European Microwave Week

Modelling, Circuit Design and Measurement Techniques for mm-Wave Systems
WTH-11 Workshop, October 27-31 2008

SiGe BiCMOS Circuits for Future mmWave and THz Applications

Ullrich Pfeiffer ullrich@ieee.org

High-frequency and Communication Technology
University of Wuppertal, Germany

EuMIC 2008

38TH EUROPEAN MICROWAVE CONFERENCE 2008

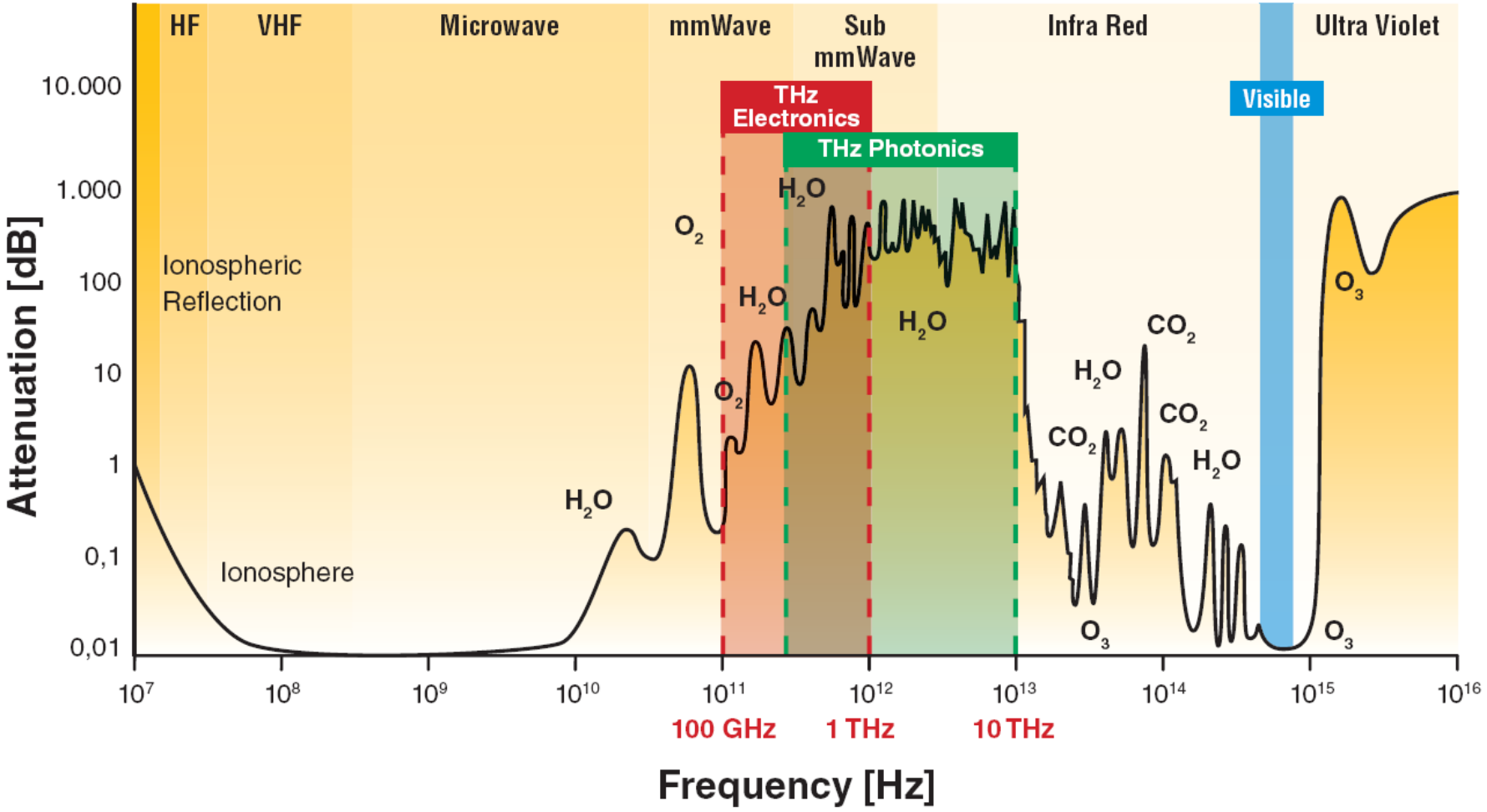
Outline (old)

- **Introduction**
  - Motivation
  - Silicon mmWave IC design tradeoffs
  - SiGe HBT Power limits at mmWaves and beyond
- **High power design concepts in silicon**
  - Power amplifier design methodology
  - Sate-of-the-art 60GHz PA examples
  - Advanced power combining techniques at 60GHz
- **94 GHz Monolithic Receiver**
- **140 GHz Schottky Barrier Diode Circuits**
- **Summary and Outlook**

Outline (new)

- **Introduction**
  - Motivation for silicon integrated THz Electronics
    - Review of THz sources and detectors
    - Potential applications
- **THz circuits based on silicon process technologies**
  - SiGe: 94, 140, 160 GHz down-conversion front-ends
  - Si SBD: 140 GHz up-conversion mixer / doubler (IBM)
  - CMOS: 650 GHz CMOS Focal-Plain Array (quarter-micron)
  - SiGe: 650 GHz Focal-Plain Array (220 GHz f_{max})
- **Imaging of postal envelopes in Silicon**
  - 3x5 focal-plane arrays
- **Summary and Conclusion**

Terahertz Electronics



Properties of Terahertz Radiation

- **Radiation properties**
  - Sub-millimeter wavelengths (1mm-30µm)
  - 1 THz has λ=300µm and E=1/2 meV
  - Black bodies above 10K generate THz radiation
- **Terahertz radiation is non-ionizing**
  - not expected to damage DNA, unlike X-rays.
- **Propagation of THz Radiation:**
  - Penetrates dry fabric, paper, cardboard, leather, plastic...
  - Detection of hidden objects: weapons, drugs, money...
  - Used for spectroscopic identification: materials, explosives...

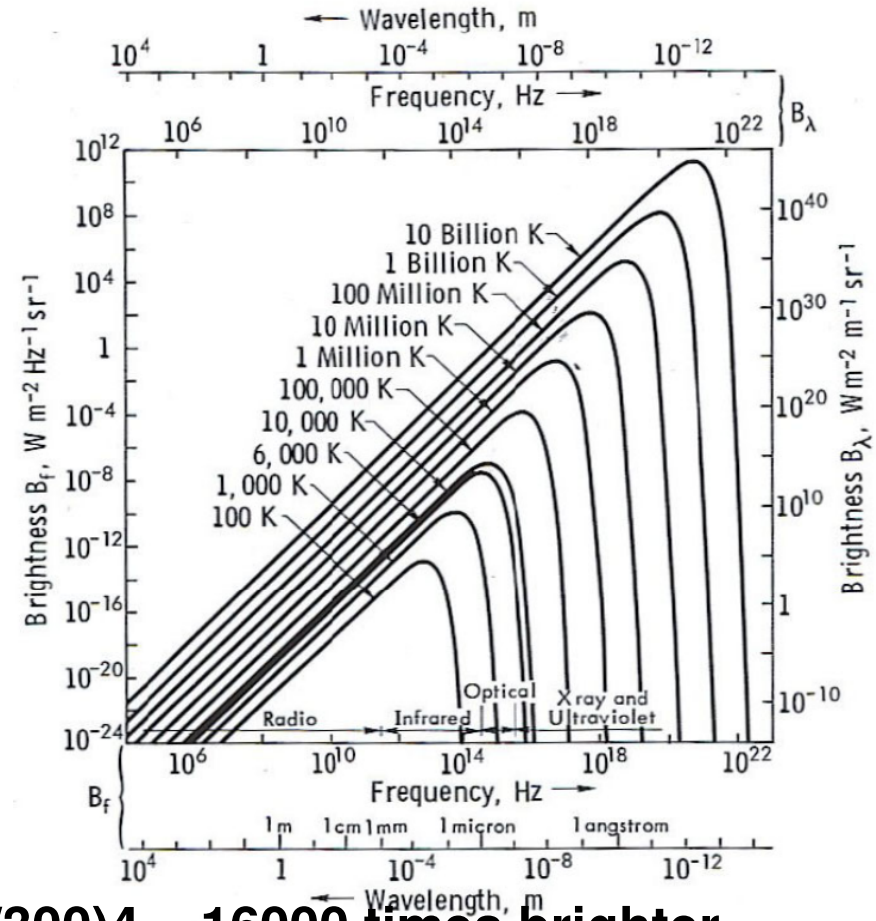
Blackbody Radiation - 19th Century Physics

- **Planck's law**
  - Brightness [wm^2 Hz^{-1} rad^{-2}]

$$B_\nu = 2h\nu^3/c^2(e^{h\nu/k_BT} - 1)$$

- **Stefan-Bolzman law**
  - Total brightness $\int B_\nu d\nu = \sigma T^4$
  - Planck's const. $h = 6.6E^{-34}$
  - Boltzmann's const. $k_B = 1.4E^{-23}$
- **Rayleigh – Jeans approx.**

$$h\nu \ll k_BT$$
$$B_\nu \approx 2k_BT/\lambda^2$$



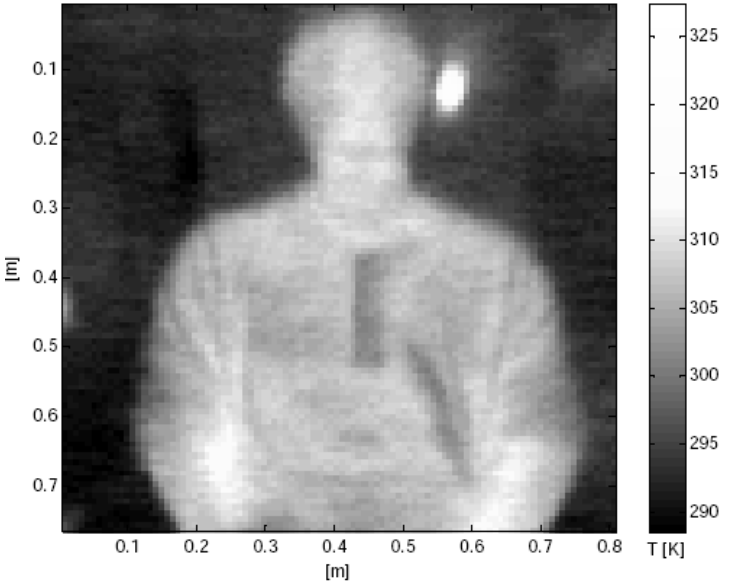
- **At 6000K, overall the sun is (6000/300)4 = 16000 times brighter than a room temperature black body, but between 10GHz-10THz it is only 20 times brighter**

Passive Imaging Examples

Outdoors



Indoors



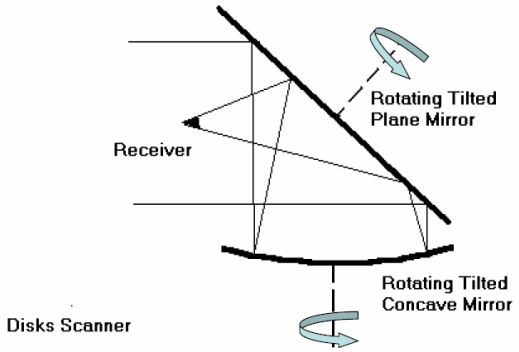
- Courtesy: QineticQ and NIST

How is THz Imaging done today?

- **Single pixel detectors**
  - E.g. bolometer (measure wave intensity only)
  - Linear-arrays operating at cryogenic temperatures



- **Sequential scanners**
  - Extremely slow, very good though
  - Laboratory environment only
  - fs-laser systems (Teraview, UK and Picometrix, USA)
  - Heterodyne Systems on InP technology (StarTiger project and now spin-off company Thruvision)

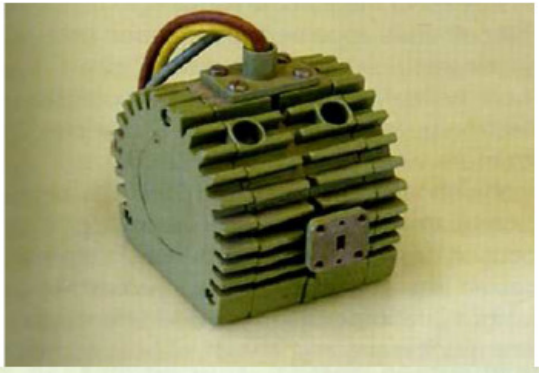


No cost efficient THz imaging solutions exist to date!!!

