Chip-Scale Terahertz Systems for Sensing, Metrology and Security Applications

Ruonan Han

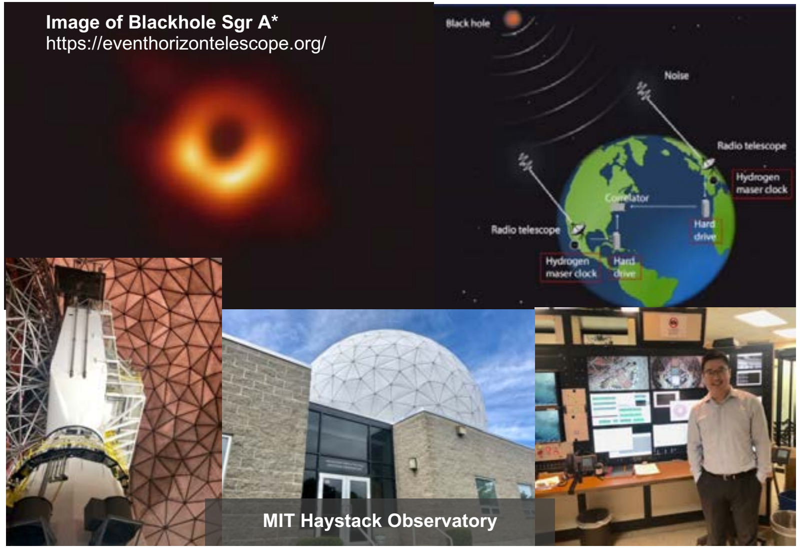
Associate Professor

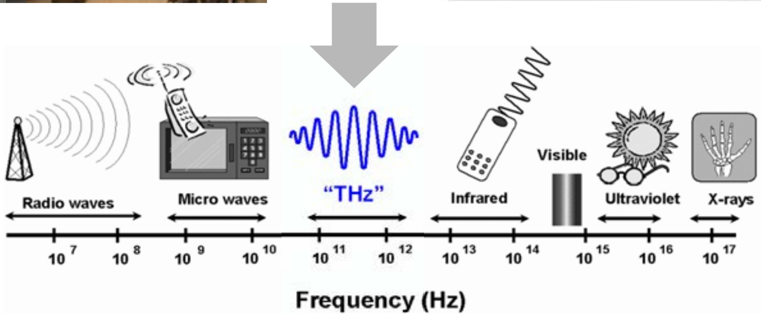
Electrical Engineering and Computer Science

Massachusetts Institute of Technology

ruonan@mit.edu, https://hangroup.mit.edu

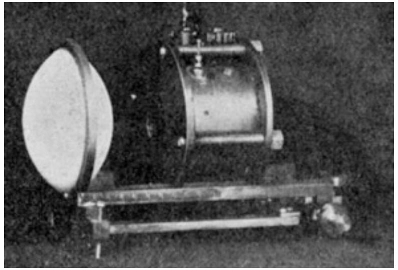
Overview of Terahertz Wave



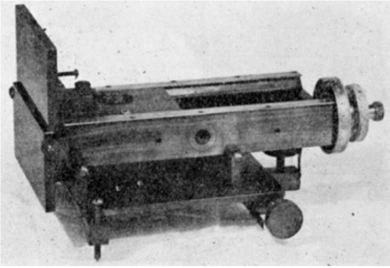


A One-Century Pursuit of Terahertz Electronics

THERE is doubtless little need of any further experimental proof of the essential identity between heat waves and electric waves, yet for the sake of completeness, further effort to bridge the existing gap between these two spectra seems warranted.

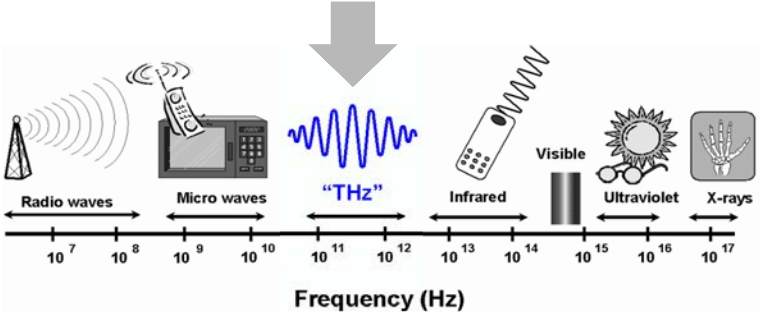


160-GHz Spark Gap Oscillator



Micro-Wire Detector/Interferometer

[E. F. Nichols and J. D. Tear, “Short Electric Waves”, Physical Review 21, 587 (1923)]



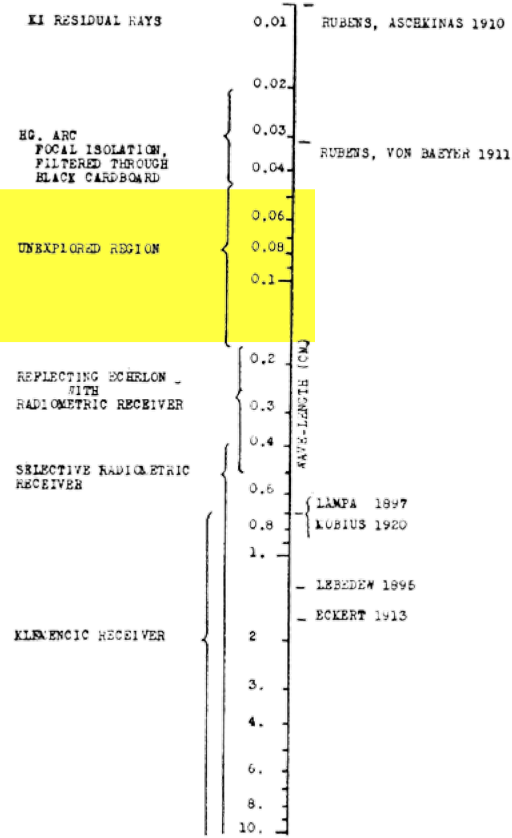
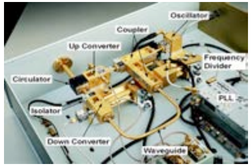
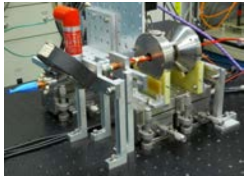


Fig. 16. Spectrum chart.

Terahertz Gap

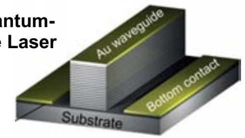


III-V Discrete Components

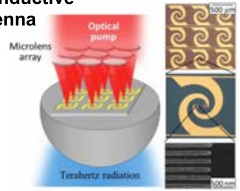


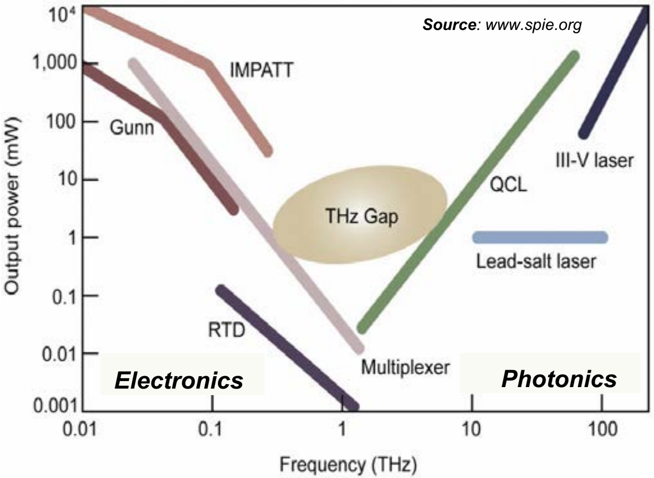
Vacuum Tube

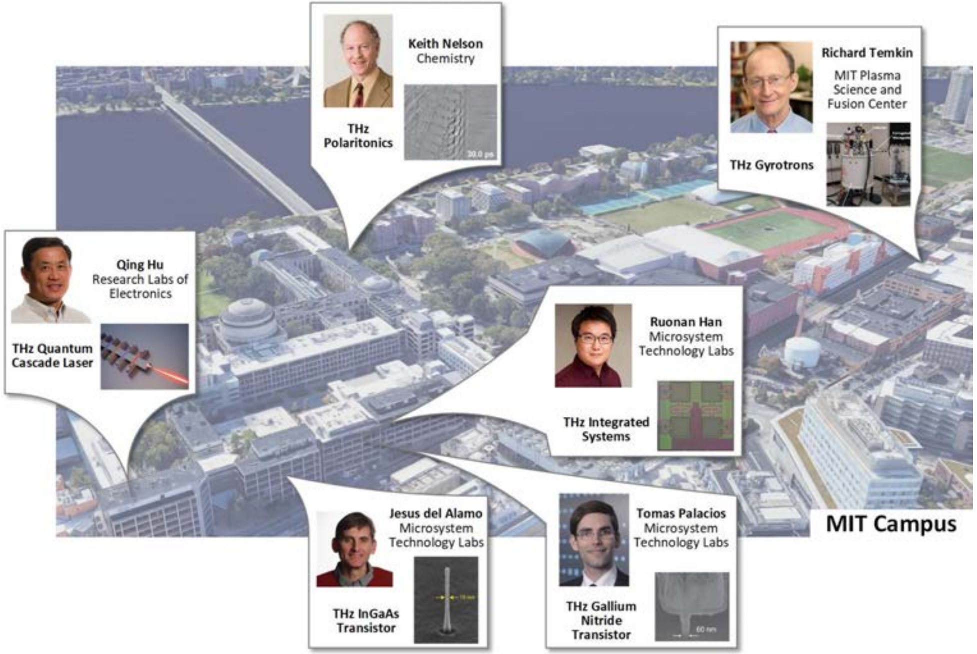
THz Quantum-Cascade Laser



Photoconductive Antenna







A Two-Dimensional Gap: Fiction or Fact?


The Truth About Terahertz

ANYONE HOPING TO EXPLOIT THIS PROMISING REGION OF THE ELECTROMAGNETIC SPECTRUM MUST CONFRONT ITS VERY DAUNTING PHYSICS

By Carter M. Armstrong

Illustration by Chad Hagen

> ANYONE HOPING TO EXPLOIT
> THIS PROMISING REGION
> OF THE ELECTROMAGNETIC
> SPECTRUM MUST CONFRONT
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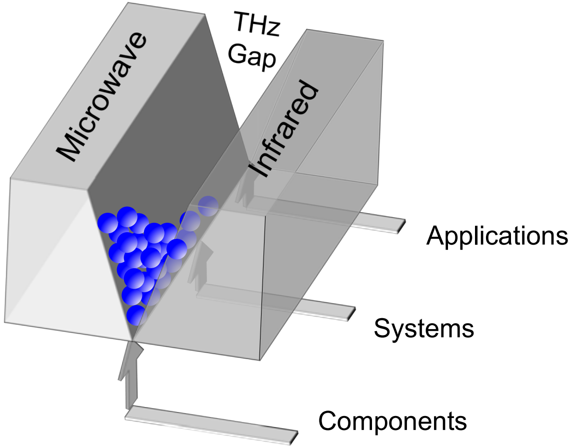
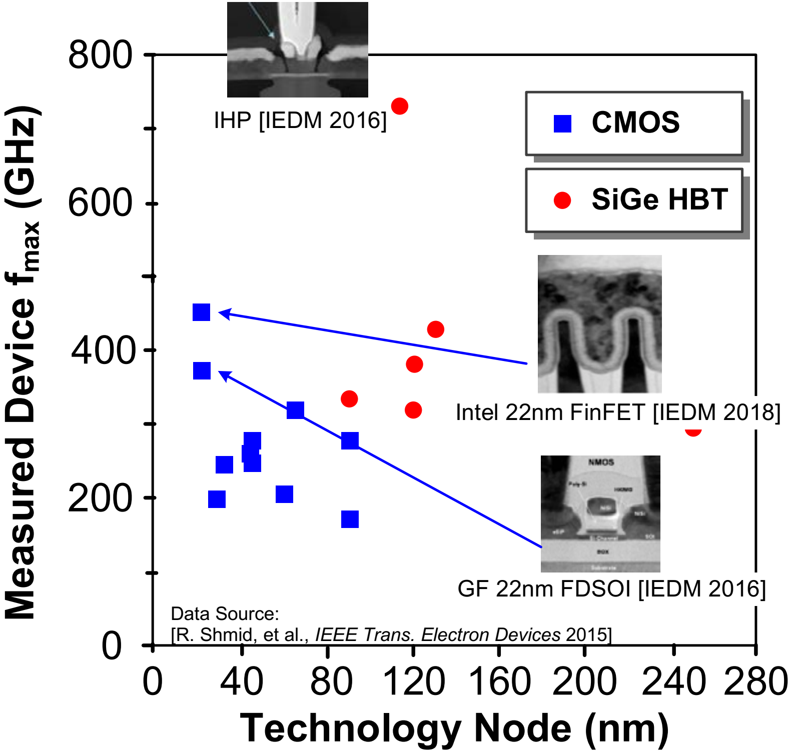
[C. Armstrong, *IEEE Spectrum*, 2012]



[R. Han, et al, “Filling the Gap: Silicon Terahertz Integrated Circuits Offer Our Best Bet”, *IEEE Microwave Magazine*, 2019]

Silicon-Based THz Circuits

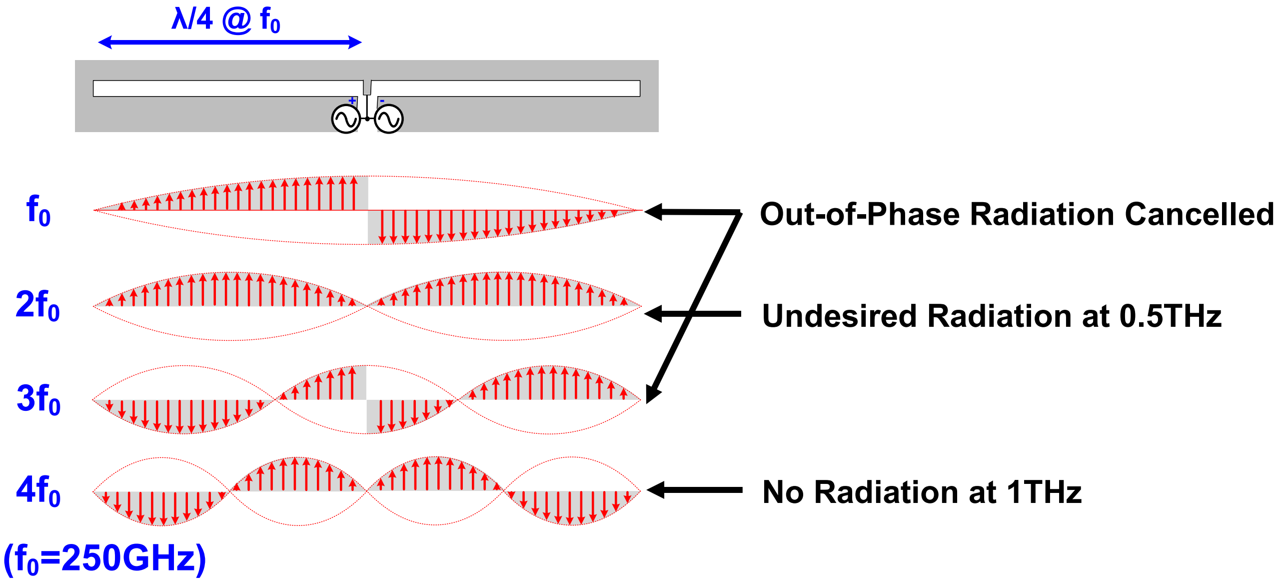


Source: National Geographics (Video Adapted by R. Han)

Fireflies in Sync: A 1-THz Radiator Array

- **How do we efficiently radiate the 4th-order harmonic power from a 250GHz silicon oscillator?**

[Z. Hu, et al., *RFIC* 2017 *(Best Student Paper Award), JSSC* 2018 (Invited)]



