Integrated Circuit Design for Terahertz Applications

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BERGISCHE UNIVERSITÄT WUPPERTAL

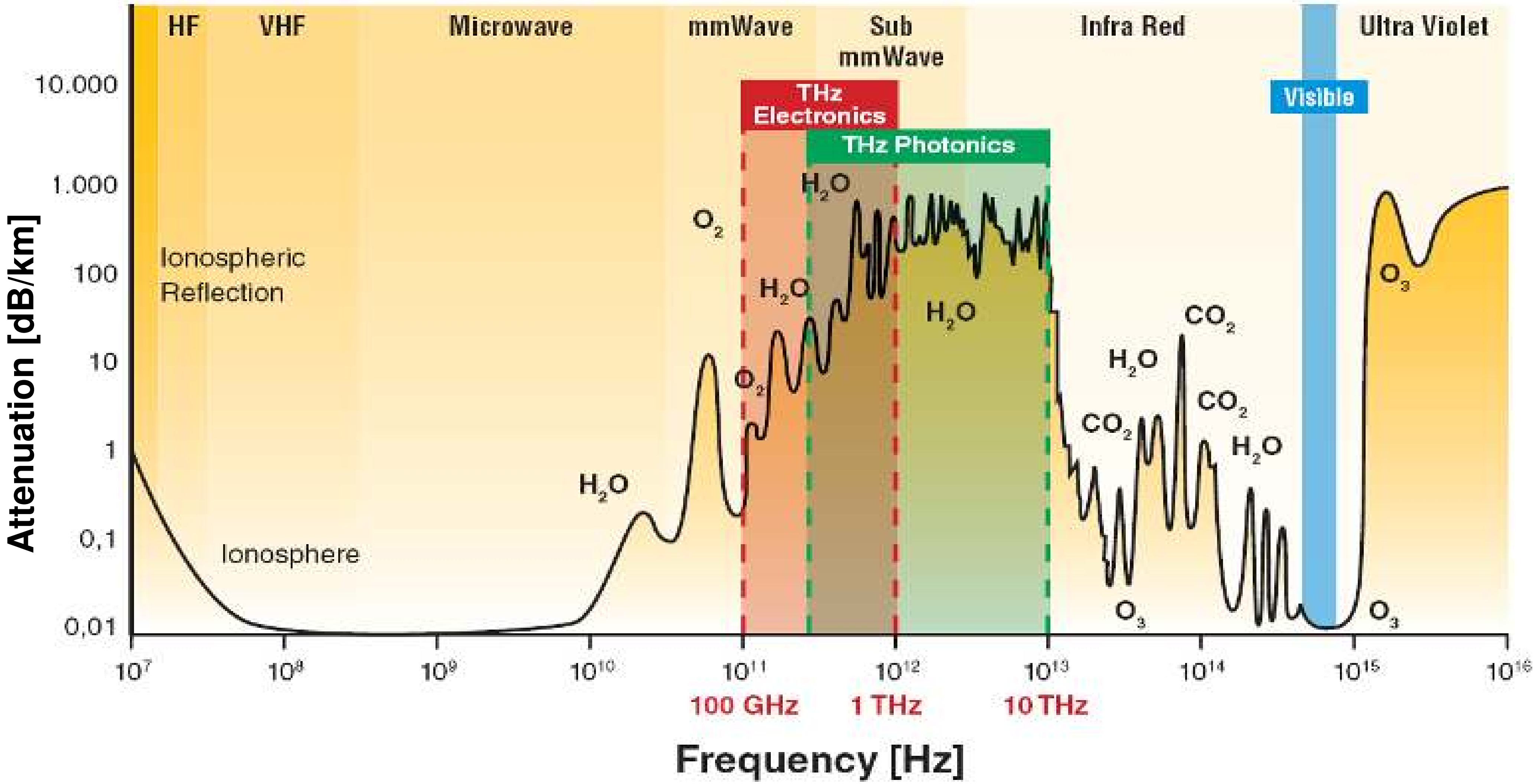
Institute for High-Frequency & Communication Technology
IHCT

Outline

- **Motivation and THz fundamentals**
  - THz applications: communication, radar, imaging and sensing
  - THz characterization essentials
  - Why silicon-based THz electronics?
1. **Illumination and detection**
   - THz detectors and video cameras
   - Sources and source-arrays
   - Imaging: Scanners, cameras, and light-fields
2. **Circuit building blocks**
   - Multipliers, amplifiers, harmonic generators, sub-harmonic RX
3. **Circuits for communication**
   - 240 GHz SiGe chip-set measured results
   - 100 Gbps Wireless Link
4. **Applications**
   - Radar, spectroscopy, multi-color imaging
   - THz imaging beyond the diffraction limit, biomedical application

- **Summary and conclusion**

Where could we use THz electronics?



Blackbody Radiation

- **Planck's law**
  - Brightness [Wm-2 Hz-1 rad-2]

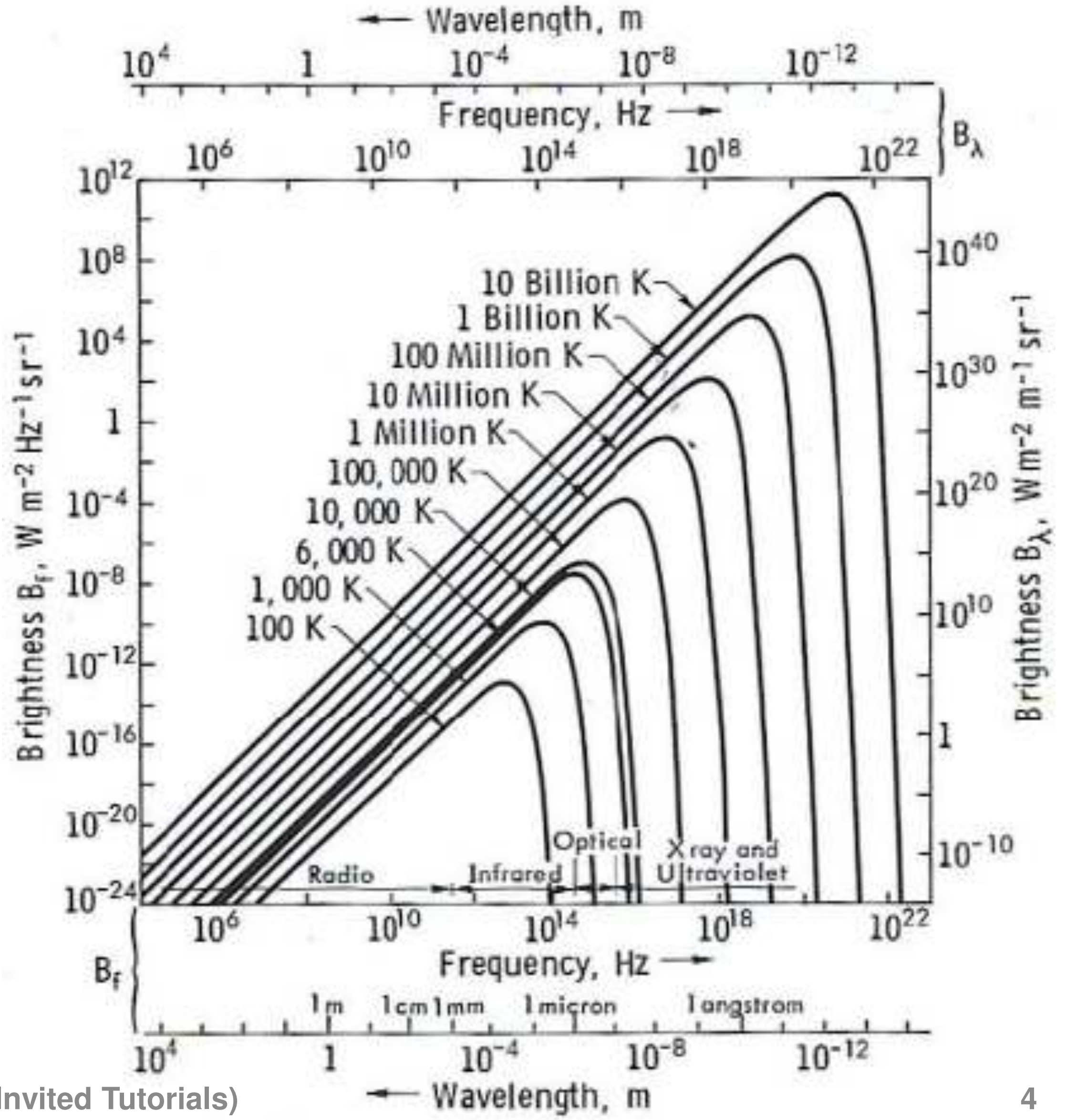
$$B_\nu = 2h\nu^3/c^2(e^{h\nu/k_B T} - 1)$$

- **Stefan-Boltzmann 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.**

$$h\nu \ll k_B T$$

$$B_\nu \approx 2k_B T/\lambda^2$$

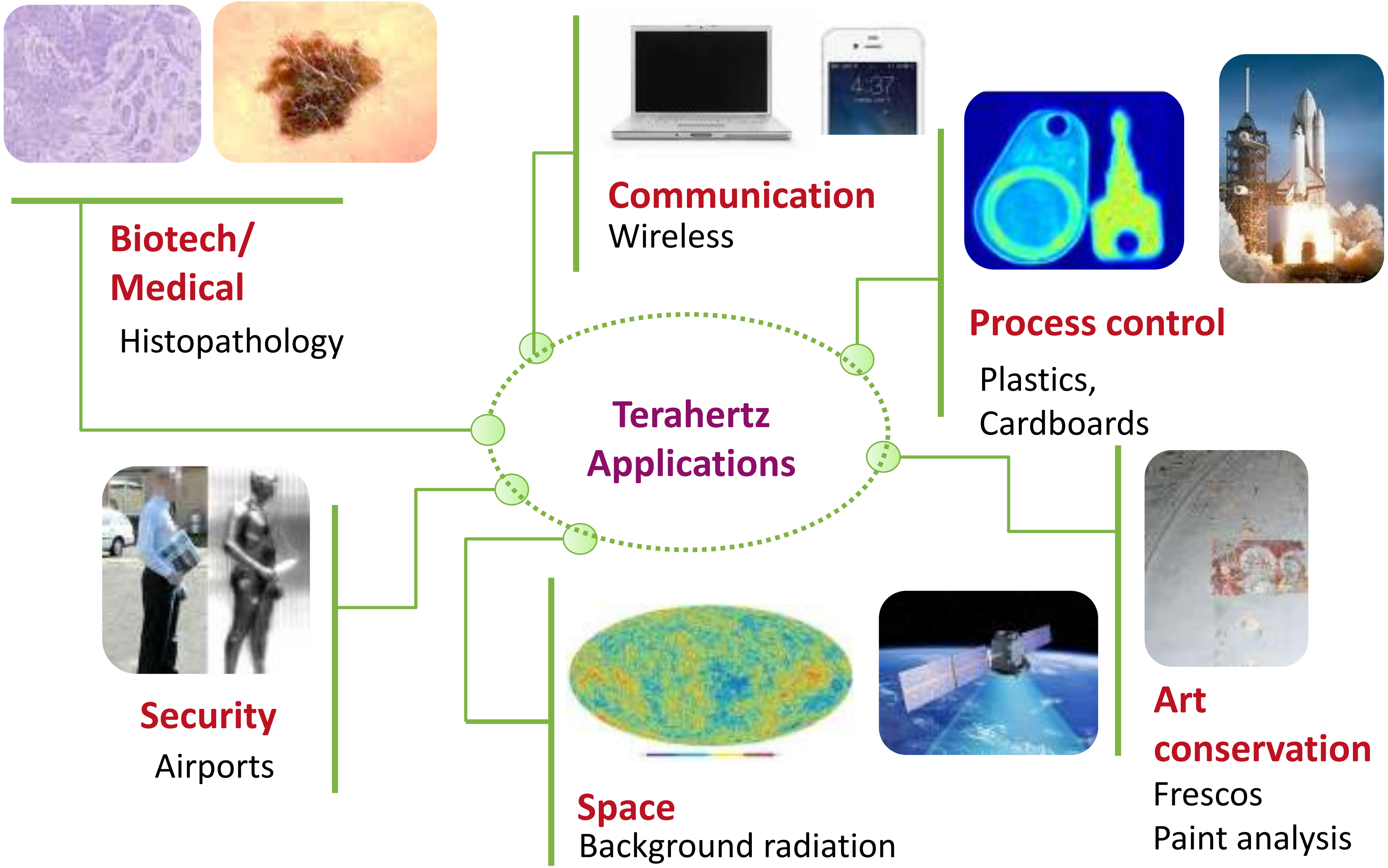
- **At 6000K, *overall* the sun is $(6000/300)^4$ = 16000 times brighter than a room temperature black body, but between 10GHz-10THz it is only 20 times brighter**



Properties of THz Radiation

- **1 THz (λ= ⅓ mm):**
  - E = 4 meV
  - 1THz = Blackbody Radiation at 17K !
- **X-Ray:**
  - E = ~10keV
  - ~10.000.000, 7 Orders higher than 1THz !
- **Cosmic background radiation T=2.7K**
  - Peaks at 160GHz
- **Conclusion:**
  - All objects emit THz radiation
  - Low radiation power, non-ionizing, not harmful

THz Applications

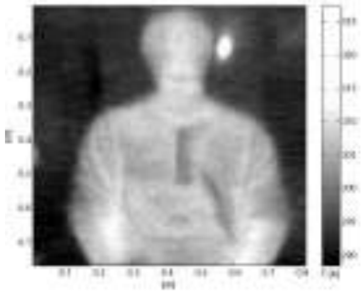


THz Generation Methods

- **Thermal sources**
  - black body radiation
- **Photonic Systems**
  - Time-domain: fempto-second laser pulses
  - Direct generation:
    - infrared 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 (two color lasers + photo mixer)
- **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.)**

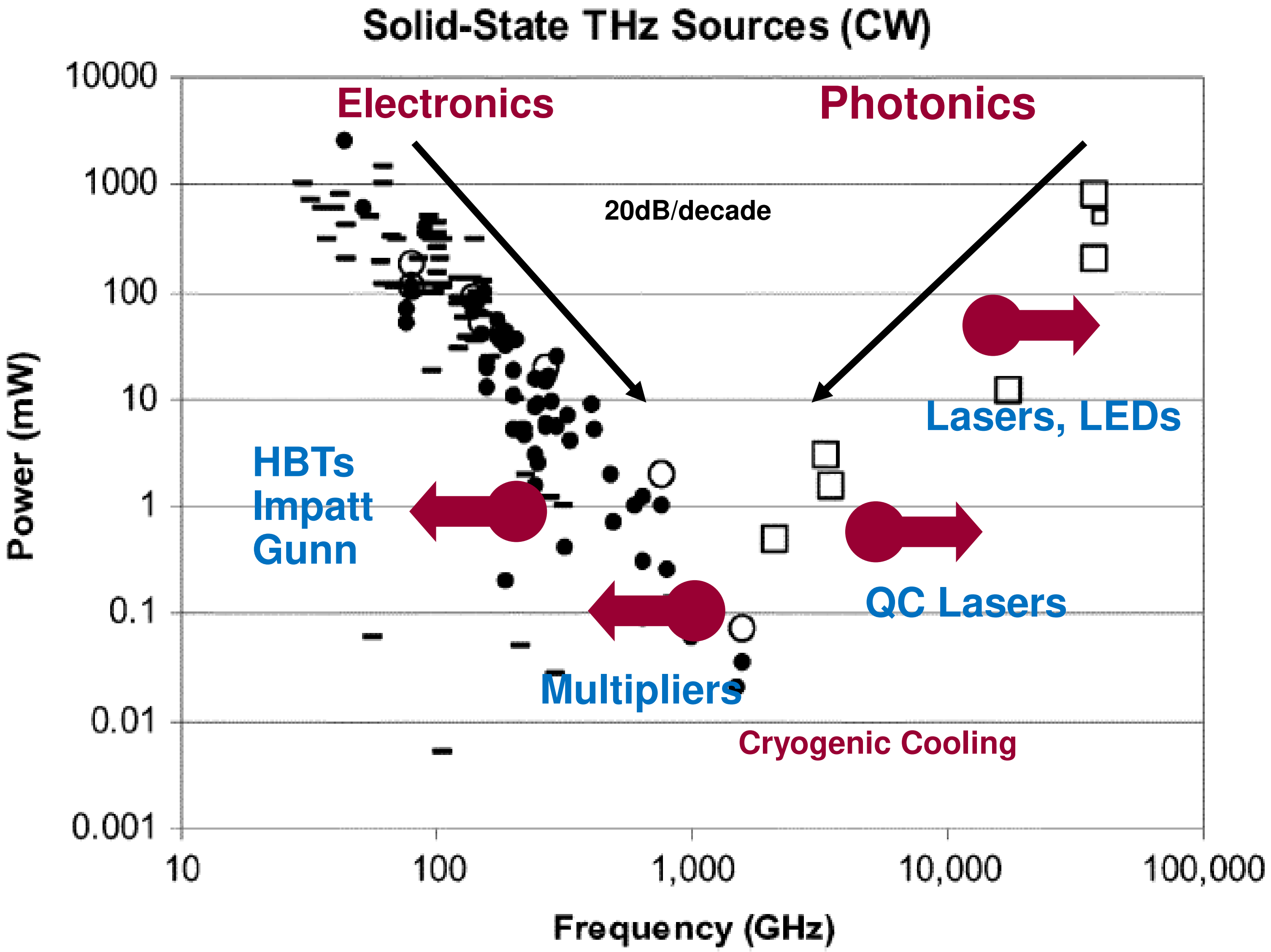
Electronic THz Transmitters

- **Thermal Sources**
  - Blackbody radiation sources
  - Low SNR, Indoor vs. outdoor
- **Oscillators**
  - BWO
  - VCO, Push-push, triple-push
- **Multiplier-based Sources**
  - Doubler
  - Tripler
- **Heterodyne Transmitters and Amplifiers**
  - I/Q transmitters
  - Amplifiers are Fmax limited
- **Lasers**
  - QCL lasers
  - Gas lasers



Can we generate THz radiation with SiGe/CMOS?

Terahertz Gap?



[1] Crowe 2005

THz Detection Methods

- **Coherent detection**
  - Heterodyne/homodyne receivers
  - MMICs, tunnel junctions, HEB bollometers mixers
  - Problem: LNAs is typically limited to below 200-300 GHz
- **Incoherent (direct) detection**
  - Calorimeters/bolometers, based on the physical principle of energy/power absorption
  - Pneumatic detectors (Golay cell)
  - Photo-acoustic detector (Thomas Keathing)
  - 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!

Electronic THz Detectors

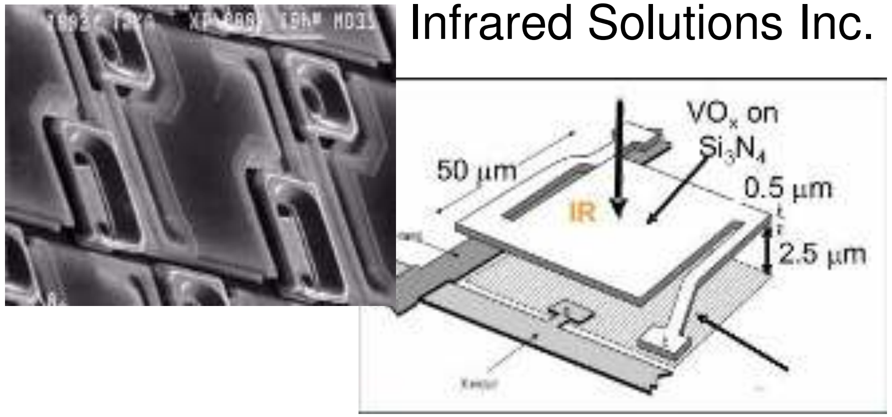
He-cooled bolometer
example taken from QMC
NEP ~ 3 pW/√Hz (0.2 – 30 THz

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 (0.6THz)

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

Microbolometer array
Infrared Solutions Inc.



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

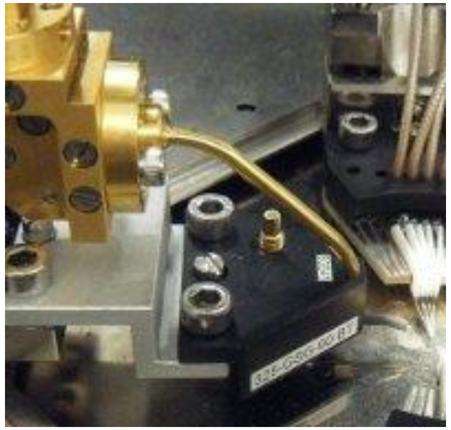
THz Test and Measurement Equipment

The Wafer Probing Challenge

DC-110 GHz

Coaxial wafer probes
- 1-mm connector
- No differential probes

110-500 GHz



Waveguide probes
- Multiple bands
- Adapted probe-station

Above 500 GHz

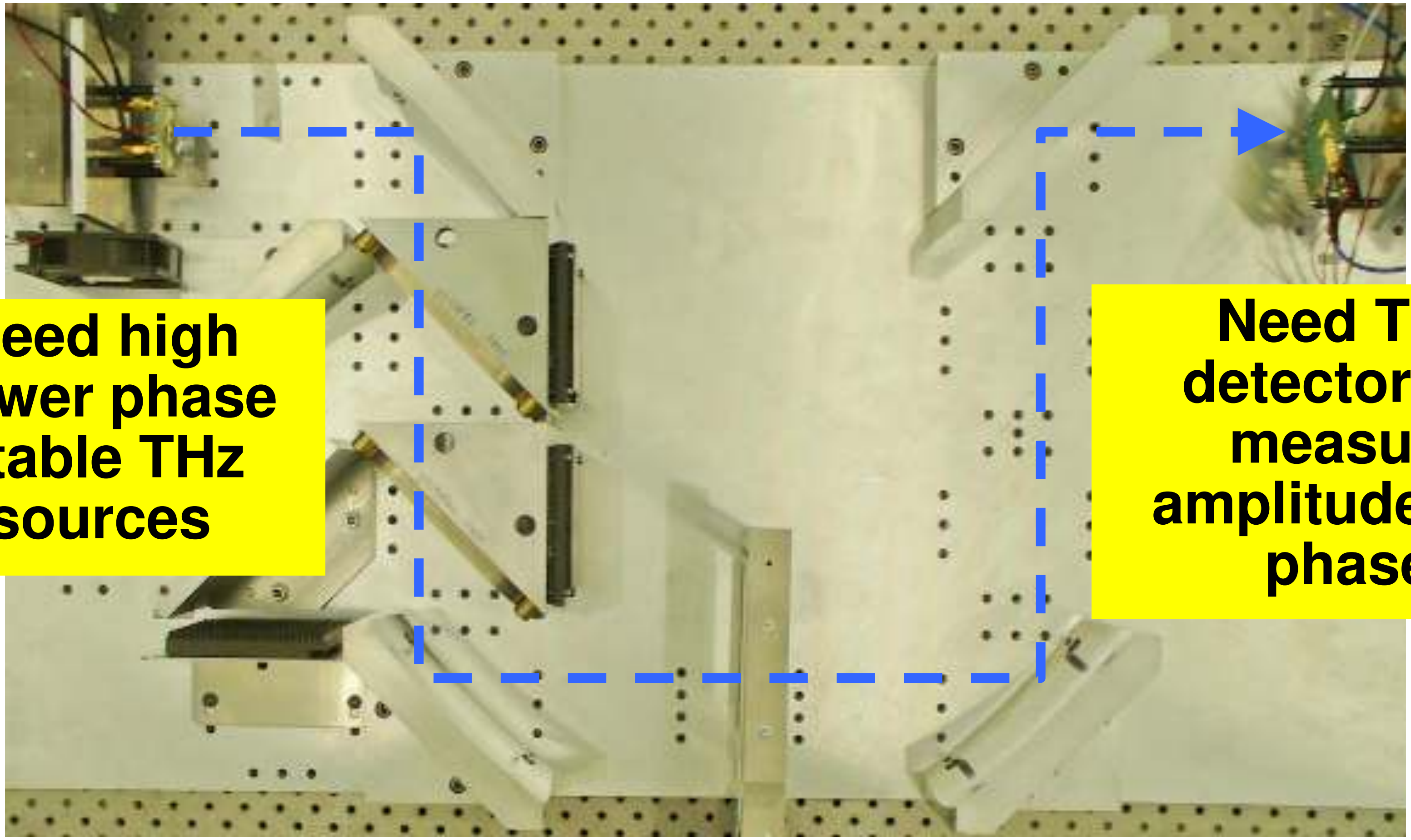
Free-space optics
- On-chip antennas
- Calibration difficult

Typical measurements to be done…

- **Small-signal S-parameters**
  - Wafer probing only up to 500GHz
  - Only free-space reflection/transmission mode measurements above 500GHz possible
- **Spectrum and freq. conversion measurements**
  - Free-space, standard gain horns, harmonic mixers
- **Absolute radiated power measurements**
  - Calibrated power meters/calorimeters
- **Noise figure or NEP measurements**
  - Noise sources, hot/cold standards, direct method
- **Antenna pattern measurements**

Optical TX/RX Measurements

Four mirror optical bench

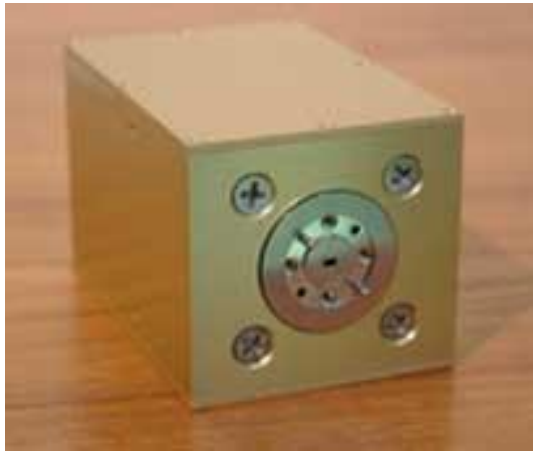


Need high power phase stable THz sources

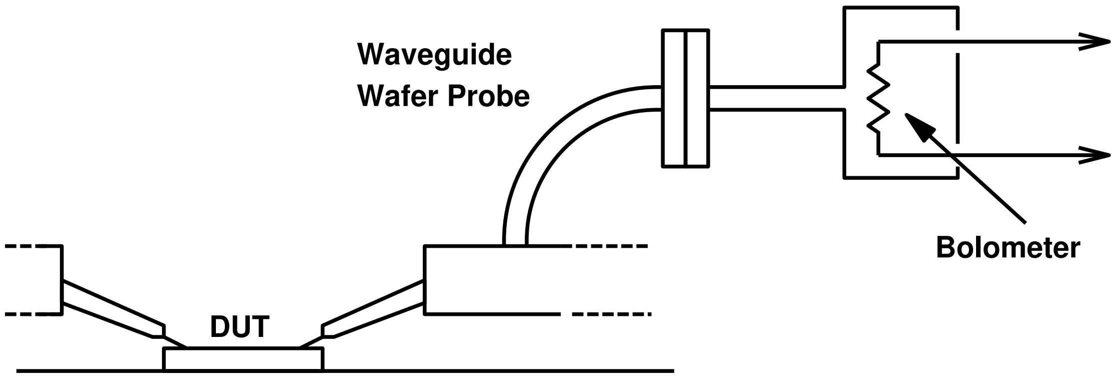
Need THz detectors to measure amplitude and phase

Power Measurements - Waveguide

- Waveguide calorimeter
- Overmoded WR10
- Freq. 75 GHz to visible
- Power up to 200 mW
- Noise down to 0.01 uW
- Lack of traceable calibration



Erickson PM4 Power Sensor, Picture courtesy Virginia Diodes Inc.



Output-power measurements of TX, PA, VCO and freq. multipliers

Power Measurements – Free Space

- **Free-space power meter**
  - Large aperture
  - Photo-acoustic detector
- **Needs chopped input signal**
- **Freq. 30 GHz to > 3 THz**
- **NEP < 5 uW/Hz½**
- **Good absolute accuracy (<10%)**
- **Horn antenna needed for probe measurements**

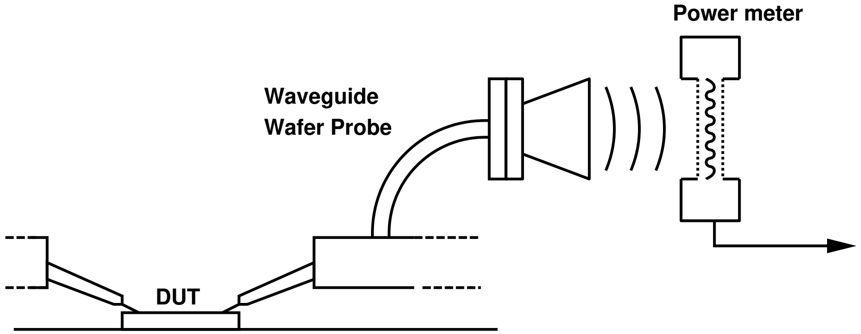


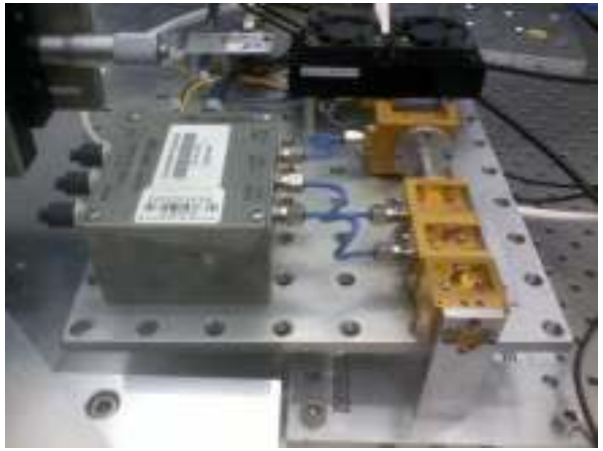
Photo-acoustic power-meter head

Primary use: Calibrated absolute power measurements

Sub-Millimeter Wave Power Generation

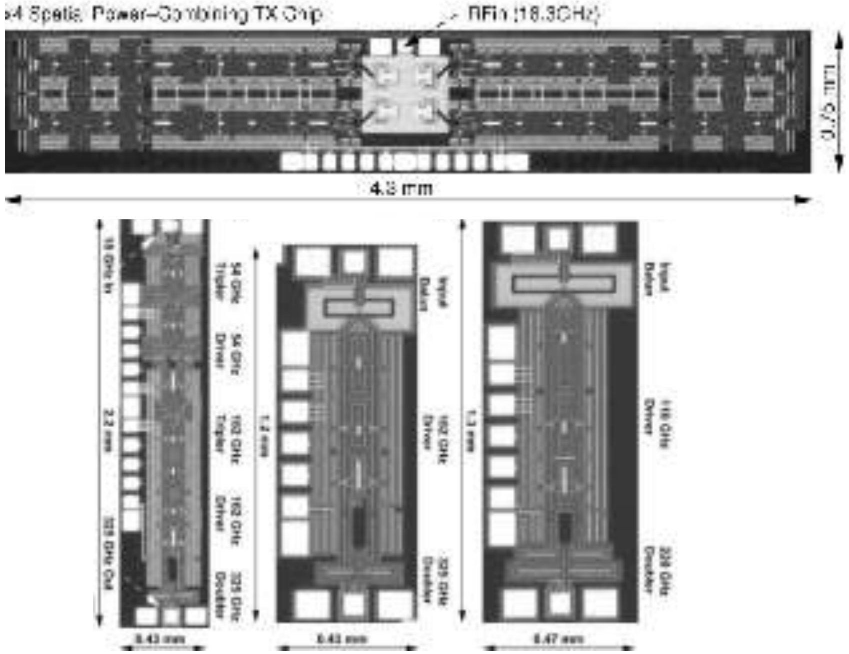
Schottky diode multipliers:

- **0.6-0.65 THz: 0.5 mW**
  Virginia Diodes
- **0.6-1 THz: 1-10 µW**
  Phillipe Goy



SiGe HBT transistor multipliers:

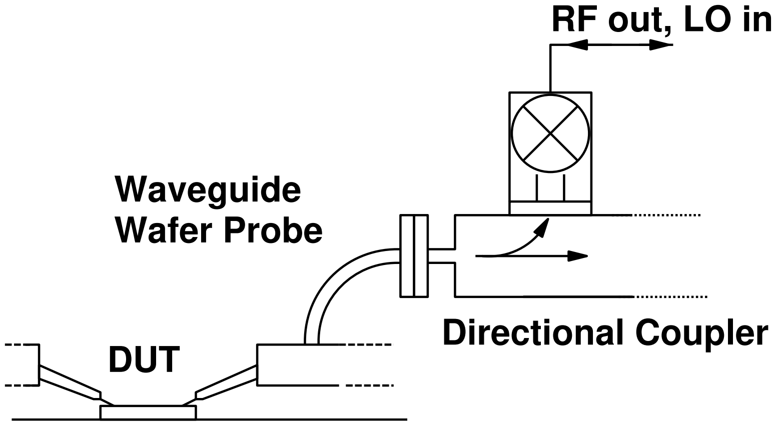
- **0.16 THz:** 6 dBm, ISSCC 2010
- **0.2 THz:** -1dBm, TMTT 2011
- **0.32 THz:** -3dBm, TMTT 2011
- **0.8 THz:** -29dBm EIRP, ISSCC 2011



Spectrum Analysis above 100 GHz

- Subharmonic Waveguide Mixers
- Used with spectrum analyzer (option needed)
- Available in waveguide bands, Example: D-band, 110-170 GHz
- High harmonic numbers, false harmonics in spectrum, sensitivity less than -80 dBm (1 kHz RBW)
- Lack of calibration data above 110 GHz!

Subharmonic mixer in wave-guide technology

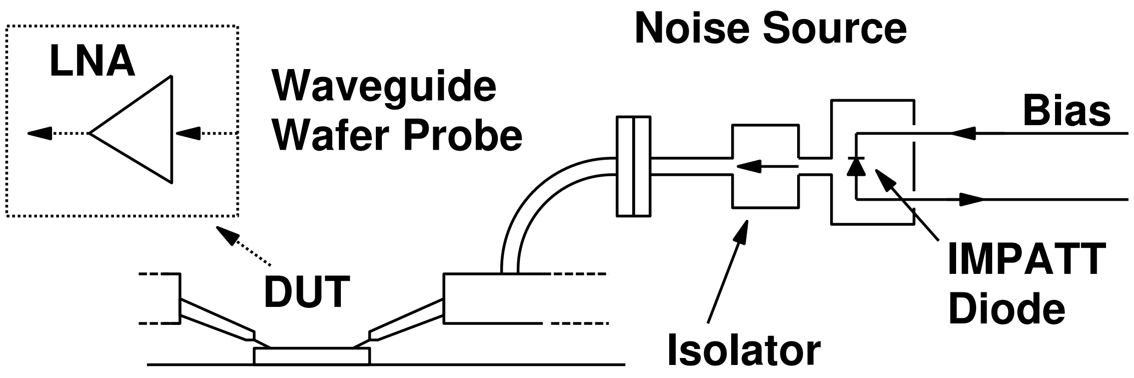


Testing of TX, upconverter, multiplier, or VCO

LO-IF diplexer at spectrum analyzer

Noise Figure – Diode Noise Sources

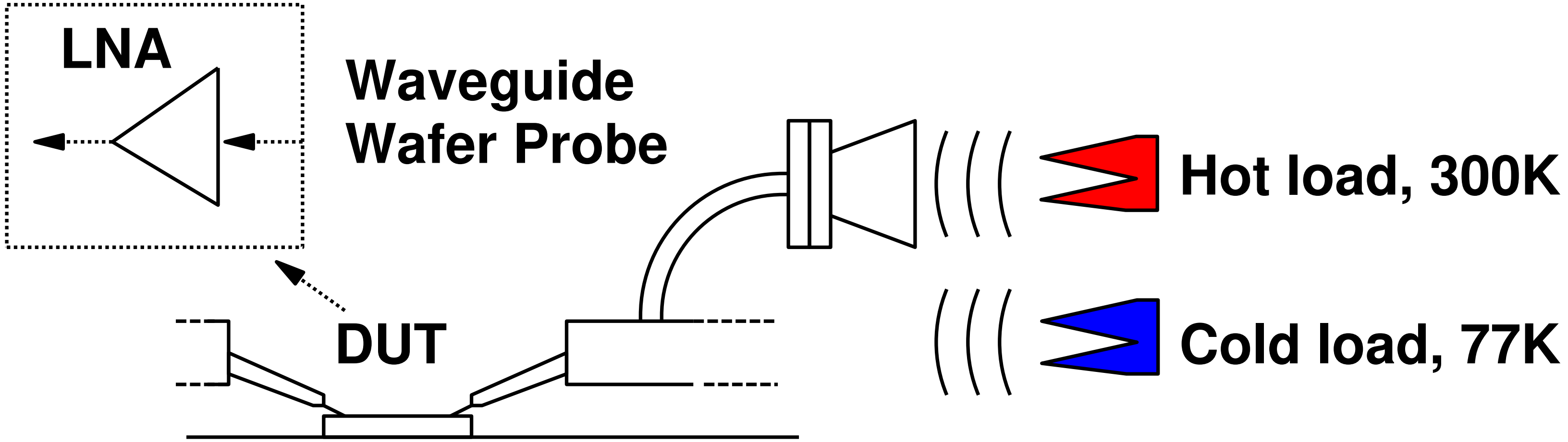
- **Y-factor method with noise source**
  - Cold: Room temp (300K)
  - Hot: Biased IMPATT diode
- **> 10 dB ENR (3000 K)**
- **Simple to use**
- **Single band (D-band 110-170 GHz)**
- **Calibration data needed (not better than 3dB)**



IMPATT D-Band Noise Source

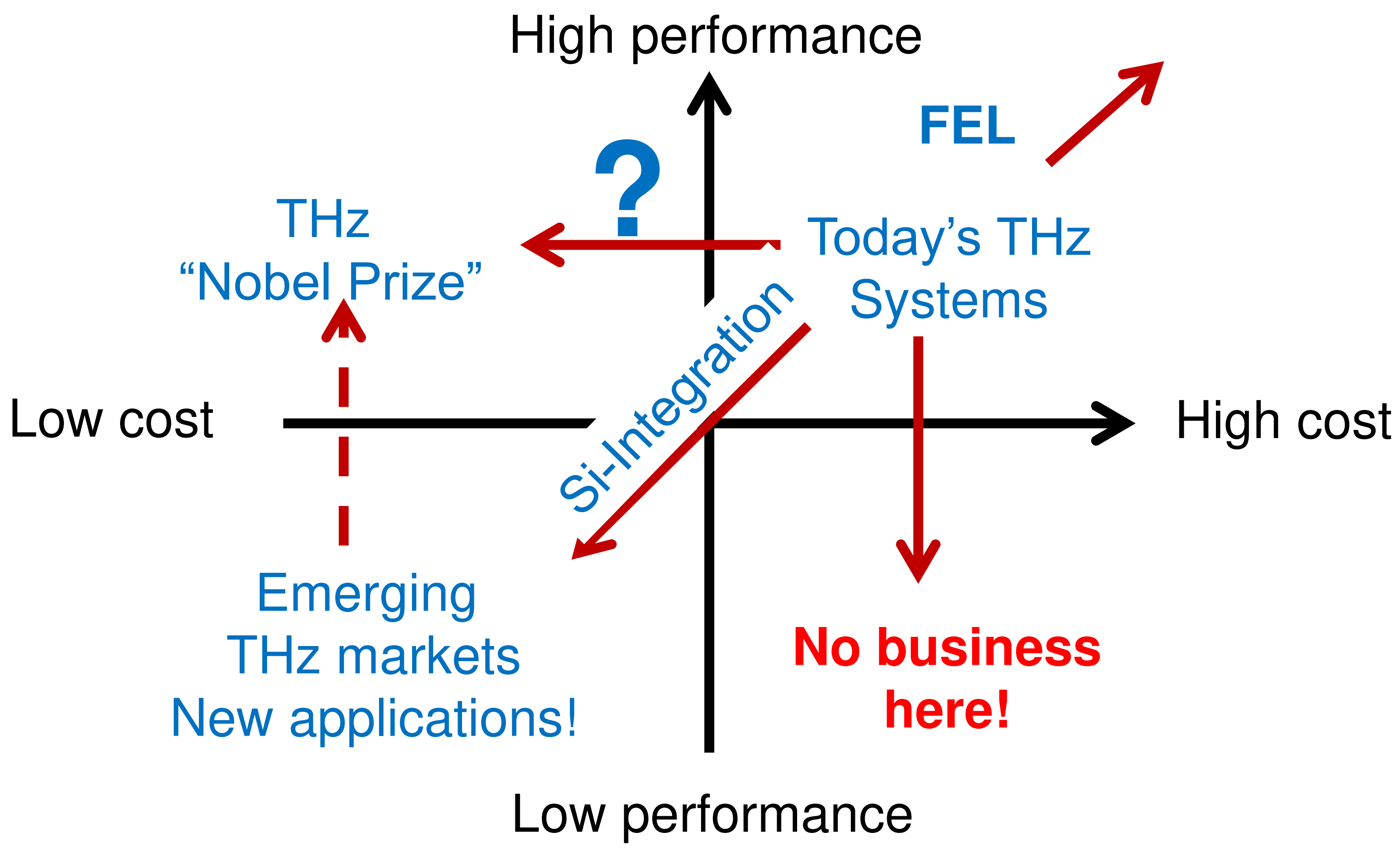
Noise Figure – Cryogenic Standards

- **Hot/cold (Y-factor) method**
  - Cold: Absorber in liquid N2
  - Hot: Absorber in room temp.
- **Physics-based standard, much more acurate**
- **Horn antenna terminates waveguide**
- **Needs cryogenic system**
- **Freq 18-325 GHz commercially available**
- **Not suitable for high-NF LNA (small Y-factor)**



Why Silicon for THz Electronics?

Cost-Performance Matrix



Why Silicon Technology for THz?

- **III/V dominated**
  - High performance
  - Low volume production
  - Low integration level

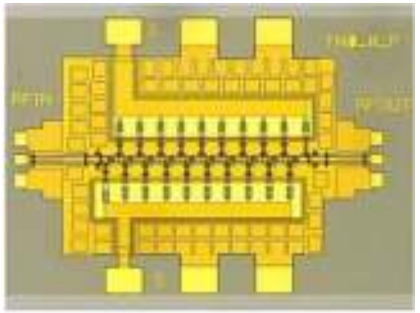
- **Silicon technologies**
  - Low performance in comparison with III/V
  - Enable system-on-chip
  - Low power consumption
  - Reduced cost at high volumes

(Source: TeraView Ltd)

(Source: TicWave GmbH)

Electronic Device Technology Options

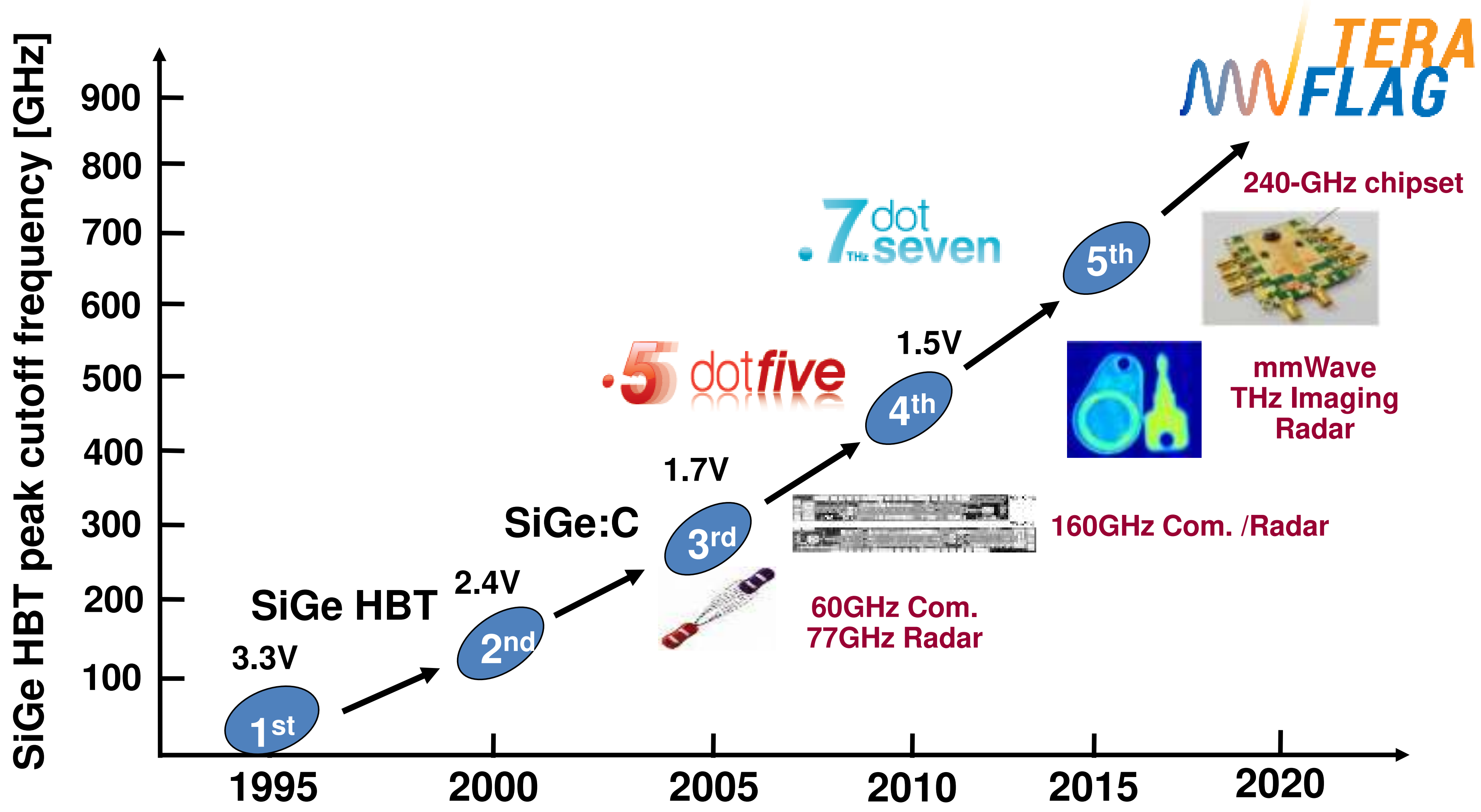
- **III/V substrates**
  - 25nm InP HEMT, fmax=1.5THz, 9dB >1THz amp
  - GaN, Fmax=0.58 THz
  - InP-GaAsSb DHBT, Fmax=1.18 THz
- **Silicon substrates**
  - CMOS bulk/SOI/FinFETs, fmax≈300-350 GHz
  - SiGe BiCMOS/SiGe HBT, fmax=700GHz
- **Heterogeneous integration**
  - InP + SiGe
- **Electronic-Photonic integration**
  - Modulators, WG, Ge photo-diodes + Silicon



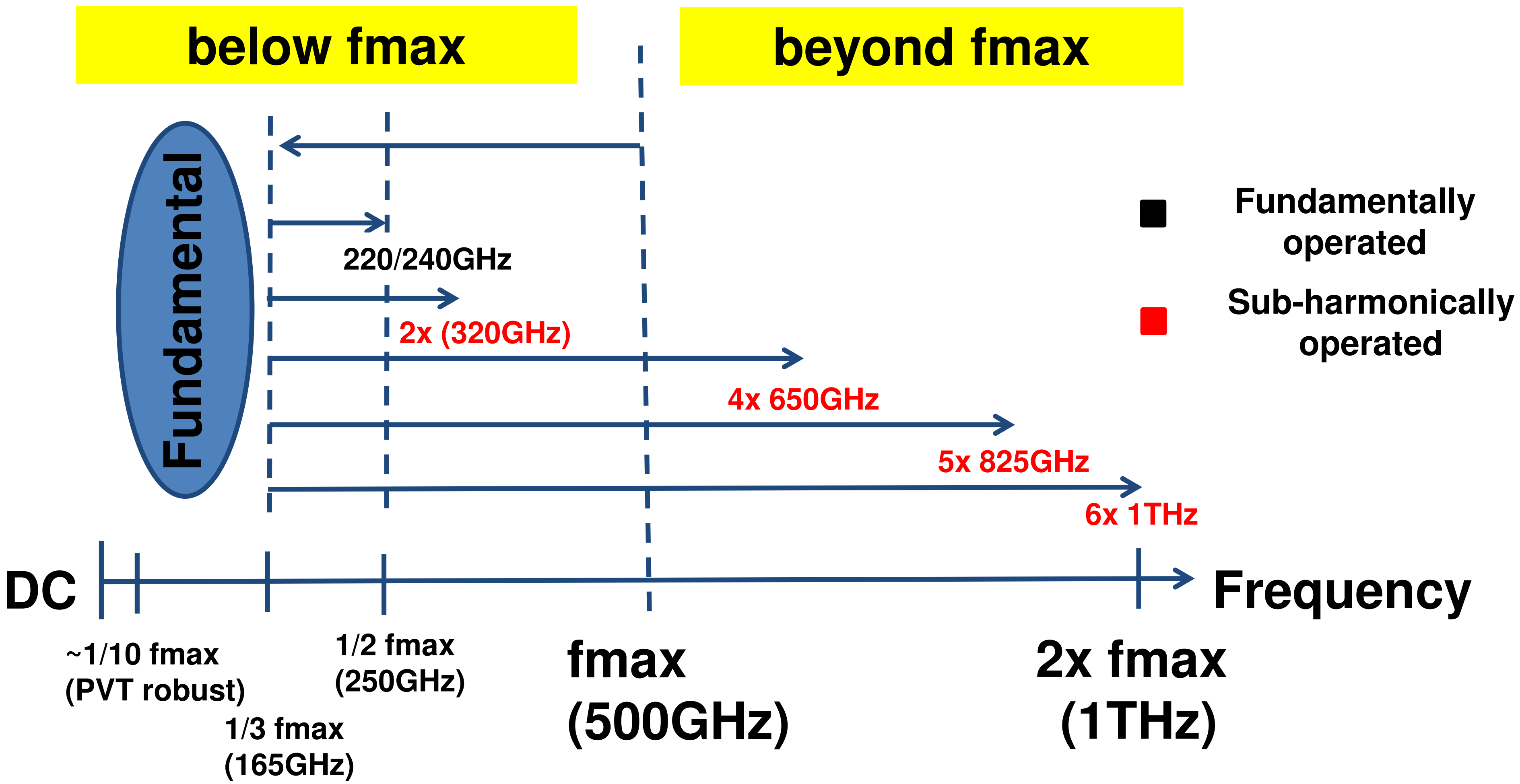
[1] X. Mei et al., "First Demonstration of Amplification at 1 THz Using 25-nm InP High Electron Mobility Transistor Process," in IEEE Electron Device Letters, vol. 36, no. 4, pp. 327-329, April 2015.

Next: Leverage economies of scale!
- **High yield & high performance**
- **Integrated electronic THz systems**
- **Monolithic & hybrid integrated**
- **Low cost**
- **Lots of devices!**

Silicon (SiGe) HBT Technology Evolution



Circuit Frequency Planning



How can DOTSEVEN help us on building-blocks?

- **Fundamental circuits:**
  - Higher carrier frequencies
  - More gain per stage (e.g. fewer gain stages)
  - Larger bandwidth
  - Lower DC power consumption
  - Higher efficiency (PAE)
  - Larger output power
  - Lower noise figure
- **Sub-harmonic circuits:**
  - Lower harmonic number
  - Higher output power
  - Lower noise figure

Consider circuit design trade-offs !

	DOTFIVE 2011	DOTSEVEN 2013	DOTSEVEN 2016	Improve (on fmax)
fT/fmax	Run 3	Run 1	Run 2	
IHP	280/430	300/450	350/550	+28%
IFX	240/340	250/360	250/370	+10%

Major Results (Building-Blocks)

OK, let's compare DOTSEVEN vs. DOTFIVE on power amplifiers.

Circuit	DOTFIVE	DOTSEVEN		Performance
mmWave PAs	Run 3	Run 1	Run 2	vs. DOTFIVE
RF	160 GHz	240 GHz	240 GHz	+50%
Psat	10 dBm	5 dBm	7.5 dBm	-2.5 dB
G_T	20 dB	10 dB	25 dB	+5 dB
BW	7 GHz	30 GHz	40 GHz	+325% !
Tech	ST	IHP	IHP	

Substantial improvements possible, but can we build fully-integrated transceivers with sufficient link budget margins?

