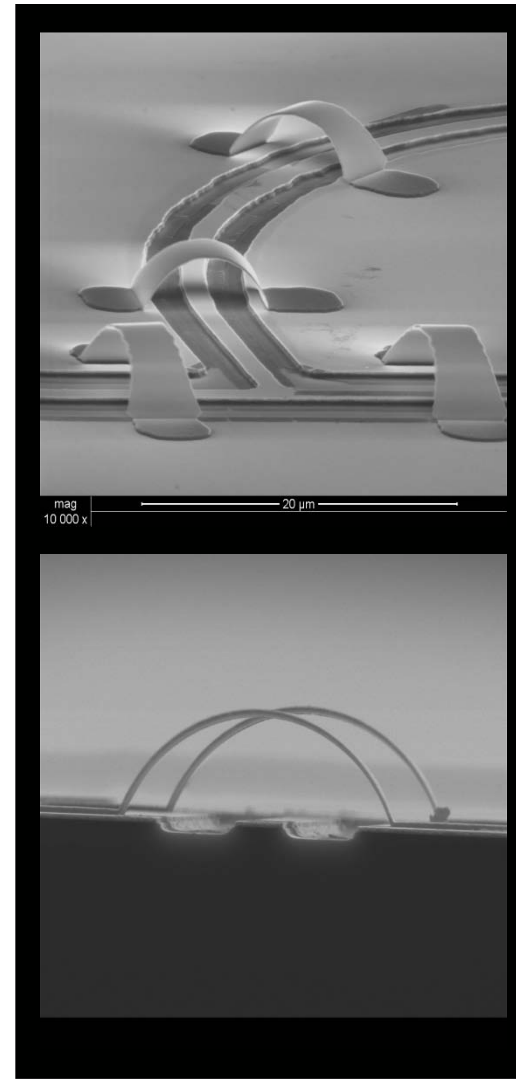
Air bridges mounted to avoid odd mode.

Measurements: good agreement!!