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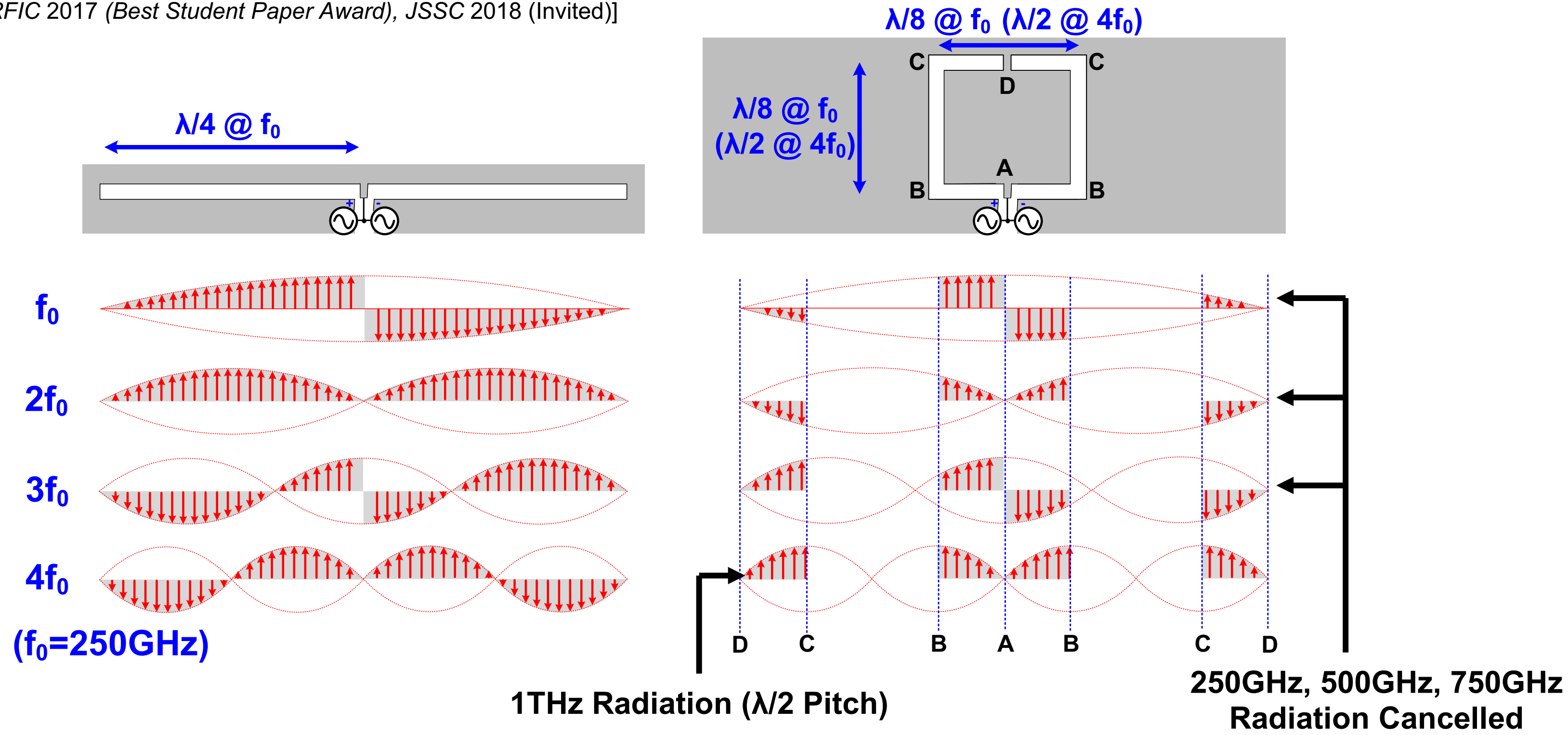

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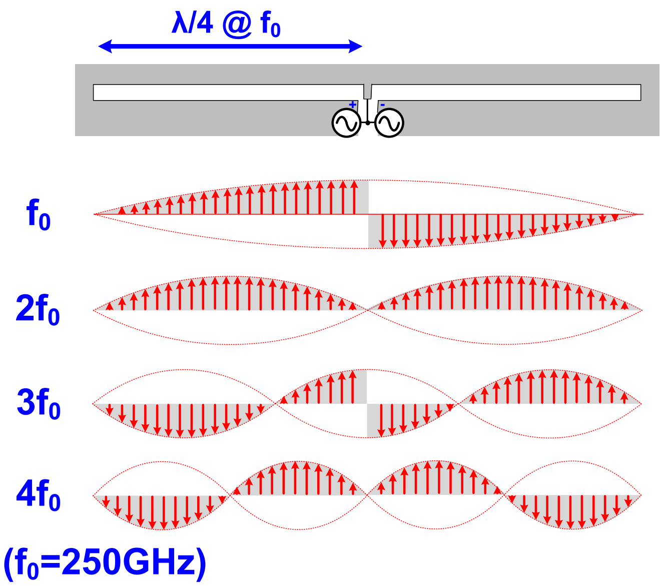

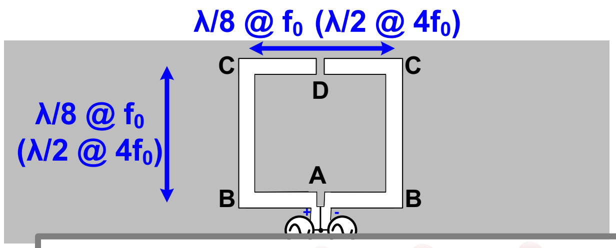

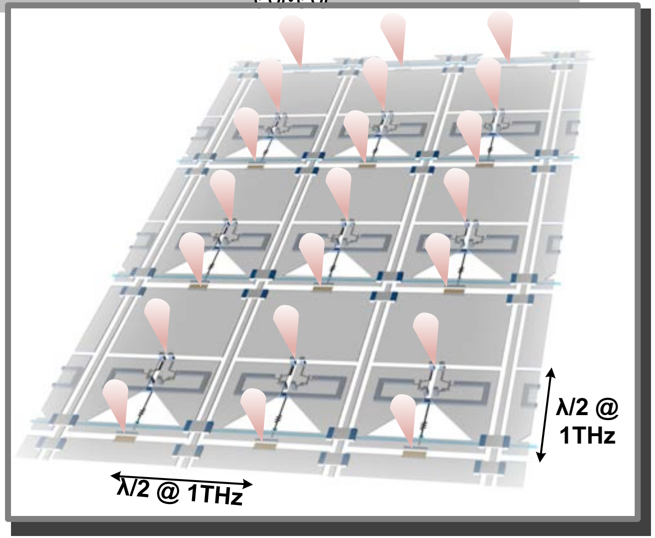

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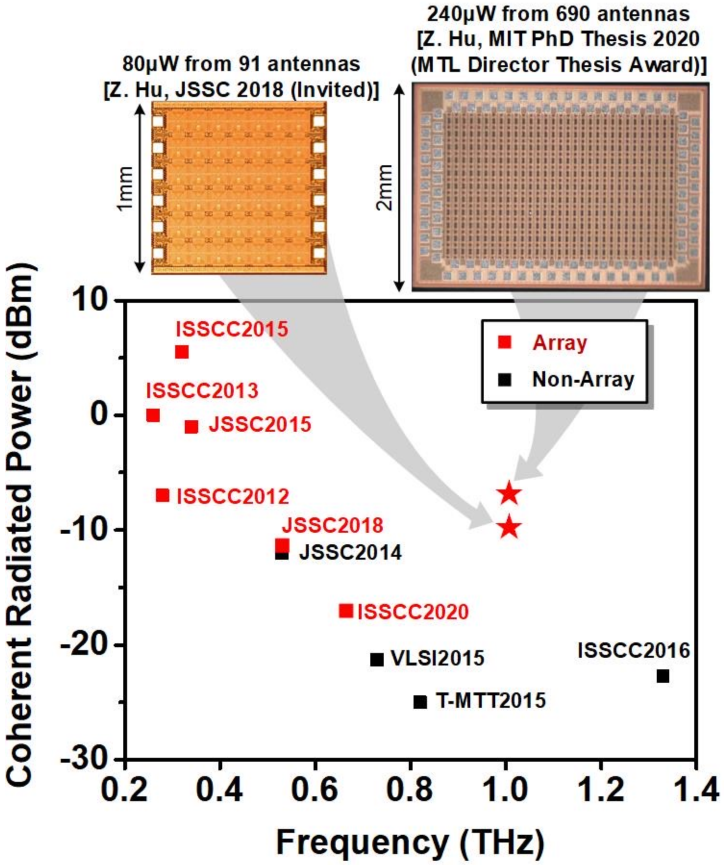
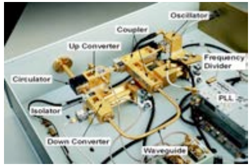


Filling the THz Gap with Sand



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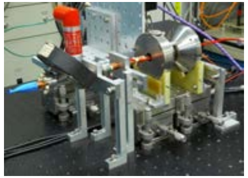

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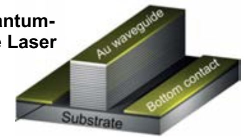

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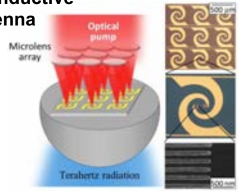
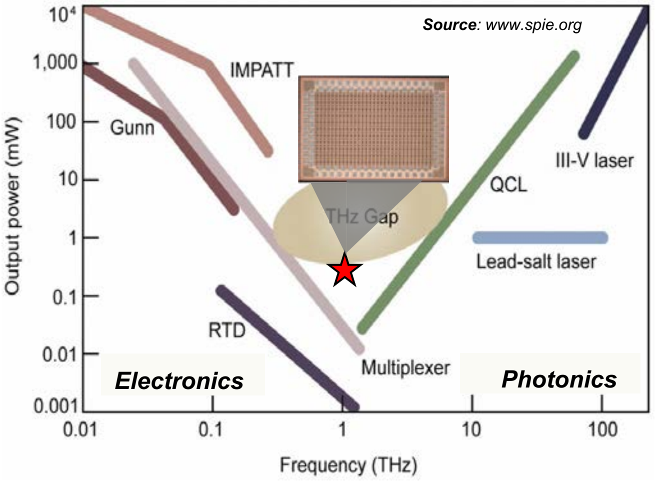
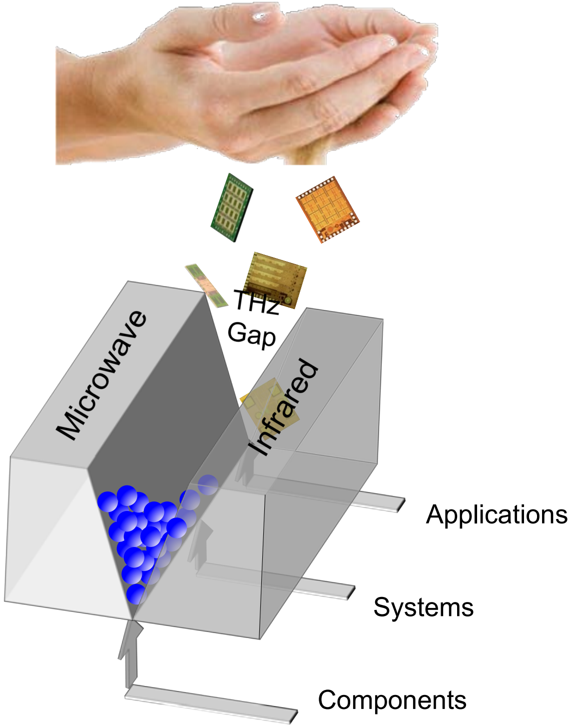
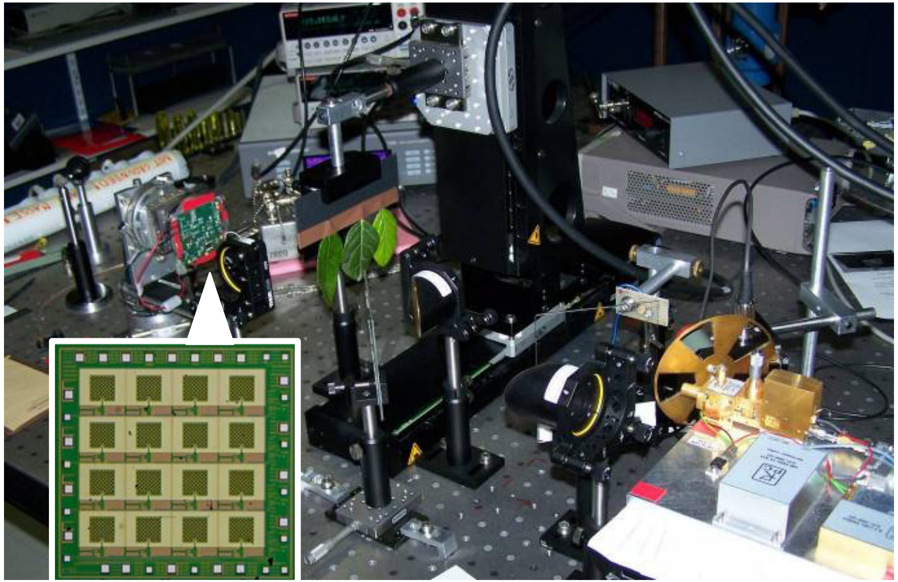






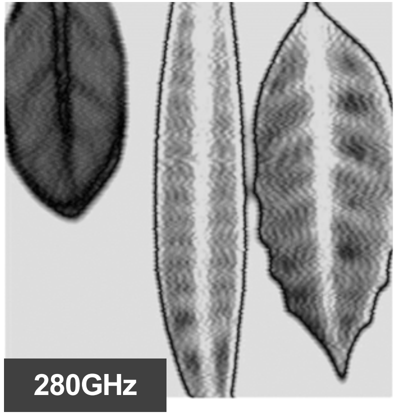
[R. Han, et al, "Filling the Gap: Silicon Terahertz Integrated Circuits Offer Our Best Bet", *IEEE Microwave Magazine,* 2019]

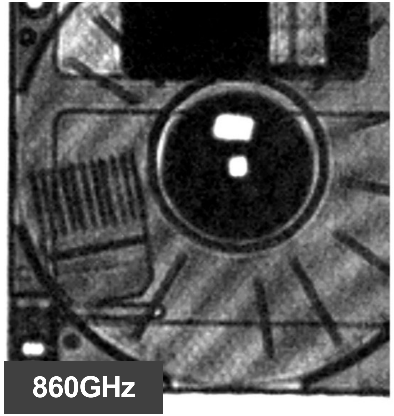
Terahertz Imaging and Its Practicality



Current THz Imaging Relies on Mechanical Scanning

[R. Han, et al, *JSSC* 2011, *ISSCC* 2012]





Towards High Angular Resolution Imaging

The missing puzzle:

- Pencil beam (<1°) formation
- Electrical beam steering in 2D

Aperture Area

Frequency

Beam Directivity

$$D = \frac{4\pi A f^2}{c^2}$$

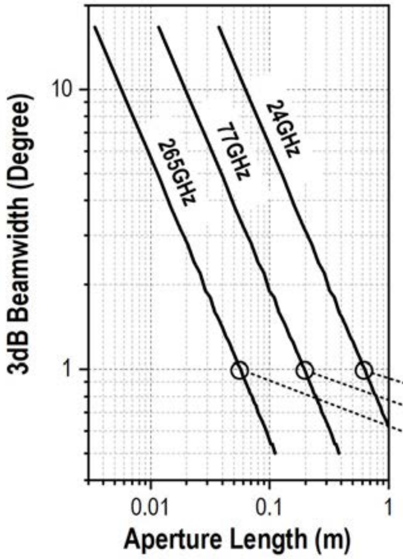
Speed of Light

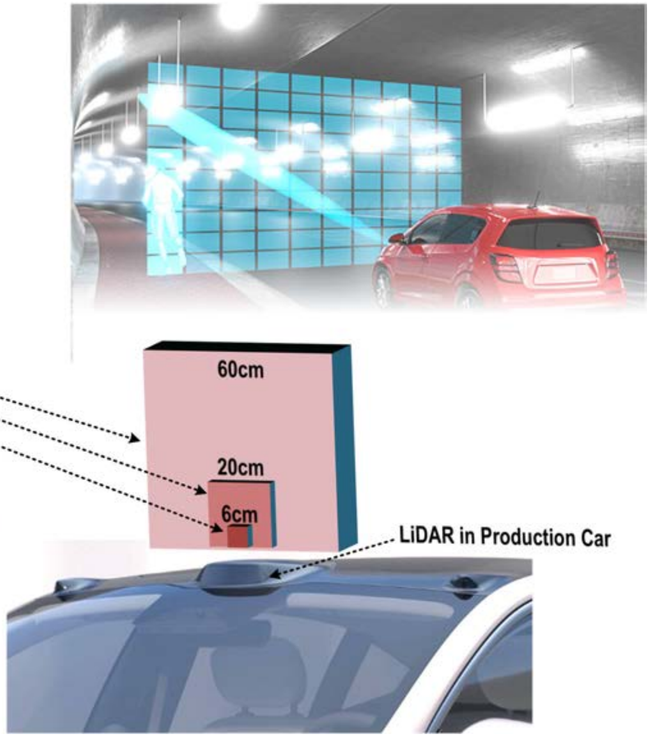
Opportunity in THz arrays:

- Smaller form factor
- Tiled chips/package modules

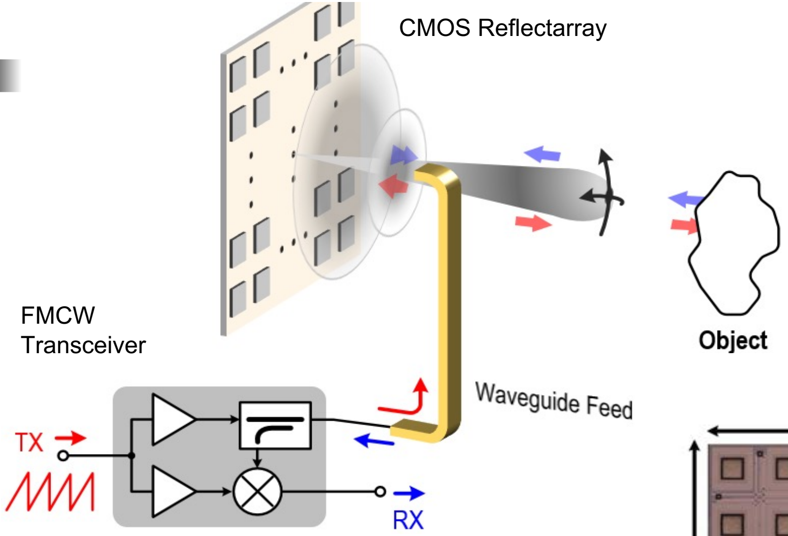
Challenges:

- Dense array: half-wavelength dilemma
- Large 2D RF-THz signal distribution
- High power consumption…



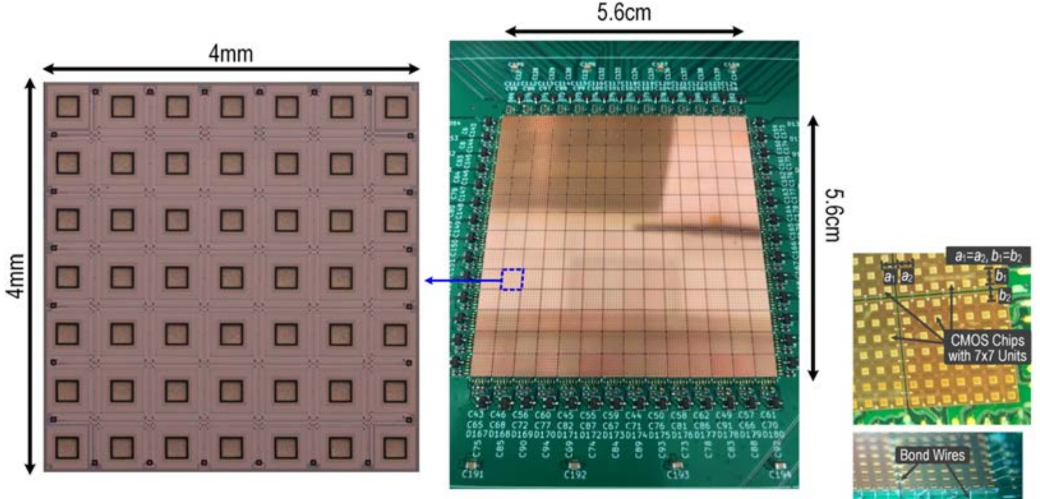


A CMOS 98x98 Reflectarray at 260GHz



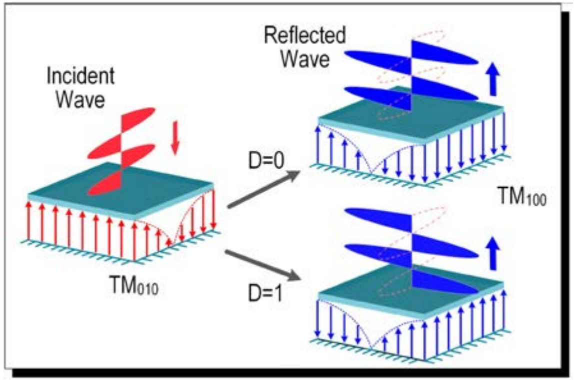
- **A 98x98 on-chip antenna array via 14x14 tiled CMOS chips**
  - Intel 22nm FinFET technology and advanced packaging
  - 5.6x5.6cm^2 total aperture size

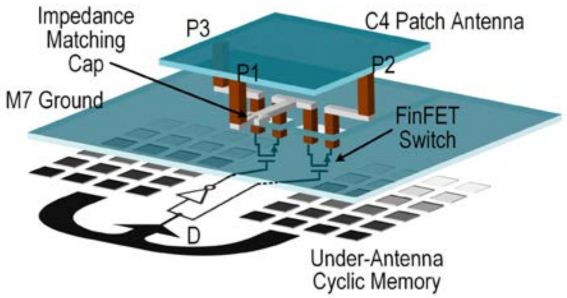
[N. Monroe, et al, *ISSCC* 2022]



- **Quasi-optical reflection and beam forming using a large-scale, phase-shifting back-scatter antenna array**

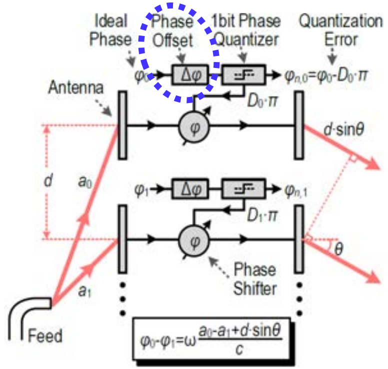
1-bit Phase-Shifting Backscatter Antenna with Built-In Memory