Future Trends

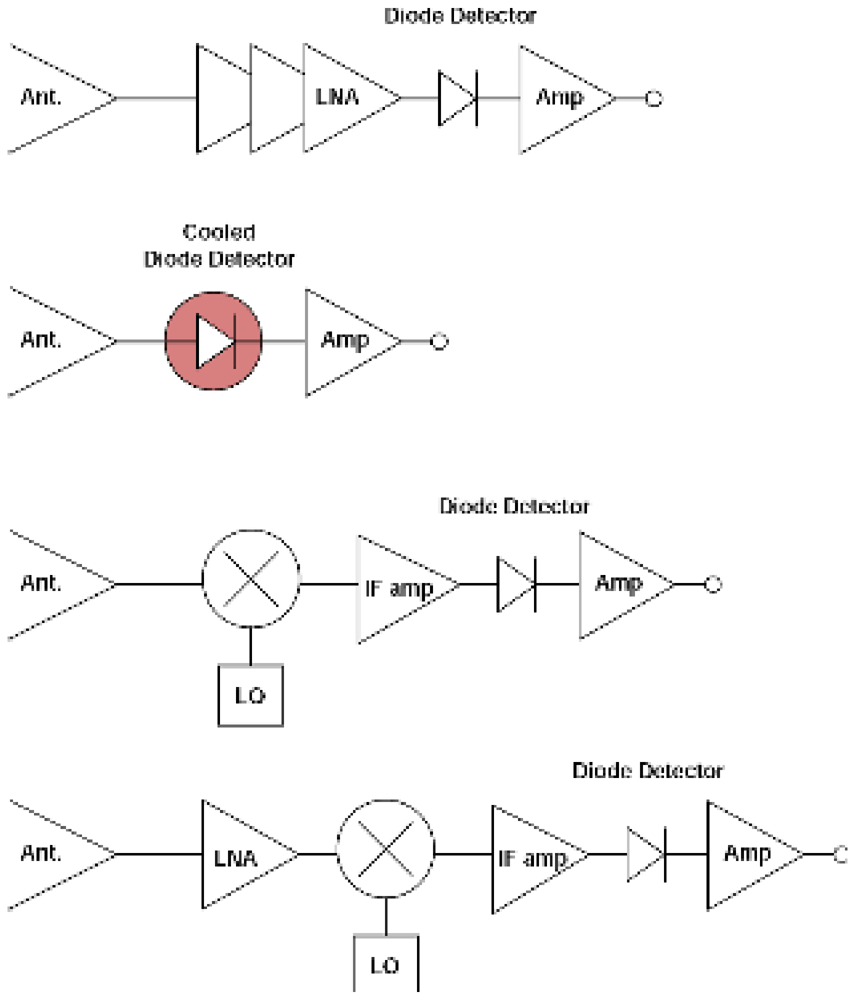
Integrated Electronic Systems Research

1. **Improve performance in existing applications**
   – Low power, high efficiency, larger band-width etc.
   – New ways for THz generation and detection
2. **Novel systems, algorithms, and applications**
   – Programmability, re-configurability, scalability, new functionality
   – Beam steering/forming
   – Computational imaging
   – Chip-scale integration and packaging
   – Mass-production
   – Sensor fusion
   – Low-cost

Take the next step!
from materials, devices/components to systems!
closing the THz “Industry-Gap”

Electronic Terahertz Receiver Approaches

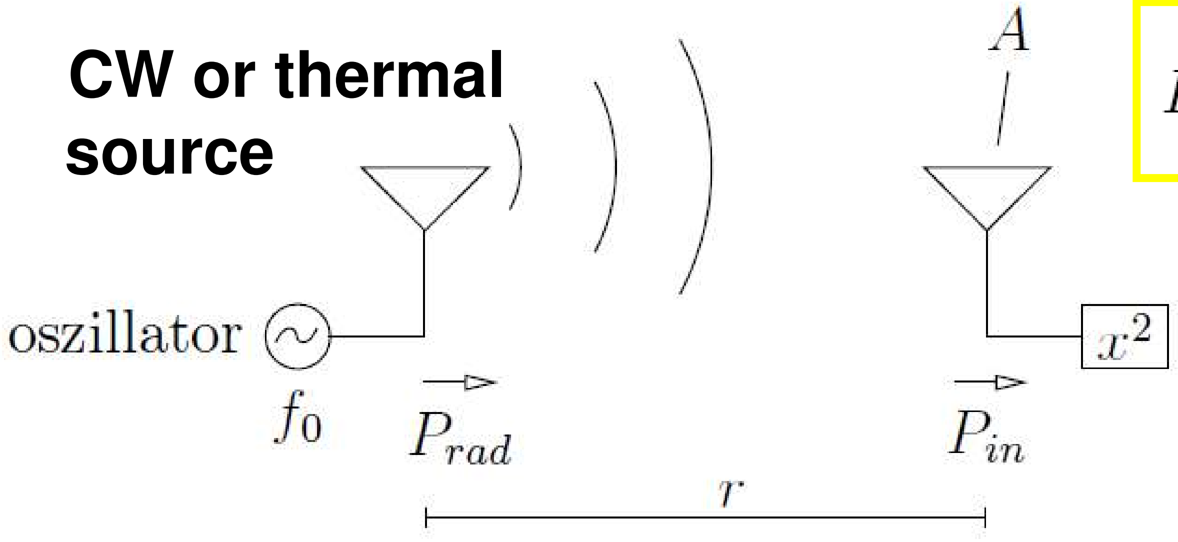
- **Direct Detection with LNA**
  - LNA gain 5-15dB/stage up to 300GHz
  - 20-50 GHz bandwidth at 94GHz
  - Schottky diode detectors
  - Rx noise TN of about 500K
- **Direct Detection**
  - Only depends on detector noise
  - Cooled detectors can have very low noise
  - Broad-band operation possible
- **Hetorodyne without LNA**
  - Above 250GHz where no LNAs available
- **Heterodyne plus LNA, super-heterodyne or direct-conversion**



Can we do this in SiGe/CMOS?

Detector Performance Measures

CW or thermal source



$$P_{in} = \frac{P_{TX} G_{TX}}{4\pi r^2} A_{eff},$$

Voltage Responsivity:

$$R_v = \frac{U_{out}}{P_{in}}$$ [V/W]

Noise equivalent power:

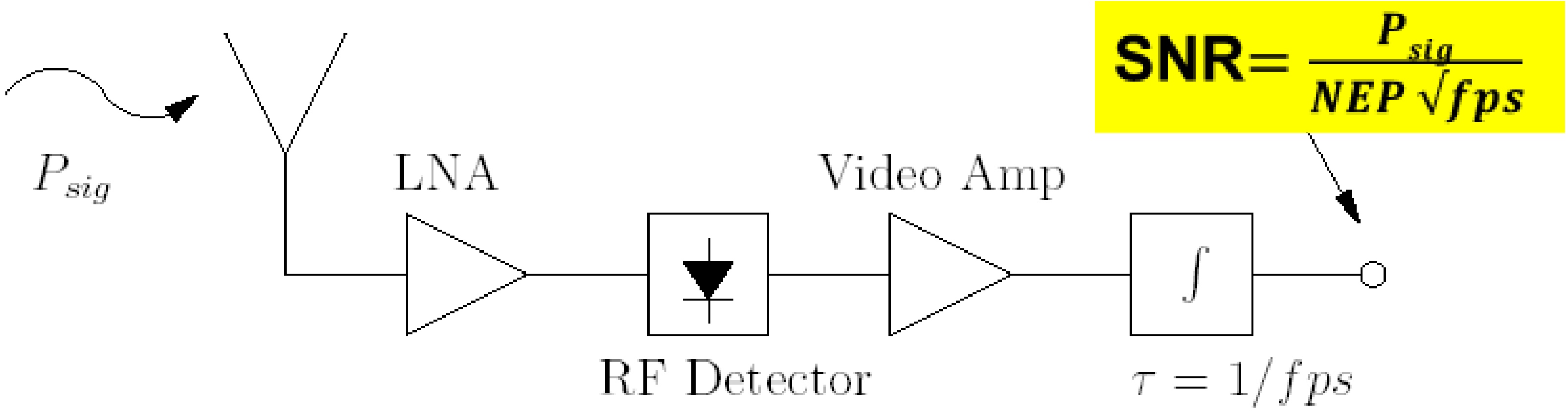
$$NEP = \frac{V_N}{R_v}$$ [W/$\sqrt{Hz}$]

Total NEP:

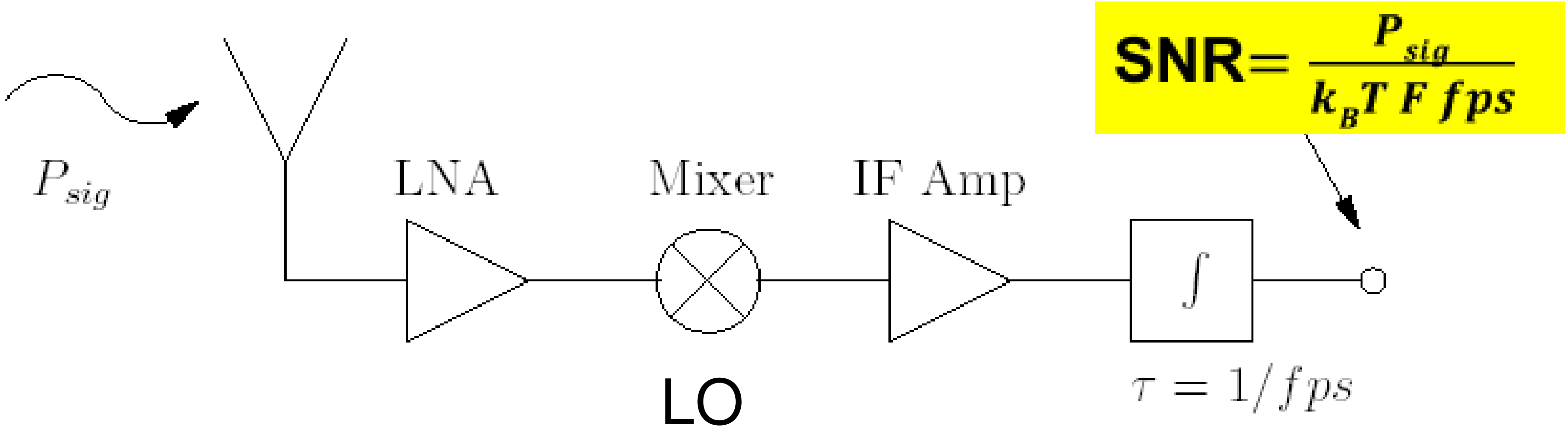
$$NEP_{total} = \frac{V_N \sqrt{BW_{IF}}}{R_v}$$ [W]

What NEP or NF are we looking for?

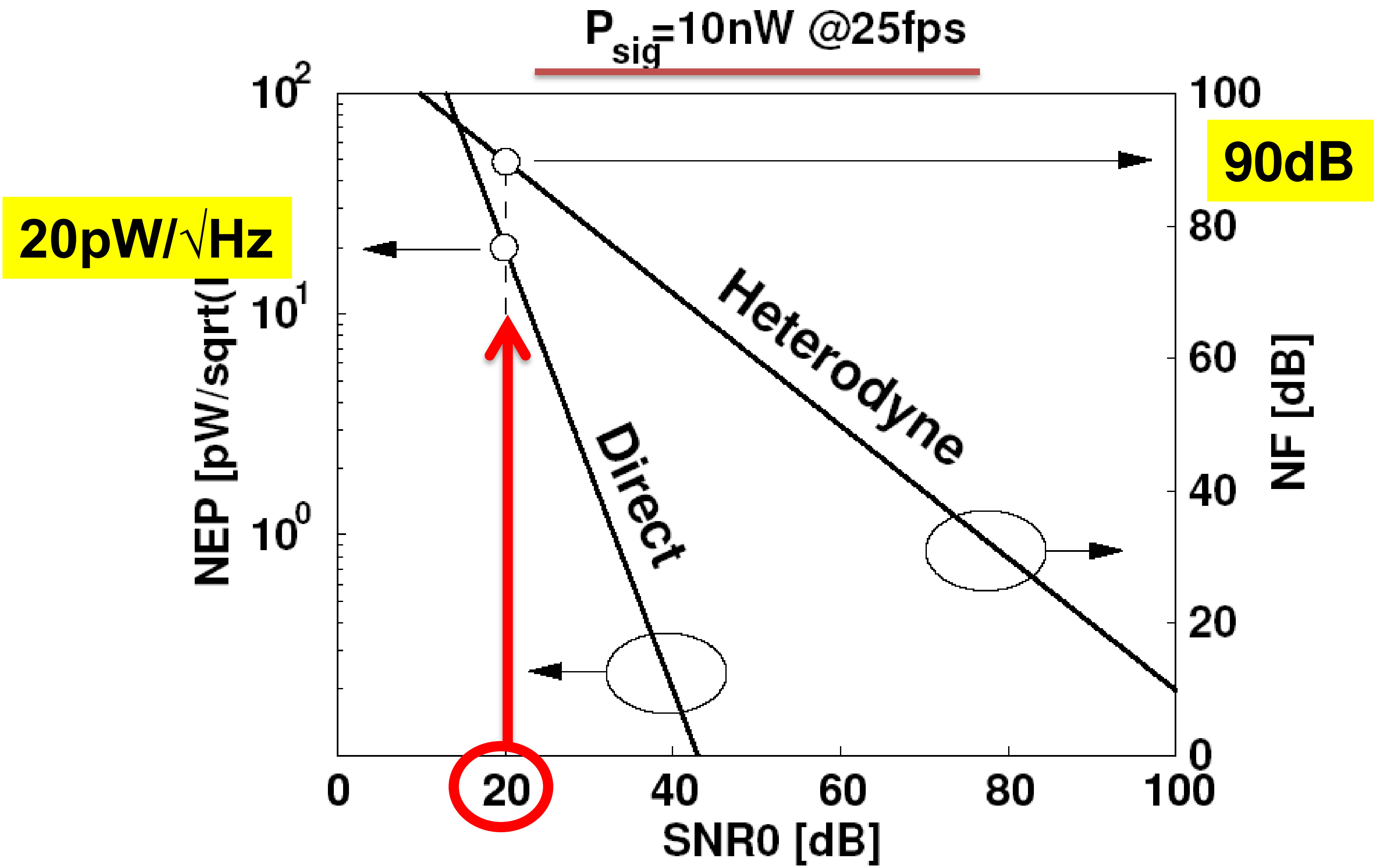
a) Active Direct Detection



b) Active Heterodyne Detection



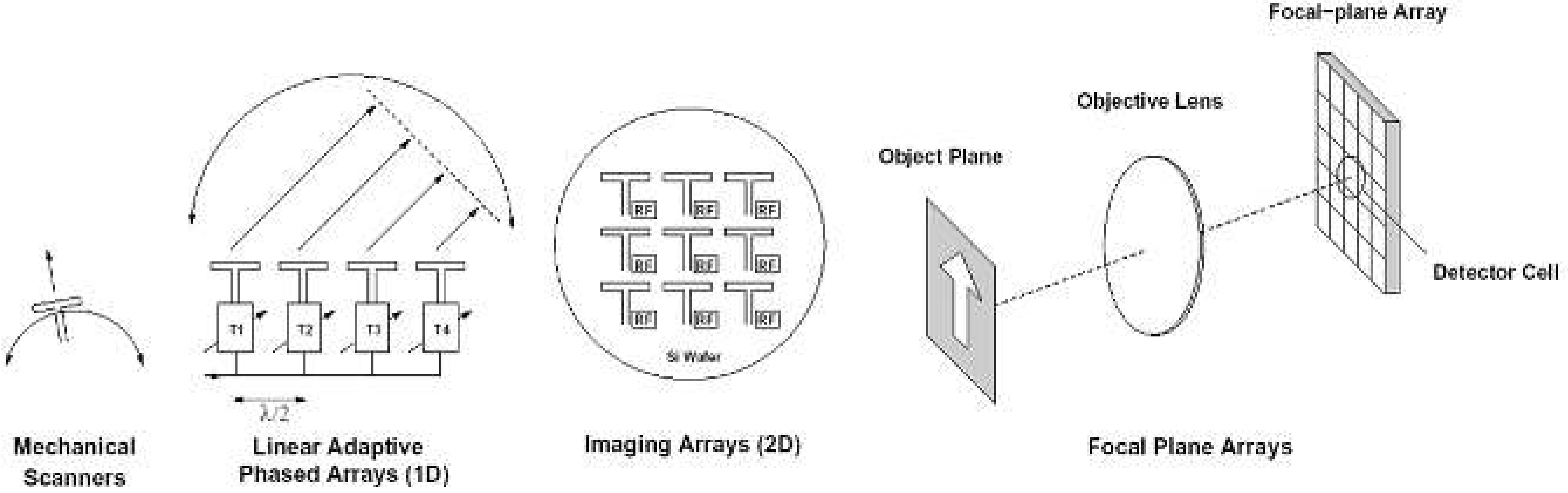
Comparison of Direct versus Heterodyne Detection



THz Imaging Systems

Scanner

Focal Plane Arrays



Wanted:

1. "Fingerprint": Amplitude **+** Phase ⇨ 3D Imaging
   (as opposed to calorimeters and bolometers)
2. Small pixels

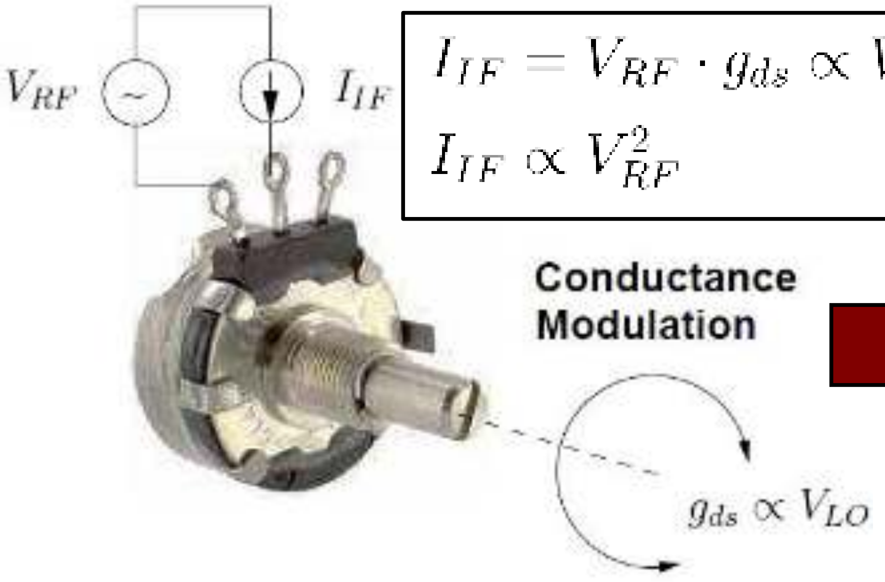
Similar to massive MIMO with thousands of elements!

THz Direct Detectors

Are the most simple Rx,
but can this be done in CMOS?

CMOS THz Direct Detectors

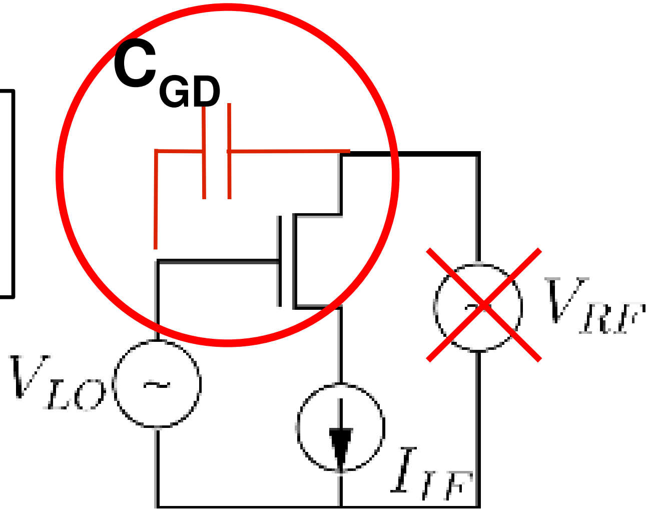
Resistive Mixer (Potentiometer):



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

$$I_{IF} \propto V_{RF}^2$$

Resistive FET Mixer:



- 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...

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

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

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

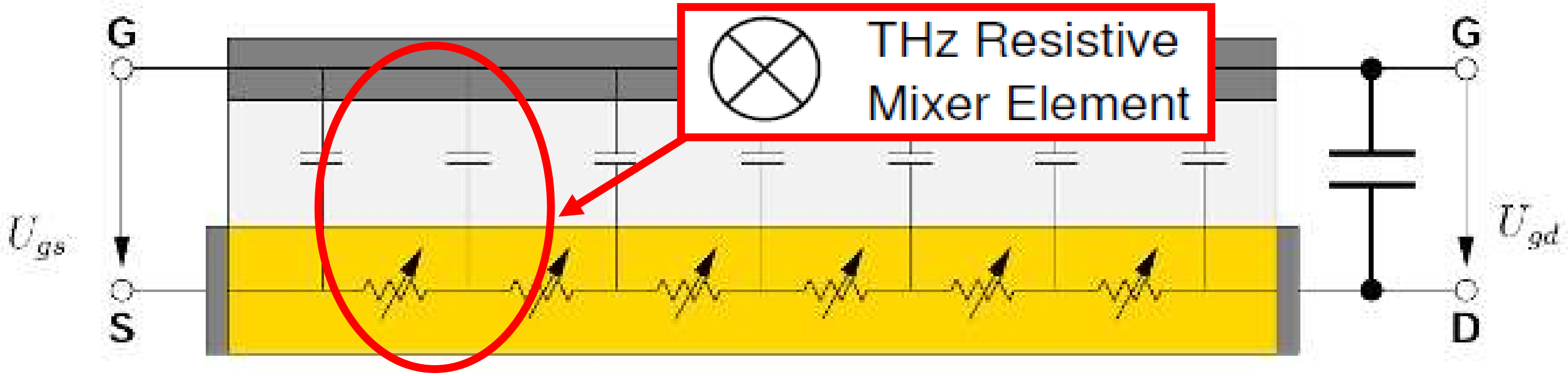
$$R_v = \frac{R_{in}}{4(V_g - V_{th})}$$

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

- **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 over-damped plasma wave dynamics:

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

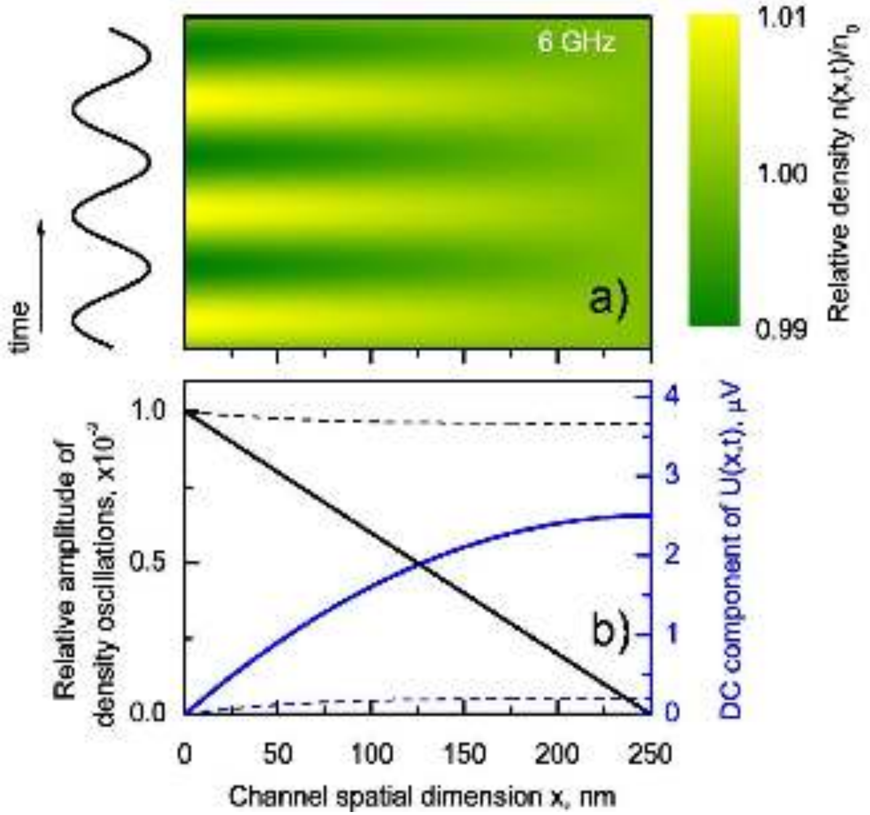
$$v_D = \mu \frac{\partial u(x,t)}{\partial x}$$

Continuity eqn.
Simplified Euler eqn.
Gradual channel approx.

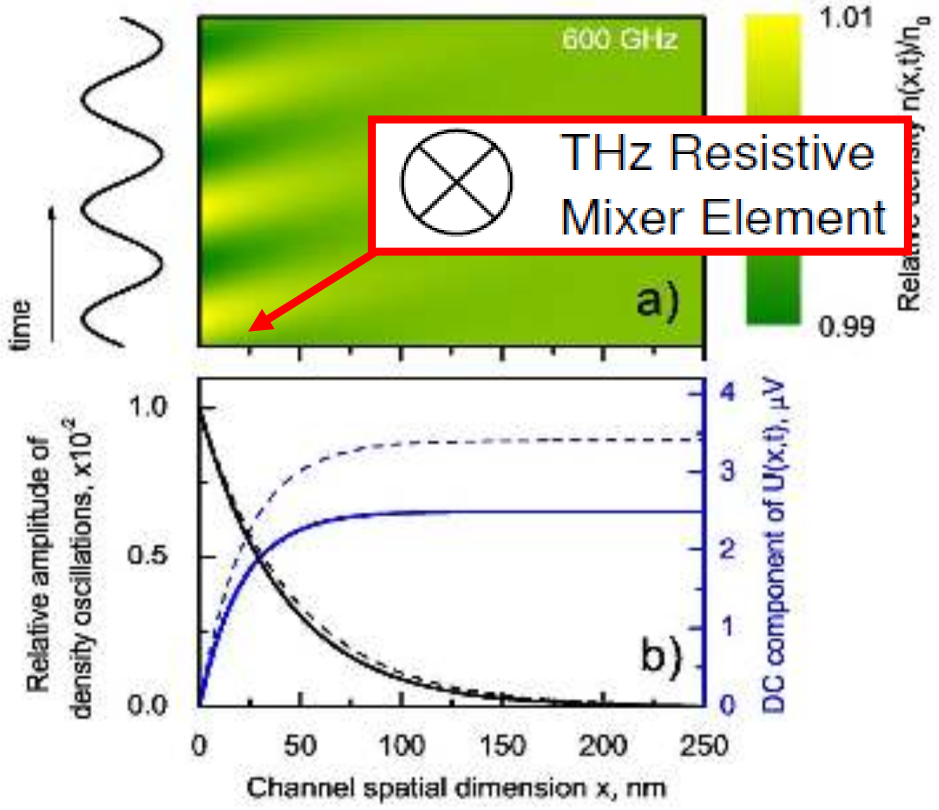
$$\frac{\partial n(x,t)}{\partial t} = -\frac{\partial}{\partial x}\left[\mu n(x,t) \cdot \frac{\partial u(x,t)}{\partial x}\right]$$

Decay of Channel Voltage (Charge Density) Modulation

6 GHz $\omega\tau = 0.0018$

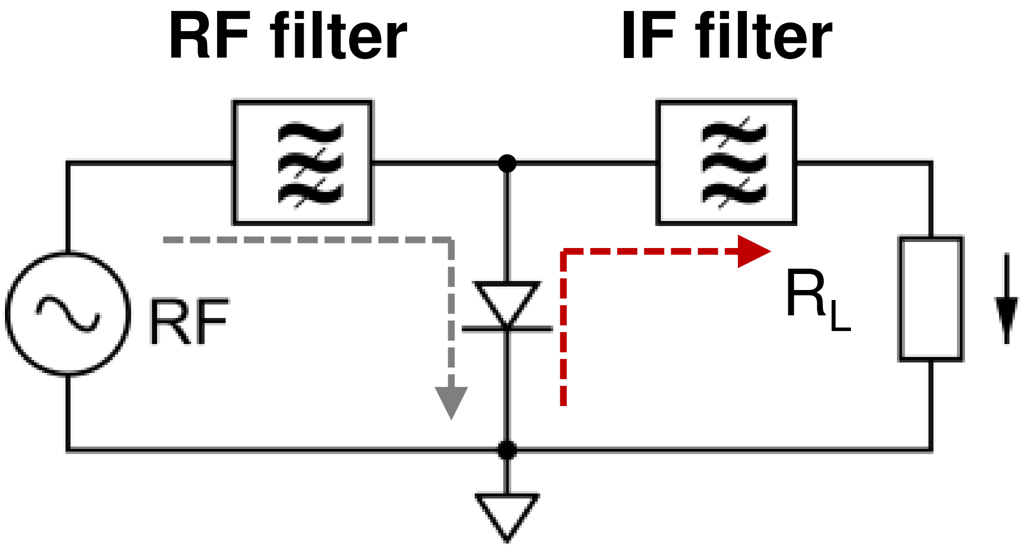


600 GHz $\omega\tau = 0.18$



[1] E. Öjefors, U. Pfeiffer, A. Lisauskas und H. Roskos, A 0.65 THz focal-plane array in a quarter-micron CMOS process technology. IEEE Journal of Solid-State Circuit, Vol. 44(Nr. 7) July 2009

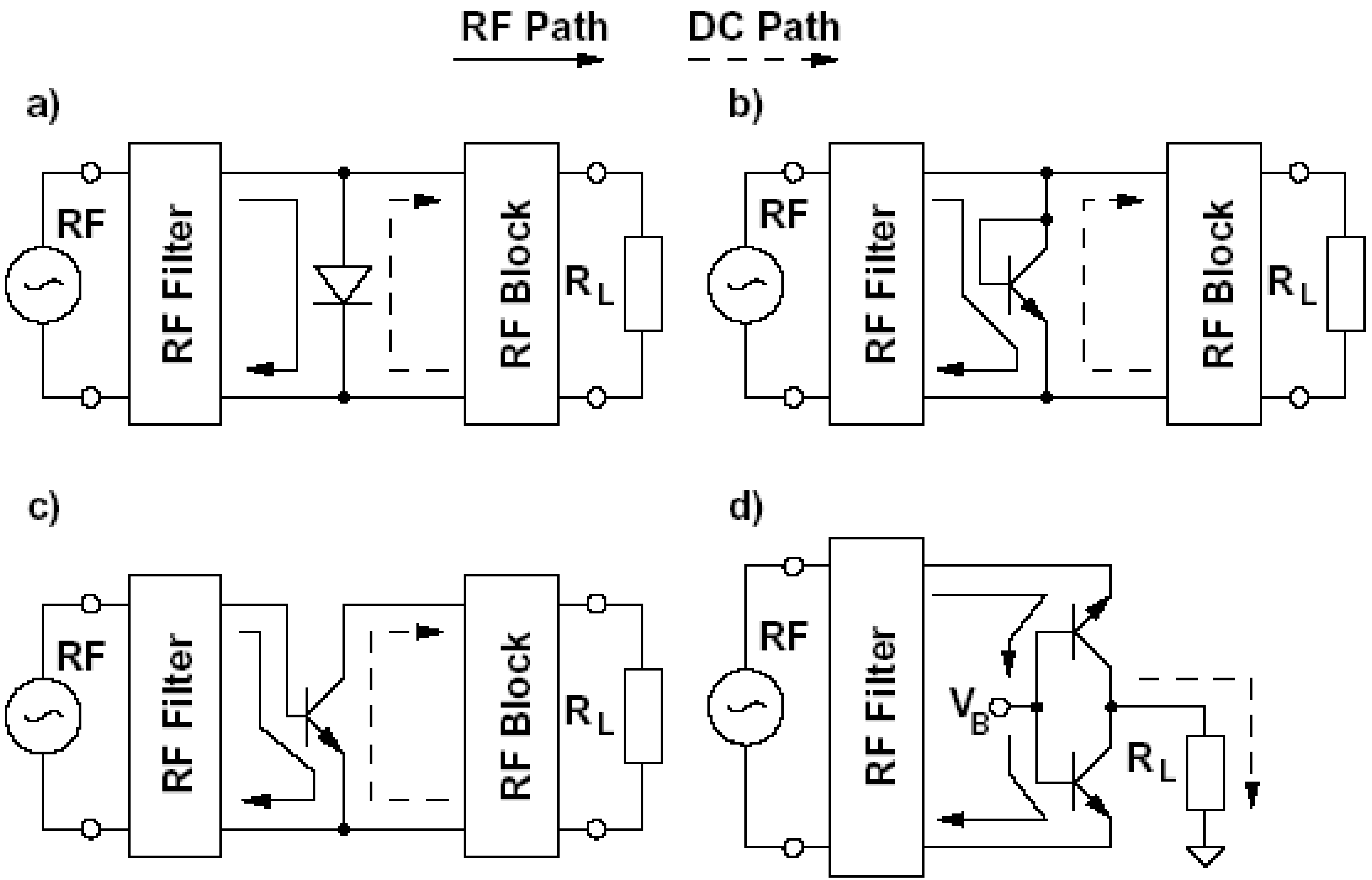
Detector design considerations



$$I_D \propto I_S \frac{{A_{RF}}^2}{4V_T}$$

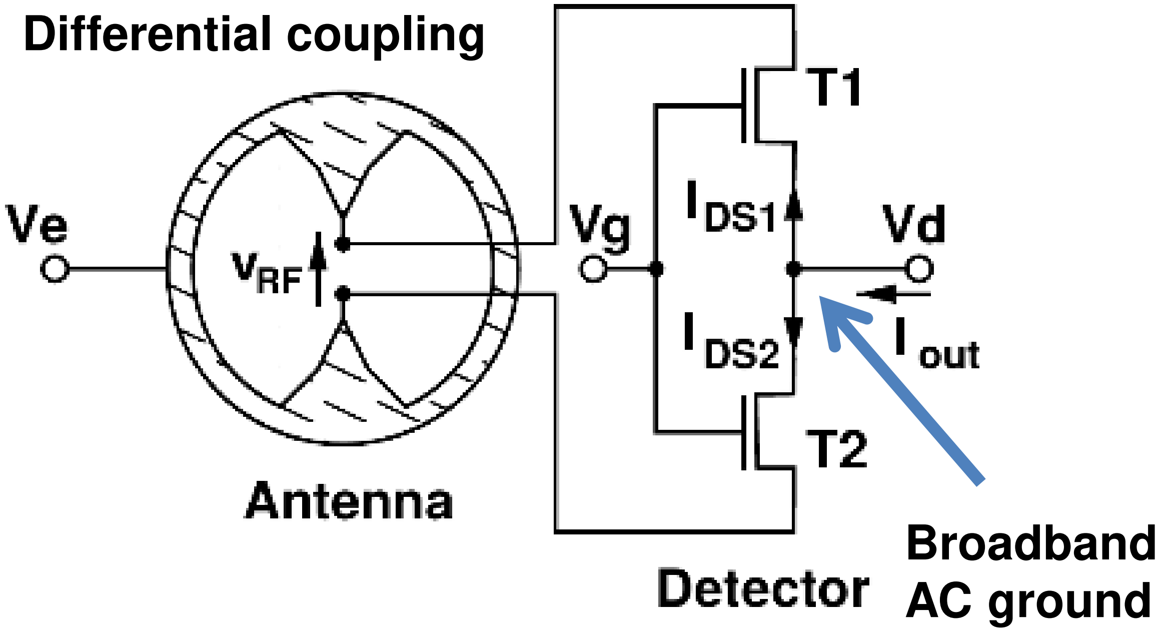
- Detection principle based on the nonlinearity of the base-emitter junction
- Commonly used square law power detector

Possible Implementations



Direct Detection in CMOS and SiGe HBTs

Resistive self-mixing in CMOS

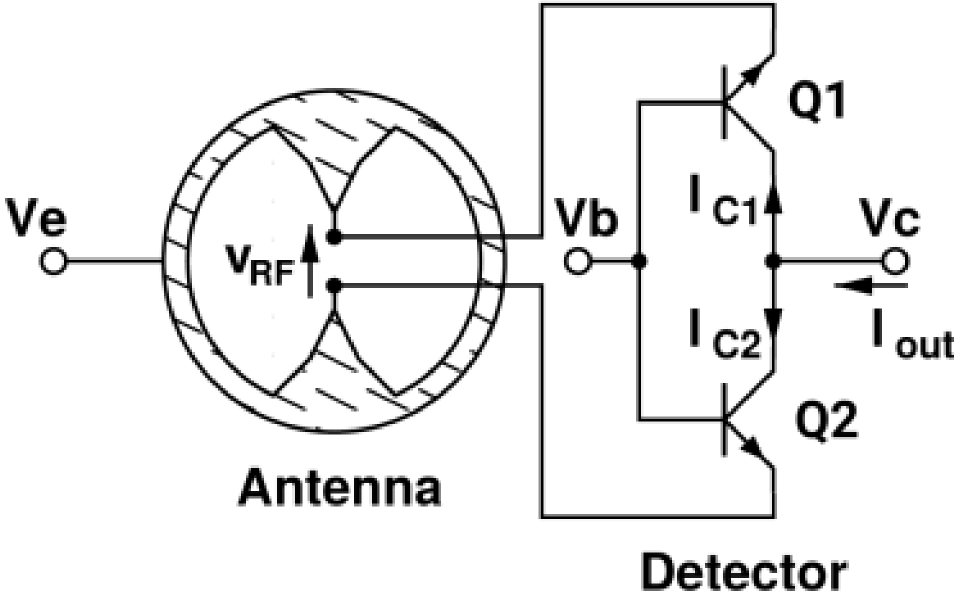


$$I_{IF} = V_{RF} \cdot g_{ds} \propto V_{RF} \cdot V_{RF}$$

$$I_{IF} = V_{RF}^2 = A^2 cos^2(\omega t) = \frac{A^2}{2} + \frac{1}{2} cos\,(2\omega t)$$

First antenna coupled FPA: ESSCIRC 2008

Diode non-linearity in BJT



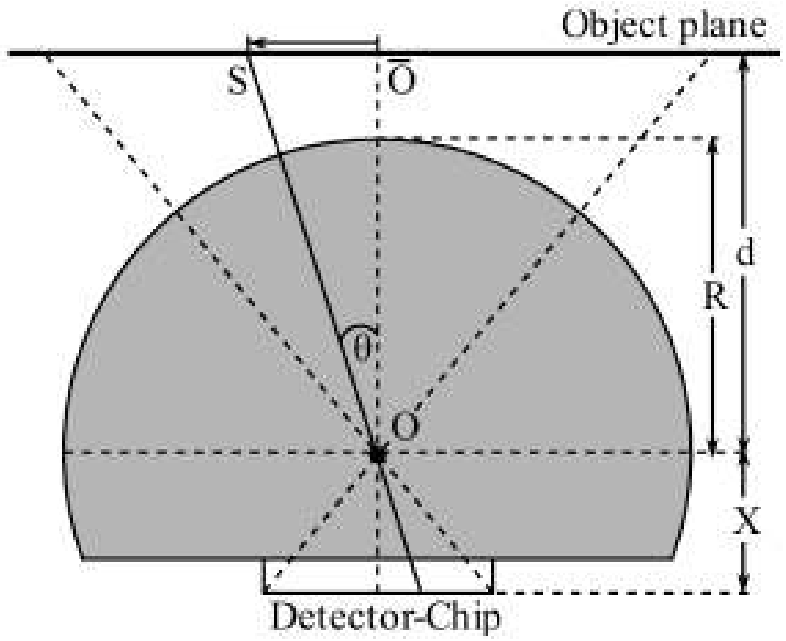
$$I_{IF} = I_{C1} + I_{C2} = I_0 \cdot e^{V_{RF}/V_T} \propto V_{RF}^2$$

$$I_{IF} = V_{RF}^2 = A^2 cos^2(\omega t) = \frac{A^2}{2} + \frac{1}{2} cos\,(2\omega t)$$

First antenna coupled FPA: BCTM 2012

Terahertz design challenges in silicon

- **Device level:**
  - Device performance lagging III-V components
  - Device operating close to or beyond fmax
  - Low breakdown voltage (limited power)
  - Fundamental operation of up to around 280 GHz

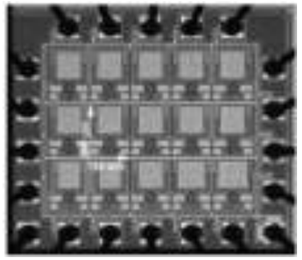


- **Interconnect level /on-chip antenna:**
  - Lossy silicon substrate (5-50 Ω-cm)
  - Thin BEOL (Back-End-of-Line) stack with challenging layout rules
  - Unfavorable for antenna integration (efficiency, operation bandwidth, directivity, quality of radiation patterns)

Lens-integrated on-chip antennas as alternative solution

CMOS FPA Design Summary

2008: 250nm

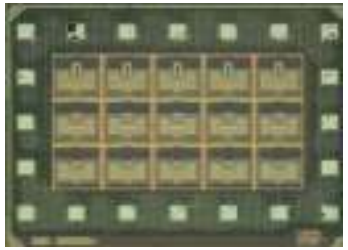


650 GHz
80 kV/W
300 pW/√Hz

2010: 65nm SOI

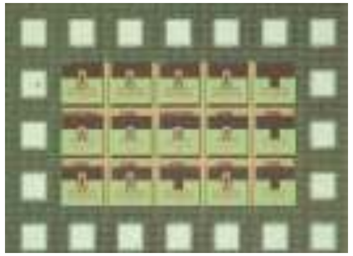
650 GHz
1.1 kV/W
50 pW/√Hz

2011: 65nm SOI



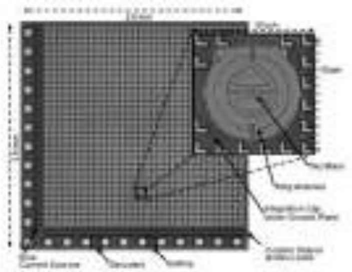
650 GHz
2 kV/W
17pW/√Hz

2011: 65nm Bulk



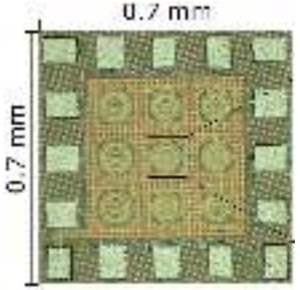
1.027 THz
800 V/W
66 pW/√Hz

2012: 65nm Bulk



0.6-1 THz
56.6kV/W
470pW/√Hz

2018: 22FDX



0.65-1.1 THz
1.2kV/W
12 pW/√Hz

[1] U. Pfeiffer und E. Öjefors, A 600-GHz CMOS Focal-Plane. IEEE European Solid-State Circuits Conference, P. 110-113, Sept. **2008**

[2] E. Öjefors, N. Baktash, Y. Zhao, R. Al Hadi, H. Sherry und U. Pfeiffer, Terahertz imaging detectors in a 65-nm CMOS SOI technology, IEEE European Solid-State Circuits Conference, Seville, Spain (pp. 486 - 489), September **2010**

[3] H. Sherry, R. Al Hadi, J. Grzyb, E. Ojefors, A. Cathelin , A. Kaiser , and U. R. Pfeiffer, Lens-Integrated THz Imaging Arrays in 65nm CMOS Technologies, RFIC **2011**

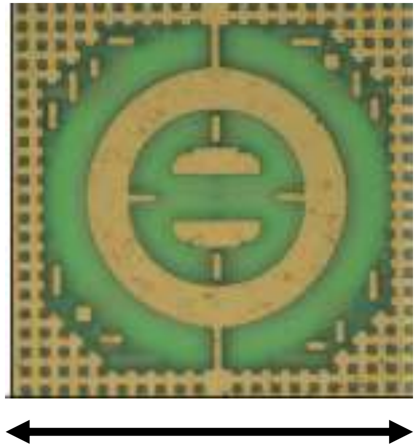
[4] R. Al Hadi et al, “A Broadband 0.6 to 1 THz CMOS Imaging Detector with an Integrated Lens,” IMS **2011**

[5] H. Sherry et al, “A 1kpixel CMOS camera chip for 25fps real-time terahertz imaging applications,” ISSCC Feb. **2012**

[6] R. Jain, A Terahertz Direct Detector in 22nm FD-SOI CMOS, EUMIC 2018

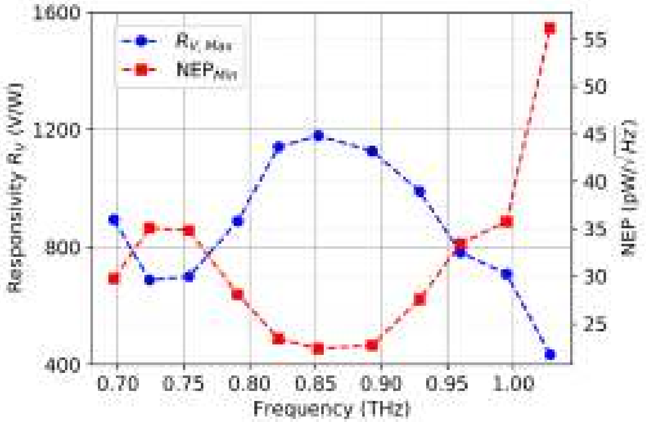
How does this compare with heterodyne RX?

GF 22nm FD-SOI



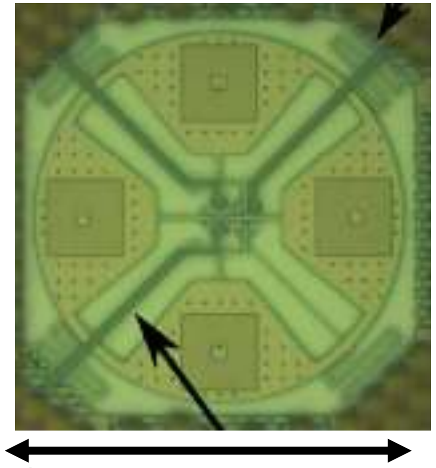
100µm

[1] R. Jain, et.al. "A Terahertz Direct Detector in 22nm FD-SOI CMOS", EUMIC 2018

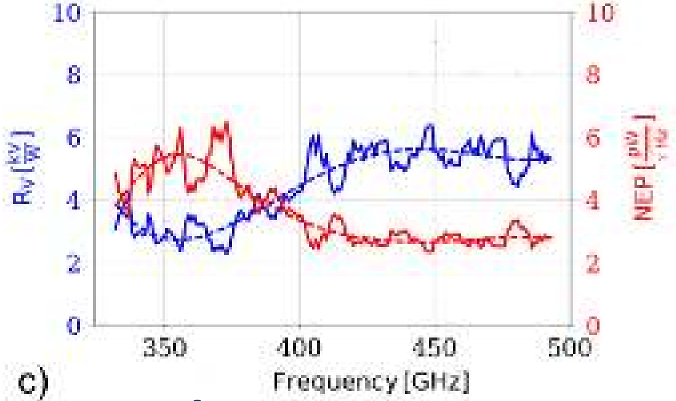


12 pW/√Hz @ 855 GHz

IHP 130nm SiGe



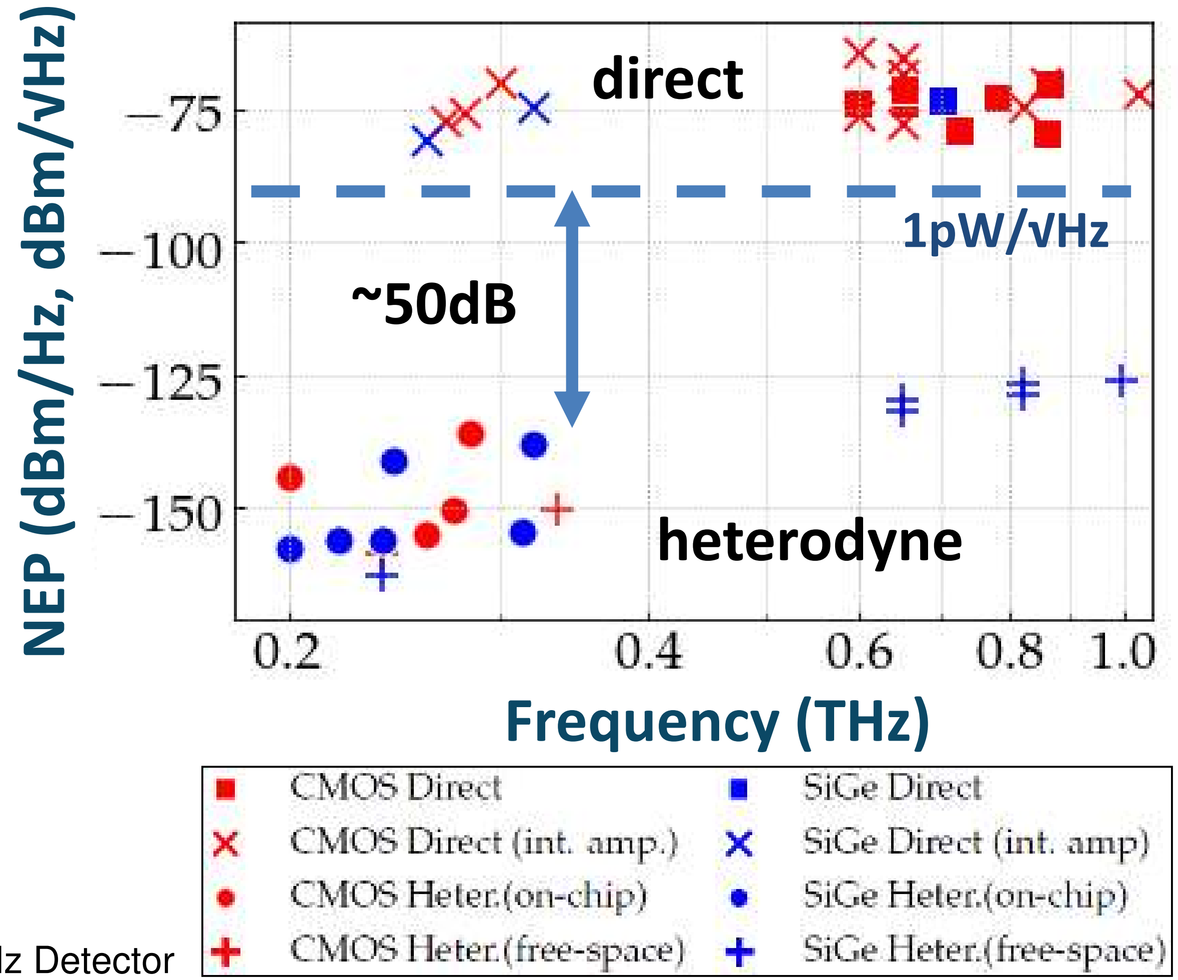
130µm



3 pW/√Hz @ 500 GHz

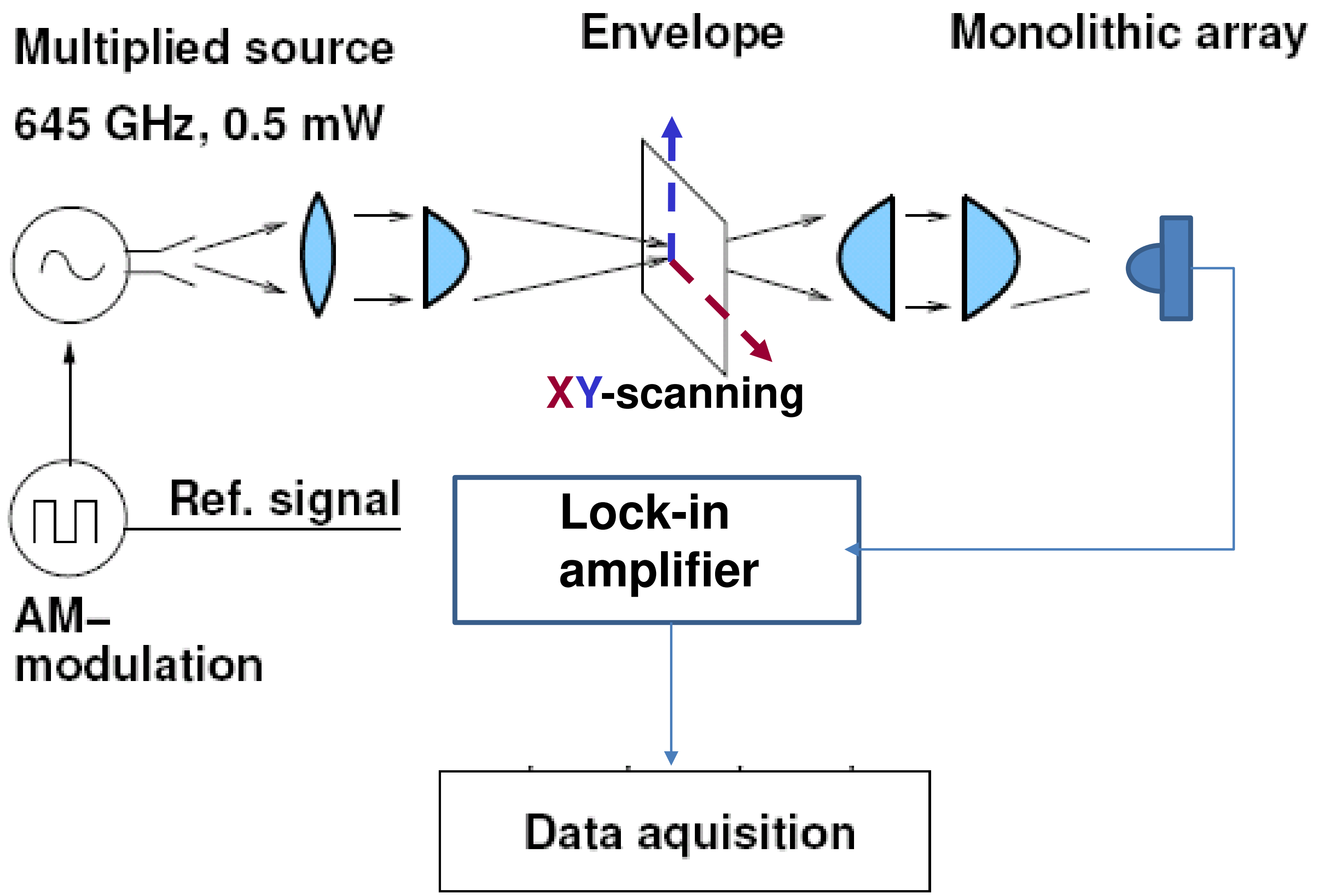
[2] M. Andre, at.al. "A Broadband Dualpolarized THz Detector in a 0.13 µm SiGe HBT Process Technology", IMS 2019

