Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: Circuits and Systems for Mobile Terahertz Imaging and Sensing Applications
Date Submitted: 19 January 2021

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Re: n/a

Abstract: [The talk will address the vision for future mobile THz imaging and sensing applications as part of the MARIE Transregio (TRR) 196, a Collaborative Research Center (CRC) funded by the German Research Foundation (DFG). The talk summarizes the MARIE challenges, research questions and outlook for 2024. It includes examples for compact systems on a chip for future mobile applications, such as a wideband THz spectroscopy system a chip, compact THz cameras and sources in silicon technologies, and mobile bio-medical applications.]

Purpose: Information of IEEE 802.15 SC THz

Circuits and Systems for Mobile Terahertz Imaging and Sensing Applications

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marie SFB/TRR 196

BERGISCHE UNIVERSITÄT WUPPERTAL

Institute for High-Frequency & Communication Technology
IHCT

UNIVERSITÄT DUISBURG ESSEN
Open-Minded

RUHR UNIVERSITÄT BOCHUM RUB

BERGISCHE UNIVERSITÄT WUPPERTAL

TECHNISCHE UNIVERSITÄT DARMSTADT

TECHNISCHE UNIVERSITÄT DRESDEN

Fraunhofer IMS

Fraunhofer FHR

Collaborative Research Center (CRC) / Transregio (TRR) 196

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Mobile Material Characterization and Localization by Electromagnetic Sensing

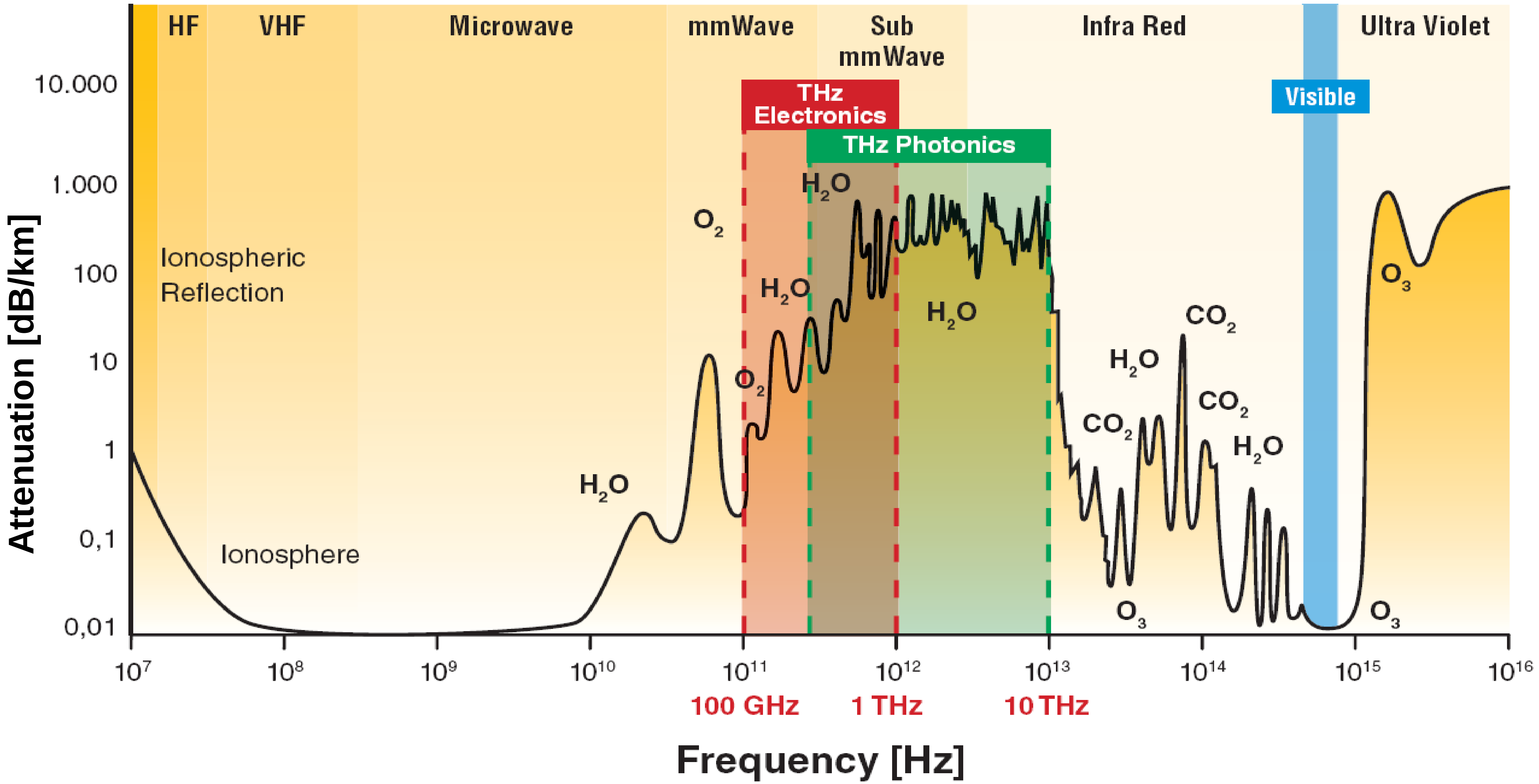
www.trrmarie.de

DFG Deutsche Forschungsgemeinschaft

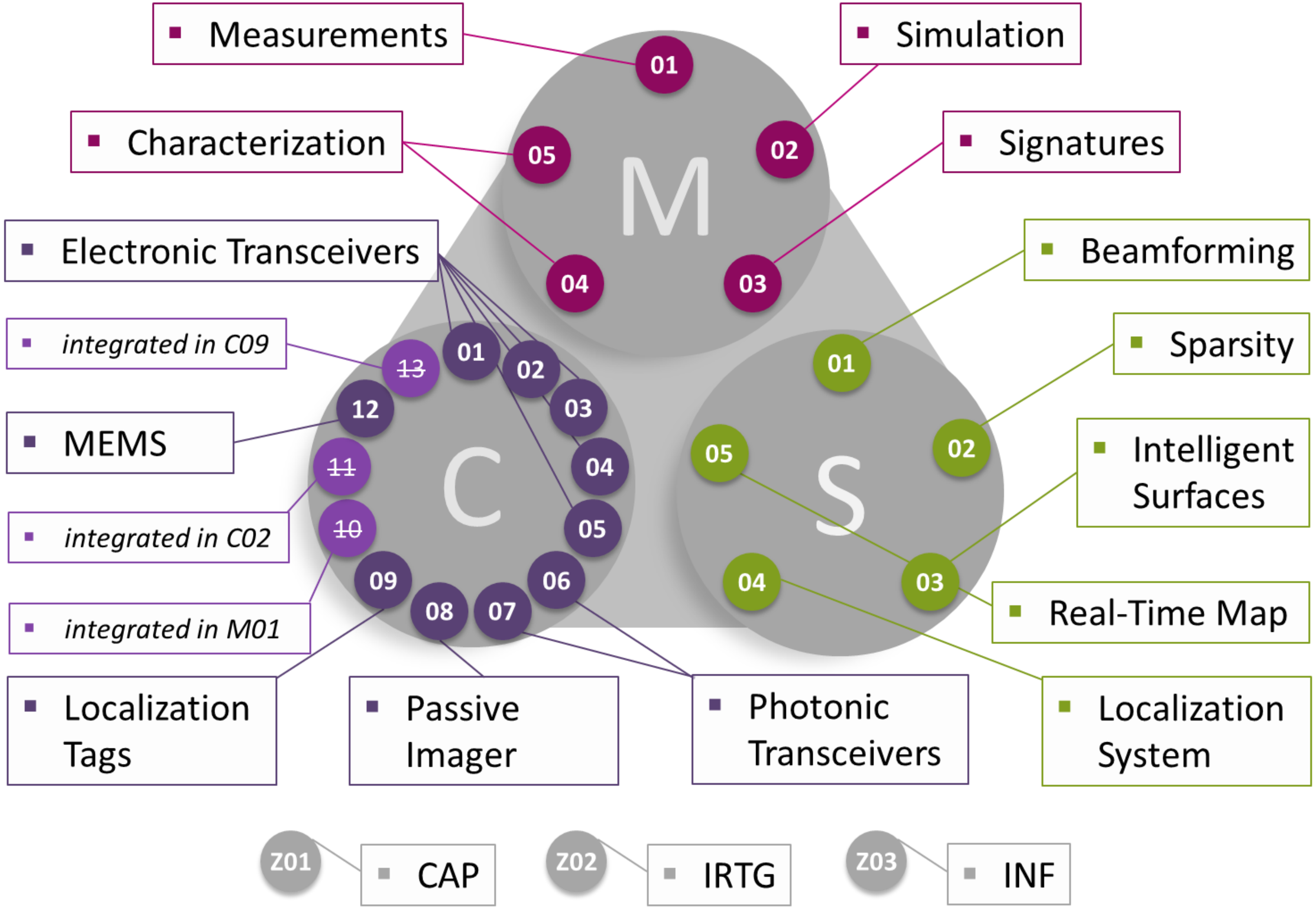
Outline

- MARIE: Collaborative Research Center (CRC) / Transregio (TRR) 196
  - Vision for future mobile THz imaging and sensing applications
  - Marie challanges
  - Research questions
  - Outlook for 2024
- Mobile Circuits and Systems Examples
  1. Wideband THz spectroscopy system a chip
  2. Compact THz cameras and sources in silicon technologies
  3. Mobile bio-medical applications
- Summary

MARIE Project Overview



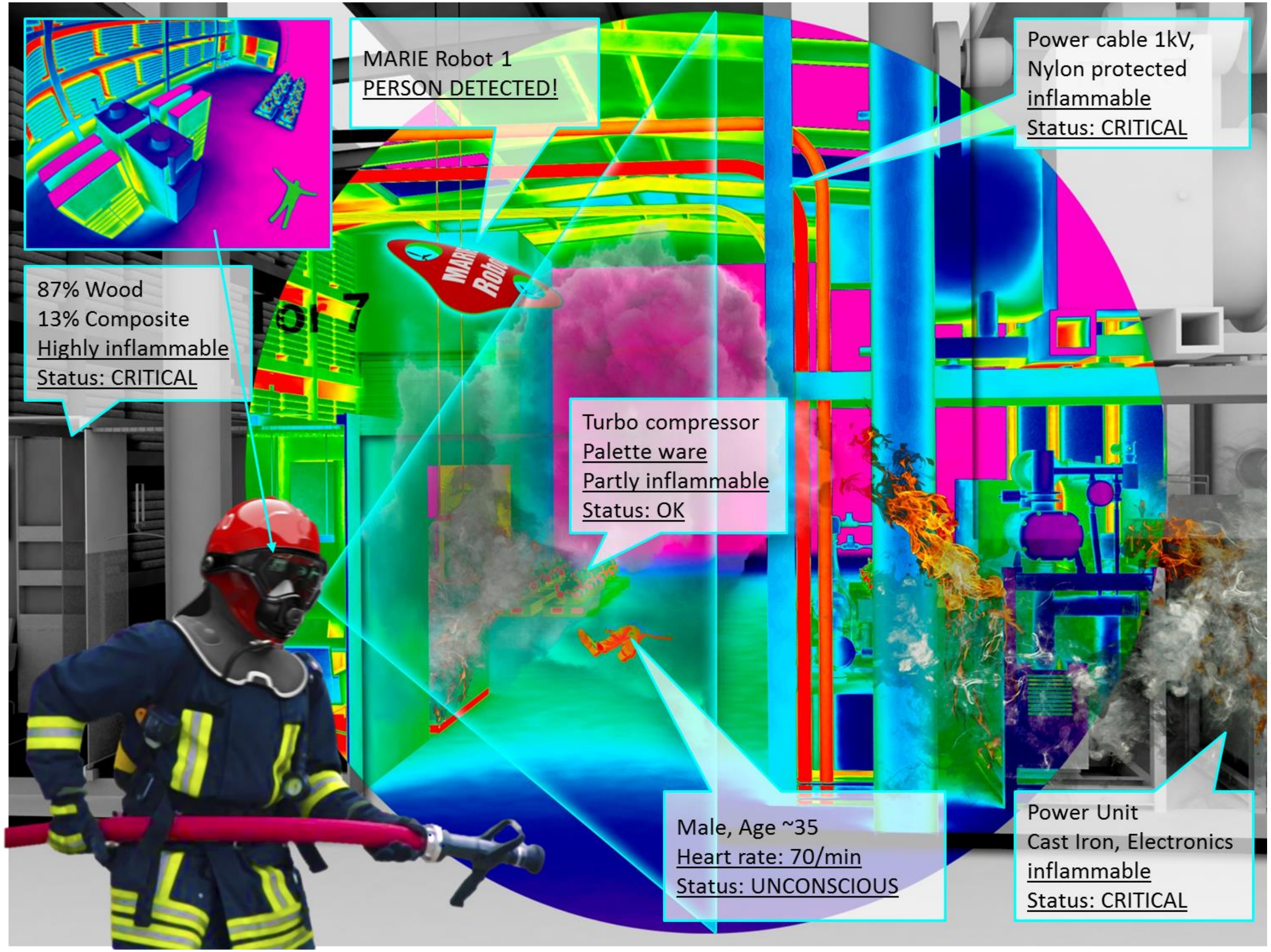
MARIE Project Overview



Facts Sheet:

- 2017 – 2024 (*2028)*
- 20 Projects, 26 PIs
- 83 Journal Papers
- 226 Conference Papers
- 1st Period: 12.8 M€
- 2nd Period: 13.7 M€
- Funded by the German Research Foundation (DFG)

MARIE Vision



What comes next for “Mobile Sensors” ?

1) Get Mobile!

2) In-room challenges

Challenge 2 … **Mobile Transceivers**
- microsystems (light-weight)
- fully-integrated (all the system needs)
- efficient (battery-operated)

Challenge 3 … **Mobile** Material Characterization
- sensitivity
- operation frequency
- bandwidth

Challenge 4 … **Sub-mm** Accurate Localization
- Precision
- Scanning
- use natural environment, sensor fusion

"Static Labs: Chips from Technologies"

Initial Questions

01 Can we **synthesize**, clean, stable, and highly tunable (linear) **reference signals** for THz?

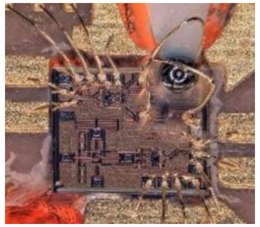
02 Can we **generate** THz on chip and lock it to a reference signal?