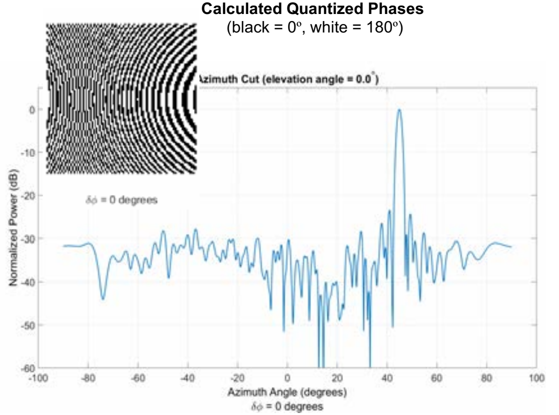




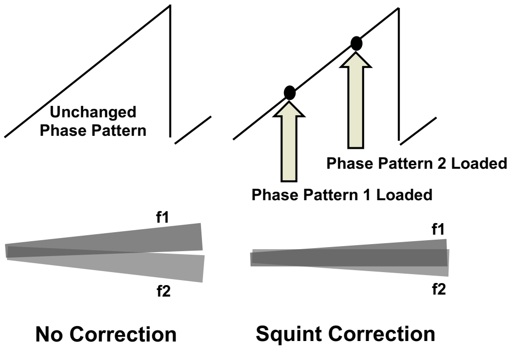
80kb memory per antenna

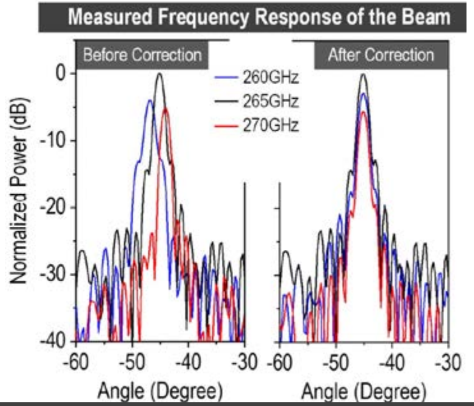
Time Dithering for Reduced Sidelobes



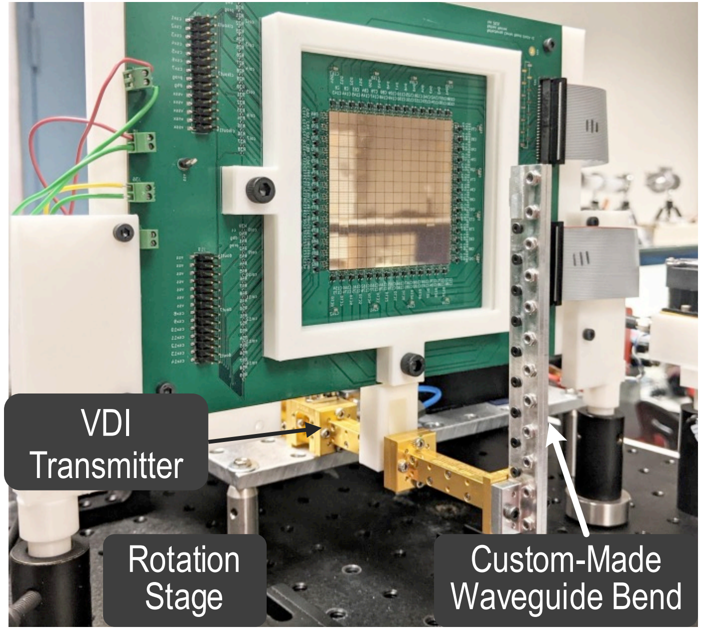


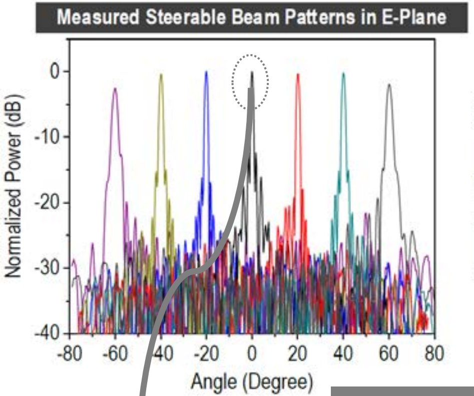
Beam Squint Correction in FMCW Scan

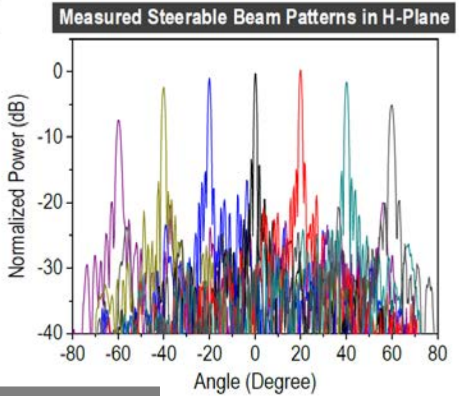




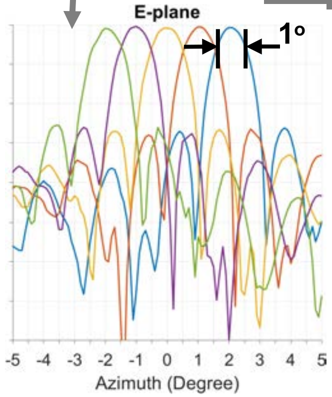
Electronic 2D Beam Forming and Steering



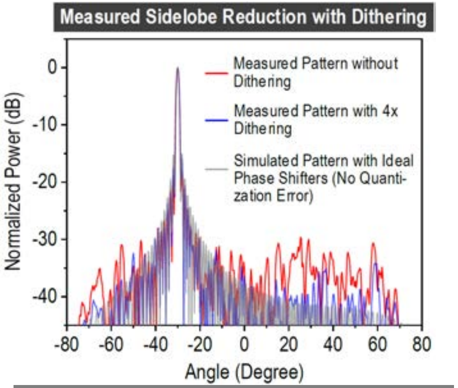




Steerable Range: >±60°

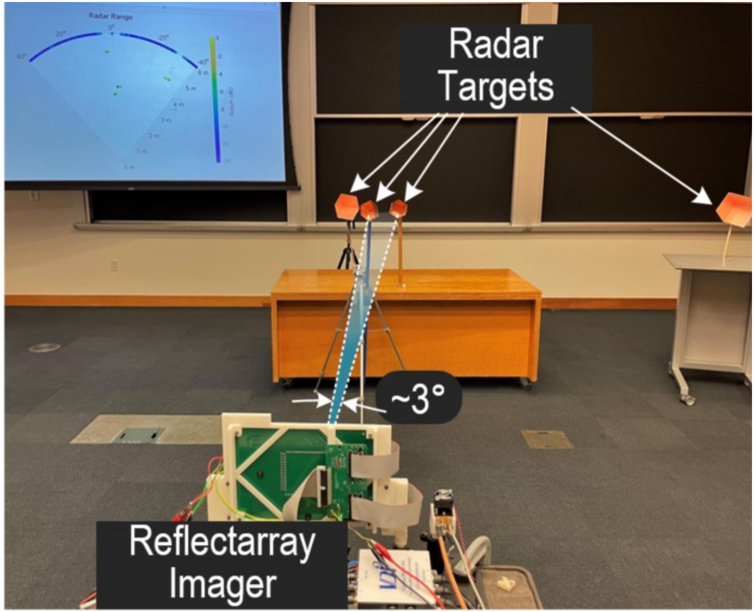


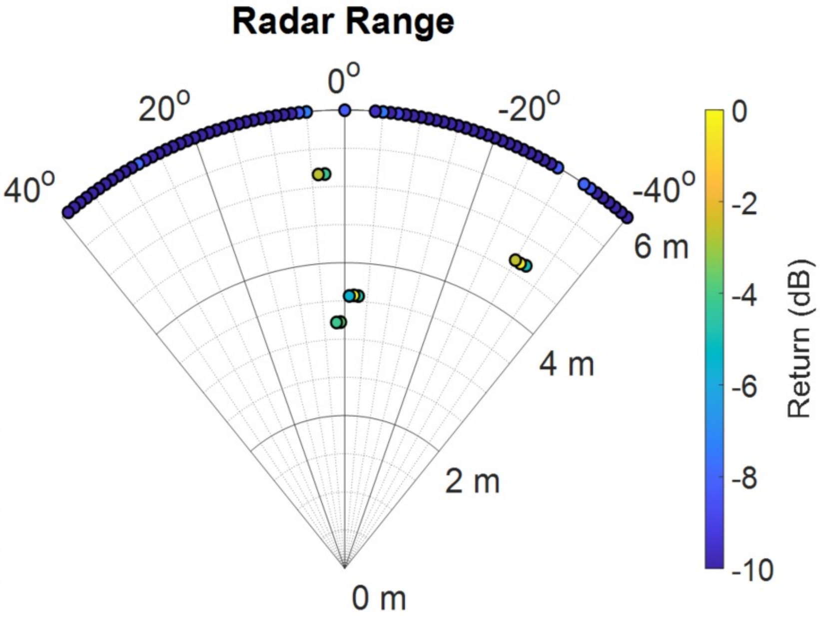
3dB Beamwidth: 1°



4.6dB Lower Integrated Sidelobe Power

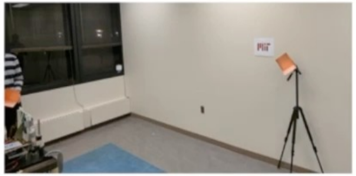
Angular-Resolution Tests

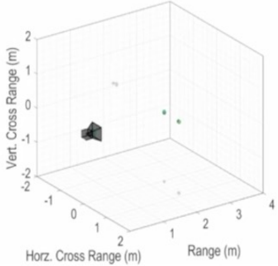




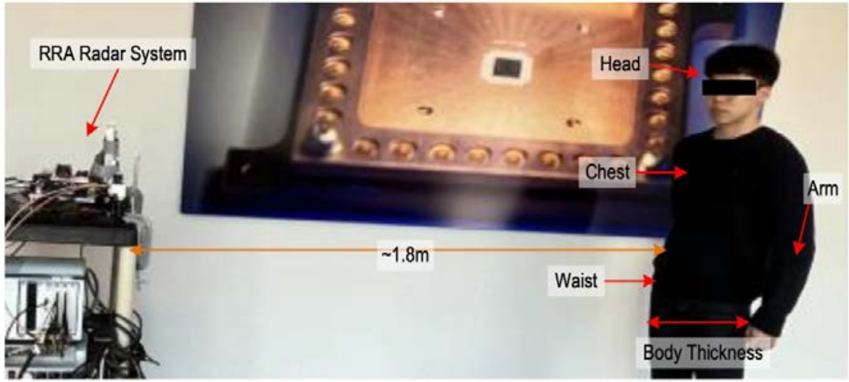
Terahertz 3D Imaging Demonstration

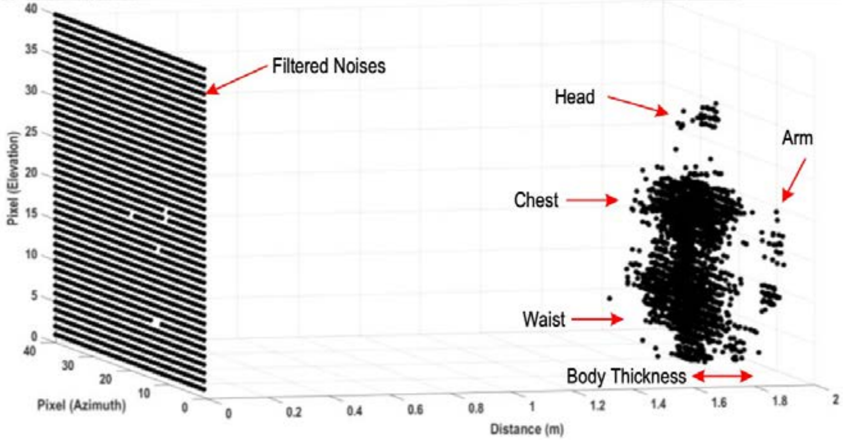
2. 3D Radar Imaging



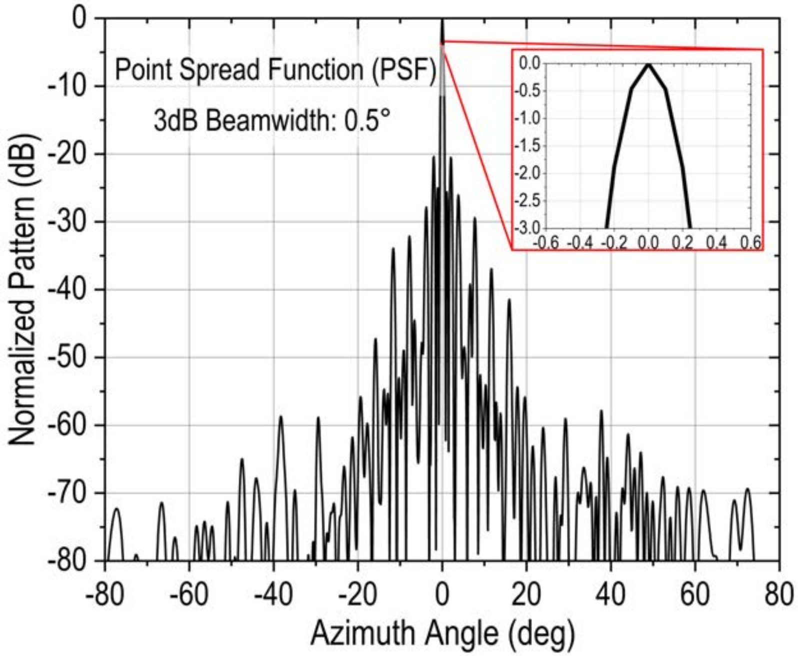


2x



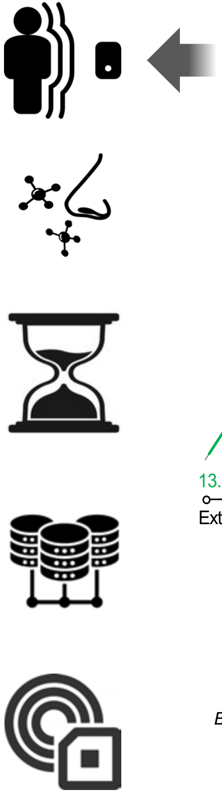


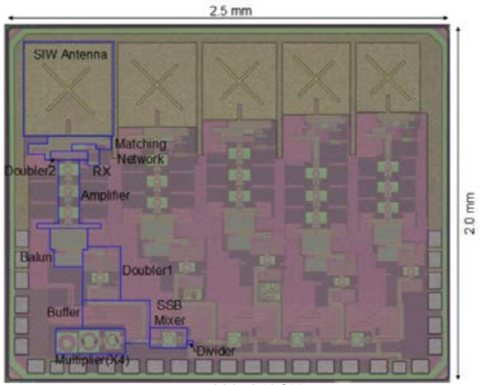
A Sneak Peek of What We Do Now with Intel



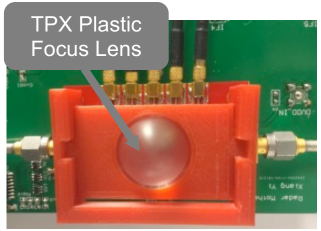
- Advanced THz antenna-in-package technology and large-scale chiplet integration
  - >10x reduction of silicon area and >1000x higher system SNR
- Expected imaging angular resolution: 0.5/2=0.25^{o} → Already similar to LiDARs!

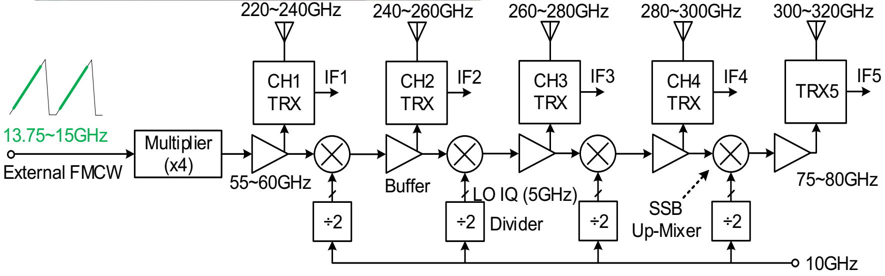
Ultra-Broadband Radar Transceiver for High Ranging Resolution

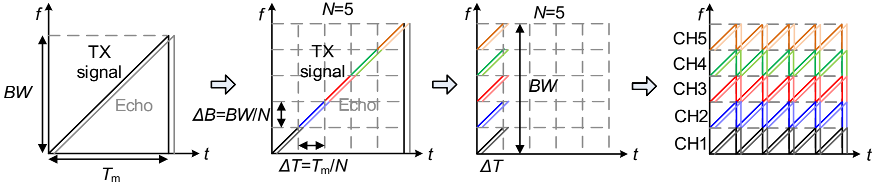




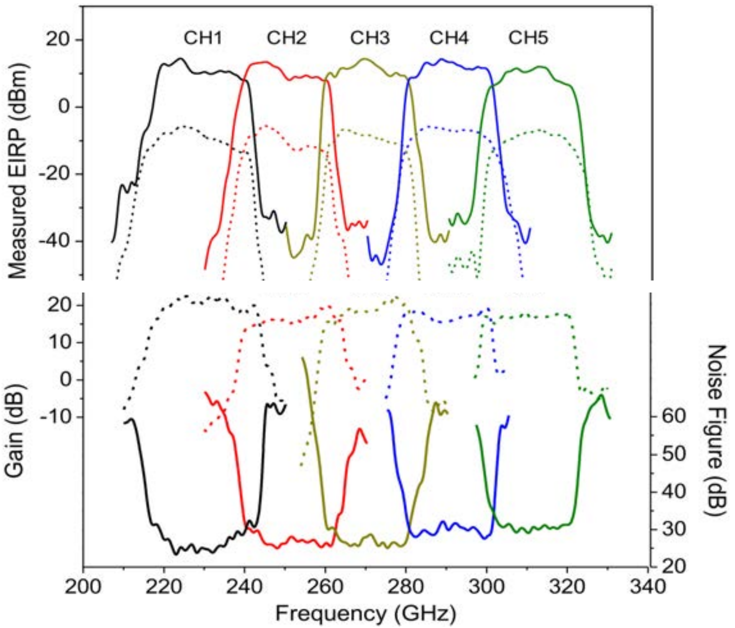
220-to-320GHz Comb Transceiver in 65nm CMOS
[X. Yi, et al, *ISSCC* 2020]





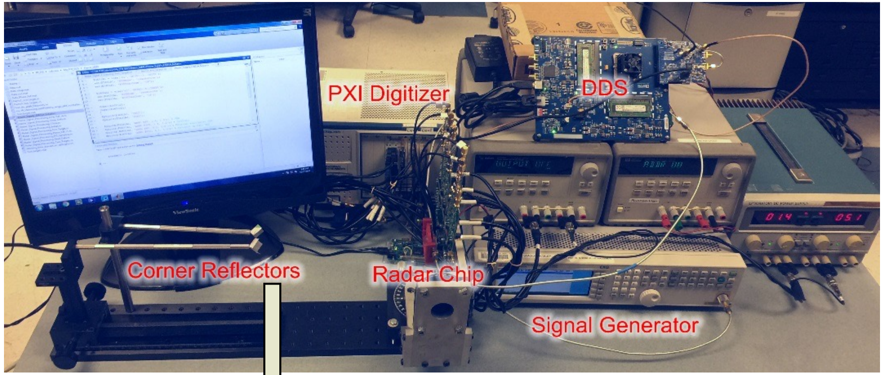


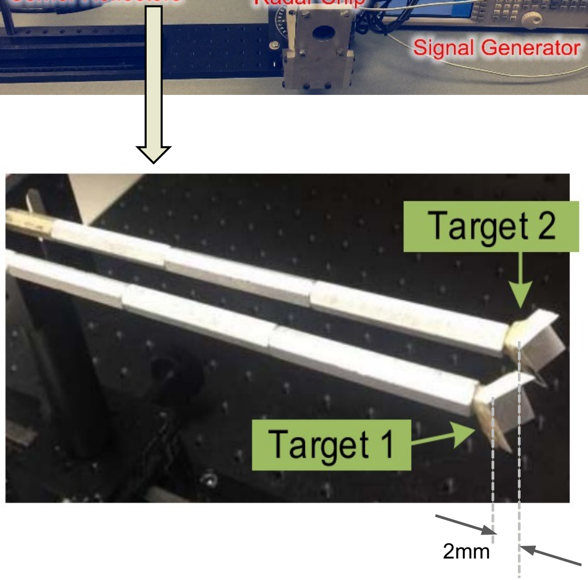
Conventional FMCW Radar to Comb Radar

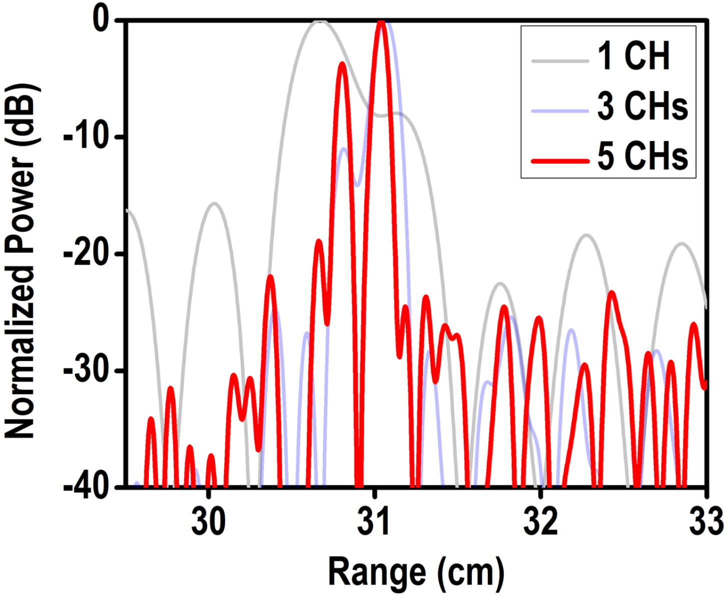


Measured Tx & Rx Performance

Ranging Resolution Test

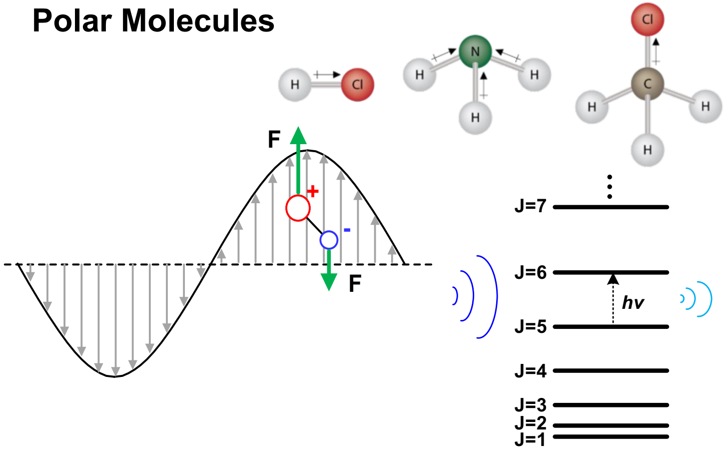


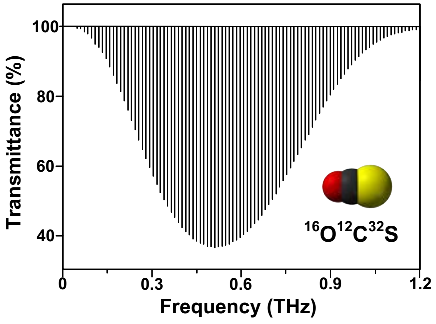




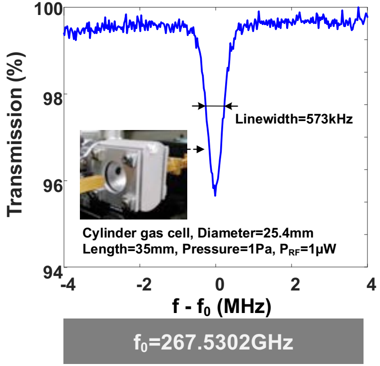
Rotational Spectroscopy

Polar Molecules

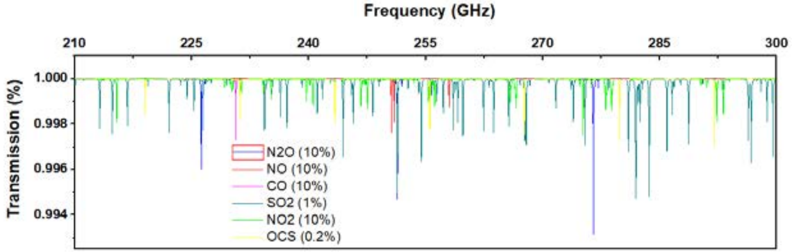




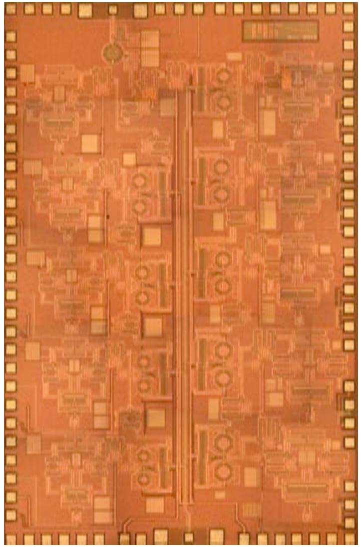
[C. Wang, et al, JSSC 2019]