Detectors (CMOS/SiGe)

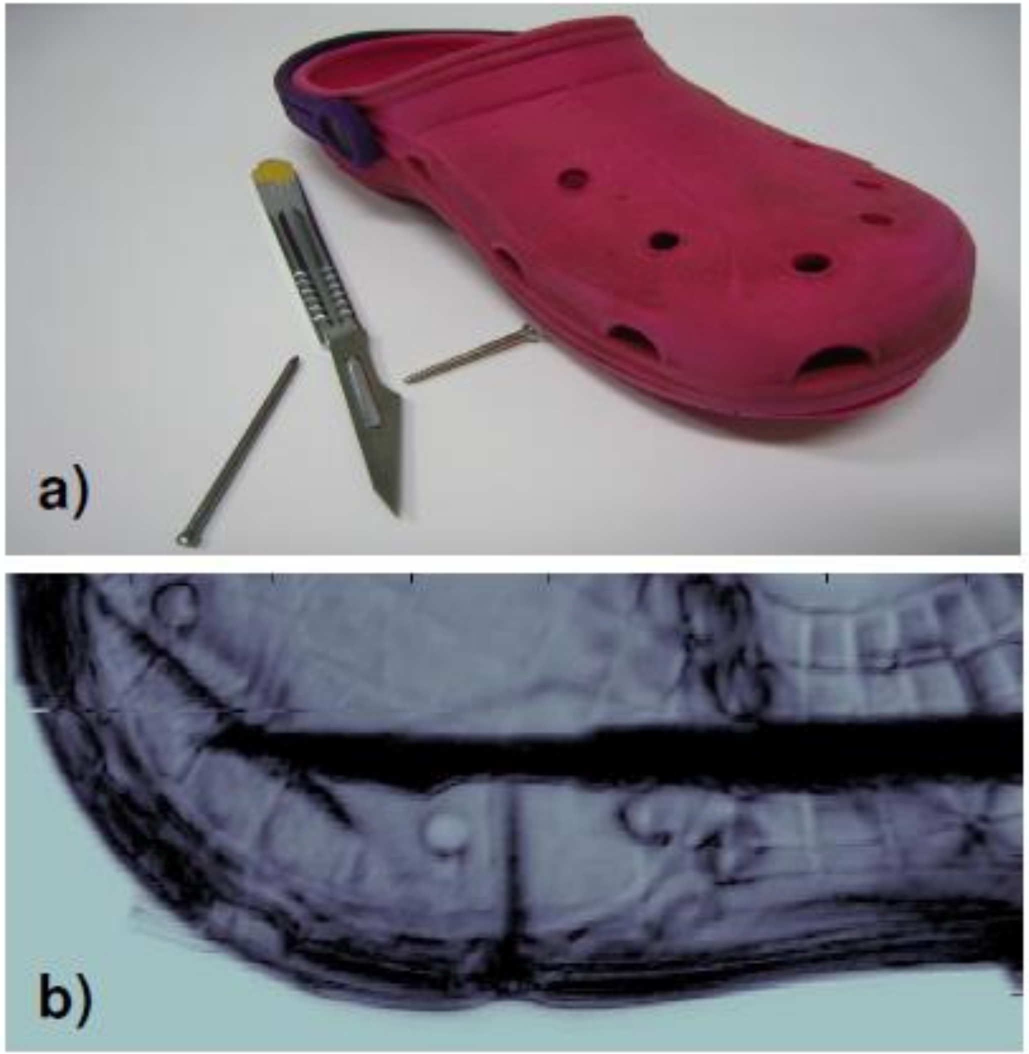


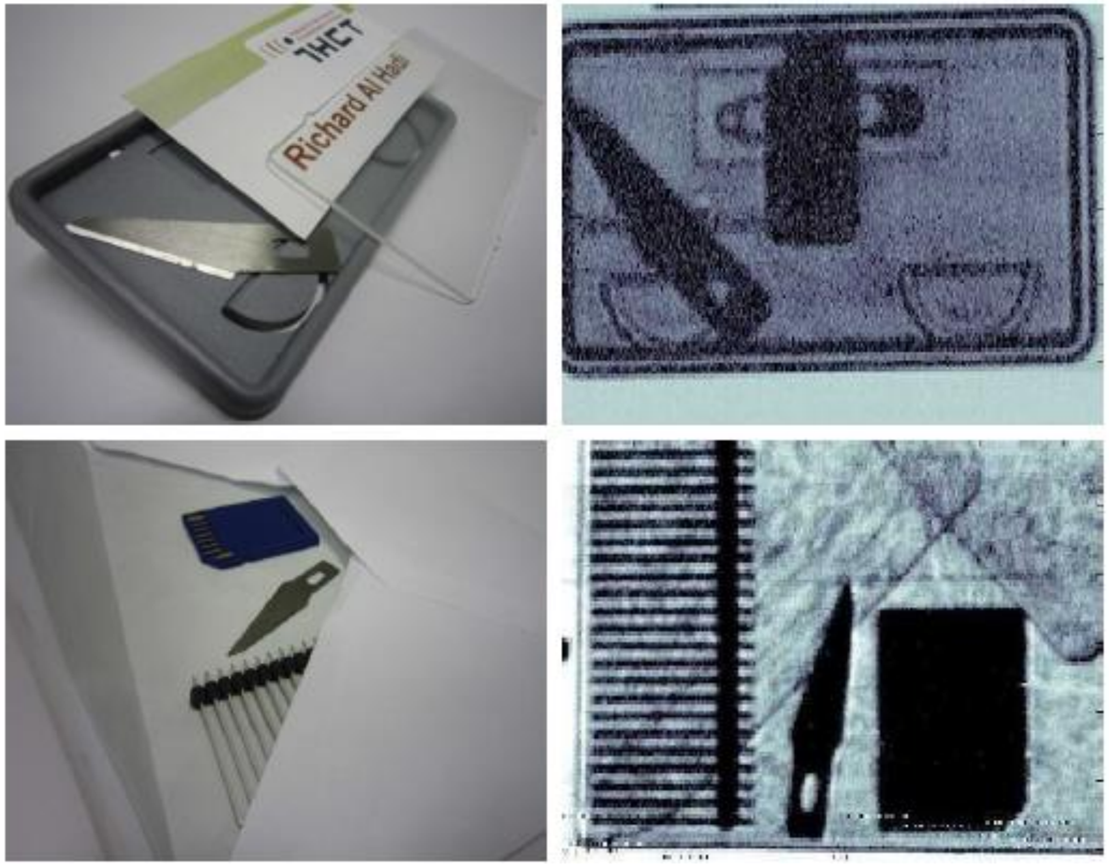
Active THz Imaging Systems (Scanner-based) …the poor man’s imagers

Scanning Approaches to THz Imaging



Example: Active Imaging at 650GHz





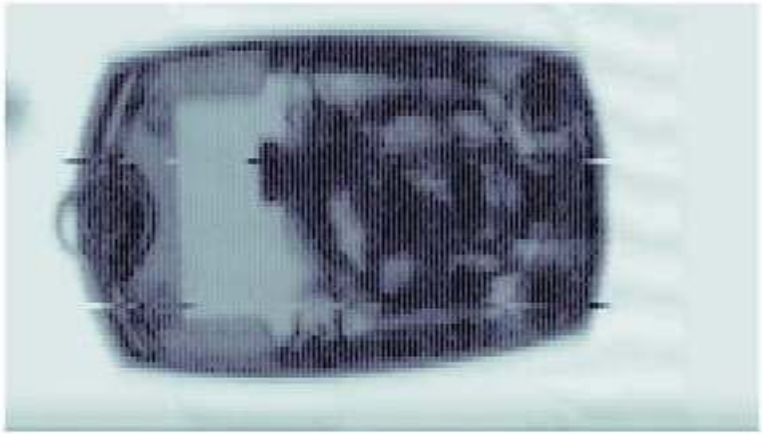
[1] H. Sherry, R. Al Hadi, J. Grzyb, E. Ojefors, A. Cathelin , A. Kaiser , and U. R. Pfeiffer, Lens-Integrated THz Imaging Arrays in 65nm CMOS Technologies, RFIC 2011
[2] R. Al Hadi, H. Sherry, J. Grzyb, N. Baktash, Y. Zhao, E. Öjefors, A. Kaiser, A. Cathelin, U. R. Pfeiffer, A Broadband 0.6 to 1 THz CMOS Imaging Detector with an Integrated Lens, IMS 2011

A 825GHz SiGe TX/RX Chipset

LED Flashlight

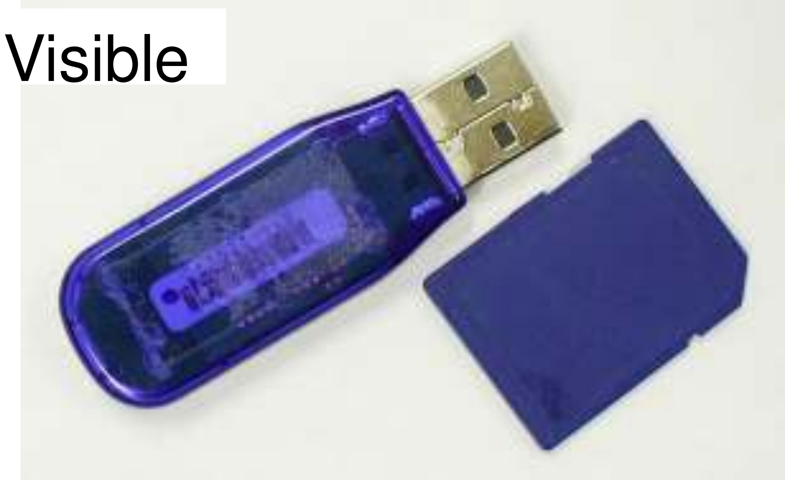
Visible

825GHz, 601x80 pixel image



Bluetooth Dongle and SD Card

Visible

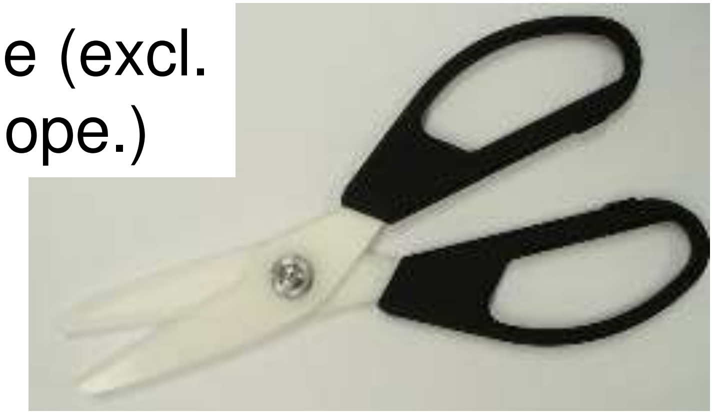


825GHz, 601x80 pixel image

A 825GHz SiGe TX/RX Chipset

Ceramic Scissors in a Paper Envelope

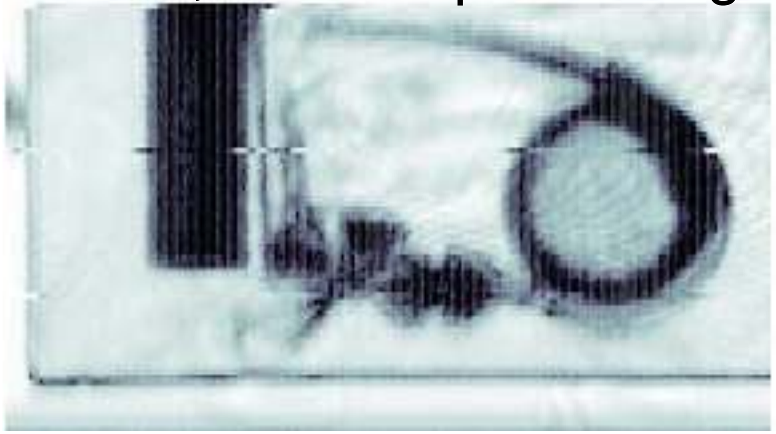
Visible (excl. envelope.)



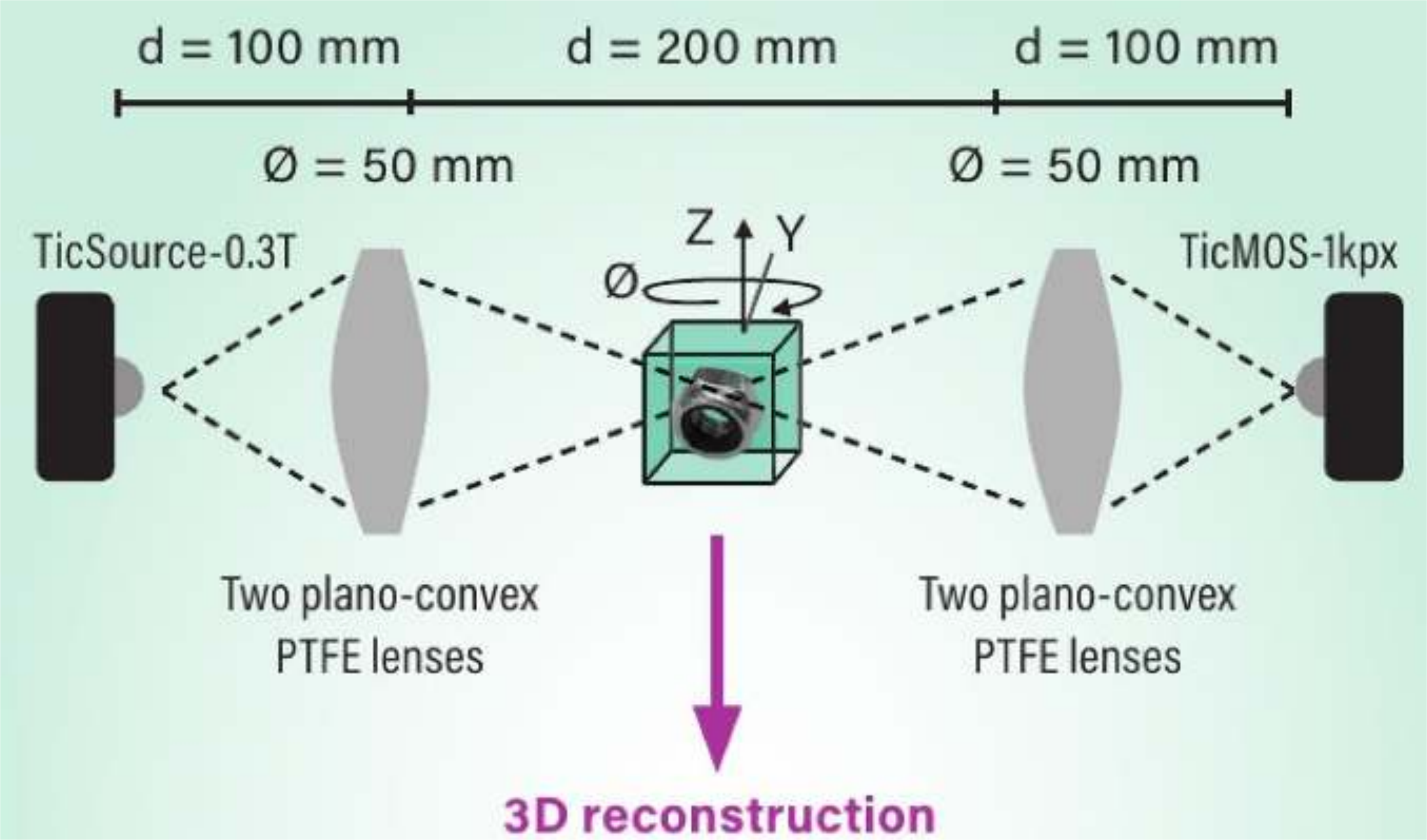
825GHz, 601x80 pixel image

Firecrackers in a Paper Envelope

825GHz, 601x80 pixel image



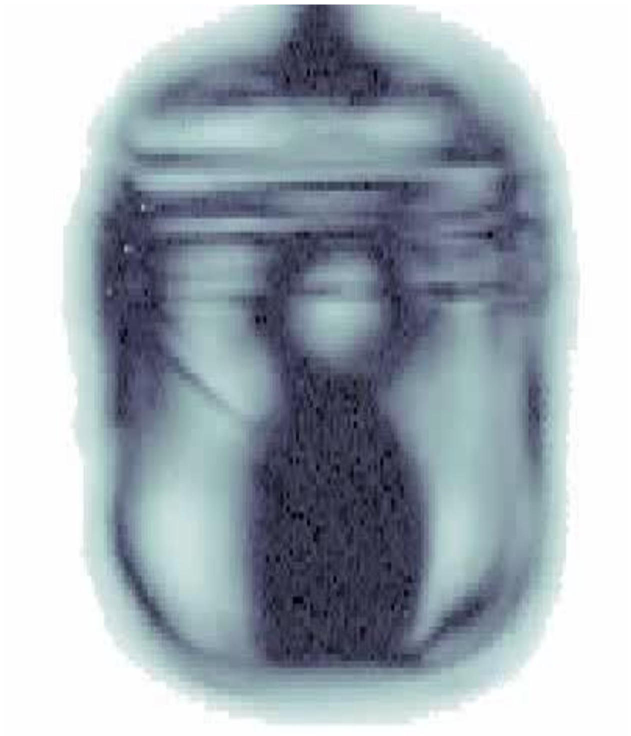
Advanced: Computed Tomography (CT) Imaging



[1] P. Hillger, et.al. "Terahertz Imaging and Sensing Applications With Silicon-Based Technologies," in TTST, vol. 9, no. 1, pp. 1-19, Jan. 2019.

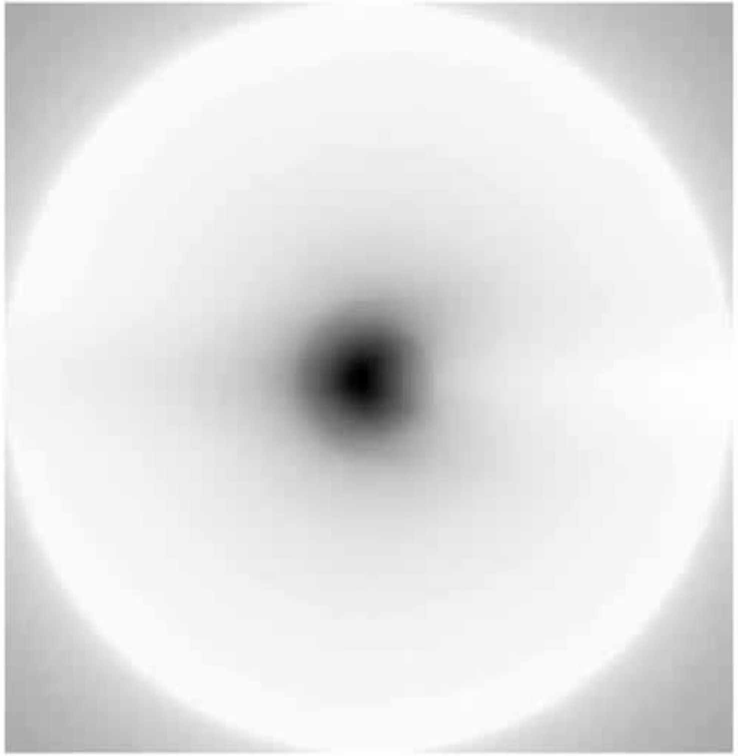
Example: CT Imaging at THz

2D raster-scanned Image [dB]:



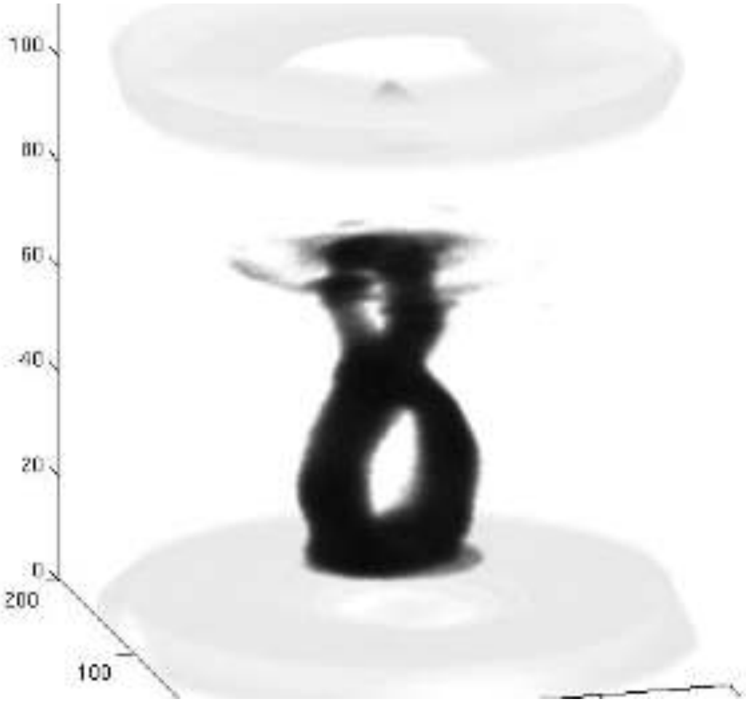
- 250µm x 500µm image resolution
- optical resolution (2 mm)
- 200 x 110 pixel (5cm x 5.5cm)
- 1 ms integration time
- 1 kHz chopping frequency
- raster-scanned image with SNR > 50dB

Example: CT Slices



200x200 pixel (5cmx5cm)

3D rendered image:

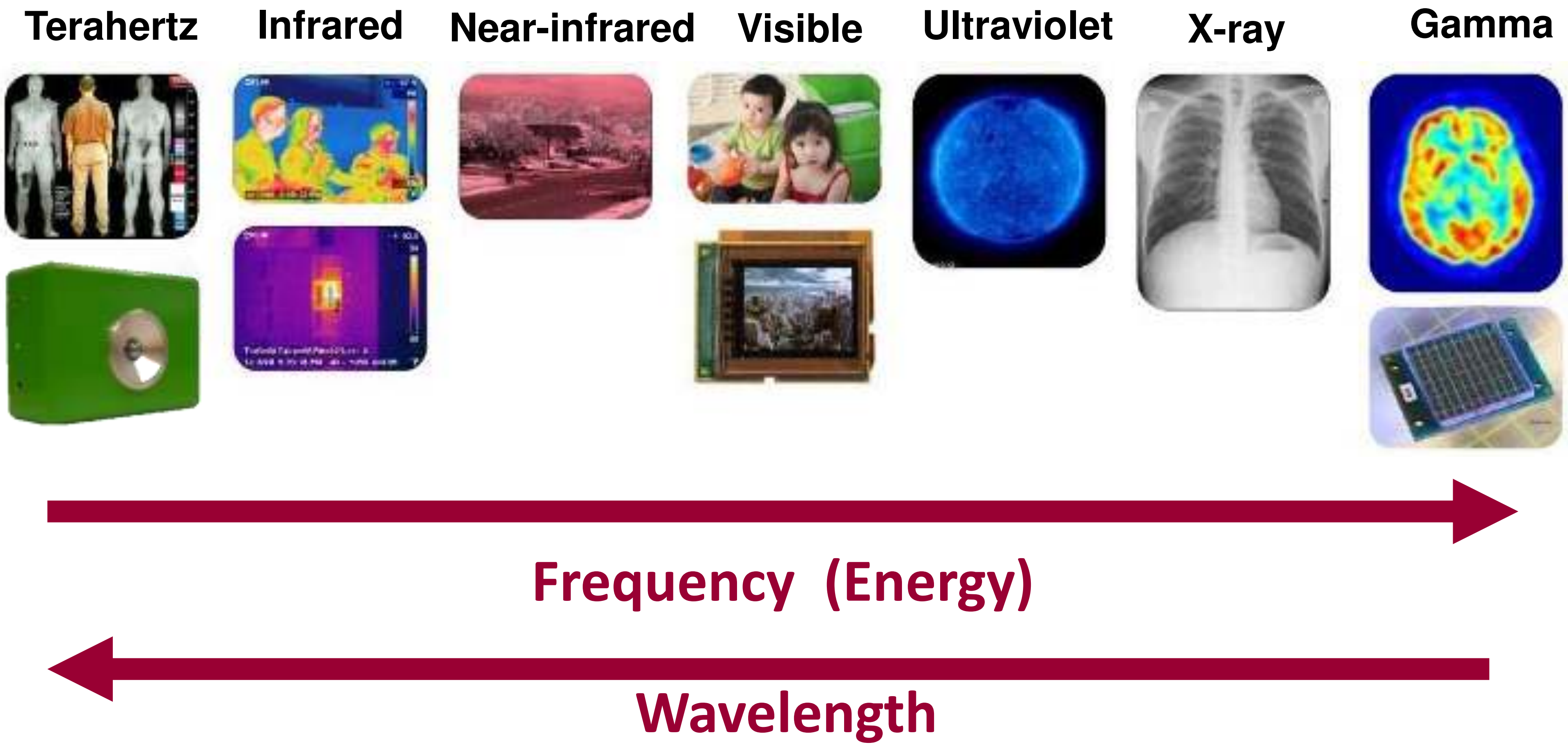


[1] U.R. Pfeiffer, „Sub-millimeter Wave Active Imaging with Silicon Integrated Circuits“, IRMMW-THz, plenary talk, Oct. 2011

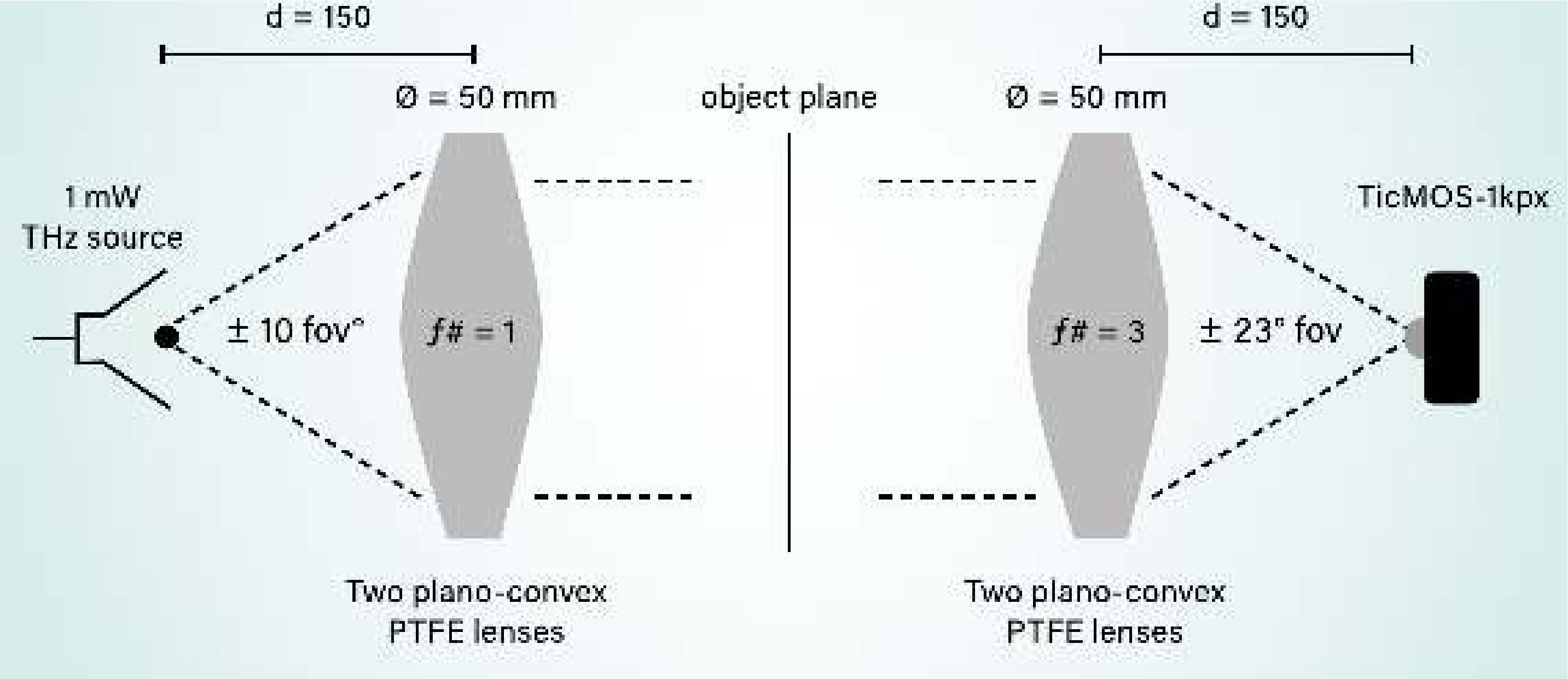
[2] P. Hillger, et.al. "Terahertz Imaging and Sensing Applications With Silicon-Based Technologies," in TTST, vol. 9, no. 1, pp. 1-19, Jan. 2019.

Active THz Video Cameras
… the real imagers!

Sensors/ Imaging Cameras



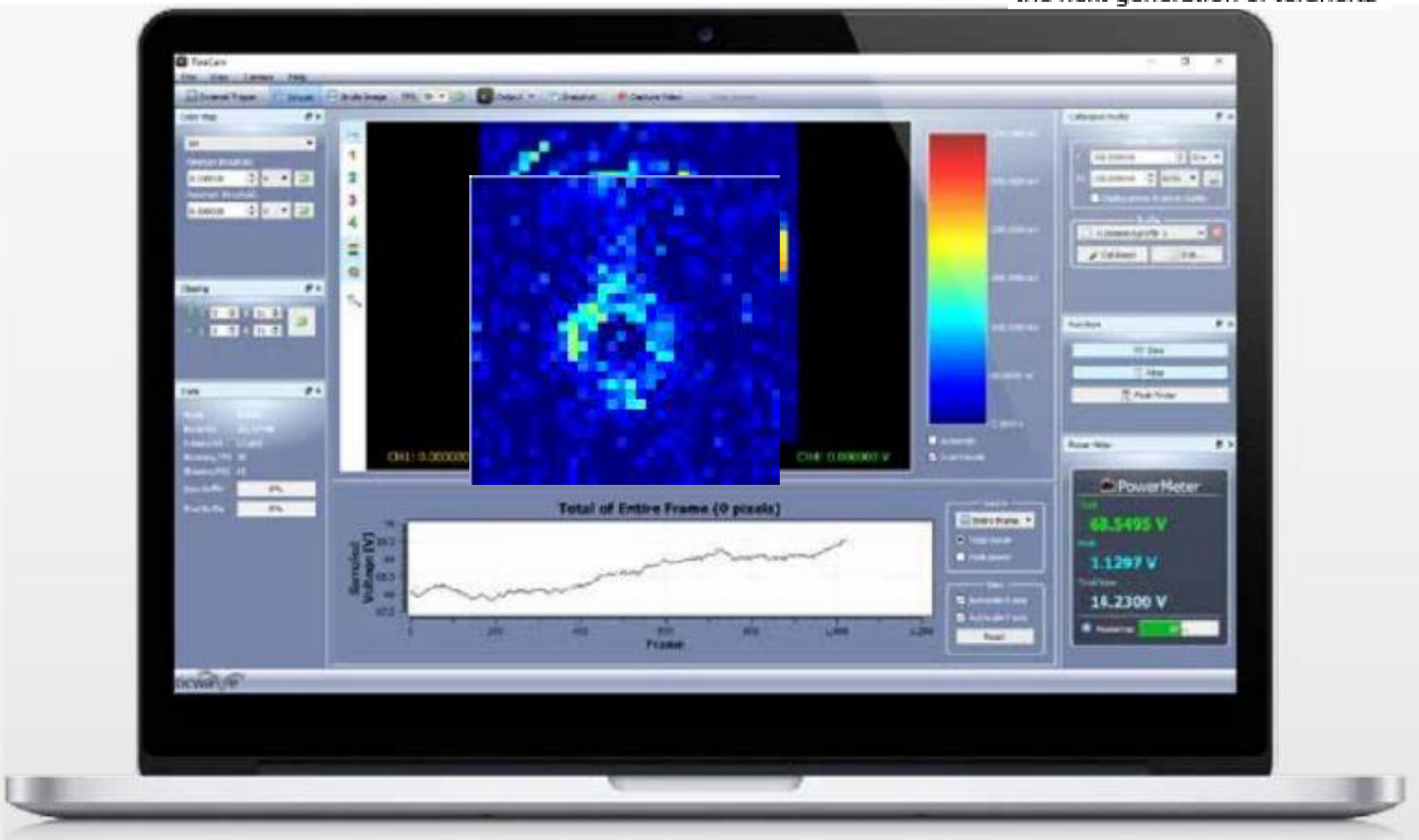
Active THz Video Camera Imaging Setup



- **Problem: Source power spread over opject plane!**

Commercial THz CMOS USB Camera

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



ST 65nm bulk CMOS

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

World's first active CMOS THz camera

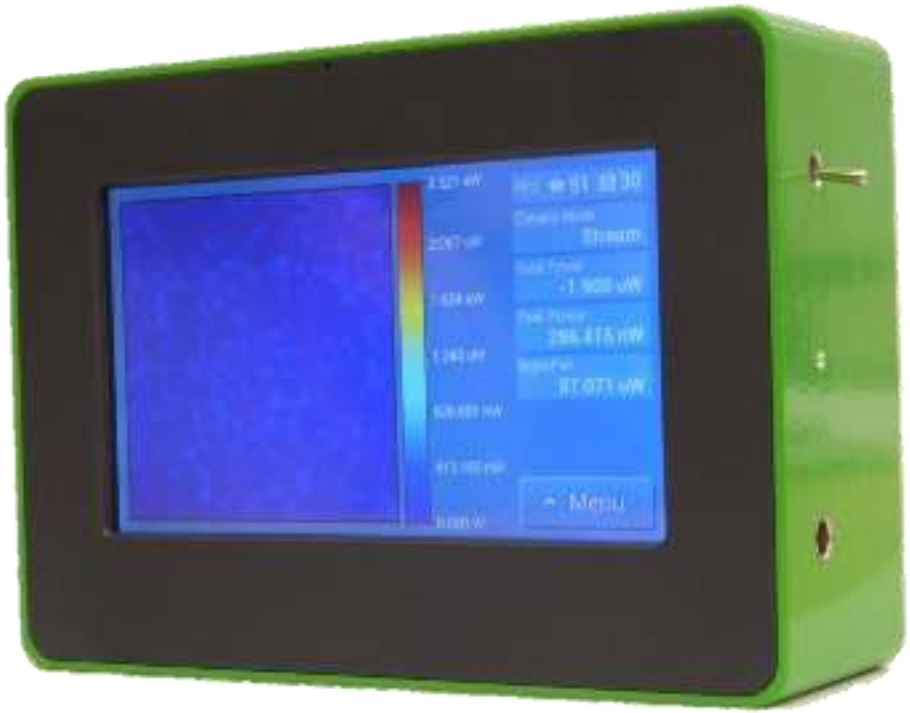
Key features:

- **Active THz real-time imaging at room temperature**
- **1024 (32x32) pixels**
- **65nm CMOS Bulk technology**
- **2.5µW/pixel power consumption**
- **0.75-1 THz (3-dB) bandwidth**
- **40dBi Silicon lens for stand-off detection**
- **Up to 500 fps video mode**
  - 100-200kV/W (856GHz)
  - 10-20nW integr. NEP (856GHz)
- **Non video-mode:**
  - 140kV/W Rv (856GHz, 5kHz chop.)
  - 100pW/√Hz NEP (856GHz, 5kHz chop.)

Handheld battery-operated THz CMOS Camera

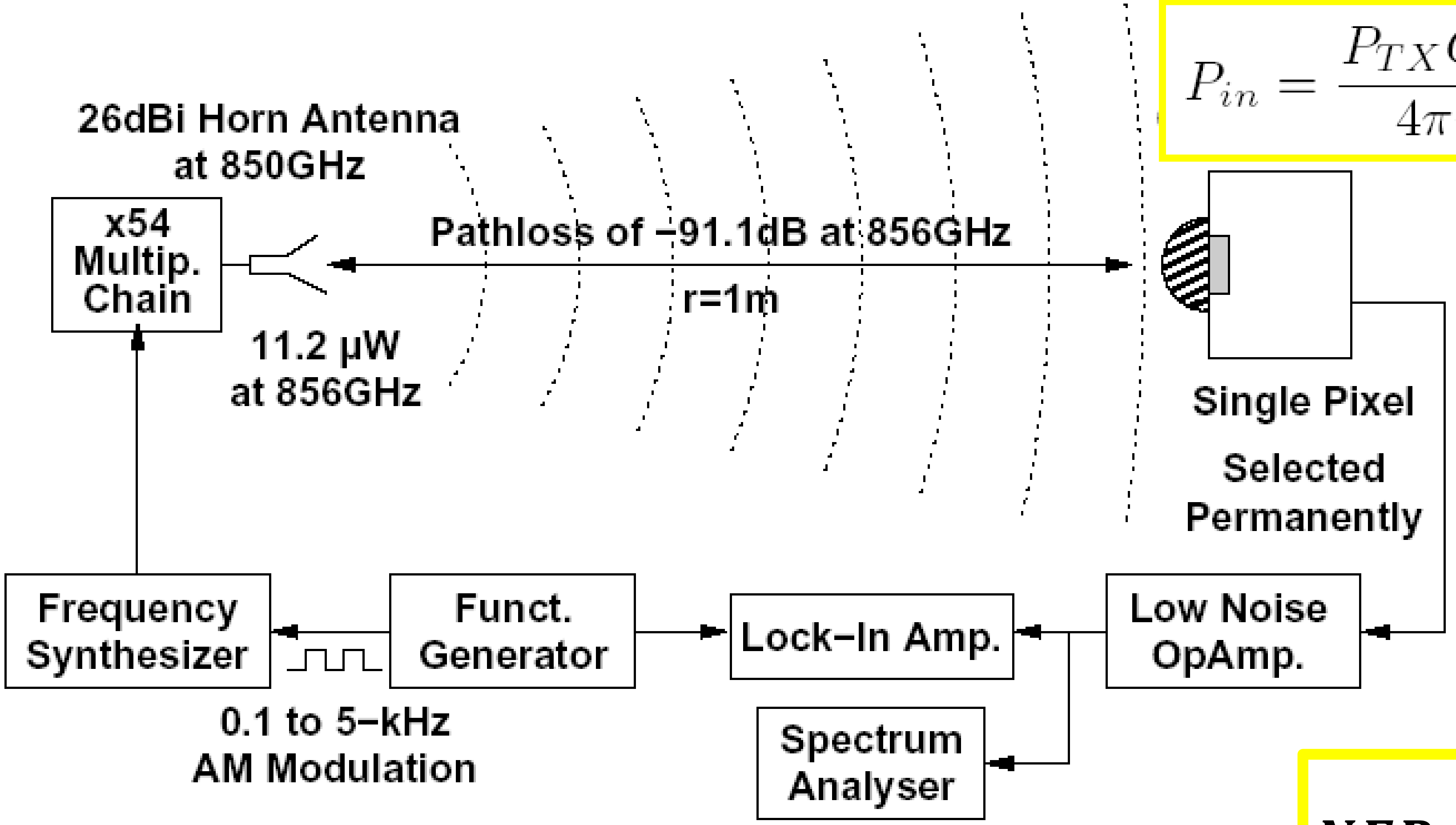
Front-side

Back-side



Video Demo at the ISSCC 2012 IDS Exibition

Pixel Characterization Essentials (non-video mode)



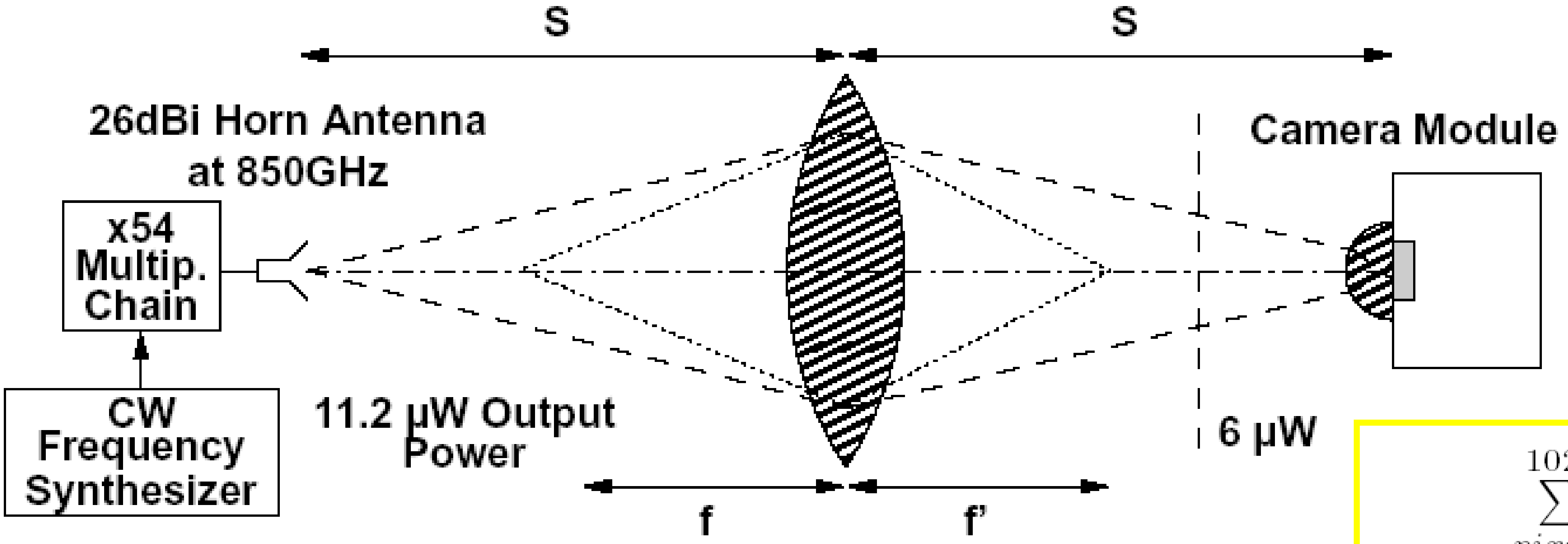
$$P_{in} = \frac{P_{TX} G_{TX}}{4\pi r^2} A_{eff},$$

$$R_v = \frac{U_{out}}{P_{in}} \quad [V/W]$$

$$NEP = \frac{V_N}{R_v} \quad [W/\sqrt{Hz}]$$

$$NEP_{total} = \frac{V_N \sqrt{BW_{IF}}}{R_v} \quad [W]$$

Direct-Method of Camera Characterization

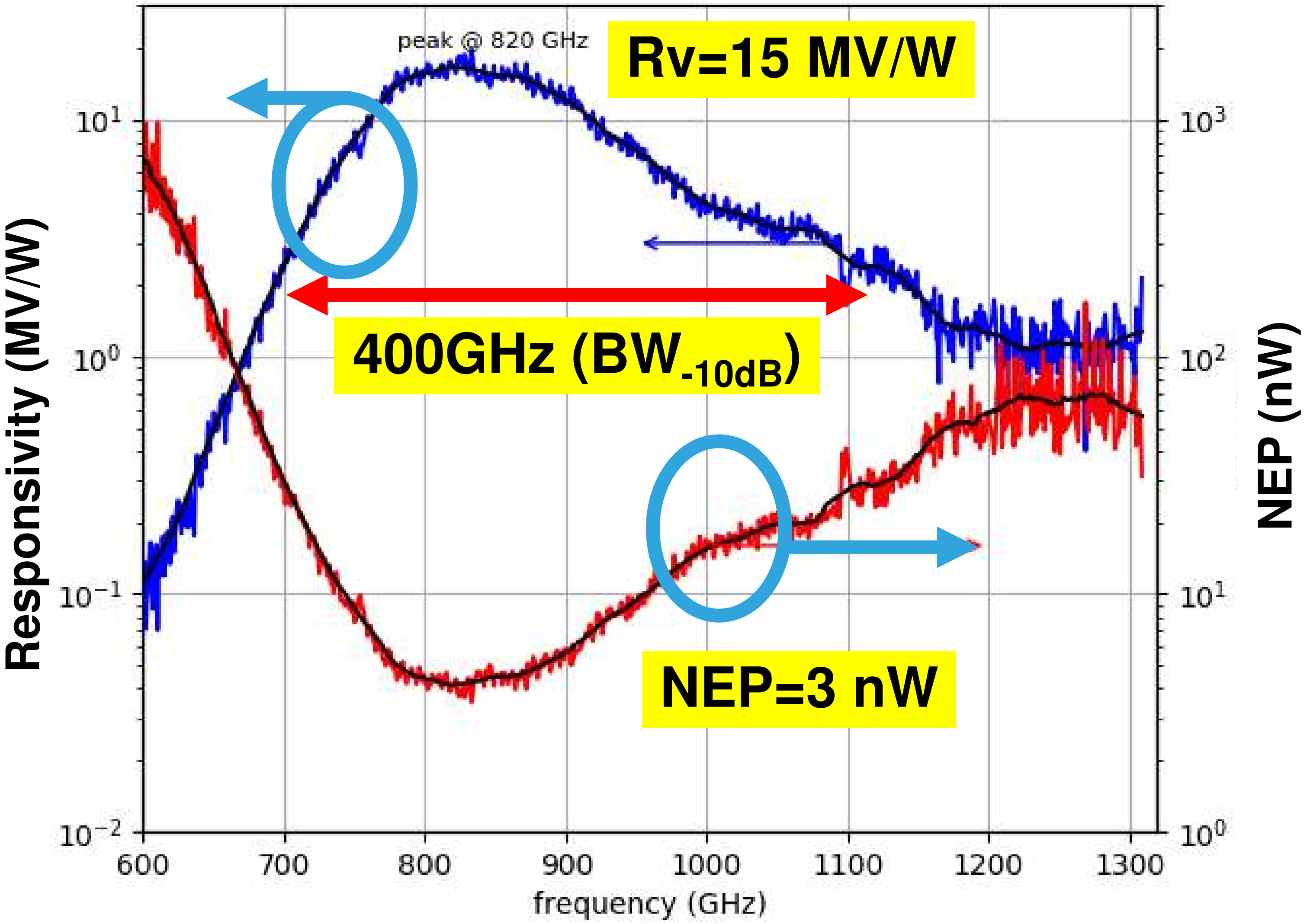


$$R_v = \frac{\sum_{pix=1}^{1024} V_{pix}}{P_{in}}.$$

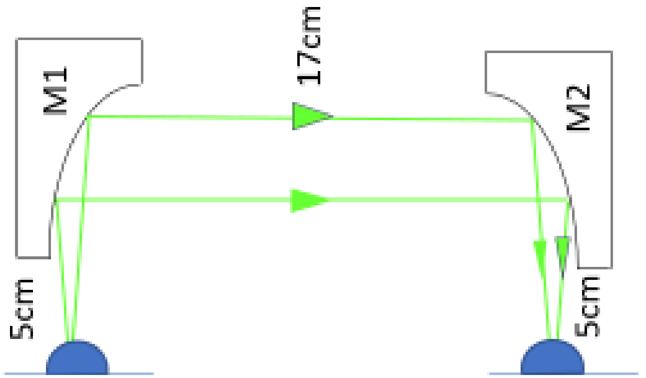
Not a chopped lock-in technique!

$$NEP_{total} = \frac{V_{N,total}}{R_v}.$$

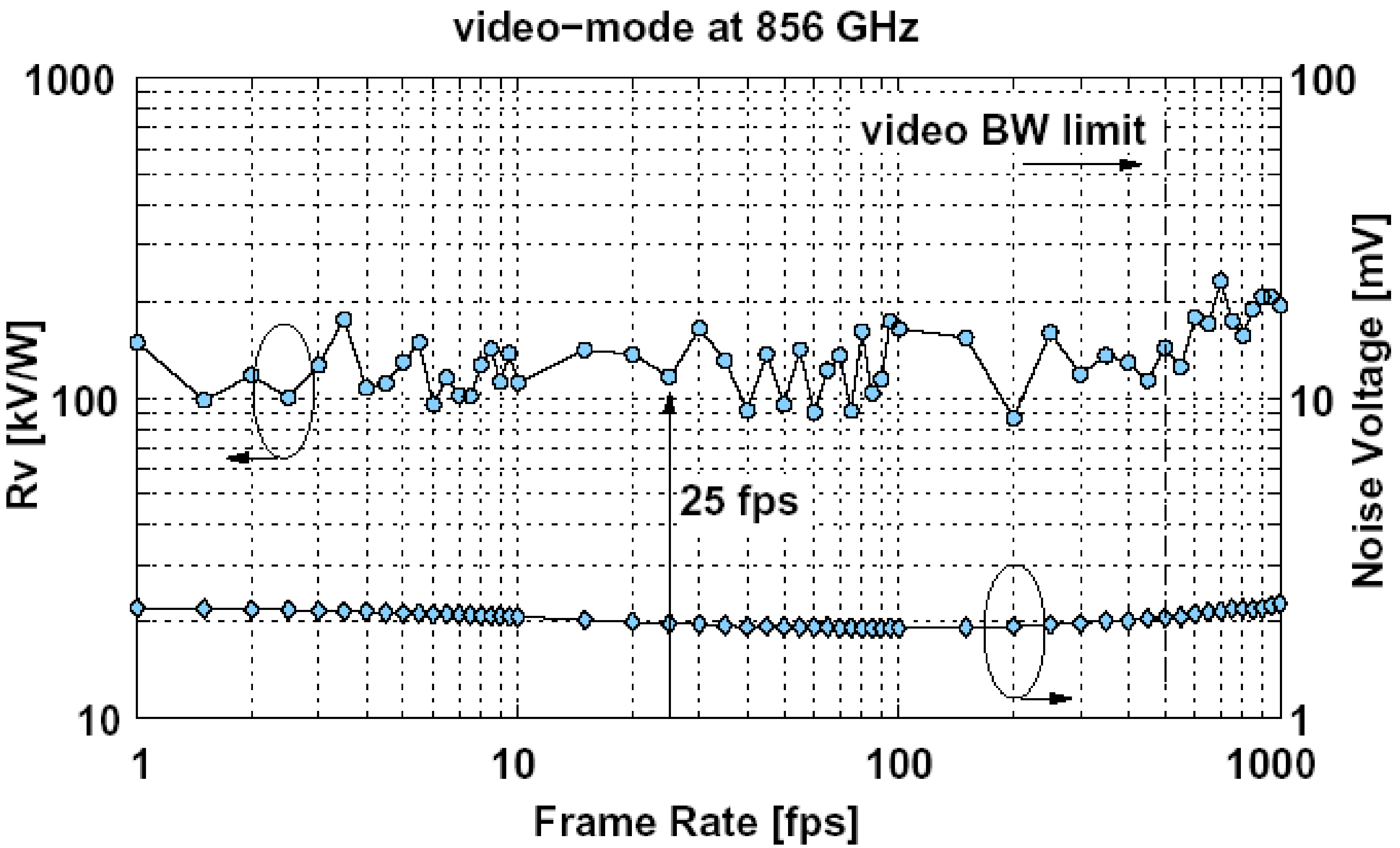
Measured RF Bandwidth



- Usable BW > 1 THz
- BW_{-10dB} = 400 GHz
- Total NEP = 3 nW @820 GHz, τ = 34 s (average over 1024 frames), 10-20 nW @ 30fps