05 Can we **efficiently radiate** THz signals?

09 Can we realize **advanced THz passives** for localization?

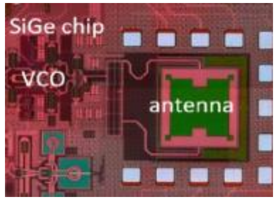
03 Can we **localize objects** in 3-D with a compact fully integrated MIMO radar?

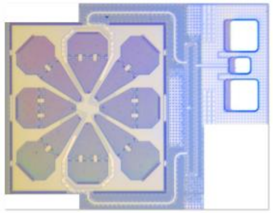
Static Lab Highlights



YIG-on-chip 20-48 GHz
-70dBc/Hz@1kHz

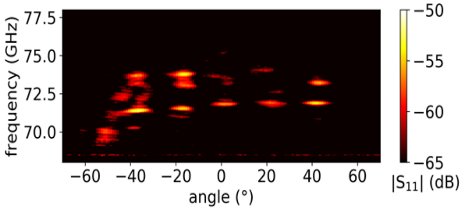
Injection locked osc.
InP **0.56THz RTDs**
InP **0.49THz HBT**

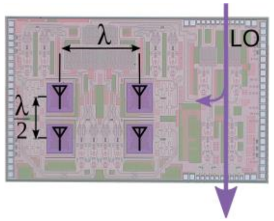




Design **recipes** &
physical **insights**.

Photonic
crystal
Luneburg lens





240GHz **MIMO radar**

"Static Labs: Chips from Technologies"

Initial Questions

07 Can we realize **photonic integrated circuits** for **1-D imaging**?

06 Can we invent novel **photonic THz spectroscopy systems** without mechanical delay lines?

04 Can narrow-band electronics measure broad band **spectral fingerprints** of materials?

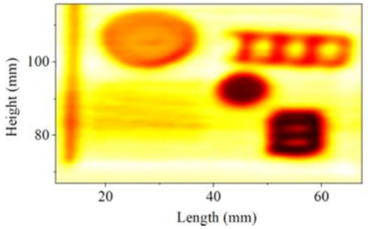
12 Can we **steer a THz beam** passively?

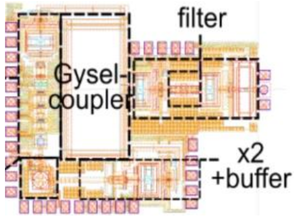
08 Is there a chance to **see the natural THz radiation** with a silicon THz camera and read a spectral fingerprint?

Static Lab Highlights

Heterointegrated antenna arrays for beam steering

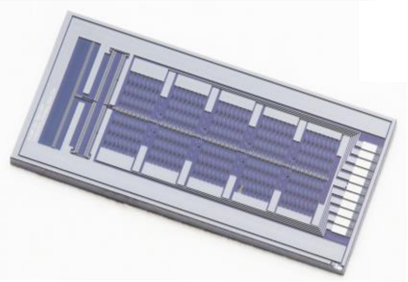
Frequency-Domain THz system

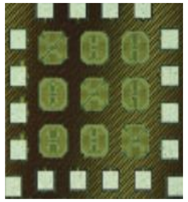




Gapless spectral coverage over **a decade up to 1.5THz**

Digital 5-bit reflectarray reflector





NEP: **1.9pW/√Hz**

Static Lab "Models from Measurement"

Initial Questions

01 How to exploit the **THz range** by **propagation measurements** and **modeling**?

02 How to cover the **different scales** in **simulating** THz propagation?

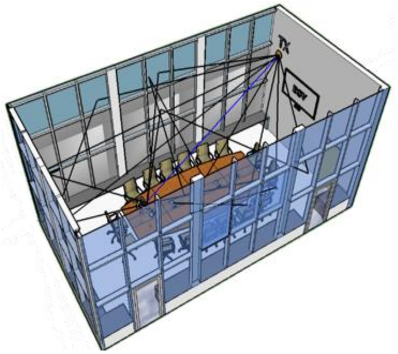
03 How to set up an efficient multiscale EM model for **complex surface systems**?

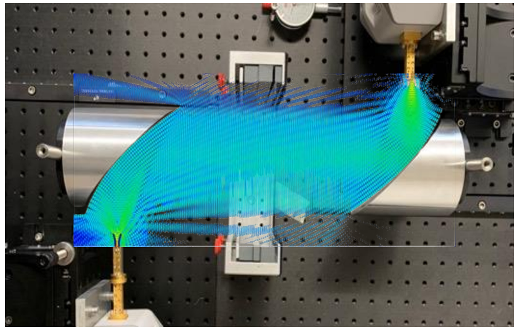
04 How obtain spatial information on the EM **material properties by MIMO radar**?

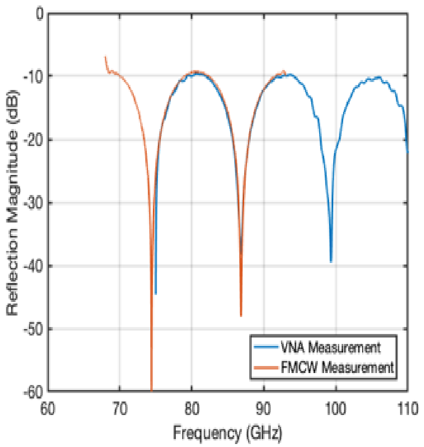
05 How to use **ellipsometry** in **super-resolution** THz imaging to **characterize** materials?

Static Lab Highlights

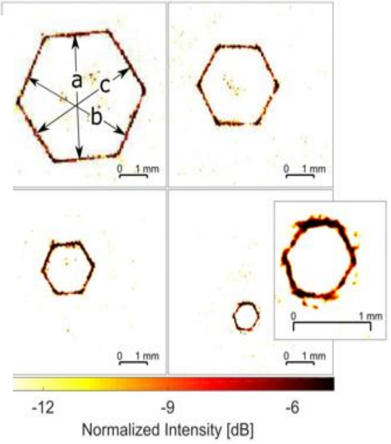
Novel GO & PO sim. engines







FMCW calibration techn.



Lensless THz imaging

Static Lab "Systems from Concepts"

Initial Questions

01 How to extend **Beamforming Concepts** to **THz Frequencies** ?

02 How to model and compensate **MIMO THz System Imperfections** ?

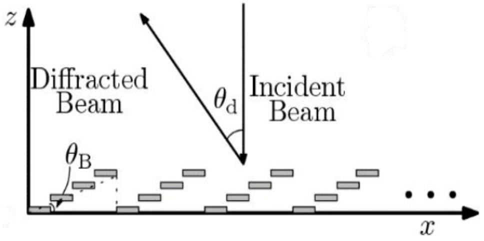
03 How to design **Space Time Signaling for MIMO THz Radar** ?

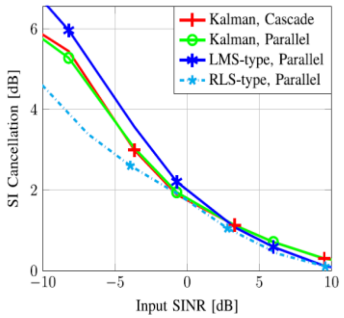
04 How to design a **Sub-mm Accurate Localization System** ?

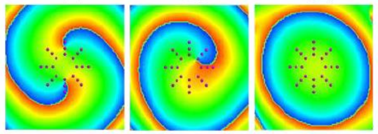
05 How to realize a **Real-Time Computing Platform for THz Algorithms**?

Static Lab Highlights

MEMS based Beam Steering

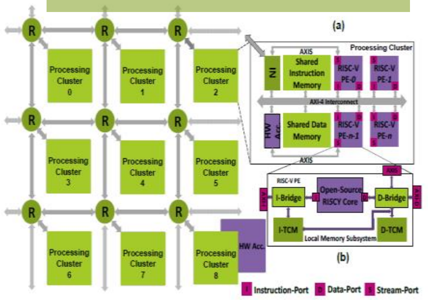




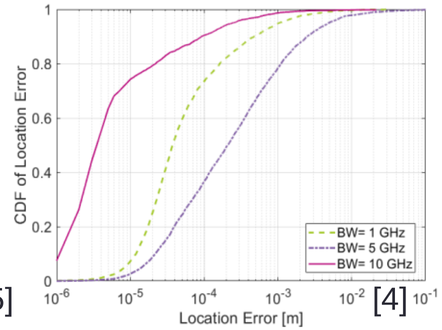


Self Interference Cancellation

MARIE Computing Architecture



[5]



[4]

What comes next for “Mobile Sensors” ?

Challenge 1 … **Mobile Beamforming up to 5 THz Bandwidth**

Challenge 2 … **MIMO THz Imperfections up to 5 THz**

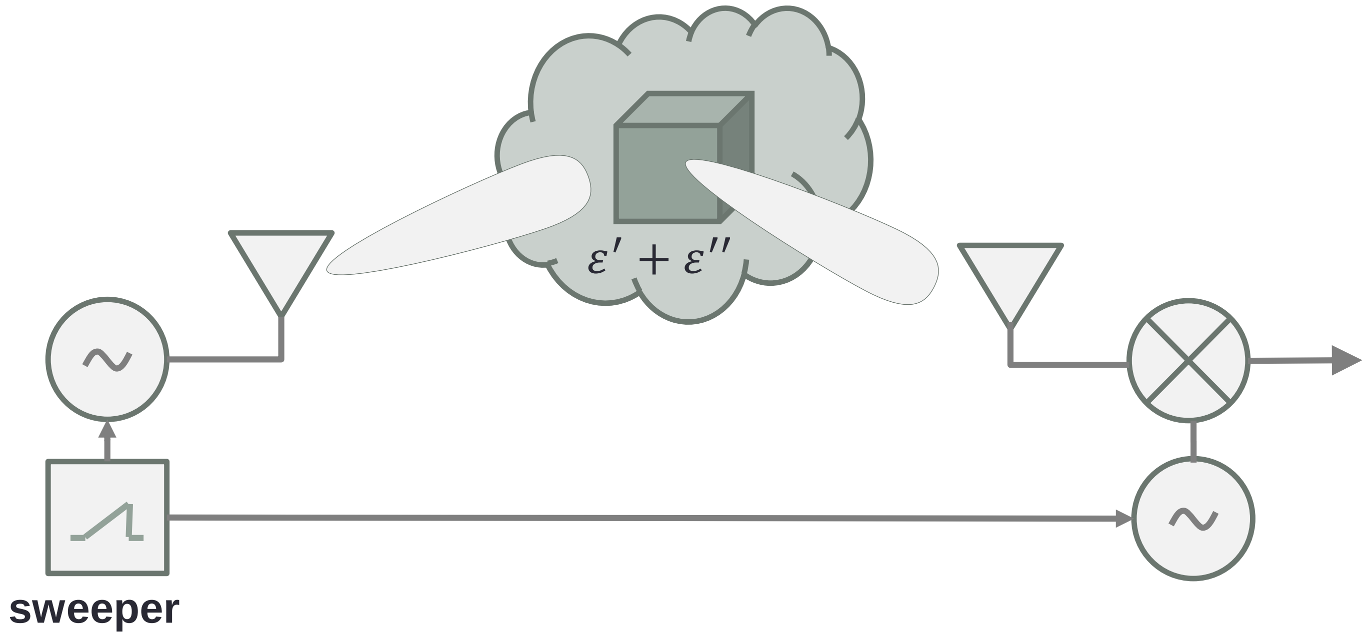
Challenge 3 … **<u>Concept:</u> First Real-Time Map**

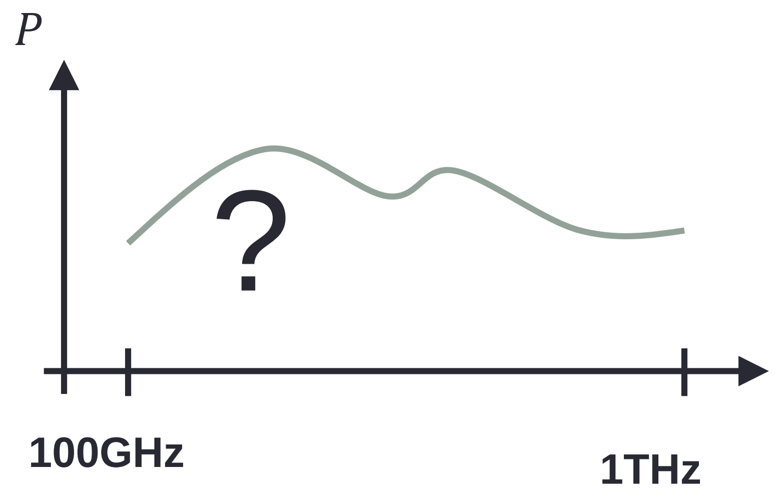
Challenge 4 … **<u>Proof:</u> Sub-mm Accurate Localization**

Example 1:
THz Spectroscopy

How about hyper spectral imaging and sensing?