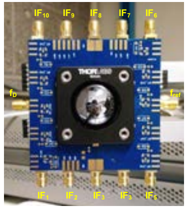


Molecule	Frequency (GHz)	Toxic?	Flammable?
Carbon Monoxide (CO)	230.538001	Y	Y
Sulfur Dioxide (SO_2)	251.199668		
Hydrogen Cyanide (HCN)	265.886441		Y
Hydrogen Sulfide (H_2S)	300.511959		Y
Nitric Oxide (NO)	250.436966	Y	
Nitrogen Dioxide (NO_2)	292.987169	Y	
Nitric Acid (HNO_3)	256.657731	Y	
Ammonia (NH3)	208.145904	Y	
Ethylene Oxide (C_2H_4O)	263.292515	Y	
Acrolein (C_3H_4O)	267.279359	Y	
Methyl Mercaptan (CH_3SH)	227.564672	Y	
Methyl Isocyanate (CH_3NCO)	269.788609	Y	
Methyl Chloride (CH_3Cl)	239.187523	Y	Y
Methanol (CH_3OH)	250.507156	Y	Y
Acetone (CH_3COCH_3)	259.6184	Y	Y
Acrylonitrile (C_2H_3CN)	265.935603	Y	Y

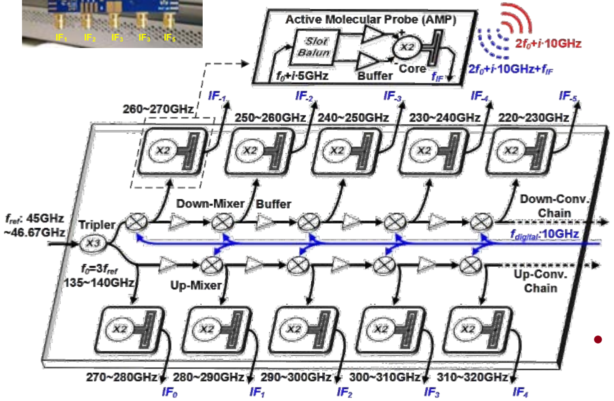


220-to-320 GHz Molecular Spectrometer

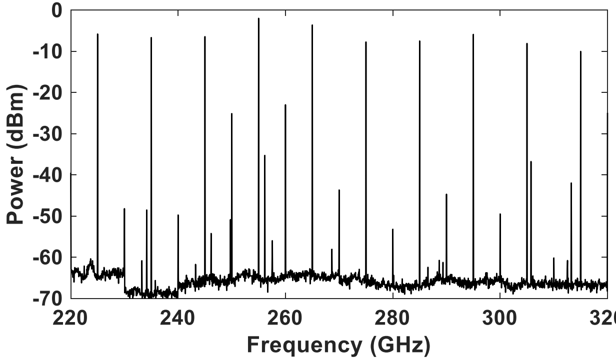




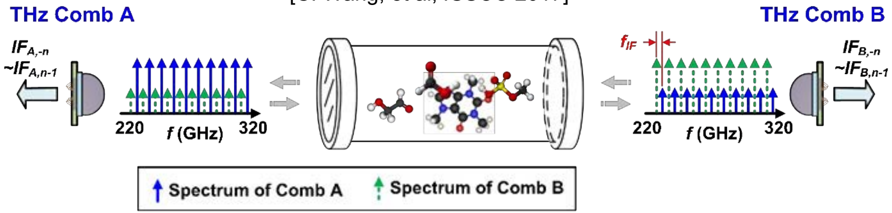
Chip Schematic and Packaging



Measured Radiation Spectrum



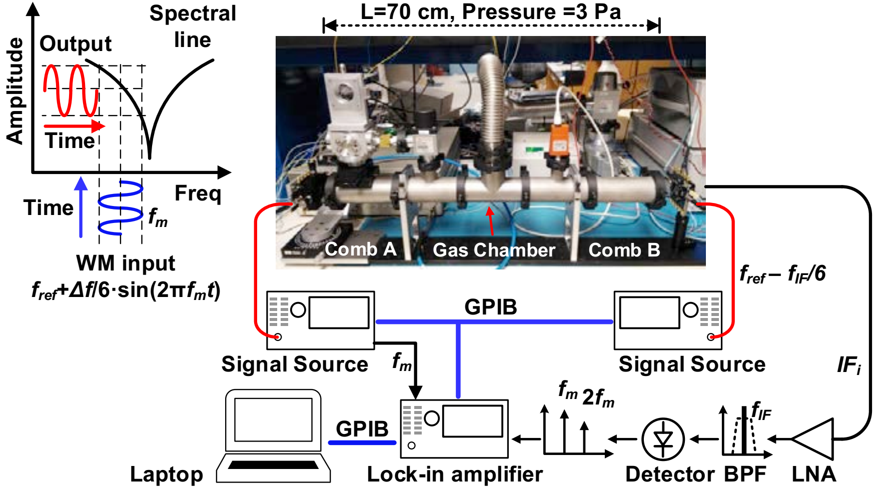
[C. Wang, et al, *ISSCC* 2017]

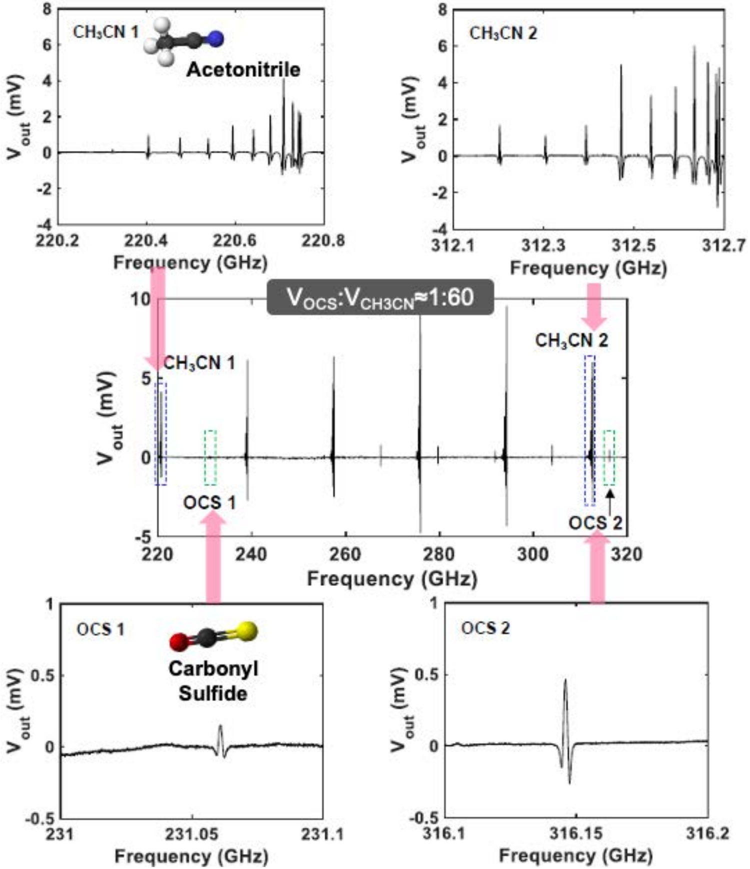


Dual-Comb Spectroscopy

- **Frequency-comb architecture**
  - 10 antenna-integrated transceivers
  - Daisy-chaining with equal frequency spacing
  - 20 tones scanning the band simultaneously → higher spectroscopic speed
  - Broadband coverage without performance degradation on the band edges
- **Chip prototype in 65nm CMOS**
  - P_{rad}=5.2mW, NF_{SSB}=14.6~19.5dB
  - P_{DC}=1.7W

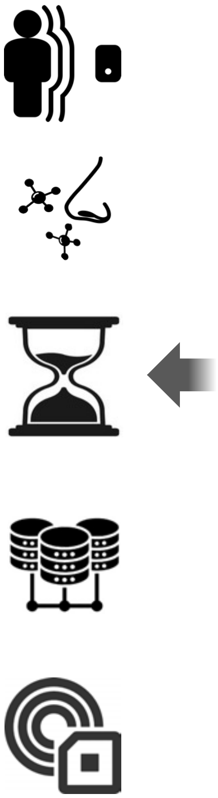
220-to-320 GHz Molecular Spectrometer

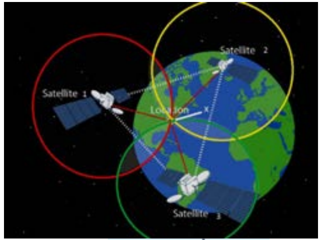


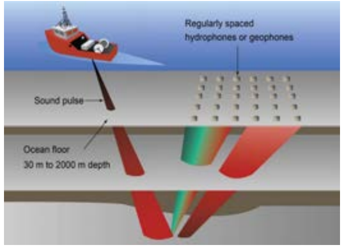


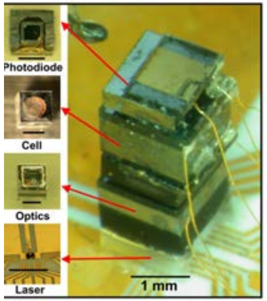
[C. Wang, et al., *T-BioCAS* 2018]

Poor Men's "Atomic Clock"





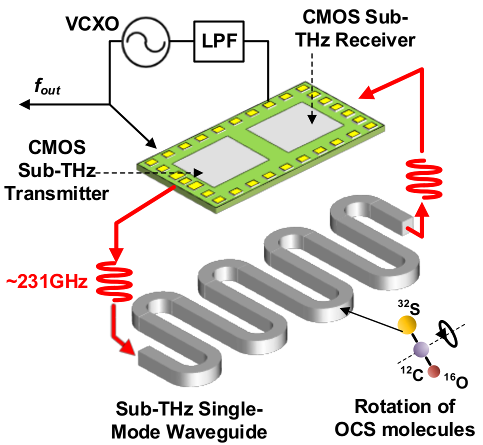


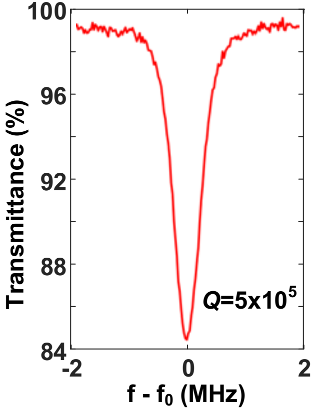


[Microsemi CSAC]

[Nguyen, Kitching, ISSCC 2005]

Chip-Scale Atomic Clock (CSAC)



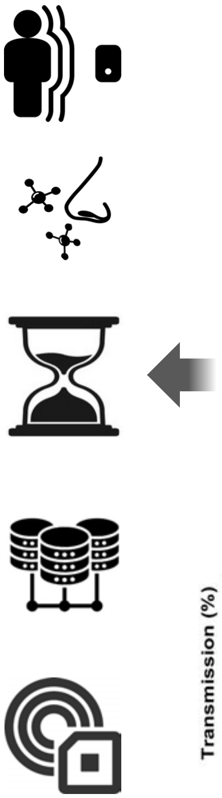


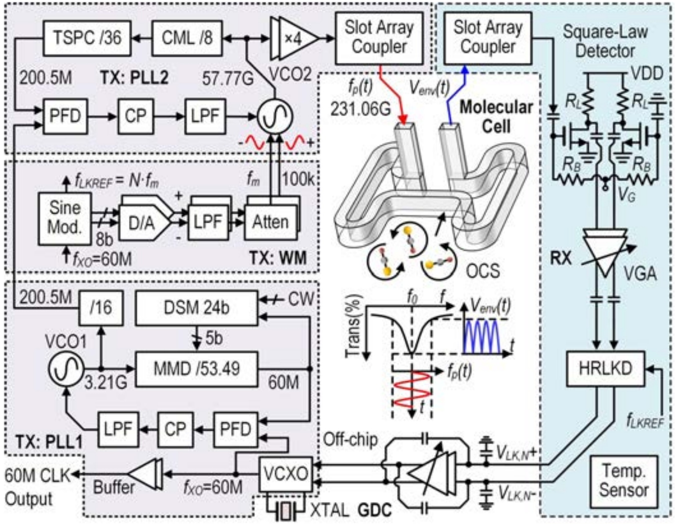
$f_0 \approx$ 231.061 GHz

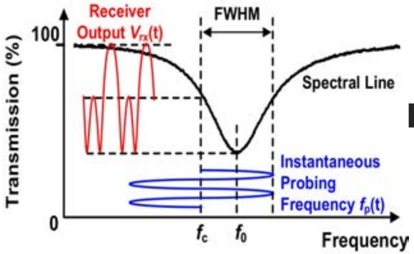
- Transition of carbonyl sulfide (OCS): f_0≈231.061GHz
- Fully-electronic operation and simplified construction with THz waveguide gas cell
- Low-cost, high-precision spectrometer on CMOS