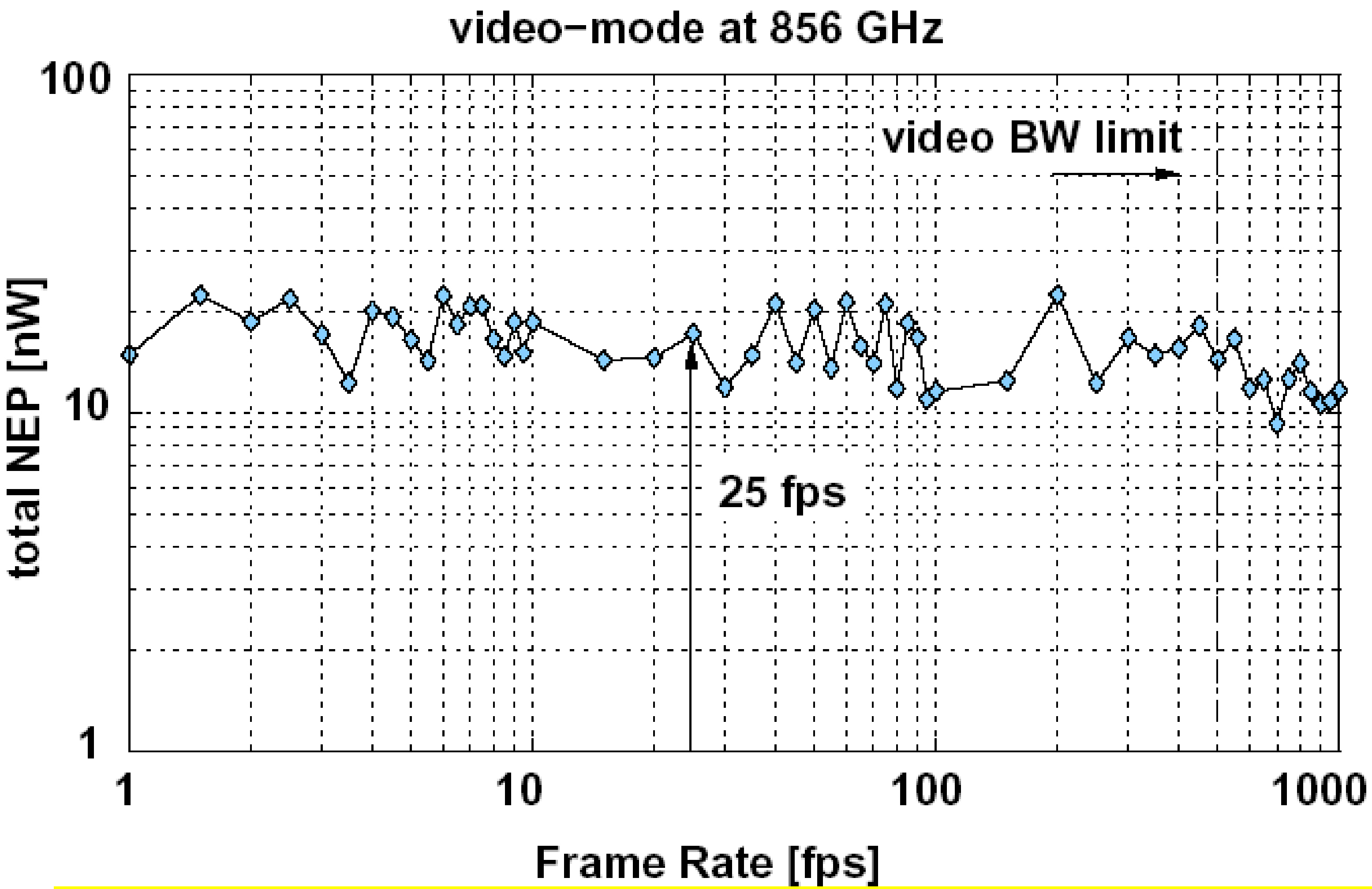


Responsivity of the camera in video mode (single-pixel)



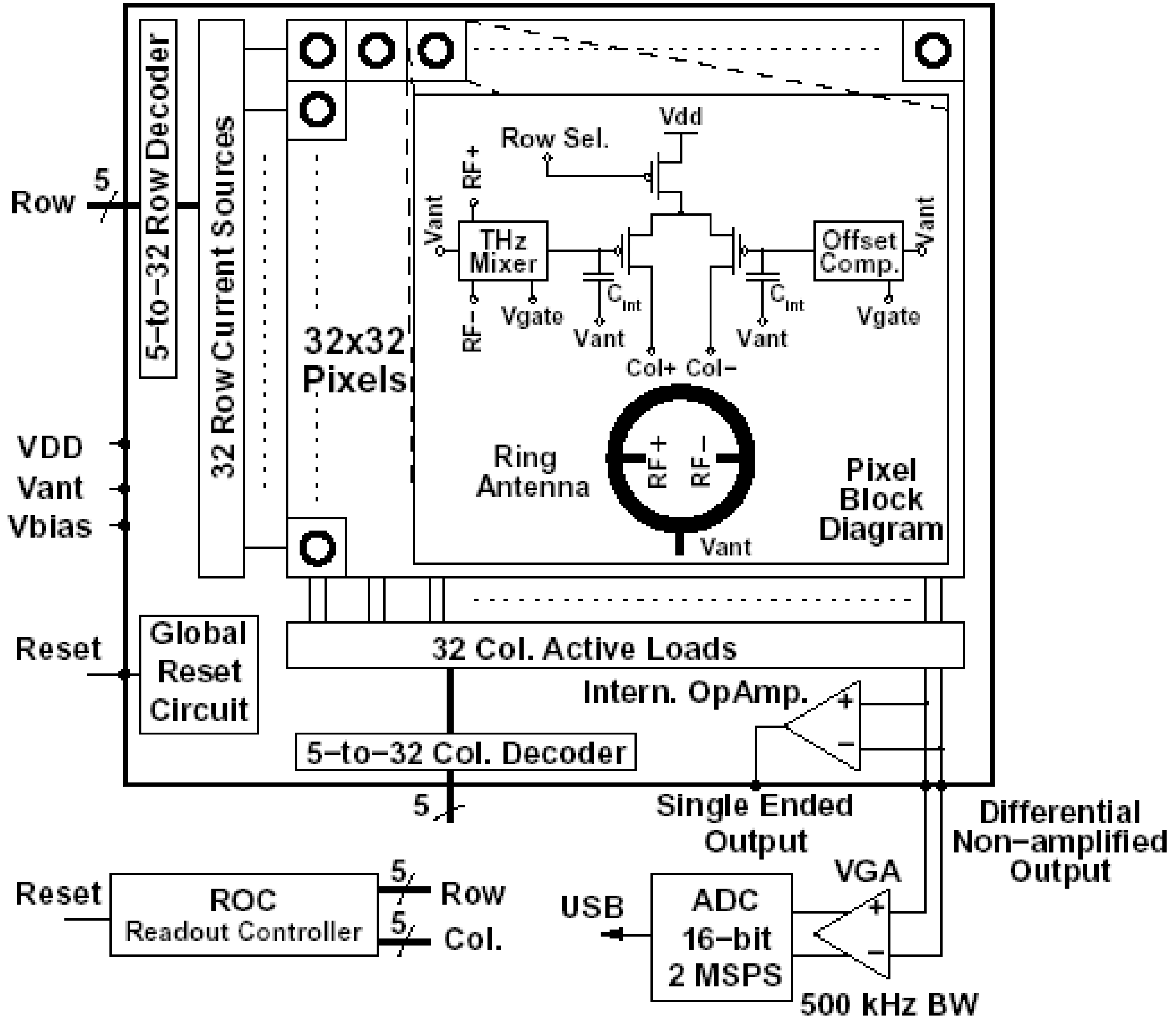
100-200 kV/W up to 500 fps

Total NEP of the camera in video-mode (single pixel)



Total NEP=10-20 nW up to 500 fps (no averaging)

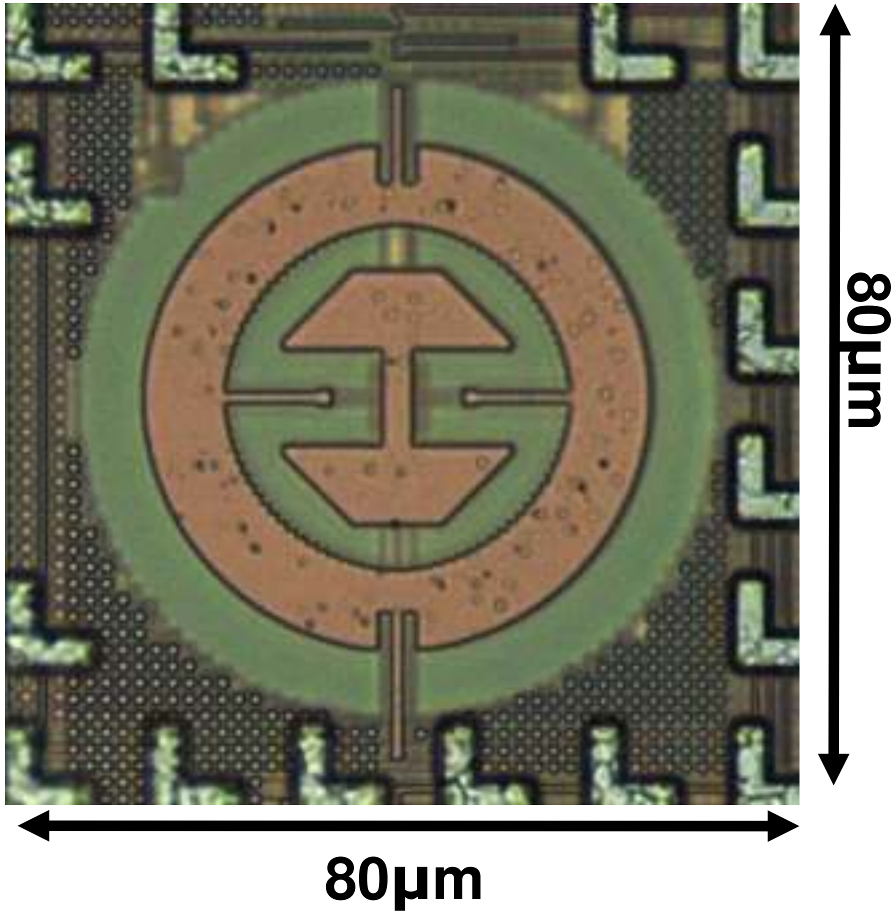
Camera Block Diagram



- No lock-in techniques
- zero-IF output
- integration capacitors per pixel
- 500 fps video-rate
- Columns share active loads

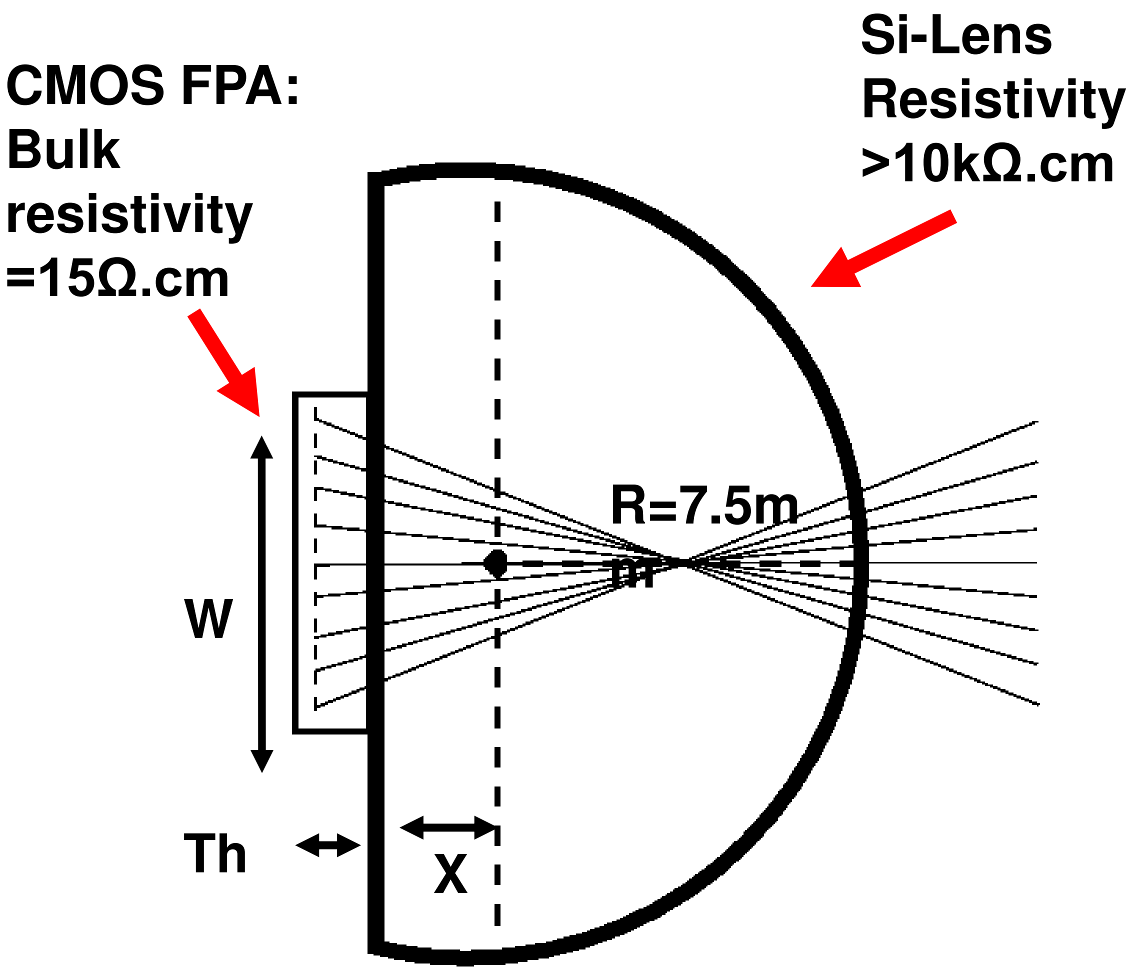
[1] R. Al Hadi et al „A 1 k-Pixel Video Camera for 0.7-1.1 Terahertz Imaging Applications in 65-nm CMOS“, Dec. 2012

Ring Antenna Design



- (HFSS) Simulated Rad. Efficiency 70-77% from 0.8 to 1THz (Semi-infinite high-res. Si through a 150µm thick 15Ω.cm Si)
- Illuminated from the back through a Silicon lens reduces Substrate-modes
- Complex conjugate matching to detector
- Fill Factor= 55%

Si Hyperhemispherical Lens Design

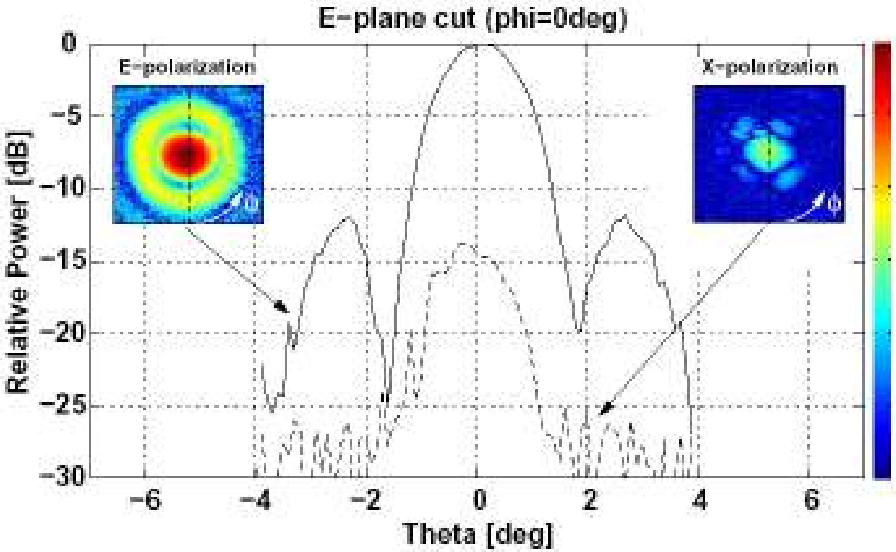


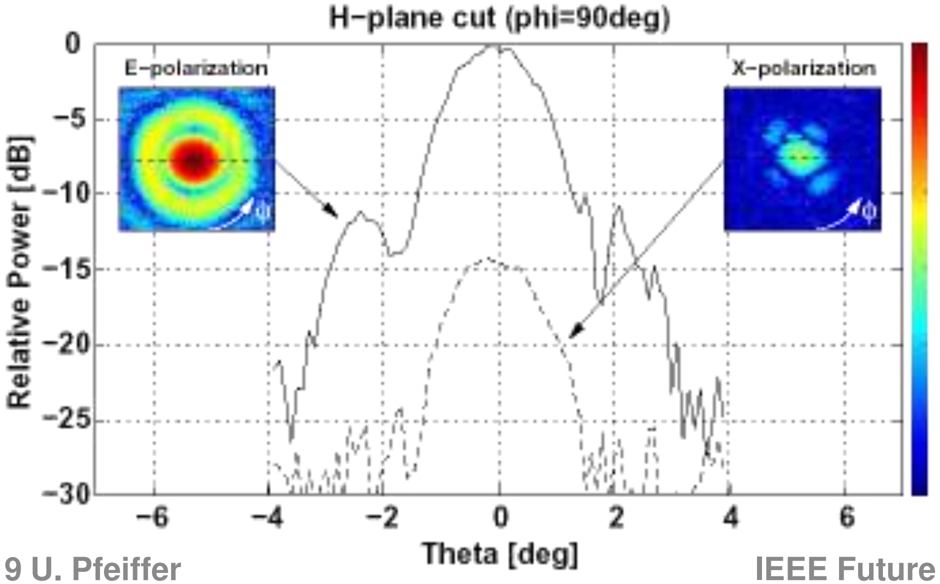
X+Th= 2.75mm

- X/R= 0.366
- W/R= 0.34
- F.O.V.= ±23° (experimentally verified)
- Residual 2-3 dB reflection loss

[1] D. F. Filipovic et al., IEEE Trans. Antennas and Propagation, 1997

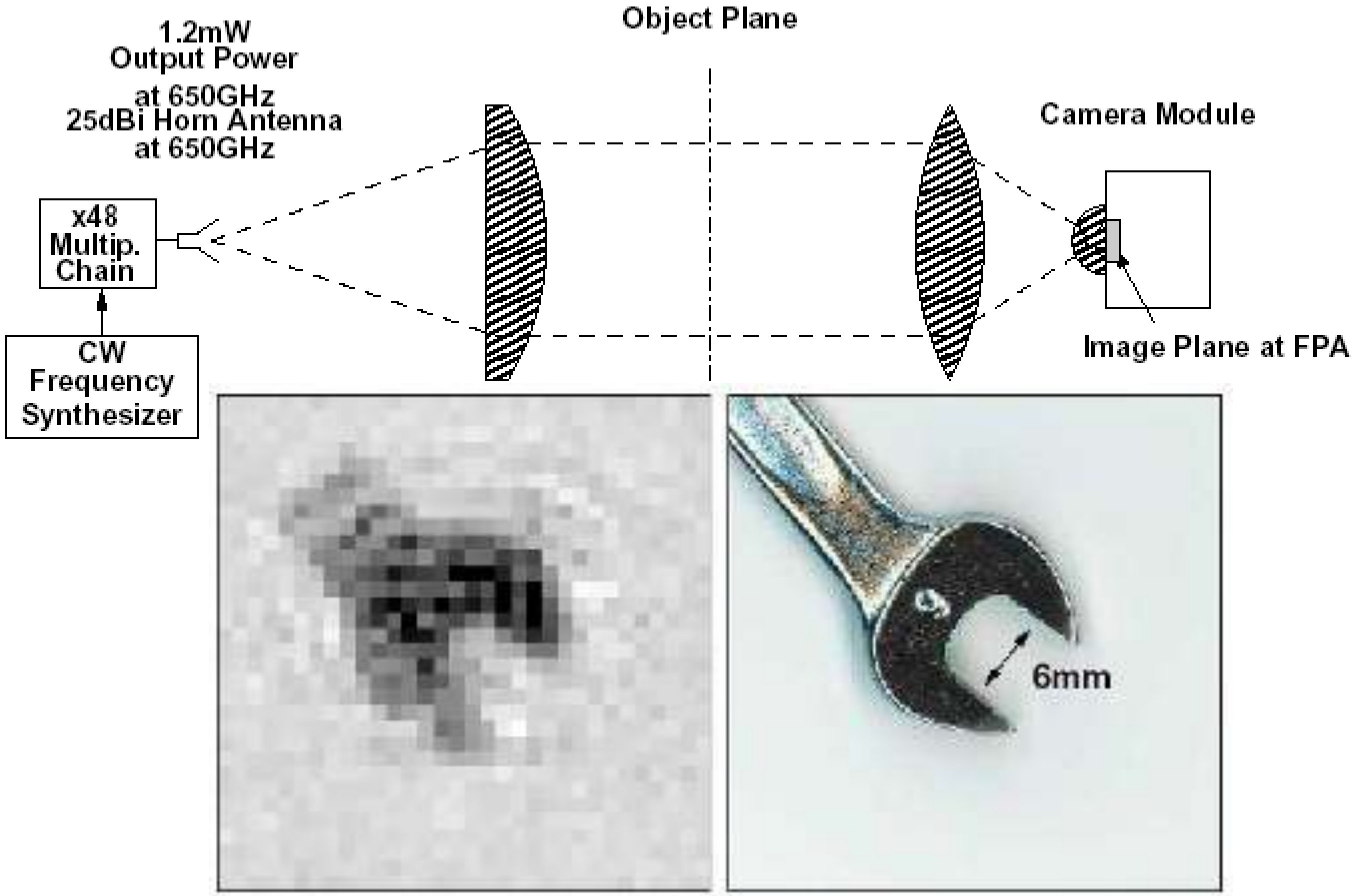
On-chip Antenna Radiation Patterns





- Measured antenna directivity is within 39.5-43.5 dBi between 650-1028GHz.
- We use the lens aperture as the collecting area (D = 15 mm) giving a directivity of 40.2-44.2 dBi between 650-1028GHz.
- ±23° Field of view
- Excelent uniformaty
- Side-lobes 15dB down

Focal-plane Imaging



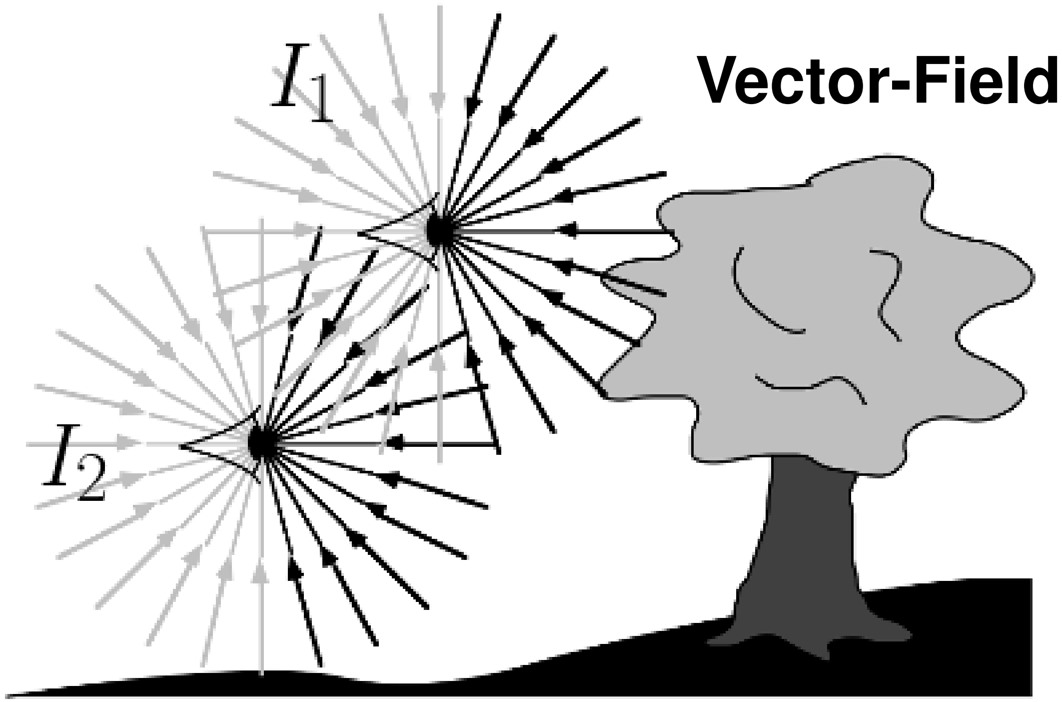
Source needs to illuminate whole object simultaneously

THz Light-Field Cameras
… even more pixels

Next step in this direction: Plenoptics

Plenoptic → Plenus ("full") + Optic

Full Light / Complete Light / All of Light



Vector-Field

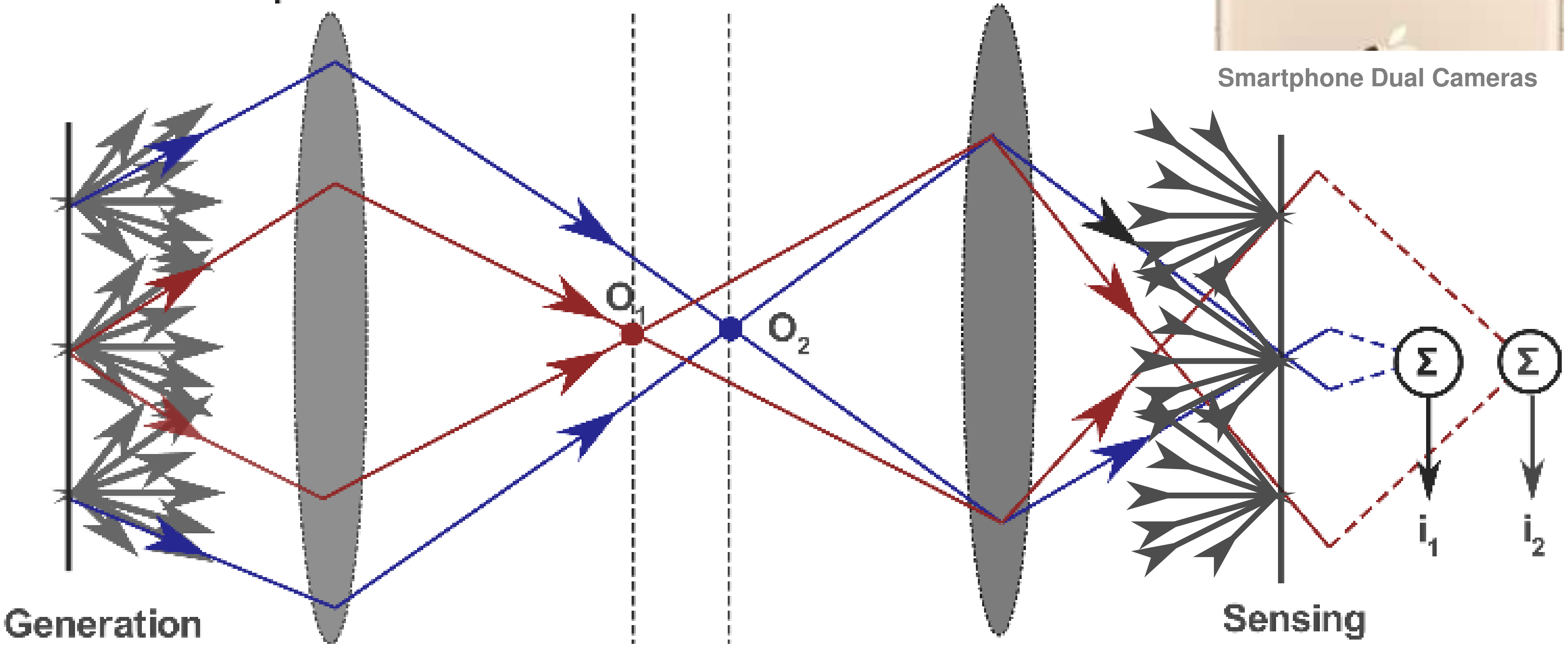
$$I_m = f(x, y, z, \theta, \phi, \nu, t, P, ...)$$

$$I_m = f(x, y, \theta, \phi)|_{z_o, v_o, t_o, P_o, ...}$$

- **4-D *Light-Field***
- **Common <u>computation method</u> in Optics**

[1] Adelson, et.al., The plenoptic function and the elements of early vision, 1991

THz Light-Field Example



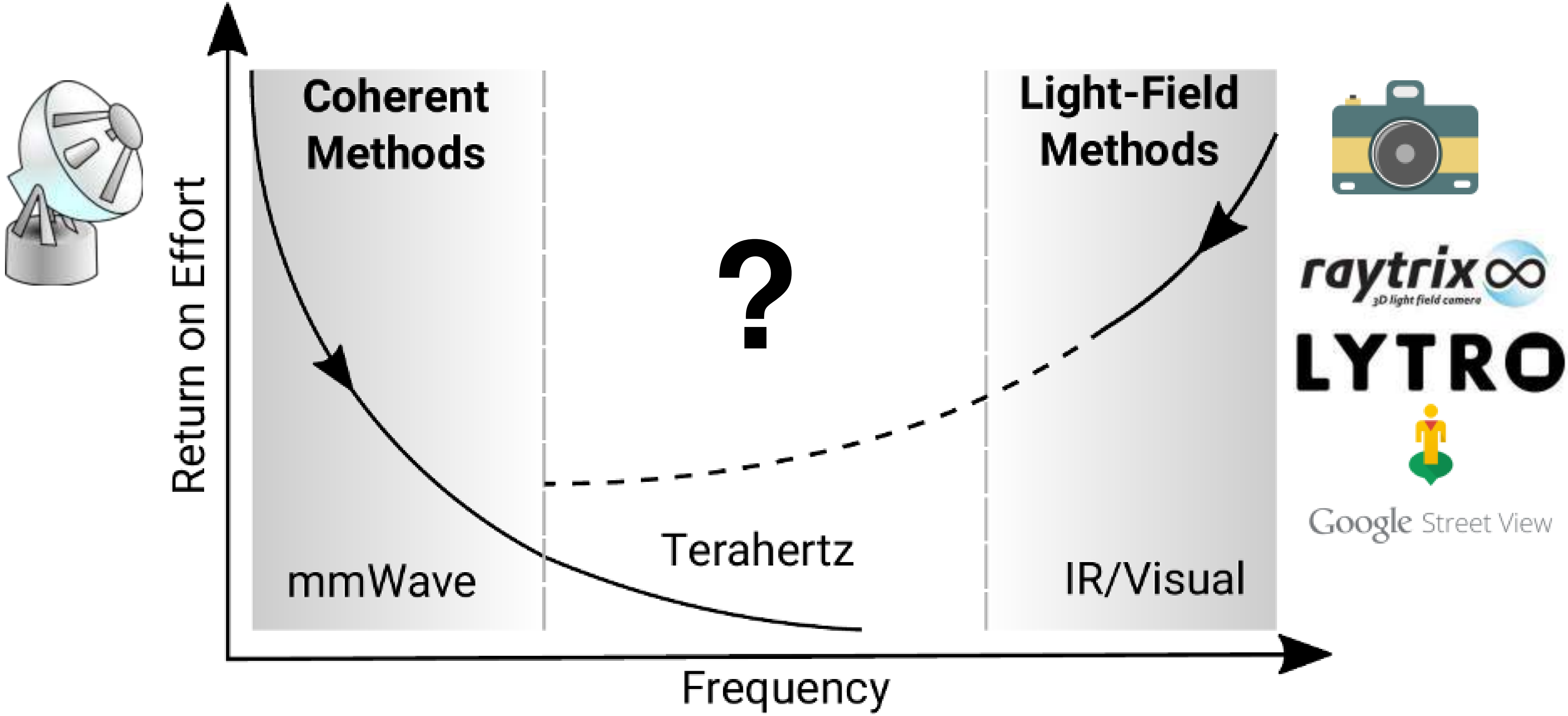
Smartphone Dual Cameras

Image: Stanford CGL

Separation of two occluded points in space

[1] R. Jain et.al., Terahertz light-field imaging, T-TST 2016

Coherent vs. Incoherent Methods



THz Illumination

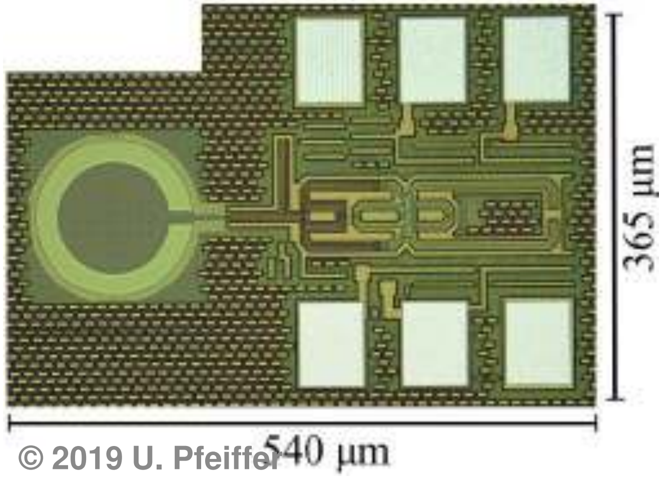
Improve performance (Devices to Components)

ST 65nm bulk CMOS

ticwave
the next generation of terahertz

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

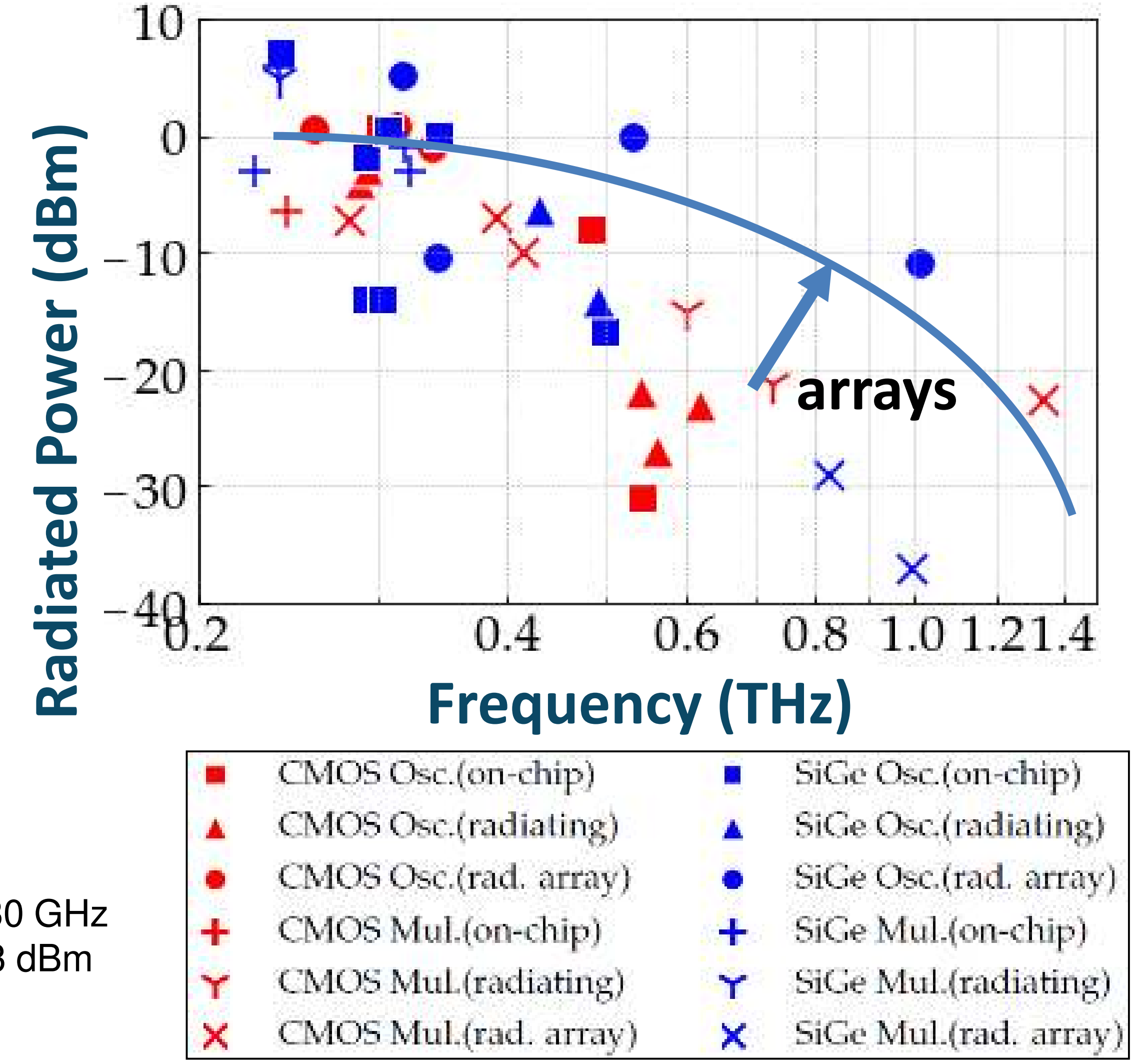
IHP 130nm SiGe



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

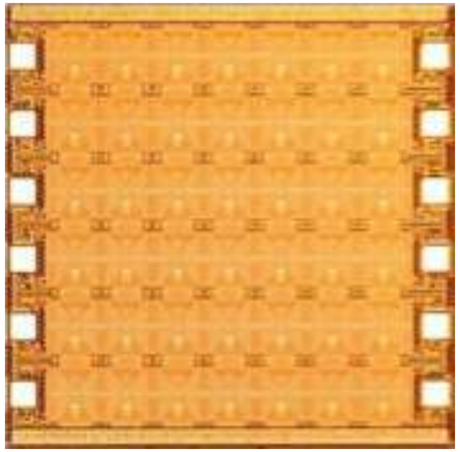
[1] P. Hilger, A Lens-Integrated 430 GHz SiGe HBT Source With Up to -6.3 dBm Radiated Power, RFIC 2017

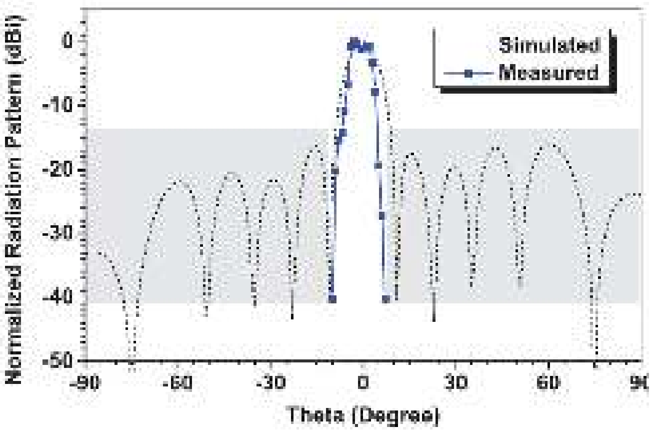
Sources (CMOS/SiGe)



Silicon Source Arrays (Coherent vs. Incoherent)

Coherent Radiators





91 elements

OSC 4-push

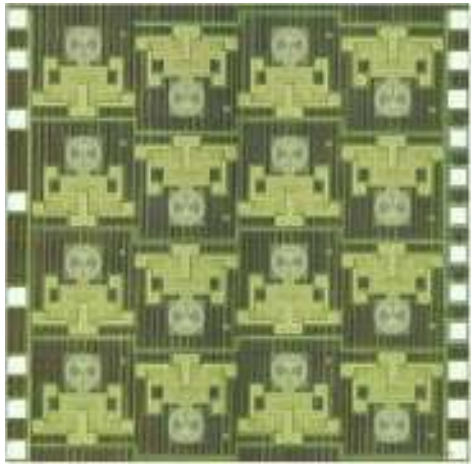
-10.9dBm @ 1.01 THz

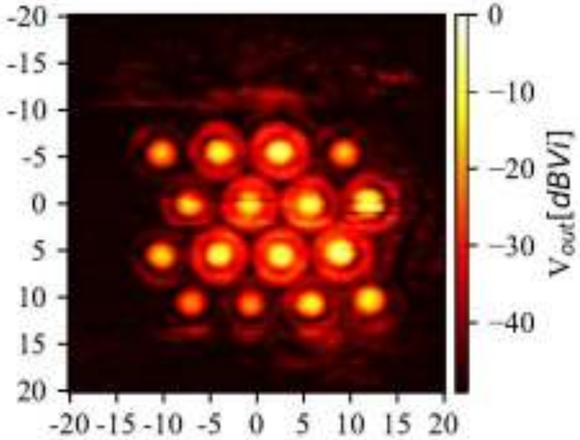
DC to RF: 0.0073%

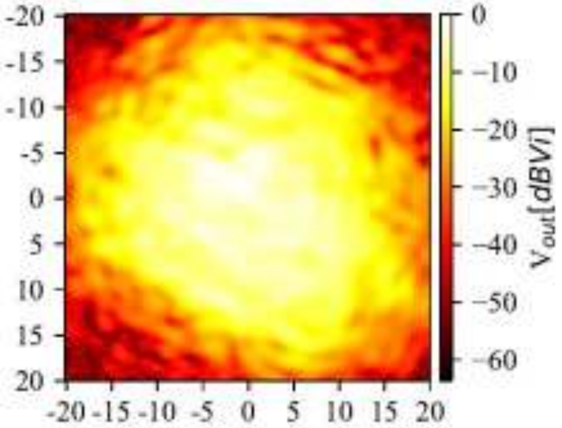
IHP 130nm SiGe

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

Incoherent Radiators







16 elements

OSC 3-push

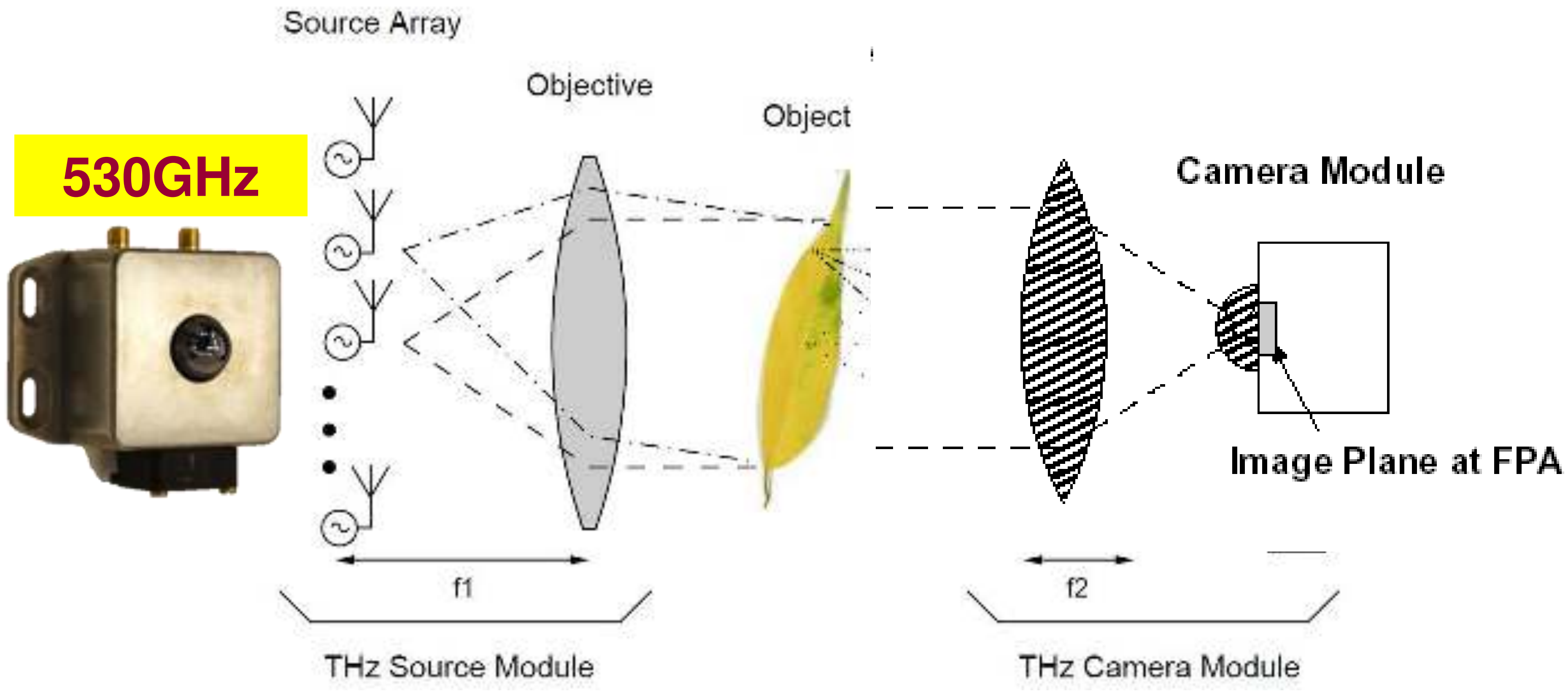
0dBm@530GHz

DC to RF: 0.04%

IHP 130 nm SiGe

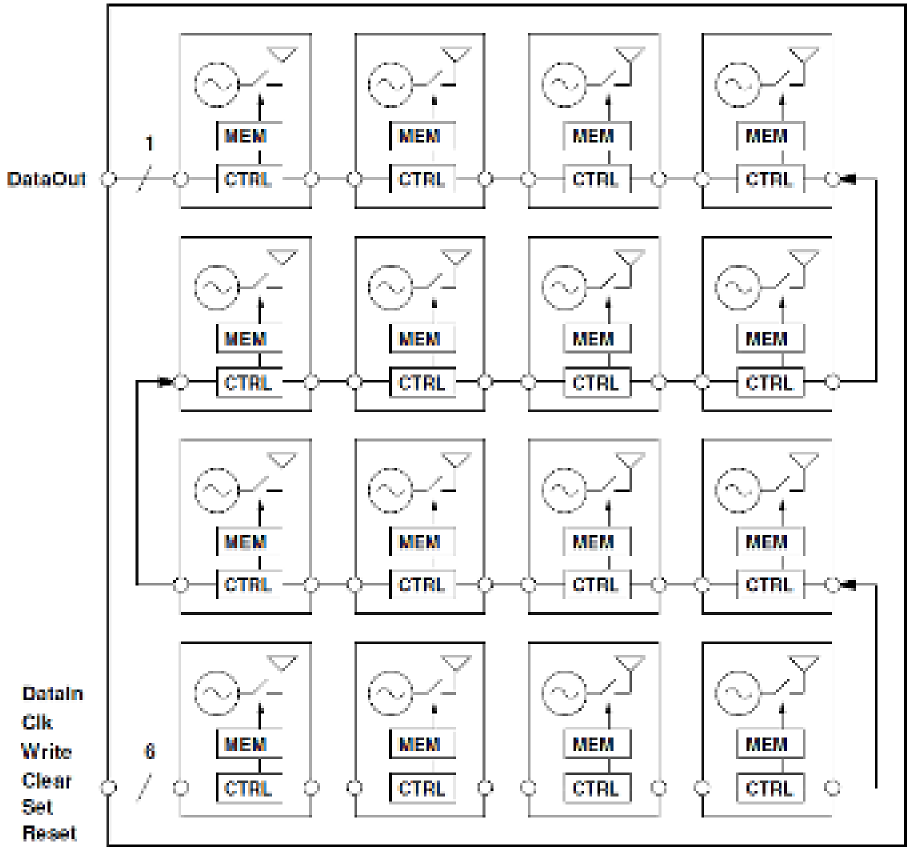
[1] U. Pfeiffer, et al., A 0.53 THz reconfigurable source module with up to 1 mW radiated power for diffuse illumination in terahertz imaging applications, JSSC 2014

Diffuse THz Illumination



Stochastically independent source pattern destroys illumination phase coherence

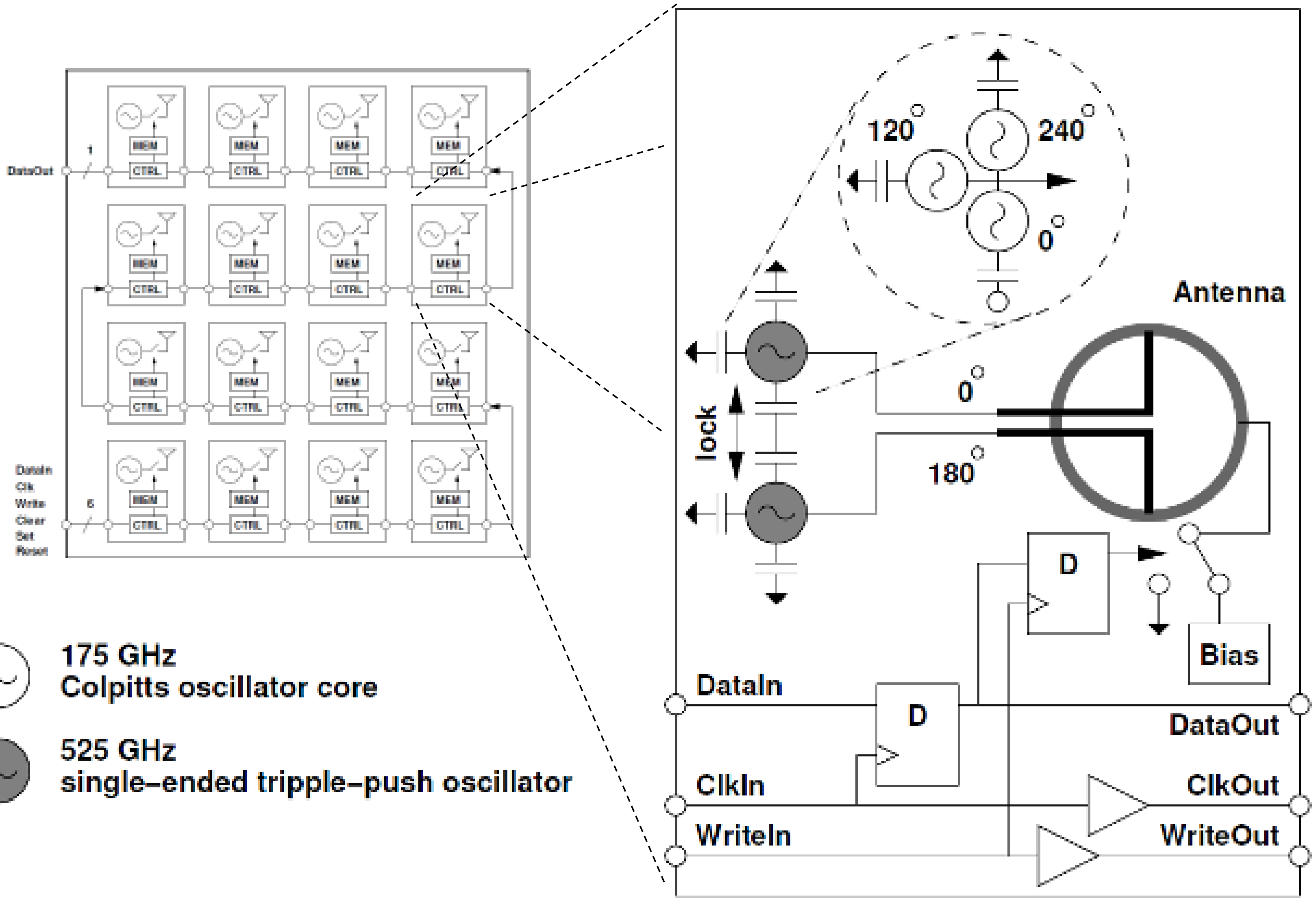
Circuit Block Diagram



[1] U.R. Pfeiffer at al, „A 0.53 THz Reconfigurable Source Module With Up to 1 mW Radiated Powerfor Diffuse Illumination in Terahertz Imaging Applications“, JSSC Oct. 2014

- 4x4 pixel source array with adjustable lighting condition
- Synchronous latched shift register in meander-type structure
- Circuit layout scalable in size and output power
- 16 output registers drive TPO power-down switch, configurable at runtime
- Fully integrated including on-chip antennas