Wanted: Materials spectral fingerprint
+
Polarization-diversity for ellipsometry

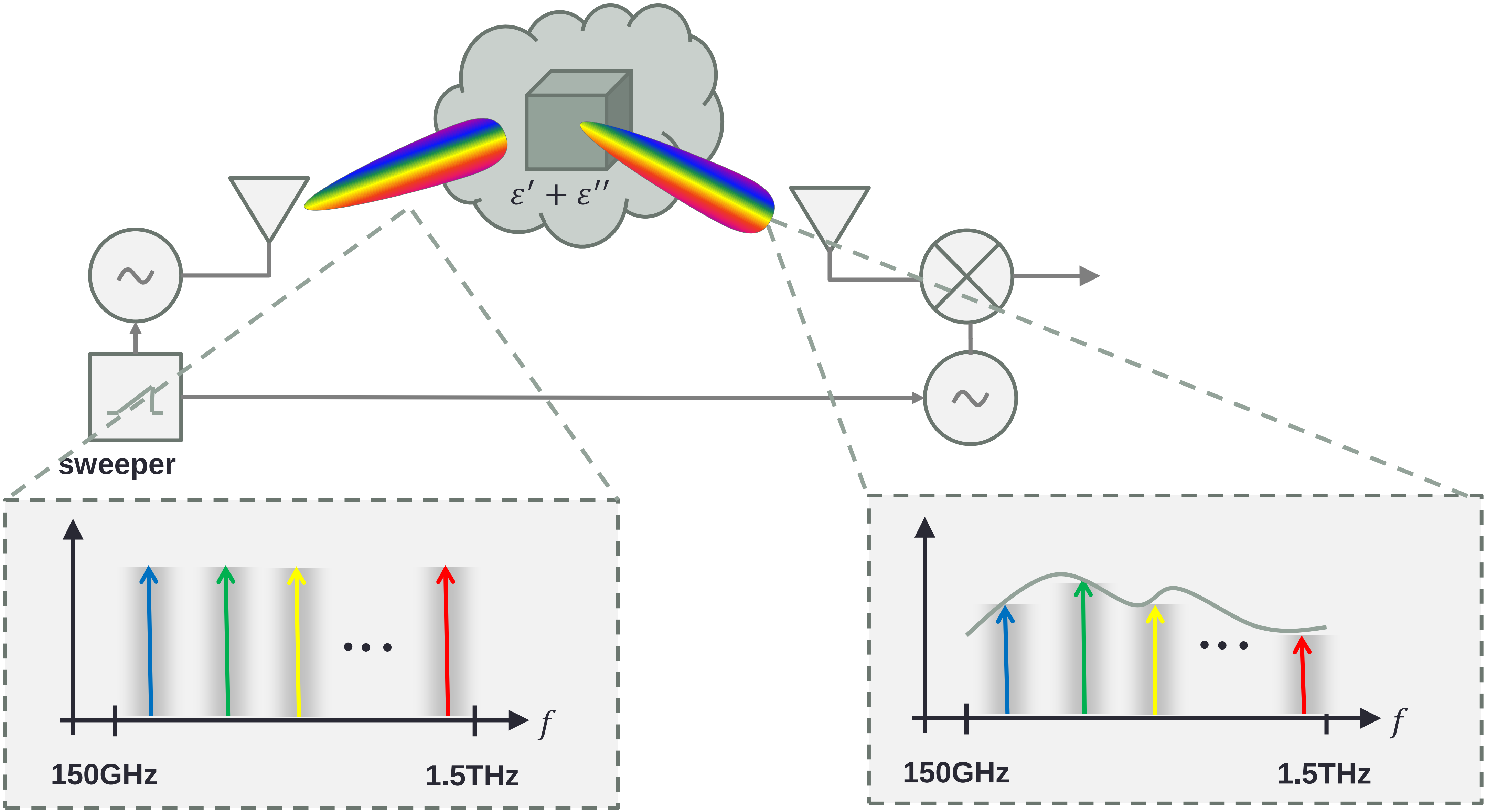




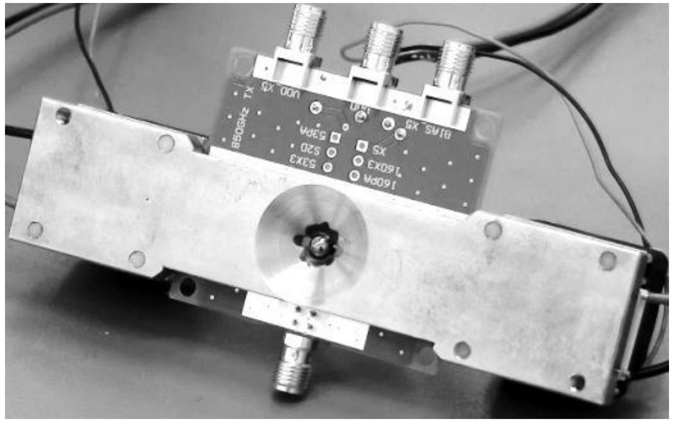
at least a decade of bandwidth!

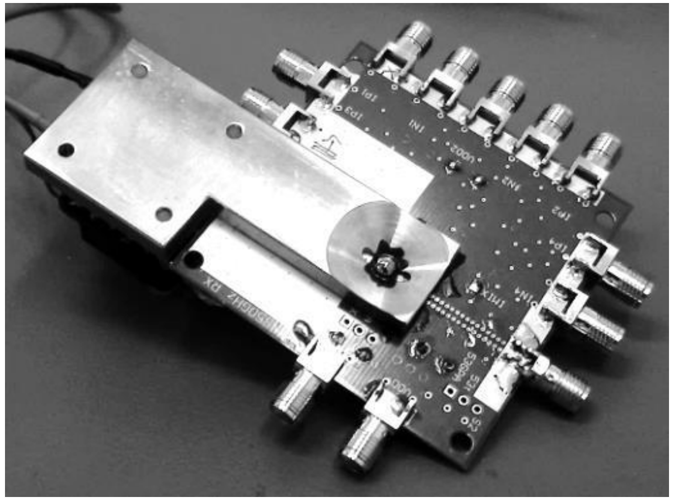
Can we do this in a compact silicon-based coherent imager?

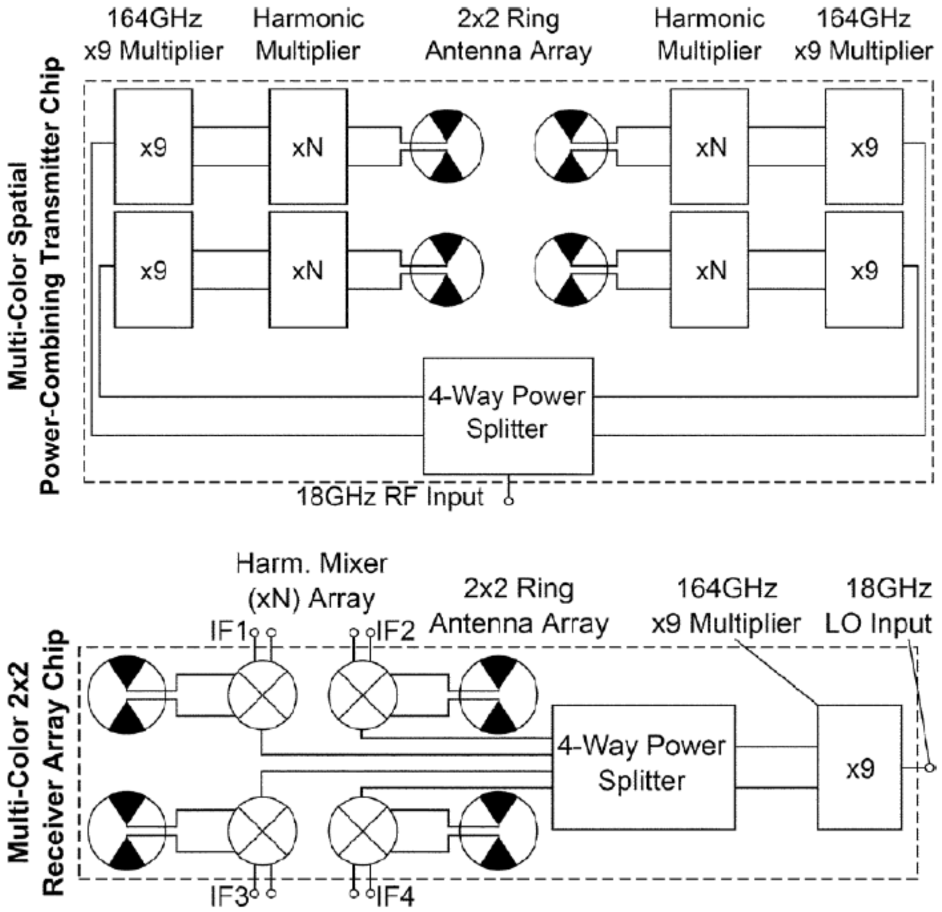
Hyper Spectral Imaging



160-GHz to 1-THz Multi-Color SiGe Chip-Set



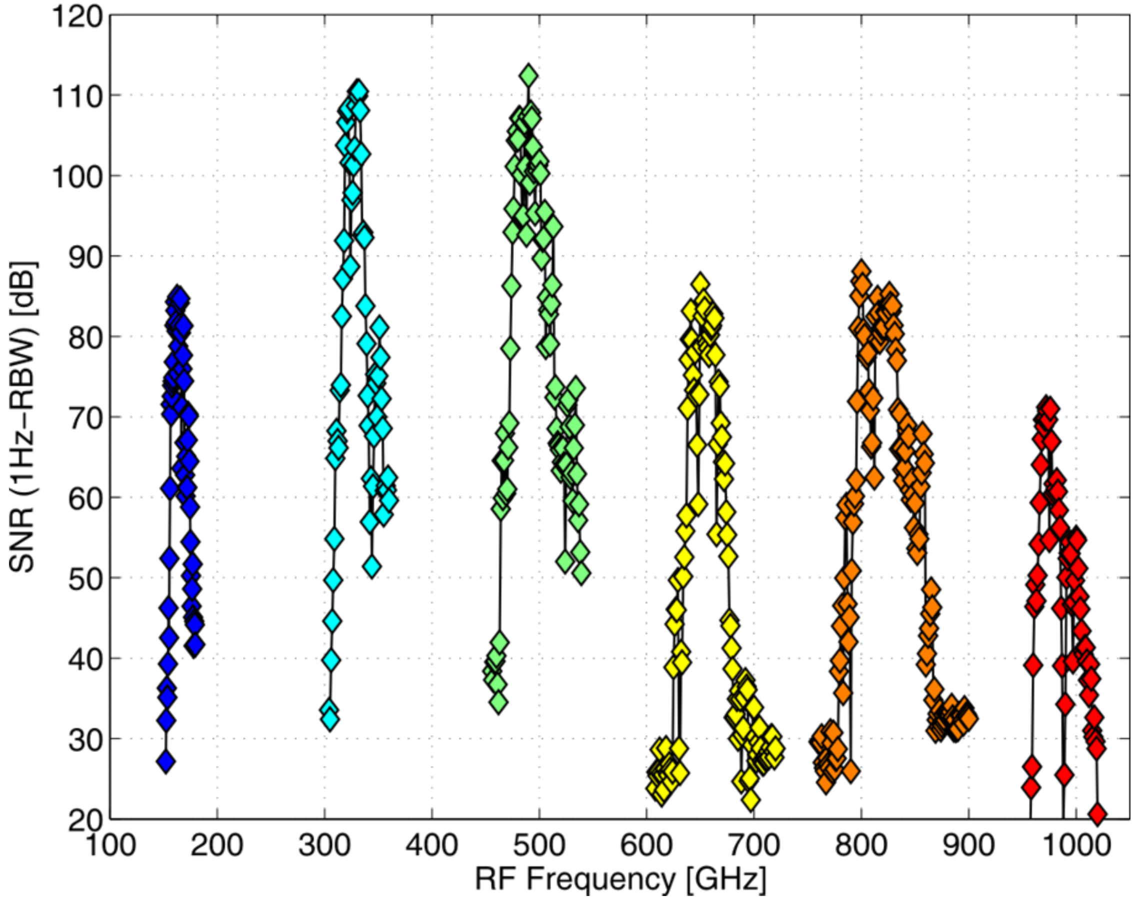


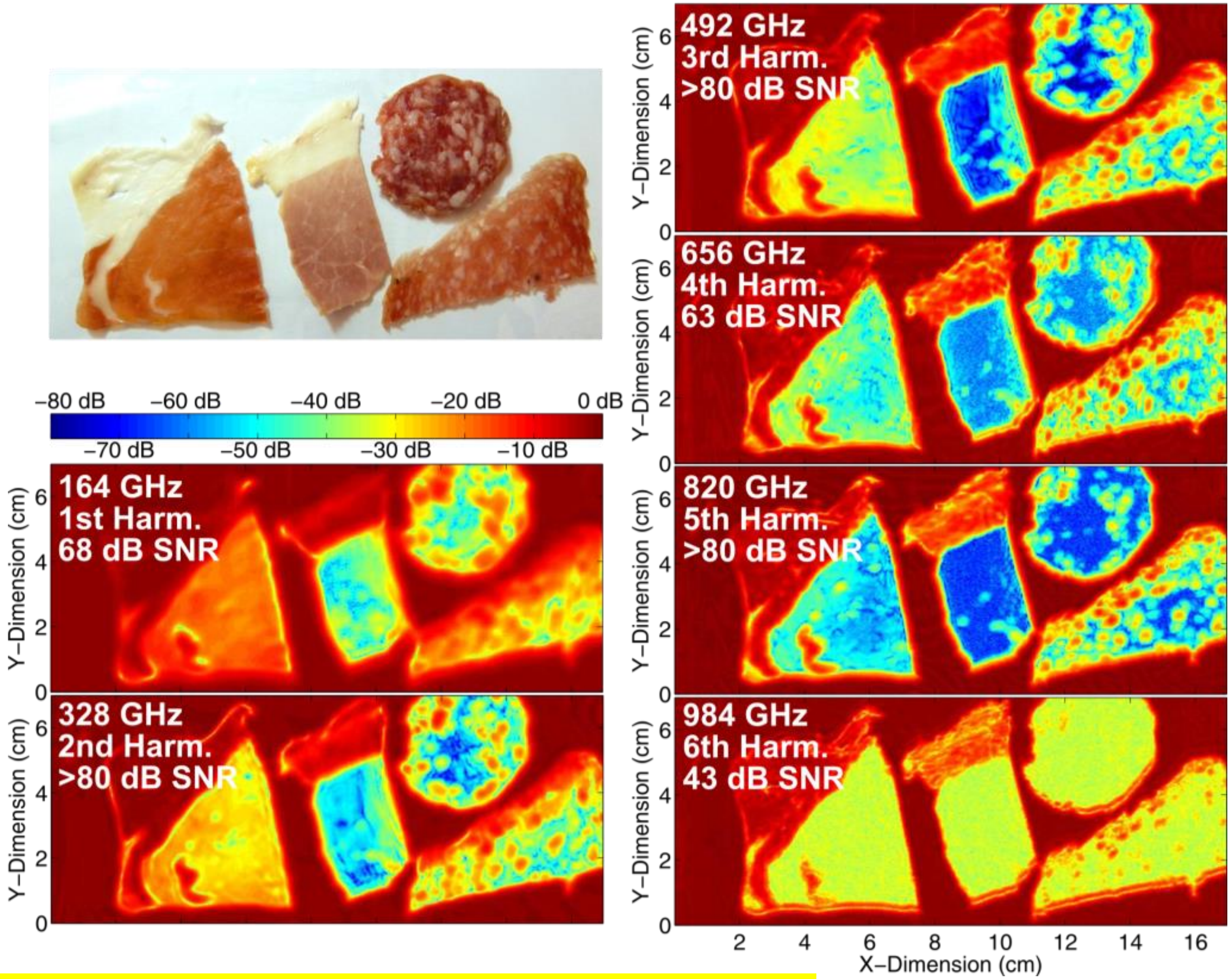


- Differential 825-GHz RF mixes with the 5th harmonic of a 162GHz LO
- CG= -15dB
- 4 freq. mult. Stages
- 4 ring antennas for spatial power combining
- 4.0 x 0.8 mm^2

