Next Generation Communication, Radar, Imaging Systems-on-Chip

(RTSP 2017, Poly Technical University of Bucharest)
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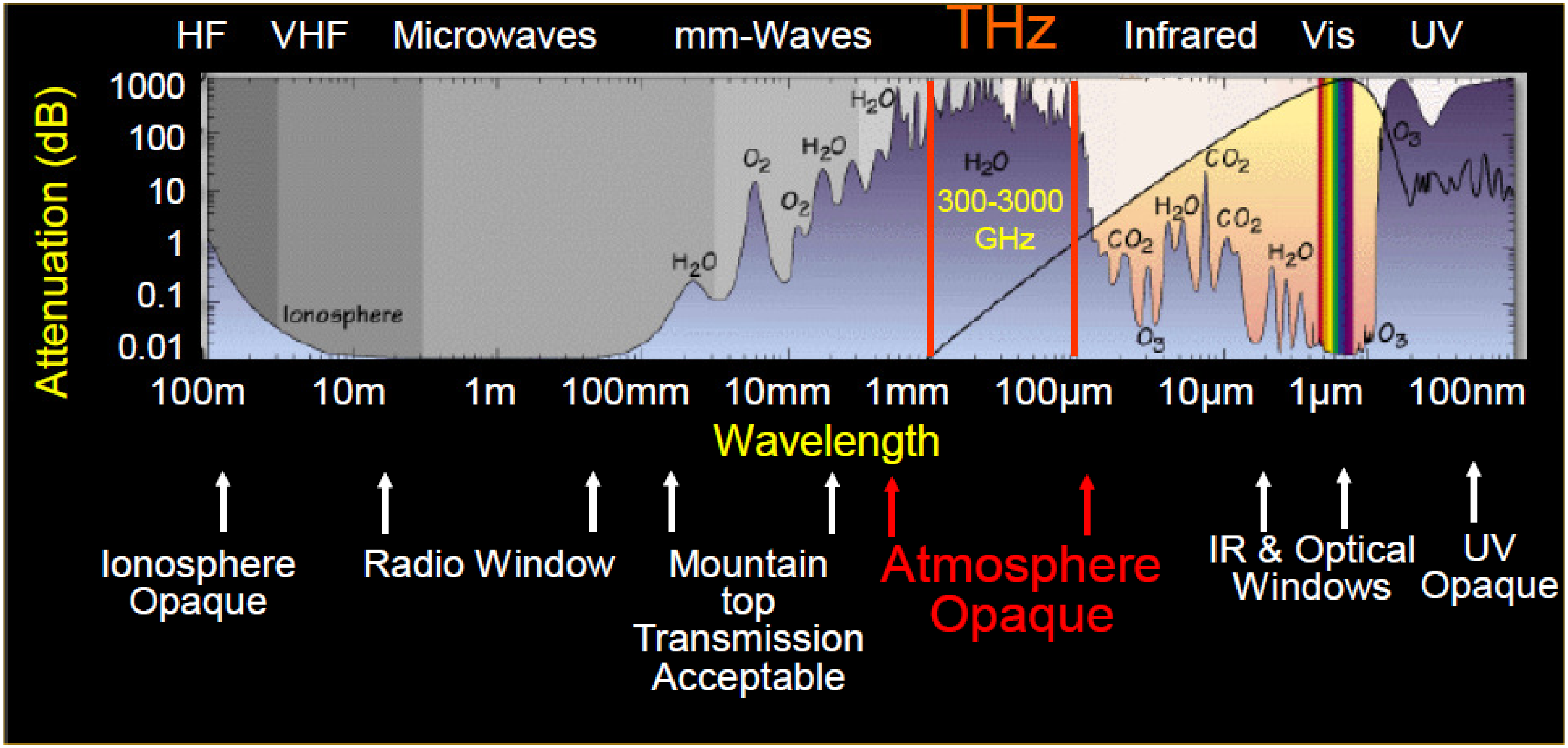
Outline

- **Introduction**
  - *Advantages and Challenges in Building Radio, Radar and Imager at (Sub)-mm-Wave or Terahertz Frequency Range*
- **Mm-Wave to Terahertz CMOS Systems-on-Chip**
  - *Wireless/Wireline Links*
  - *Broadband Self-Healing Radio-on-a-Chip*
  - *144-495GHz Radar and Imaging*
- **Digital Controlled Artificial Dielectric *(DiCAD)* with Tunable Permittivity for Reconfigurable Terahertz Systems**
  - *Historical Artificial Dielectric*
  - *Synthesizing DiCAD in Deep-Scaled CMOS*
  - *Reconfigurable/Scalable DiCAD Circuit Designs*

Electromagnetic Wave Spectrum

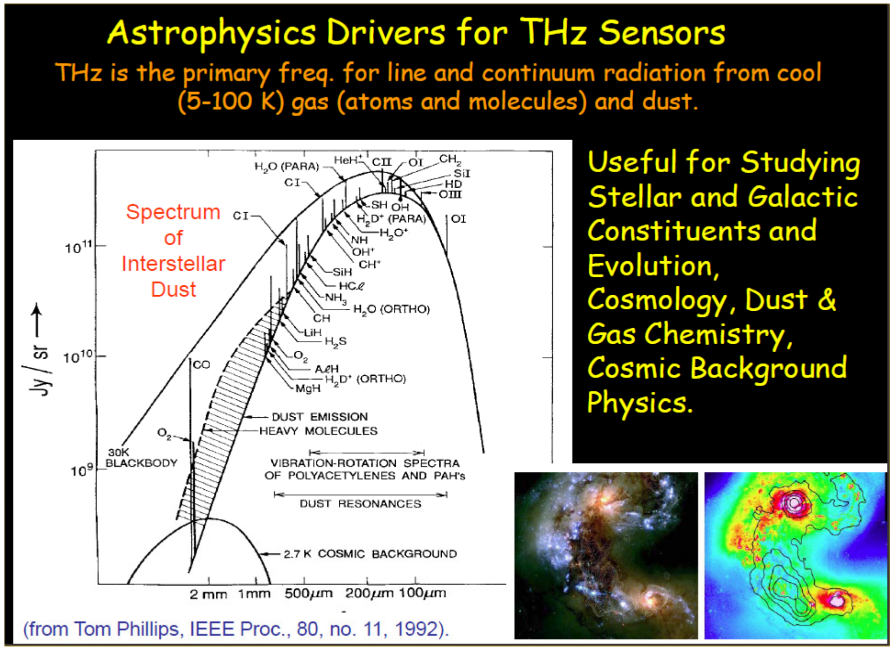


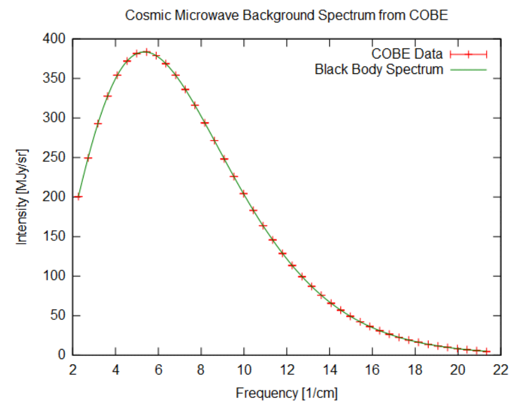
1 Tera-Hertz = 10^{12}/sec (one trillion times per sec)

US National GDP \$16.8 trillion

(Courtesy JPL)

Galactic Evolution Since Big Bang





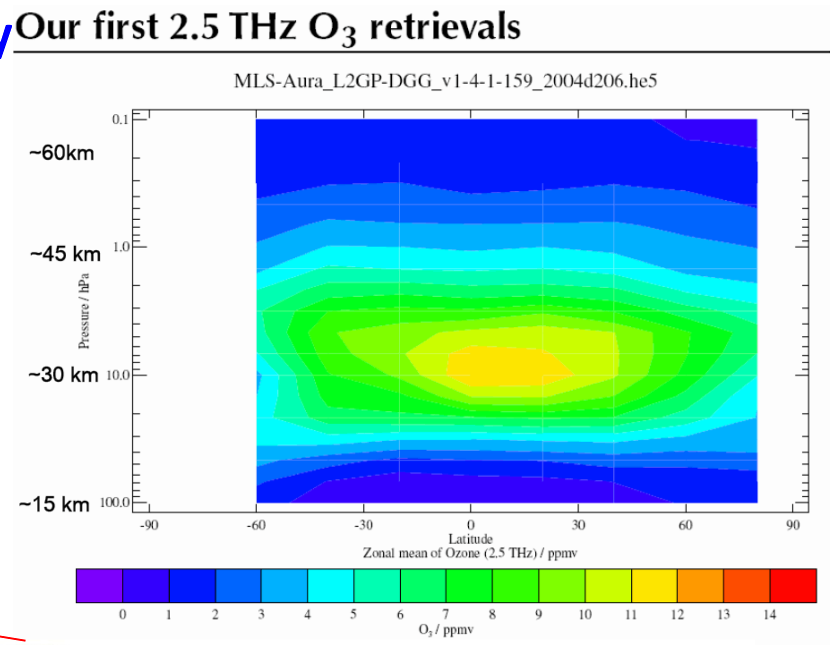
2.7K Cosmic Microwave Background from COBE

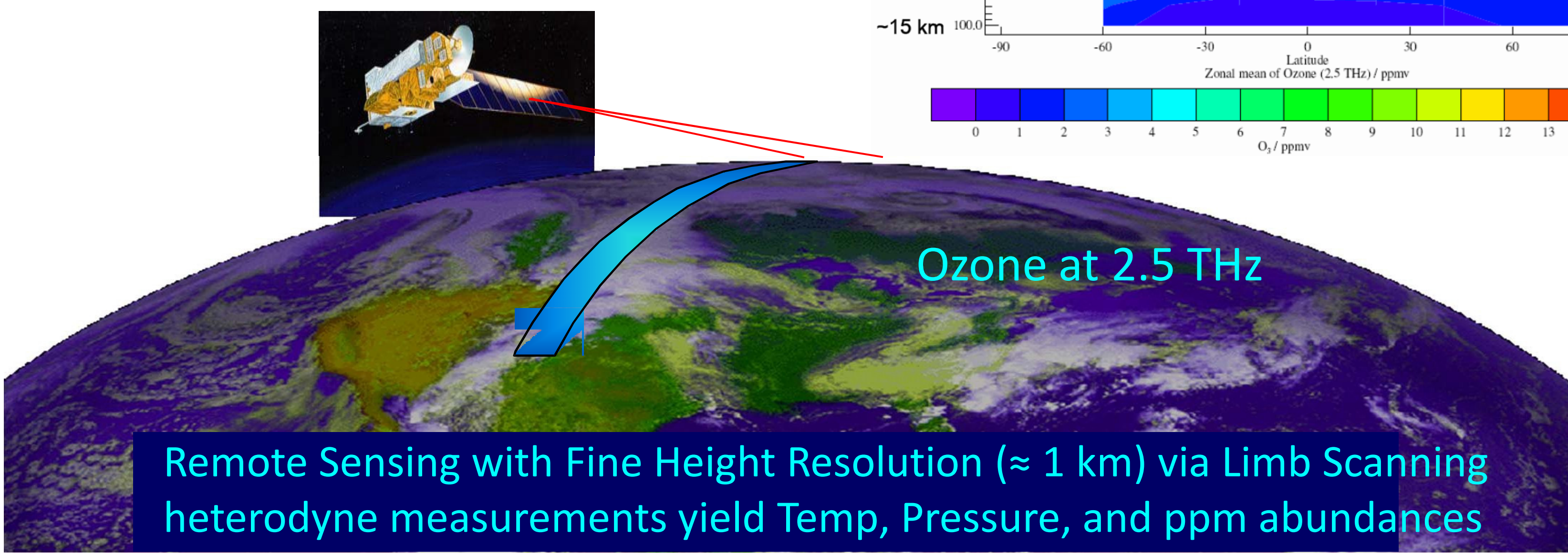
Cosmic Microwave Background (CMB) was detected by Arno Penzias and Rob Wilson in 1964 by using a Dicke Radiometer with perfectly fitted Planck Blackbody radiation temperature of 2.7K