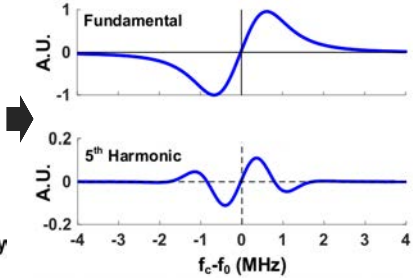
Chip-Scale Molecular Clock

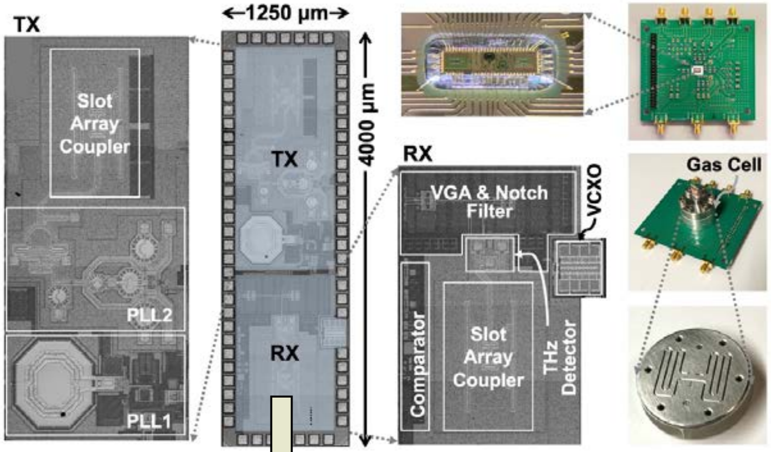
Three Generations of Development

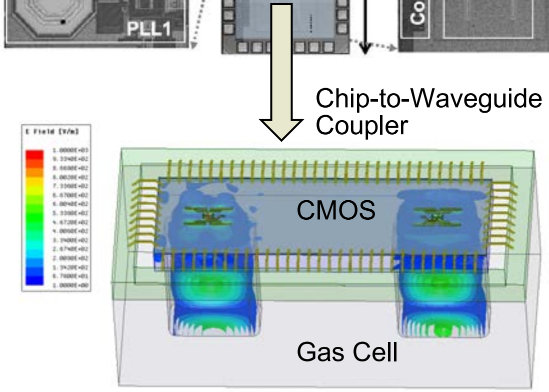


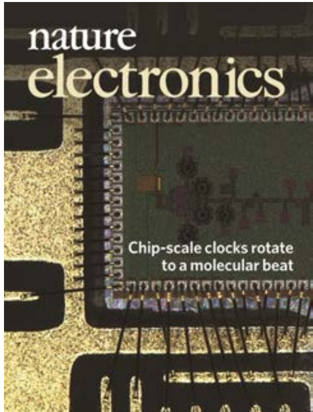






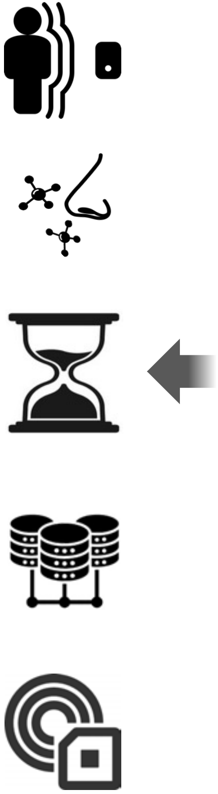


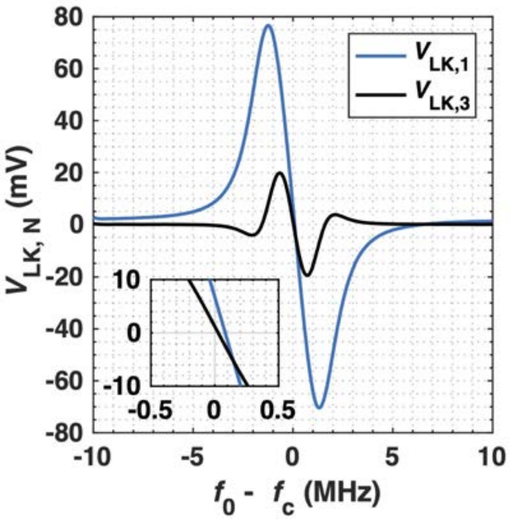


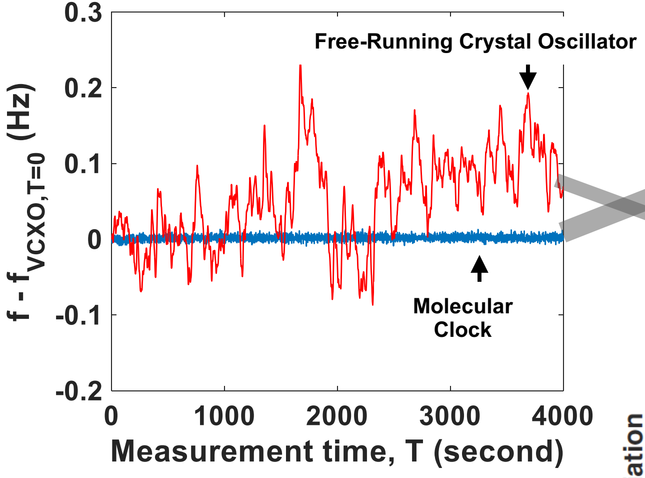


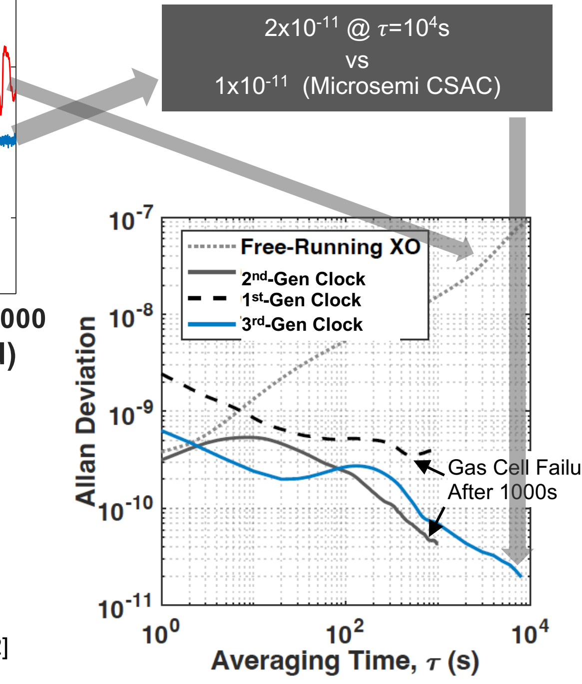
[C. Wang, *Nat. Electron.* 2018]
[C. Wang, *ISSCC* 2020]
[M. Kim, *RFIC* 2022]

Experimental Results of the 3rd-Gen Molecular Clock





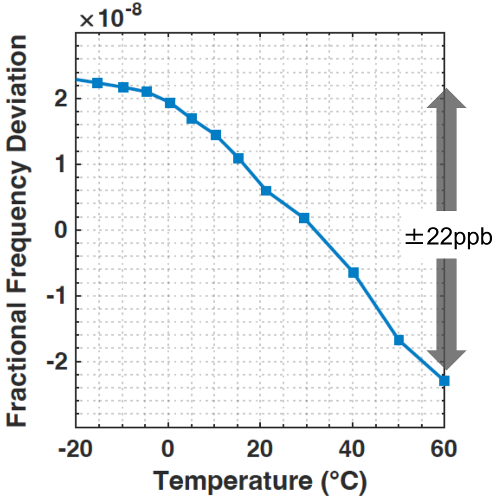




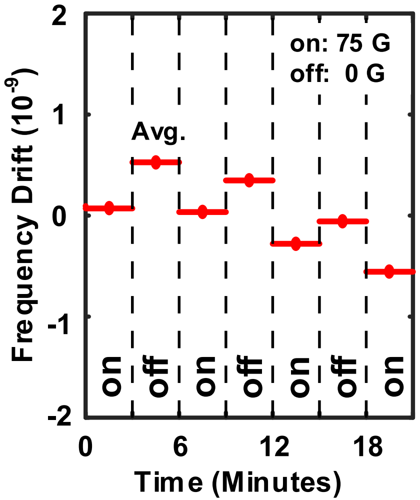
- **70 mW (vs 120 mW for Microsemi CSAC)**
- **15 cm^3 (vs 17 cm^3 for Microsemi CSAC)**
  - <1 cm^3 expected in the future
- **Low-cost implementation**

[M. Kim, RFIC 2022]

Experimental Results of the 3rd-Gen Molecular Clock

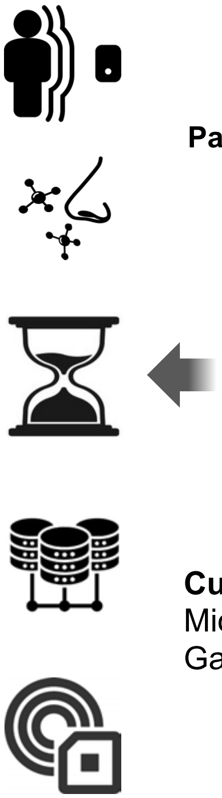


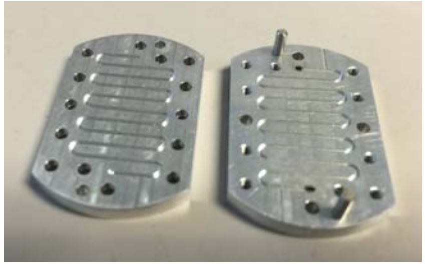
±22ppb @ -20~60°C
(No Thermal Stabilization,
No Temp. Compensation)
vs
±0.5ppb Microsemi CSAC
(with Built-In Oven)



$\pm 3\text{x}10^{-12}$/G
(No Magnetic Shield)
vs
$\pm 9\text{x}10^{-11}$/G Microsemi CSAC
(100x Magnetic Shield)

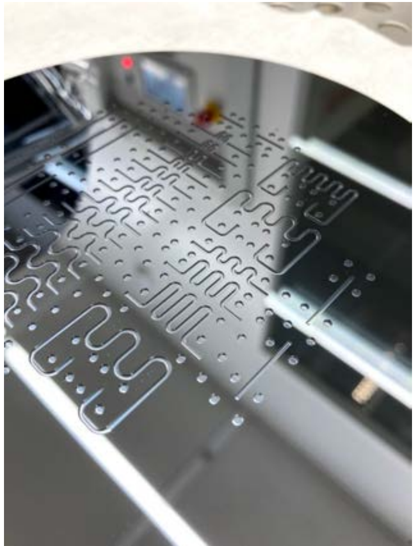
Gas Cell Miniaturization in the Future



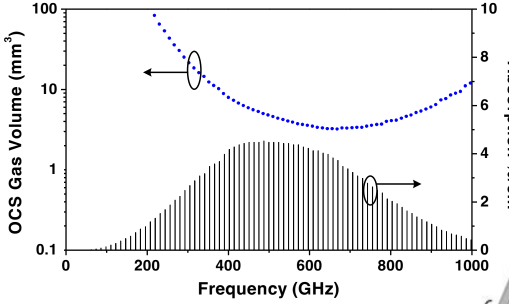


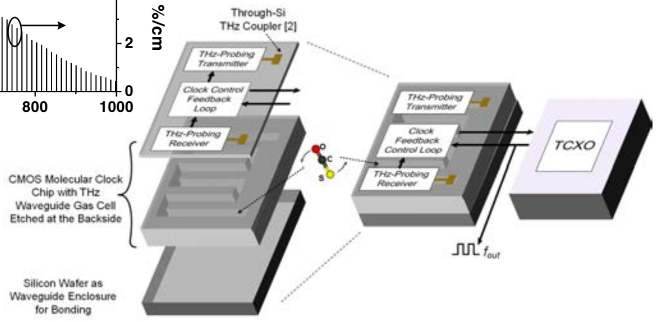
Past: CNC Metal Gas Cell

Current: Gas Cell via 3D Metal Printing



Current: Silicon Micromachined Gas Cell

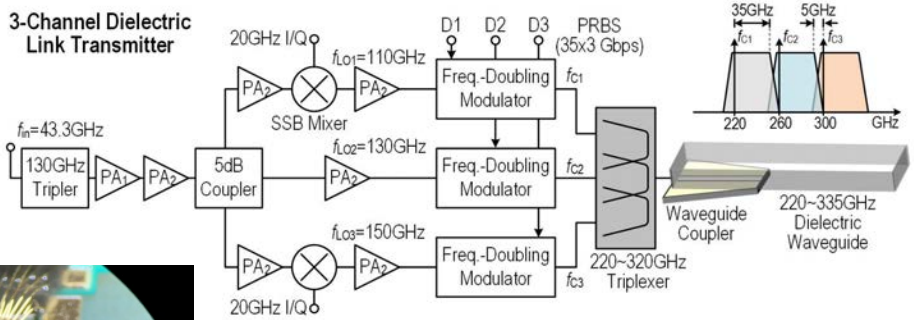


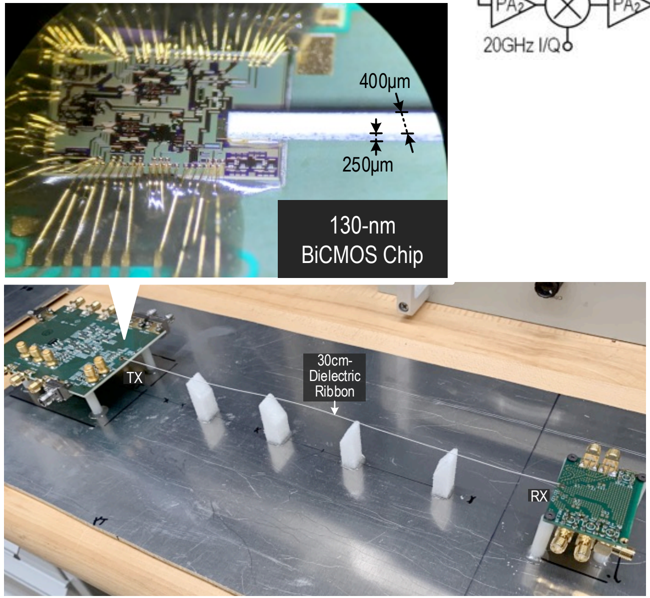


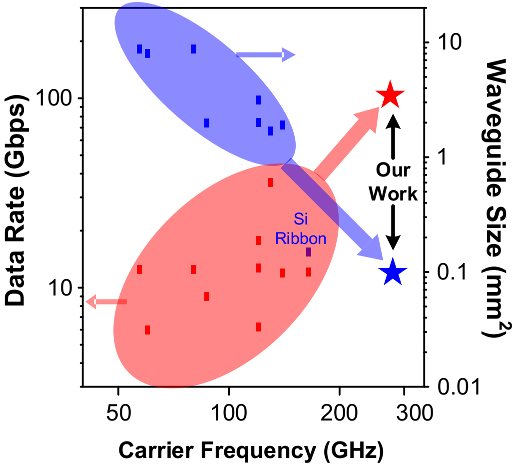
Future: In-Substrate Gas Cell

Funded By Intel. Collaborator: George Dogiamis

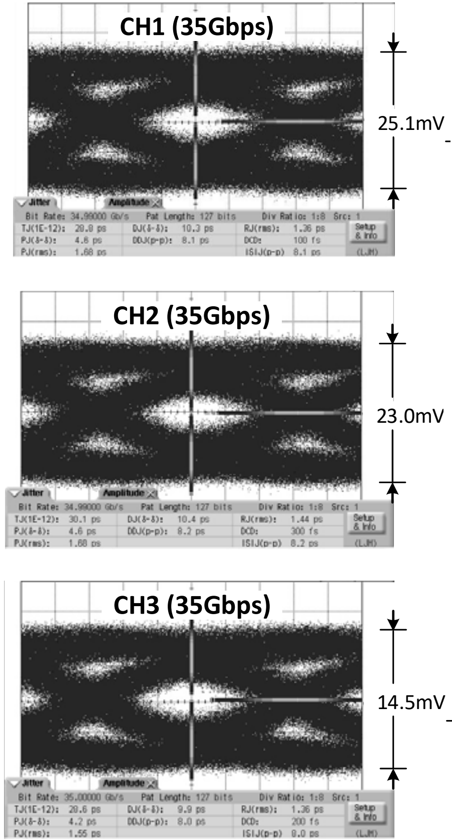
Big Data Over A Piece of Plastic



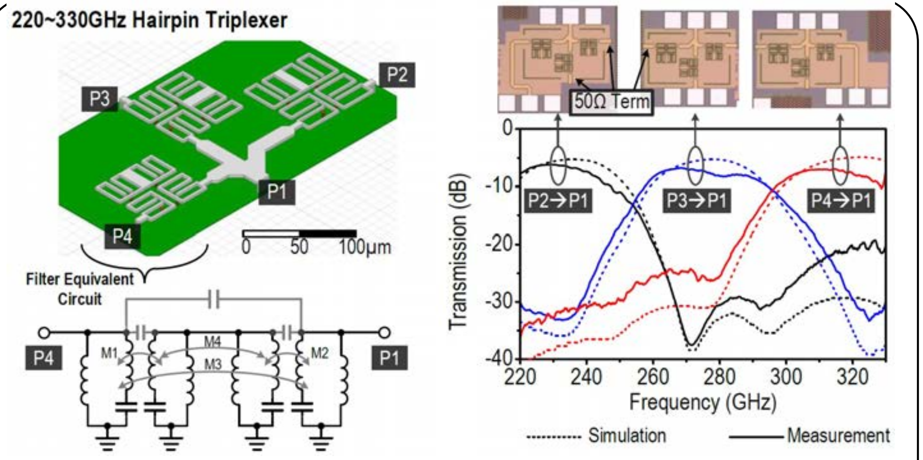




[J. Holloway, et al., *ISSCC*, 2021]

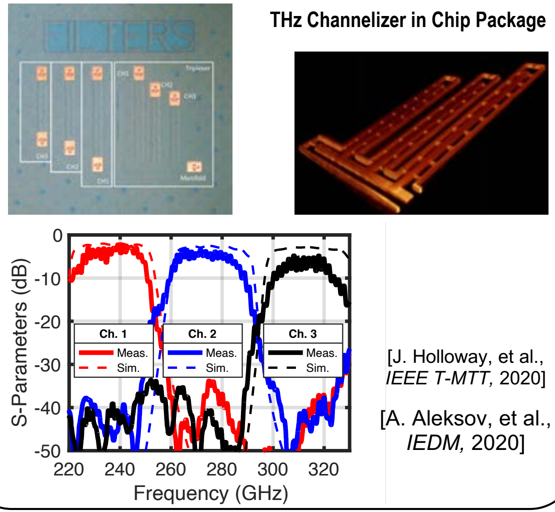


Big Data Over A Piece of Plastic



[J. Holloway, et al., *IEEE Microwave Magazine*, 2020 (Invited)]

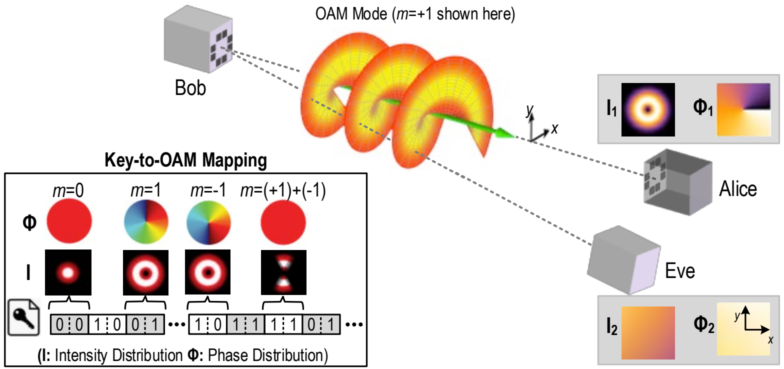
THz Channelizer in Chip Package



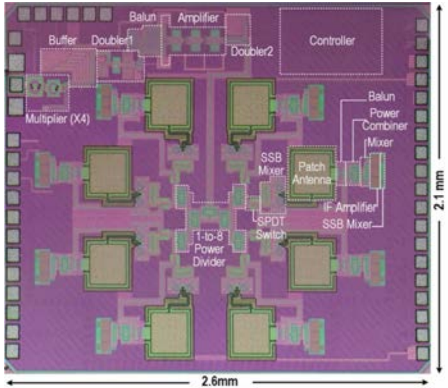
[J. Holloway, et al., *IEEE T-MTT*, 2020]