[1] K. Statnikov et.al. 160-GHz to 1-THz Multi-Color Active Imaging With a Lens-Coupled SiGe HBT Chip-Set, TMTT 2015

Imaging Results



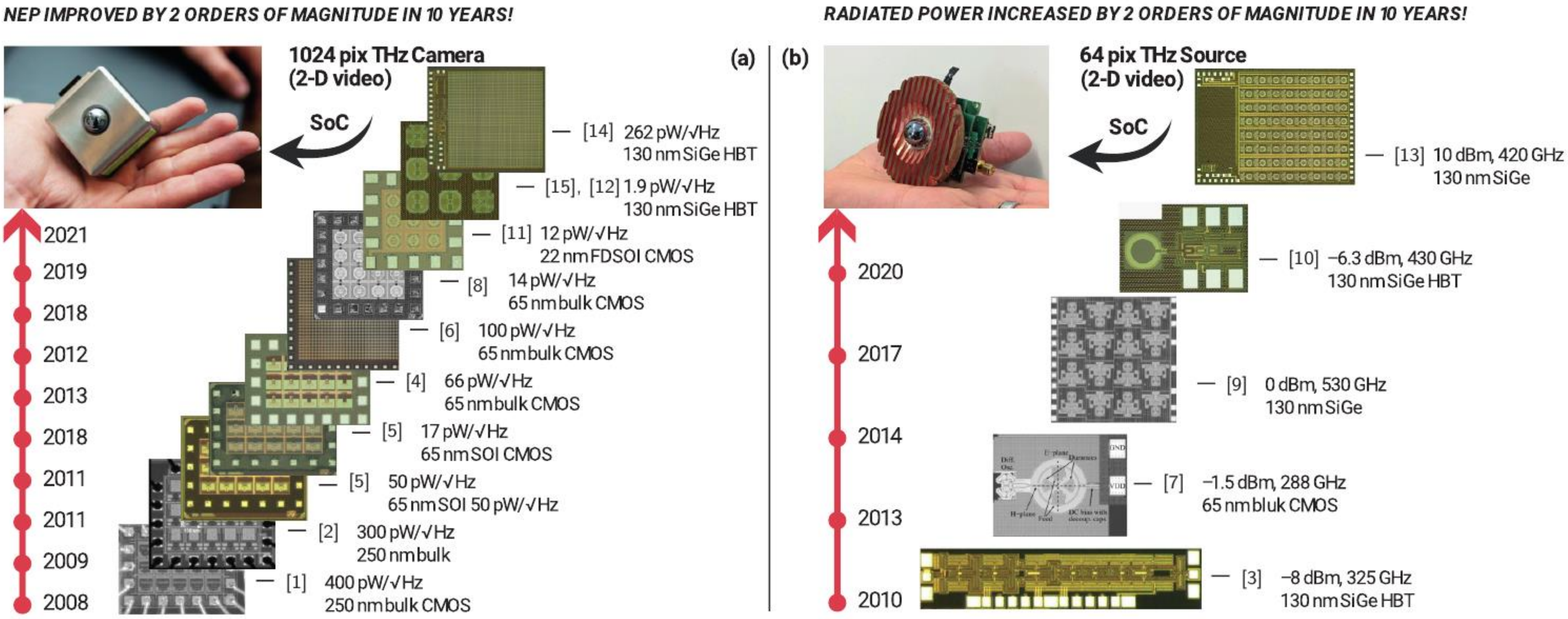


Coherent System: High imaging SNR even at 1THz possible!

How about in-coherent imager?

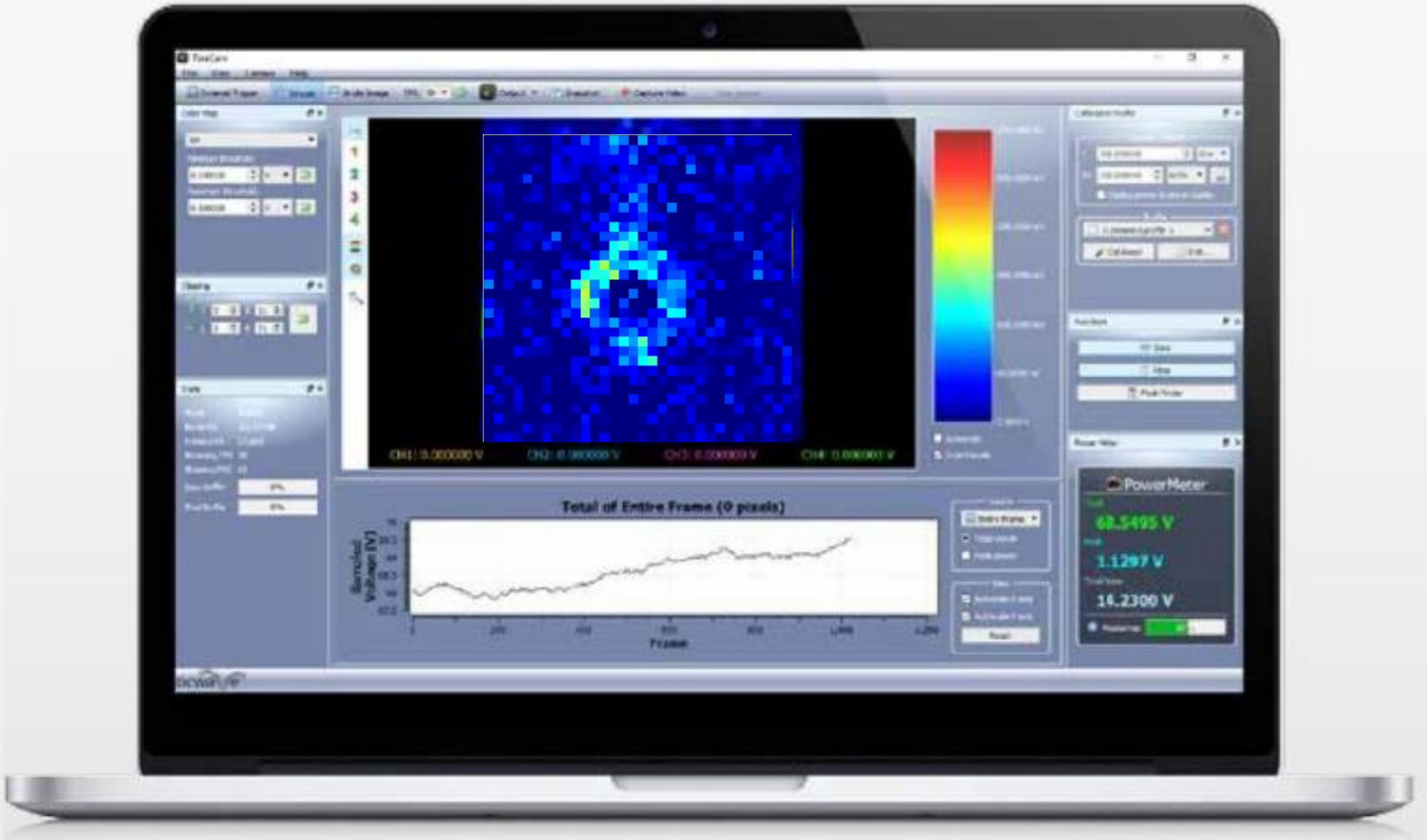
Example 2:
THz Imaging

Past work on THz incoherent detectors and THz sources



Commercial THz CMOS USB Camera

- 1 THz real-time demo at VDI both at IMS 2017



ST 65nm bulk CMOS

Courtesy TicWave (Camera) and VDI (1THz Source)

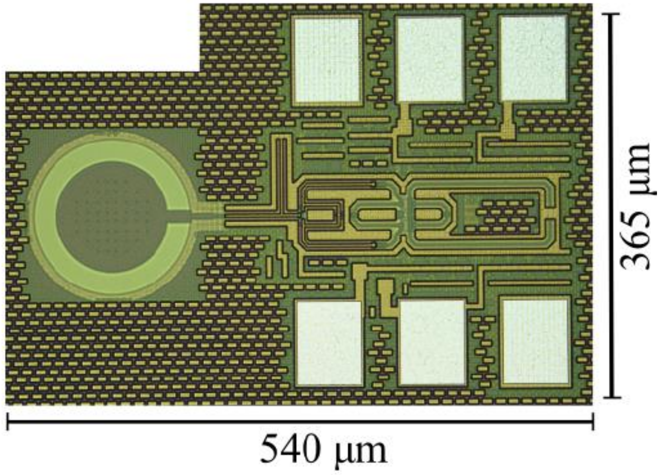
1. Improve performance (Devices to Components)

ST 65nm bulk CMOS

ticwave
the next generation of terahertz

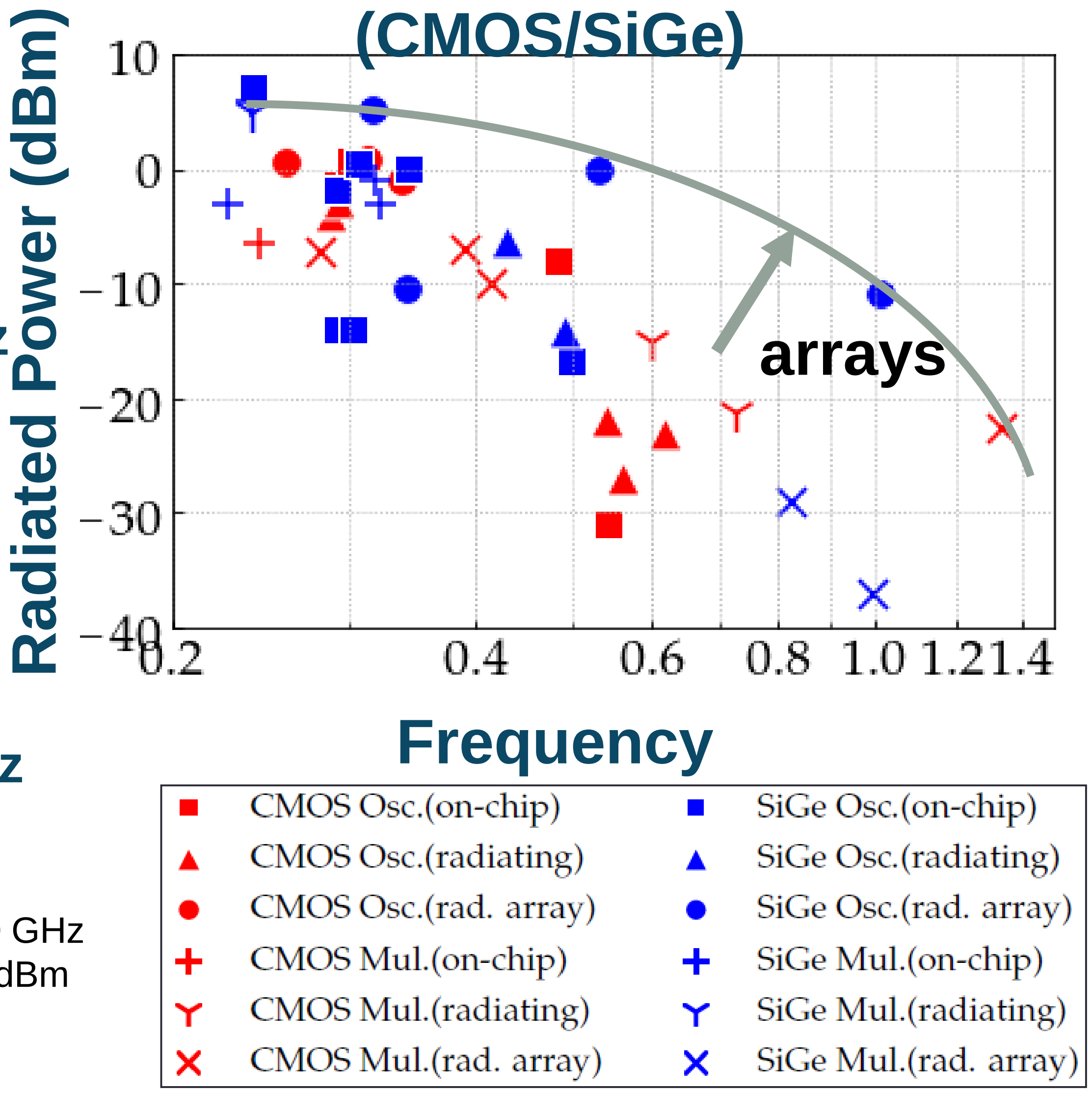
3-push ring OSC
-4dBm@288GHz
PN@10MHz: -93dBc/Hz
DC to RF: 0.15%

IHP 130nm SiGe



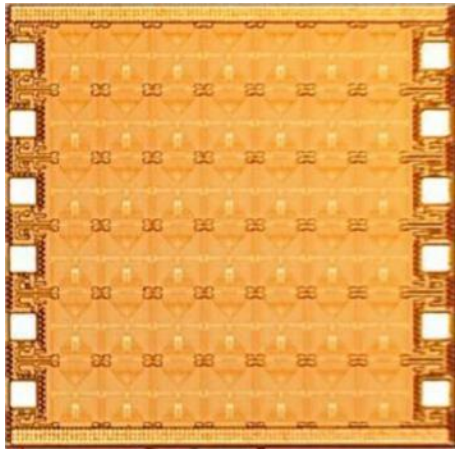
VCO+doubler
-6.3dBm@430GHz
PN@10MHz: -89dBc/Hz
DC to RF: 0.14%