THz Generation Methods

- **Thermal sources**
  - black body radiation
- **Photonic Systems**
  - Time-domain: fempto-second laser pulses
  - Direct generation:
    - infraread pumped gas lasers (discreet molecular transitions within 600G-3THz, 13dBm)
    - solid state lasers (germanium, silicon, QCD lasers) (20dBm, but require liquid He-cooling)
  - Photo down-conversion mixers
- **Electronic Sources**
  - frequency up-conversion
  - Problem: Power on the order of -20dBm (10µW) at 1 THz
  - Direct generation: tubes (backward wave oscillators)
- **Short electron bunches in accelerators (synchrotron rad.)**

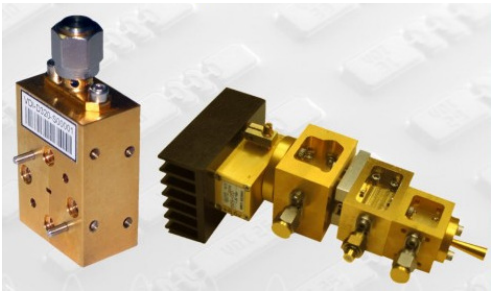
Commercial Available THz Sources



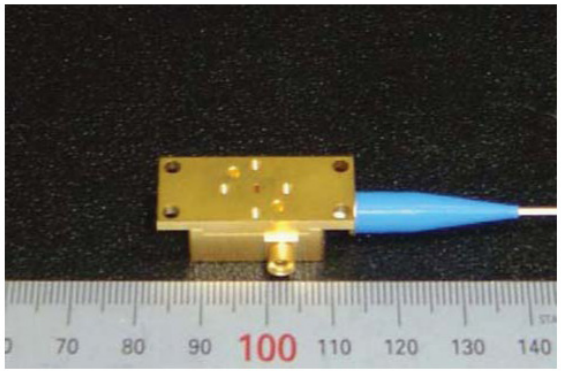
BWO oscillator



SIFIR-50 Gas Laser
from Coherent



Multiplier based
source
for 0.6 THz from
Virginia Diodes



Uni-travelling-carrier
photo diode produced by
NTT, Japan



QUANTA® TERA QCL
laser from LaserComponents

THz Detection Methods

- **Coherent detection**
  - heterodyne receivers
  - radar front ends
  - MMICs, tunnel junctions, HEB bollometers mixers
  - Problem: LNAs is typically limited to below 200 GHz
- **Incoherent (direct) detection**
  - calorimeters/bolometers, based on the physical principle of energy/power absorption
  - pneumatic detectors (Golay cell)
  - square-law detectors, e.g. SBDs or transistors non-linearities
- **Emerging detection principles**
  - semiconductor nano-devices
  - quantum dot arrays
  - plasma wave detectors
  - tunnel diodes and band gap materials

Problem: Compatibility with conventional microelectronics!

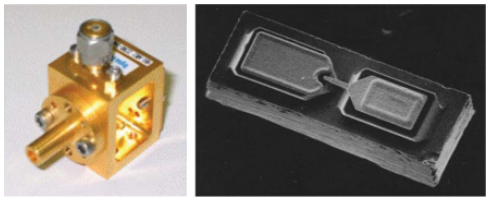
Commercial Available THz Detectors



He-cooled bolometer
example taken from QMC
NEP ~ 3 pW/√Hz (0.2 – 30 THz)



Pyroelectric detectors
for ex. Spectrum
Detector Inc.
NEP ~ 400 pW/√Hz
(0.1-30 THz)

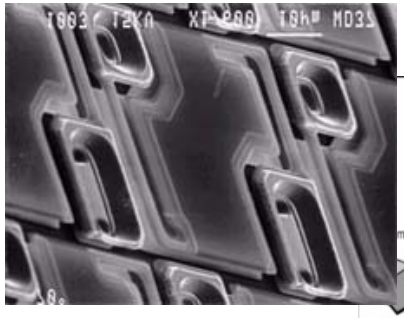


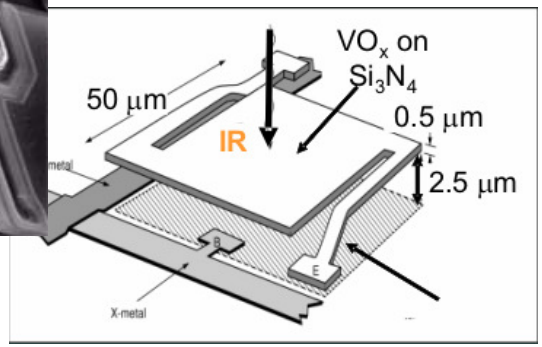
Zero-bias Schottky diode
detector, Virginia Diodes
NEP ~ 20 pW/√Hz (0.6 THz)



Golay cell, example taken from
QMC NEP ~ 200 pW/√Hz (0.2 –
30 THz)

Microbolometer array
Infrared Solutions Inc.

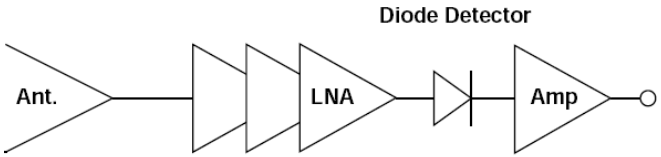


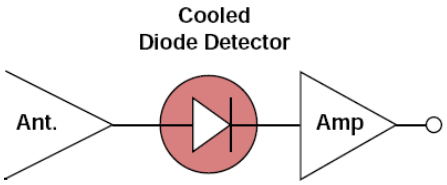


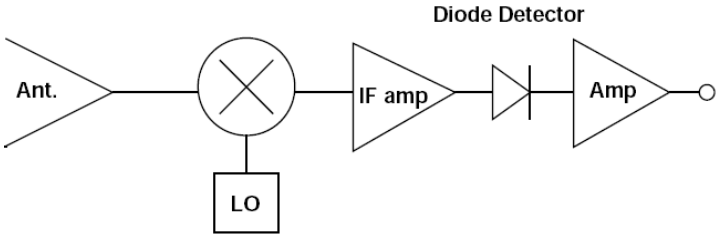
NEP ~ 300 pW/√Hz
(4.3 THz, absorption only 4%!)

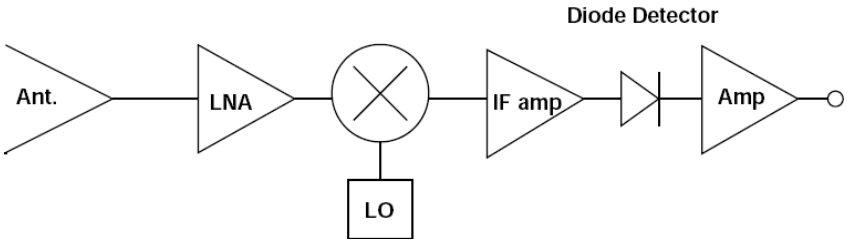
Terahertz Receiver Approaches

- **Direct Detection with LNA**
  - LNA gain 5-15dB/stage up to 200GHz
  - 10-30 GHz bandwidth at 94GHz
  - Schottky diode detectors
  - Rx noise T_N of about 500K
- **Direct Detection**
  - Only depends on detector noise
  - Cooled detectors can have very low noise
  - Broad-band operation possible
- **Hetorodyne**
  - Above 200GHz where no LNAs available
- **Heterodyne plus LNA**









Why Silicon for THz Applications?

- **mmWave and THz systems are currently III/V dominated**
  - Low volume applications
  - Low integration levels
  - Expensive packages and chips
- **Silicon technologies promise:**
  - Do it all on a single chip
  - High integration levels
  - Low cost at high volumes
  - Simpler chip packages, sub-systems etc.
- **Problem:**
  - Performance roll-off, e.g NF, gain, efficiency, **output power…**
  - Killer **applications…**

Potential Applications for Silicon THz Electronics

High-speed Communication

Wireless:
- Personal and Local Area Networks (PANs/LANs)
  - consumer electronic devices
- Consumer electronic devices
- Wireless backhaul
- Inter-building communication, E-band (71-76, 81-86GHz)
- Secure links and surveillance
- Space and inter-satellite communication

Digital:
- High-speed interconnects
- Data switches (Mux/DeMux)
- Analog to Digital Conversion (ADC/DAC)

Radar Applications

Automotive:
- Long Range Radar (LRR)
  - collision avoidance, automated cruise control (77GHz)
- Short Range Radar (SSR)
  - pre-crash detection, stop-and-go, lane change assistant (77-81GHz)
- Road condition detection

Space:
- Aviation safety in extremely poor visibility (94GHz)
- Airport ground control (94GHz)

Industrial:
- Distance measurement
- Alarm systems and motion detection

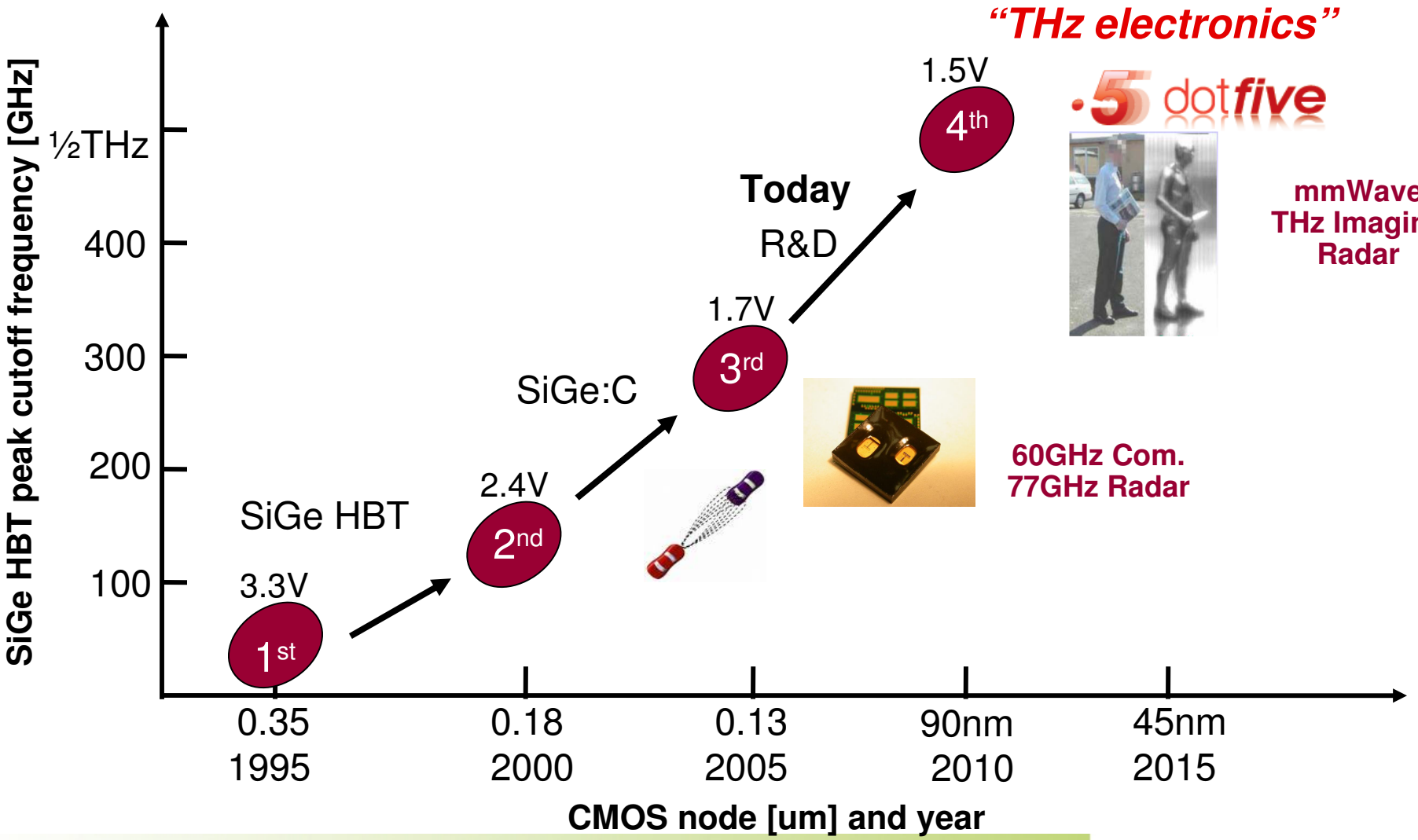
mmWave, THz Imaging and Sensing

Security:
- Non-invasive imaging
- Drug and explosive detection

Sensing:
- Earth sensing and climate control
- Industrial process control
- Astronomy, microwave background

Biotechnology:
- Medical imaging, tumor recognition
- Genetic screening

Silicon (SiGe) HBT Technology Evolution



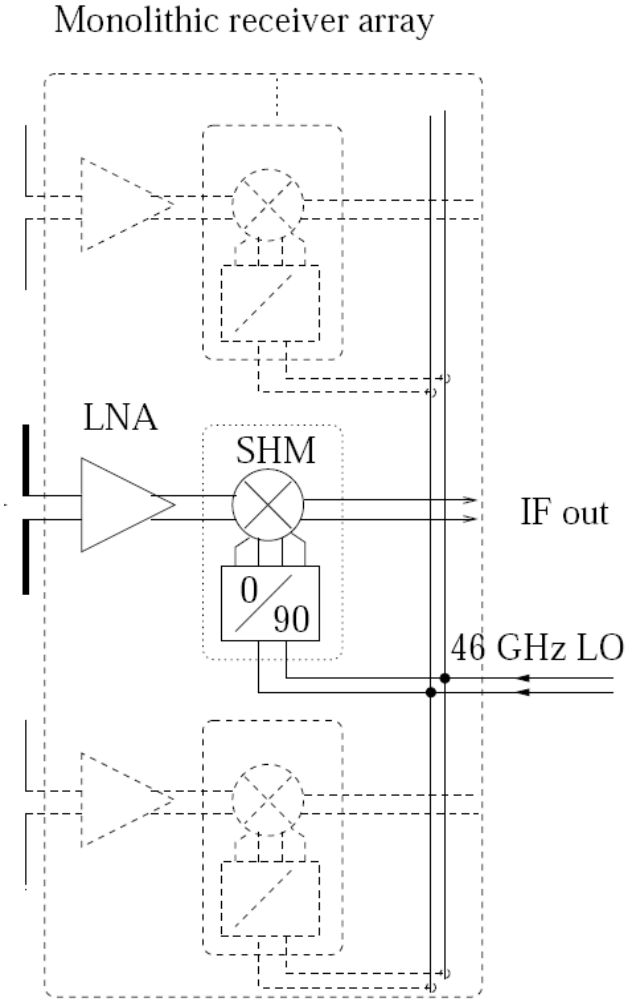
Challenges for Silicon Technologies

- **Output power limitations**
  - Power amplifier (active systems)
  - LO drive power (heterodyne)
  - Efficiency
- **Noise performance**
  - Applications have no headroom to trade noise performance
  - Sensitivity is at limit

Outline

- **Introduction**
  - Motivation for silicon integrated THz Electronics
    - Review of THz sources and detectors
    - Potential applications
- **THz circuits based on silicon process technologies**
  - **SiGe: 94, 140, 160 GHz down-conversion Front-ends**
  - Si SBD: 140 GHz up-conversion mixer / doubler (IBM)
  - CMOS: 650 GHz CMOS Focal-Plain Array (quarter-micron)
  - SiGe: 650 GHz Focal-Plain Array (220 GHz f_{max})
- **Imaging of postal envelopes in Silicon**
  - 3x5 focal-plane arrays
- **Summary and Conclusion**