Dicke Radiometer at Crawford Hill of ATT Bell Laboratories

Earth Science Applications

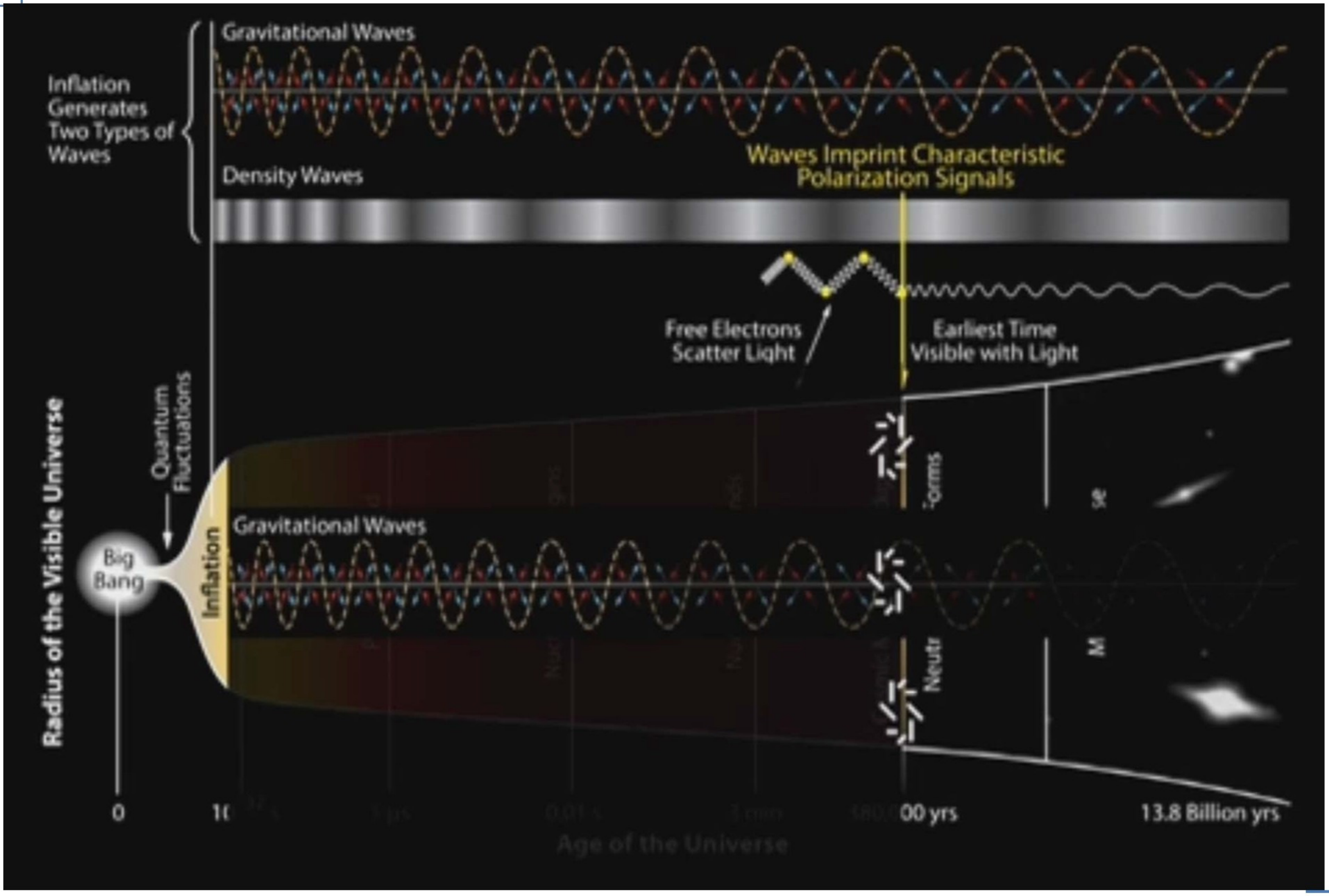
- **Stratospheric and Tropospheric Chemistry**
  - ozone layer modeling
  - economics vs. environment
  - water distribution/pollutants
- **Clouds: Global Warming**
  - ice crystal: size & distribution
- **Aerosols, Volcanism, Dust**





(Courtesy JPL)

CMB Polarization at mm-Wave



Terahertz Advantages & Issues

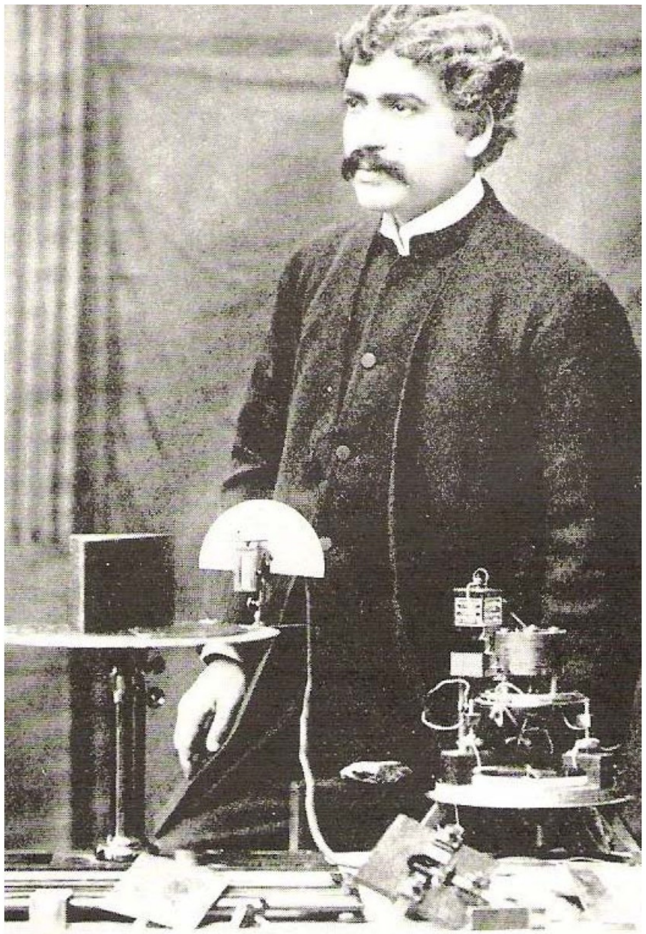
Potential Advantages

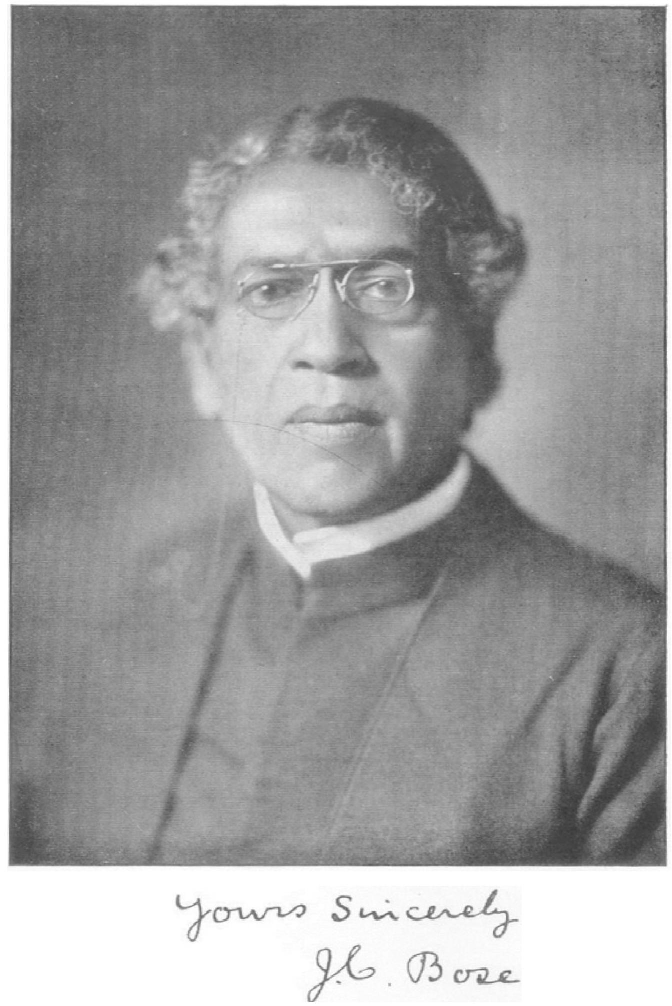
- **Higher data rate at a fixed fractional bandwidth**
- **Quasi-optical nature**
- **Easier formation of radiation beam**

Issues

- **Technology constraints (Terahertz Gap)**
- **High Path loss due to H_2O/O_2 absorption**

Prof. J. C. Bose and Terahertz





Prof. J. C. Bose laid the foundation of Terahertz Technology

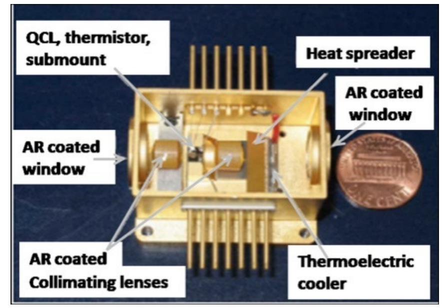
Can We Generate THz Signal Performance/Cost-Effectively ?

(By Using TSMC CMOS)

Generating THz Signals

- **Quantum cascade lasers (QCL)**
- **Free electron lasers (FEL)**
- **Laser driven THz emitters**
- **Solid state circuits**
    - III/V technologies (multiplier chain in waveguides)
    - Silicon SoC technologies (compact, monolithic integrated with digital circuits)
        - SiGe HBT technologies
        - CMOS technologies

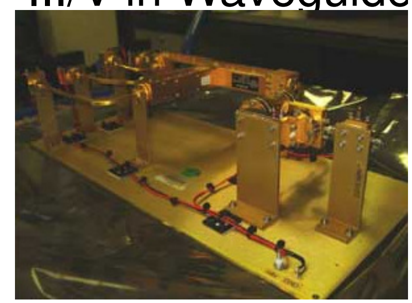
QCL



FEL

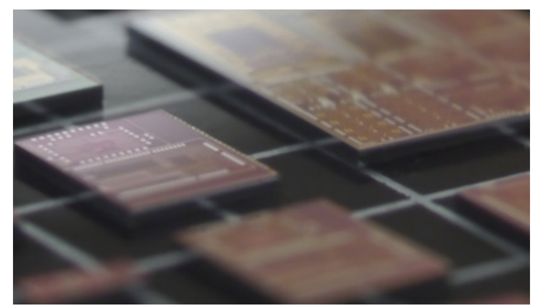
Laser THz emitter

III/V in Waveguide

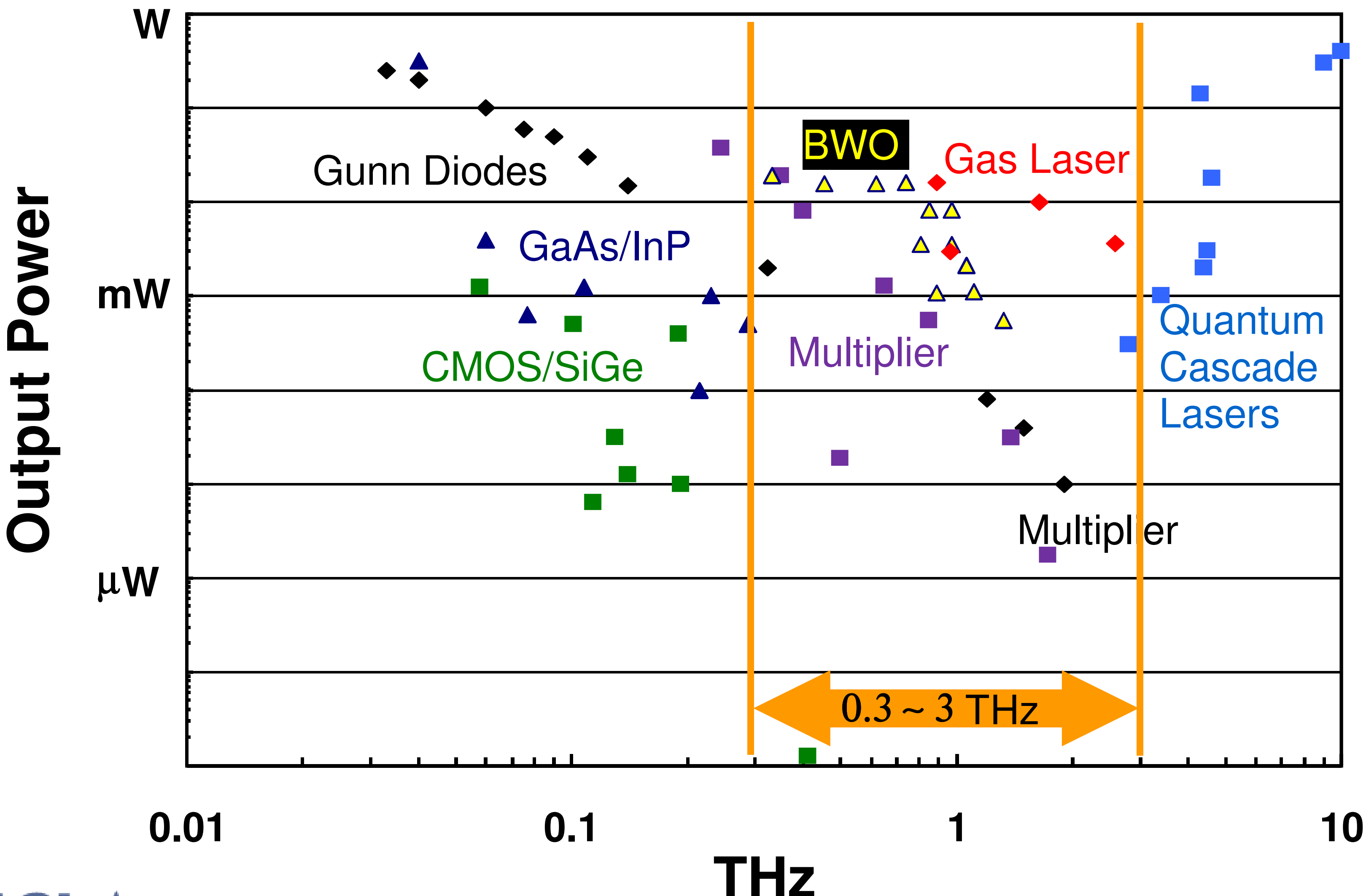


CMOS THz source

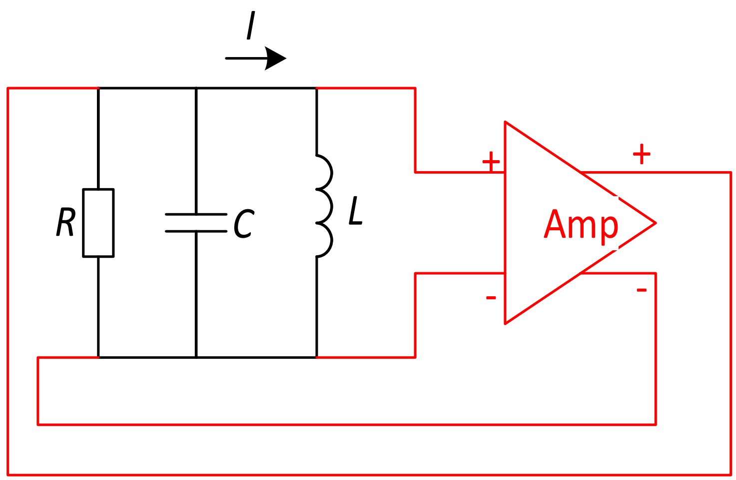
2x2 mm^2



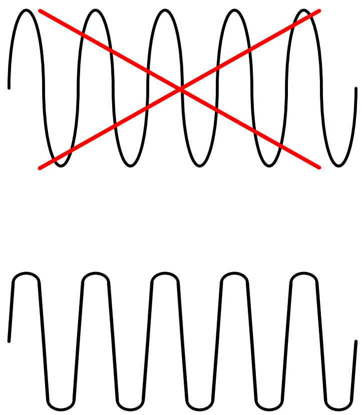
Terahertz Gap

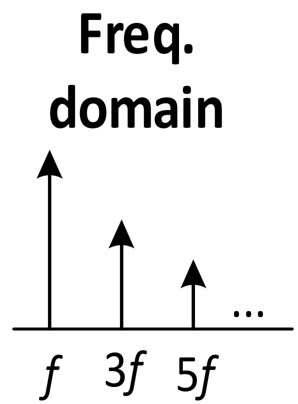


Generating Harmonics from Oscillator



Oscillation waveforms





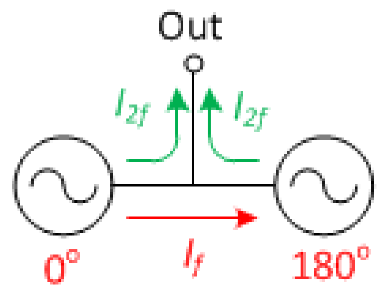
Question:

How to suppress power at fundamental frequency (*f*) but enhance signal power at specific harmonics (*N*f*) ?**

THz Harmonic Oscillator

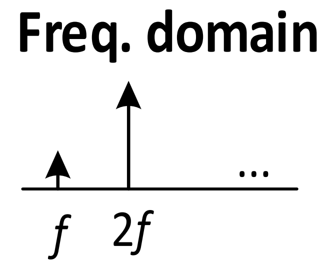
Enhancing 2nd harmonic:

Push-push oscillator



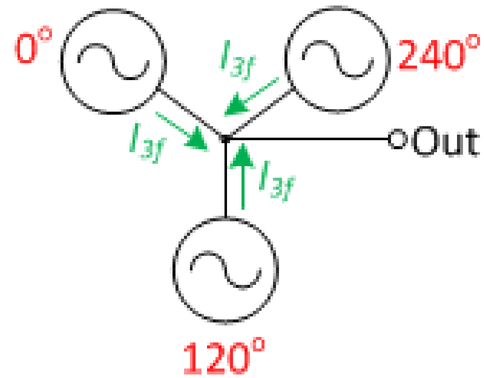
$0^\circ \times 2 = 0^\circ$

$180^\circ \times 2 = 0^\circ$



Enhancing 3rd harmonic:

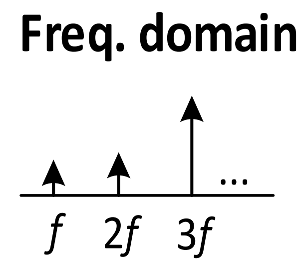
Triple-push oscillator



$0^\circ \times 3 = 0^\circ$

$120^\circ \times 3 = 0^\circ$

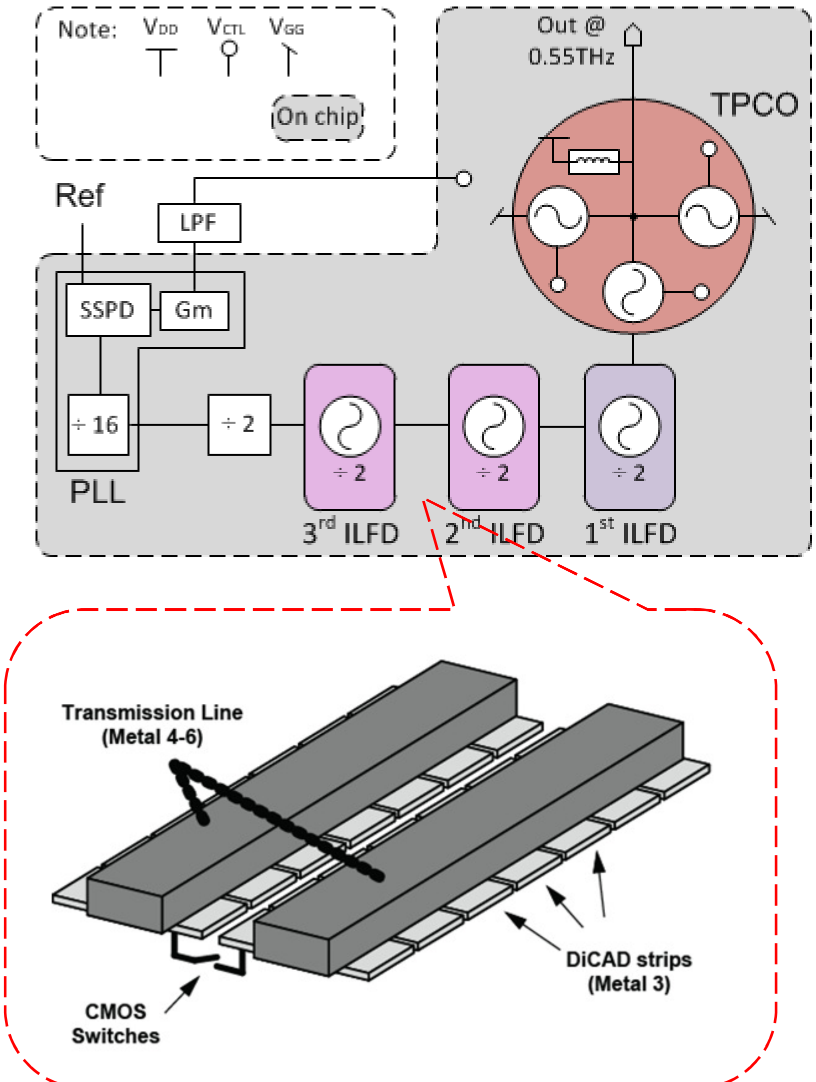
$240^\circ \times 3 = 0^\circ$



Enhancing *N*-th harmonic:

- Quadruple …
- Quintuple …
- …

Phase Locked 550GHz Radiator Element

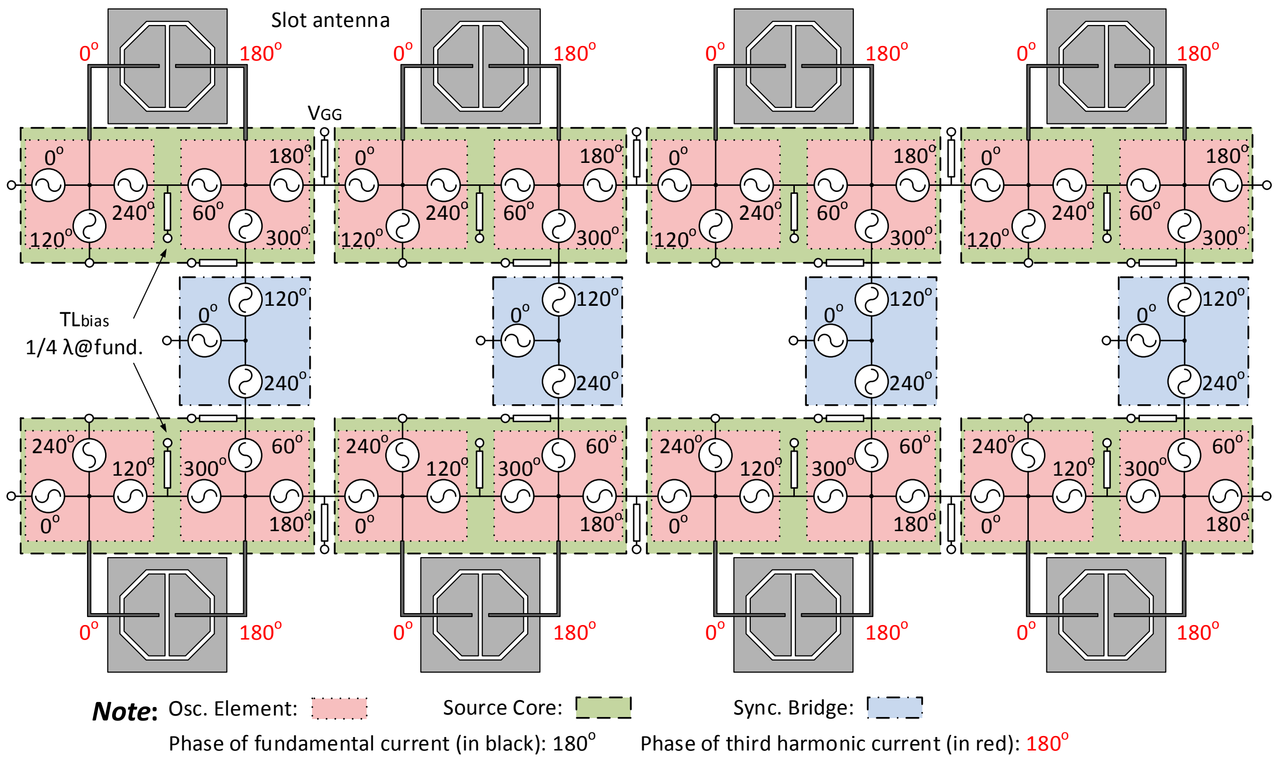


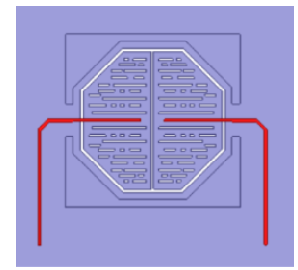
- TPCO front-end plus frequency dividers
- Digital back-end plus off-chip 106MHz reference source.

TPCO: triple-push Colpitts oscillator
ILFD: injection-locked frequency divider
PLL: phase locked loop
SSPD: sub-sampling phase detector
Gm: transconductance cell
LPF: low pass filter

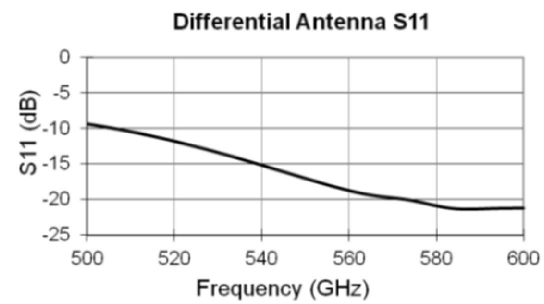
DiCAD enables 2nd and 3rd ILFDs to work in a wide band range from 41 to 52 GHz, potentially support THz range from 0.49 to 0.62THz.

Generating Locked Signal at 550GHz Using SoC





Simulated Antenna Input Matching



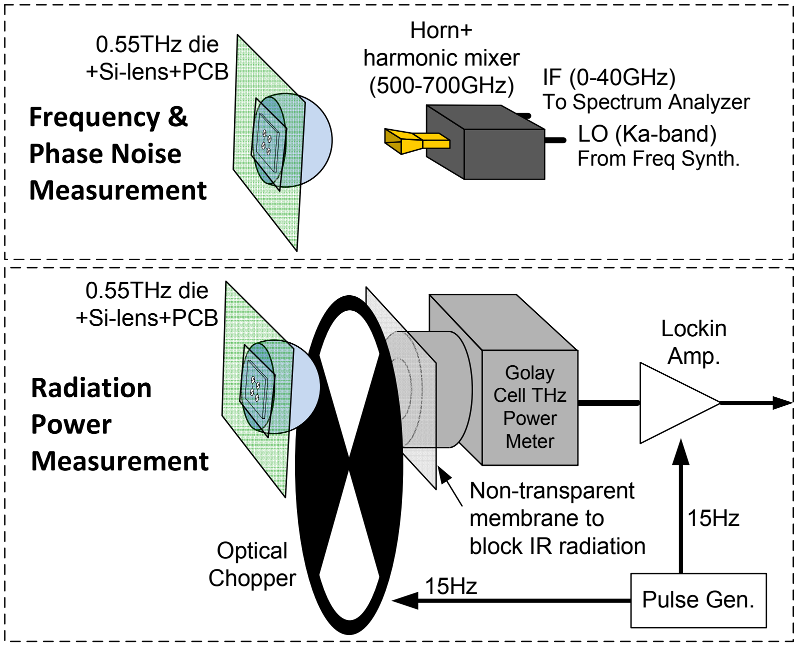
550GHz Coherent VCO array

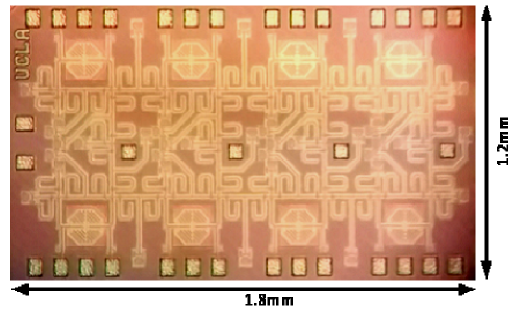
- **2x4 differential antenna array driven by 8 pairs of synchronized VCOs at 550GHz.**
- **In-phase feeding enabling spatial power combining**

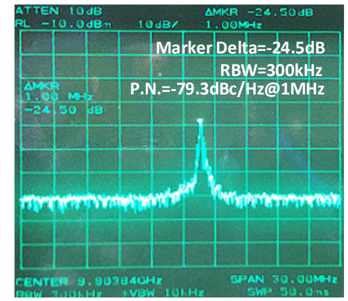
[3] Yan Zhao, M.-C. Frank Chang, et. al, “A 0.54-0.55 THz 2x4 Coherent Source Array with EIRP of 24.4 dBm in 65nm CMOS Technology", to be presented in IEEE International Microwave Symposium (IMS), 2015,

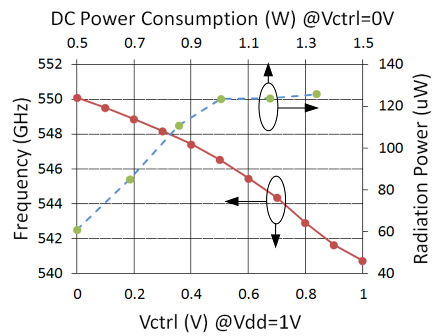
Characterizing 0.54-0.55THz VCO Array Radiator