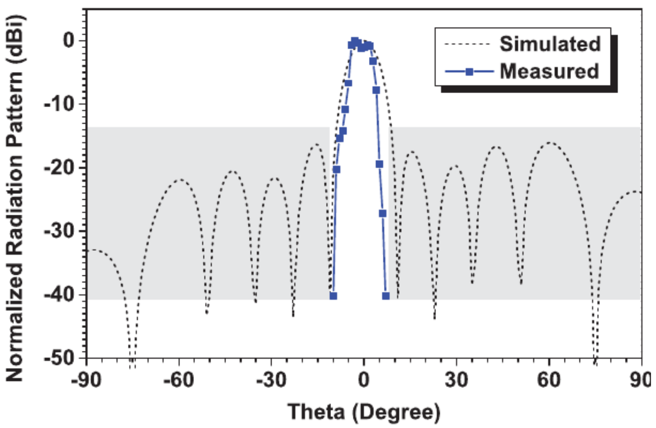
[1] P. Hilger, A Lens-Integrated 430 GHz SiGe HBT Source With Up to -6.3 dBm Radiated Power, RFIC 2017



Silicon Source Arrays (Coherent vs. Incoherent)

Coherent Radiators





91 elements

OSC 4-push

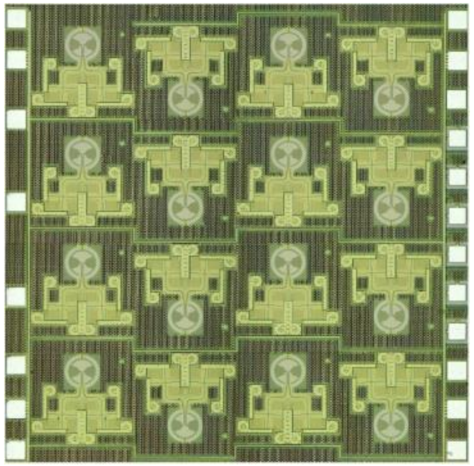
-10.9dBm @ 1.01 THz

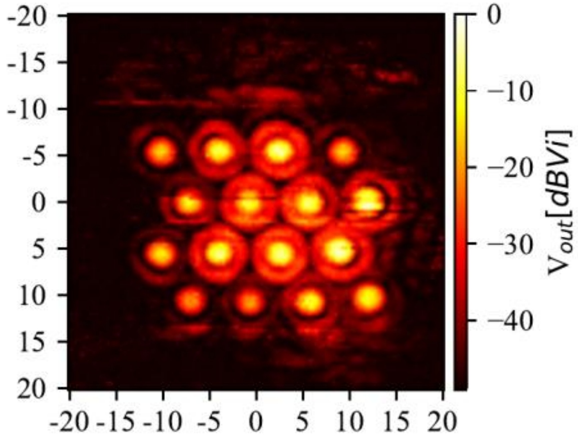
DC to RF: 0.0073%

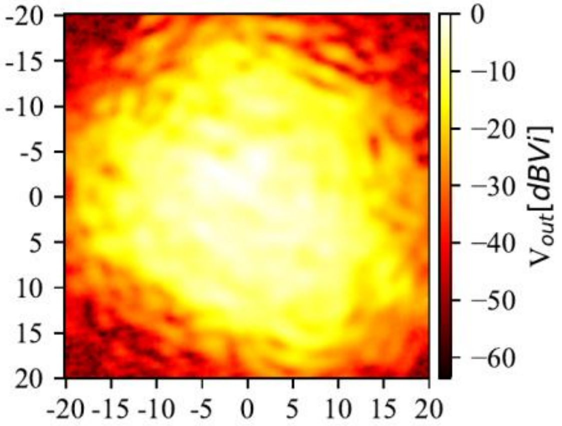
IHP 130nm SiGe

[1] Zhi Hu et.al., High-Power Radiation at 1 THz in Silicon: A Fully Scalable Array Using a Multi-Functional Radiating Mesh Structure, JSSC 2018

Incoherent Radiators







16 elements

OSC 3-push

0dBm@530GHz

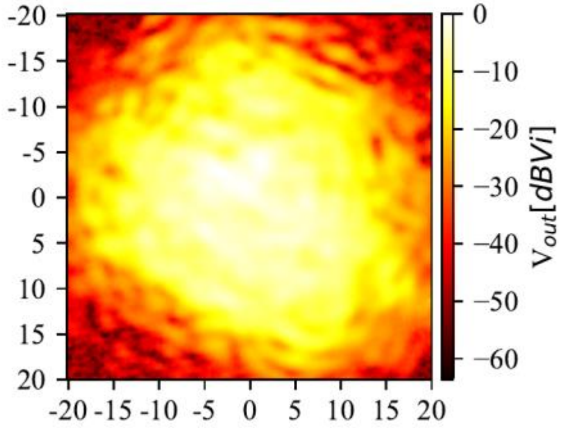
DC to RF: 0.04%

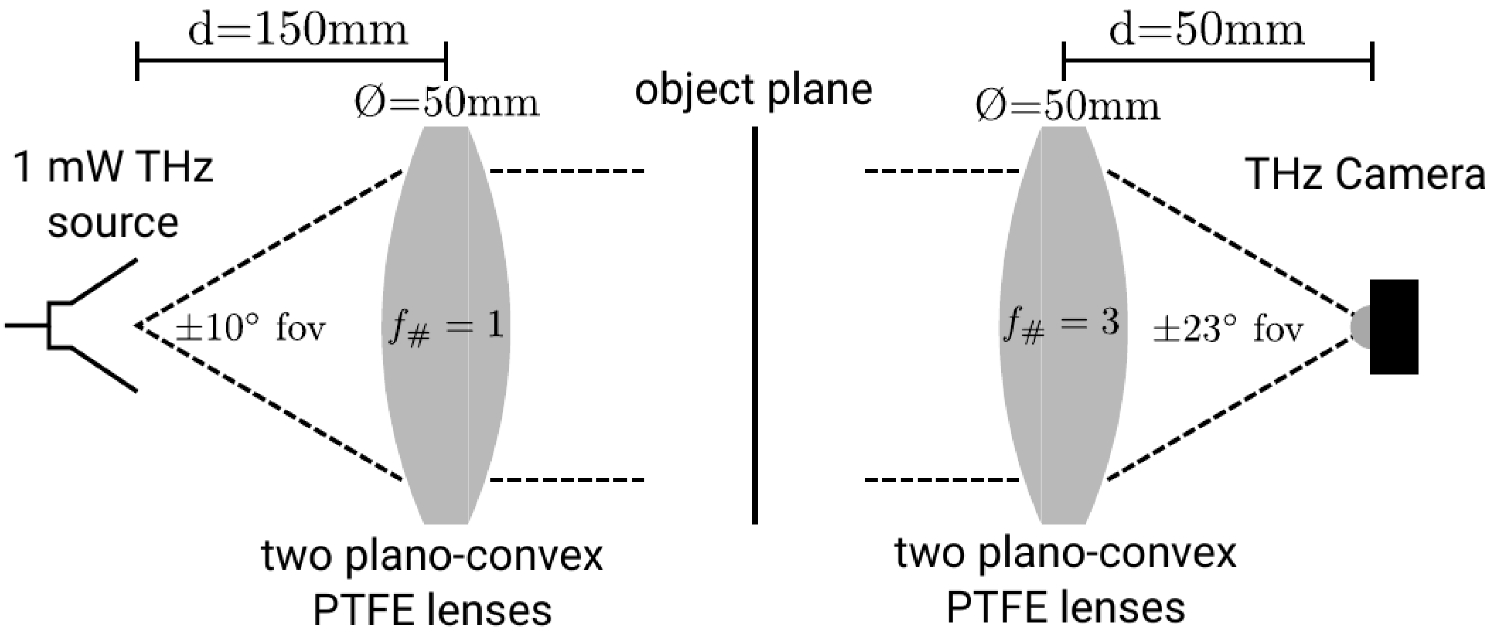
IHP 130 nm SiGe

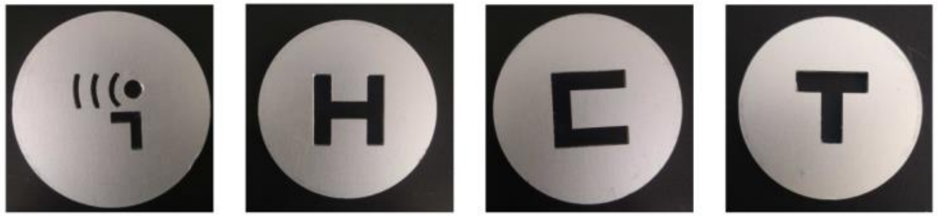
[1] U. Pfeiffer, et al., A 0.53 THz reconfigurable source module with up to 1 mW radiated power for diffuse illumination in terahertz imaging applications, JSSC 2014

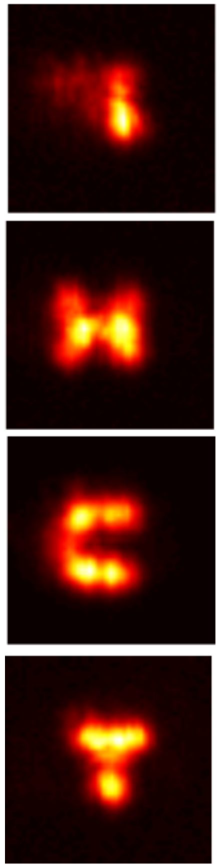
Diffused Illumination

1mW ½ THz diffuse illumination





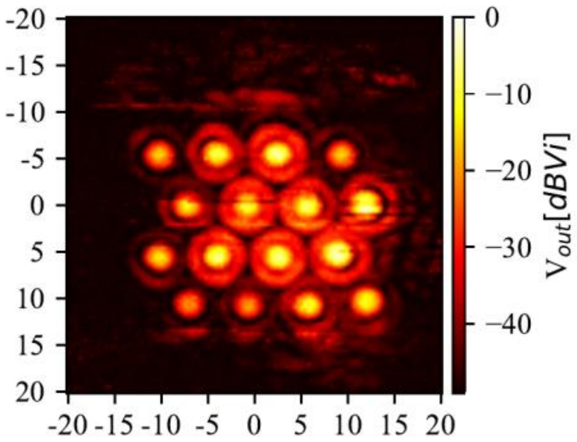


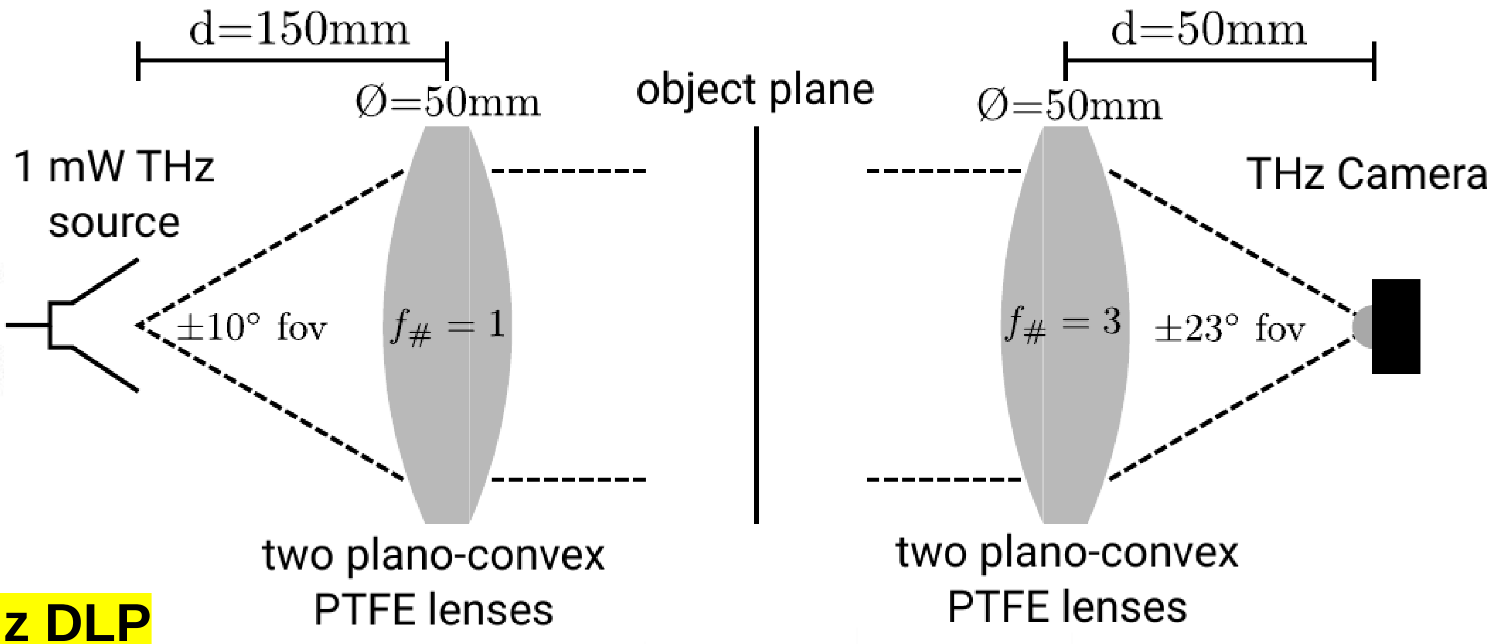


[1] D. Headland et.al., Diffuse beam with electronic terahertz source array, IRmmW-THz 2018

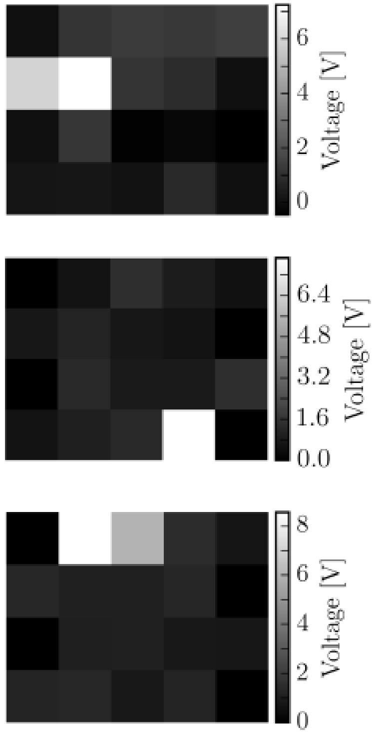
Computational Imaging and Diffused Illumination