94GHz Subharmonic Receiver Array Architecture

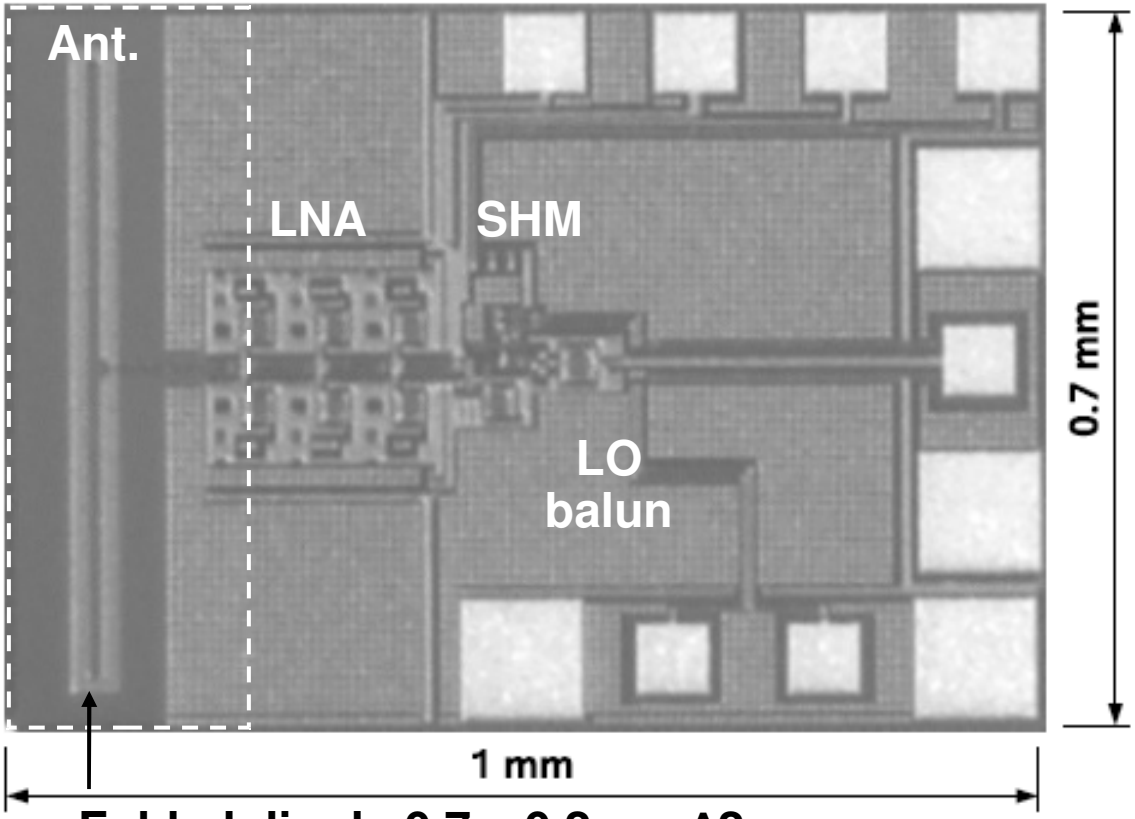


- 0.25µm SiGe:C BiCMOS Technology with a 220GHz fmax
- Sub-harmonically pumped mixer (47-GHz LO) based on cascaded switching quads
- Lumped RC poly-phase network for quadrature LO generation

[1] E. Öjefors and U. Pfeiffer, "A 94-GHz Monolithic Front-End for Imaging Arrays in SiGe:C Technology", European Microwave Integrated Circuits Conference (EuMIC), October 2008.

Chip Micrograph

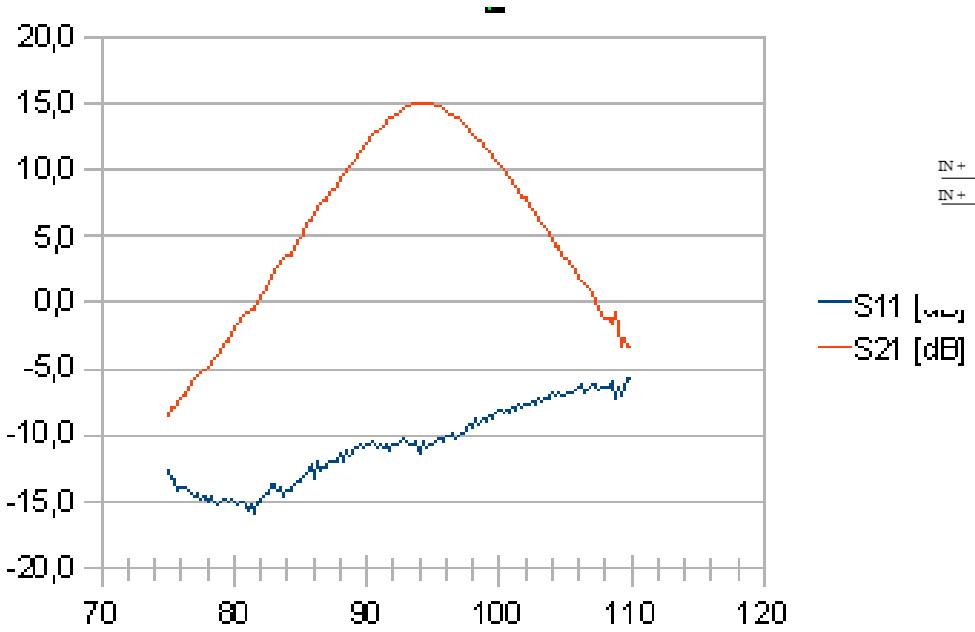
On-chip integration with folded dipole

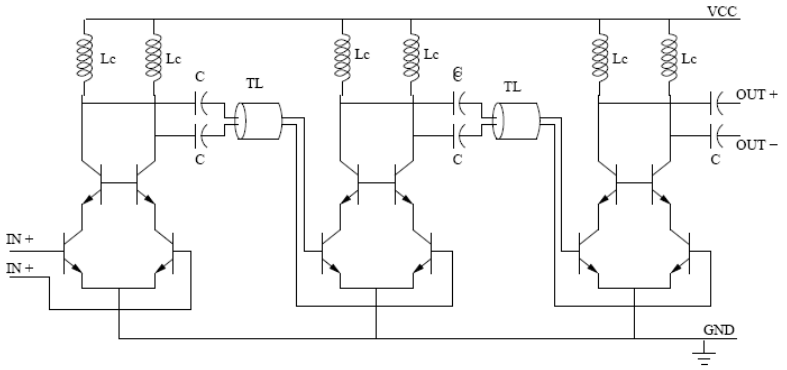


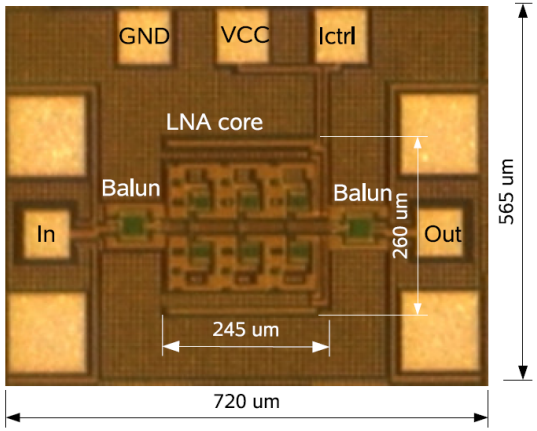
Folded dipole 0.7 x 0.2 mm^2
Metal filler and p+ blocked out

- folded dipole fits within pad frame
- On-chip antenna only marginally larger than 150 um GSG pad
- Low directivity (single dipole radiator), can be improved by reflector backing
- Efficiency limited 10-20% due to the use of a low resistivity substrate, with high resistivity substrate > 50%!

Three stage 94 GHz balanced LNA





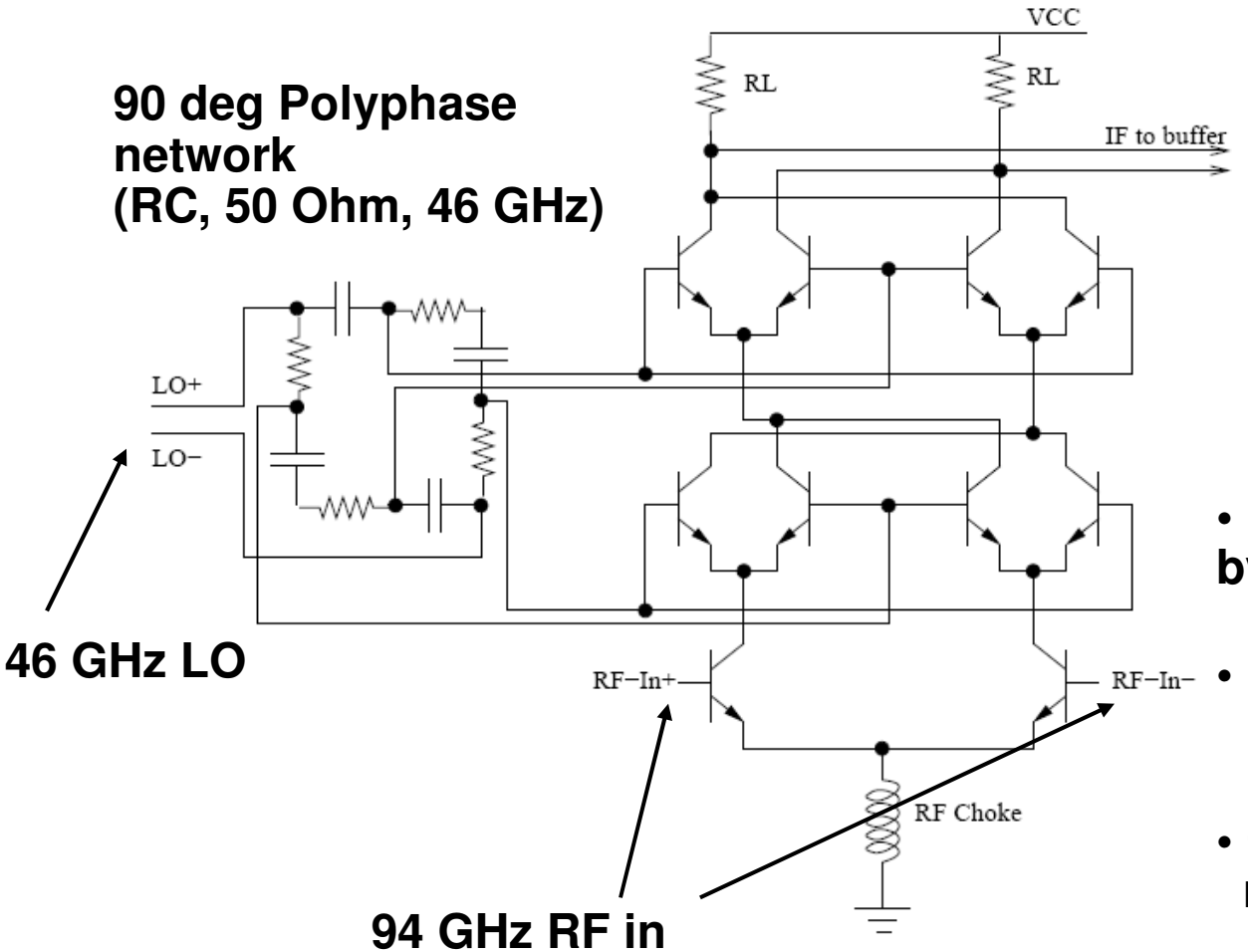


- 3-stage differential cascode with 14-dB gain
- Current consumption 28 mA (can be reduced to 15 mA)
- Simulated noise figure 11 dB @ 94 GHz, < 6 dB expected with 500GHz Technology

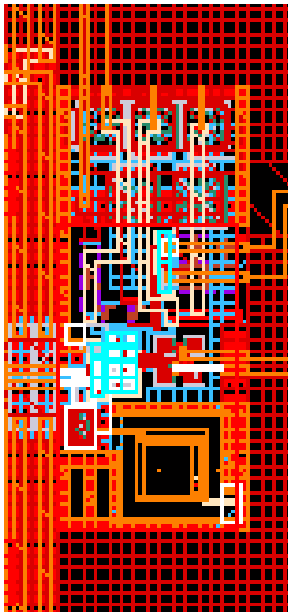
94 GHz Sub-Harmonic Mixer (SHM)

SHM Architecture and Layout

90 deg Polyphase network (RC, 50 Ohm, 46 GHz)