Source Pixel Block Diagram



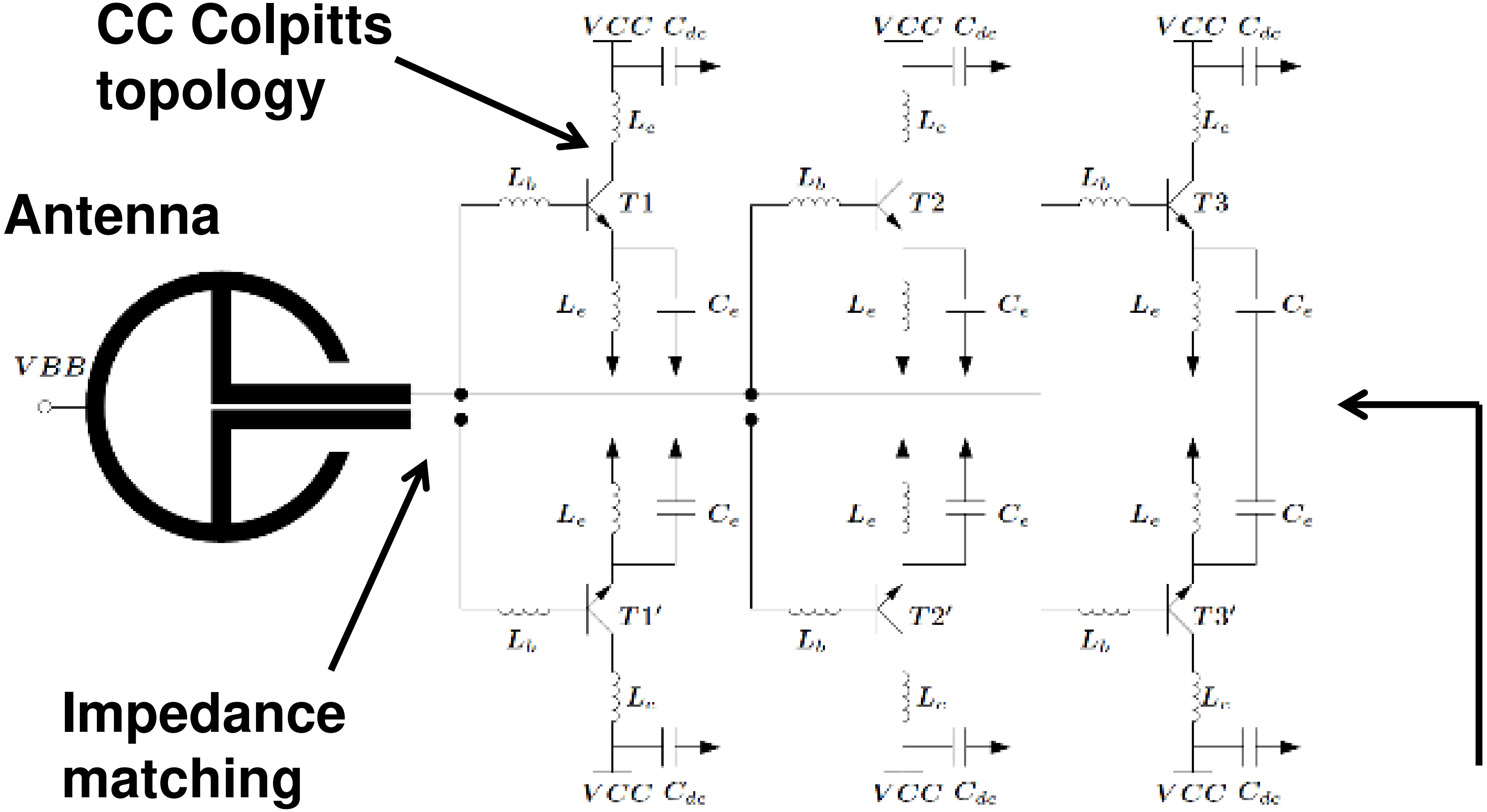
175 GHz
Colpitts oscillator core

525 GHz
single–ended tripple–push oscillator

Core TPO Circuit Schematic

CC Colpitts topology

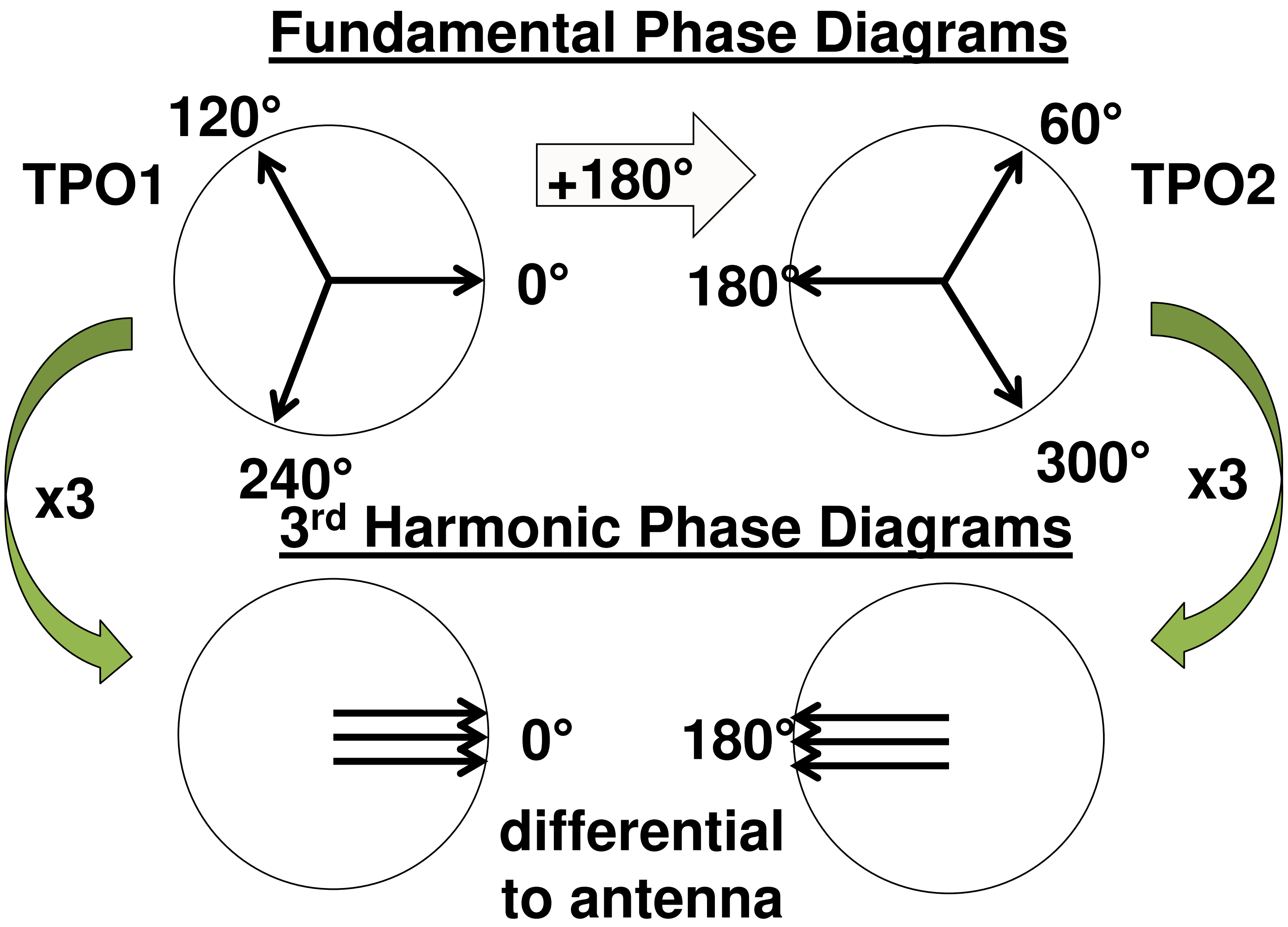
Ring Antenna



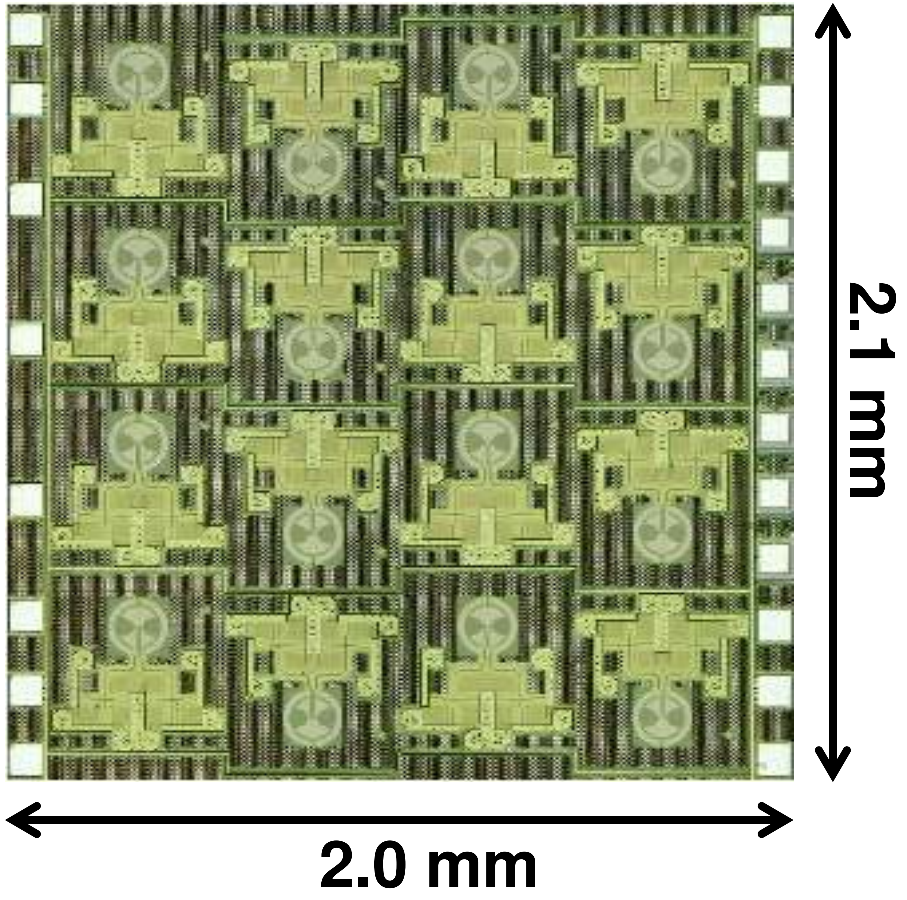
Impedance matching network

Two TPOs locked 180deg out of phase to drive antenna

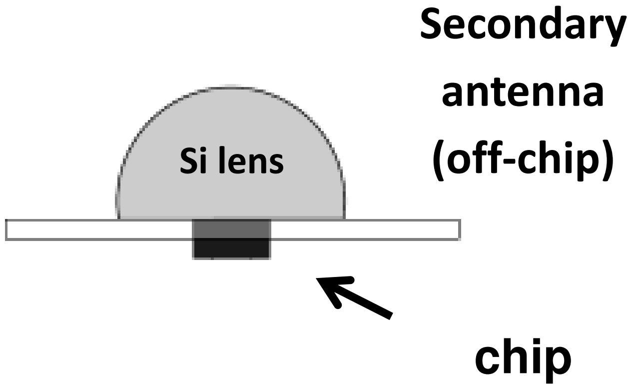
Illustration of the Locking Method



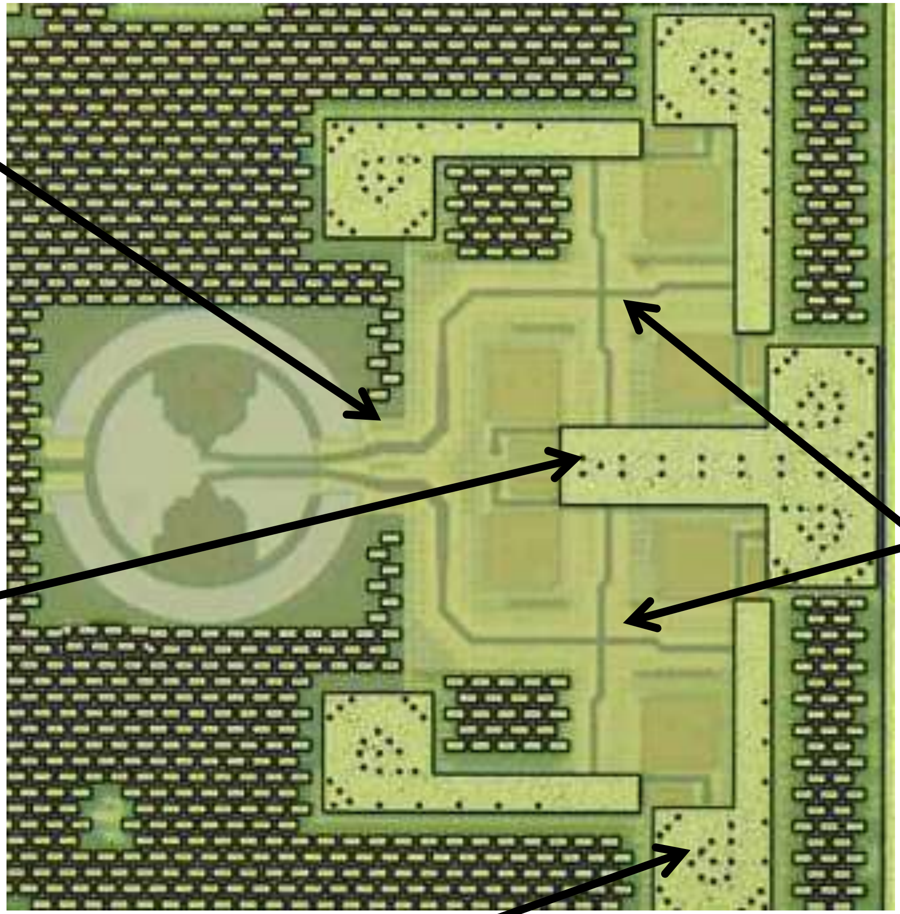
Chip Micrograph



- Honeycomb tessellation to save die area
- Total die area of 2x2.1mm2 for all 16 source pixel
- 510µm pitch



Single Source Pixel Micrograph



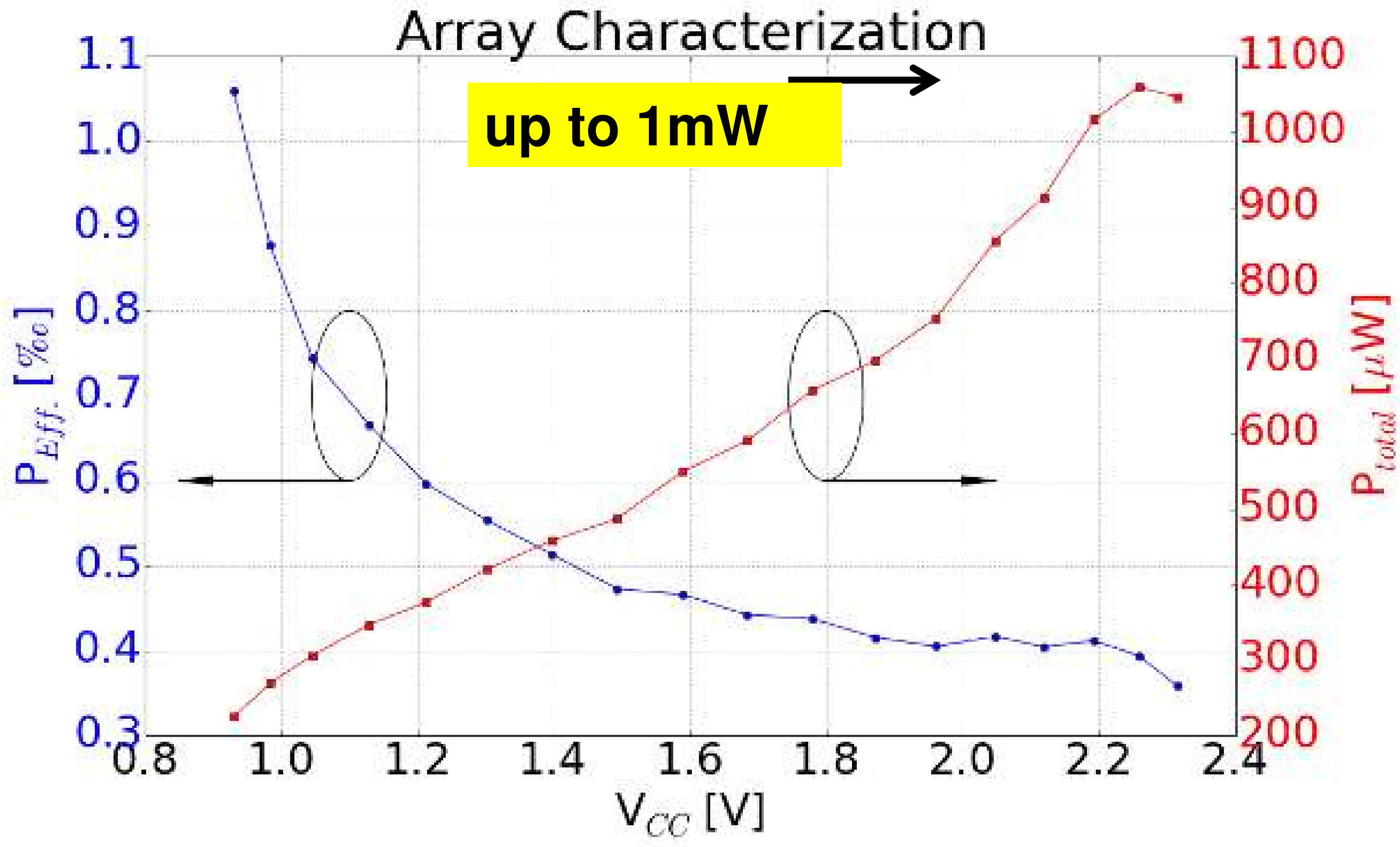
Tapered line used for impedance matching at 3rd harmonic

Locking cap (Ce)

TPO output nodes

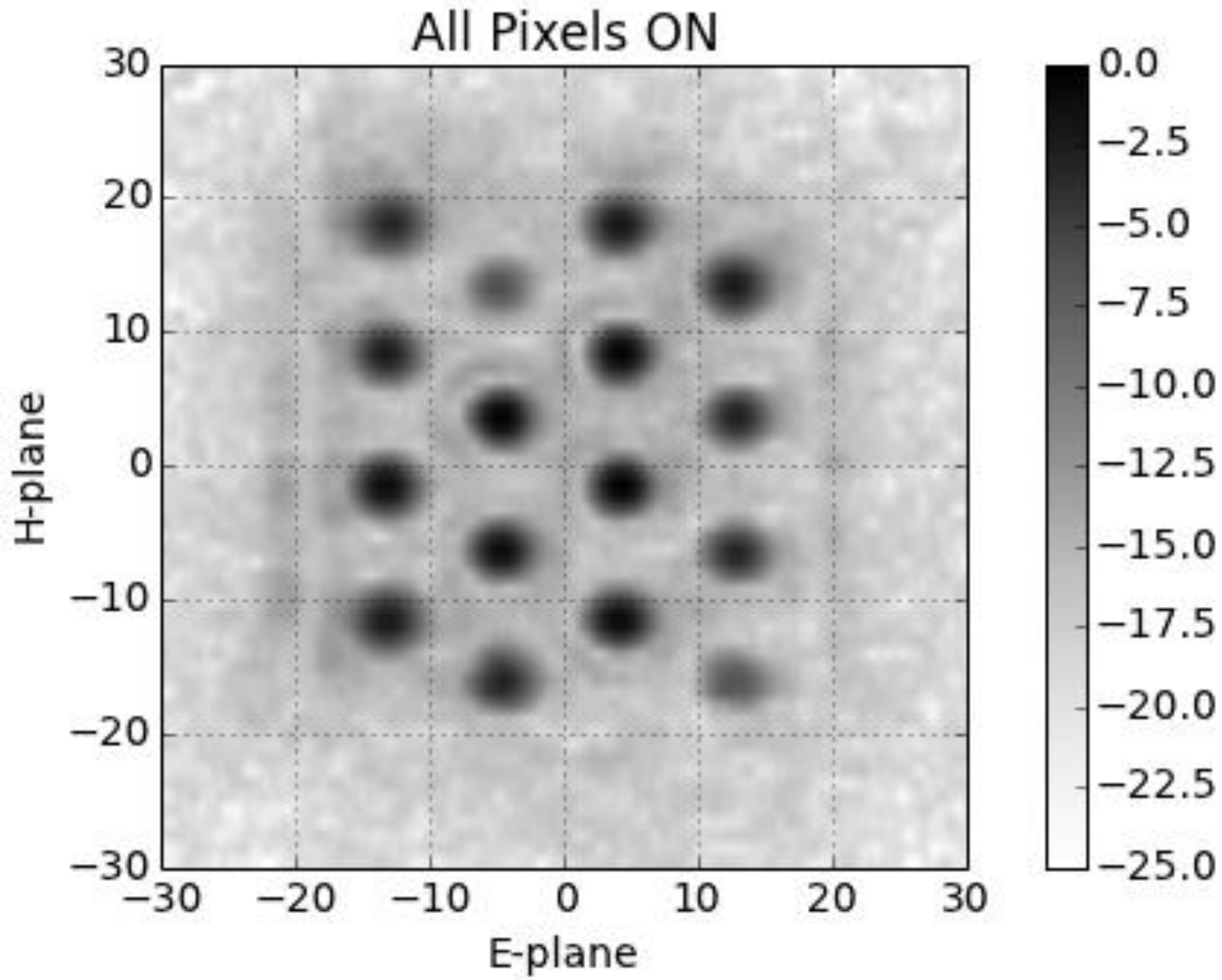
Le (RF choke)

Measured Total Power (all on)



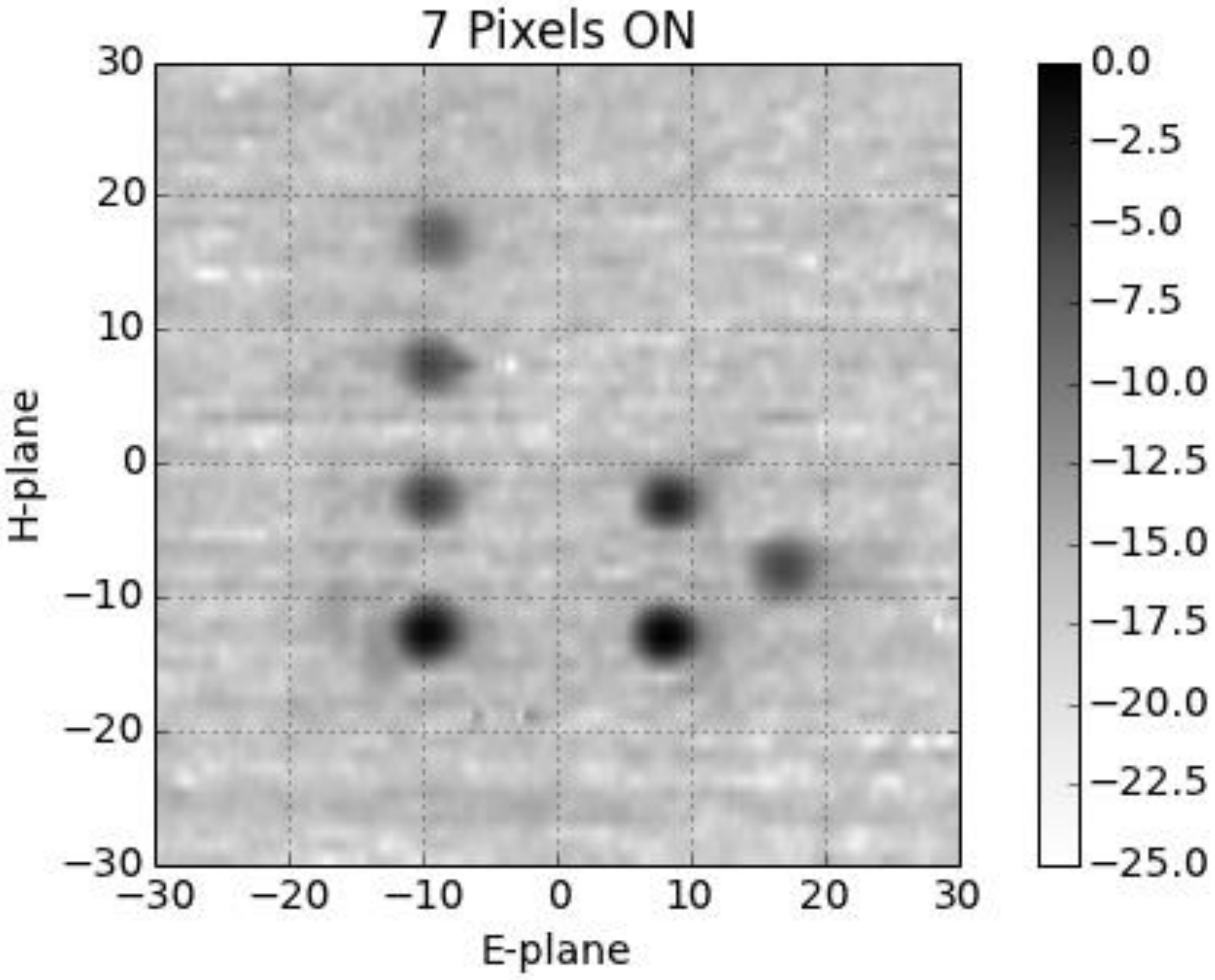
- Full array can deliver up to 1mW (0dBm) RF power
- DC to RF conversion efficiency is 0.4 to 1‰
- Draws up to 2.5W from a 2.5V supply

Measured Antenna Patterns



- Pattern depend on the secondary antenna
- Other lenses can be used to fit application requirements
- Side lobes are 15dB down
- Loaded source configurations for 16, 7, 4, and 1pixel
- Power down switching time is 0.5ns
- 16 beams cover a ±15º field-of-view

Measured Antenna Patterns



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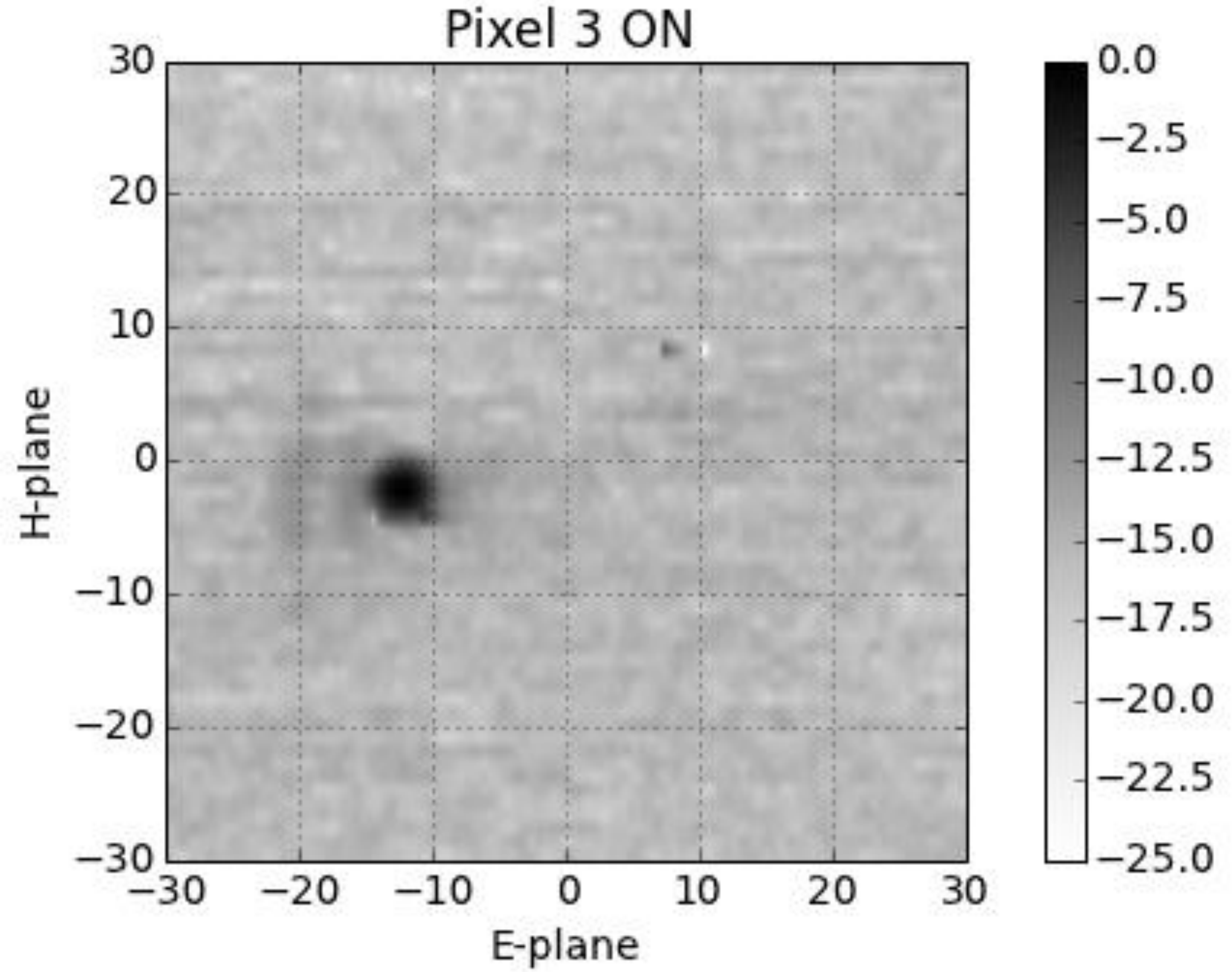
Measured Antenna Patterns



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- Other lenses can be used to fit application requirements
- Side lobes are 15dB down
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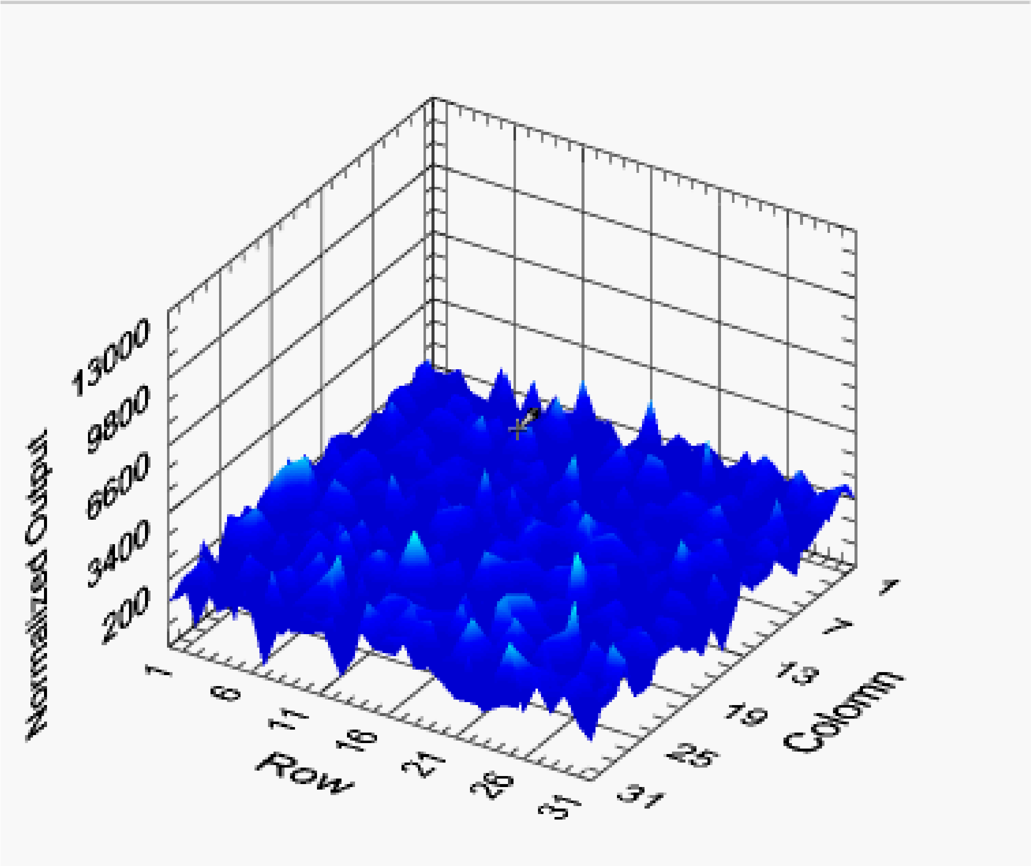
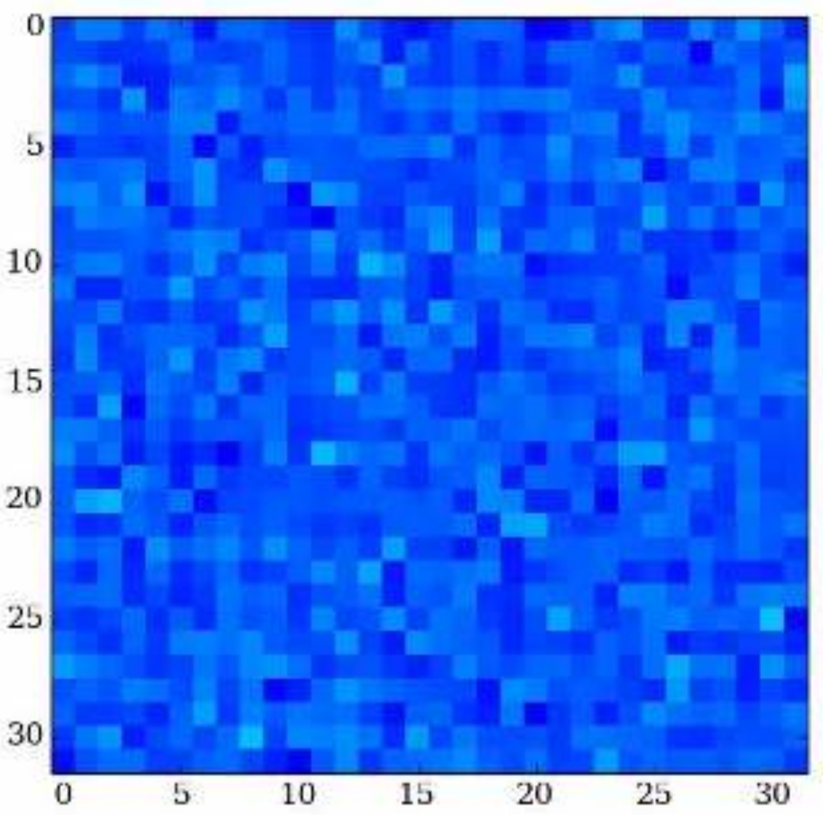
- Power down switching time is 0.5ns
- 16 beams cover a ±15º field-of-view

Recorded Illumination

Single beams

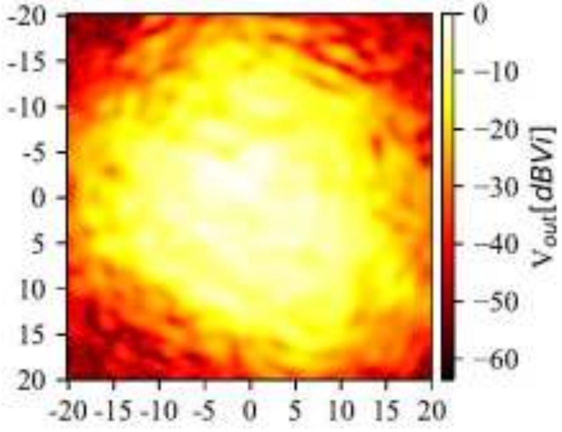


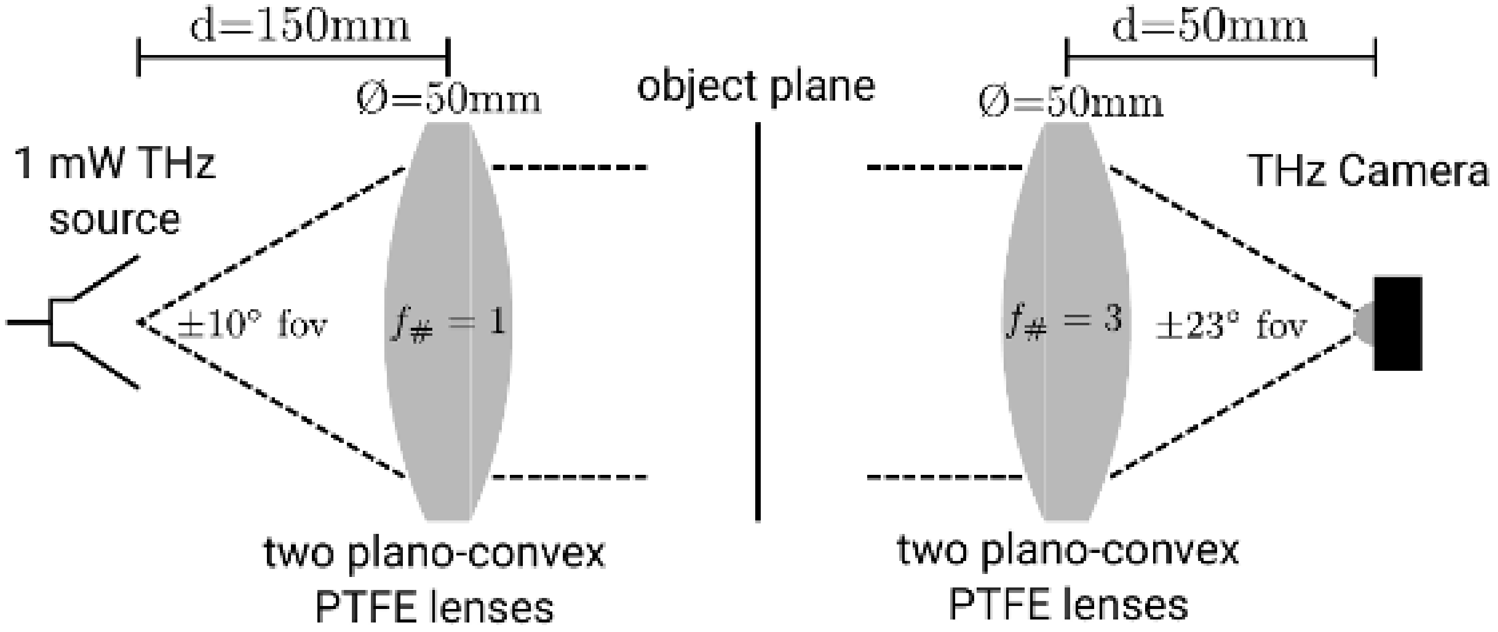
Diffused background

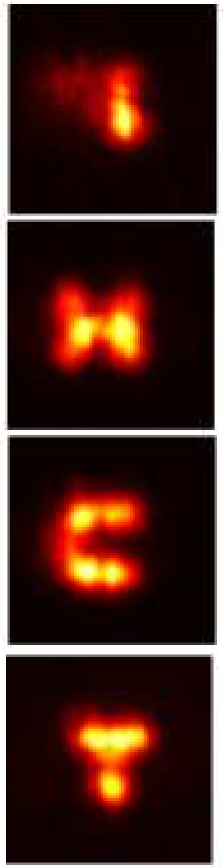


Diffused Illumination

1mW ½ THz diffuse illumination



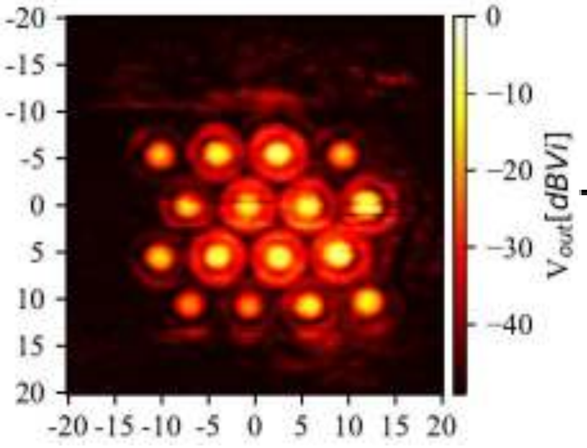


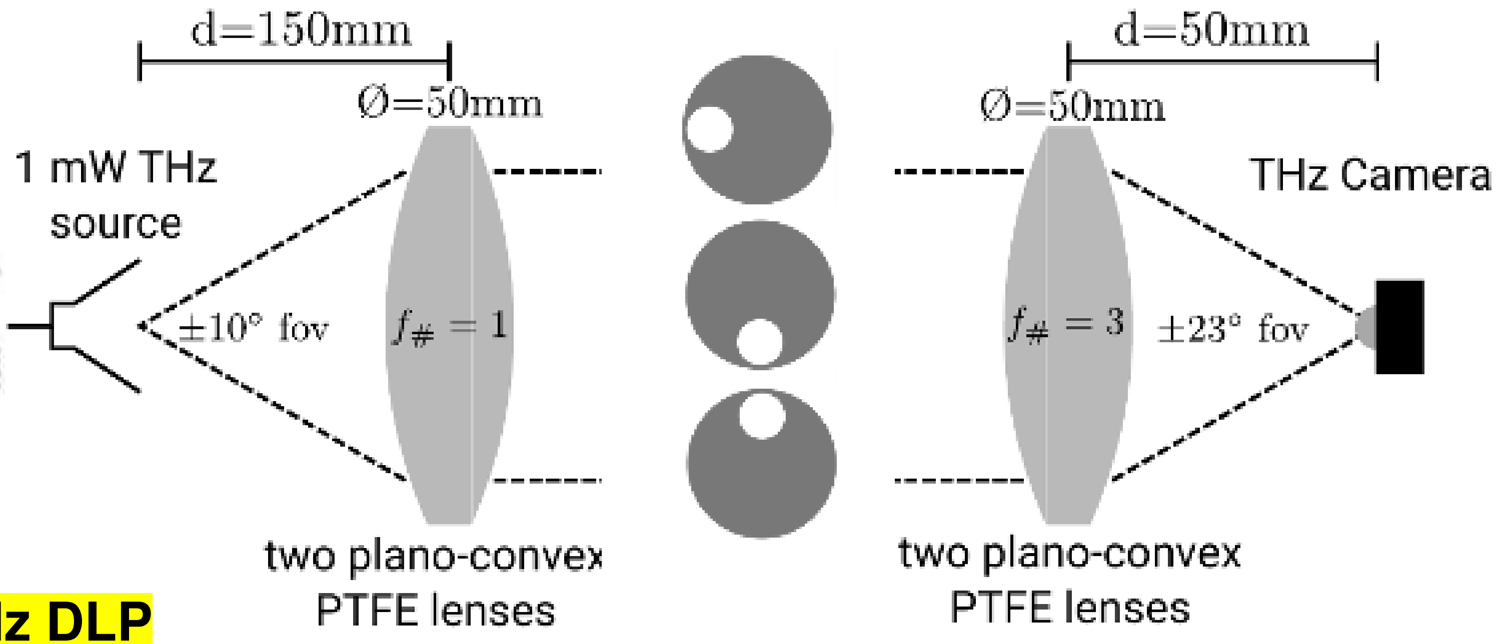


[1] D. Headland et.al., Diffuse beam with electronic terahertz source array, IRmmW-THz 2018

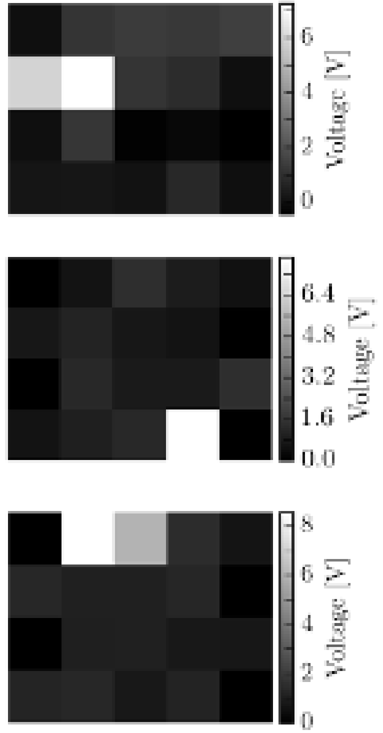
Computational Imaging and Diffused Illumination

1mW ½ THz digital light processor

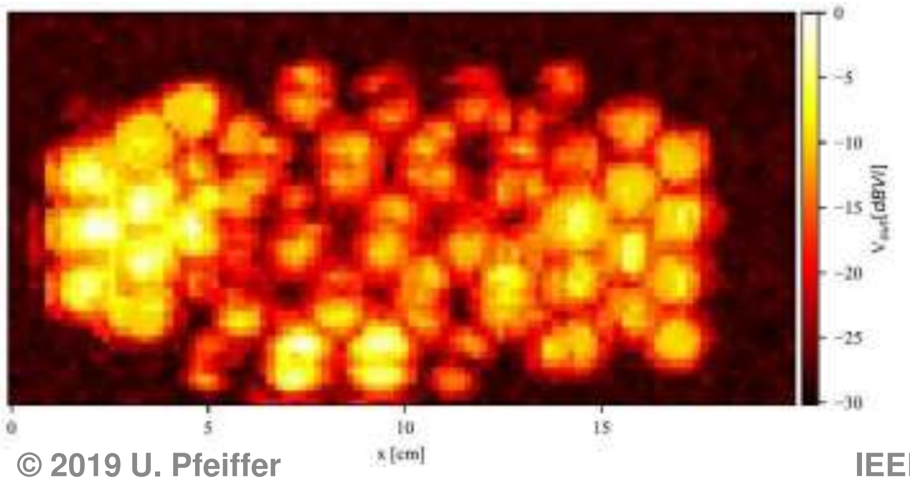




Computational imaging



4mW 62 pixel THz DLP



On-the-fly APEG-LDPC sensing matrix generation, OMP reconstruction

– Compression ratio ≤ 50%

[1] P. Hilger et.al., Terahertz Imaging and Sensing Applications With Silicon-Based Technologies, submitted T-TST 2018

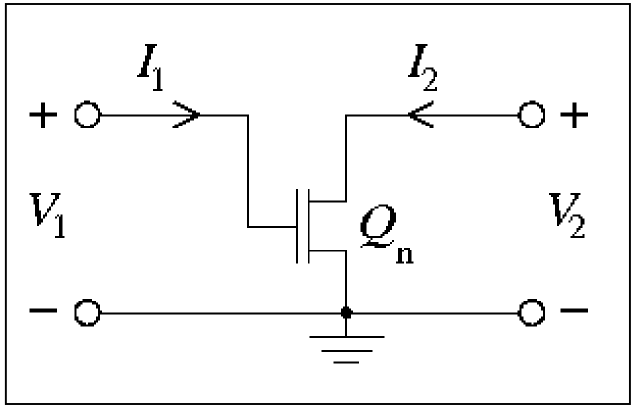
[2] M.H. Conde et.al. Simple adaptive progressive edge-growth construction of LDPC codes for close(r)-to-optimal sensing in pulsed ToF. Int. WS on Compressed Sensing, 2016

CMOS sources

Triple-Push Topology

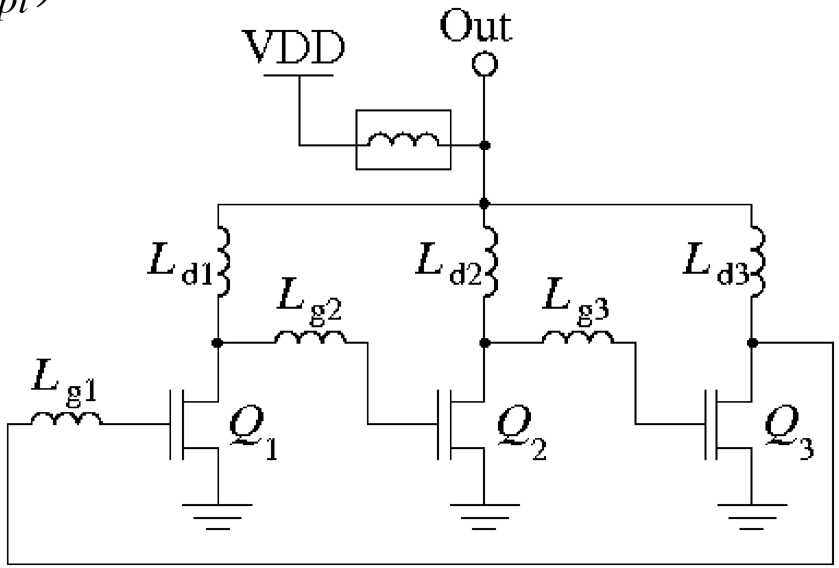
3-stage ring in CMOS achieves the maximum oscillation frequency [1]

$$A = \frac{|V_2|}{|V_1|} \quad \phi = \angle \frac{V_2}{V_1} \quad G_m\big|_{\max} @(A_{opt}, \phi_{opt})$$



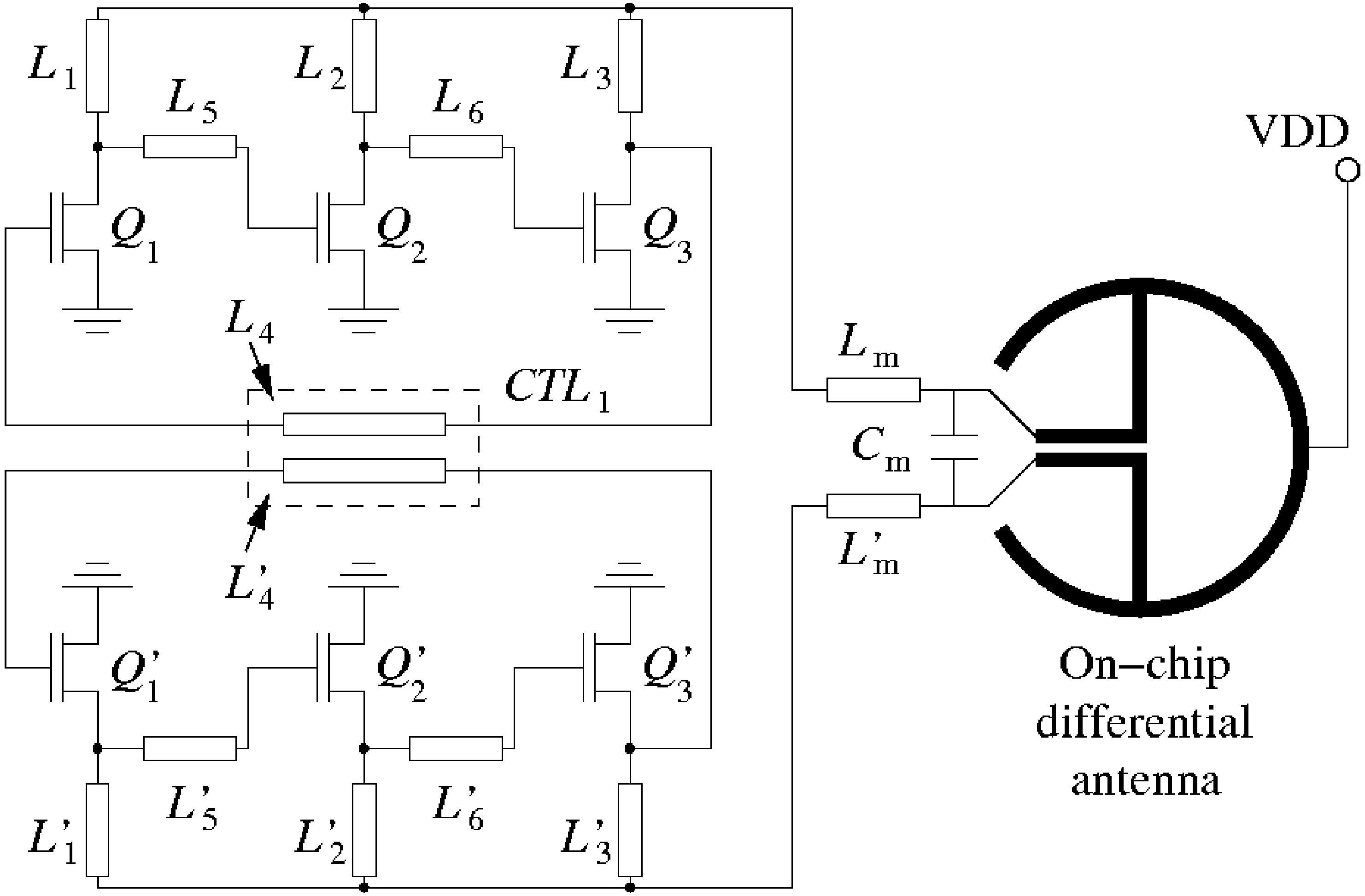
Optimization for high power harmonic generation by adding an extra gate inductor

Drawback: single-ended output



[1] O. Momeni and E. Afshari, "High power terahertz and millimeter-wave oscillator design: A systematic approach," JSSC, vol.46, no.3, pp.583–597, 3.2011

Balanced Triple-Push Sources in CMOS

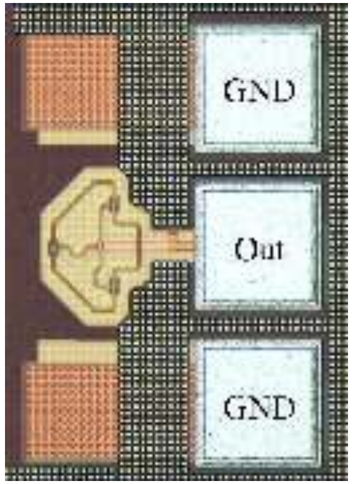


- **Two identical ring oscillators mutually locked out-of-phase by magnetic coupling between one pair of gate inductors**
- **The length of L4 and L4' are fine tuned**

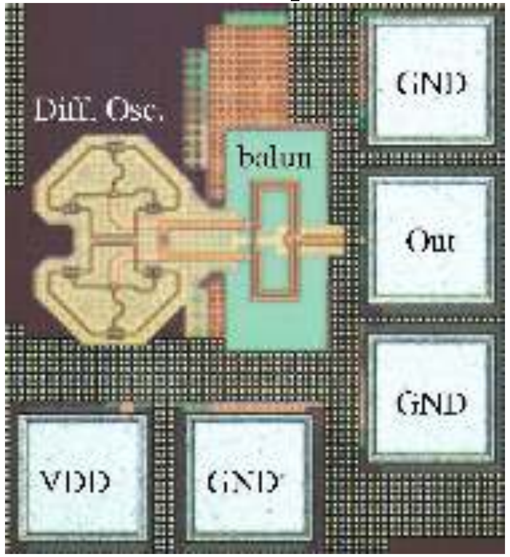
[1] Yan Zhao, Janusz Grzyb, and Ullrich R. Pfeiffer, A 288-GHz Lens-Integrated Balanced Triple-Push Source in a 65-nm CMOS Technology, ESSCIRC 2012

Chip Micrographs

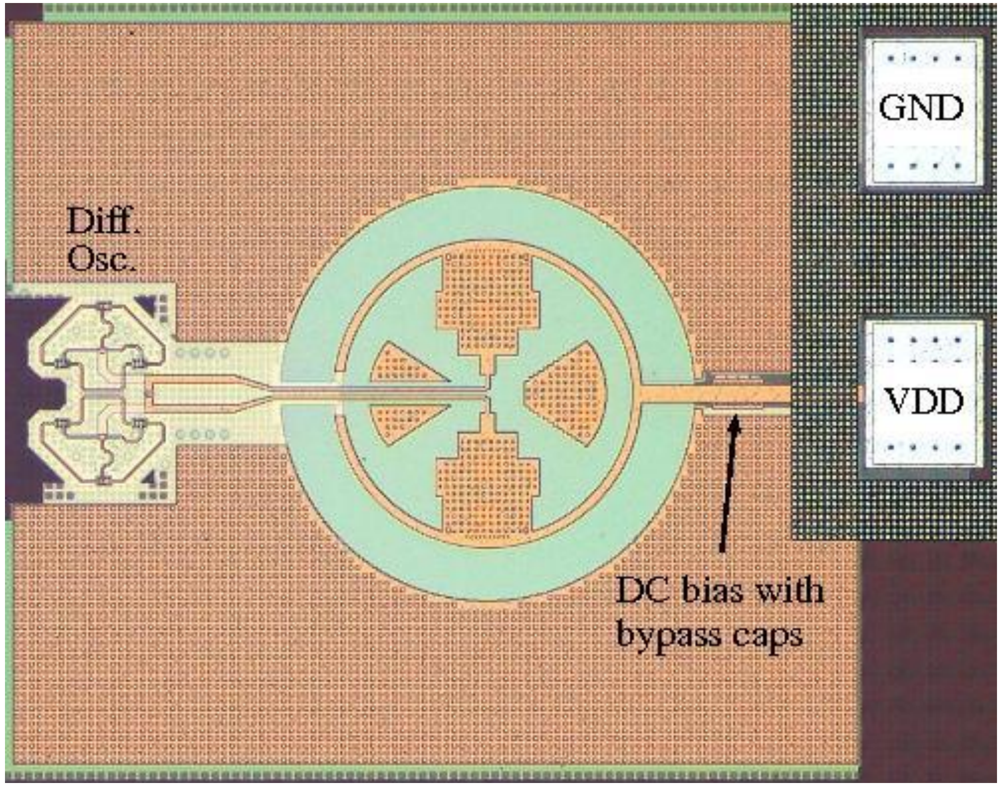
Single oscillator



Balanced oscillator (core: 120x150μm^2)