1mW ½ THz digital light processor

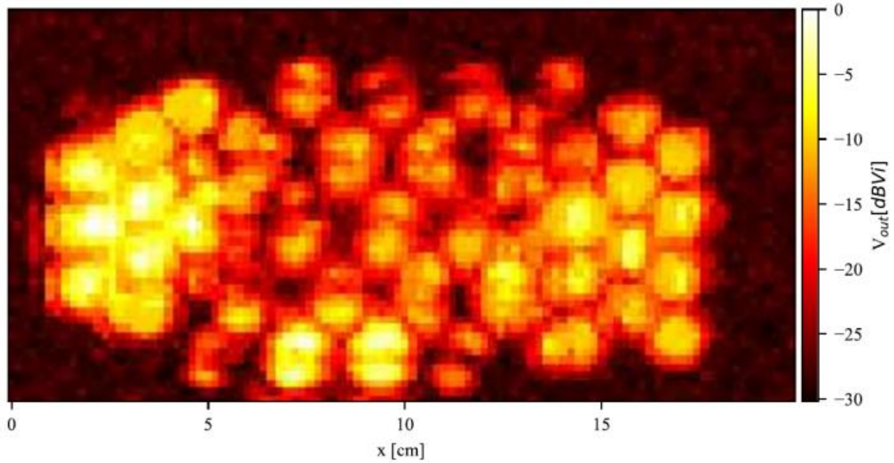


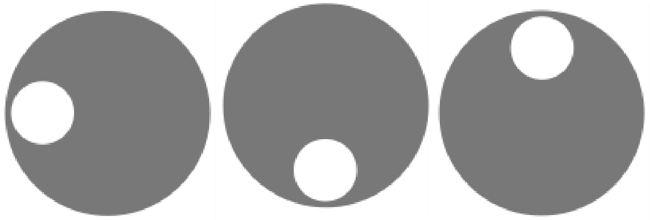


Computational imaging



4mW 62 pixel THz DLP





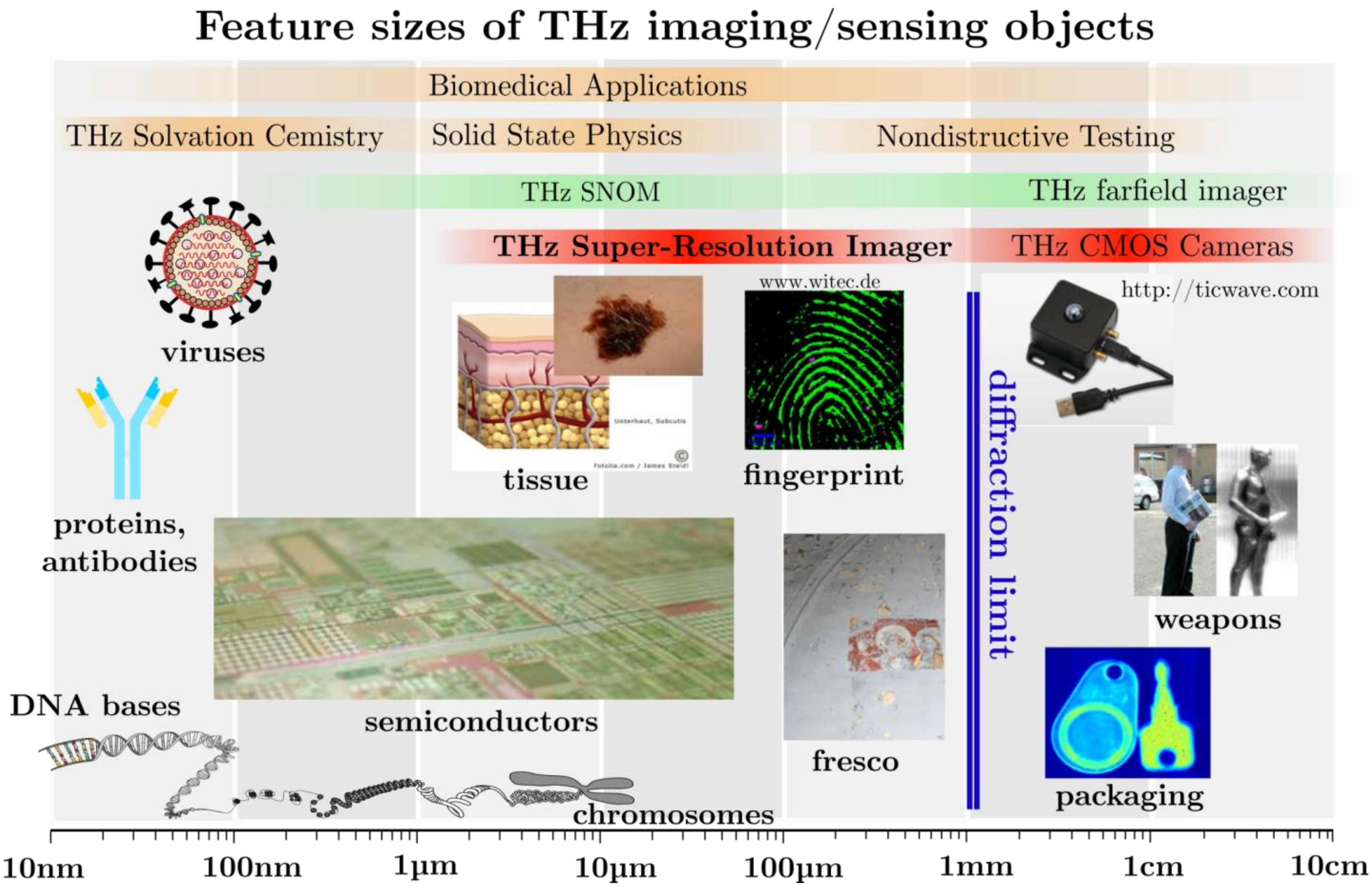
plications With Silicon-Based

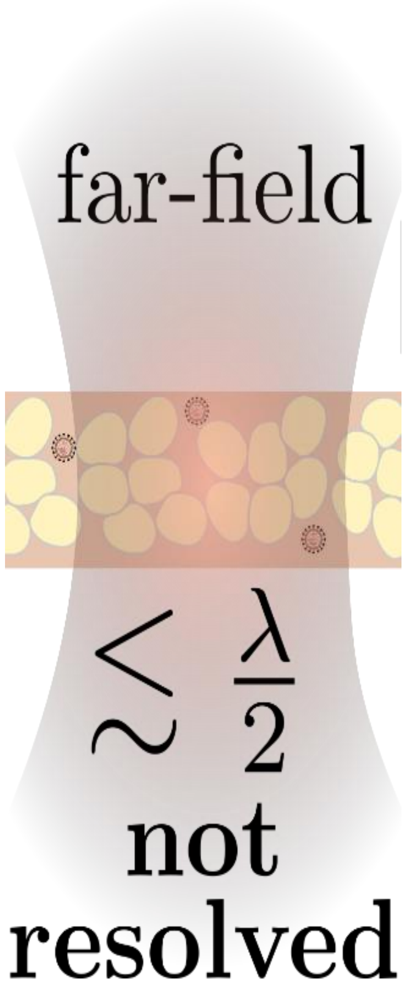
ge-growth construction of LDPC codes
onal Workshop on Compressed

- On-the-fly APEG-LDPC sensing matrix generation
- OMP reconstruction
  - Compression ratio ≤ 50%

Example 3:
THz Near-Field Imaging

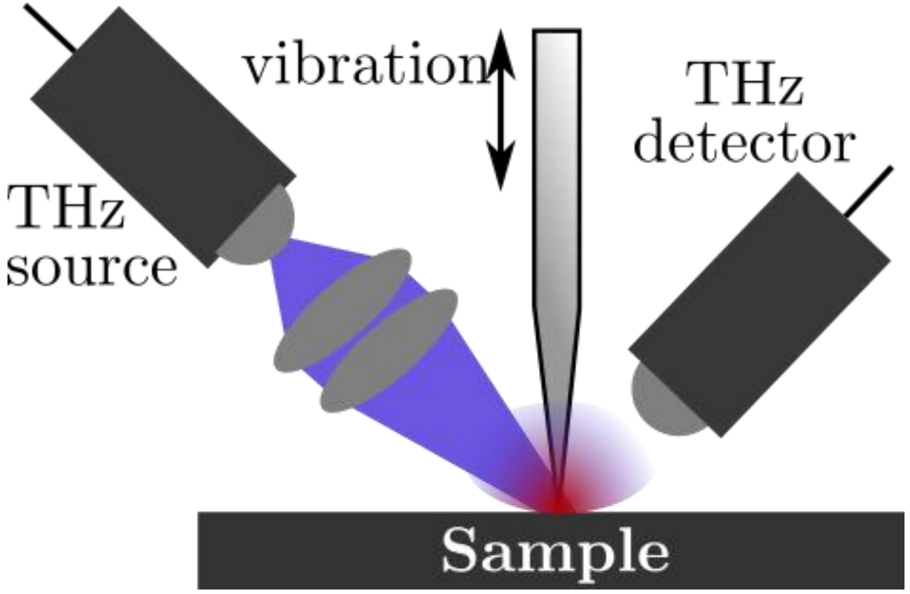
However, resolution is diffraction limited…





SoA Near-Field Imaging

Near-Field Scanning Optical Microscopy (NSOM)



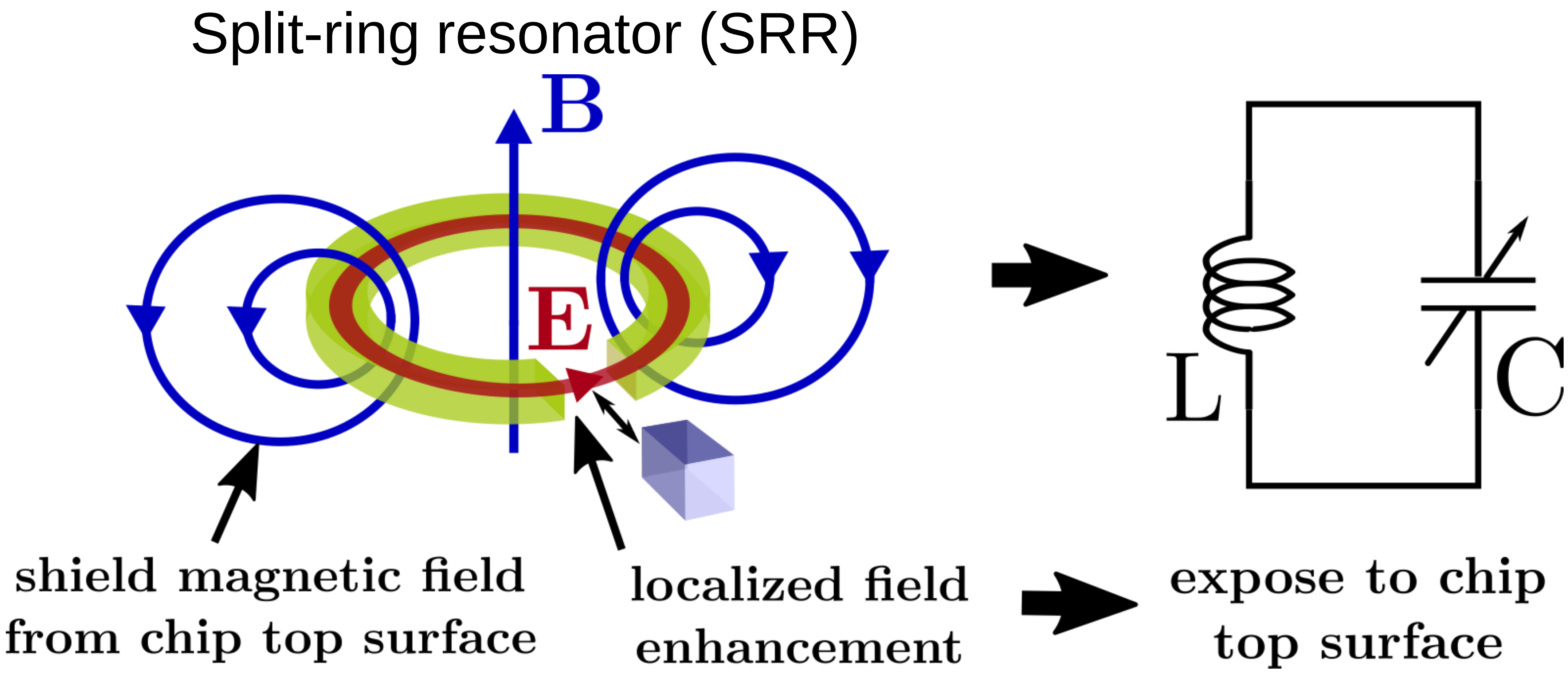
Source or detector placed remotely

- Poor power coupling efficiency
- High-power sources & cooled detectors
- Low dynamic range & contrast in far-field clutter