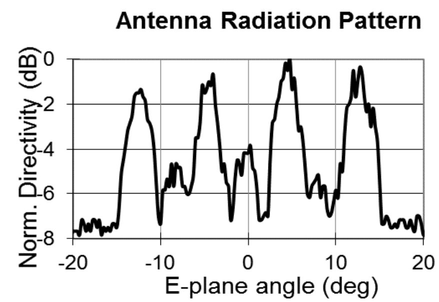
Radiation Power Test Setup





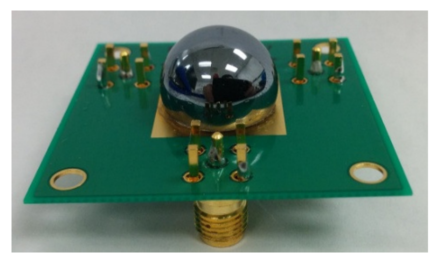






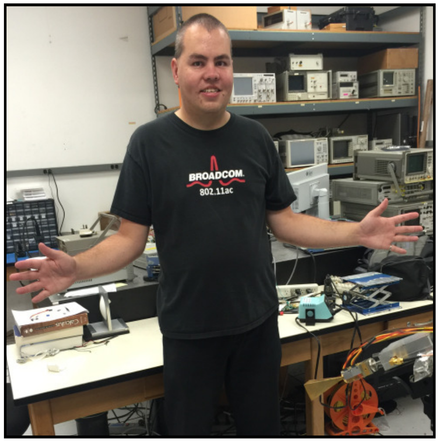
- Silicon lens on backside of Si-substrate
- 0.54 to 0.55 THz frequency tuning range
- 126uW total radiation power at 0.55 THz
- -79dBc/Hz@1MHz phase noise at 0.55 THz
- 4 separate antenna beams in E-plane

Assembled THz source



Can We Receive THz Signal Performance/Cost-Effectively?
(By Using TSMC CMOS)

Passive Image Capture Testing



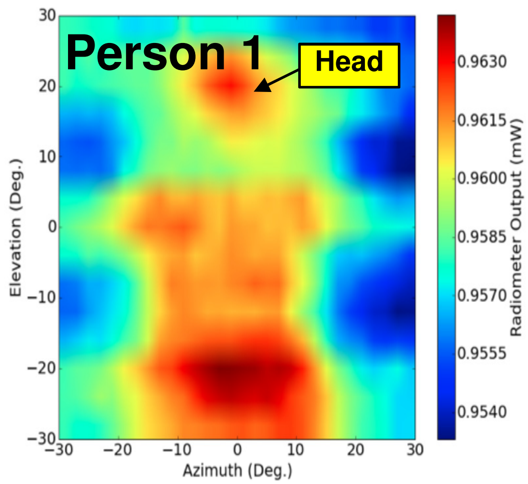
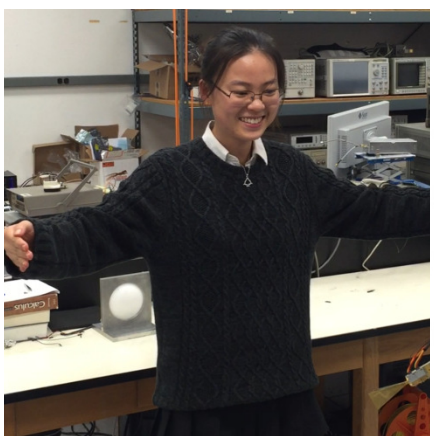
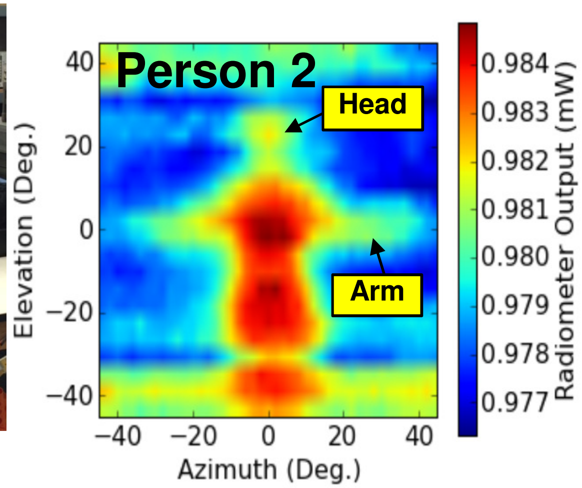
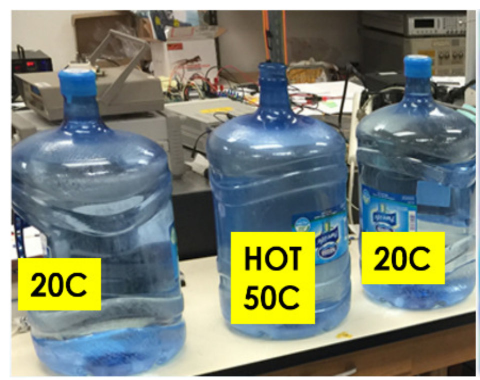


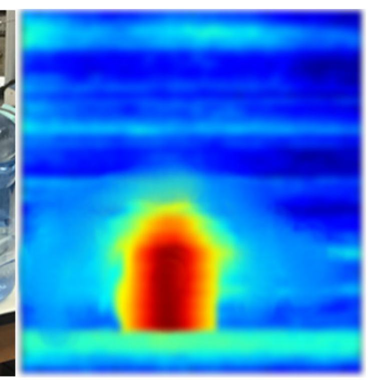
Image Capture Experiment Details

- ❖Uses a 20dBi standard horn
- ❖No reflectors or lens so λ/D is terrible
- ❖Shows that we are sensitive
- ❖Scans of 100 x 100 pixels
- ❖Integration time of 10ms
- ❖Scan time of about 6 minutes
  (yes we had to stand still this long)

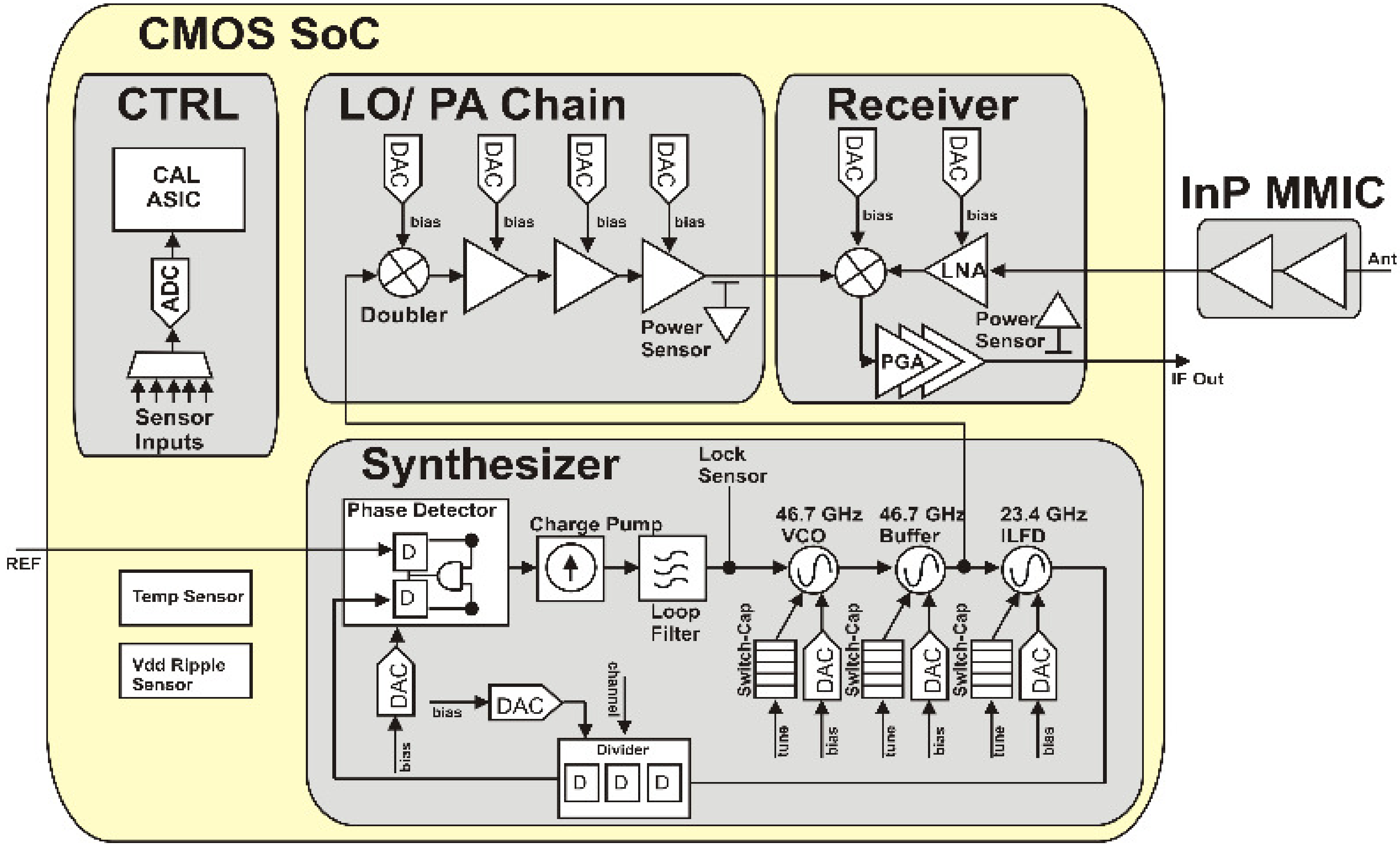




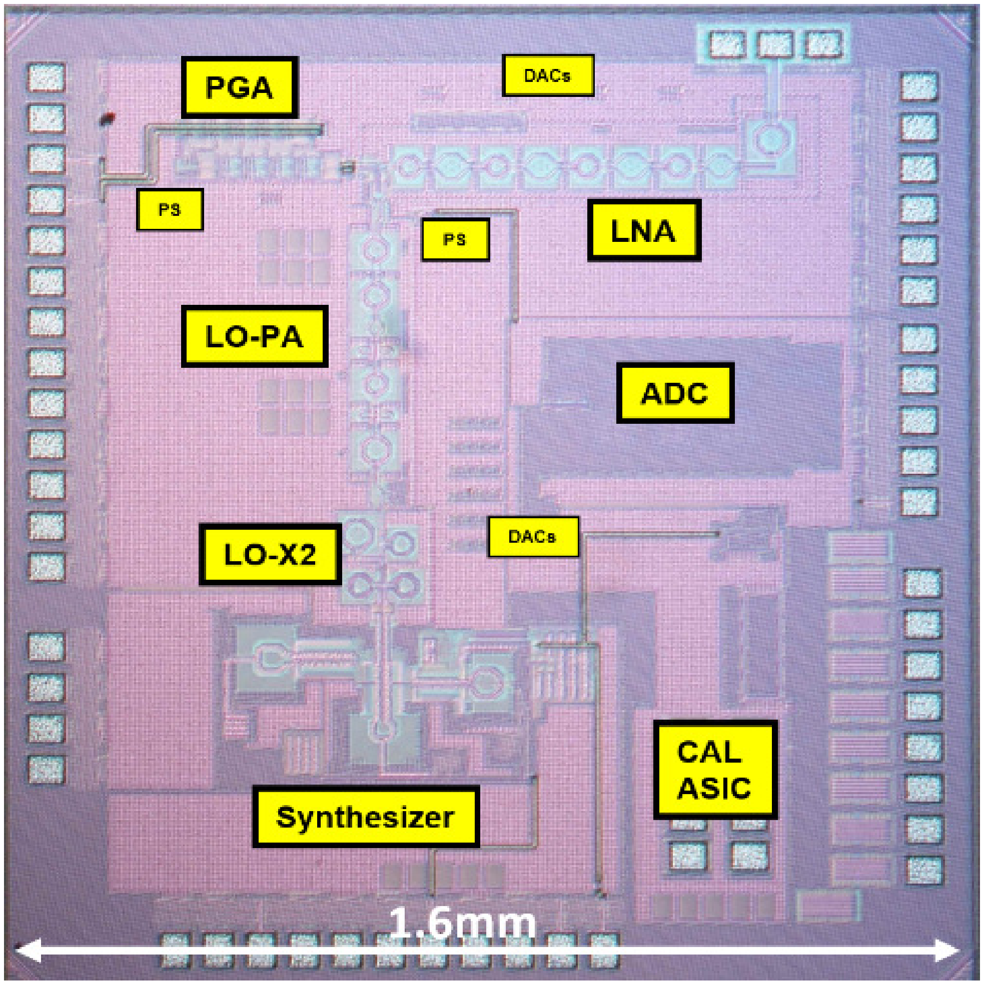




Block Diagram of Hybrid Radiometer



CMOS SoC Photograph



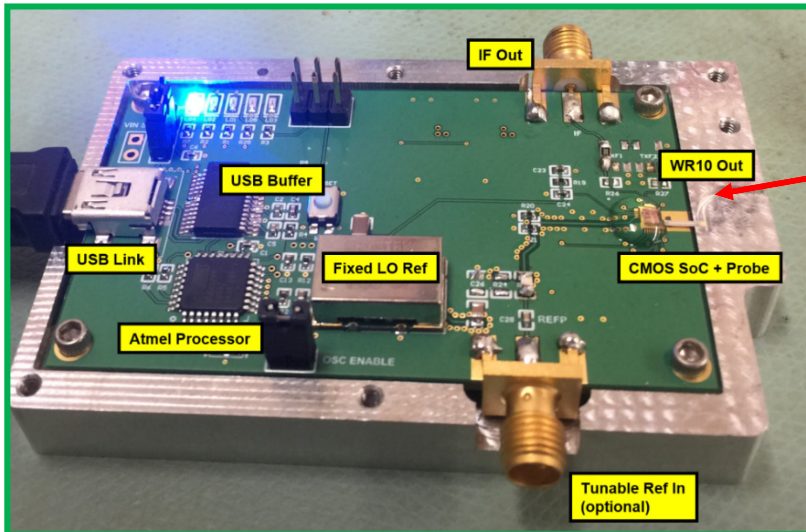
Heterodyne Receiver SoC

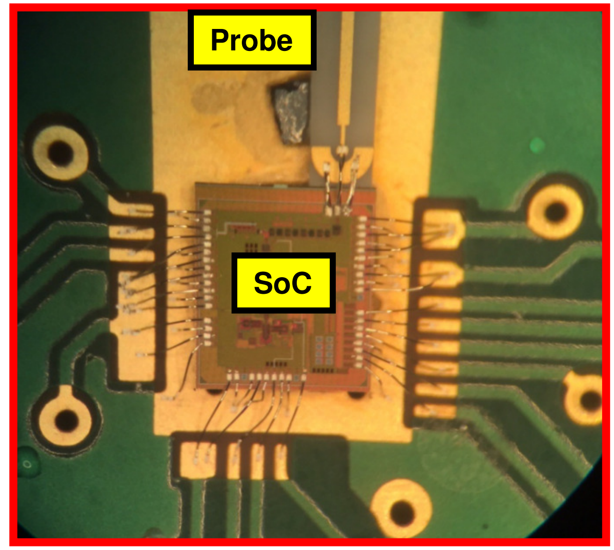
- Integrated ADC for calibration
- Integrated power and temp sensors
- Integrated USB control port