Balanced Source incl. ant. (500x570μm^2) (no pads)



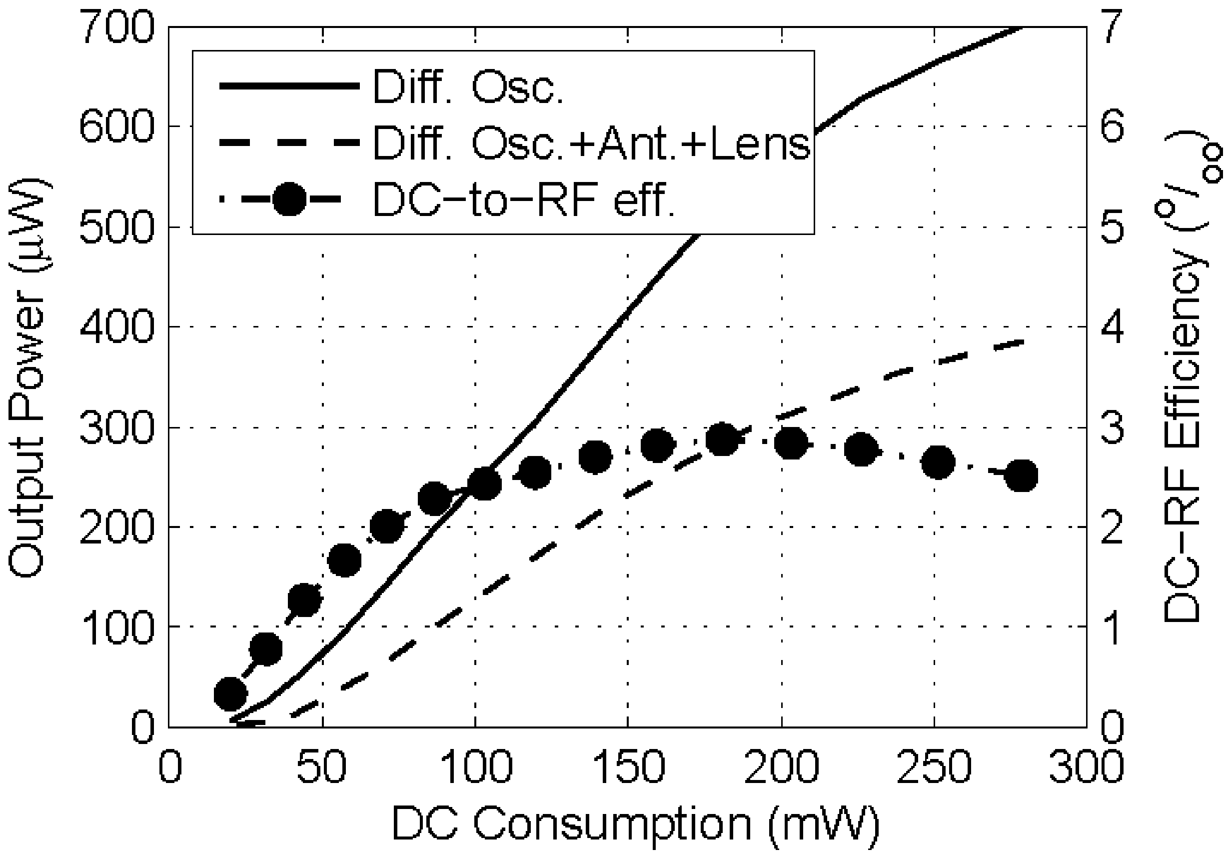
Measured Output Power

Max Pout on wafer:
700 µW (-1.5 dBm)

Max Pout (free space): 390 µW (-4.1 dBm)

EIRP= 14.2 dBm

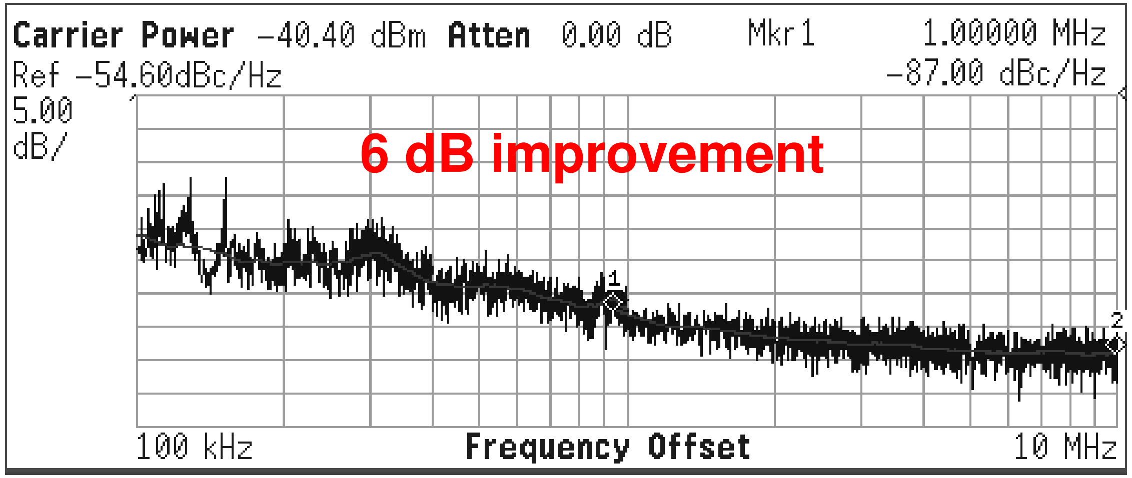
Max DC-to-RF efficiency:
2.9 ‰



Measured Phase Noise

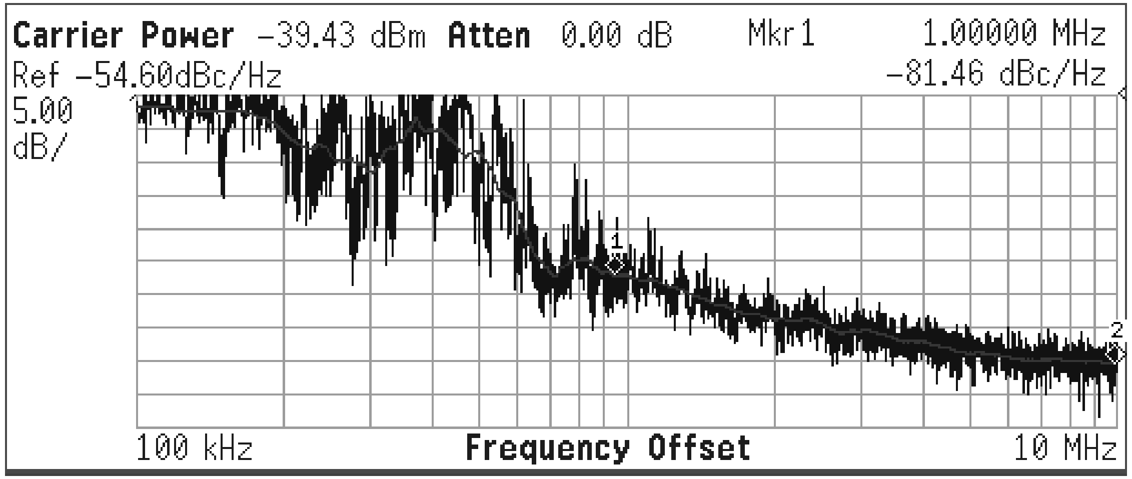
Double osc.:

-87 dBc/Hz @1 MHz



Single osc.:

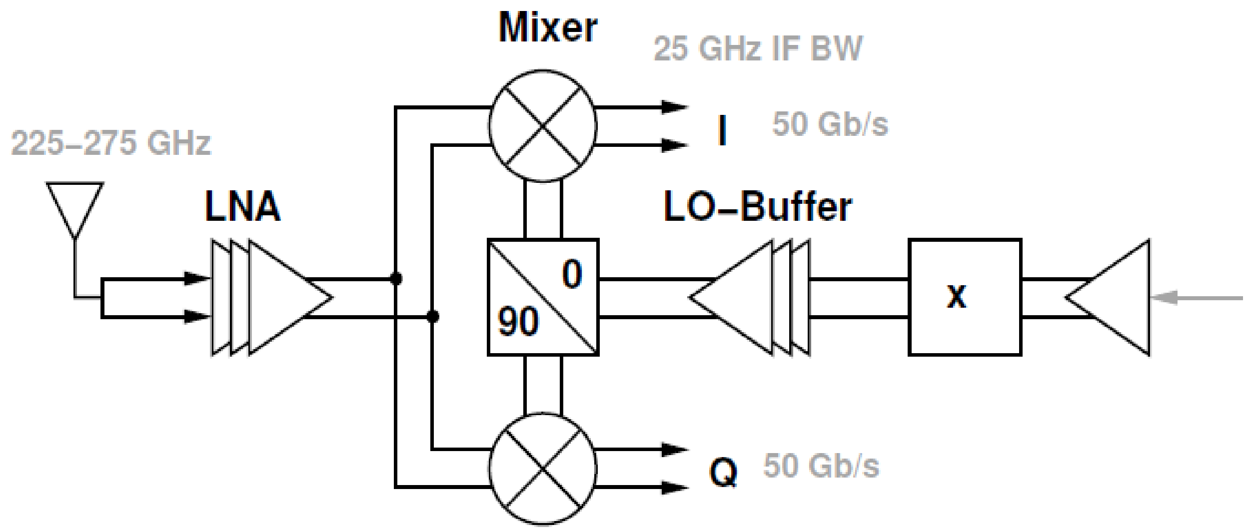
-81 dBc/Hz @1 MHz



Circuit Building Blocks

Can we build a generic receiver?

- Circuit *approach: generic wideband I/Q radios with spectral efficiencies of 2-3 bit/s/Hz at* 240 GHz



Challenges: limitations in transmit power, receiver noise figure, IF/RF bandwidth, linearity and I/Q imbalance over a very wide bandwidth

Approach: apply wide-band circuit matching techniques

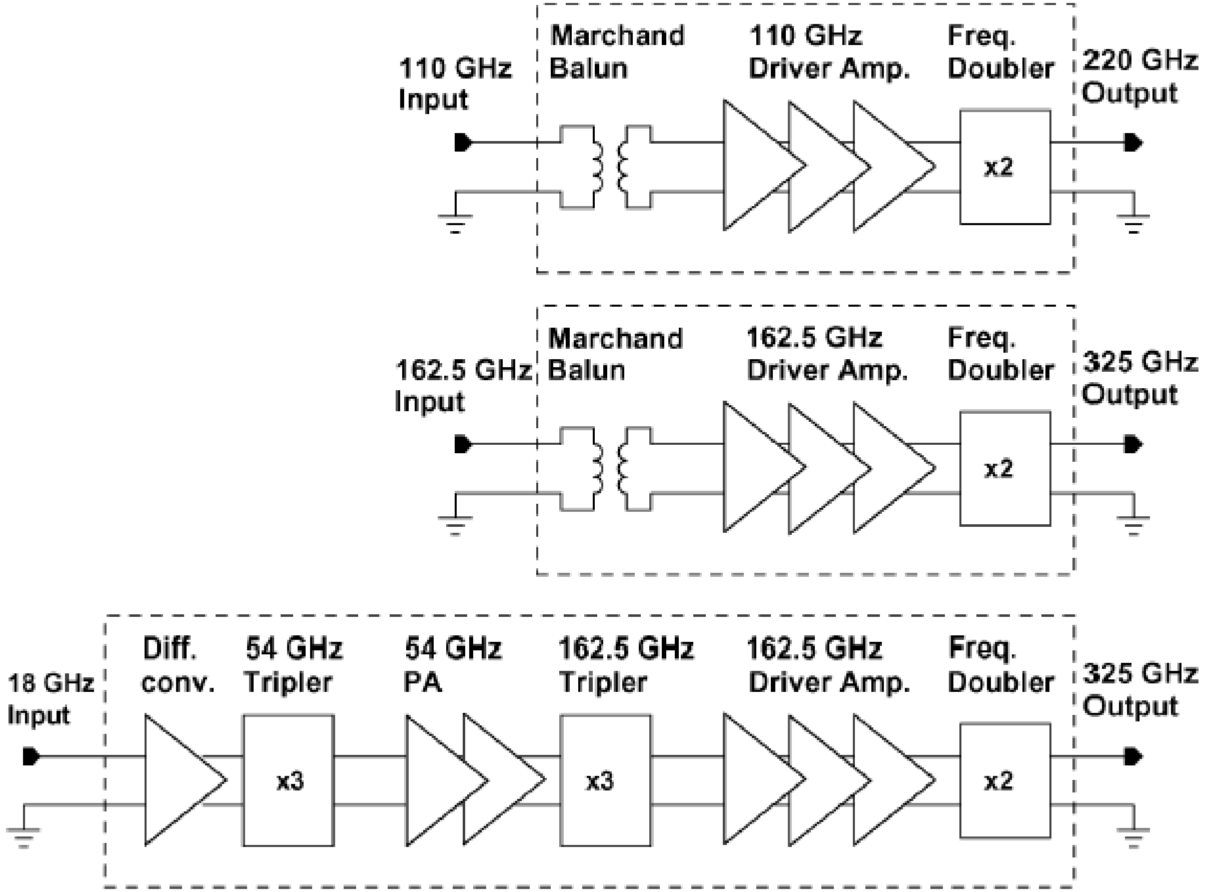
Frequency Multiplier Chains

Circuit Block Diagrams

120GHz: (x2)

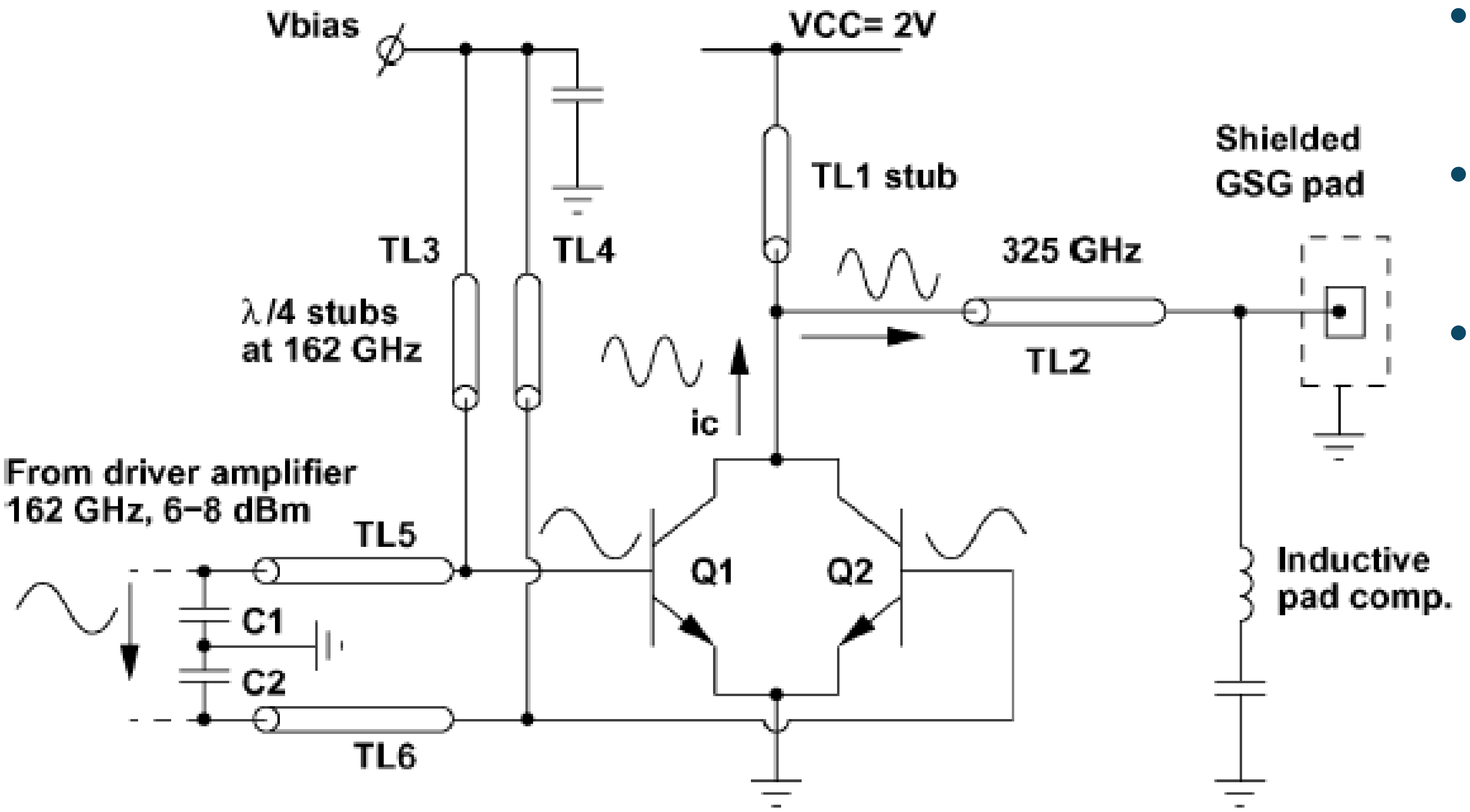
320GHz: (x2)

325GHz (x18)



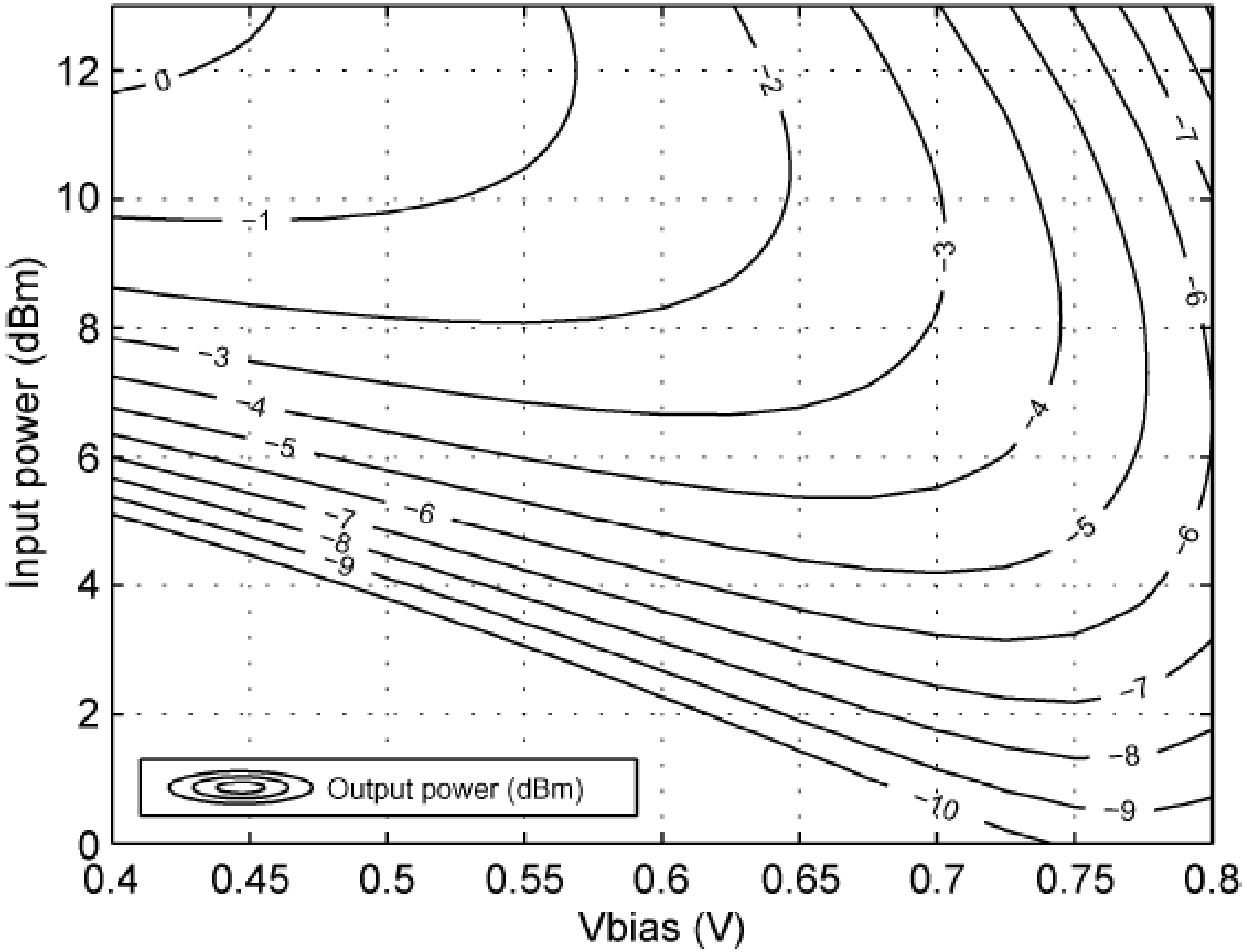
[1] Erik Öjefors, Bernd Heinemann und Ullrich R. Pfeiffer, Active 220- and 325-GHz Frequency Multiplier Chains in an SiGe HBT Technology IEEE-TMTT, 59(5):pp 1311-1318, May 2011

325GHz Doubler Schematic (push-push)



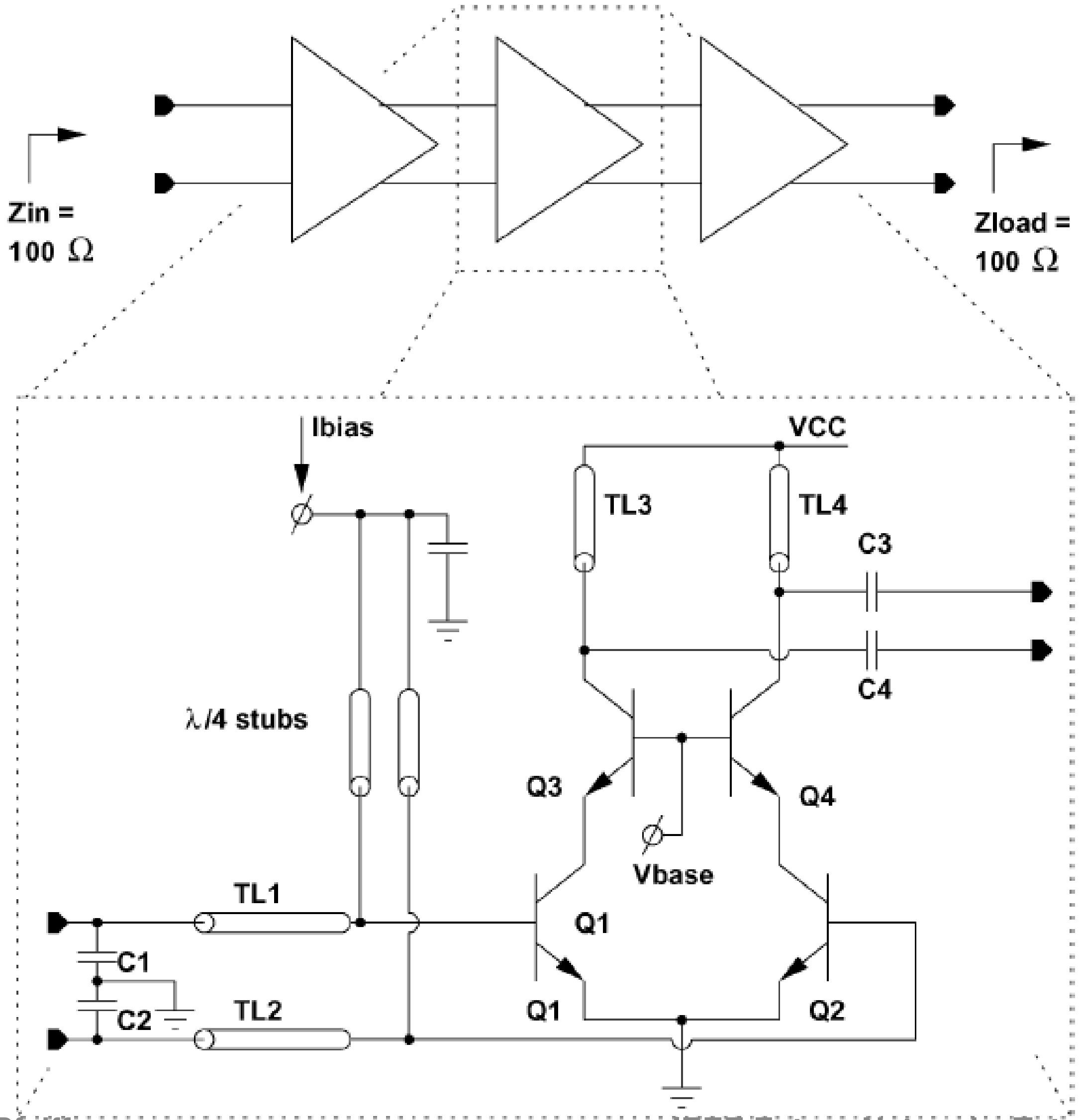
- Class-B biased amplifier
- Driven into compression
- Differential drive

Simulated Doubler Performance Power Contour Plots



Depends on available LO drive, up to 0dBm expected

Driver Amplifier Design



- Differential cascode amplifier gain stage
- Cascaded multistage design
- Typically 2-3dB gain per stage at fmax/3

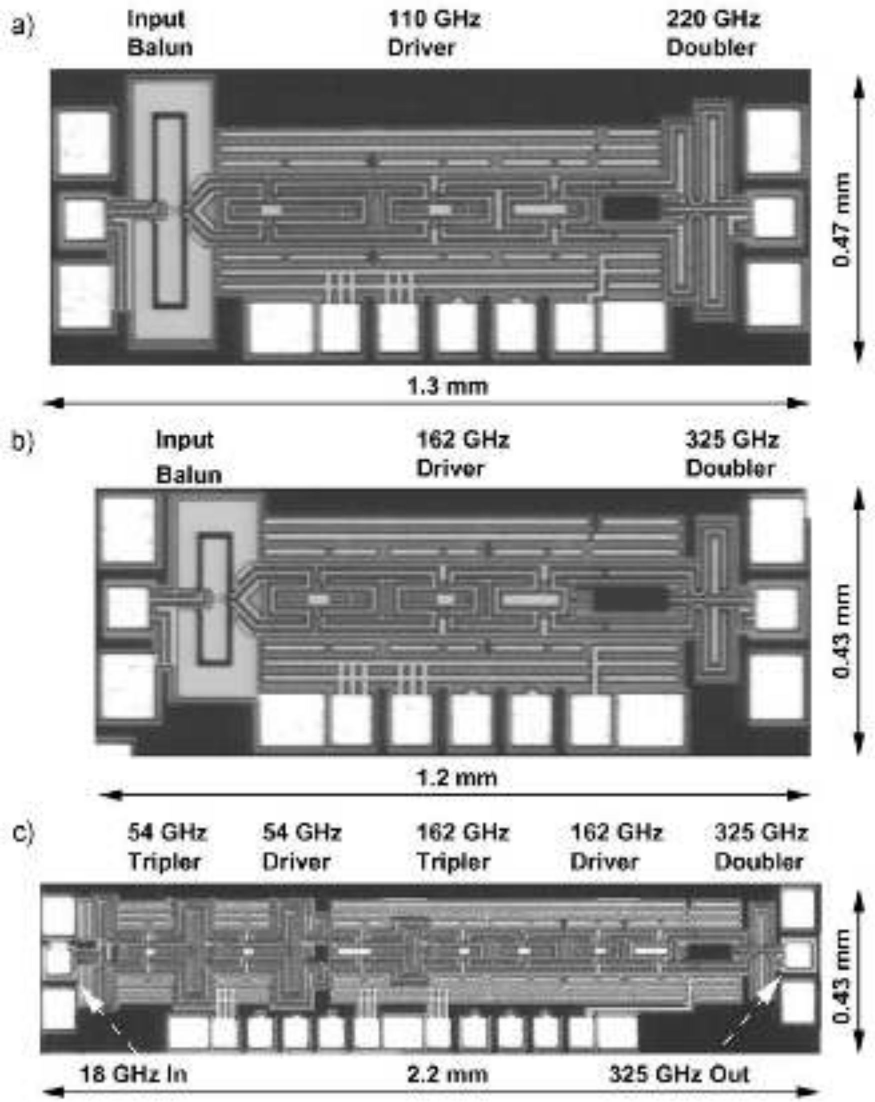
- **More than 10dBm at 160GHz on chip**
- **Close to 10dBm at 220GHz**

Chip Micrographs

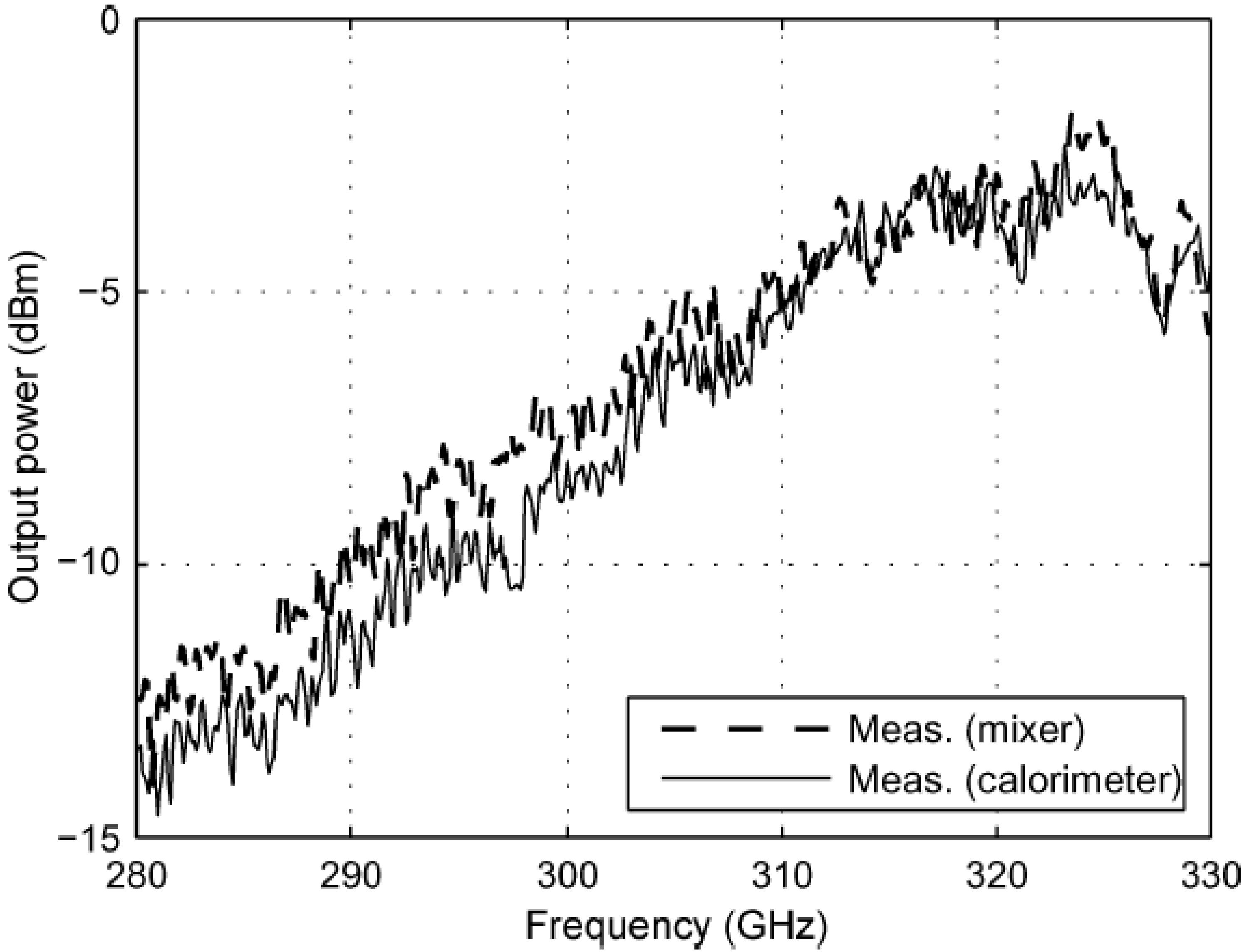
100GHz:

160GHz:

325GHz:

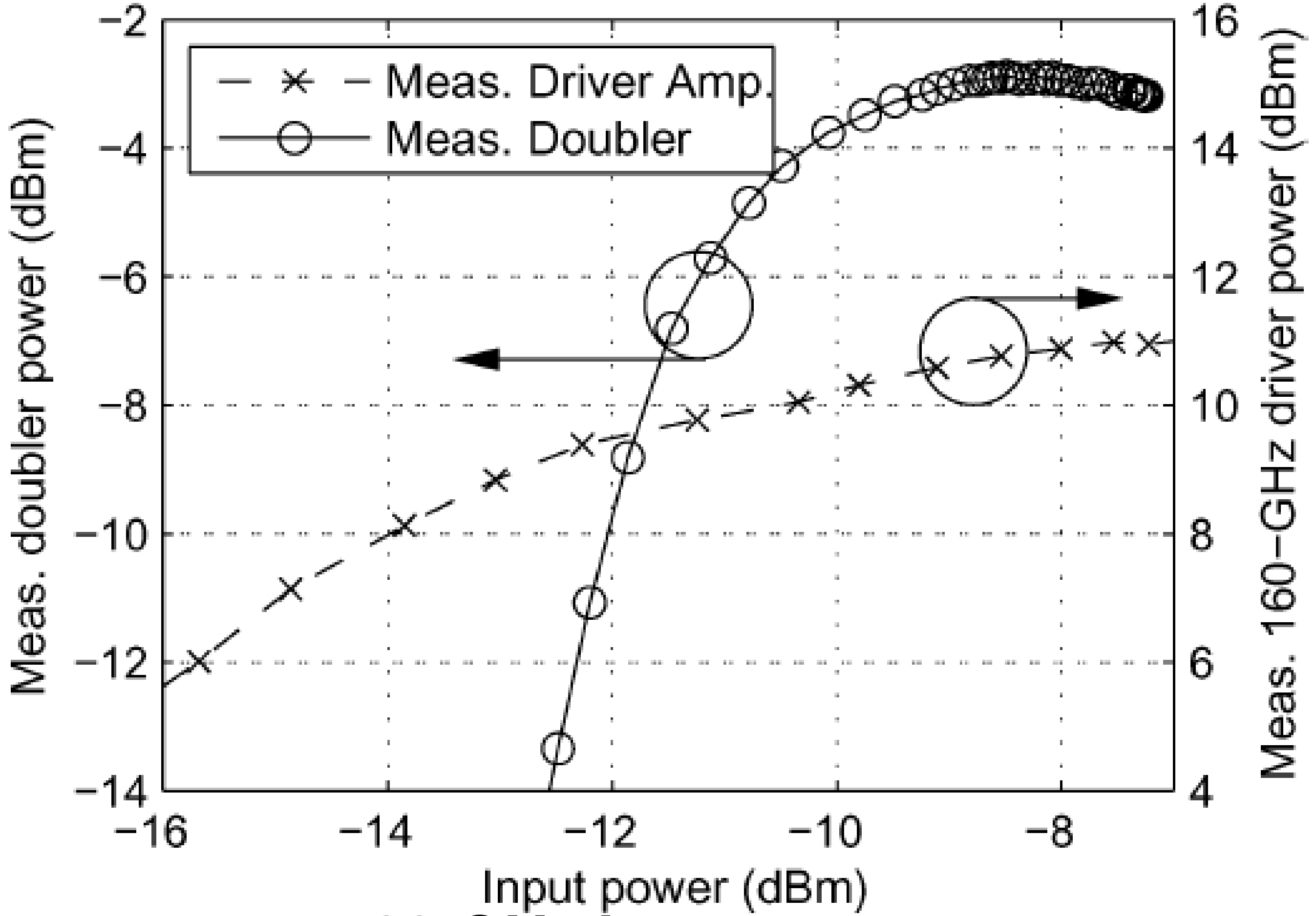


Measured Output Power vs Frequency



-3dBm @325GHz

Output Power Compression at 320GHz Doubler

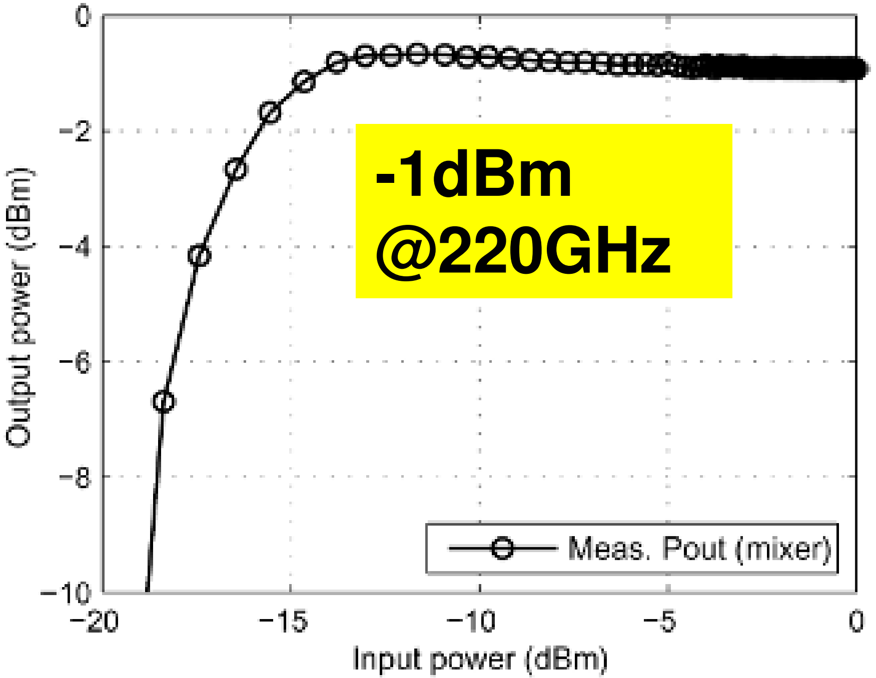


160 GHz input power

-3dBm @325GHz (PA may overdrive doubler)

Output Power Compression

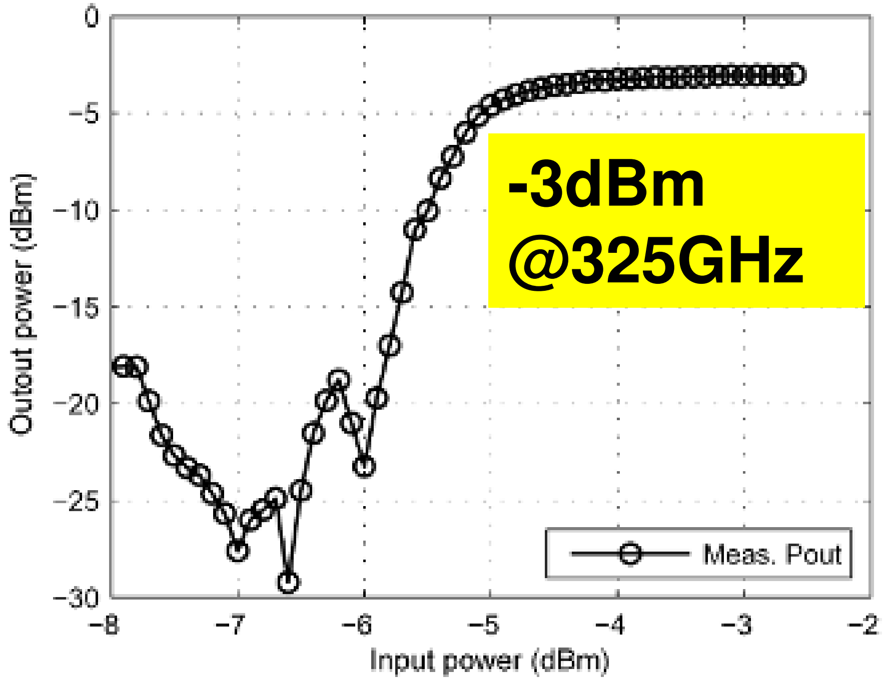
220GHz doubler



-1dBm @220GHz

110 GHz input power

x18 Multiplier



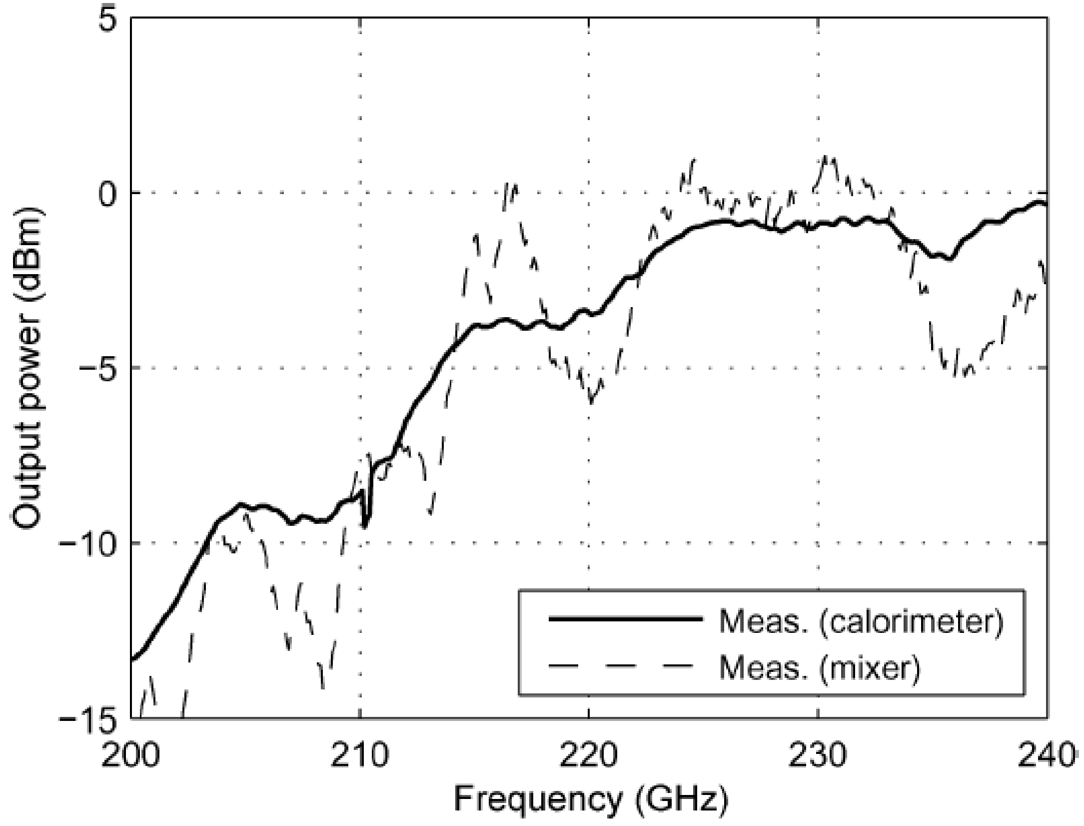
-3dBm @325GHz

18 GHz input power

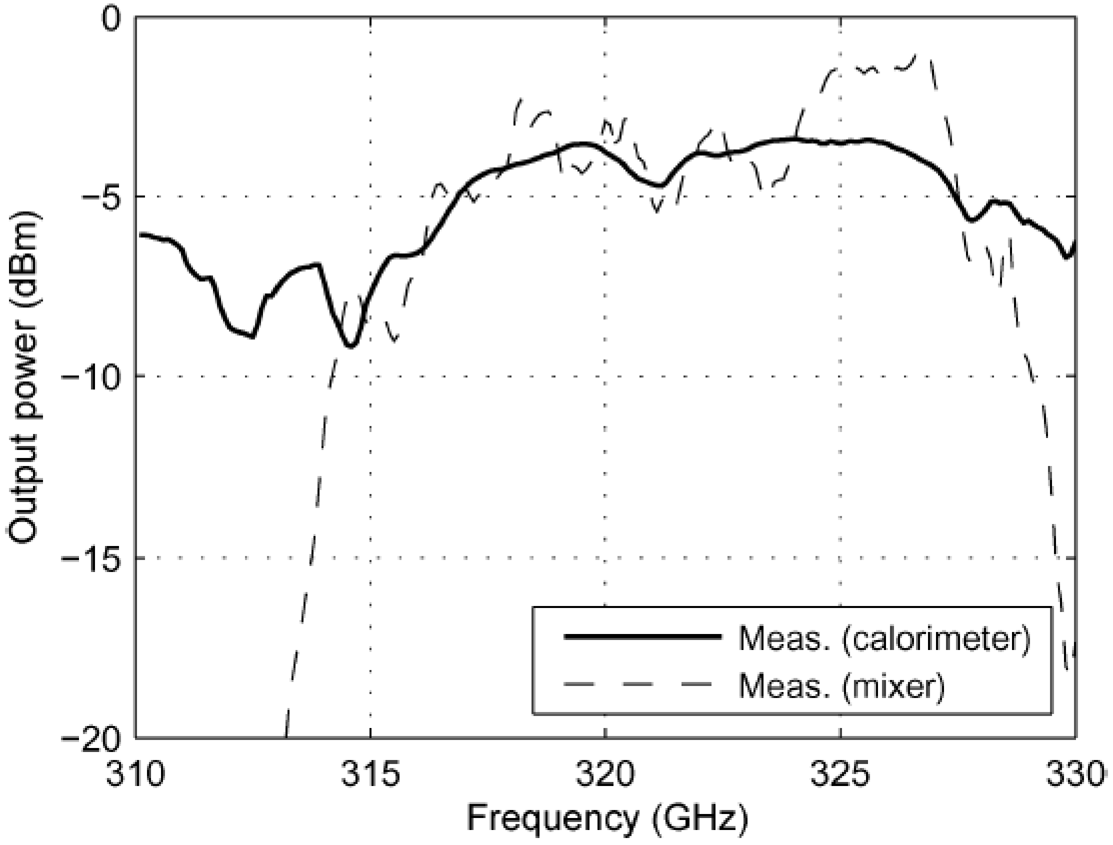
PA drive sufficient for 320GHz doubler (reaches -3 dBm of breakout)

Measured Output Power vs Frequency

220GHz

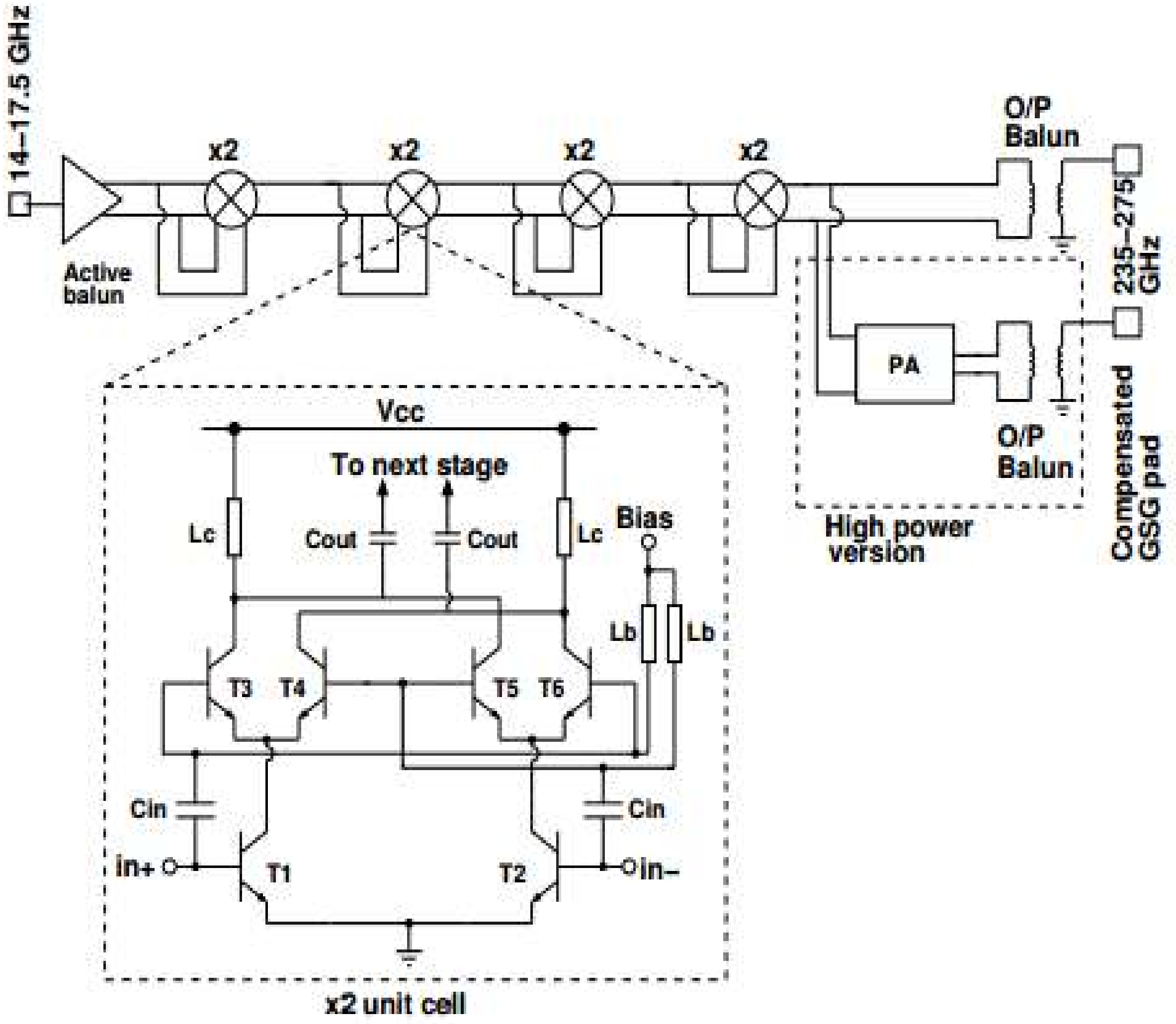


320GHz



Tuning range is about 20 GHz (limited by driver)
Q: Can we do better than this?

x16 Frequency Multiplier Chain



[1] N. Sarmah et al, RFIC 2014

- x16 frequency multiplier
- Wideband LO drive for I/Q Tx and Rx chipset
- 4 cascaded Gilbert-cell based doublers
- In-phase multiplication eliminate lossy quad generation circuit

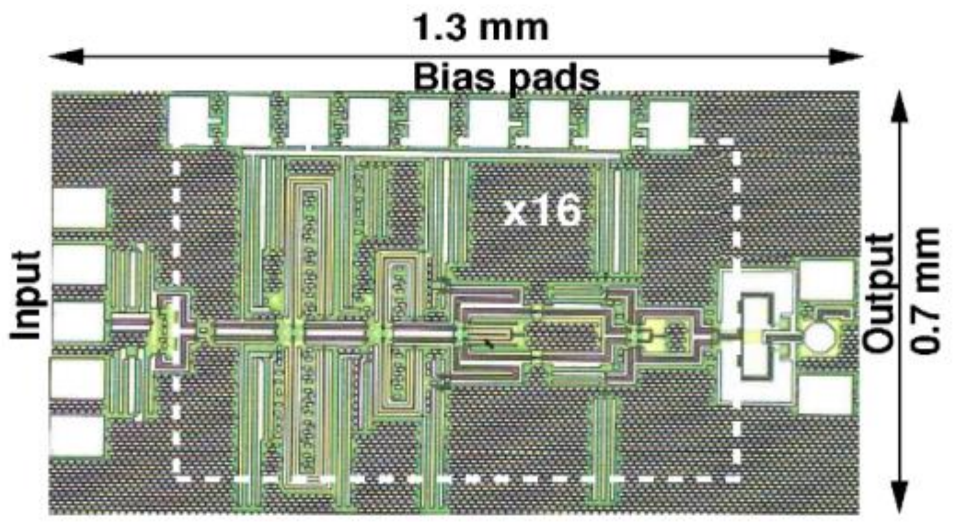
$$A^2 cos^2(\omega t) = \frac{A^2}{2} + \frac{1}{2} cos\,(2\omega t)$$

- DC-offset generated is eliminated using interstage decoupling capacitors.