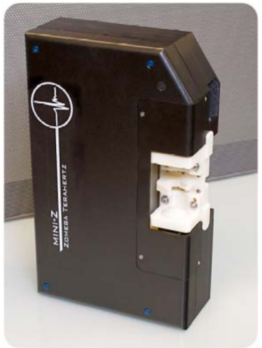
Patterns at 670 GHz



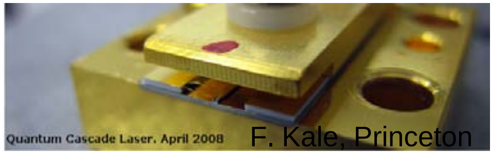


TNO-SRON co-operation

Research directions

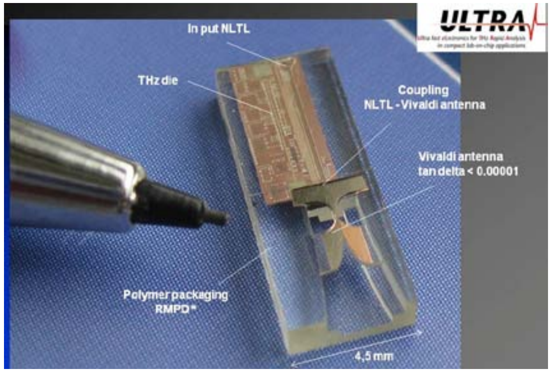


Electro-optic setups based on femtosecond lasers



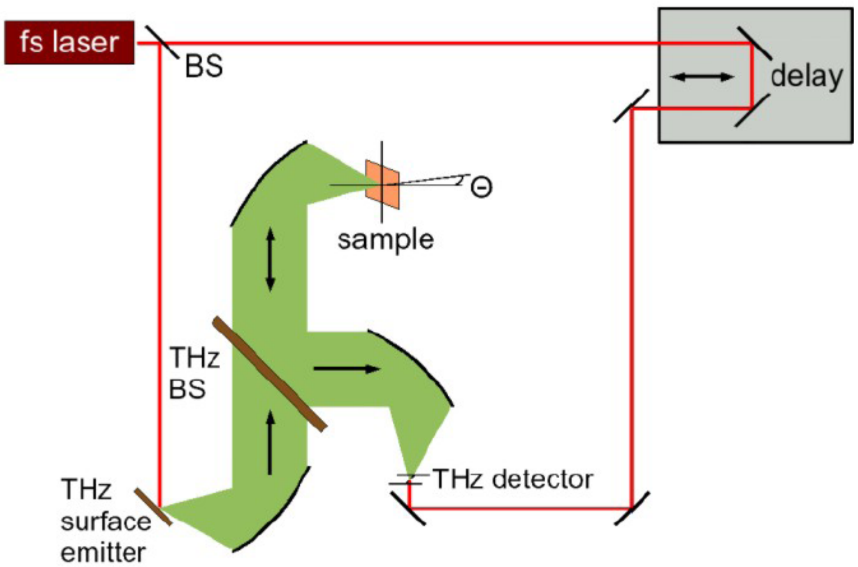
Hybrid approach:
Quantum cascade laser

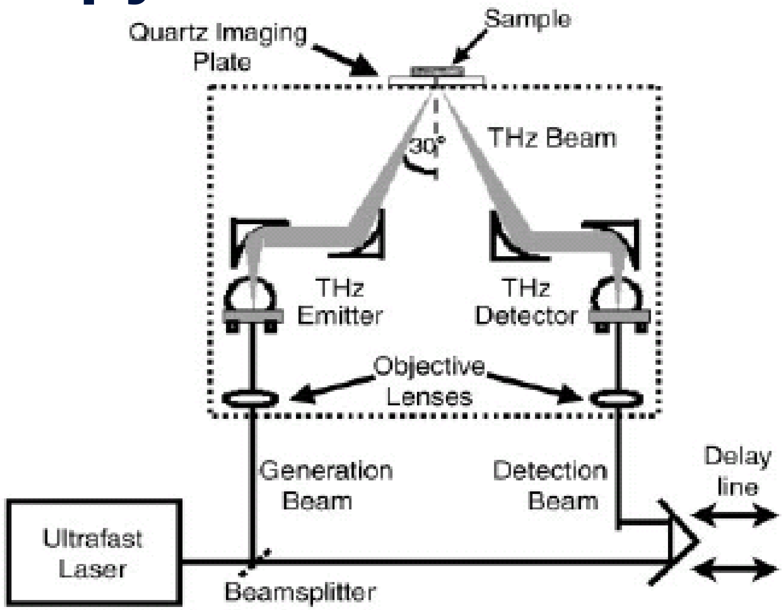
All-electronic approach:
THz-CMOS
GaAs-systems