IF out

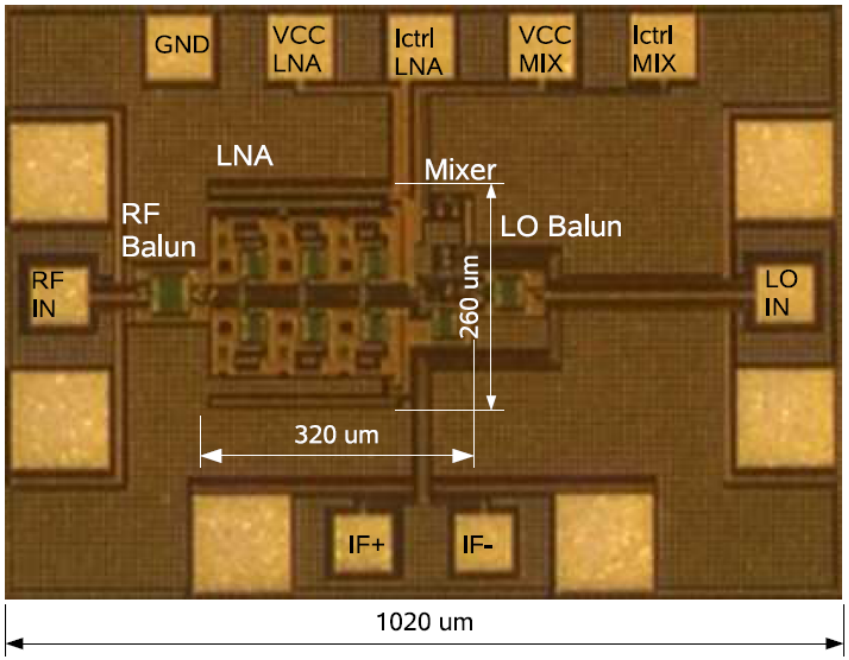


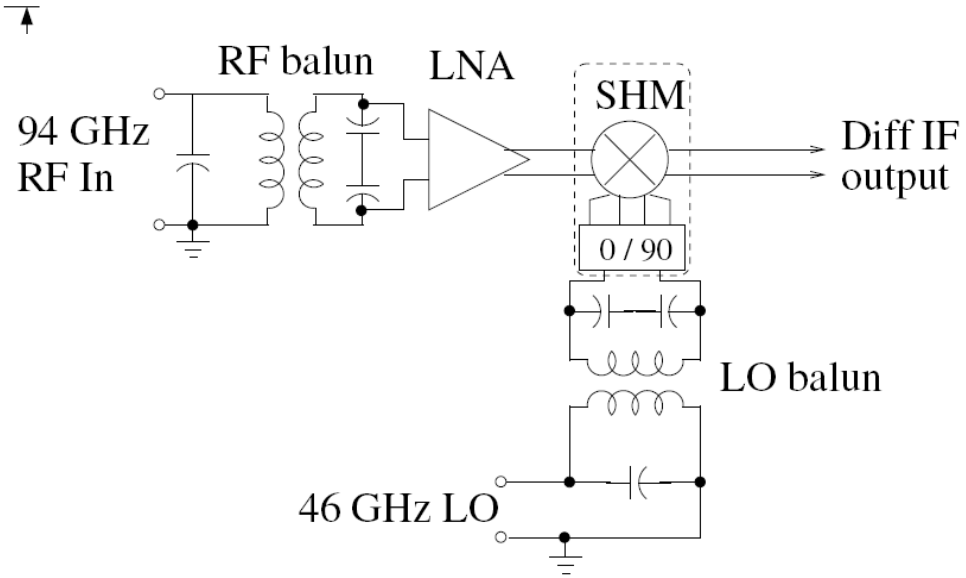
46 GHz LO

94 GHz RF in

- LO generation facilitated by subharmonic mixing
- $V_{if} = V_{rf} \cos(\omega_{lo}t)\sin(\omega_{lo}t) = V_{rf} \sin(2\omega_{lo})/2$
- Can be designed as I/Q mixer for zero-IF

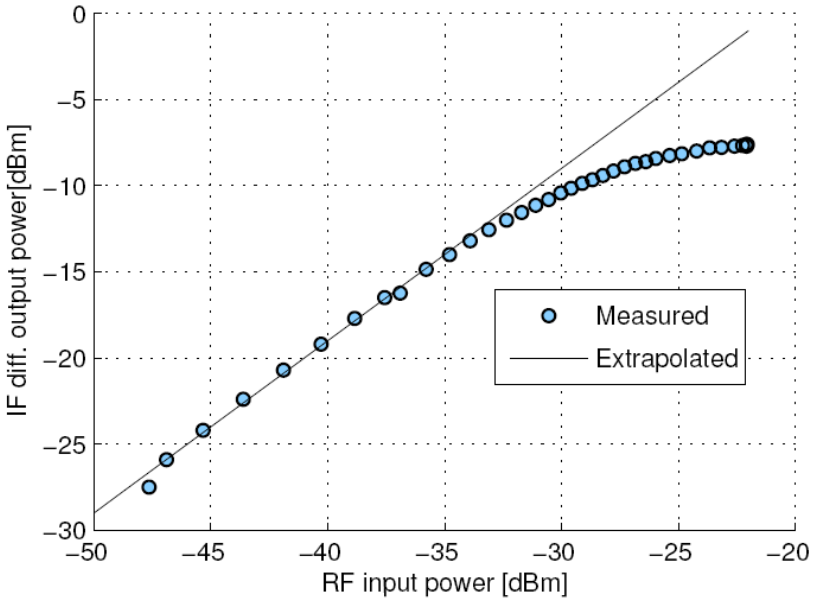
LNA and Mixer Breakout

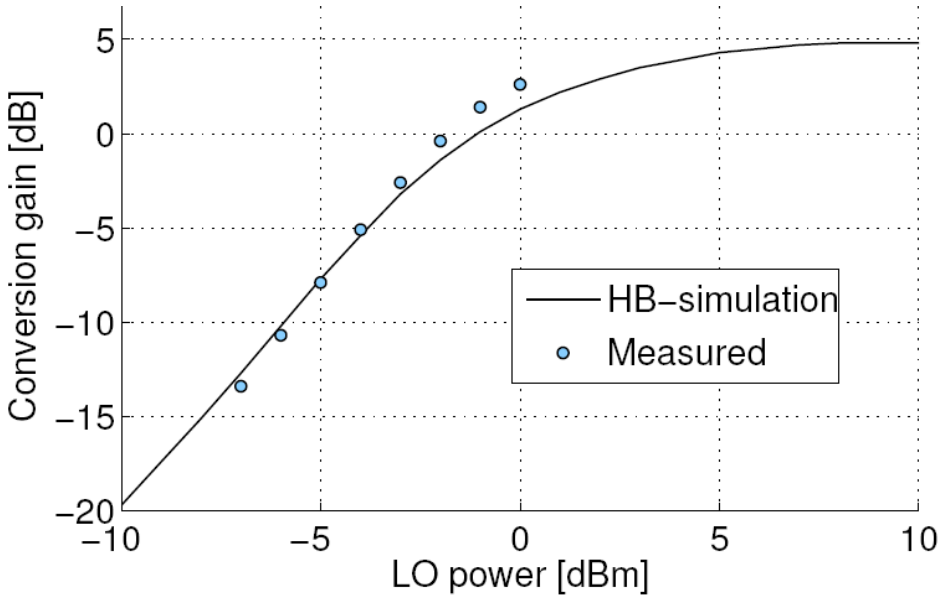




- Padframe 0.8 mm², down-converter core (LNA+mixer) less than 0.1 mm²

Measured Conversion Gain





- **20-dB conversion gain at 94 GHz**
- **Measured input-referred 1-dB compression point: -32 dBm**

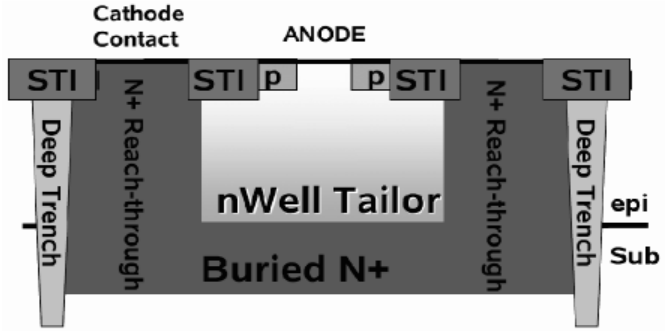
[1] E. Öjefors and U. Pfeiffer, “A 94-GHz Monolithic Front-End for Imaging Arrays in SiGe:C Technology”, European Microwave Integrated Circuits Conference (EuMIC), October 2008.

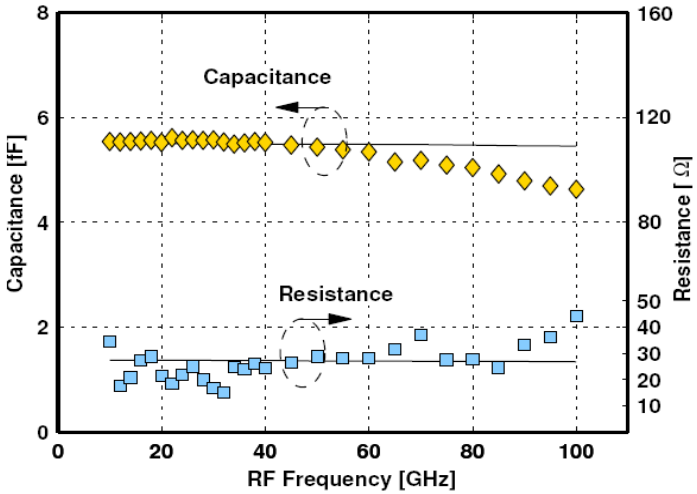
Outline

- **Introduction**
  - Motivation for silicon integrated THz Electronics
    - Review of THz sources and detectors
    - Potential applications
- **THz circuits based on silicon process technologies**
  - SiGe: 94, 140, 160 GHz down-conversion Front-ends
  - **Si SBD: 140 GHz up-conversion mixer / doubler (IBM)**
  - CMOS: 650 GHz CMOS Focal-Plain Array (quarter-micron)
  - SiGe: 650 GHz Focal-Plain Array (320 GHz f_{max})
- **Imaging of postal envelopes in Silicon**
  - 3x5 focal-plane arrays
- **Summary and Conclusion**

1 THz Schottky Barrier Diodes (SBD) in Silicon

- IBM Silicon Germanium Technology (f_{max}/f_T=240/200)
- SBD: F_c=1THz, (C=5.5fF, R=28Ohm)

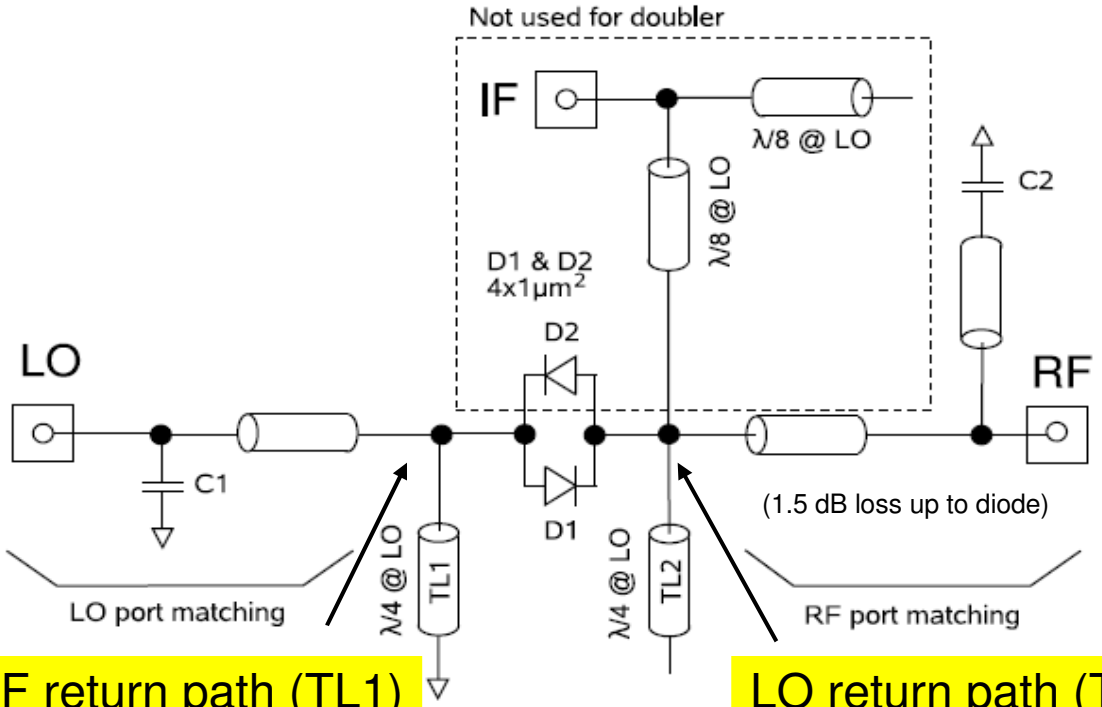




FET	1.2V NFET	$L_p \geq 0.092$, T_{ox}=2.2nm
	1.2V PFET	$L_p \geq 0.092$, T_{ox}=2.2nm
	2.5V NFET	$L_{eff} \geq 0.24$, T_{ox}=5.2nm
	2.5V PFET	$L_{eff} \geq 0.24$, T_{ox}=5.2nm
	1.2V Isolated NFET	$L_p \geq 0.092$, T_{ox}=2.2nm
	2.5V Isolated NFET	$L_{eff} \geq 0.24$, T_{ox}=5.2nm
Resistors	p-polysilicon	340Ω/sq, 1700Ω/sq
	Subcollector	8.8Ω/sq
	n-diffusion	73Ω/sq
	BEOL	60.5Ω/sq
Capacitors	MIM	up to 4fF/μm^2
	MOS Varactor (T_{ox}=2.2)	11fF/μm^2, tunability 5:1
	MOS Varactor (T_{ox}=5.2)	5.8fF/μm^2, tunability 3.5:1
	HA Junction Varactor	2.05fF/μm^2, tunability 3.6:1
Diodes	p-i-n diode	IL=1dB, isol.=16dB at 60GHz
	SBD	F_c=1.1 THz
BEOL	Passives	inductors, bends, tees, inverters, dividers

[1] U. Pfeiffer, C. Mishra, R. Rassel, S. Pinket, and S. Reynolds “Schottky Barrier Diode Circuits for mmWave and THz Applications”, submitted to Trans. Microw. Theory and Tech., Feb. 2008, Vol. 56, Nr. 2, p: 364-371.