[A. Aleksov, et al., *IEDM*, 2020]

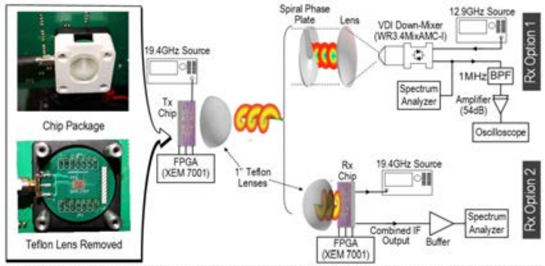
Secured Communication Using THz OAM Wave

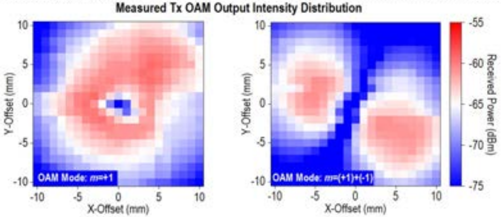


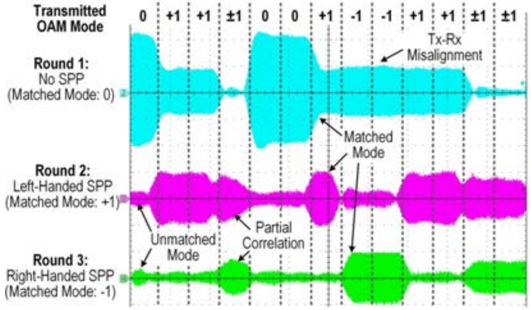
- **One-way transmission of secret key**
  – Information encoded in spatial-distributed modes
  – Precise co-axial alignment required
- **The first OAM generation & detection chip**
  – TSMC 65nm CMOS
  – Data-driven OAM mode switching



310GHz OAM Transceiver
[M. Khan, et al, *RFIC* 2021
(Best Student Paper Award, First Place)]

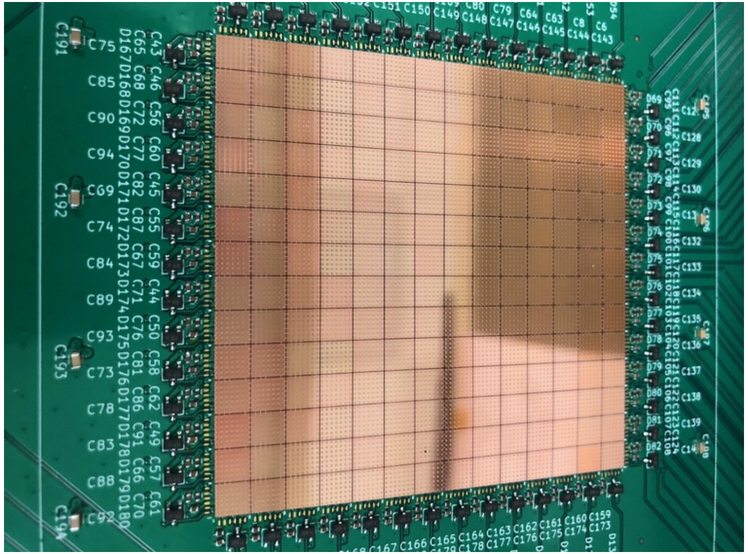






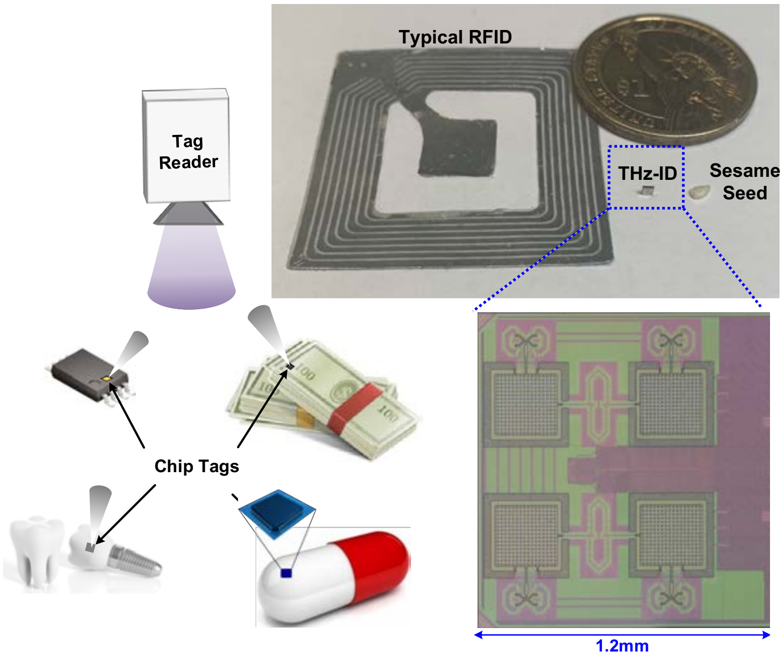
What’s the Missing Opportunity in THz Wireless?

USAF PAVE-PAWS Radar (*f*=0.4 GHz)
2.2^{o} beamwidth, 2677 antennas, 22x22 m^2

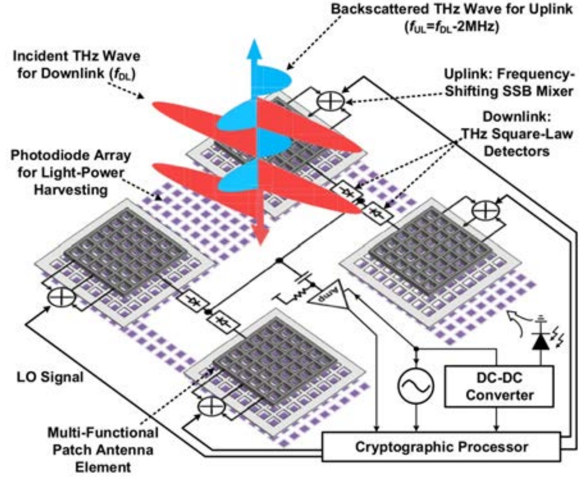


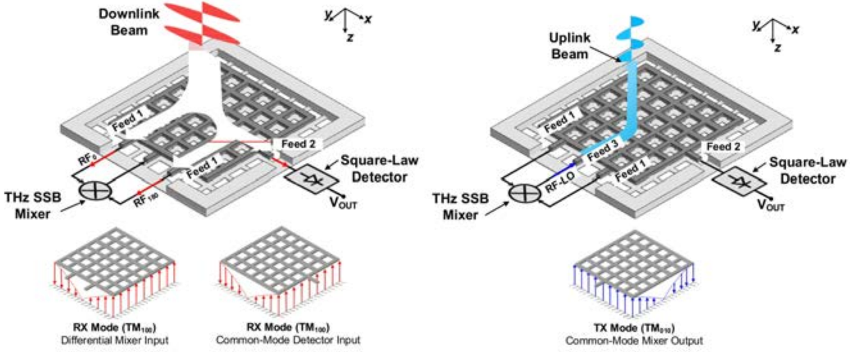
MIT-Intel CMOS Reflectarray (f=265 GHz)
1^{o} beamwidth, 9604 antennas, 0.05x0.05 m^2

THz-ID: Ultra-Miniaturized Tag with Built-In Security

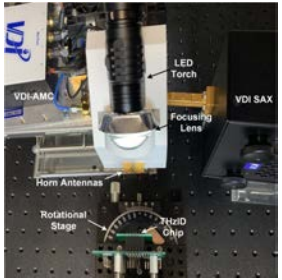


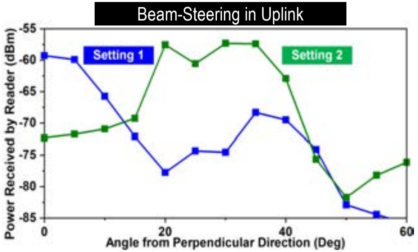
THz-ID: 1.5mm² Tag with 260-GHz Backscatter Communication and Built-In Security
[M. Ibrahim, et al., *ISSCC* 2020]

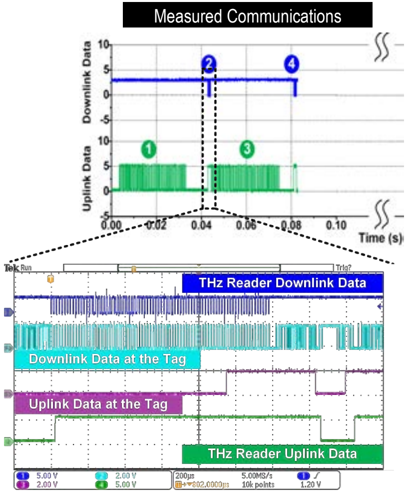


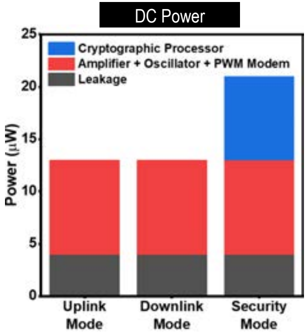


Tag of Everything



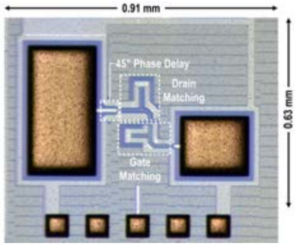






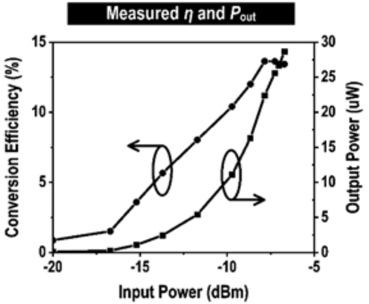
- 5-cm operation distance
- Built-in ECC authen-tication processor
- Photovoltaic powering

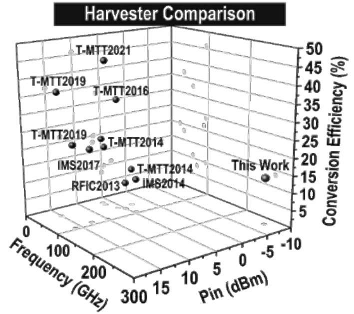
[M. Ibrahim, et al., *ISSCC* 2020]

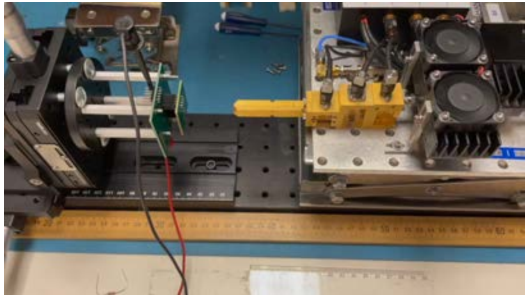


- Recent progress: 260-GHz energy harvesting in Intel-16 CMOS
  - 15% THz-to-DC efficiency @ -8dBm input power
  - 25μW output DC power

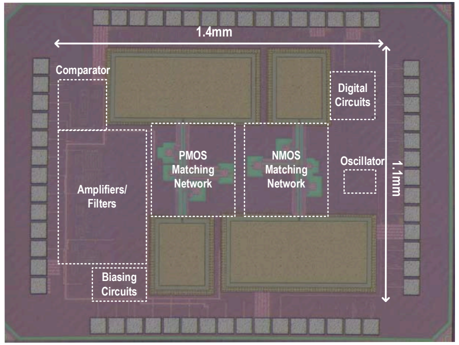
[M. Ibrahim, et al., *RFIC* 2022]



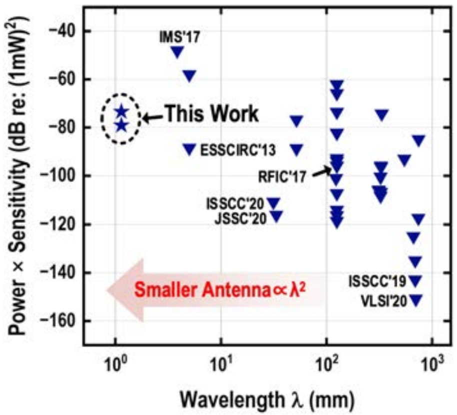


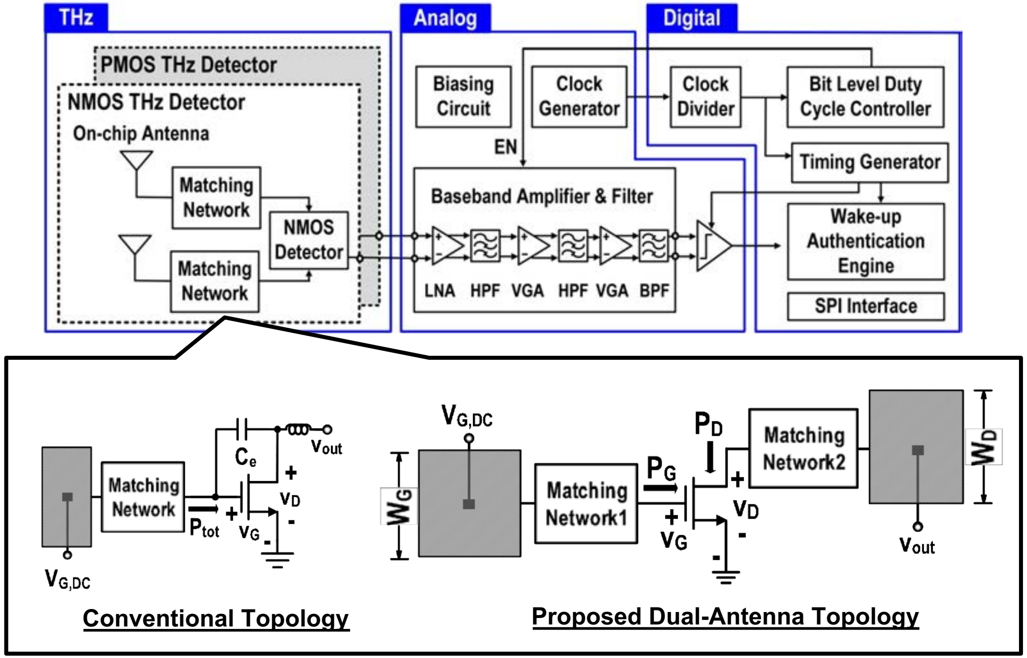


THz Wake-Up Receiver for Ultra-Miniaturized Sensing Platform



EM wake-up receiver

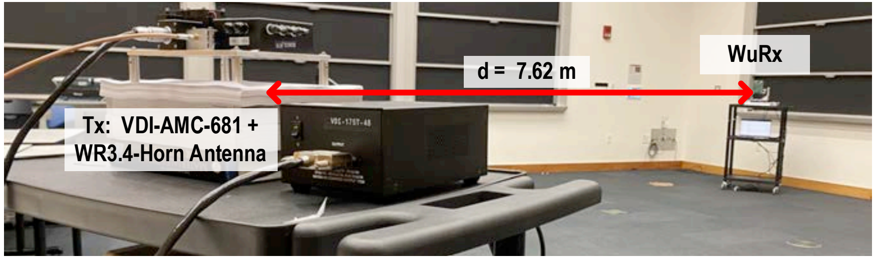




- **260-GHz CMOS wake-up receiver** [E. Seok, et al., *CICC* 2023]
  - The smallest RF wake-up receiver (1.5mm^2)
  - 750nW DC power
  - Built-in security authentication against denial-of-sleep attack