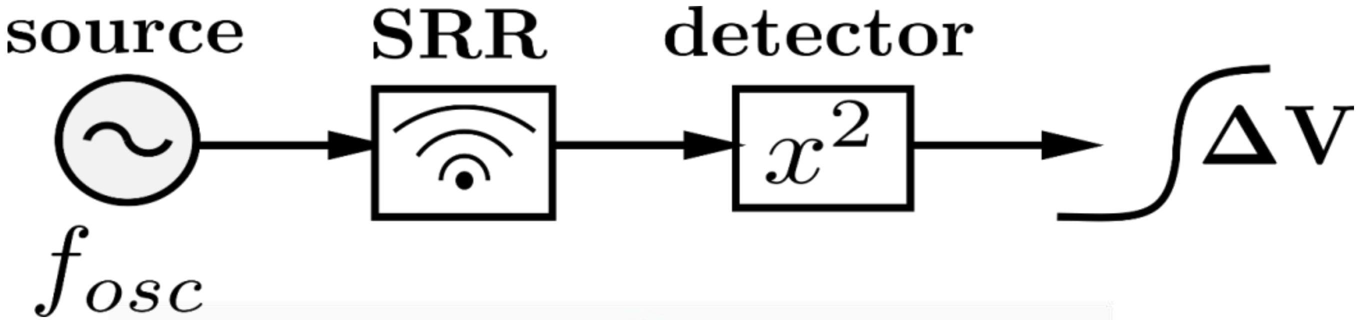
µm/nm-range resolution

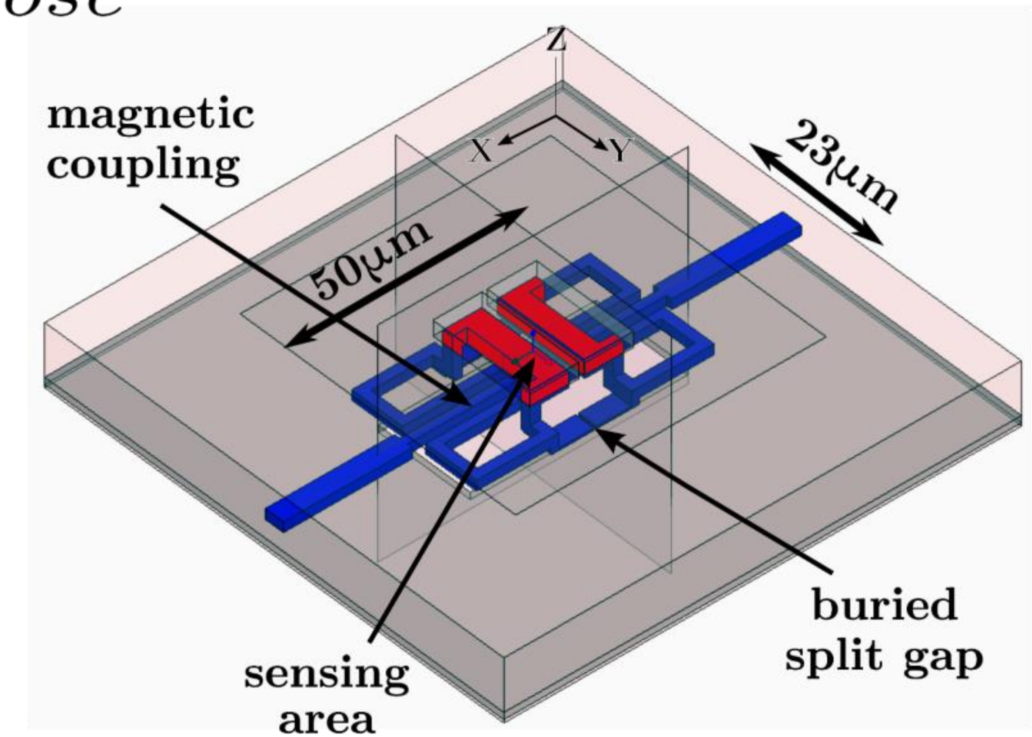
Laboratory technique

Sensing Mechanism

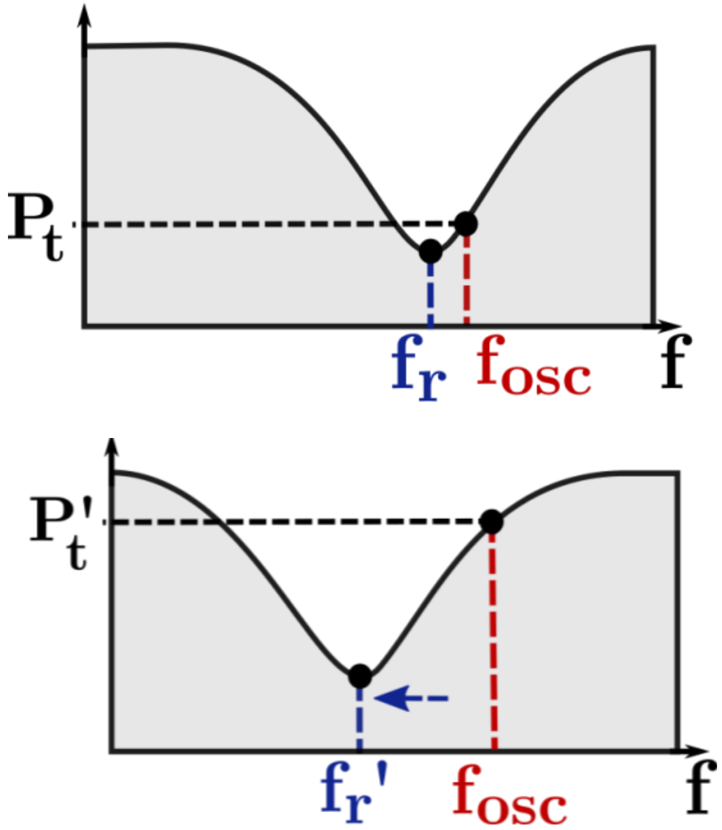


Resonator Design



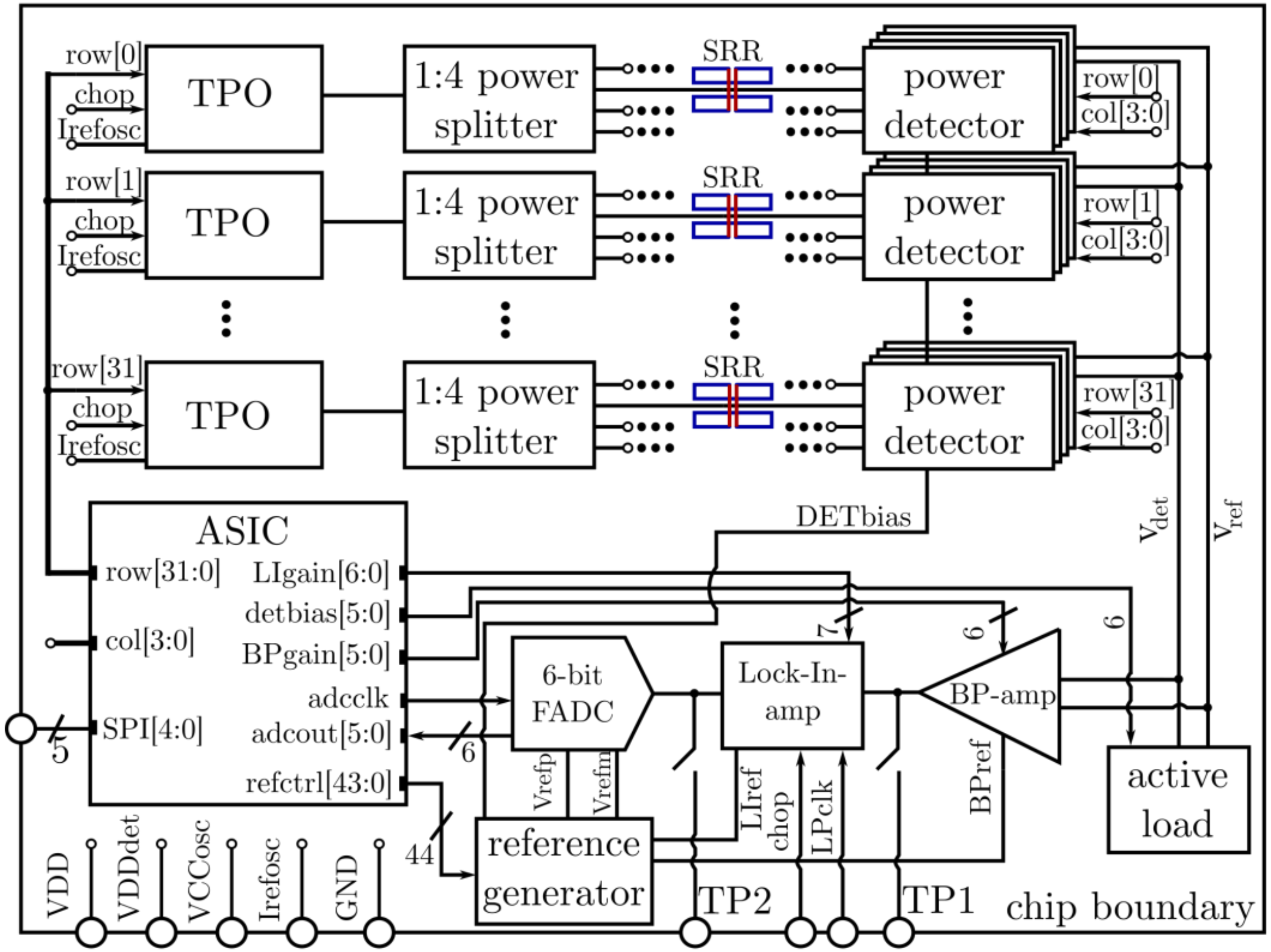


Free-running oscillator and power detector



[1] Janusz Grzyb et.al. A 0.55 THz Near-Field Sensor With a um-Range Lateral Resolution Fully Integrated in 130 nm SiGe BiCMOS, JSSC 2016

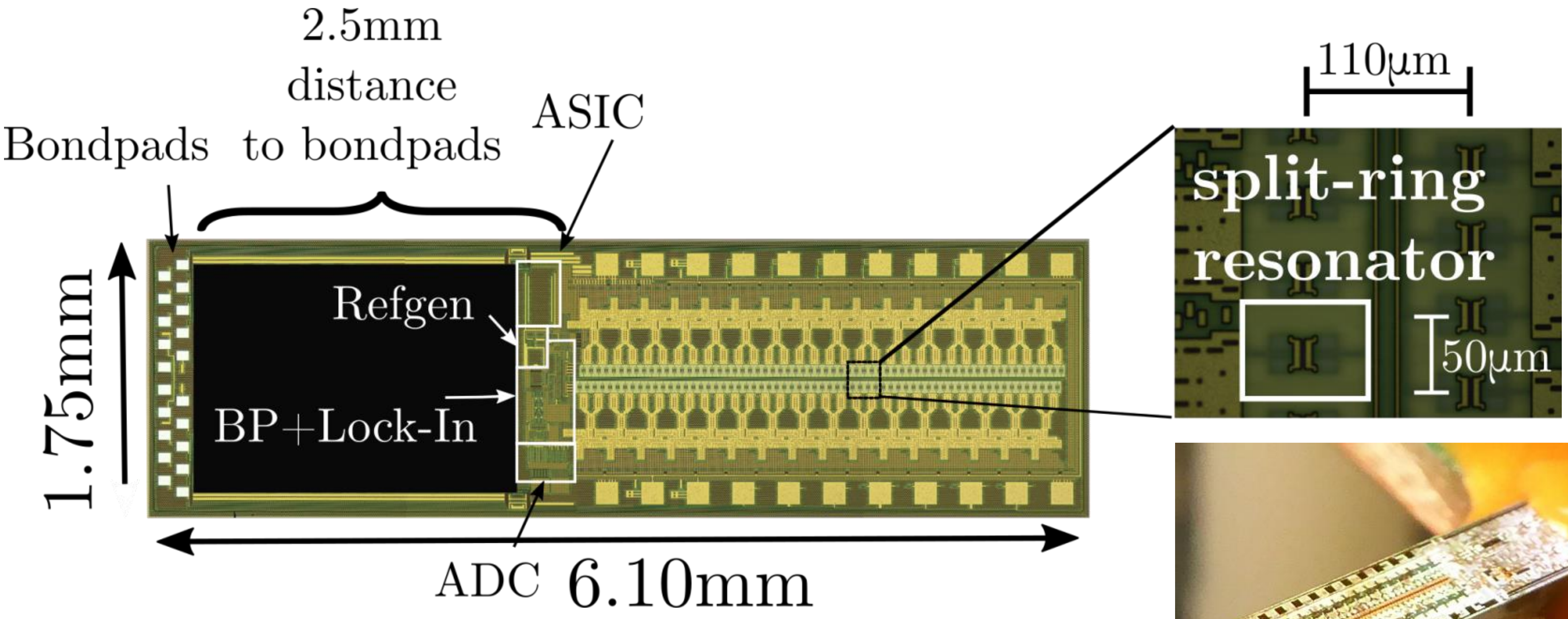
128-pixel Near-field Imager (THz SoC)

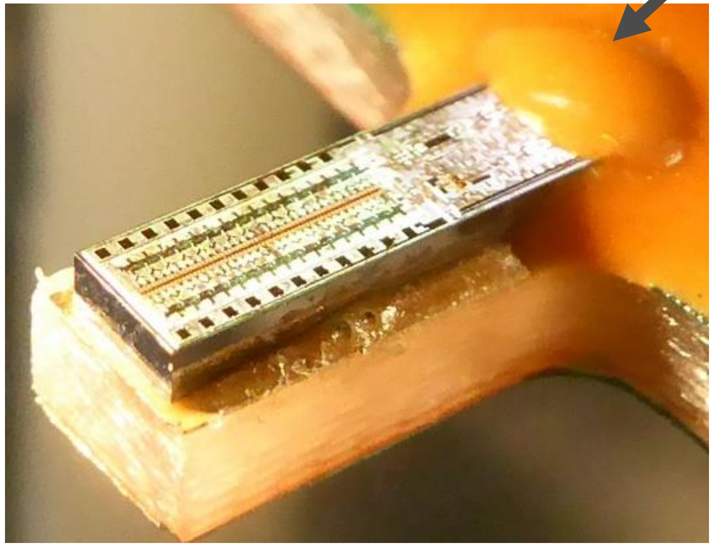


- IHP 0.13µm SiGe-BiCMOS (fT/fmax=300/450GHz)
- Each row divided into 16 sub-arrays of 4 pixels
- Driven from single triple-push oscillator
- Connected by 4-way power splitter
- Sequential operation

[1] P. Hillger et.al. , A 128-pixel 0.56THz sensing array for real-time near-field imaging in 0.13 µm SiGe BiCMOS, ISSCC 2018