SBD SHM Upconverter and Doubler (IBM)



- Zero-bias anti-parallel diode pair (APDP)
- Quarter-wave transformers provide the ground return path

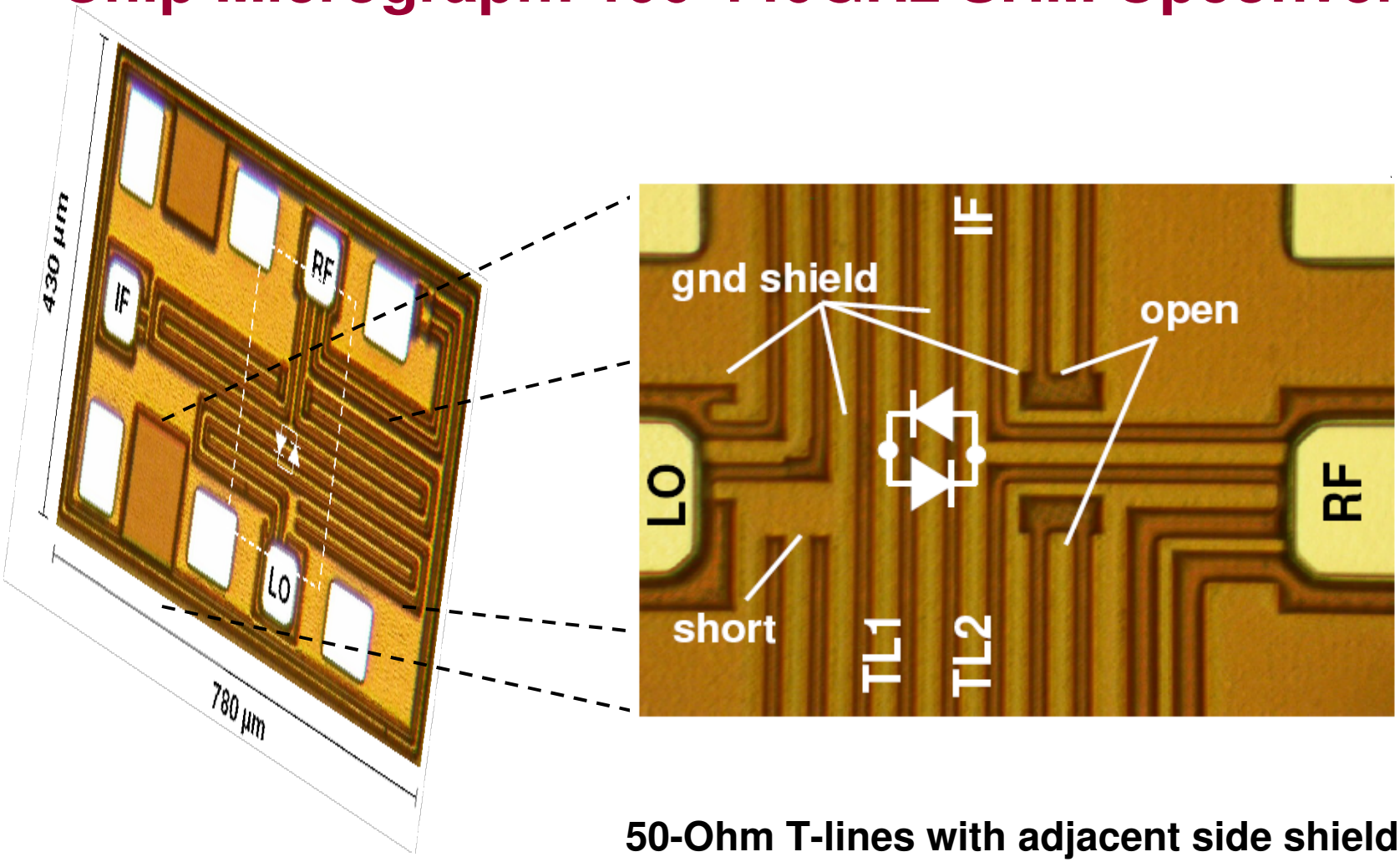
SHM:

- **Pumped with the second harmonic of a 60-GHz LO**
- **The LO port is matched for maximum power transfer to the diodes.**

Doubler:

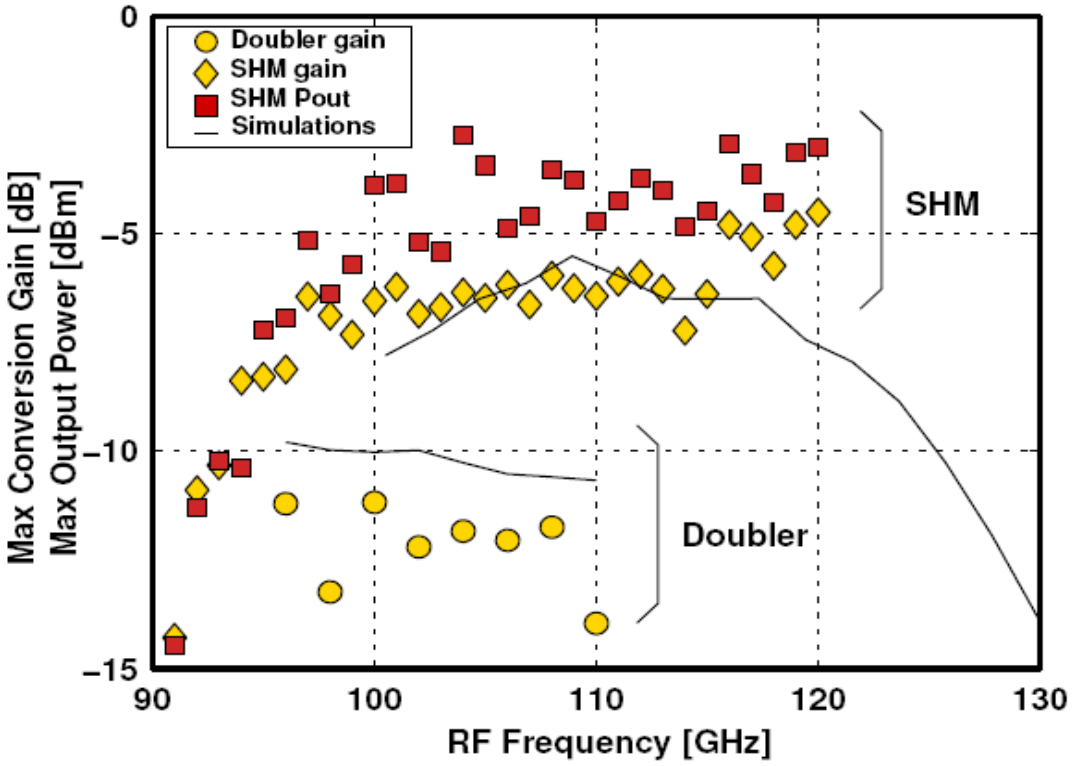
- **Doubler is a subset of SHM (D2 is omitted)**
- **single SBD diode to create the second harmonic**

Chip Micrograph: 100-140GHz SHM Upconverter



50-Ohm T-lines with adjacent side shields

Conversion Loss and Output Power



SHM 100-120 GHz:

- G = -6 to -7dB
- Pout = -4 dBm

110GHz Doubler:

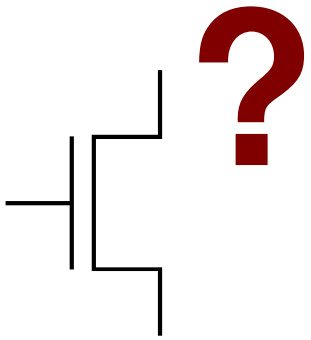
- G = -12 to -14 dB
- Pout = -2.5 dBm

Measurement accuracy within ± 1dB

Outline

- **Introduction**
  - Motivation for silicon integrated THz Electronics
    - Review of THz sources and detectors
    - Potential applications
- **THz circuits based on silicon process technologies**
  - SiGe: 94, 140, 160 GHz down-conversion Front-ends
  - Si SBD: 140 GHz up-conversion mixer / doubler (IBM)
  - **CMOS: 650 GHz CMOS Focal-Plain Array (quarter-micron)**
  - SiGe: 650 GHz Focal-Plain Array (220 GHz f_{max})
- **Imaging of postal envelopes in Silicon**
  - 3x5 focal-plane arrays
- **Summary and Conclusion**

How to do THz Detection in FET Transistors?



Detection = Direct Power Detection (Heterodyne)

You will need to understand:

1) Resistive (self-) Mixing

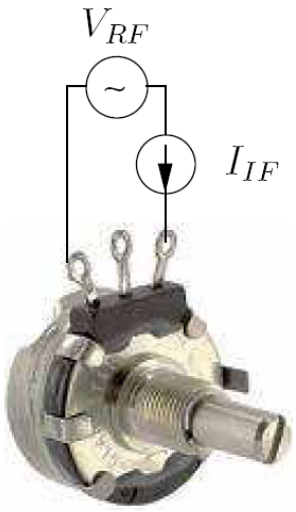
- Boundary conditions
- Works well up mmWave frequencies

2) Distributed Resistive Self-Mixing

- Voltage dependent RC-Transmission Lines
- Works well up to THz frequencies
- Consider Higher Order Effects
- Additional non-linearities

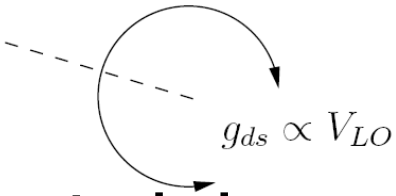
How Does it Work?

Resistive Mixer (Potentiometer):

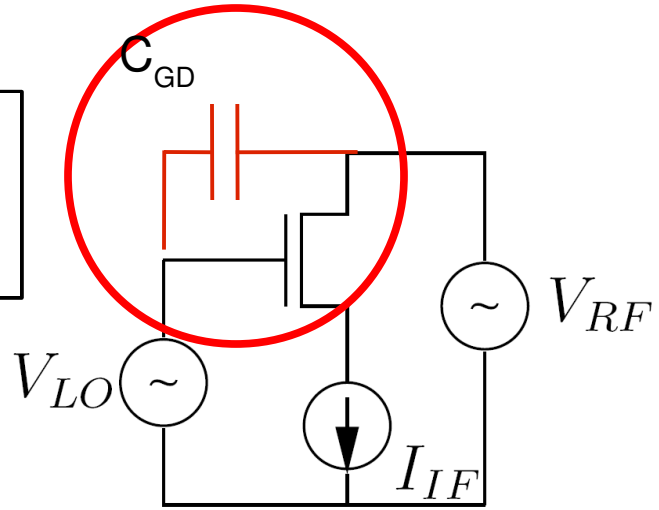


$$I_{IF} = V_{RF} \cdot g_{ds} \propto V_{RF} \cdot V_{LO}$$
$$I_{IF} \propto V_{RF}^2$$

Conductance Modulation



Resistive FET Mixer:



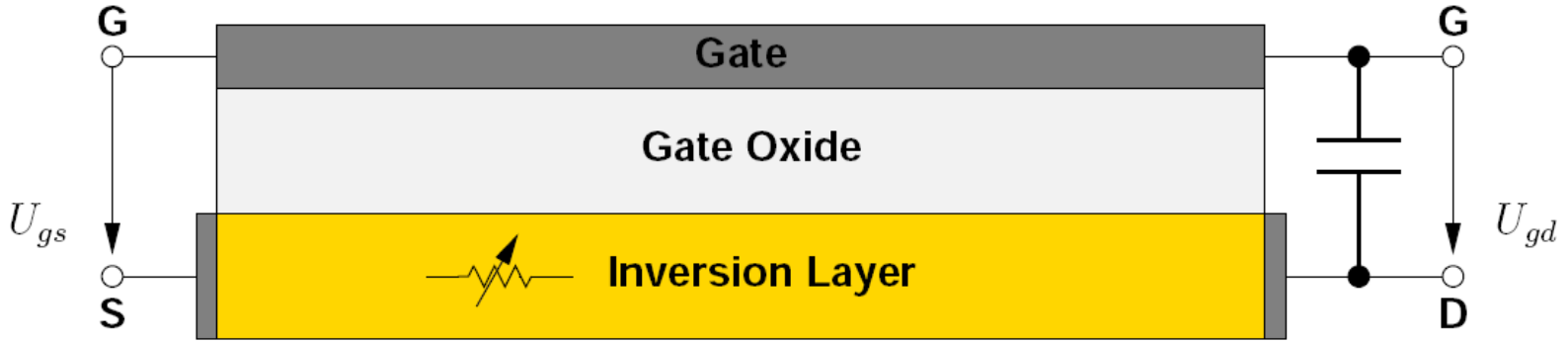
Similar to circuit presented in US Pat 4647848, filed 1983

- **Parasitic gate-drain cap causes self-mixing in resistive mixers**
- **Self-mixing causes DC a offset (usually unwanted)**

Add extra capacitance to enhance self-mixing !

-> Square law detector converts RF power to DC current / voltage

Let's take a closer look...



$$i_{ds}(t) = v_{ds}(t) g_{ds}(t) = v_{ds}(t) \frac{W}{L} \mu Q_{ch}(t)$$

$$Q_{ch}(t) = C_{ox}(v_{gs}(t) - V_{th} - v_{ds}(t)/2)$$

$$i_{ds}(t) = \frac{W}{L} \mu C_{ox}(v_{ds}^2(t)/2 + v_{ds}(t)(V_g - V_{th}))$$

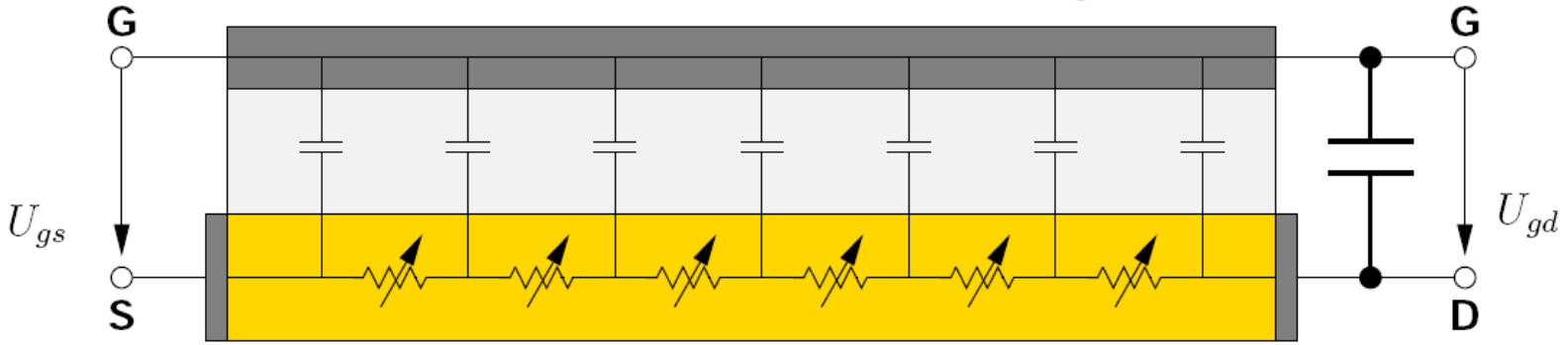
$$R_v = \frac{R_{in}}{4(V_g - V_{th})}$$

$$\mathrm{NEP} = \sqrt{\frac{4^3 k_B T}{R_{in}^2 \frac{W}{L} \mu C_{ox}} (V_g - V_{th})}$$

- **Channel is NOT biased, only thermal noise!**

What happens at very high frequencies?