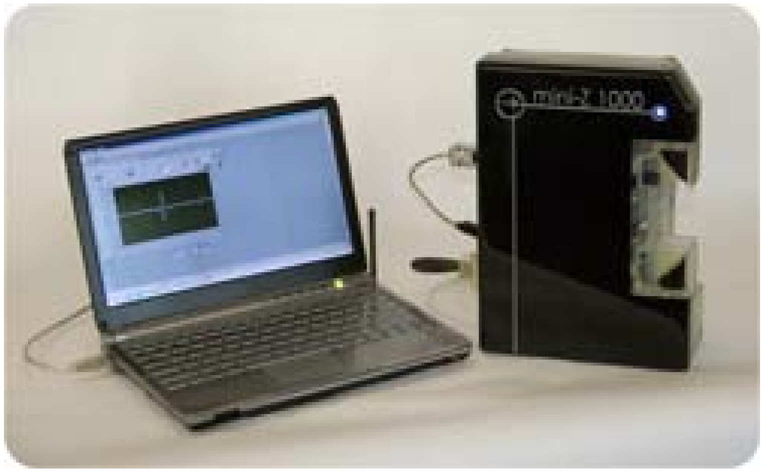
Miniaturized and integrated THz systems

Time-domain spectroscopy: lab instruments

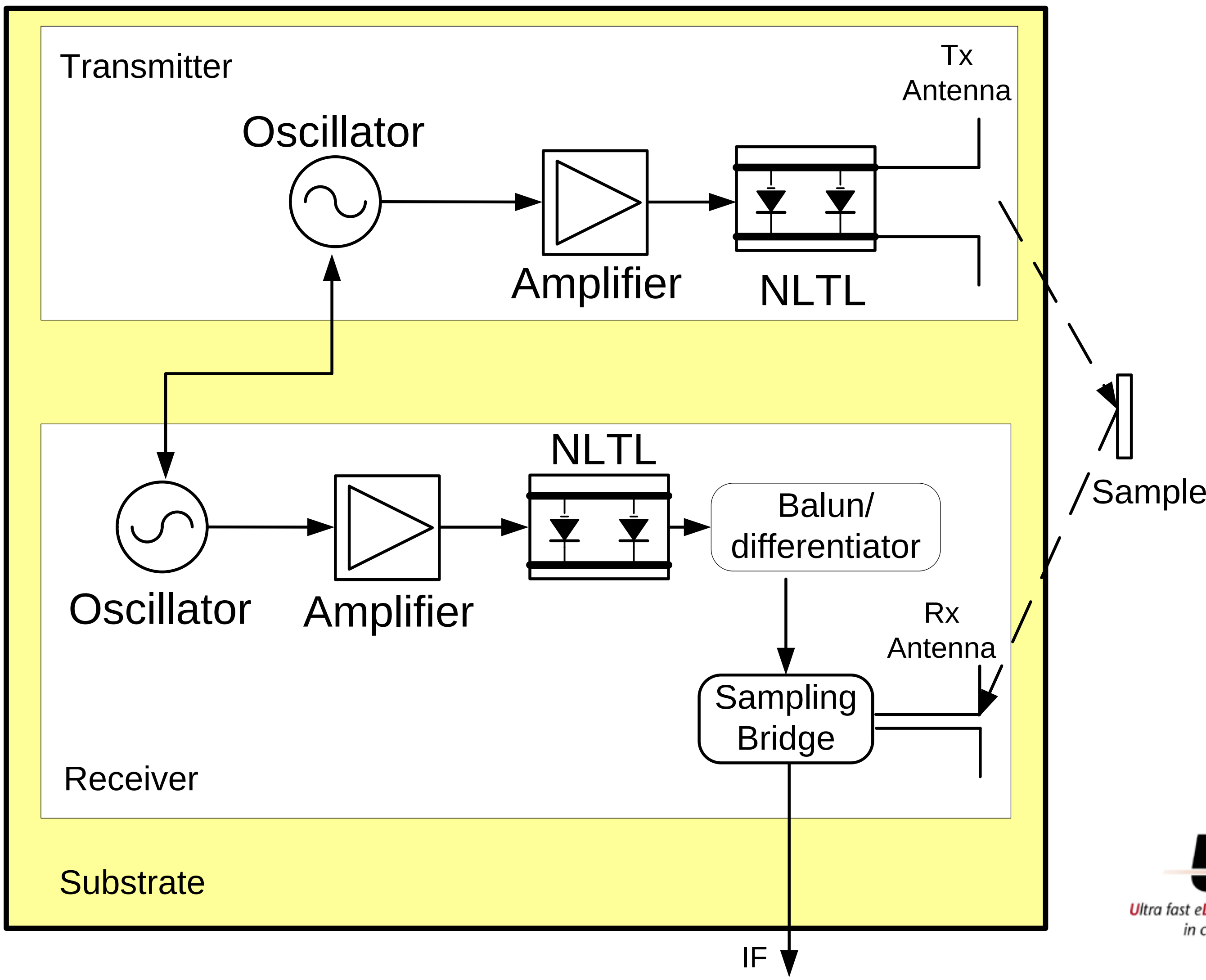




- Commercially available:
    - Teraview,
    - T-Rays,
    - Picometrix,
    - Zomega,
    - …
- Also portable
- Only lab measurements



Schematic of all electronic THz-spectrometer



NLTL: Nonlinear transmission line

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- THz applications
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- **Opportunities and limits of CMOS technology**
- Conclusions

THz CMOS circuits

U. Pfeiffer and E. Öjefors,
“A 600 GHz CMOS Focal-Plane Array for THz Imaging Applications”, ESSCIRC 2008.

- *0.25 µm CMOS with f_T=35 GHz used to receive 600 GHz signal*
- *Distributed resistive self mixing concept used*

D. Huang et al.,
“THz CMOS Frequency Generator Using Linear Superposition Technique”,
IEEE J. Solid-State Circuits, vol. 43, No. 12, Dec. 2008

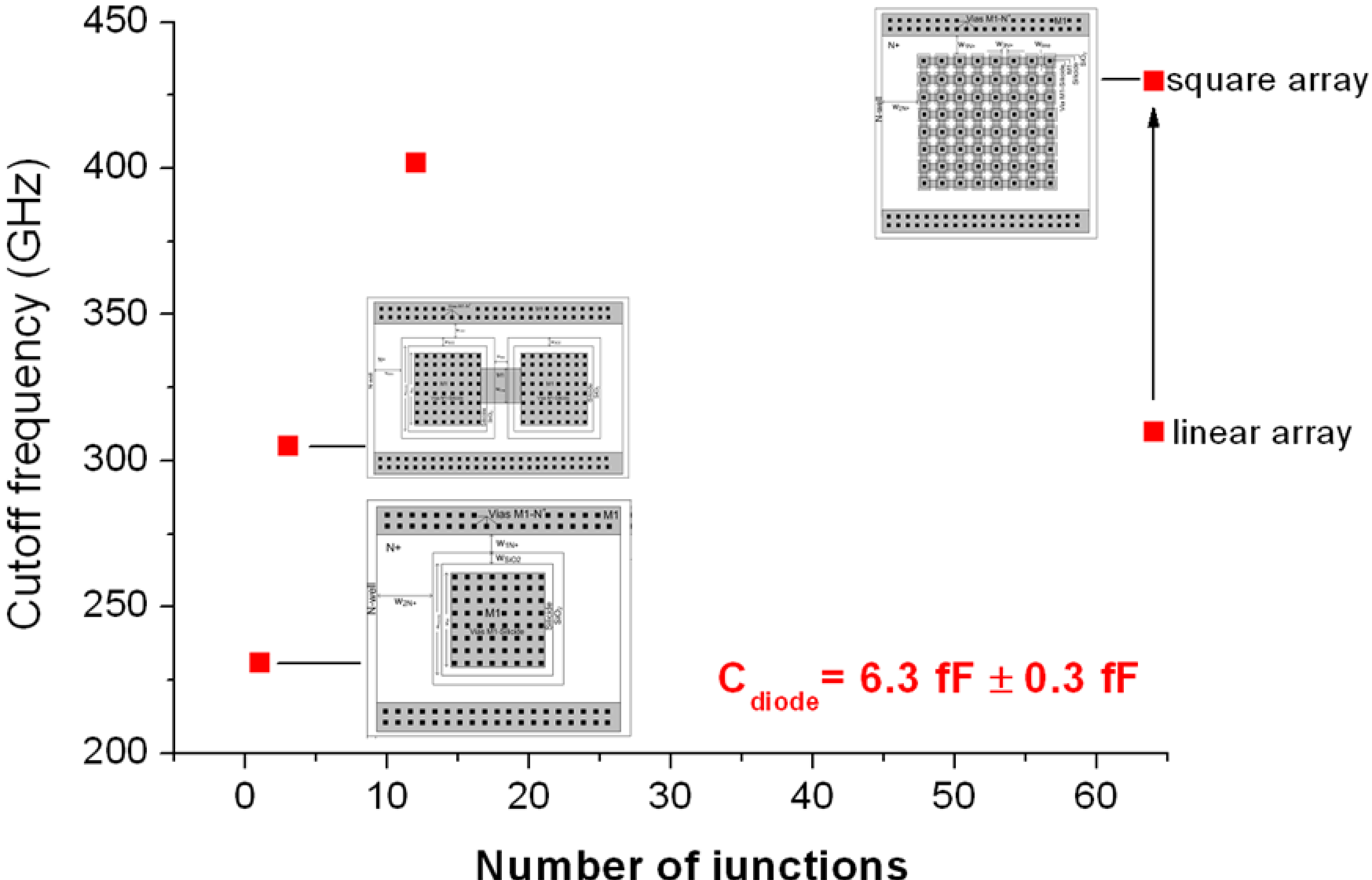
- *90 nm CMOS with f_{max}<160 GHz used to generate -46 dBm at 324 GHz*
- *Linear superposition technique used*