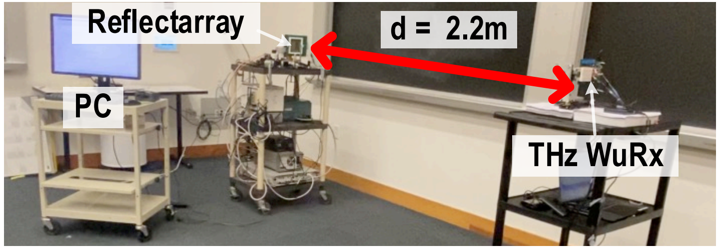
Demonstrations

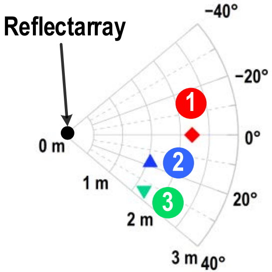
Demo1



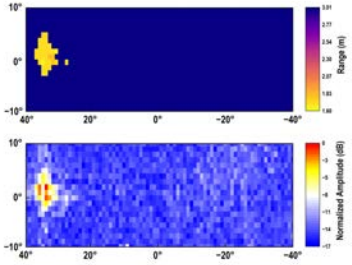
Tx - WuRx Distance	Bit Error Rate (BER)
5.1 m	5.7×10^{-3}
7.6 m	1.7×10^{-2}

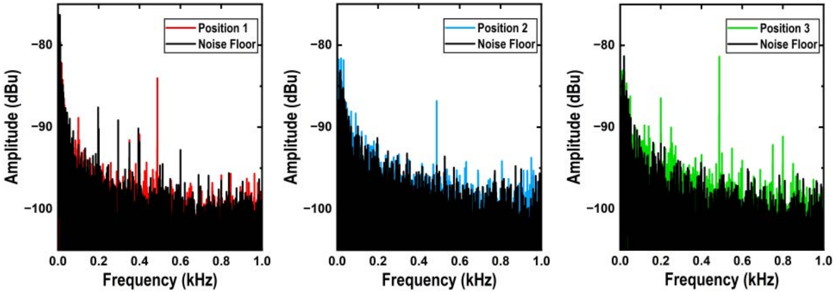
Demo2



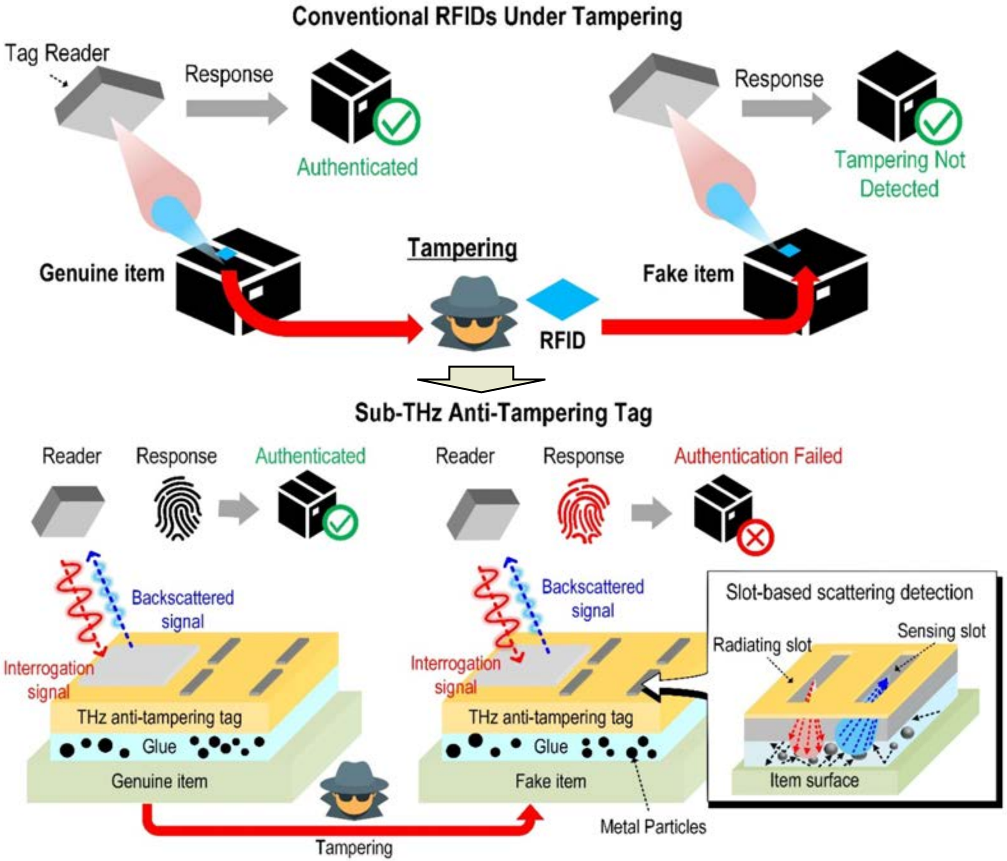


Location of the WuRx @ 30°(Nominal)

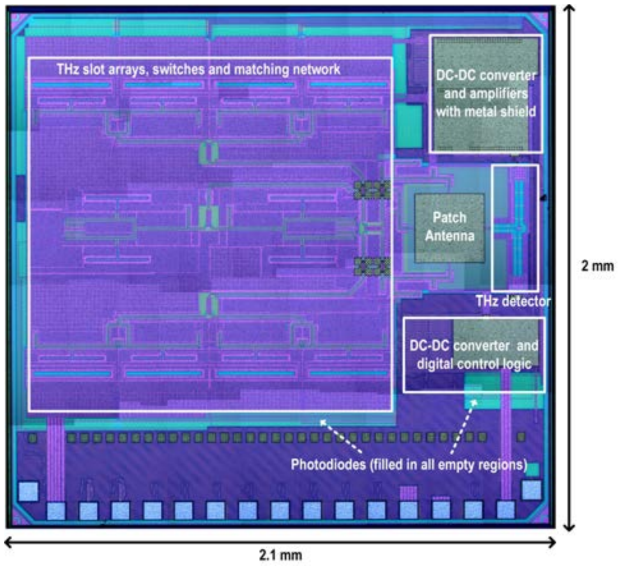


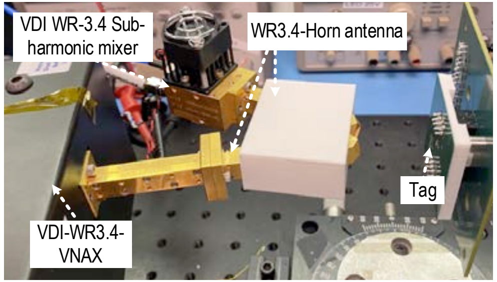


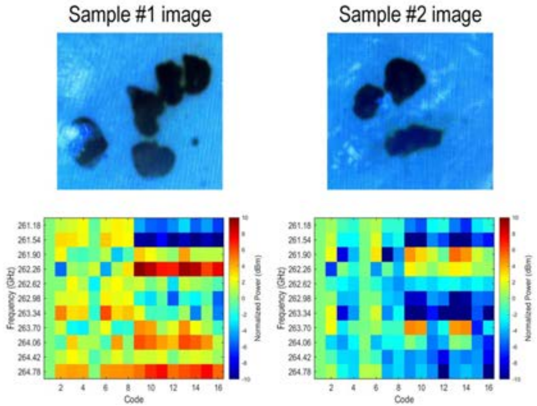
Unclonable THz Tag for Anti-Tampering Function

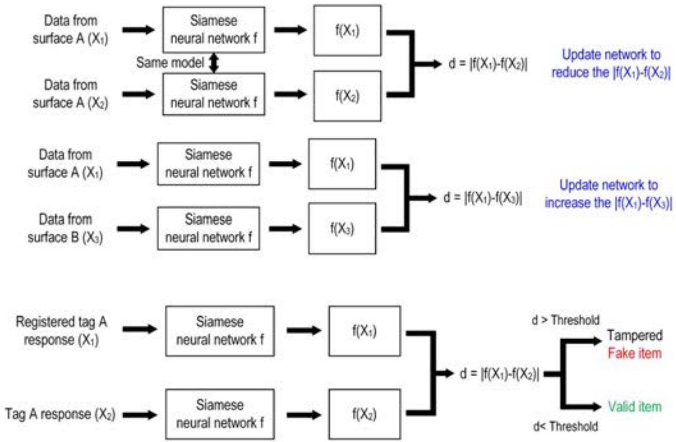


Unclonable THz Tag for Anti-Tampering Function

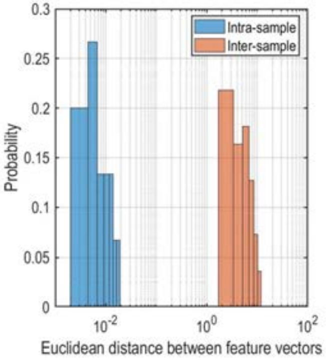






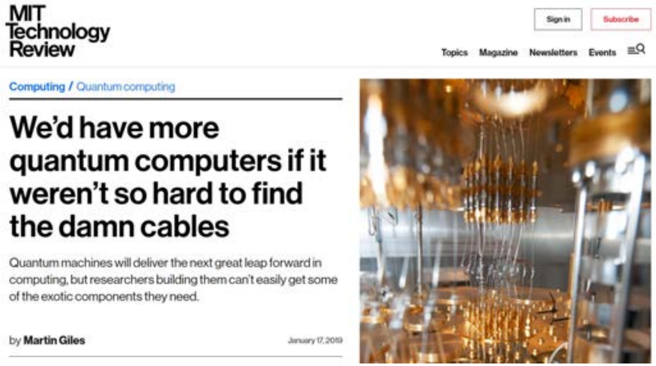


[E. Seok, et al., to be presented on *ISSCC* 2024]



Training data	Test data	Distance (d) threshold	Total accuracy
820 pairs	153 pairs	0.5	99.34%

THz Cryogenic Backscatter Transceiver



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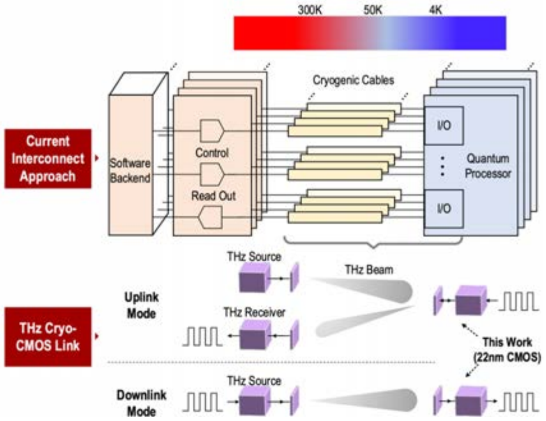
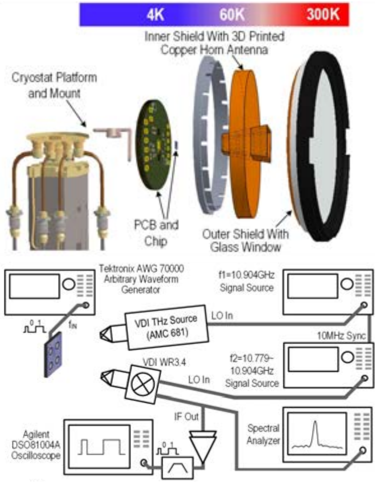
Computing / Quantum computing

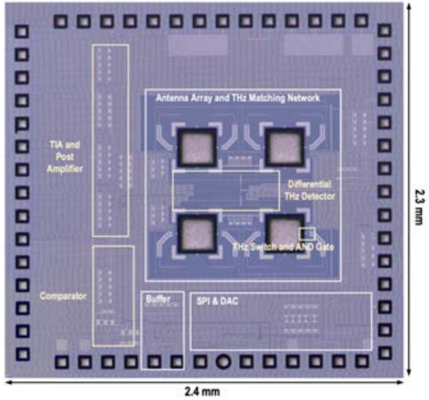
We'd have more quantum computers if it weren't so hard to find the damn cables

Quantum machines will deliver the next great leap forward in computing, but researchers building them can't easily get some of the exotic components they need.

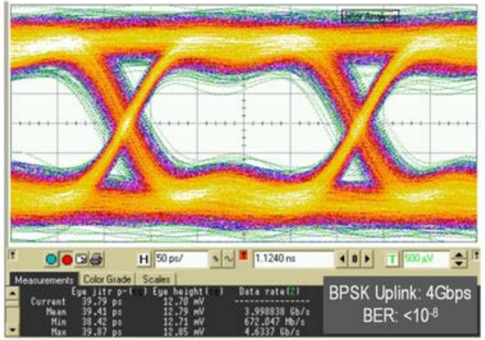
by Martin Giles — January 17, 2019





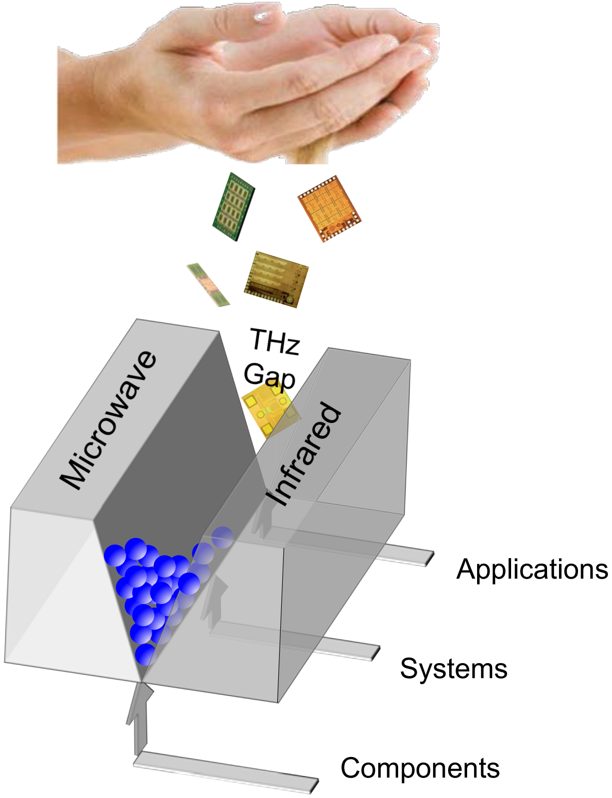


[J. Wang, et al., *ISSCC* 2023]



- Current metal RF/data cables pose large thermal load to the cryogenic platform of quantum system
- Proposal: non-contact wireless up/down links using THz waves
  - Intel 22nm FinFET CMOS
  - Uplink: 176fJ/bit @ 4Gbps
  - Downlink: 34fJ/bit @ 4.4Gbps

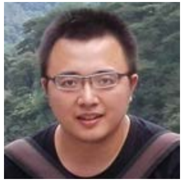
Conclusion



- High-Angular-Resolution Imaging
- Electronic Nose
- Precision Timing
- High-Speed Wireline Link
- Tag of Everything

Acknowledgements

Past and Current Group Members



Cheng Wang
(Professor at UESTC, China)

Jack Holloway
(Raytheon)

Zhi Hu
(Apple)

Mohamed Ibrahim
(Assistant Professor at Cornell University)

Xiang Yi
(Professor at SCUT, China)

Nathan Monroe
(Cambridge THz)

Mina Kim
(Apple)

Muhammad Khan
(MediaTek)

Xibi Chen
(Ph.D)

Eunseok Lee
(Ph.D)

Jinchen Wang
(Ph.D)

Daniel Sheen
(Ph.D)

Collaborators

Anantha Chandrakasan (MIT), Harry Lee (MIT), Dirk Englund (MIT)

George Dogiamis (Intel), Lin Yi (NASA JPL), Tim Hancock (MIT Lincoln Lab)

Brad Perkins (MIT Lincoln Lab), Ken Kolodziej (MIT Lincoln Lab),

Rui Ma (pSemi Murata), Dennis Buss (TI & MIT), Jim Hwang (Cornell)

Robert Field (MIT, Steve Coy (MIT), Rabia Yazicigil (Boston Univ.)

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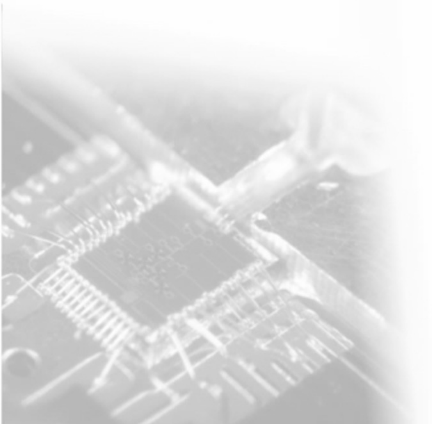
Chip-Scale Terahertz Systems for Sensing, Metrology and Security Applications



Ruonan Han

Associate Professor

Electrical Engineering and Computer Science

Massachusetts Institute of Technology

ruonan@mit.edu, https://hangroup.mit.edu