Distributed Resistive Self-Mixing



Non-Linear RC Transmission Line Model:

Voltage *v(x,t)* along the channel is described as Partial Differential Equation:

$$\frac{\partial u(x,t)}{\partial t} = -\frac{\partial}{\partial x}\left[\mu\left(u(x,t) - V_{th}\right) \cdot \frac{\partial u(x,t)}{\partial x}\right]$$

Note, PDE is identical to non-resonant plasma wave detection in FETs:

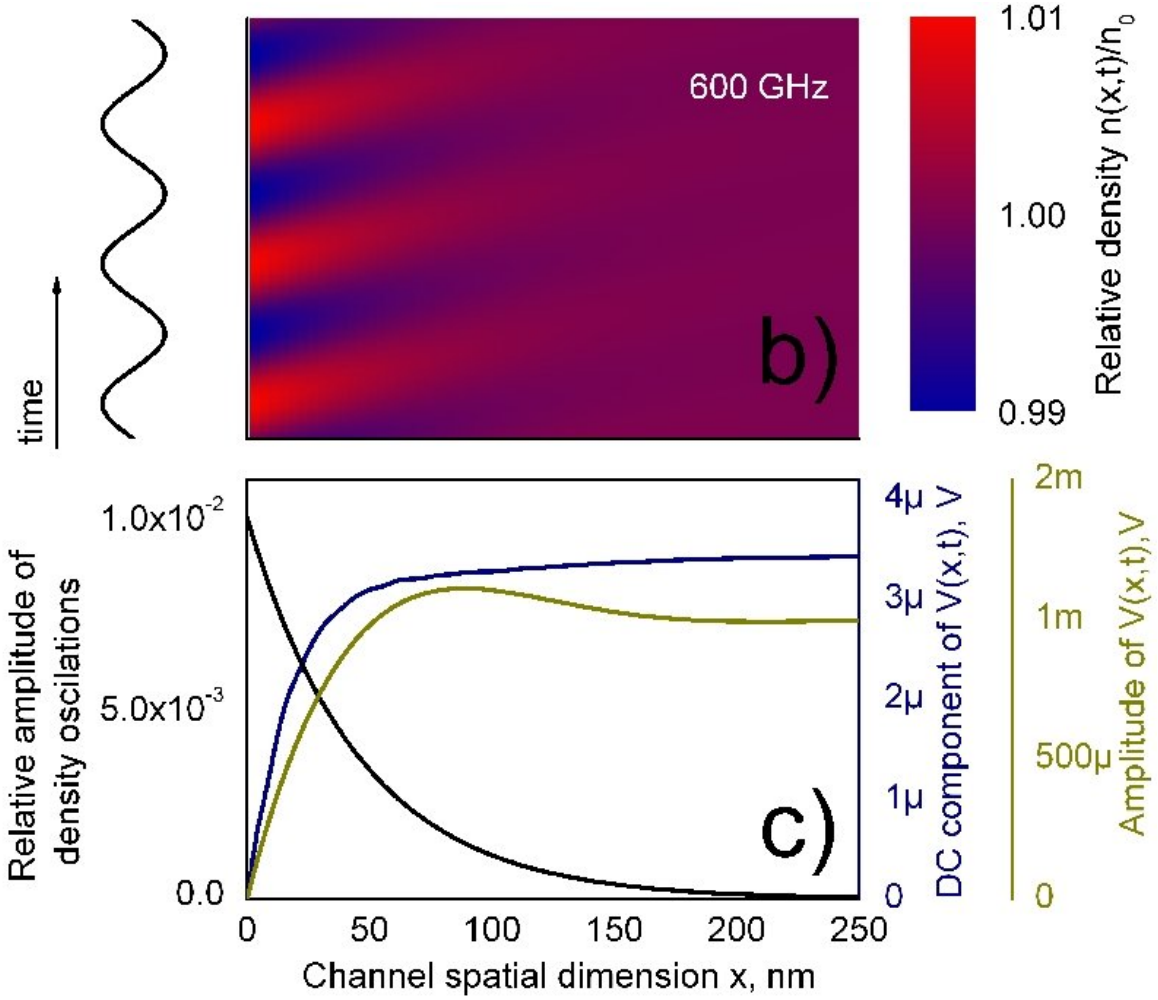
$$\frac{\partial n}{\partial t} = -\frac{\partial (n \cdot v_D)}{\partial x}$$

$$v_D = \mu \frac{\partial u(x,t)}{\partial x}$$

Continuity eqn.
Simplified Euler eqn.
Gradual channel approx.

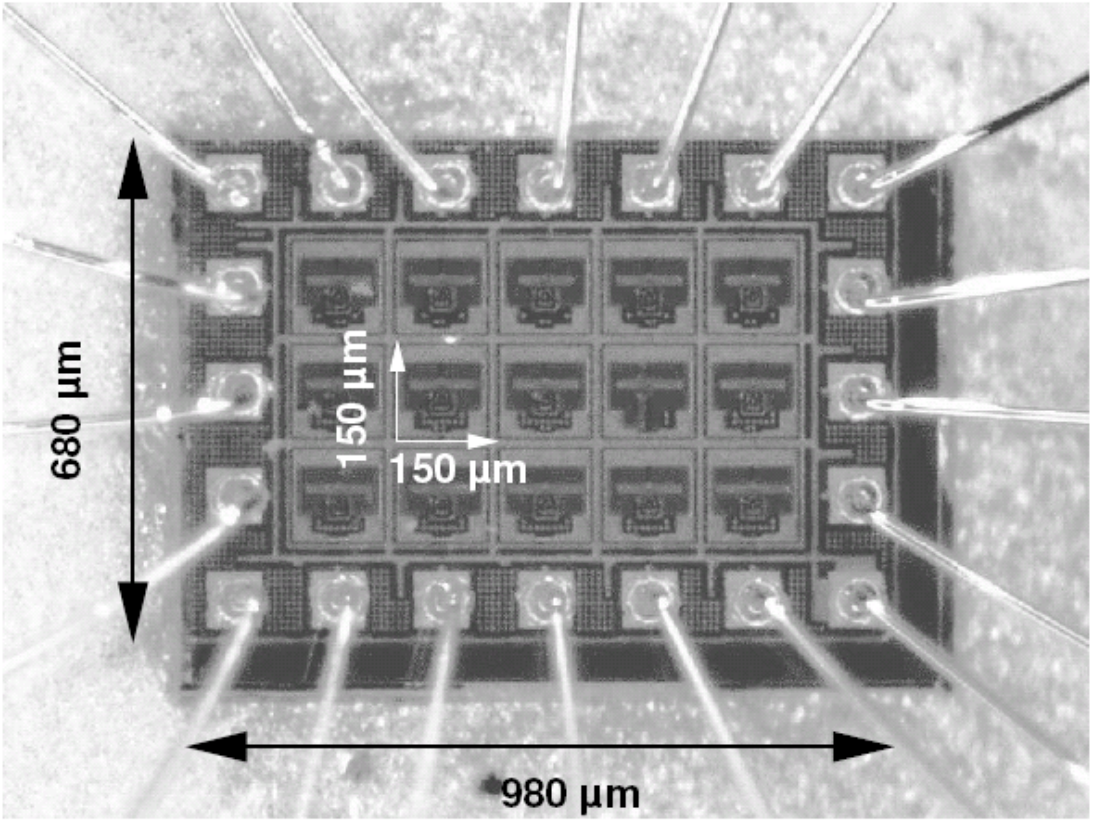
$$\frac{\partial n(x,t)}{\partial t} = -\frac{\partial}{\partial x}\left[\mu n(x,t) \cdot \frac{\partial u(x,t)}{\partial x}\right]$$

Decay of Charge Density Modulation



CMOS Focal-Plane Arrays

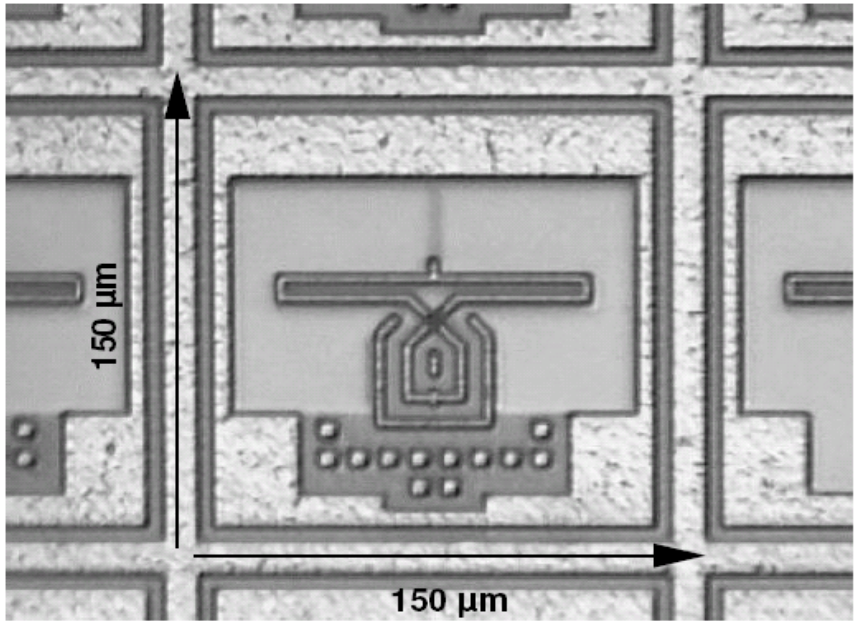
- 3x5 Pixel Incoherent Detector Array

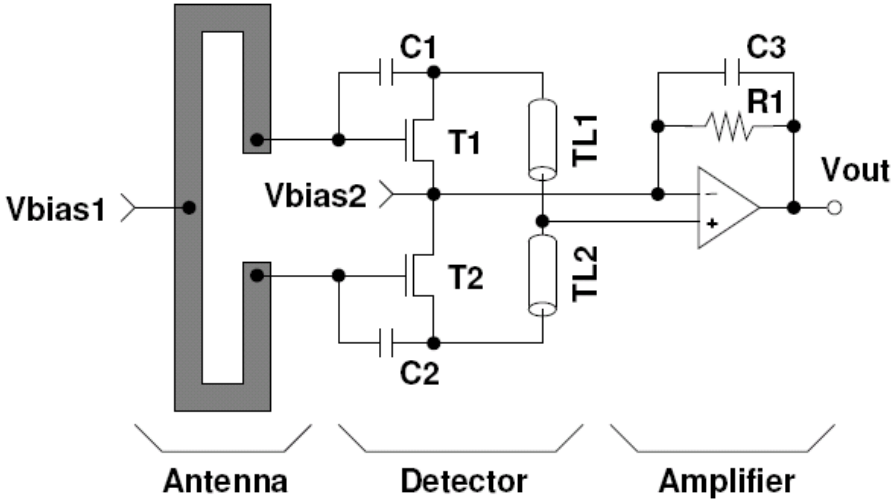


- Based on distributed resistive self-mixing in NMOS transistors
- Commercial available quarter-micron CMOS technology f_t = 35 GHz !
- 3x5 Pixel Array
- Integrated 43-dB amplifiers
- On-chip Antennas
- Dipole antennas for backside illumination
- Patch, and notch antennas available

[1] U. Pfeiffer and E. Öjefors, “A 600-GHz CMOS Focal-Plane Array for Terahertz Imaging Applications”, IEEE European Solid-State Circuits Conference, September 2008.