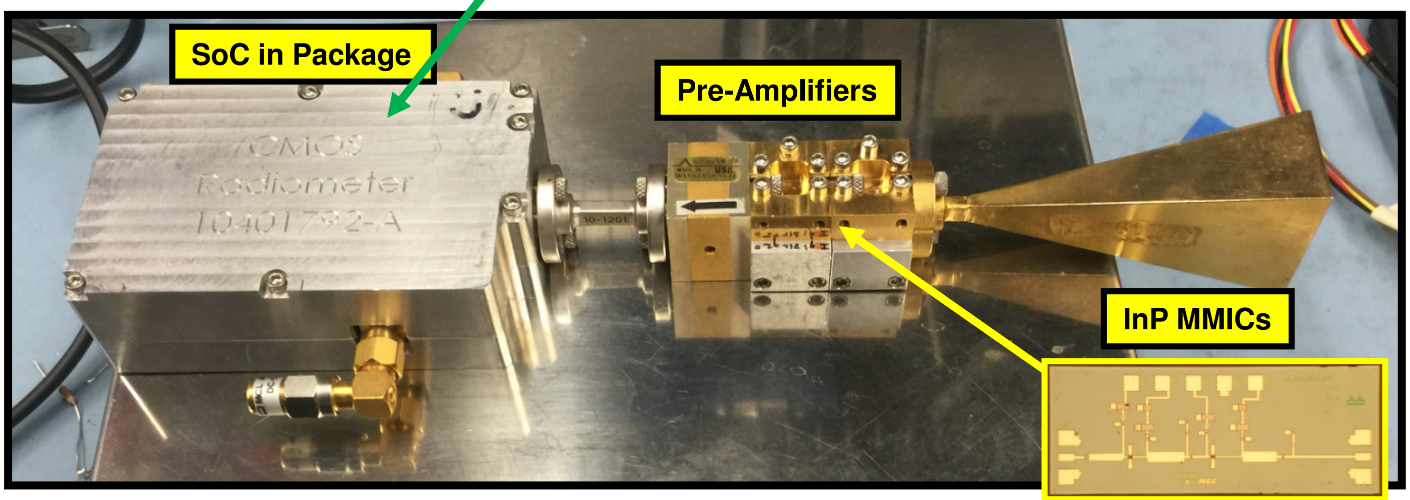
Block	Power
RX Chain	60 mW
LO Amplifier	55 mW
Synthesizer	79 mW
IF Amplifier	10 mW
Control	3 mW
ADC	20 mW
CMOS Total	227 mW

InP Pre-Amp 30mW

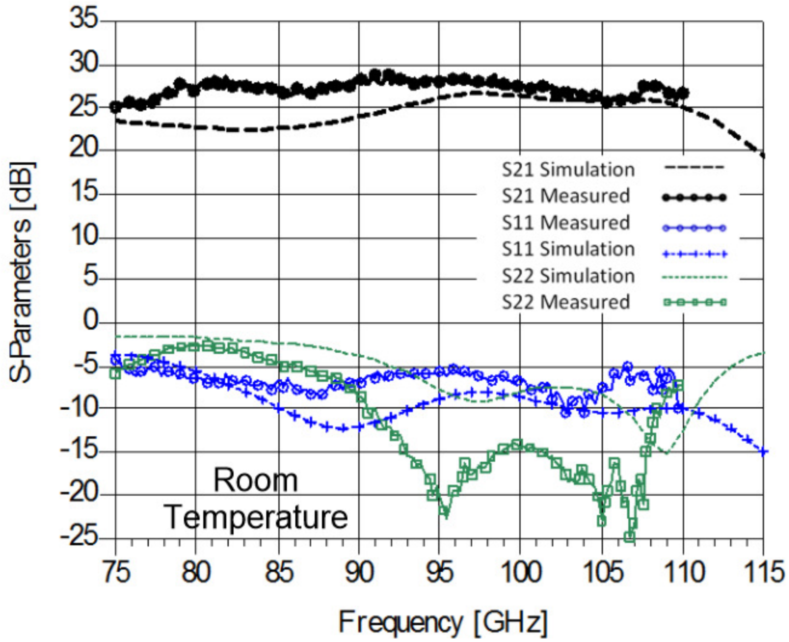
Packaged Passive Imager Prototype

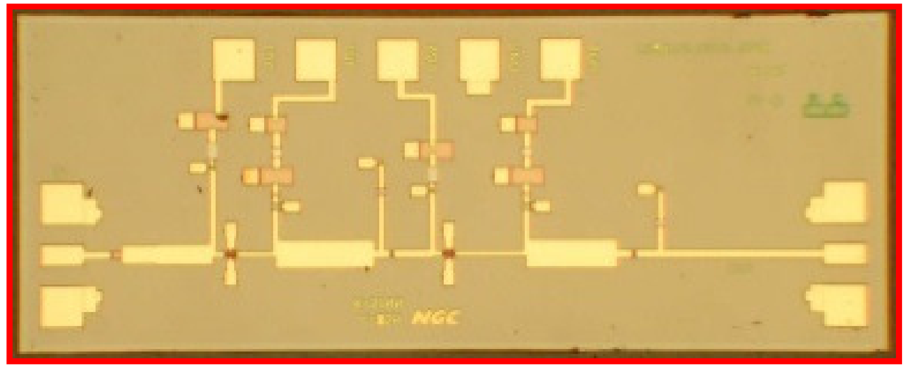


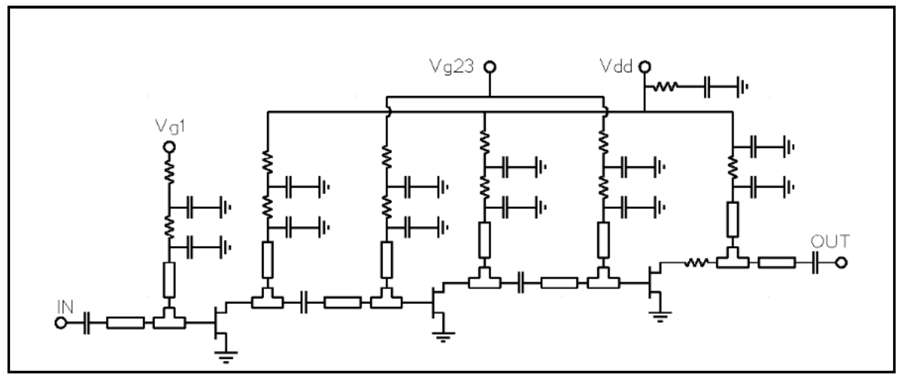




InP MMIC Pre-amplifiers





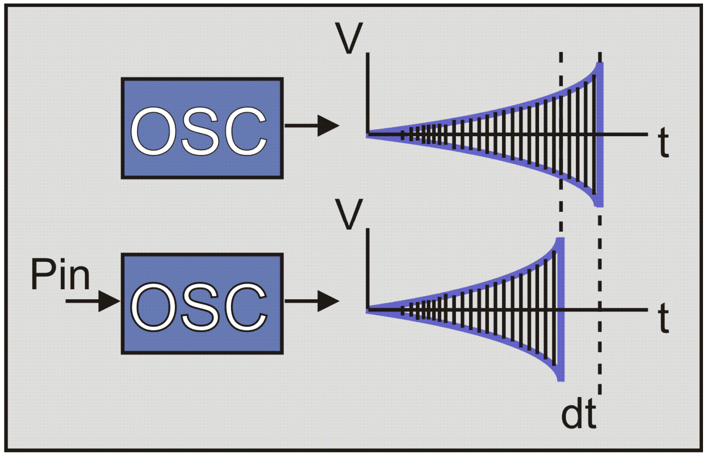


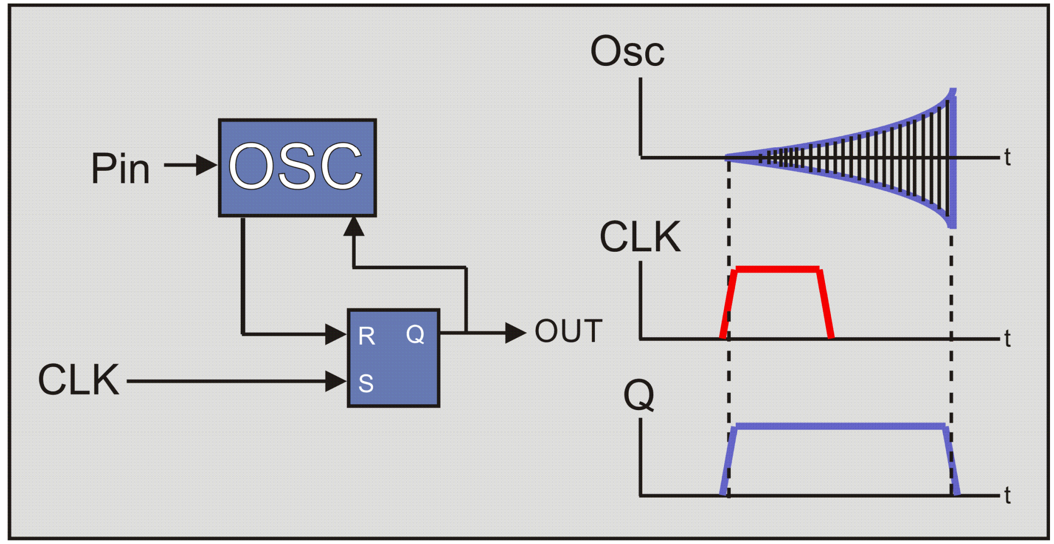
MMIC Pre-Amplifier

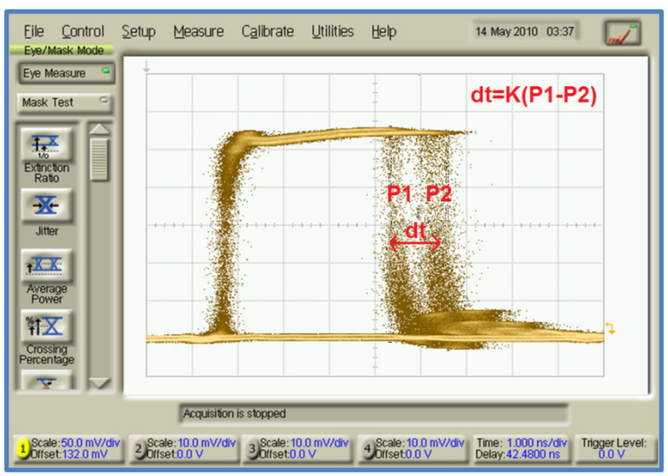
- ❖ **Traditional MMIC techniques in awesome NGC technology (InP HEMT 35nm)**
- ❖ **Reasonable 25-30 dB gain in the frequency band of interest.**
- ❖ **Burns about 30mW total for both stages.**

For Radar and Imaging Systems

Digital Regeneration Receiver
(Non-Coherent Receiver)





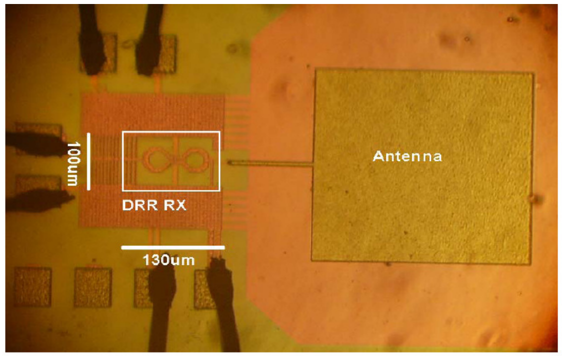


Adding a digital latch circuit allows the oscillator to restart each clock. When the oscillator starts it triggers the digital reset creating a pulse width inversely proportional to input power