Schottky diodes in CMOS

- Schottky diodes are non-standard in CMOS technology
- They are key components for THz-systems

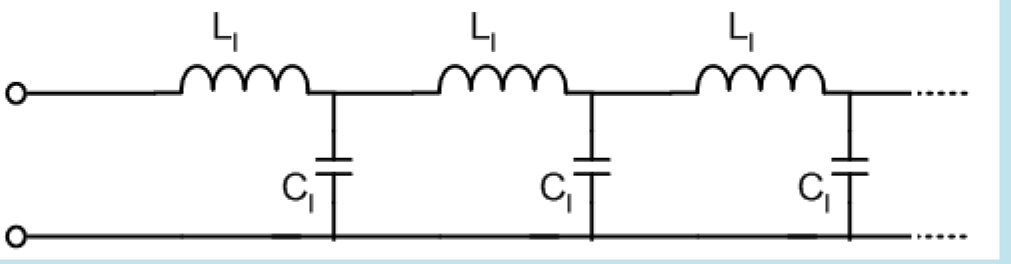
M. Matters et al., RF Characterization of Schottky Diodes in 65-nm CMOS
IEEE TRANSACTIONS ON ELECTRON DEVICES
Volume: 57 Issue: 5 Pages: 1063-1068 Published: 2010