[[(• Institute for High Frequency & Communication Technology IHCT

x16 Measurement Results

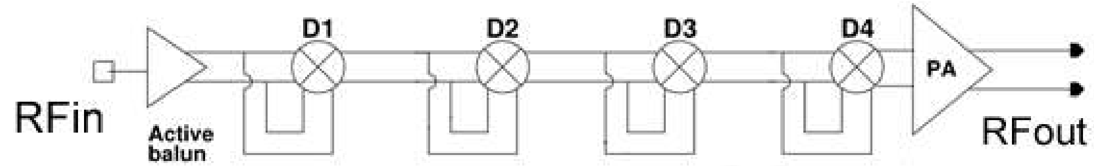
Chip-micrograph

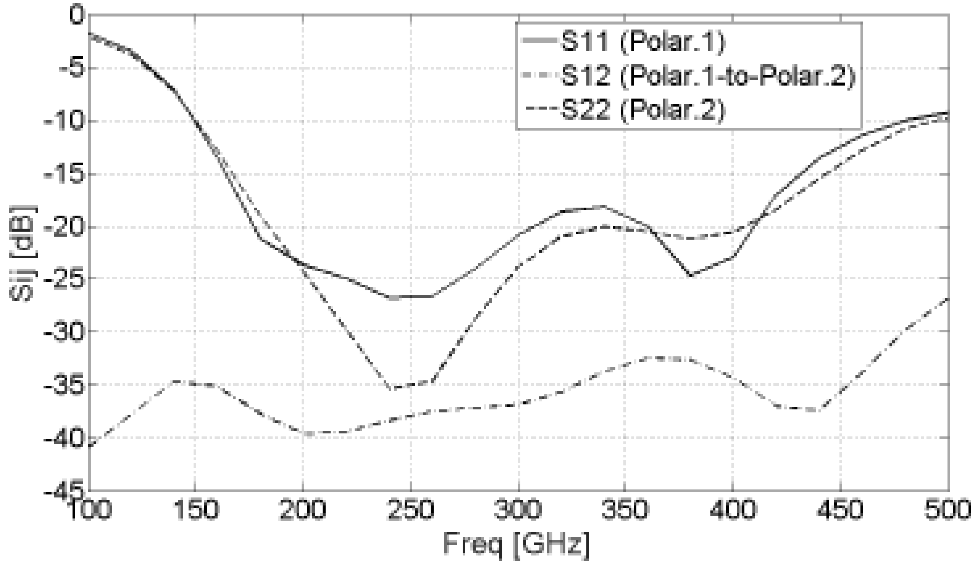


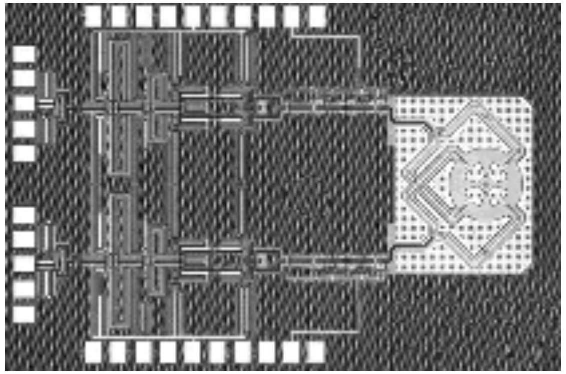
- Identical circuits in run 1 and run 2.
- Higher output power due to process improvement

Technology	Multiplication factor	Psat (dBm)	3dB BW (GHz)
IHP run 1	X16	0 @ 250 GHz	30
IHP run 2	X16	6.4 @ 230 GHz	50

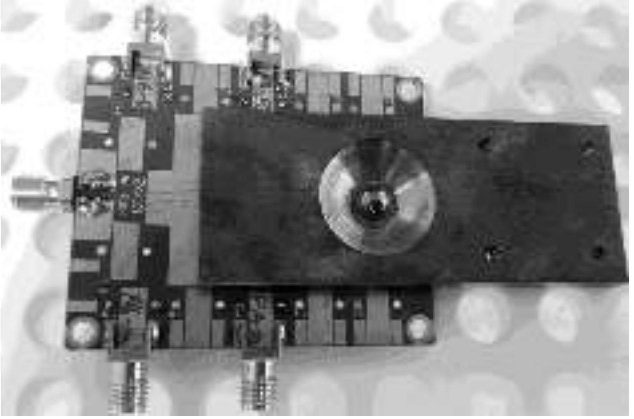
Broadband 240 GHz power source







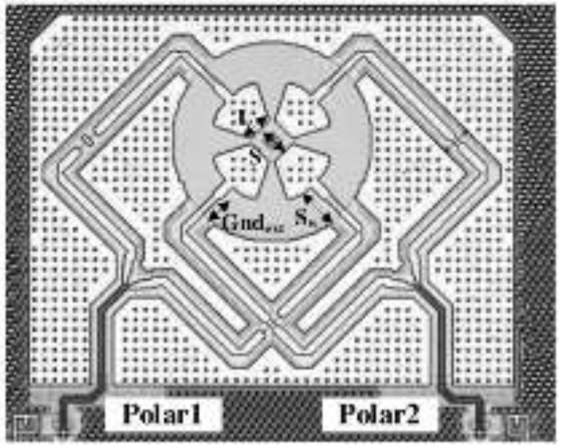
2.2 x 1.45 mm^2

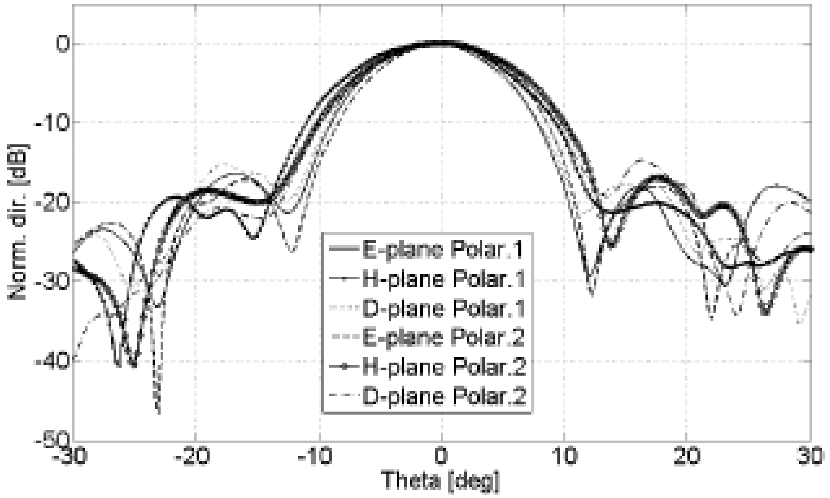


Module assembly with a 7-mm silicon lens

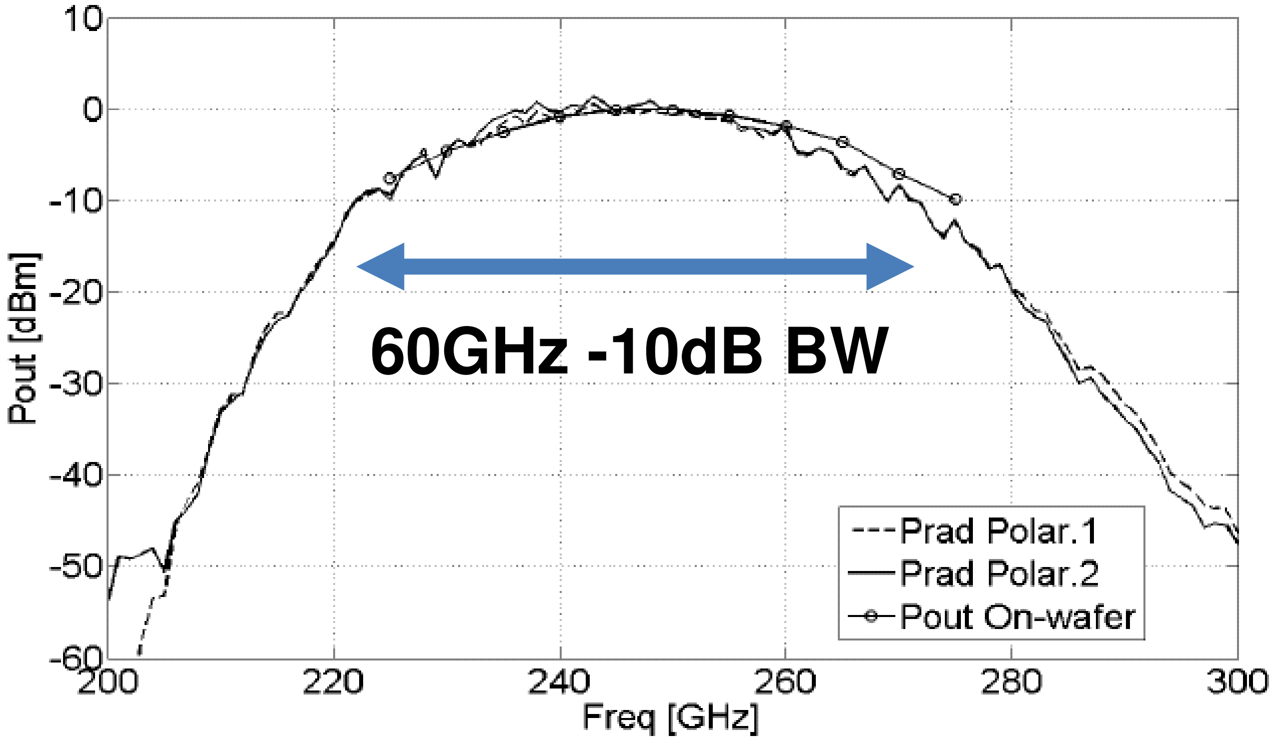
- Simulated input match and isolation
- Simulated amplitude imbalance <0.13dB
- Simulated axial ratio better than 1.3 for quadrature excitation

Measured results





Measured patterns at 250 GHz

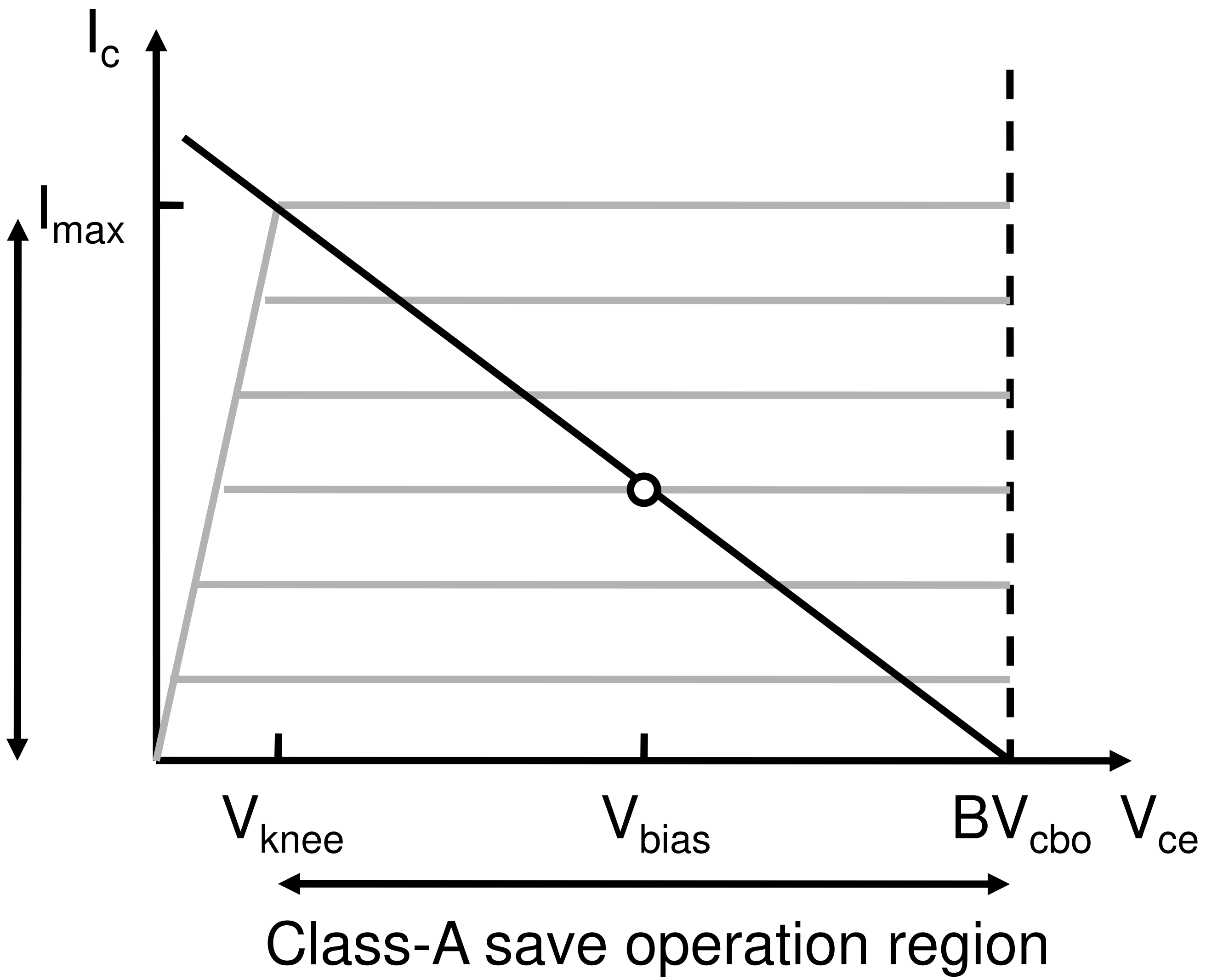


- **Peak radiated power: 4.06 dBm at 243 GHz and in excess of -10 dBm for 221-275 GHz**

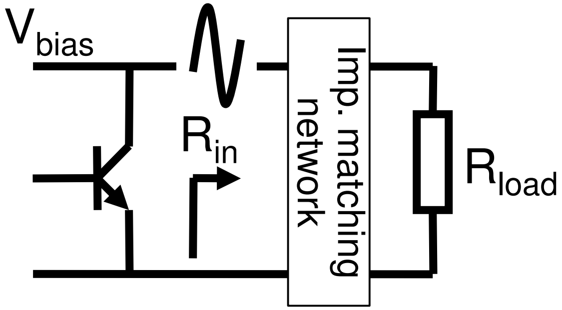
Yes, much more BW (PA is BW limiting), but worse harmonic content!

Power Amplification Techniques

Loadline Match (Common-Emitter Class-A)

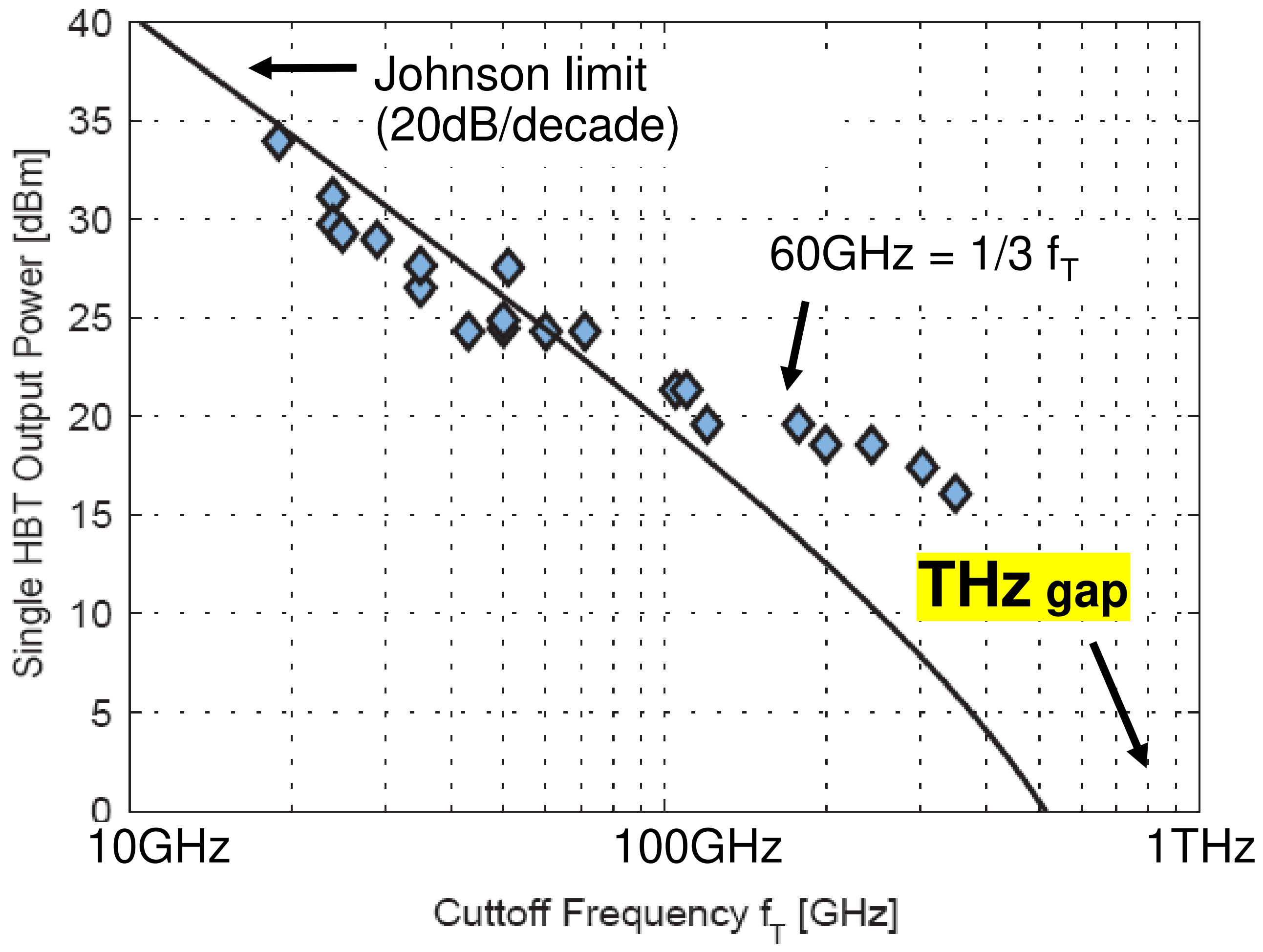


- **No conjugated match at output!**
- **Maximum power delivery with load-line match**



$$P_{out} = \left(\frac{xBV_{ceo} - V_{knee}}{2\sqrt{2}}\right)^2 / R_{in},$$

Single SiGe HBT Output Power Limits



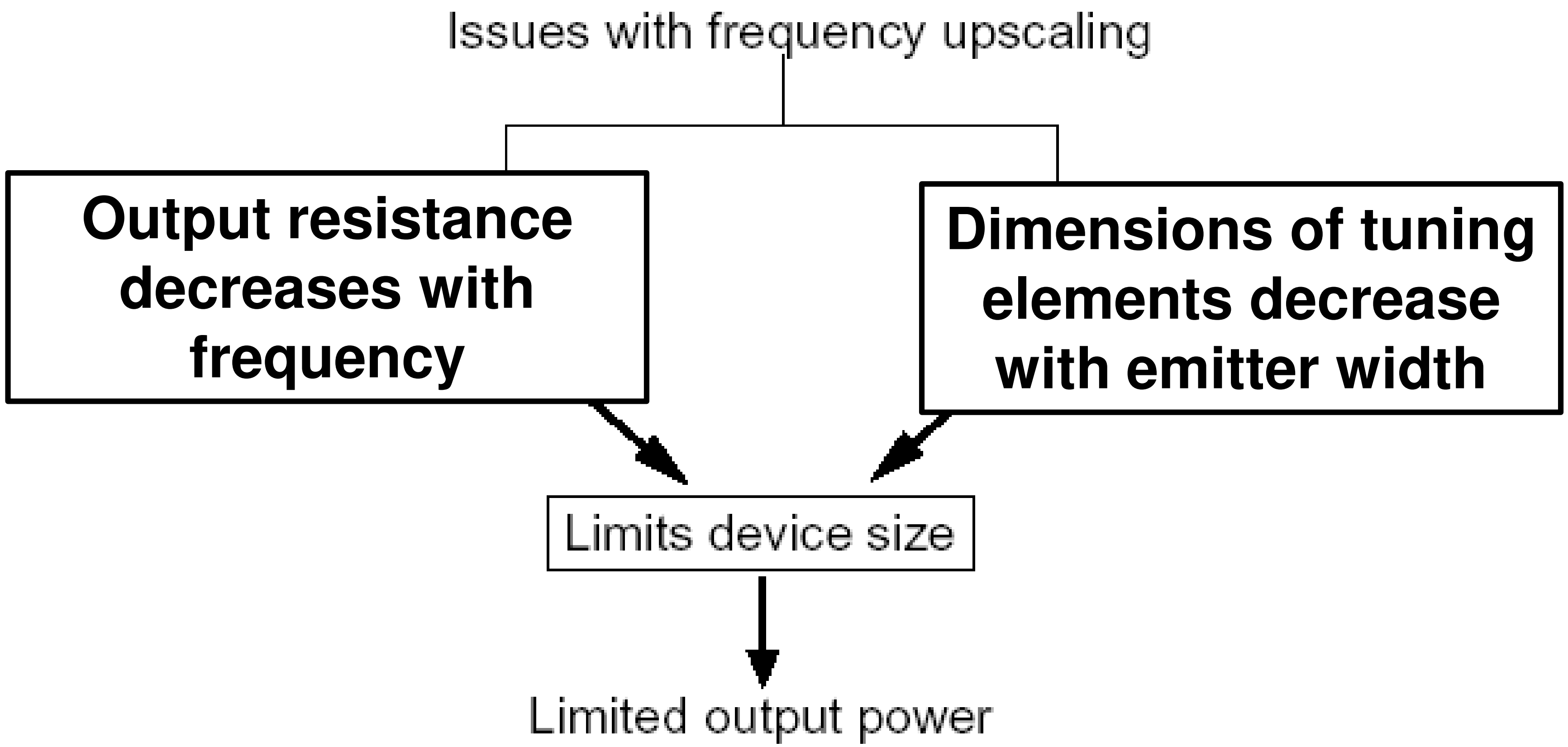
THz gap ≡ Transistor can not be switched

Class-A, no power combining:

$$P_{out} = \left(\frac{xBV_{ceo} - V_{knee}}{2\sqrt{2}}\right)^2 / R_{in},$$

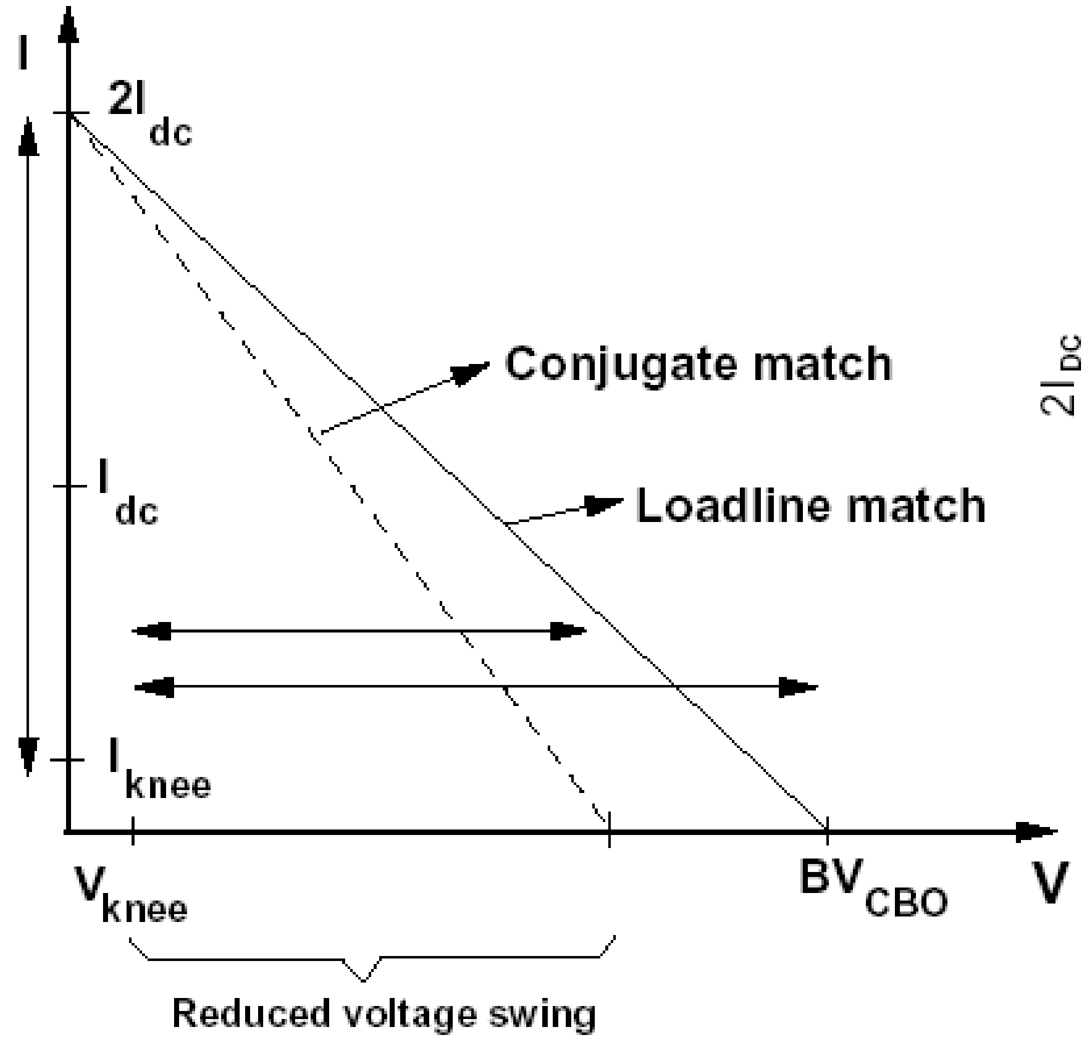
- **Assumes: class-A, x=50% above BVceo, load-line Rin=10Ω (r = 5, Rload = 50Ω)**
- **Note, other values may shift this data within 3 dB or more but its trend remains**
- **Johnson limit SiGe:**
  - **Bvceo + fT = 200 GHz V**

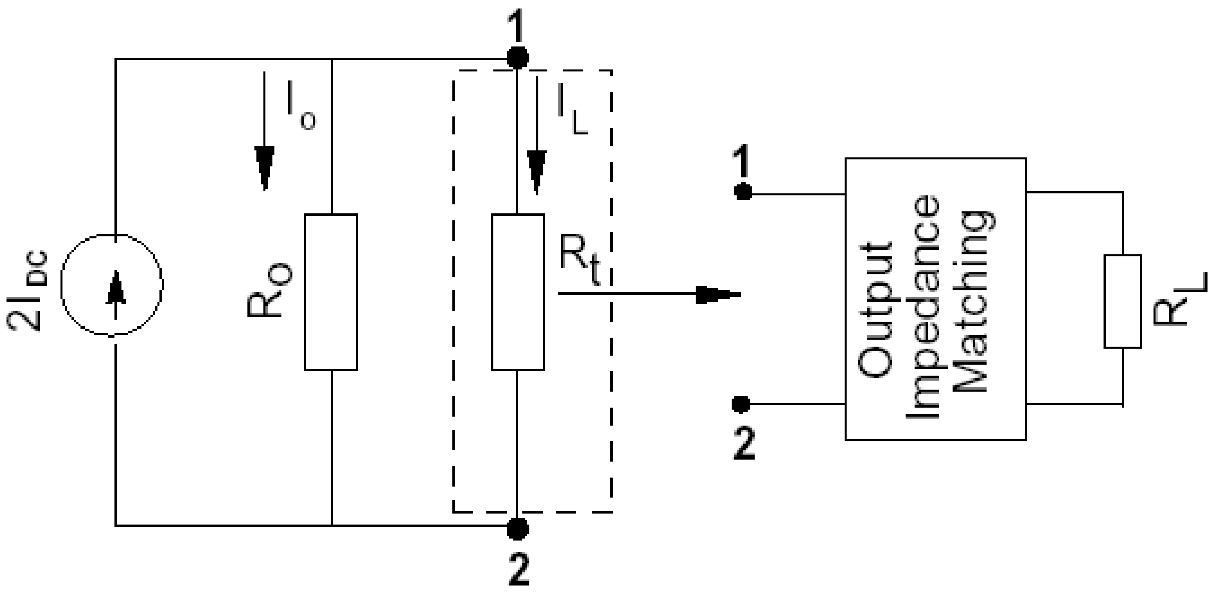
Practical Limitation for THz PA design



[1] **N. Sarmah, P. Chevalier, U.R. Pfeiffer,** 160-GHz Power Amplifier Design in Advanced SiGe HBT Technologies with Psat in Excess of 10 dB, TMTT 2012

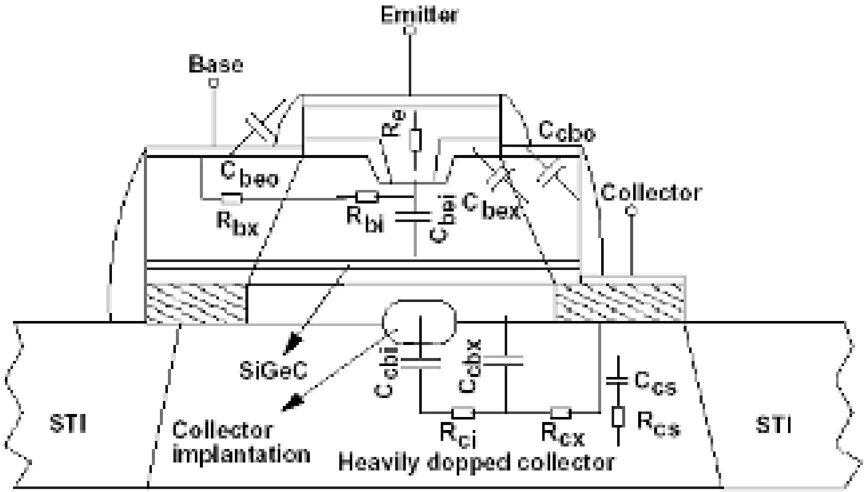
Recap: Load-line Impedance Match

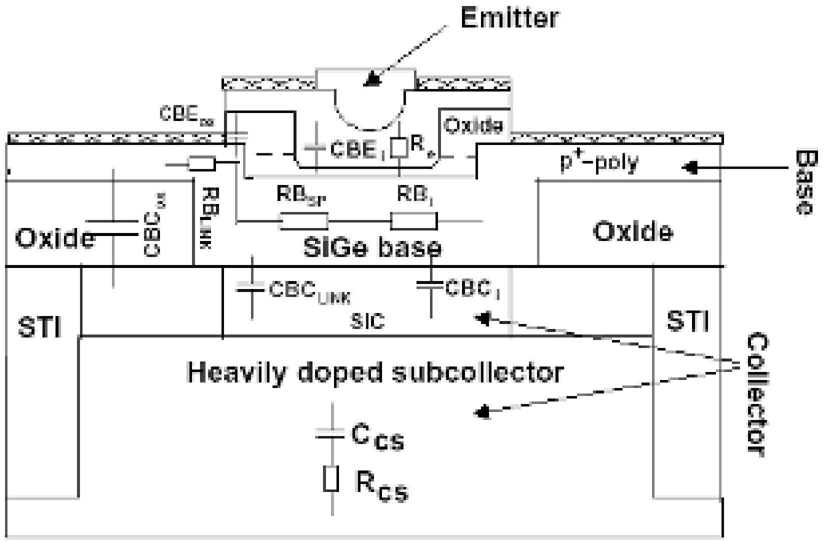




How does Ro limit Pout?

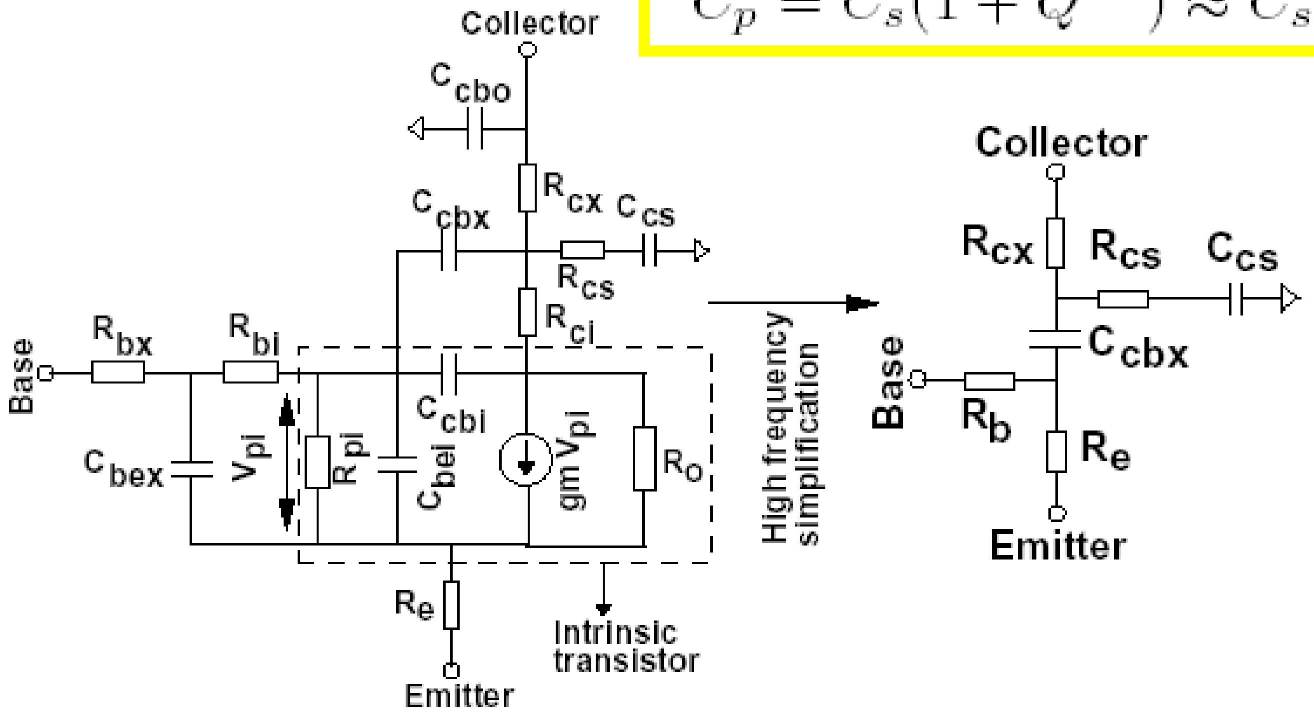
Ananlysis of Device Parasitics





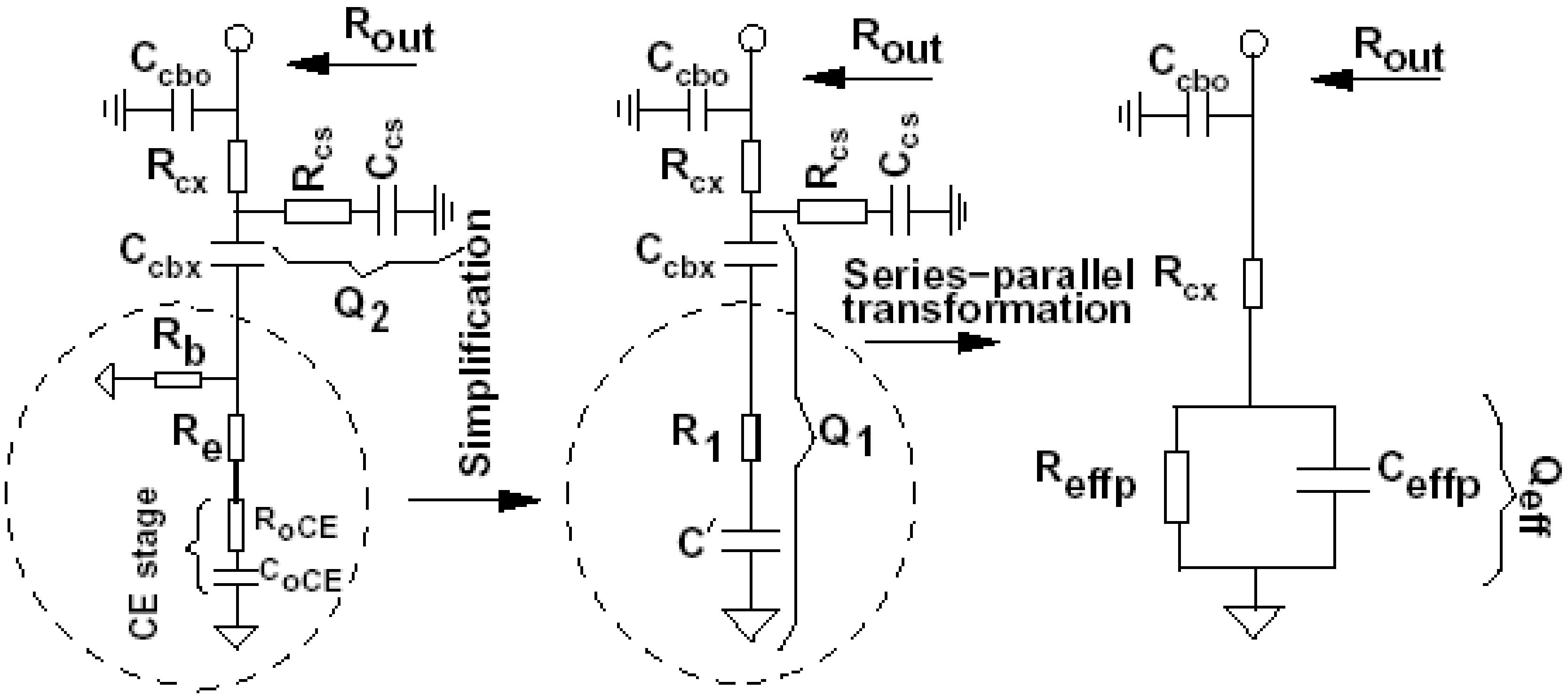
$$R_p = R_s(1 + Q^2) \approx R_s Q^2$$

$$C_p = C_s(1 + Q^{-2}) \approx C_s.$$



Which are the key elemens which limit Ro?

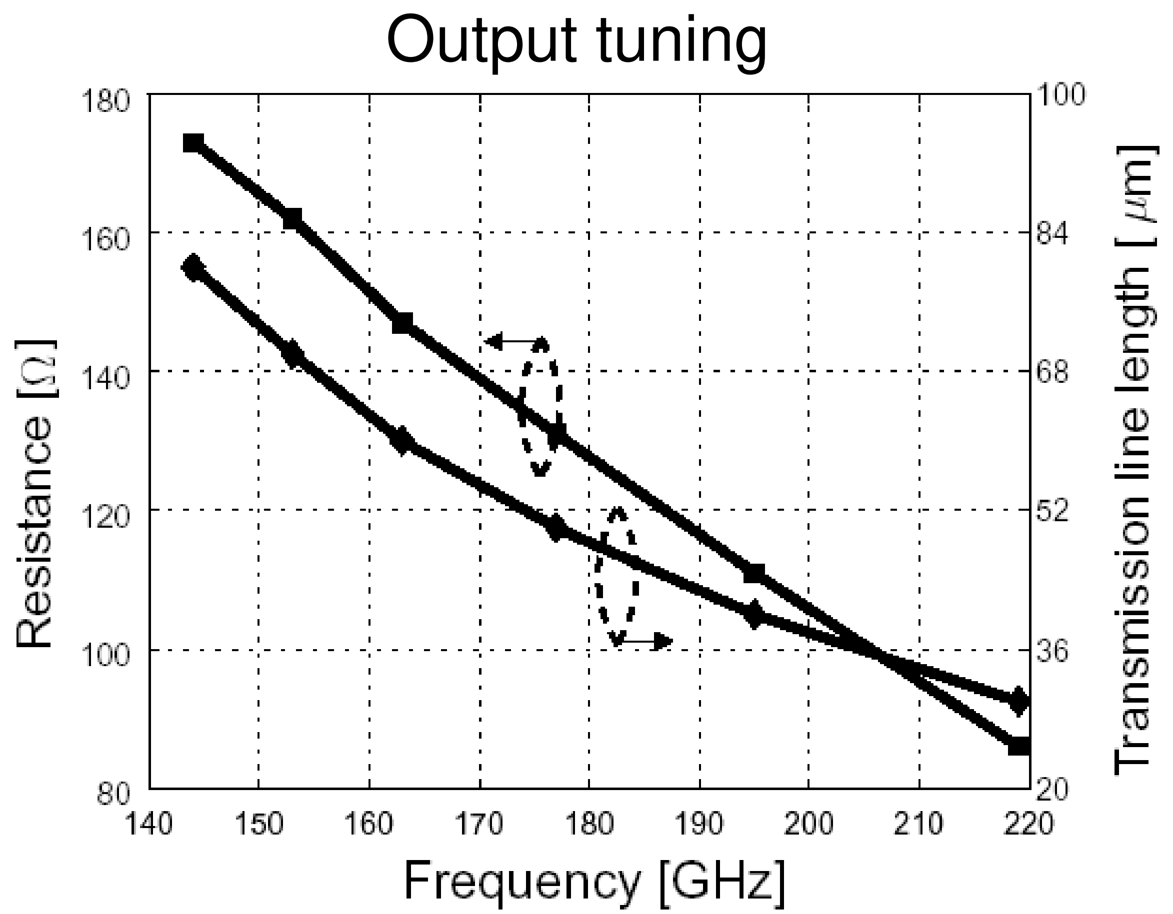
Dominant Parasitic Elements

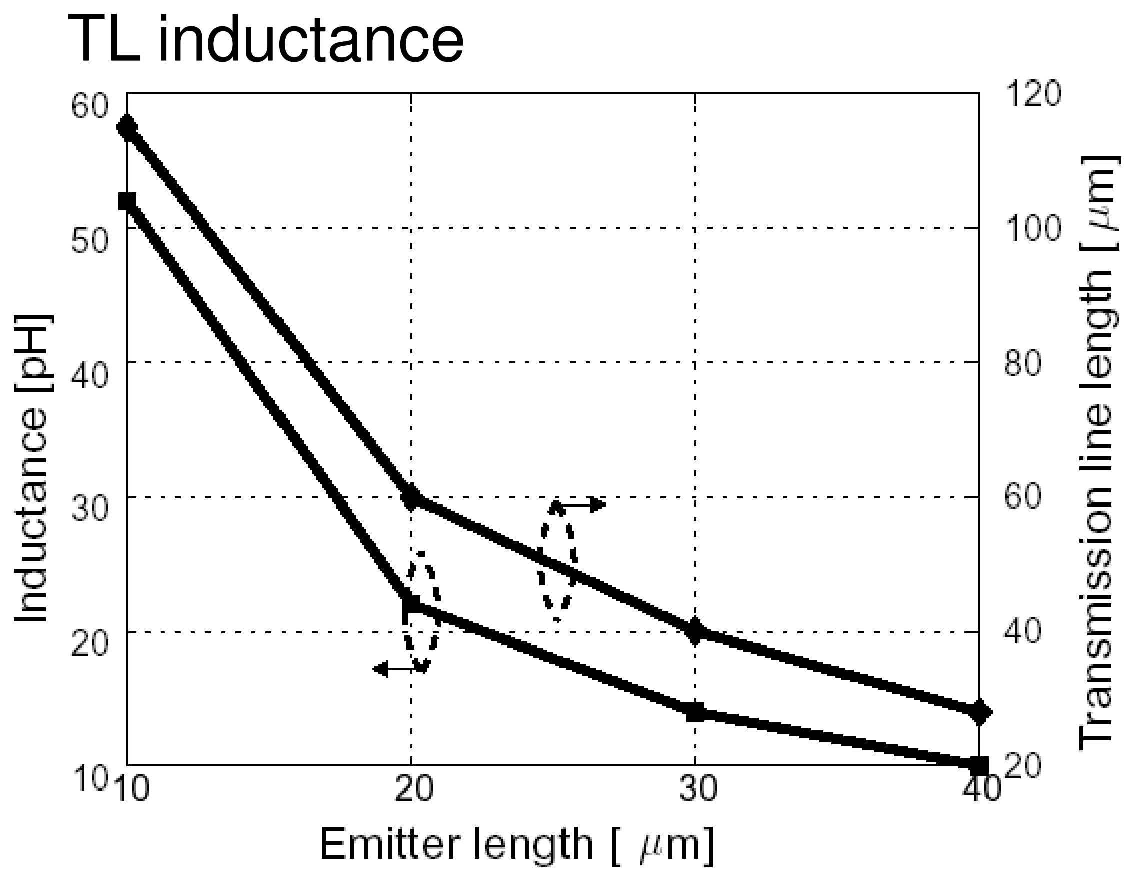


Overall Rout scales down with frequency as:

$$R_{out} = \frac{R_{effp}^2}{(R_{effp} + R_{cx}Q_{eff}^2)} = \frac{1}{\omega^2}\left(\frac{k^2}{k + R_{cx}k_1^2}\right)$$

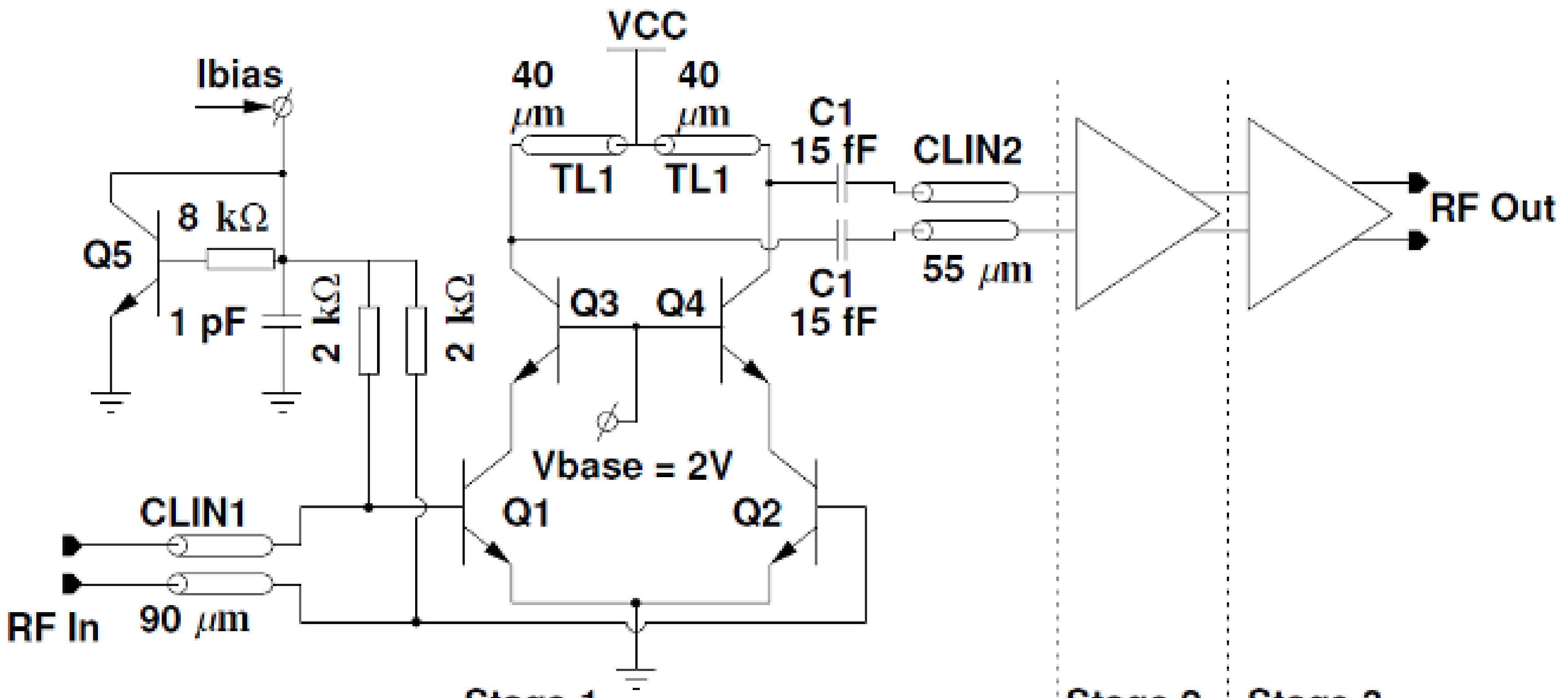
Simulated Characteristics of Output Matching Network





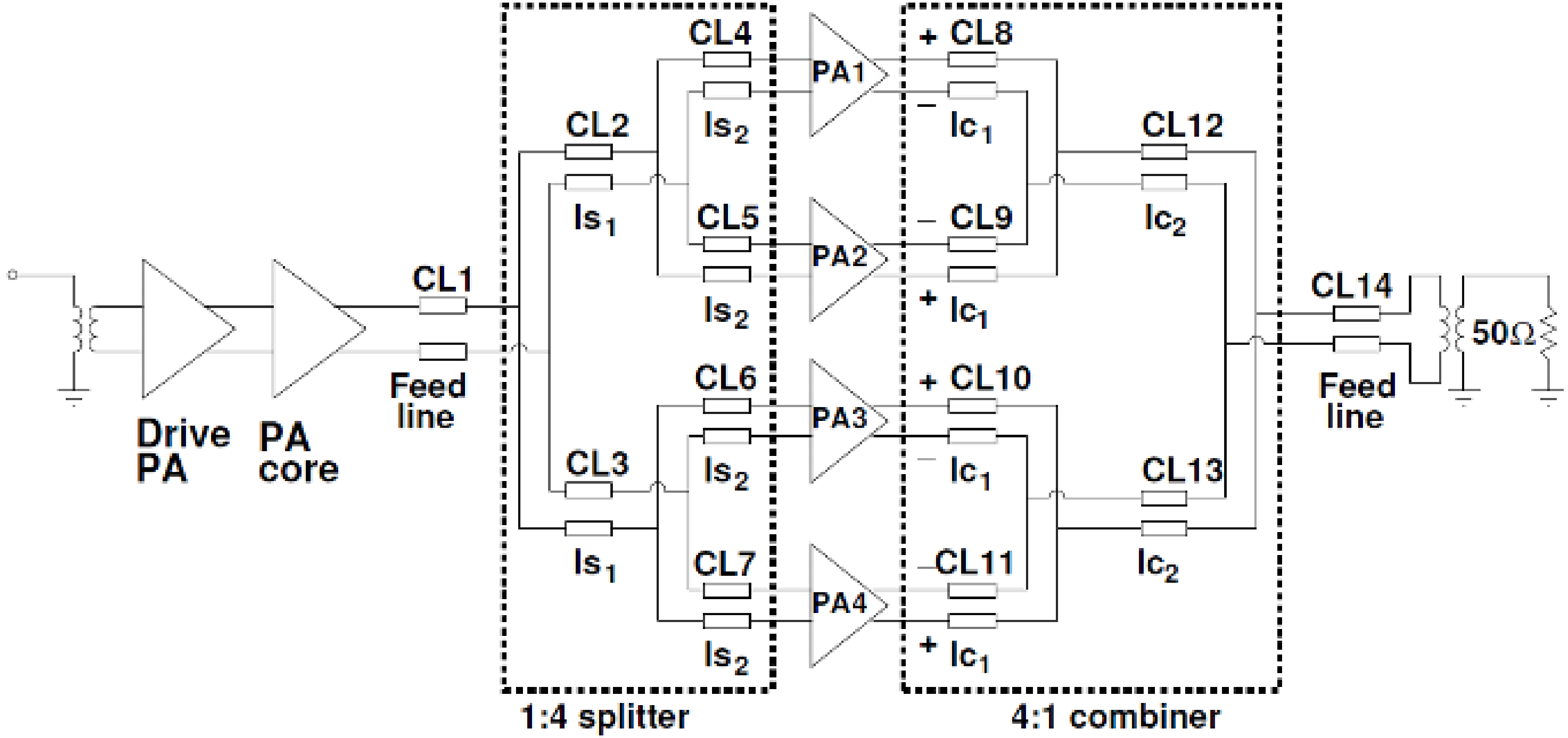
-> We need to reduce the emitter length at higher frequencies
-> less power can be delivered!