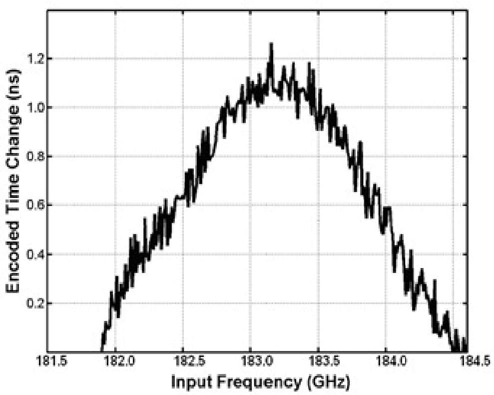
183GHz CMOS Active Imager

Electrical Measurements

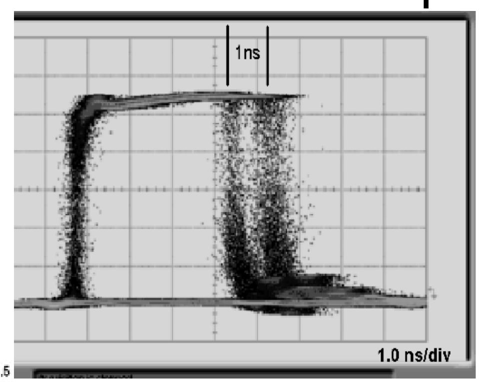
Measurement	Value
Frequency	183 GHz
NF	9.9 dB
Power	13.5mW
Sensitivity	-72 dBm
Area	13100 um²
NEP	1.5fw/Hz$^{0.5}$
Gain	1.3ms/W



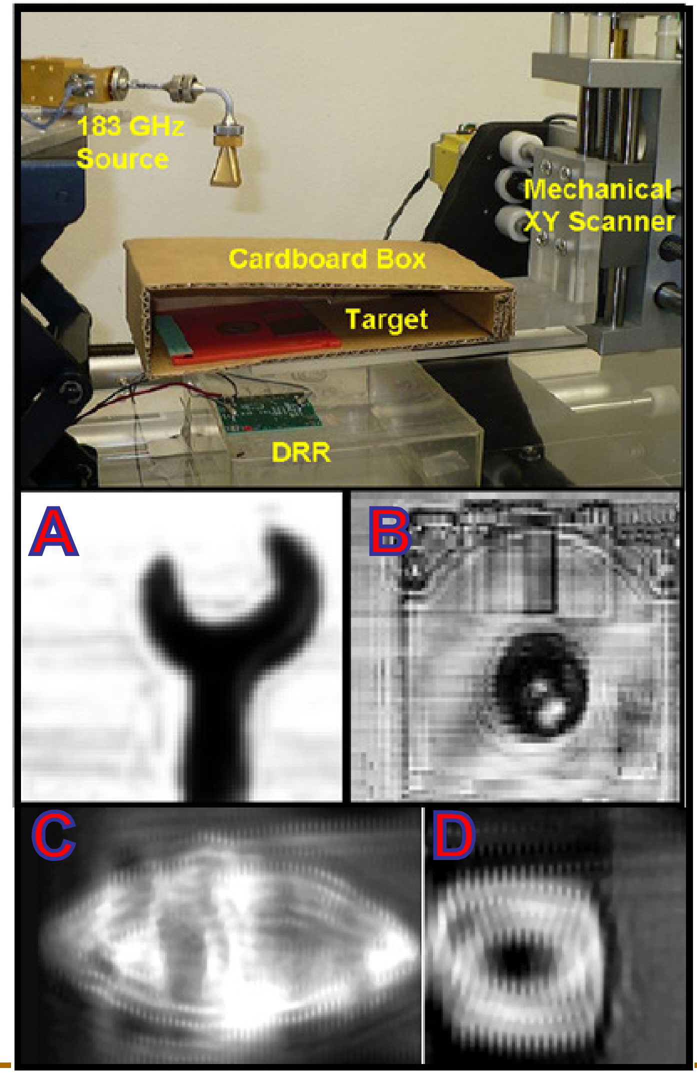
Frequency Response



Time-Encoded Output



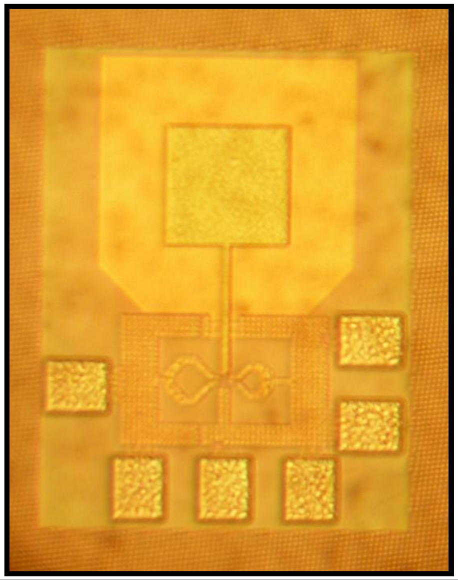
Imaging Results



Sample-Targets (metals and non-metals)

A) Metallic Wrench B) Computer floppy disk
C) Football D) Roll of tape
*All items were concealed in cardboard boxes

495 GHz CMOS Super-Regenerative Receiver



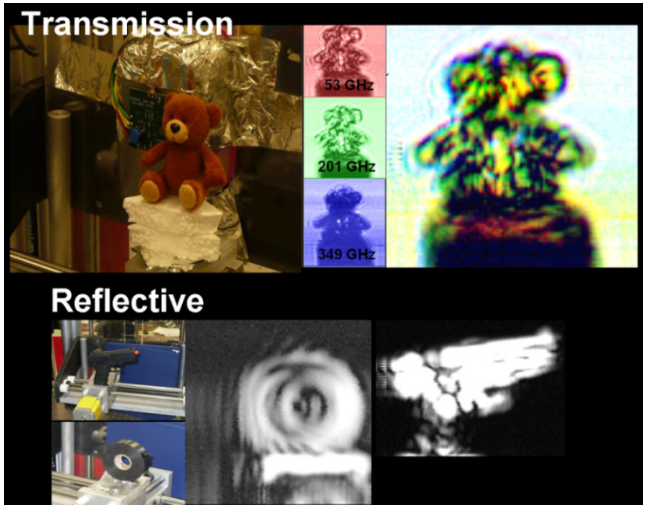
495 GHz Regenerative Receiver based on 40nm TSMC CMOS technology with total power consumption of 5mW under 1V supply voltage

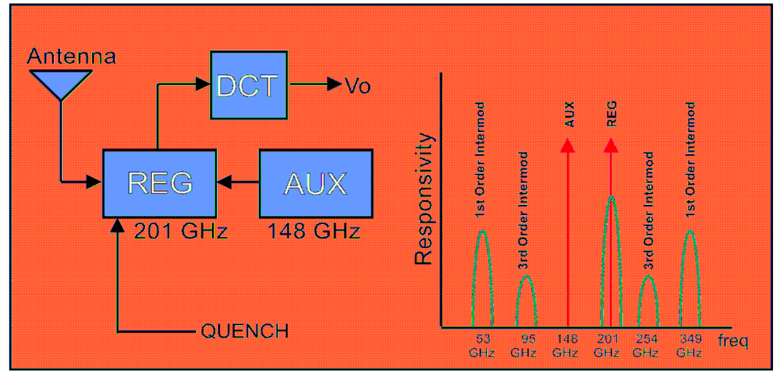
495GHz Image Capture

Terahertz System Demonstrations

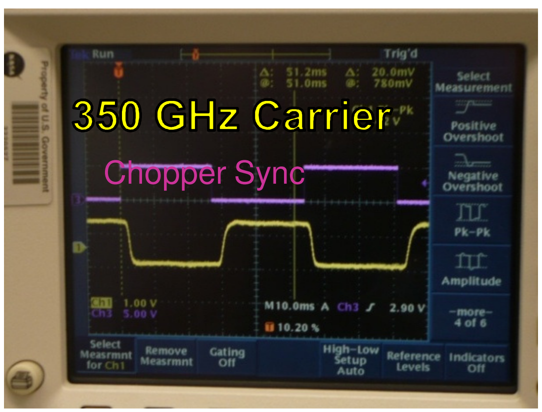
1. Sensitivity measurement of antenna-less 245 GHz
   http://www.ee.ucla.edu/~atang/250_demo.mp4
2. 495 GHz antenna-less imager
   http://www.ee.ucla.edu/~atang/494_demo.mp4
3. Imaging Radar Demo
   http://www.ee.ucla.edu/~atang/Radar_Demo.mp4

Tri-Color (350/200/50GHz) IRR Imager
(Inter-modulated Regenerative Receiver)

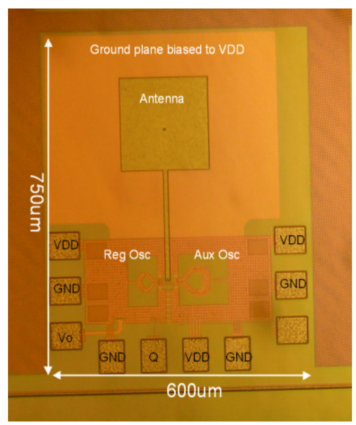




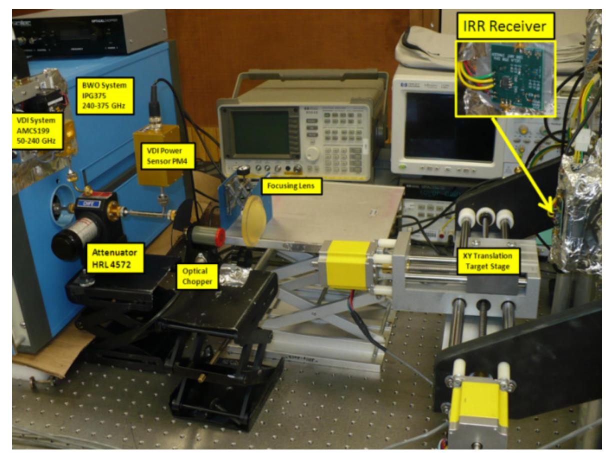
- **First reported architecture for RX to operate above F_{max}**
- **Fastest reported silicon receiver (SiGe or CMOS)**
- **First multi-band sub-millimeter-wave receiver (3 bands)**



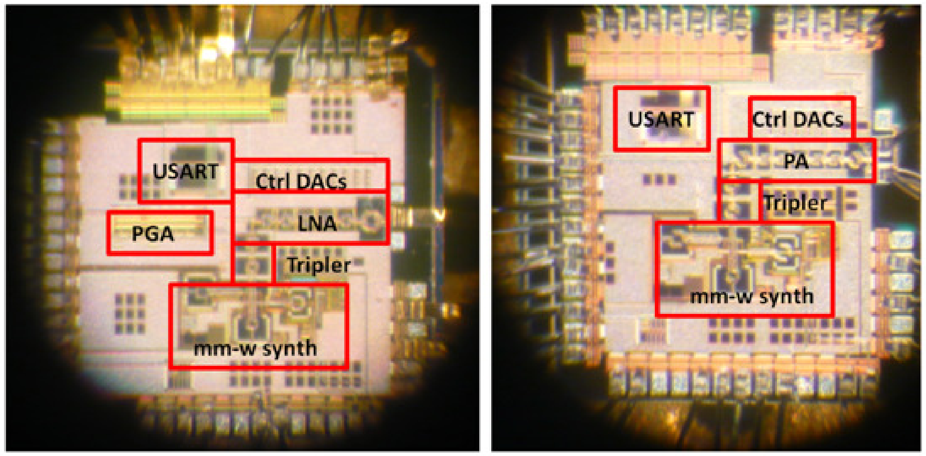
350 GHz Chopper Response



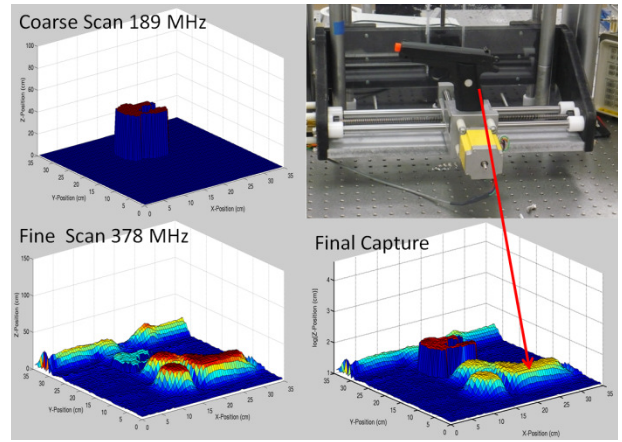
CMOS Tri-band Receiver



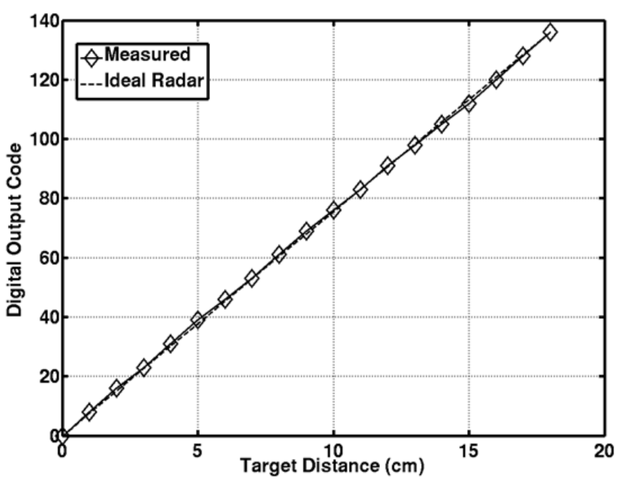
144 GHz CMOS Sub-Ranging 3D Imaging Radar with <0.7cm Depth Resolution (Coherent Receiver)