Cut-off frequency of diodes in 65 nm CMOS



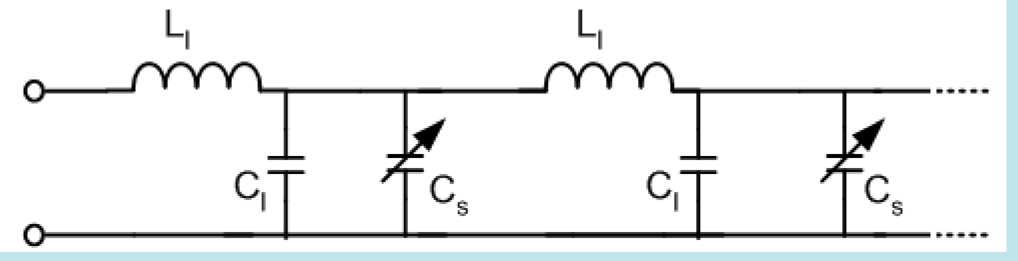
Broadband signal generation: NLTL

Equivalent circuit of a **linear** transmission line

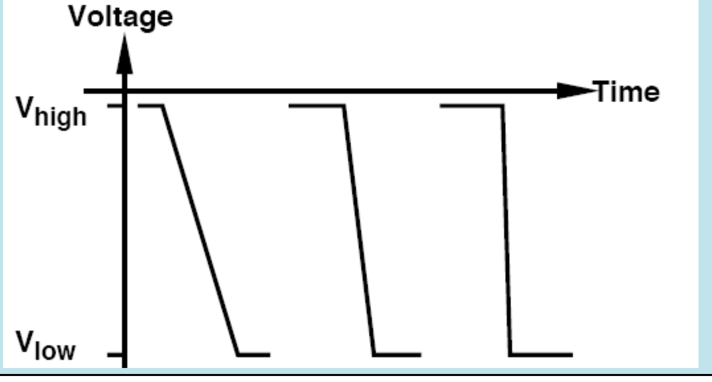


$$v = \sqrt{\frac{1}{L_l C_l}}$$

Equivalent circuit of a **nonlinear** transmission line



$$v = \sqrt{\frac{1}{L_l\left(C_l + C_S(V)\right)}}$$



Shock-wave generation