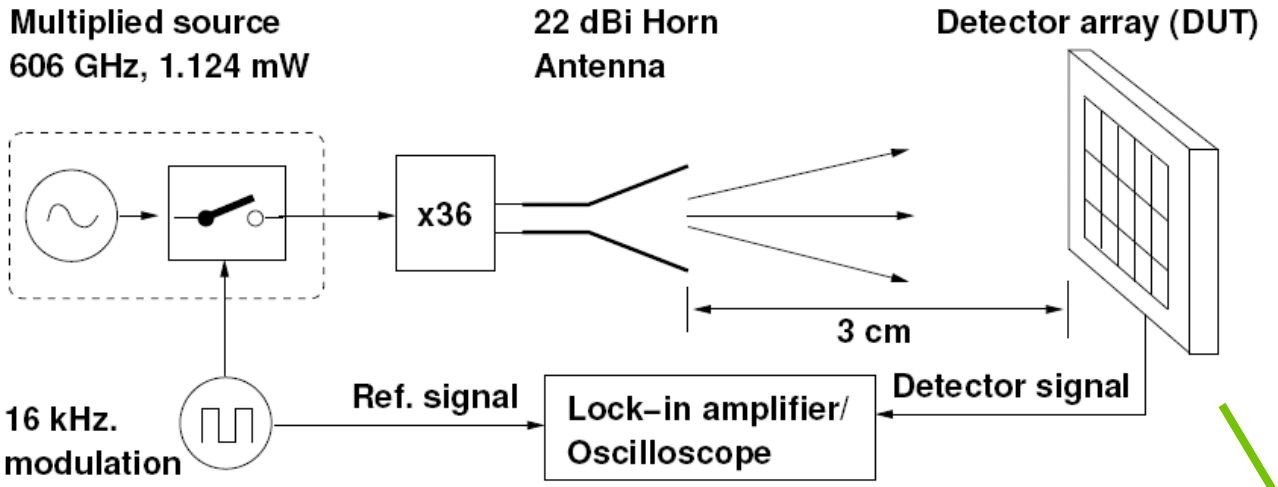
600-GHz CMOS Incoherent Detector (Pixel)



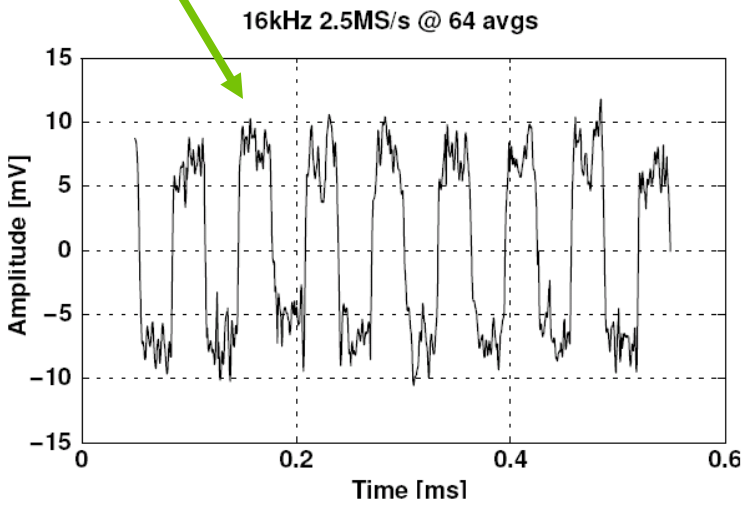


- Differential circuit, virtual ground at shared T1/T2 source, gate bias provided through folded dipole antenna
- Capacitors C1/C2 tie drain to gate AC potential
- TL1/TL2 microstrip stubs tune out detector input capacitance
- 43-dB OP-amp operates FET in voltage mode (low impedance output)

Experimental Verification

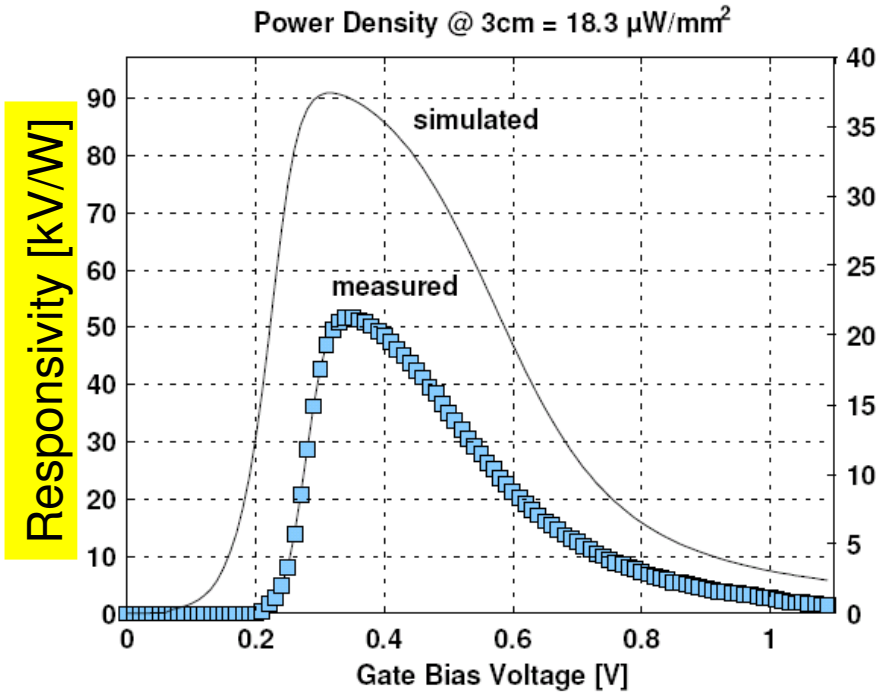


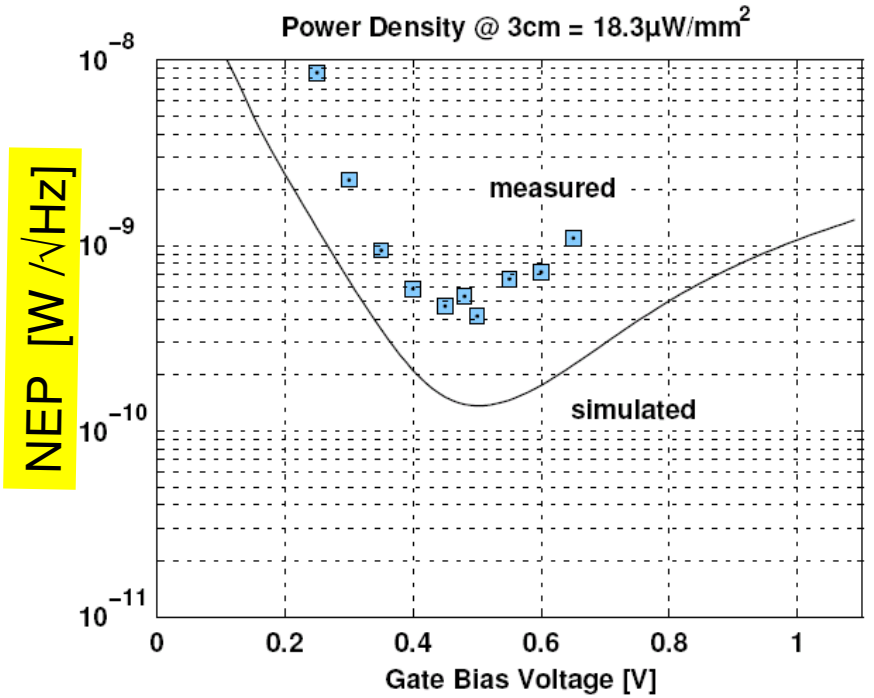
- At Scope



- Equipment limited to 4-ch readout
- Setup provides 18.3 µW / mm2
- AM mod. used for lock-in detection

Responsivity & Noise Equivalent Power



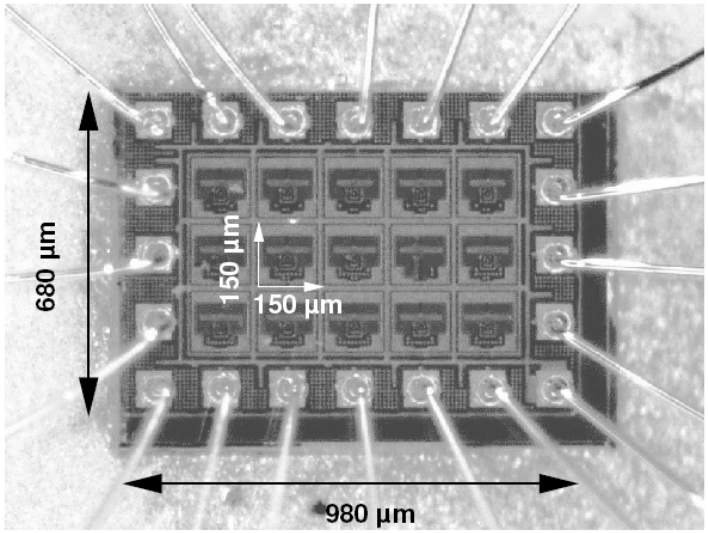


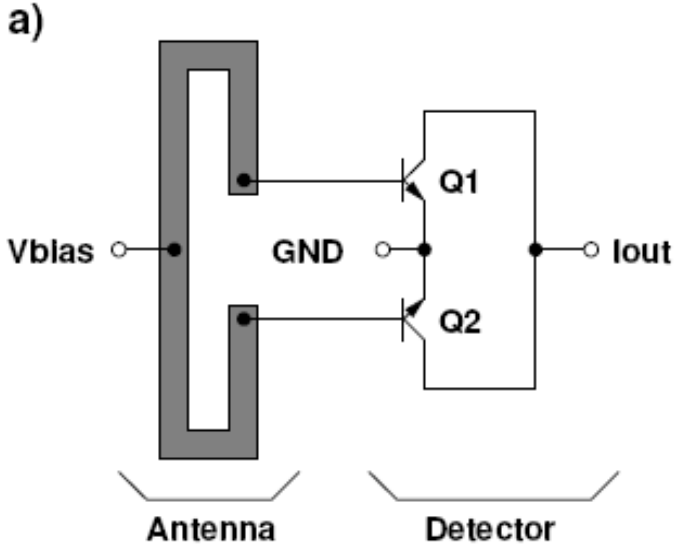
- Responsivity (Rv) = 50 kV/ Watt (incl integrated OP-amp)
- Noise Equivalent Power (NEP) = 400 pW /√Hz (150 pW/√Hz simulated)
- Simulations with BSIM model (no RC-line, no antenna losses)
- (Commercial Schottky detector: Rv = 200 V/W, NEP = 20 pW/√Hz)

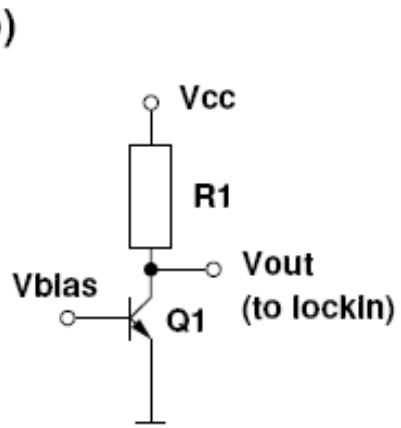
Outline

- **Introduction**
  - Motivation for silicon integrated THz Electronics
    - Review of THz sources and detectors
    - Potential applications
- **THz circuits based on silicon process technologies**
  - SiGe: 94, 140, 160 GHz down-conversion Front-ends
  - Si SBD: 140 GHz up-conversion mixer / doubler (IBM)
  - CMOS: 650 GHz CMOS Focal-Plain Array (quarter-micron)
  - **SiGe: 650 GHz Focal-Plain Array (220 GHz f_{max})**
- **Imaging of postal envelopes in Silicon**
  - 3x5 focal-plane arrays
- **Summary and Conclusion**

0.6 THz SiGe Direct Detector Focal-Plane Array







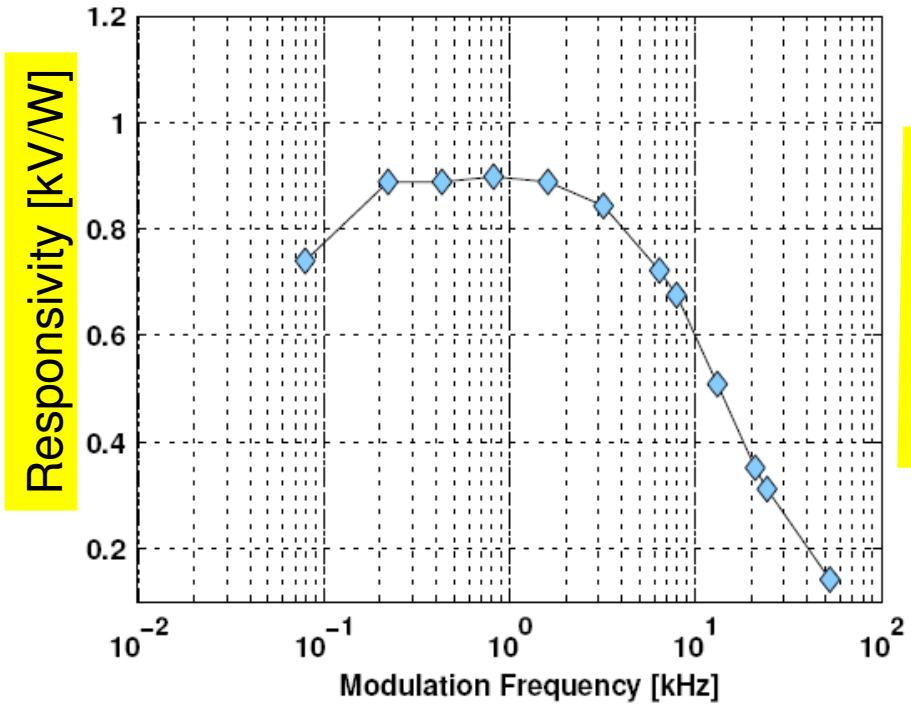
- **Class-B biased differential amplifier**
- **Biased through off-chip load resistor (R1)**