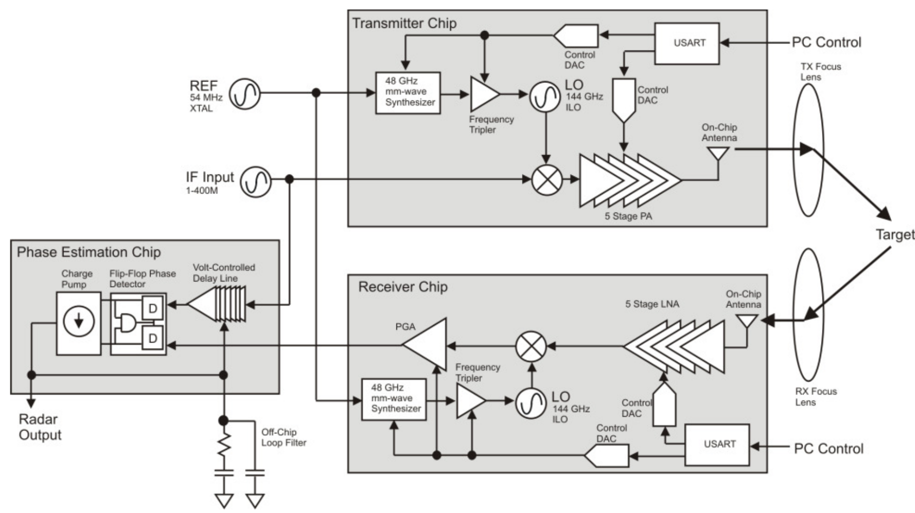


Receiver Transmitter



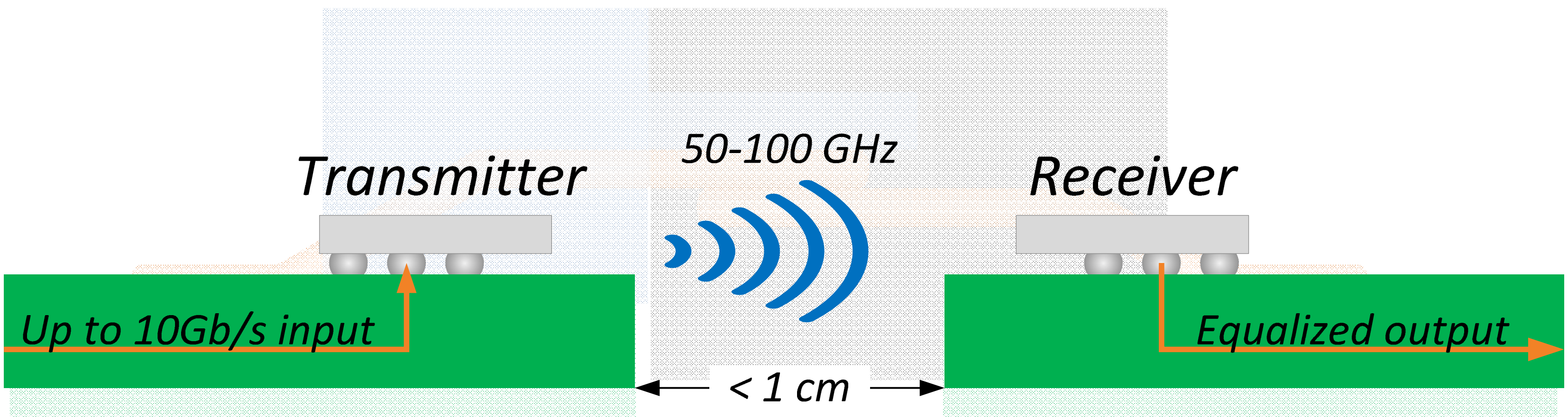
- **First mm-wave 3D imaging radar in silicon!**





For Communications

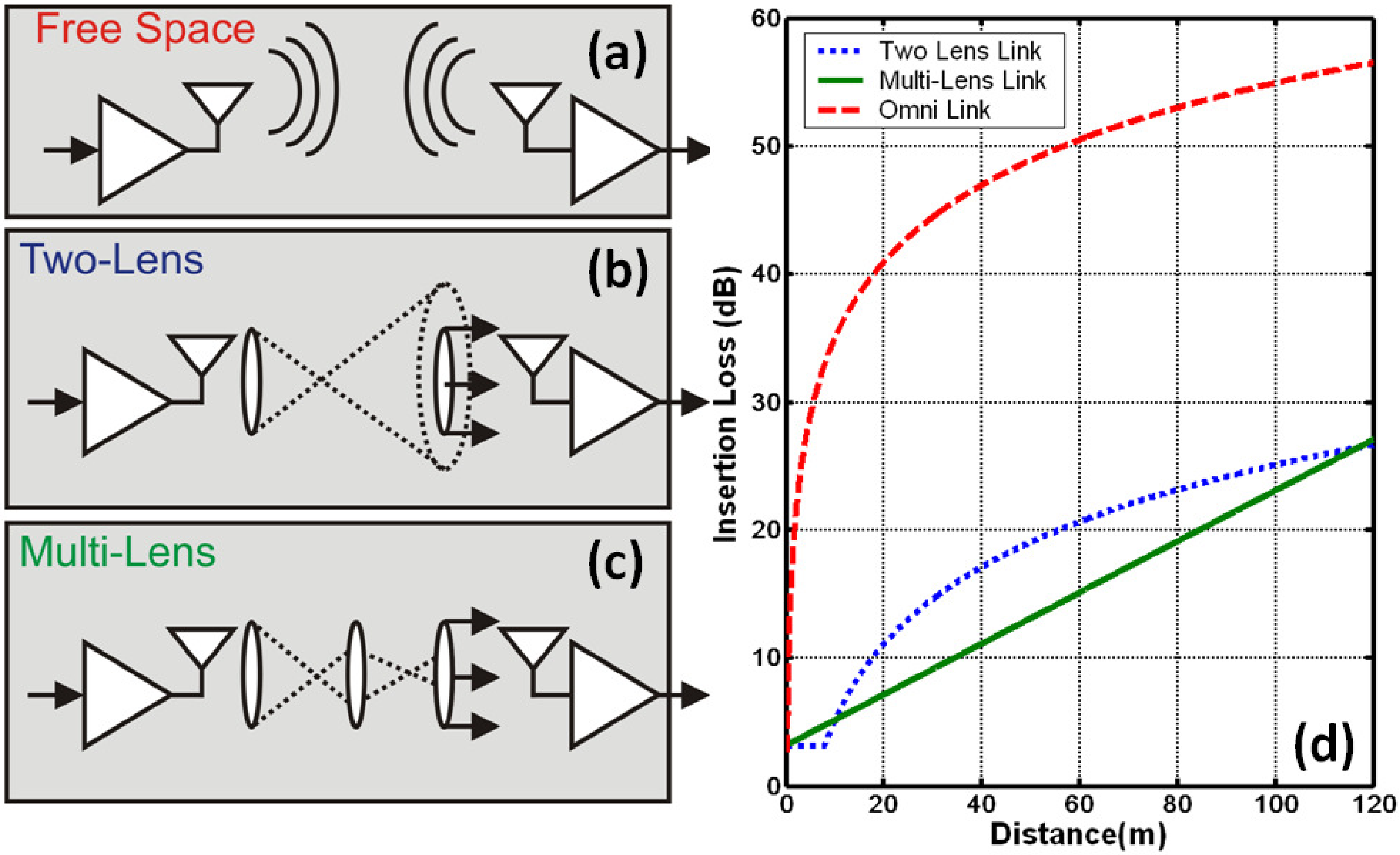
Near Field Coupled "WaveConnector"



- **Near-field-Communication at multi-Giga-Bit/sec**
  - Ultra-high data rate (>10Gbps) for short distance and secured communications
  - Protocol-transparent, near-universal applications

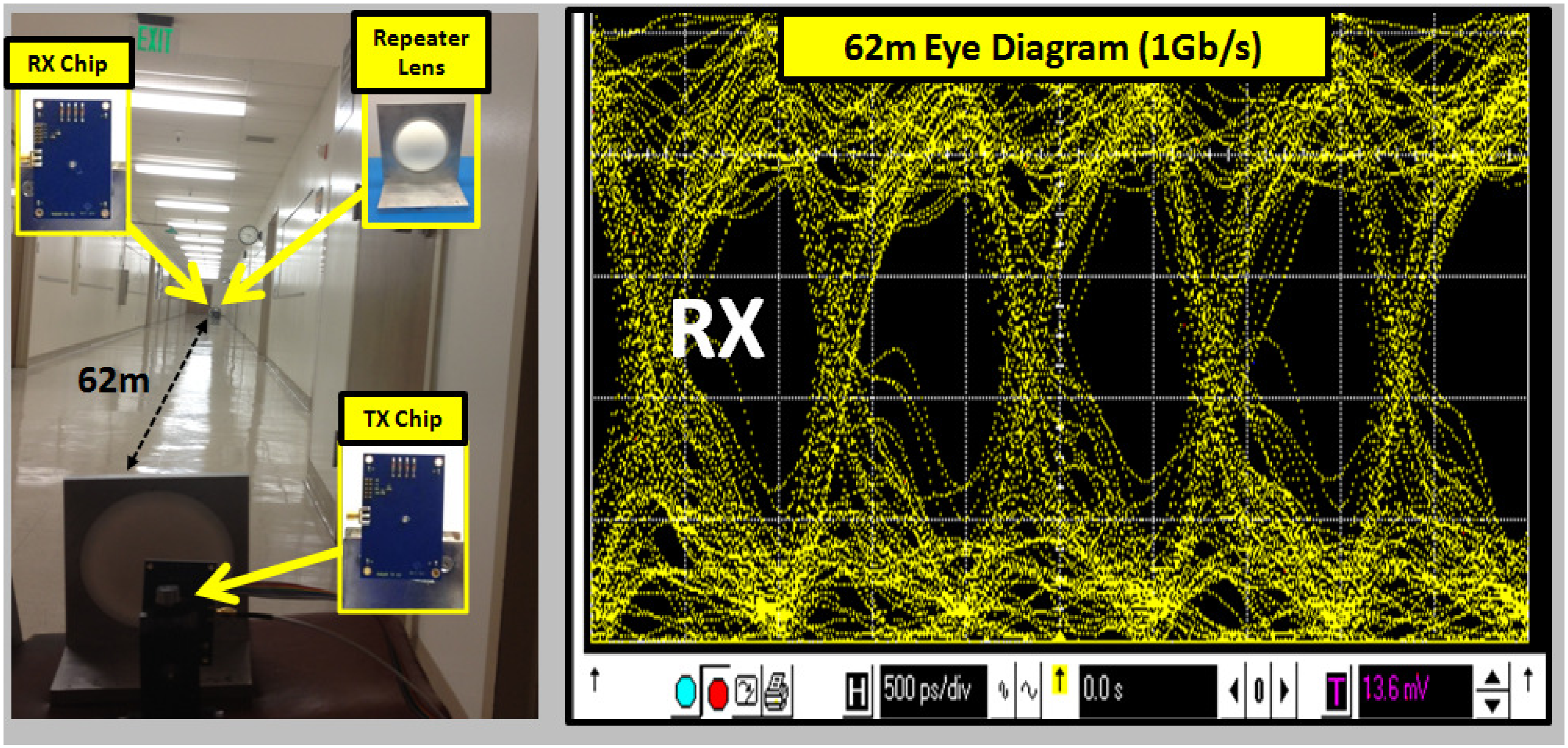
1 cm mm-Wave Wireless Link:
http://www.youtube.com/watch?v=WH92oeedNIU

1Gbps 100m Optically Collimated Link at 160GHz



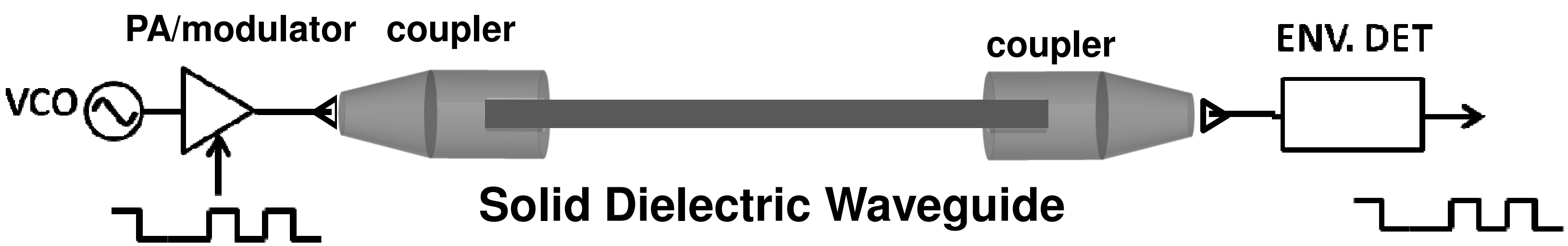
100 cm mm-Wave Wireless Link:
https://www.youtube.com/watch?v=uFDrHLZKNuM

1Gbps 100m Optically Collimated Link at 160GHz



Data Link Energy Efficiency: **~3pJ/bit/meter**

Terahertz Link through Plastic Waveguide

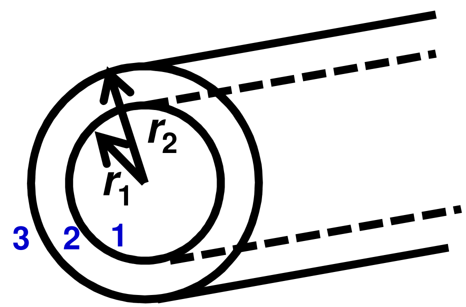


Choice of material: Non-polar plastic materials with low loss tangent.