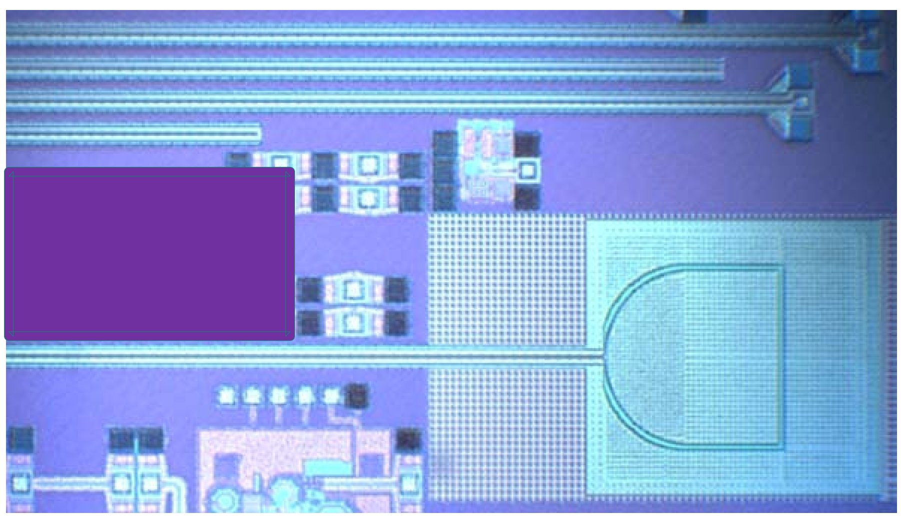
⇔

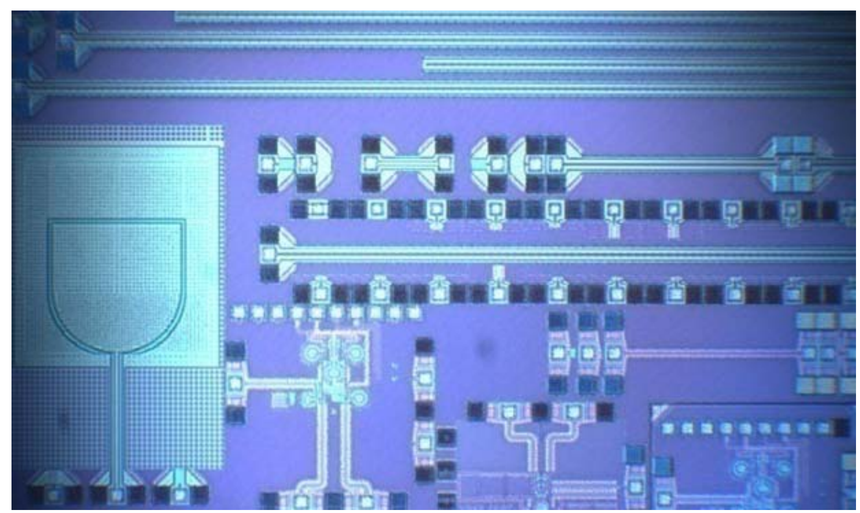
Broadband signal

CMOS NLTL fabrication

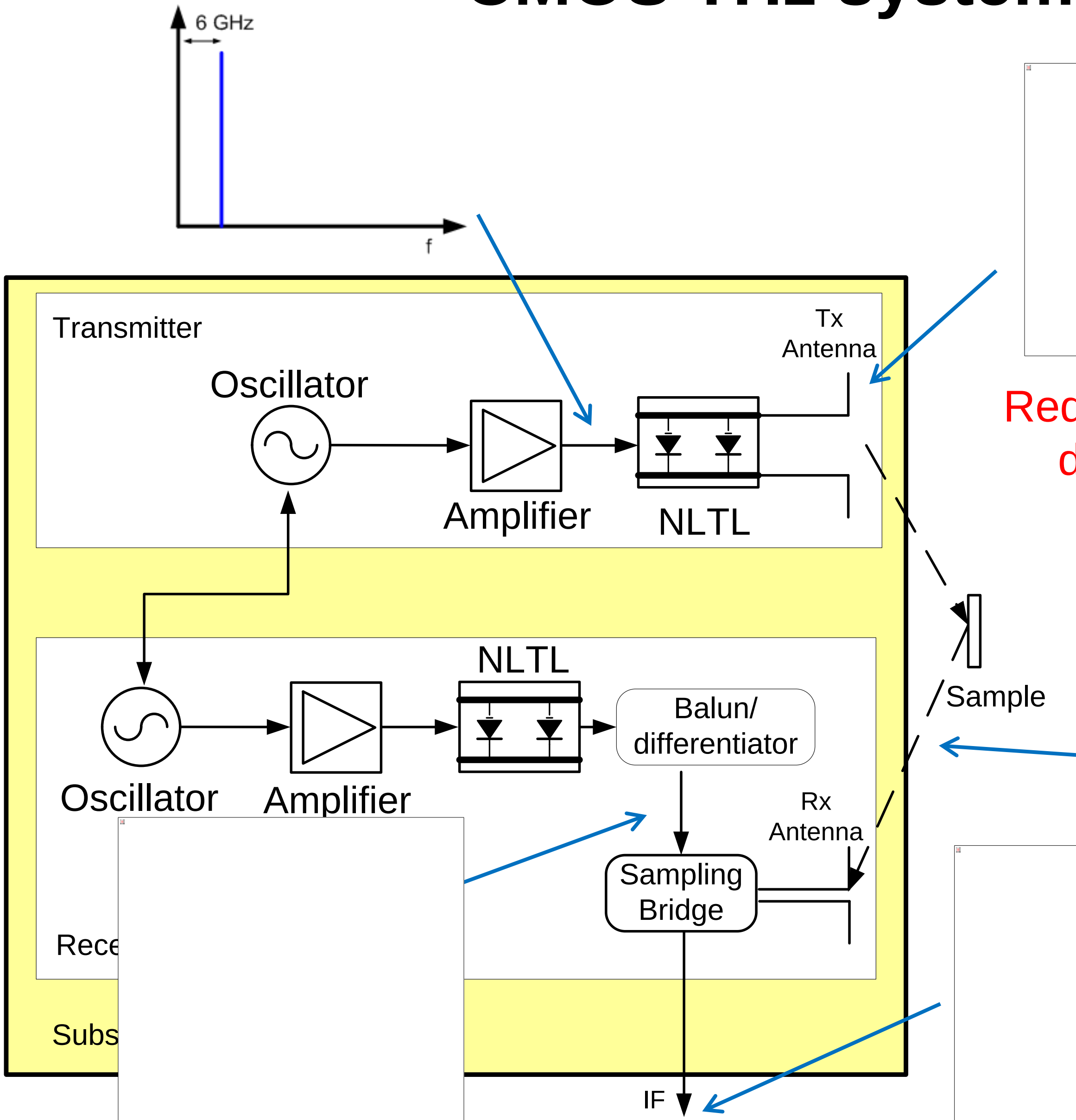
Commercial 65-nm CMOS technology

5-7 mm

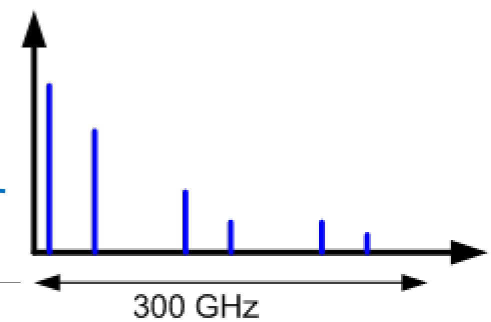




CMOS THz system



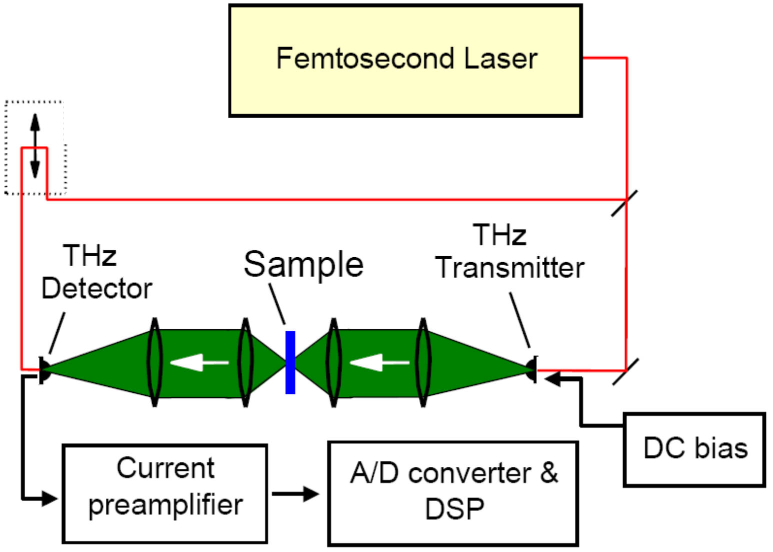
Required spectral resolution depends on application



Sampling of broadband signals

Optics:

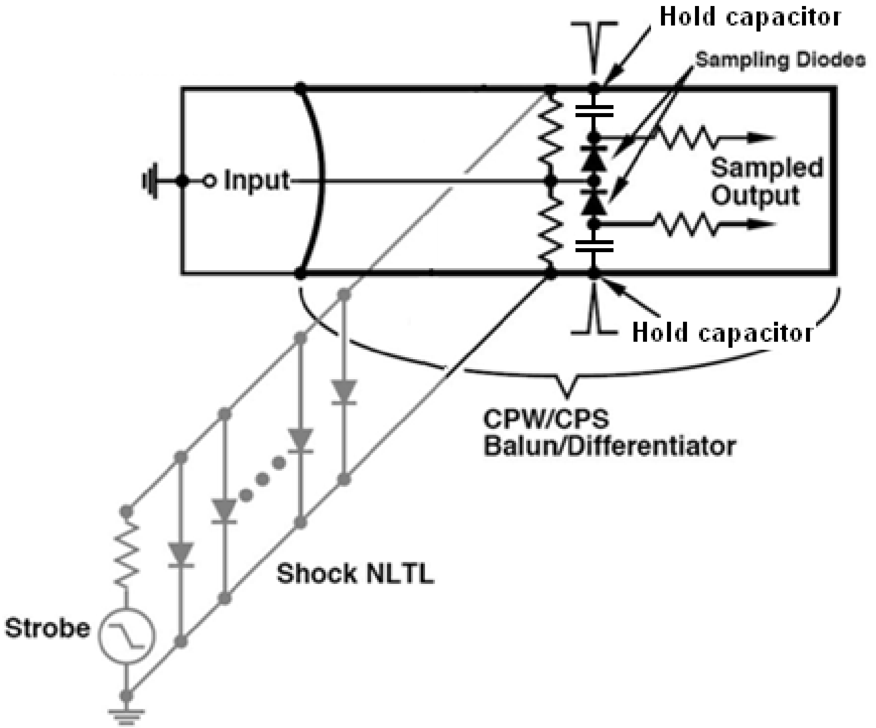
THz-time-domain spectroscopy



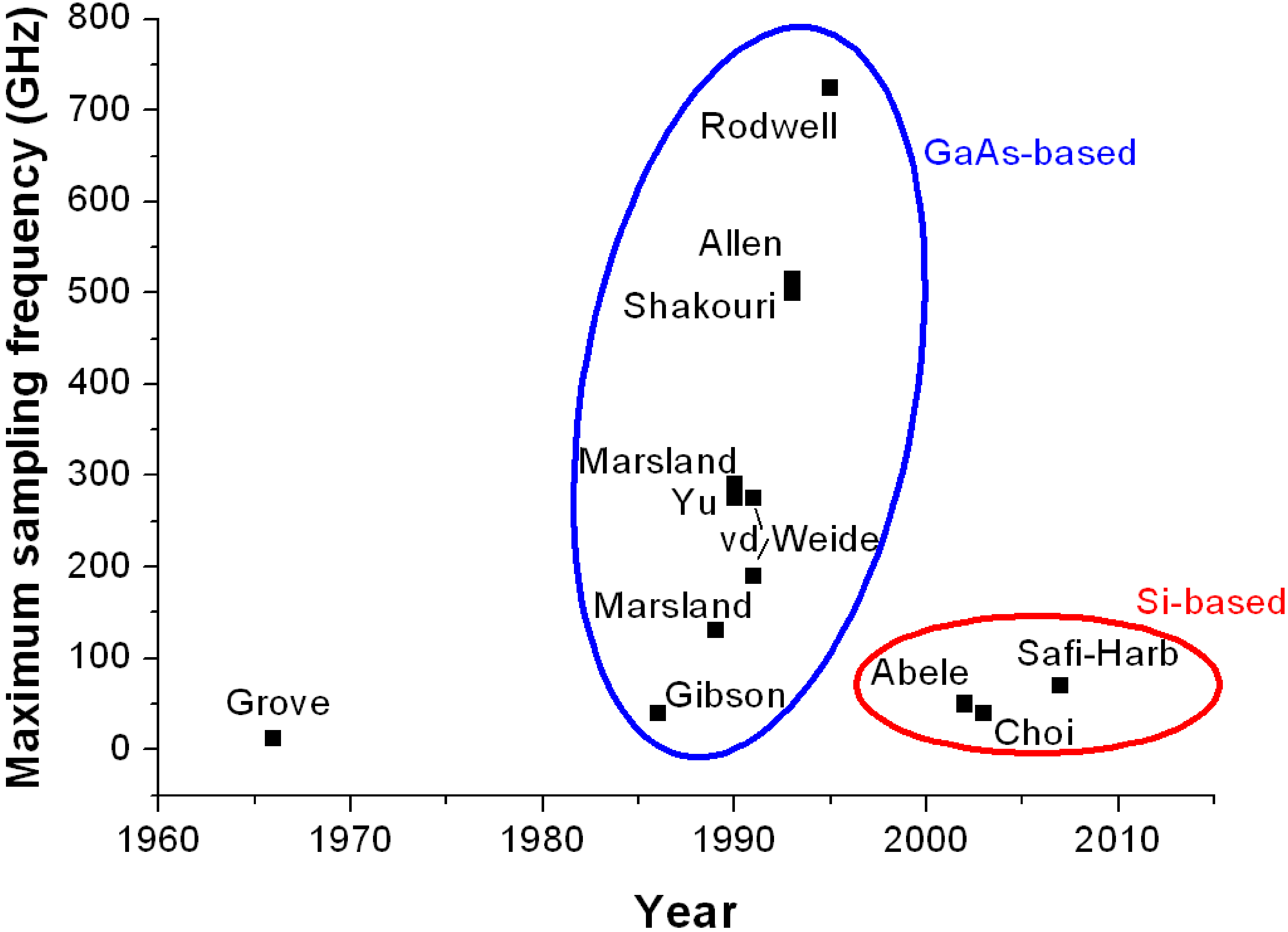
D. M. Mittleman
cm.physics.tamu.edu/seminars/D_Mittleman_02_02_05.pdf

Electronics:

High speed sample and hold circuits
Sub-harmonic mixer



Overview high speed electronic samplers



Content

- Background
- THz applications
- THz systems and technology
- Opportunities and limits of CMOS technology
- Conclusions

SWOT analysis

Strengths

- THz radiation go through packages
- THz radiation is sensitive to molecules not detectable in the IR range (large molecules)
- Sensitivity can be increased using plasmonics
- Highly integrated, miniature devices
- Handheld devices, easy to use
- Sensitivity to several compounds with the same instrument
- High sensitivity to water content
- THz is the most reasonable technique to achieve >10GB/s communication links