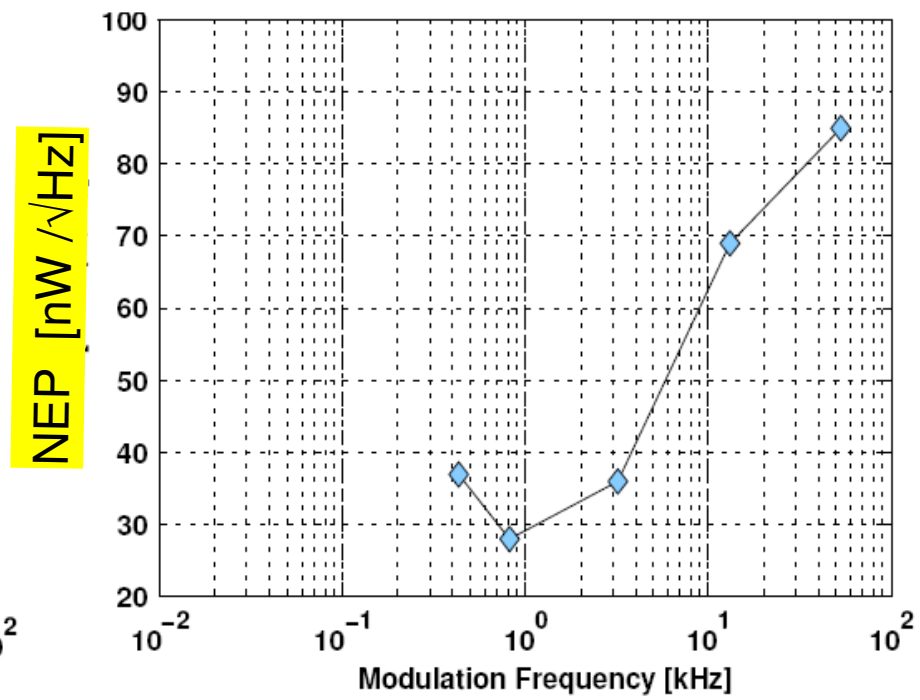
$$I_C = I_0 e^x \approx I_0(1 + x + x^2/2! + x^3/3! + ...)$$

$$I_{C1+C2} \propto x^2$$

$$x_0^2 cos^2 i\omega t = x_0^2/2(1+cos(2i\omega t))$$

0.6 THz SiGe Direct Detector (Measured Results)



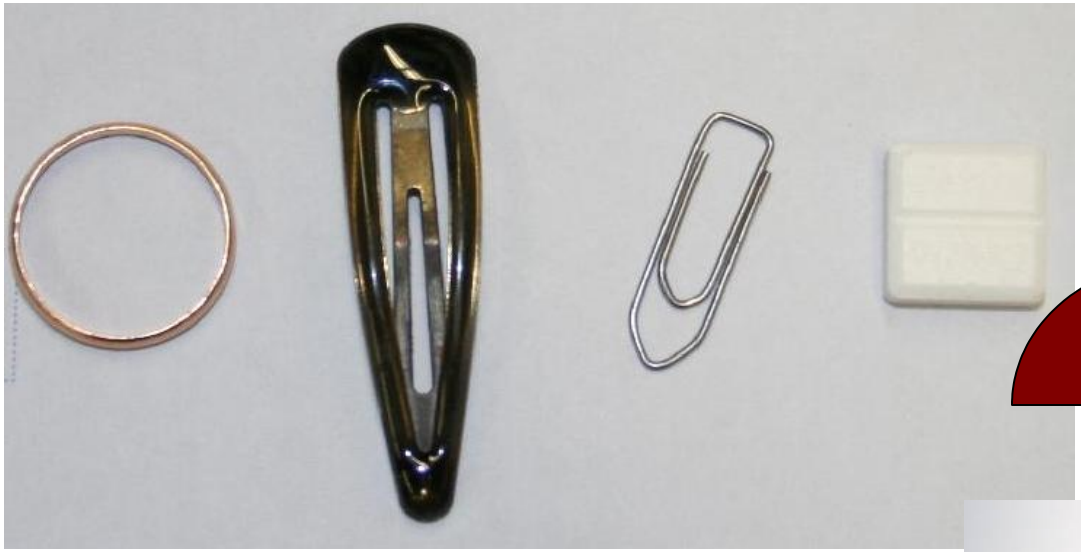


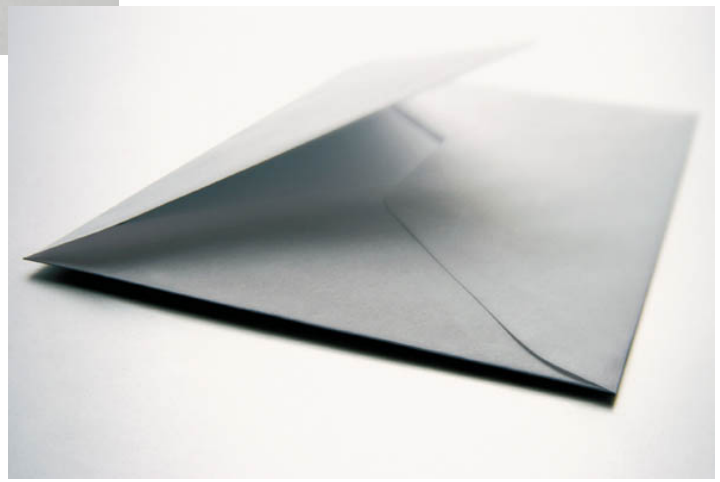
- **Responsivity (RV) = 900 V/ Watt**
- **Noise Equivalent Power (NEP) = 30 nW /√Hz**
- **Higher noise due to external load resistors (room for improvement)**

Outline

- **Introduction**
  - Motivation for Silicon integrated THz Electronics
    - Review of THz sources and detectors
    - Potential applications
- **Terahertz Circuits in Silicon Technologies**
  - **SiGe HBT: 94, 140, 160 GHz down-conversion Front-ends**
  - Silicon SBD: up-conversion mixer (140 GHz)
  - FETs: Incoherent direct detection (650 GHz)
  - SiGe HBT: Incoherent direct detection (650 GHz)
- **Multi-pixel imaging of postal envelopes**
  - 650-GHz Silicon CMOS and SiGe 3x5 focal-plane arrays
- **Summary and Conclusion**

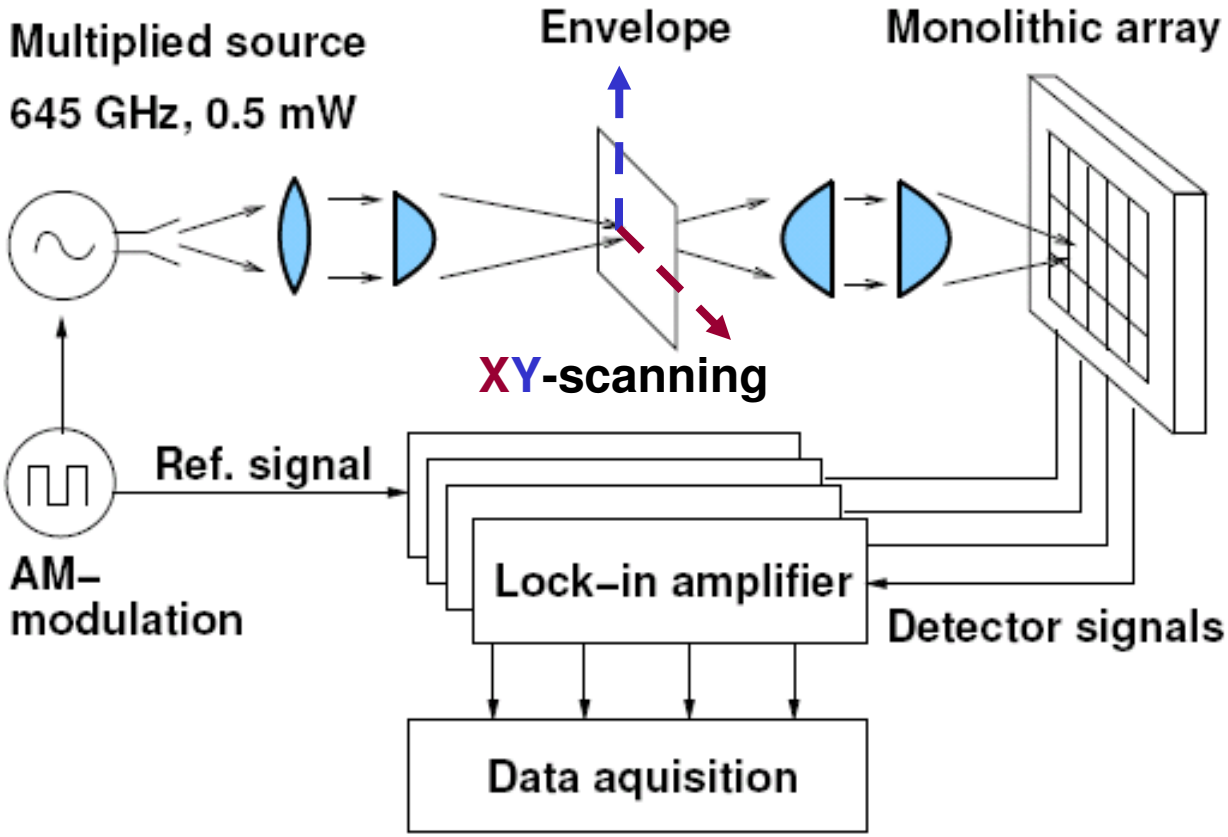
Multi-pixel imaging of postal envelopes





650GHz Imaging with CMOS Focal Plane Array

Scanning of Postal Envelope with Four Pixel Parallel Readout

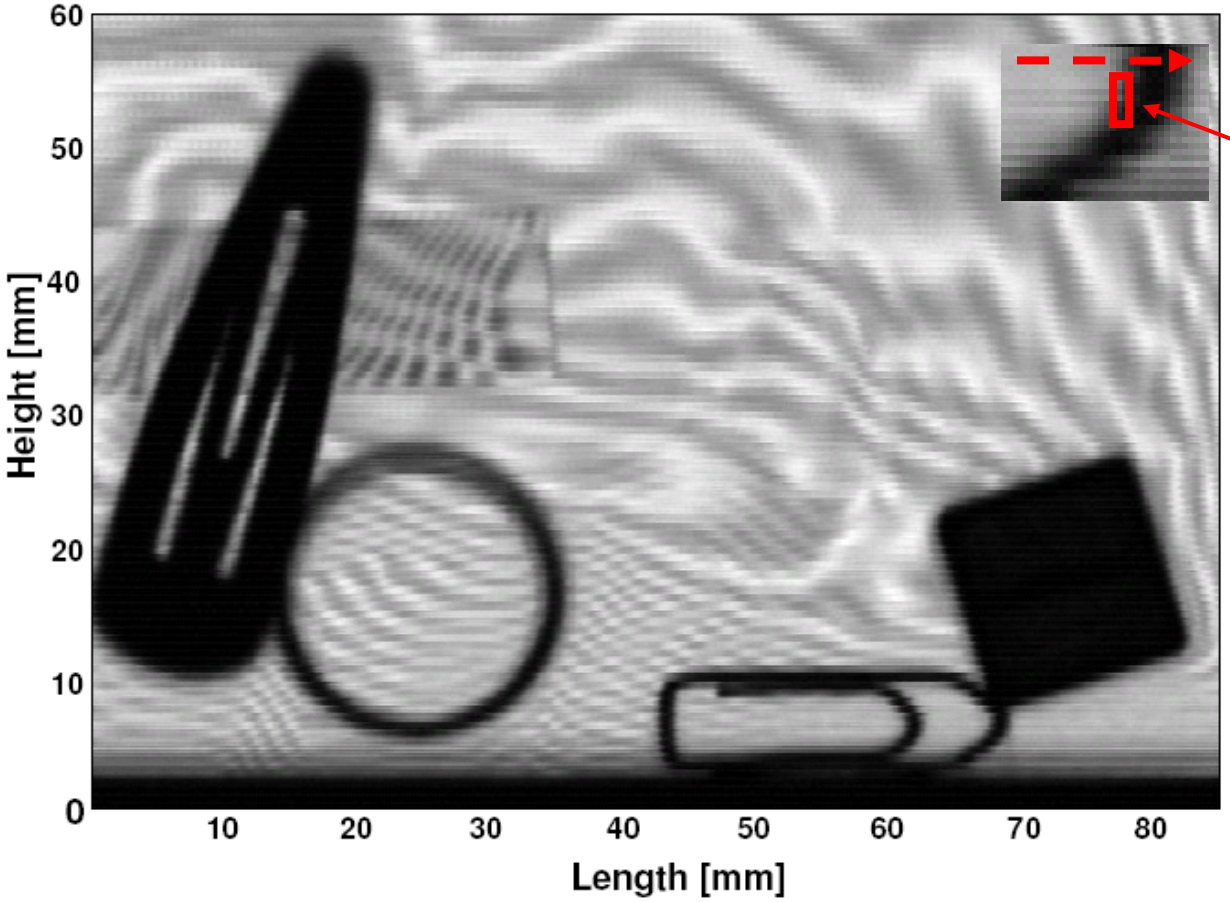


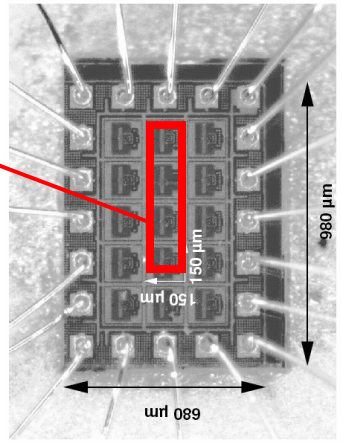
- 645 GHz
- Diffraction-limited resolution (600µ m)
- 1ms integration time

Multi-pixel (4-ch) readout, limited by available test equipment

CMOS Focal Plane Array

Scanning of Postal Envelope with Four Pixel Parallel Readout





Picture scanned with readout of four rows simultanously

Summary and Conclusion

- **Vast number of potential applications for Silicon at mmWave and THz frequencies**
  - 94 GHz single-chip imaging receivers in SiGe are possible today
  - Challenges are NF, gain, power, and efficiency roll-off.
- **Alternative THz Devices can complement silicon design kits**
  - 140 GHz SBD circuits with f_c=1 THz demonstrate by IBM
- **THz imaging with quarter-micron CMOS possible!**
  - Misconception: One can do THz electronics in a f_t=35GHz process technology
  - 650-GHz CMOS and SiGe 3x5 focal-plane arrays demonstrated for the first time
  - BiCMOS: SiGe for Tx and NMOS for Rx

Silicon process technologies have the potential to transform the way THz science and technologies are conducted.

Thanks

- European Young Investigator Award (EURYI-Award)
- DotFive, European seventh framework programme for research and technological development, http://www.dotfive.eu



- IHP Microelectronics, Frankfurt-(Oder), Germany
  - Bernd Heinemann and Bernd Tillack
- IBM T.J. Watson Research Center