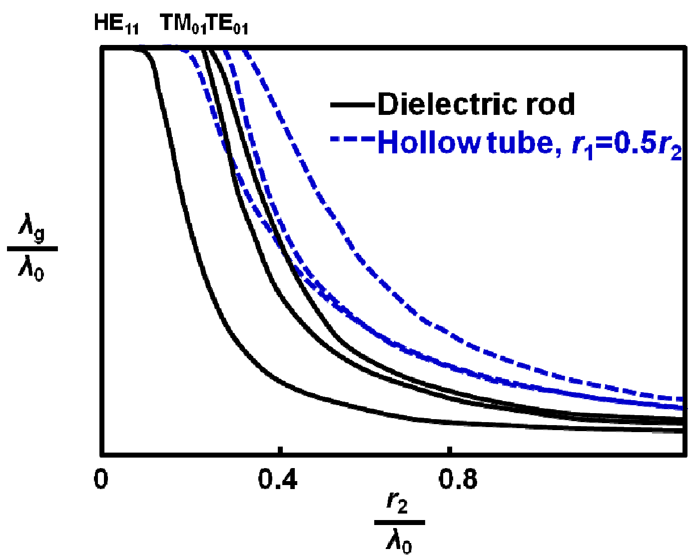
Material	ε_r	tanδ ($\times 10^{-4}$) <1GHz [1]	tanδ ($\times 10^{-4}$) in Ka-band [2]
Teflon	2-2.1	<2	2-3
Polyethylene	2.2-2.4	<2	3-4
Polystyrene	2.4-2.6	<5	8-10
Polypropylene	1.5-2.2	<5	5

Terahertz via Hollow Plastic Cable

Noble gas filled
Hollow Dielectric Waveguide

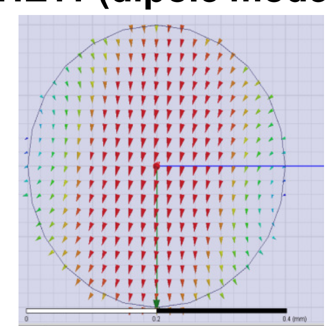


1,3: air
2: dielectric



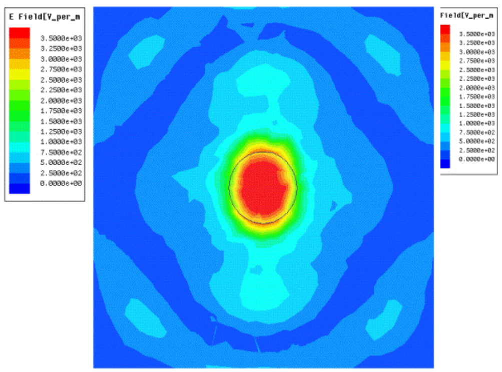
Lowest order mode

HE11 (dipole mode)

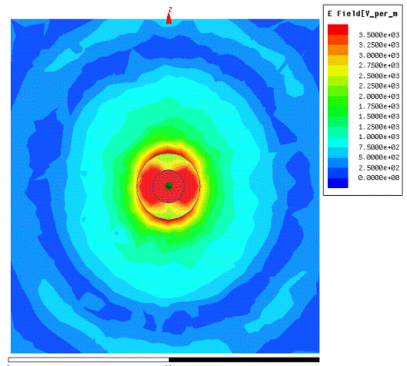


Plastic Cable for (sub)-mm-Wave Communications:
https://www.youtube.com/watch?v=WQRSOdLNIGk

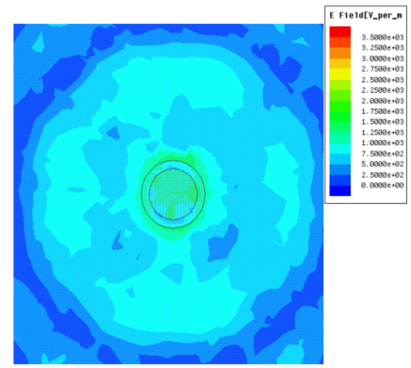
Reduced Loss via Hollow Plastic Cable



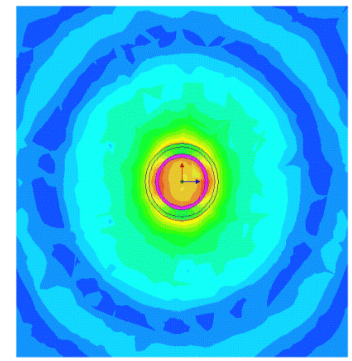
Solid Cable



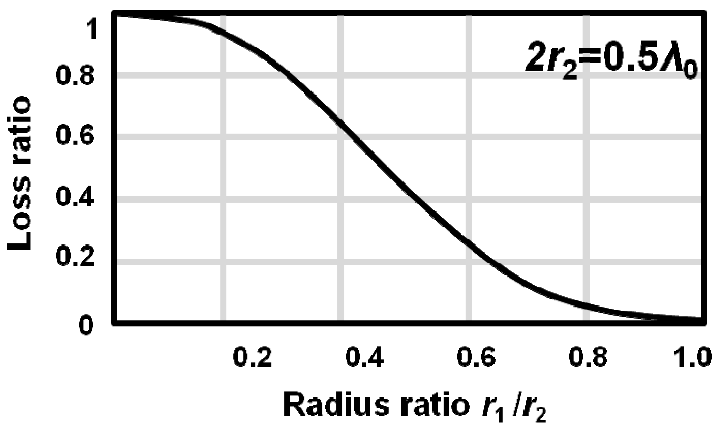
Thick
Hollow Cable

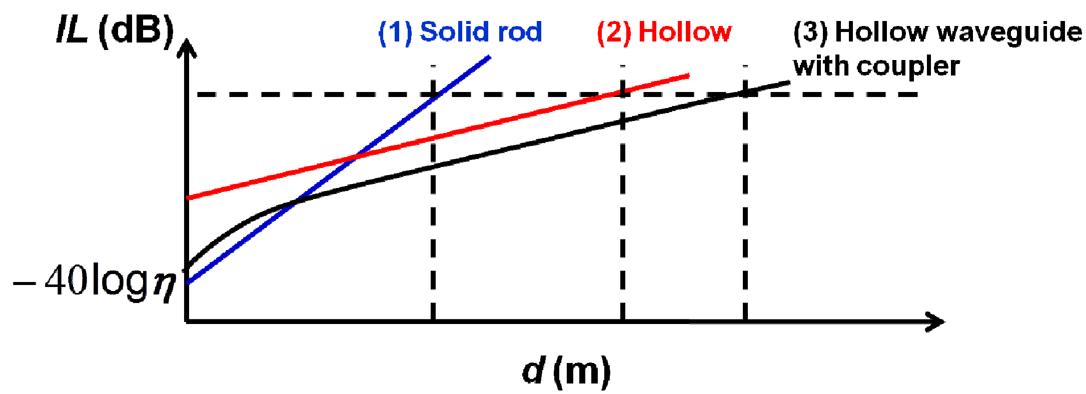


Thin
Hollow Cable

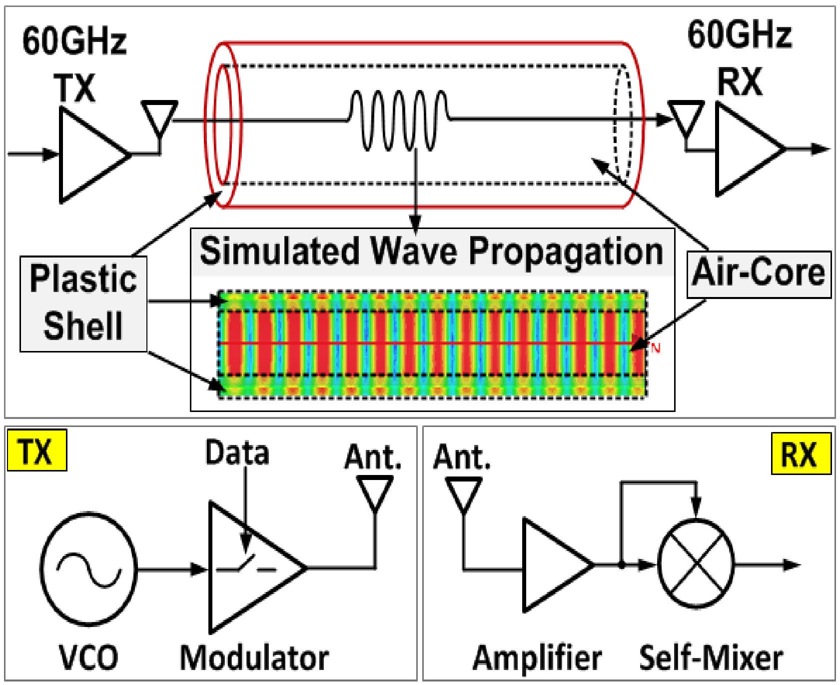


Hollow Cable
with Cladding

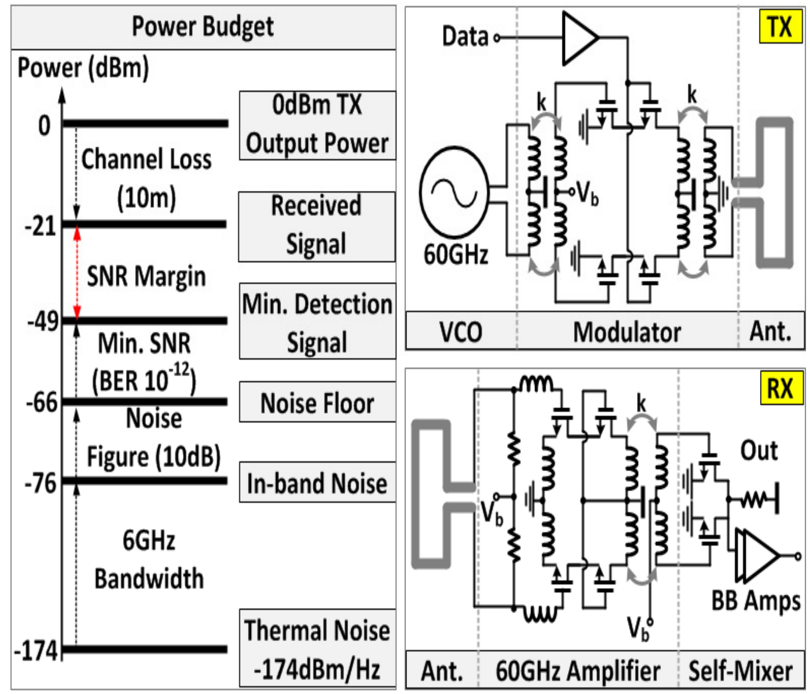




Transceiver Circuits and System for Hollow Plastic Cable Data Link

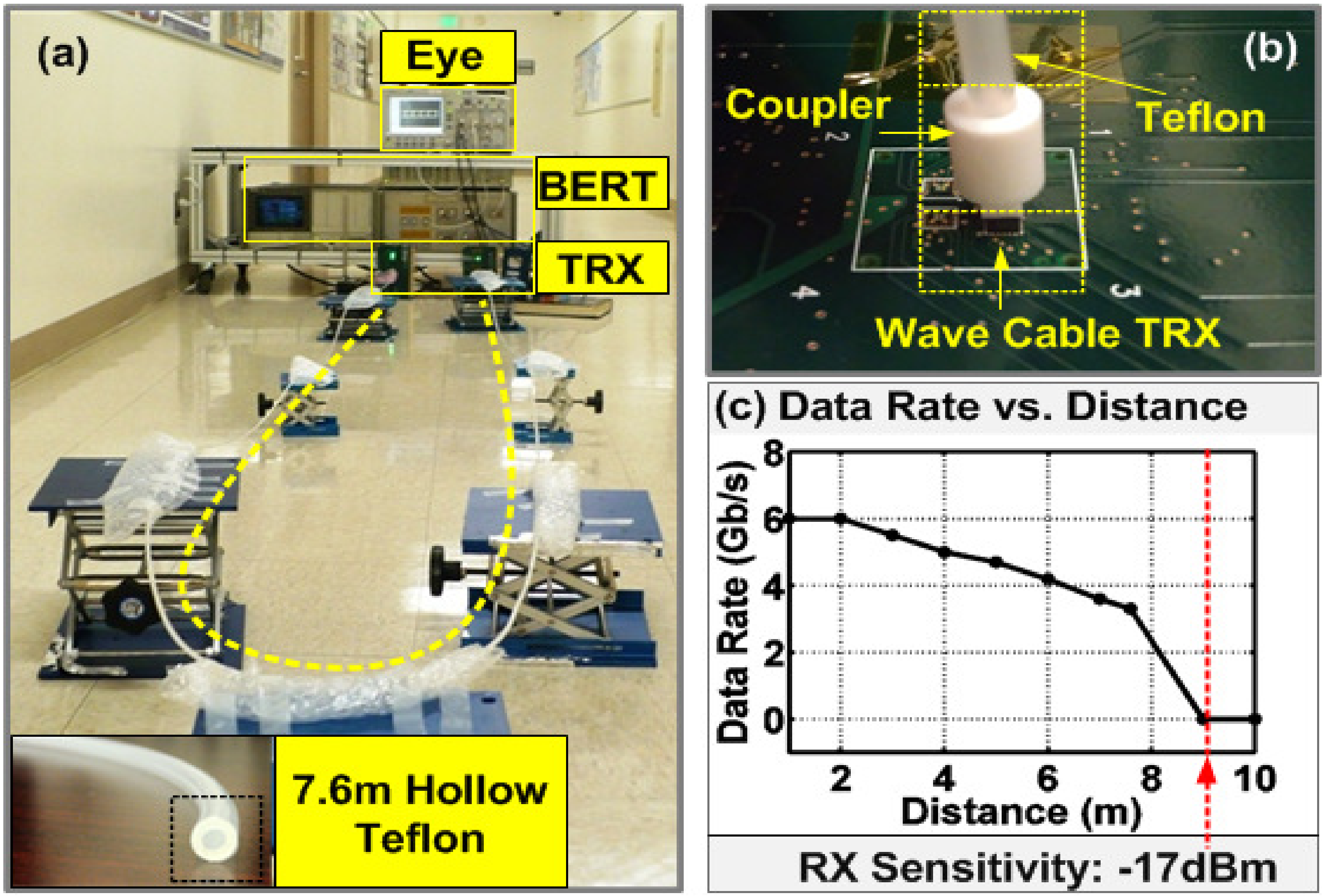


Transceiver diagrams with an air-core hollow plastic waveguide



Link system power budget and transceiver schematics

Multi-Giga-bit/sec Data Link via Hollow Plastic Water Cable



Summary

- Terahertz communication is constrained by technology / air absorption, but may be benefitted from its quasi-optical characteristics

- Terahertz has great potential to offer multi-Giga-bit/sec inter-server / container data links for modern data centers with low power (<1pJ/bit/m) and low cost by using
  - ❖ Collimated beam transmission in free space
  - ❖ Guided I/O signaling via plastic cable

- Circuit/Device Innovations are key enablers to facilitate Radio, Radar and Imaging Systems-on-Chip with high performance yield and cost-effectiveness
  - ❖ On-Chip Self-healing for performance yield
  - ❖ DiCAD for dynamic permittivity tuning