Weaknesses

- THz is yet an unexplored region. Knowledge of matter property in this region is yet very little.
- Generated power is very low
- Sensitivity yet to be checked
- Spectroscopy possible, spectrometry difficult
- Only some compounds are sensitive to THz

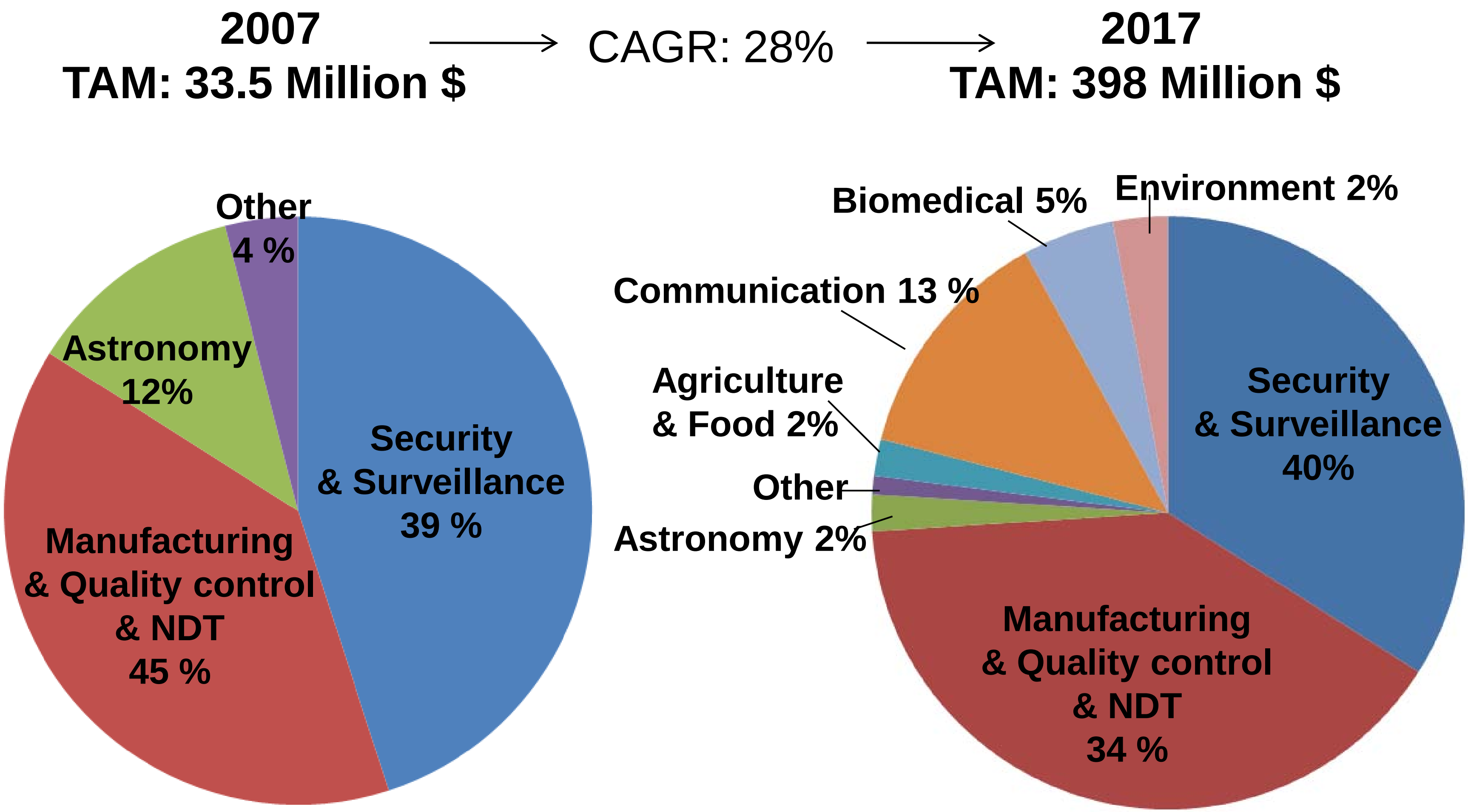
Opportunities

- Several distinct applications areas could be addressed
- Research on THz is currently receiving more and more worldwide attention. Trends towards THz seems clear in the electronic domain. Electronic approach is supported by scientific community.
- THz is a new technique: huge possibilities in term of generating patents and licensing.

Threats

- Alternative solutions actively developed using many techniques (miniature MS, E-noses, nanowires)
- Healthcare market very conservative

THz market



Source: The THz technologies, Fuji-Kezai USA, 2007

Conclusions and Directions

- THz radiation is a promising new scientific and business opportunity
- CMOS THz microelectronics is a very active research topic
- Integrated miniaturized electronic for THz imaging and spectroscopy
  is currently developed to enable new types of applications
  for the consumer and professional market
- Philips leads the FP7 ULTRA project and will look for application opportunities
- TNO has an ongoing co-operation with SRON in the development of THz technology for future space missions
- CWTe has chosen for THz as research direction
- Strong knowledge base in the Netherlands in various research groups
- Need for coordination to create a competitive position with sufficient critical mass

PHILIPS

TNO

TU/e