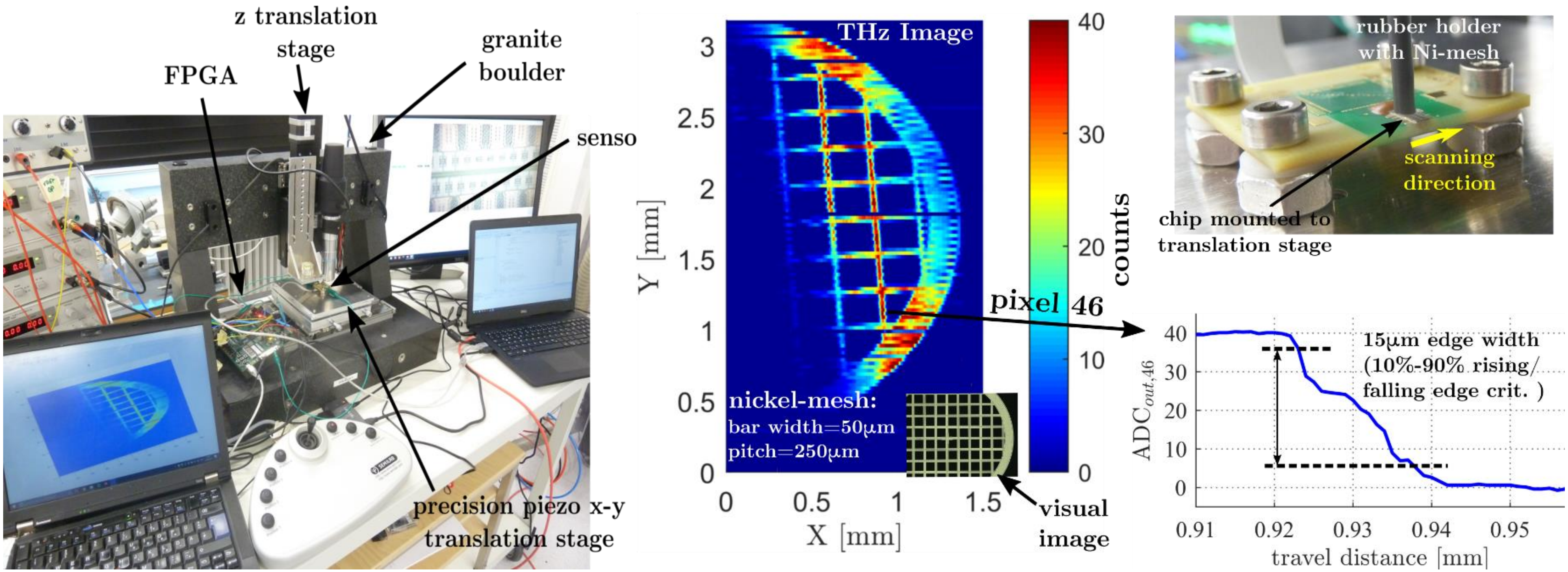
Chip Micrograph and Packaging





Imaging Results

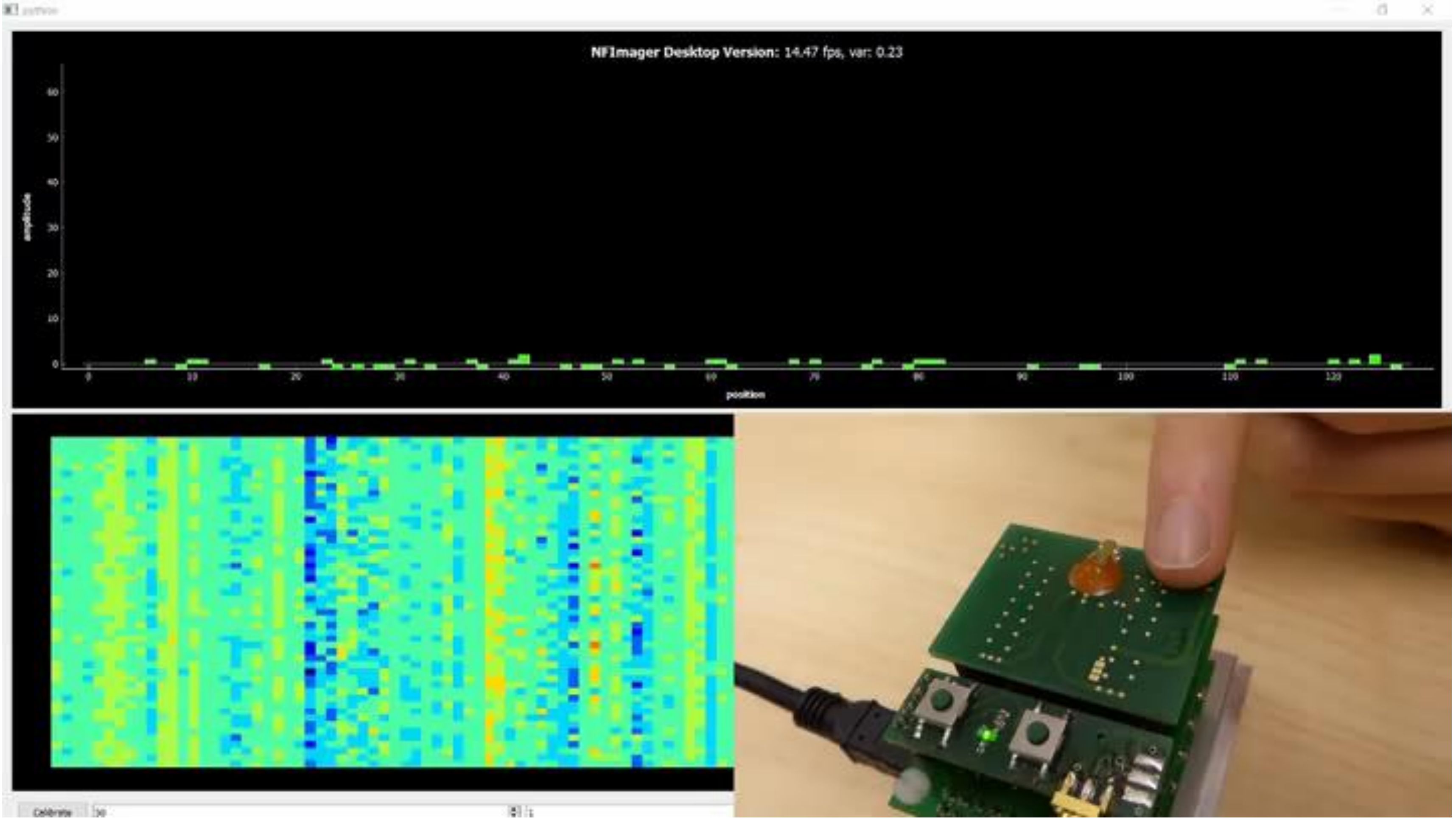
Main Challenge: Mechanical stability / accuracy

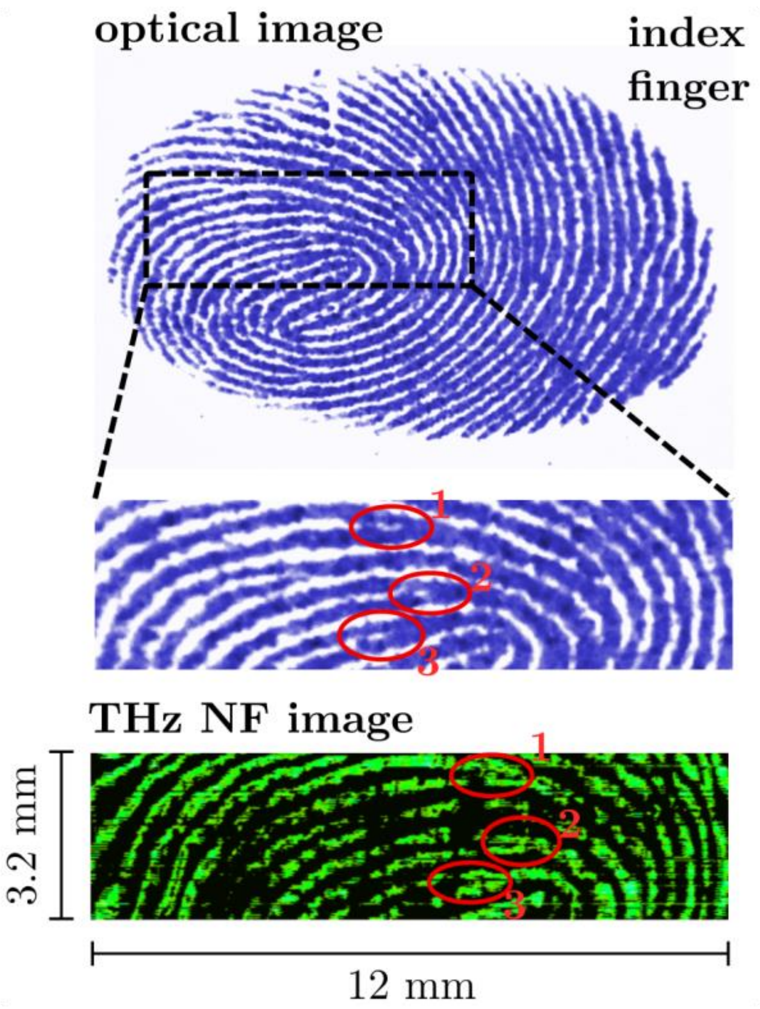


128x1500 pixel (1-D scan, 1µm step)

Tscan=6min 45 sec !

Real-time Near-field Imaging

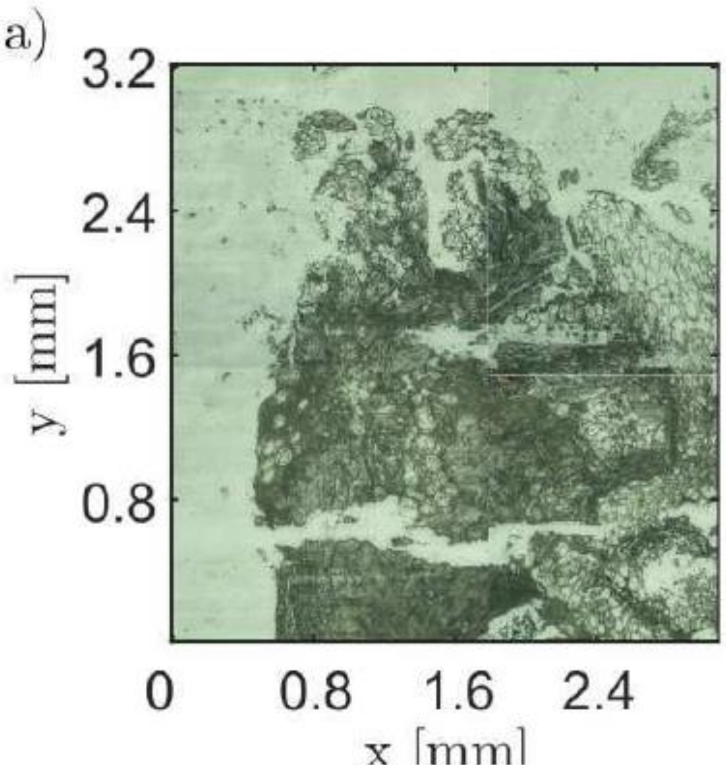




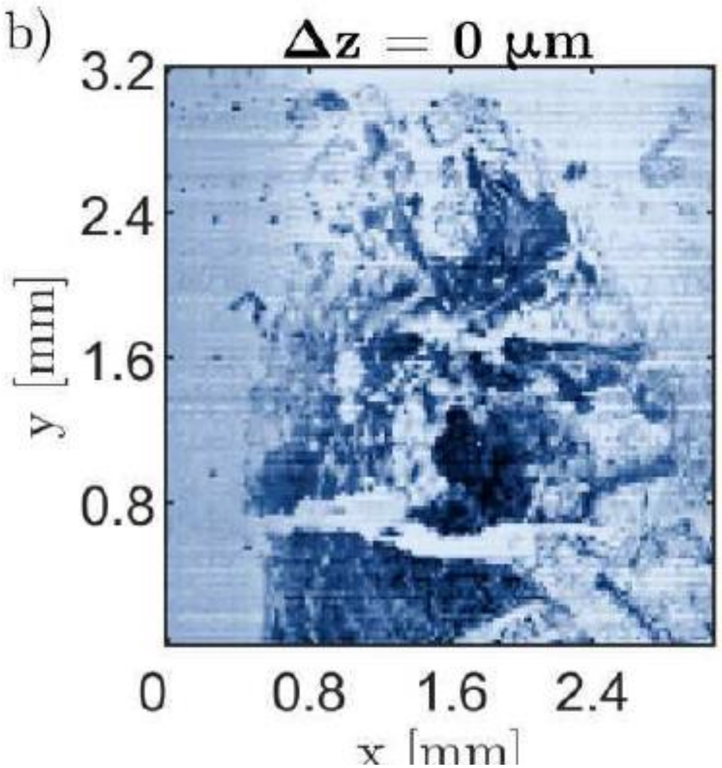
842x128 pixel Tscan=30 sec !

Outlook – Biomedical Applications

Microscopic Image



THz NF Image



- Direct contact
- Image size
  - 142 × 128 pixels
- Pixel pitch
  - 22 µm × 25 µm
- Tstep/Tdwell
  - 2 s/2.5 s

More results to come…

Summary

- THz imaging and sensing applications addressed by large-scale collaborative research projects, 26M€ funded just by the DFG!
- Sensitivity and output power of compact THz cameras and sources have improved by 2 orders of magnitude over the last 10 years!
- Fully integrated THz systems on a chip are feasible today!

Outlook and discussion:

- Imaging and sensing as add on to mobile communications?
- Spectrum sharing with communications?

IWMTS 2021

www.iwmts.org

2021 Fourth International Workshop on Mobile Terahertz Systems (IWMTS), 5-6 July 2021
Hybrid Workshop taking place in Duisburg, Germany and online

Deadline Paper submission: February 15th

- Confirmed Key Note Speakers
  - Ian F. Akyildiz, Georgia Institute of Technology, USA
  - Joseph R. Demers, Bakman Technologies, USA
  - Theodore Rappaport, NYU Tandon School of Engineering, USA
  - Mats Pettersson, Blekinge Institute of Technology, Sweden

    Title: THz SAR - a New Way to Monitor the World
- Panel Session: Will Mobily push THz to Mass Markets?
- TalentTravel Program: Travel Grants available

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