4-Stage PA



- Differential cascode topology in IHP technology
- Run 1 : 10 dB gain and 30 GHz BW, Run 2 :26 dB and 28 GHz BW
- Run 1: Psat 5 dBm at 240 GHz, Run 2: 7.5 dBm at 240 GHz
- Higher gain and output power is due to process improvement

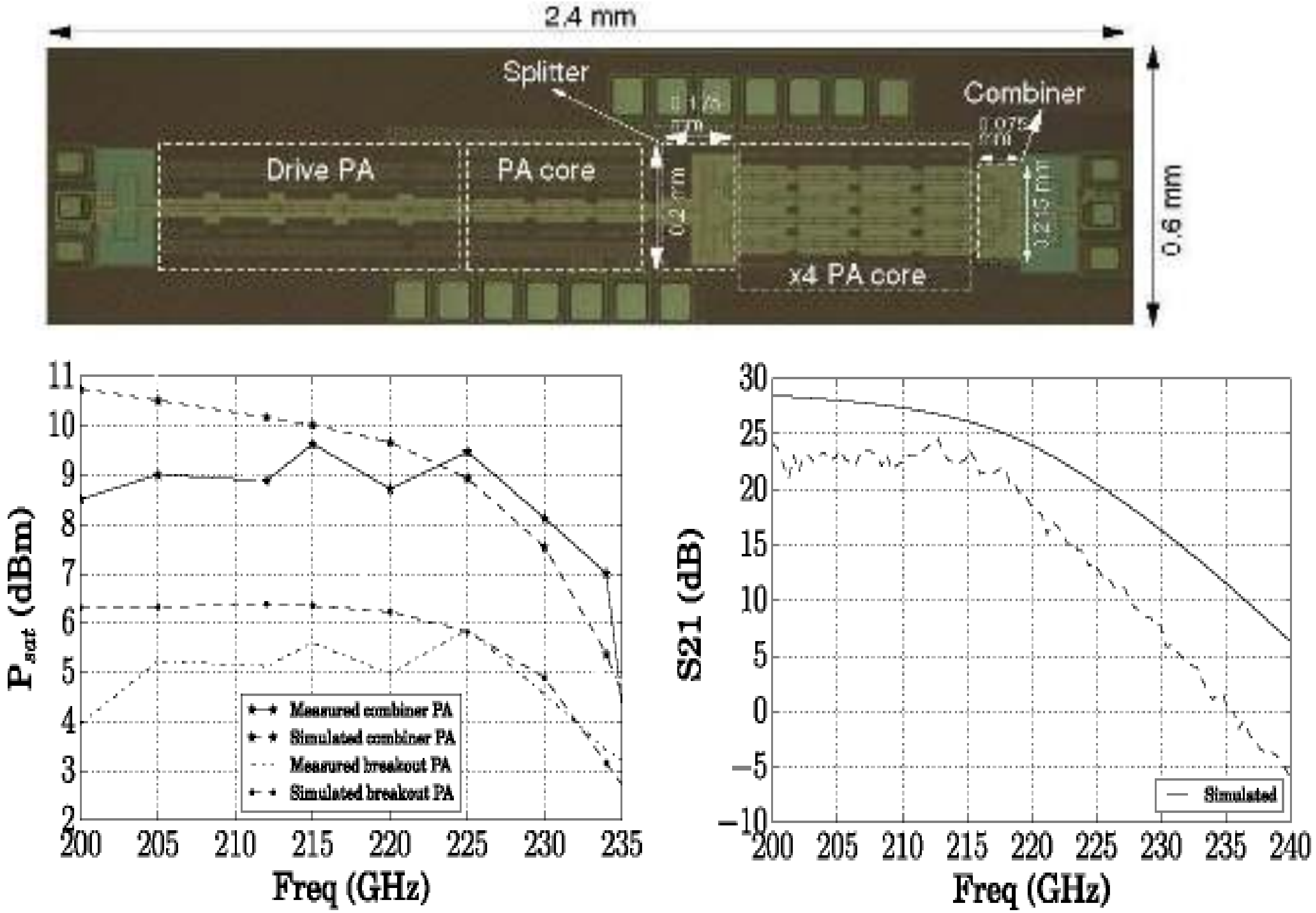
Power Combining Amplifier (IFX) 200-225GHz Combiner



- **4:1 parallel power combining using transmission line based zero-degree combiner**

[1] N. Sarmah et al, ESSIRC 2016

Combiner PA Measurement Results



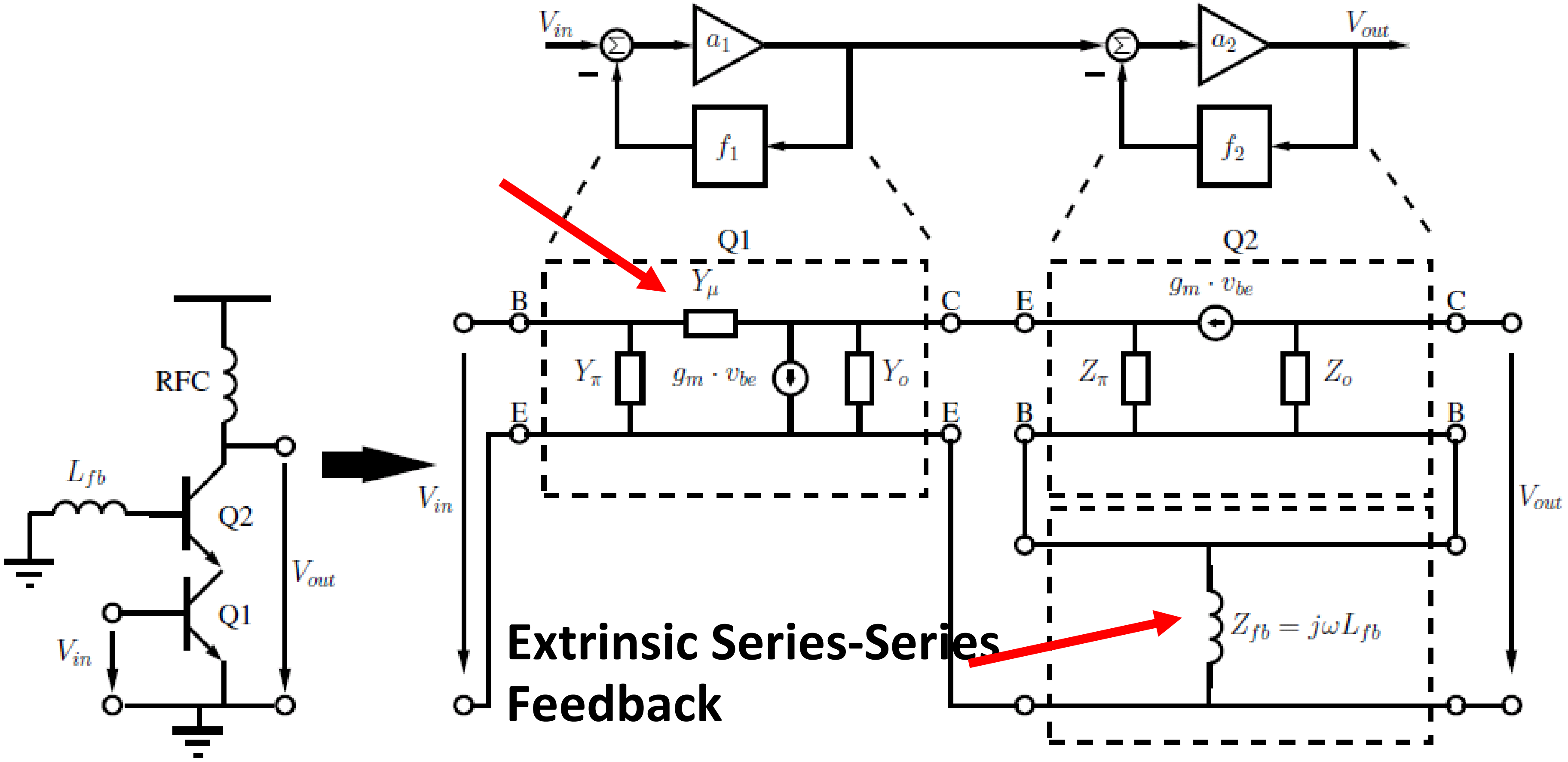
- At 215 GHz, the Psat is 9.6 dBm and from 200-225 GHz the average Psat is 9 dBm.
- From 200-225 GHz, the power enhancement is factor of 3.5-4 dB.

This is the highest reported output power for silicon PAs above 200 GHz.

Gain-enhanced signal amplification LNA cascodes in 0.13µm SiGe (EuMIC14, IJMWT15)

Two Port of an Enhanced Cascode

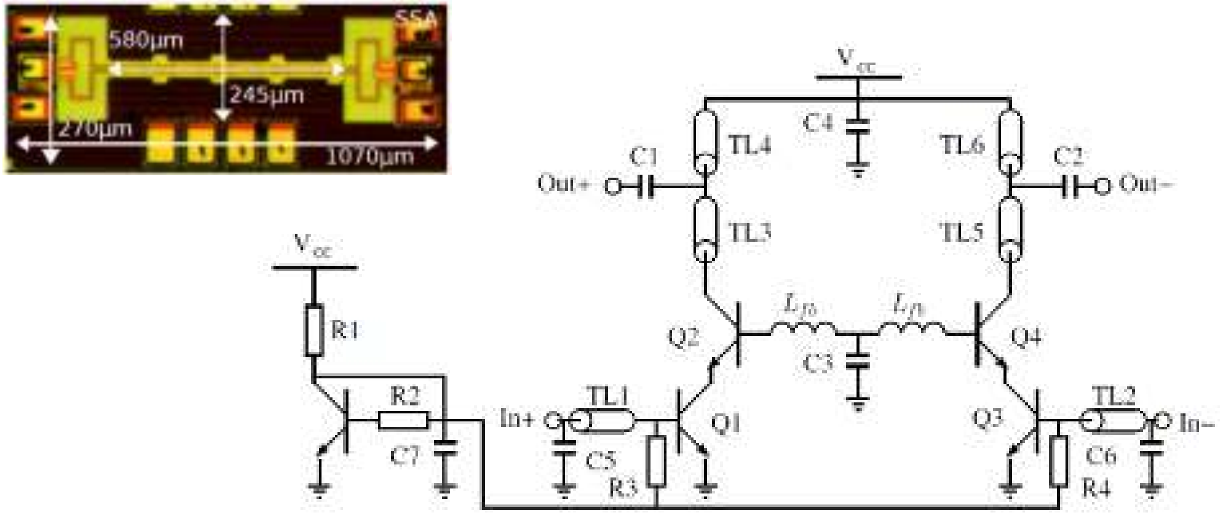
Intrinsic Shunt-Shunt Feedback

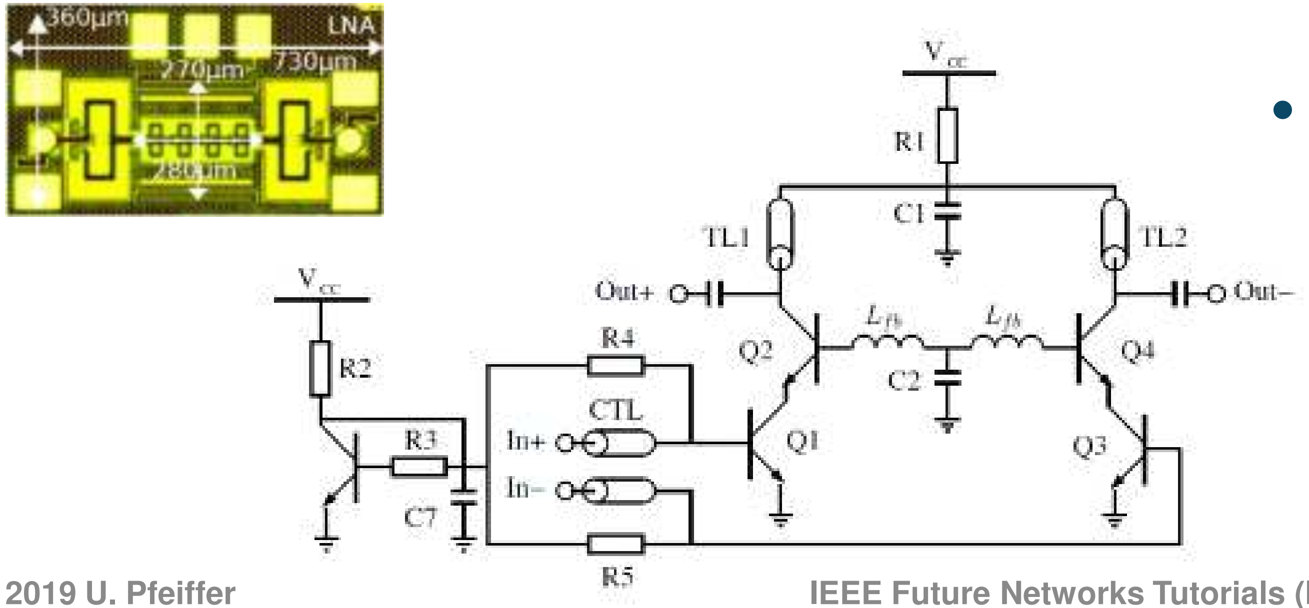


Extrinsic Series-Series Feedback

[1] S. Malz et al, EuMIC 2014 and IJMWT15

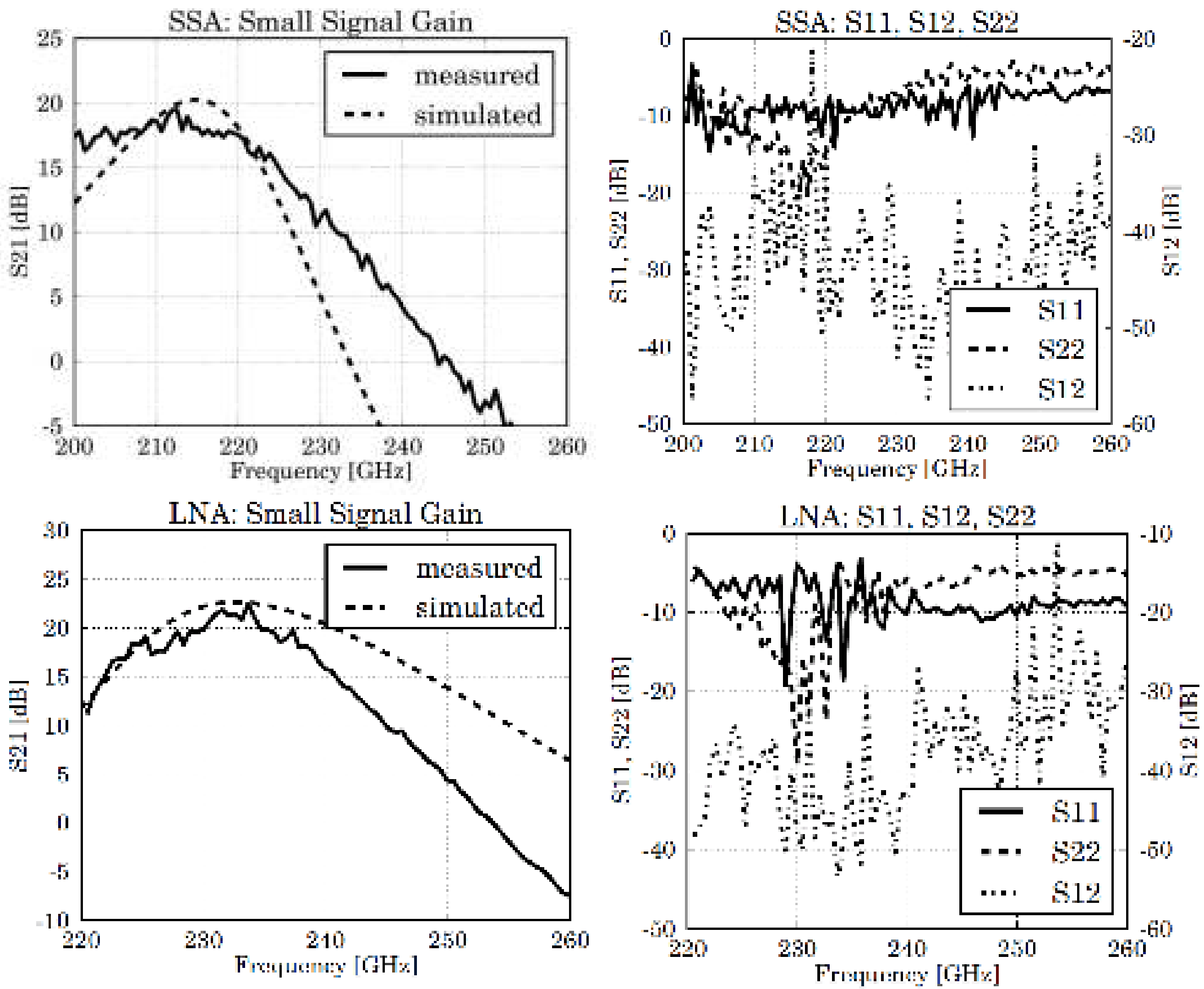
Infineon & IHP Amplifier





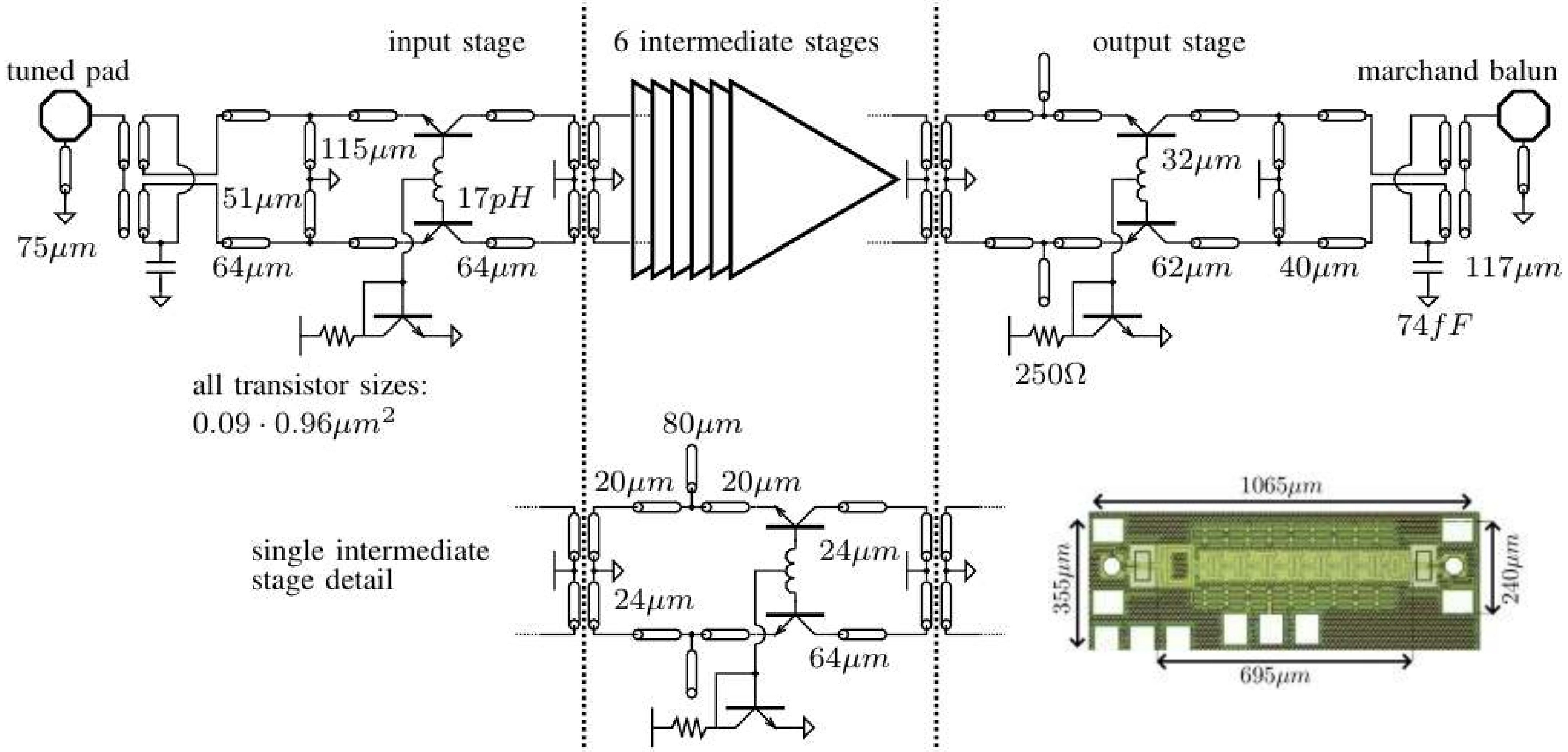
- **Infineon 212 GHz 4-stage Amplifier**
  - f_T/f_{max} = 250/360 GHz
  - Gain: 19.5 dB
  - BW: 21 GHz
  - NF: 14dB (sim)
  - 65 mA @ 3.3 V
- **IHP 230 GHz 4-stage LNA**
  - f_T/f_{max} = 300/450 GHz
  - Gain: 22.5 dB
  - BW: 10 GHz
  - NF: 12.5 dB (sim.)
  - 17 mA @ 4 V

Infineon & IHP Measurement Results



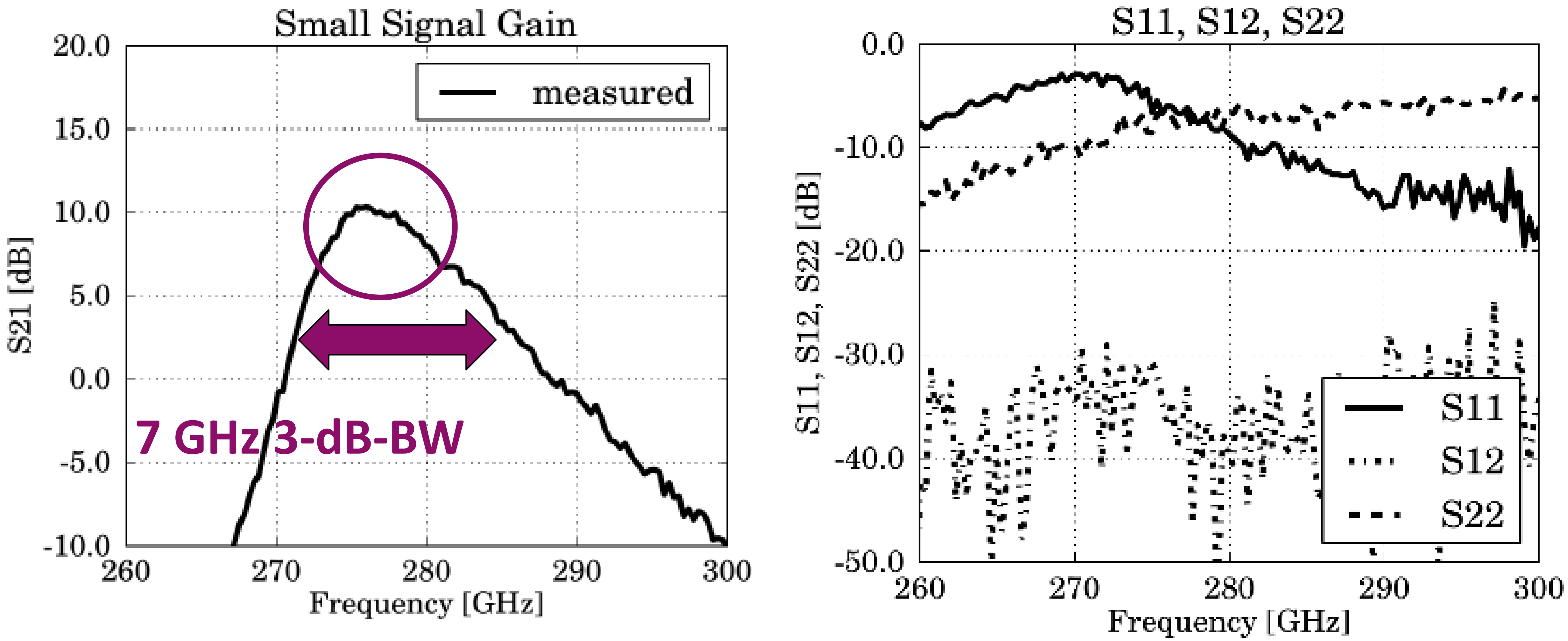
- **Both amplifiers show ≥ 20 dB gain in H-Band**
- **High reverse isolation attests stability in both cases**
- **Design methodology described in detail in IJMWT EuMW14 special issue**

275 GHz Amplifier



[1] S. Malz et. al., A 275 GHz Amplifier in 0.13 µm SiGe, EUMIC 16

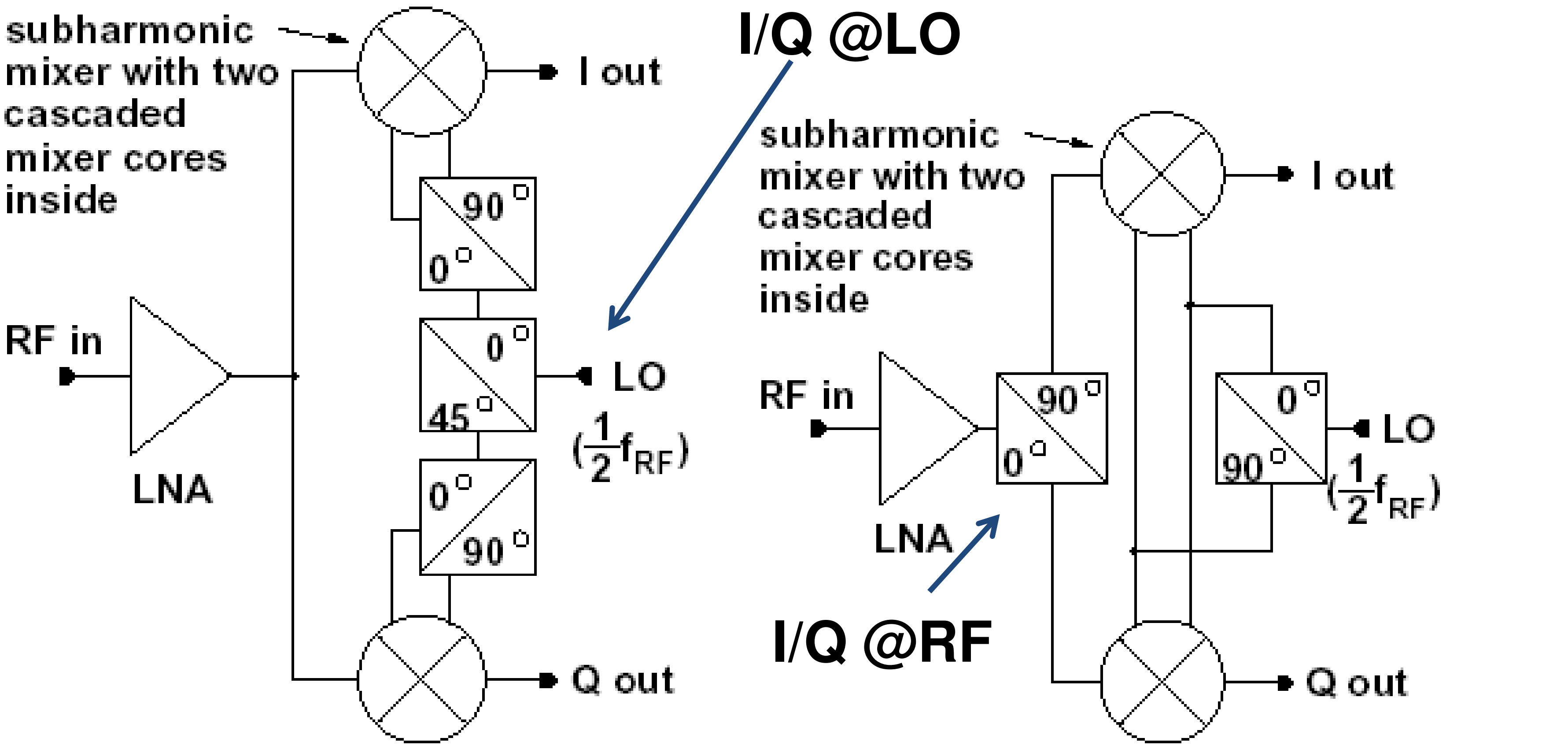
Small Signal S-Parameter



[1] S. Malz et. al., A 275 GHz Amplifier in 0.13 µm SiGe, EUMIC 16

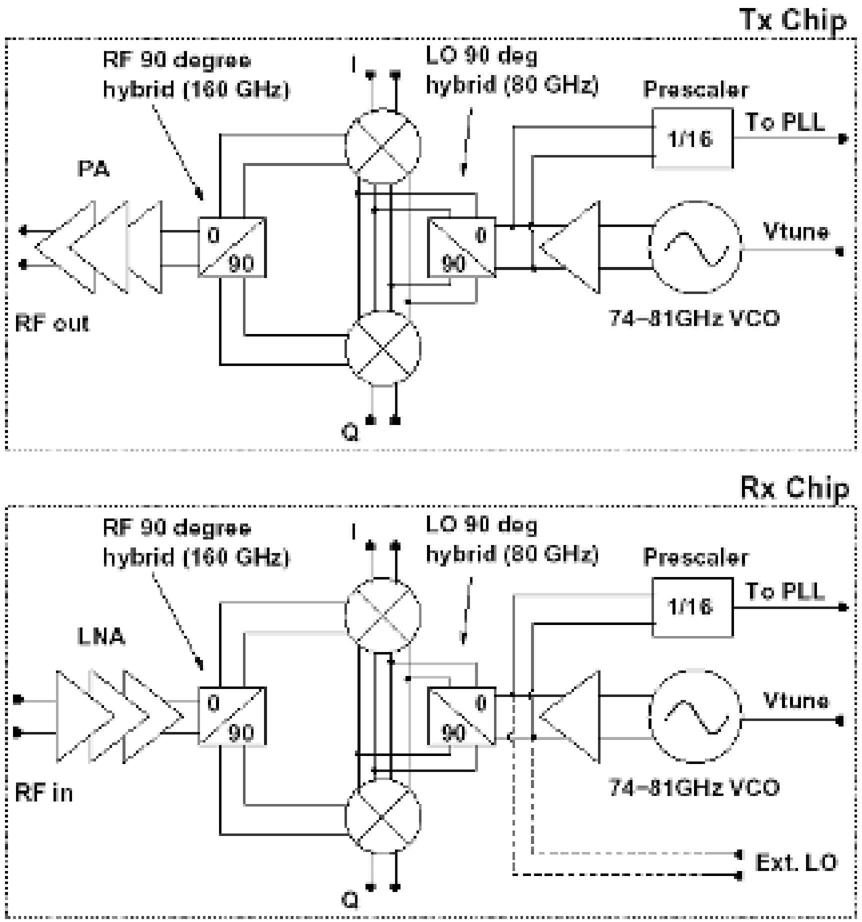
Subharmonic Techniques

Subharmonic I/Q Mixer Design

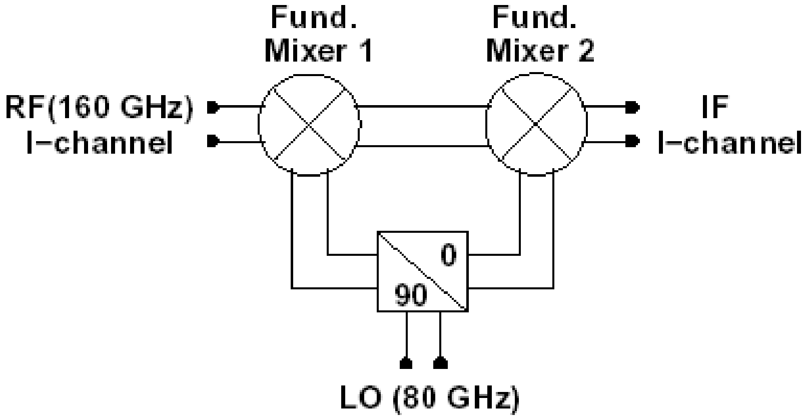


Advantage of sub-harmonic architecture: relaxed LO drive requirements!

Example: 160GHz Rx/Tx Chip-Set



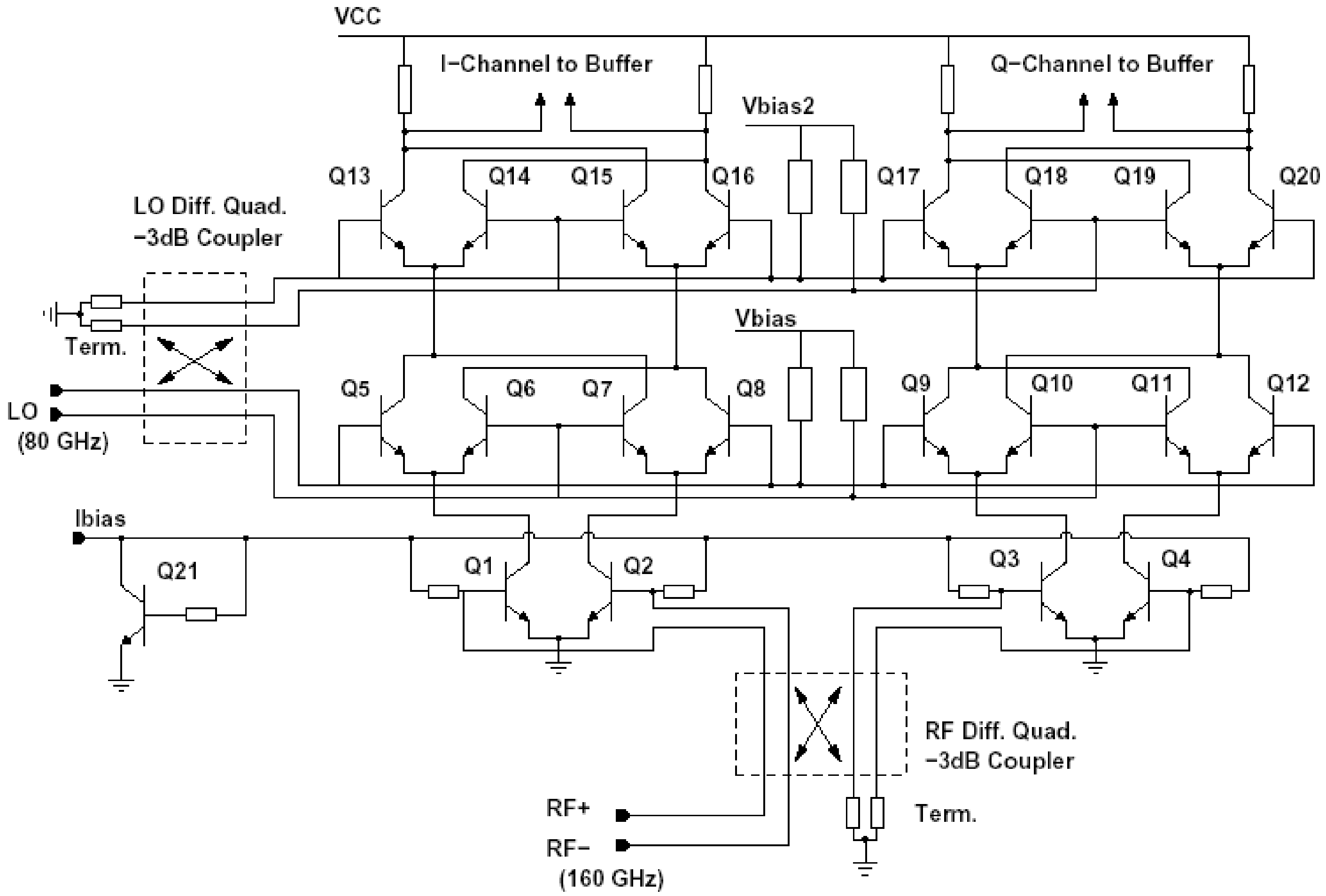
Subharmonic mixer
= super heterodyn mixer
with same LO



Why use trig. identity:
sin(2x) = 2 cos(x) * sin(x)
and not:
1+sin(2x) = 2 sin(x) * sin(x)

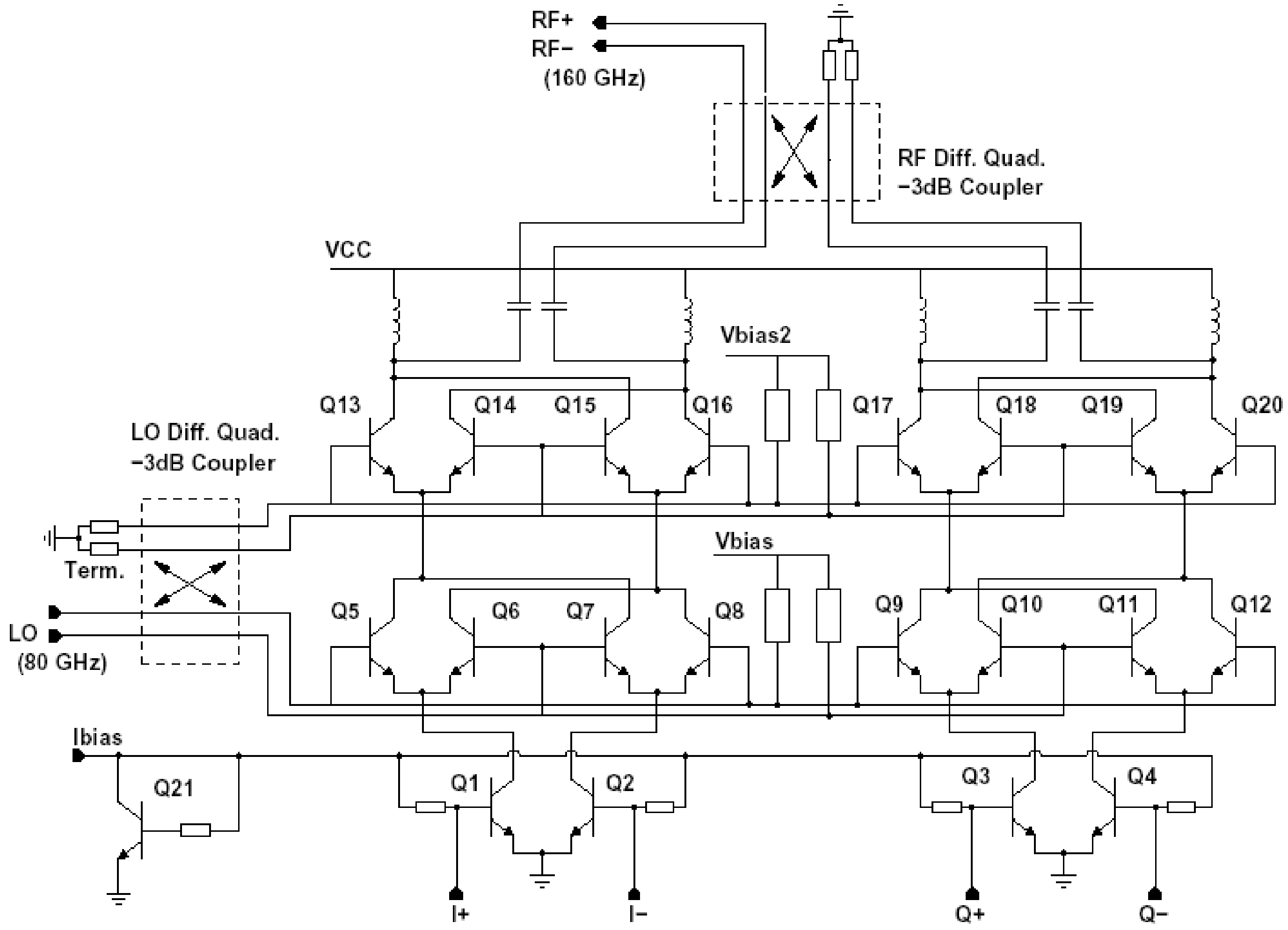
[1] Yan Zhao, Member, Erik Öjefors, Klaus Aufinger, Thomas F. Meister, Ullrich R. Pfeiffer, A 160-GHz Subharmonic Transmitter and Receiver Chip-set in a SiGe HBT Technology, TMTT 2012

Sub-Harmonic I/Q Receiver Schematic



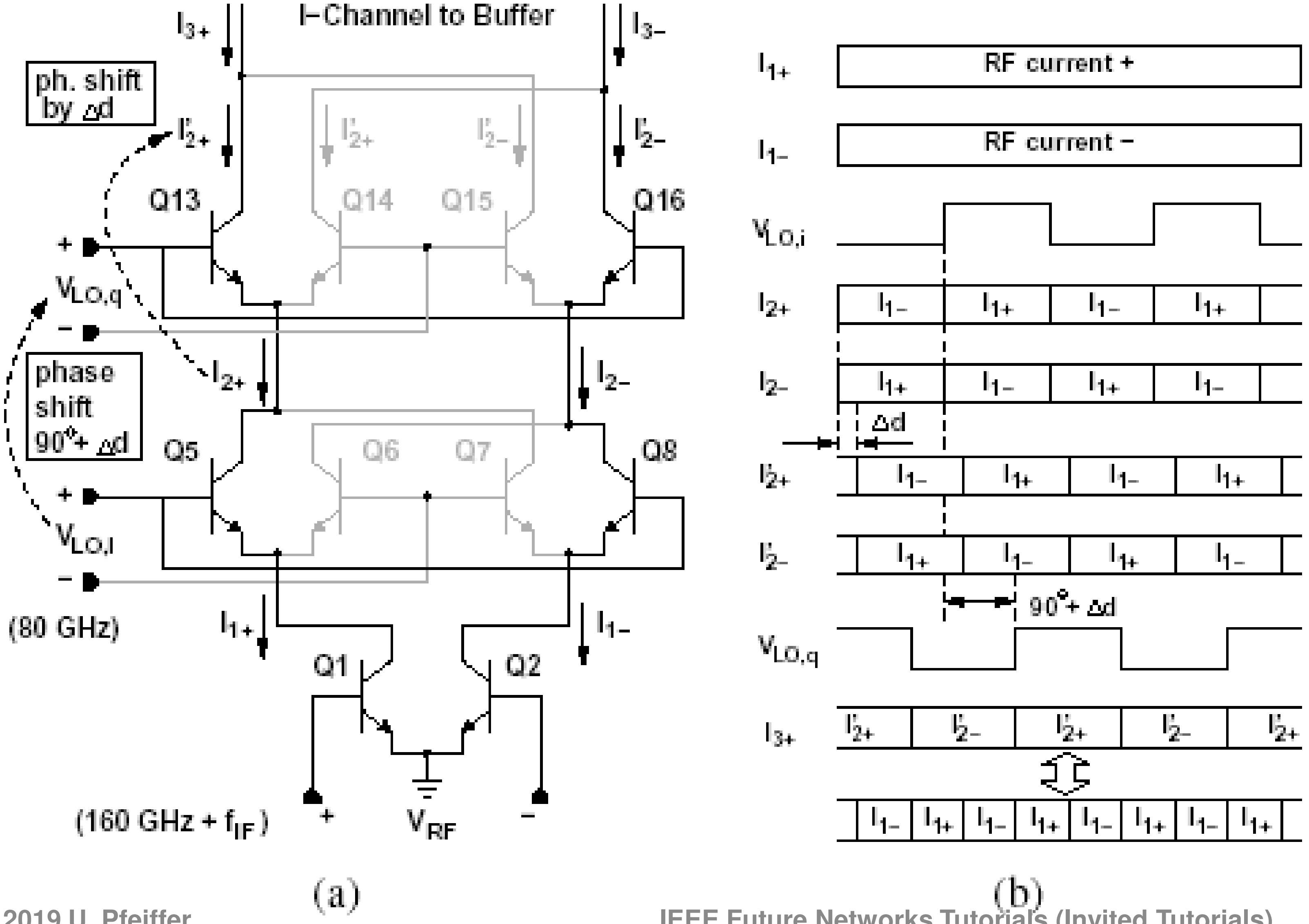
Complex design at 160GHz:
two 90deg hybrids, 4 switching quads, 20 HBTs

Sub-Harmonic I/Q Transmitter Schematic



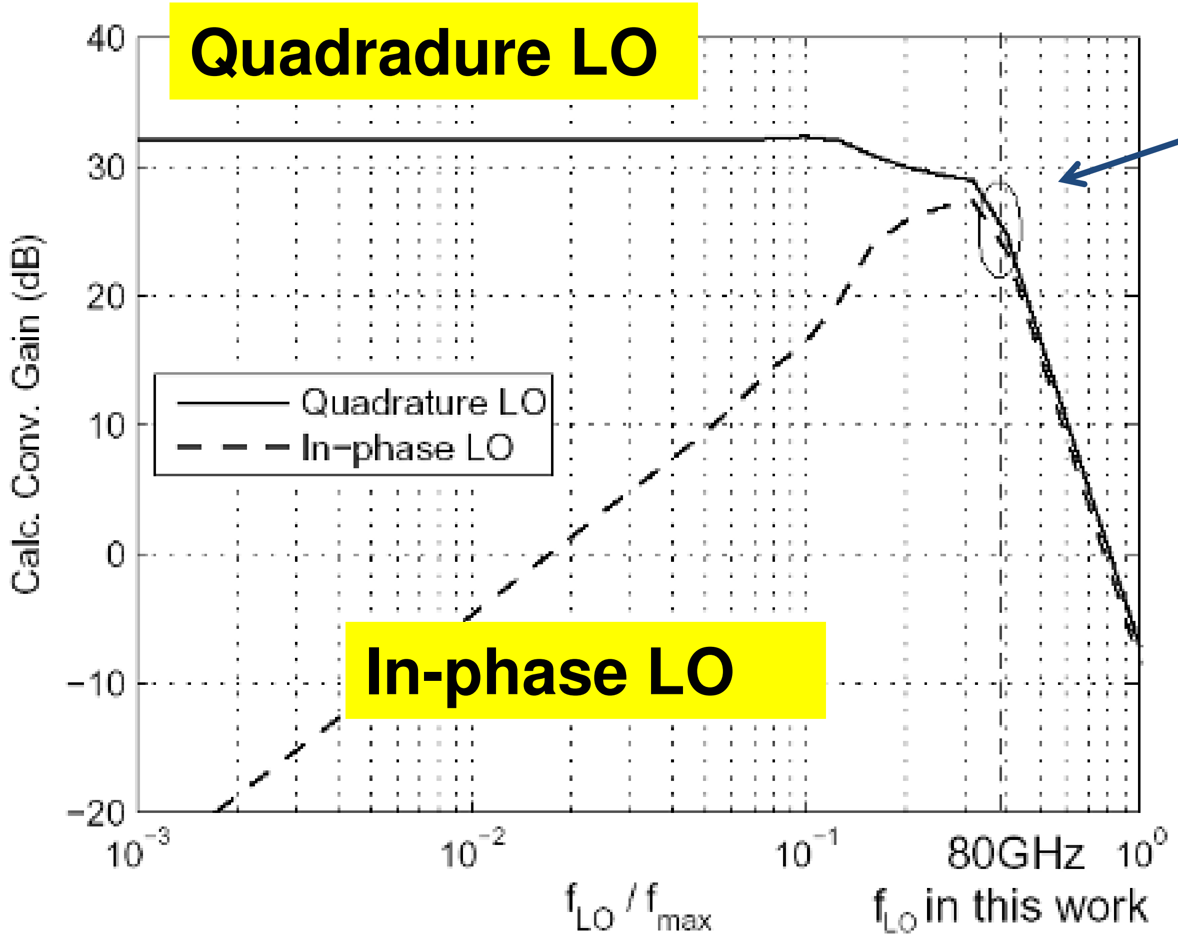
Similar complexity at TX

Principle of Operation (RX)



What are the limitations for operation close to fmax? Quadrature LO require square waves (ideal switching quads)!

How close to Fmax can we operate?

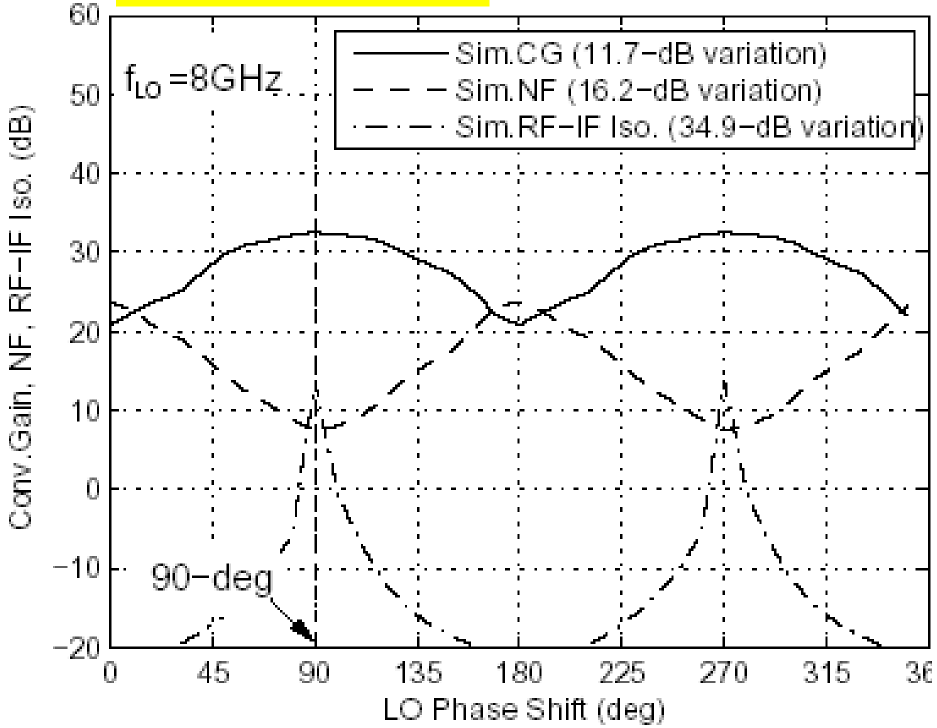


We are here!
(no square-waves)

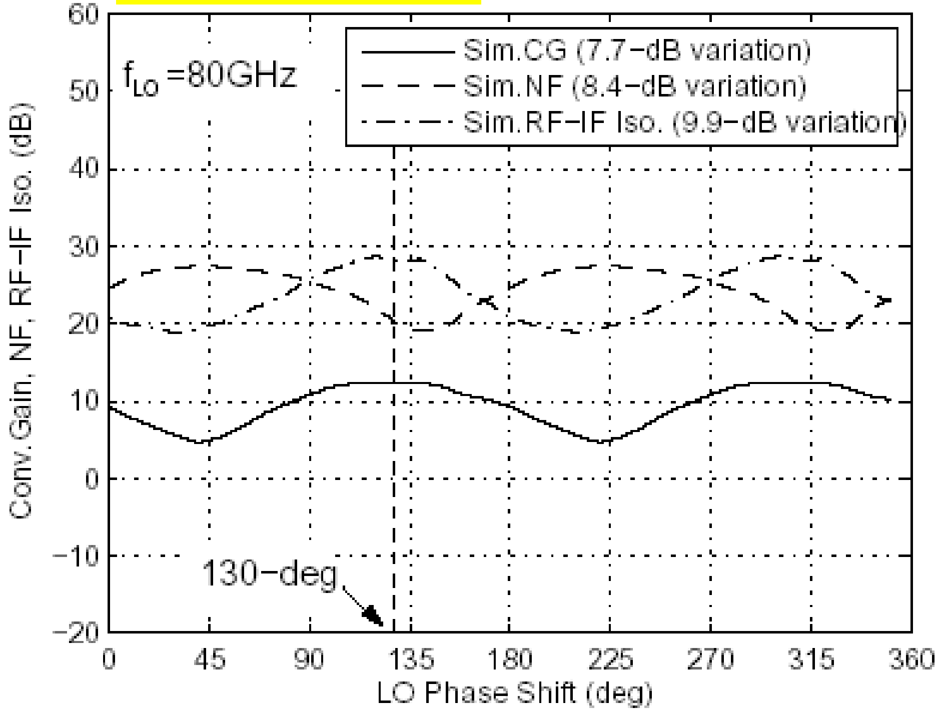
Large-signal HB simulation

Optimum LO phase shift

8 GHz LO



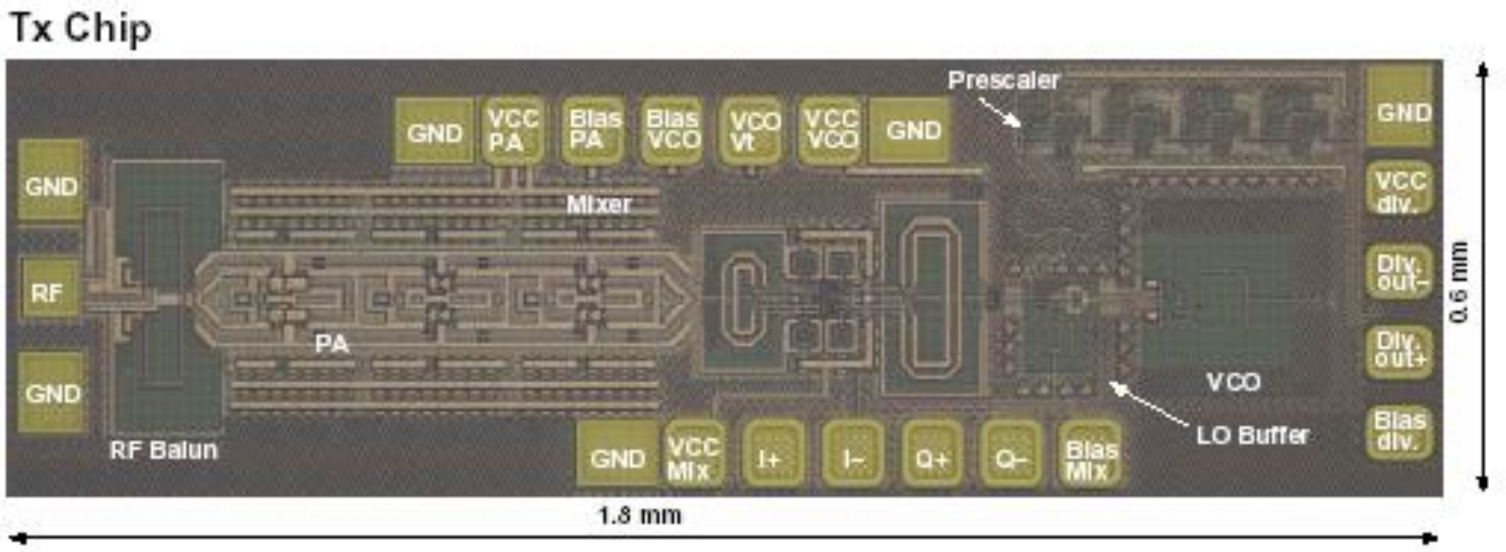
80 GHz LO



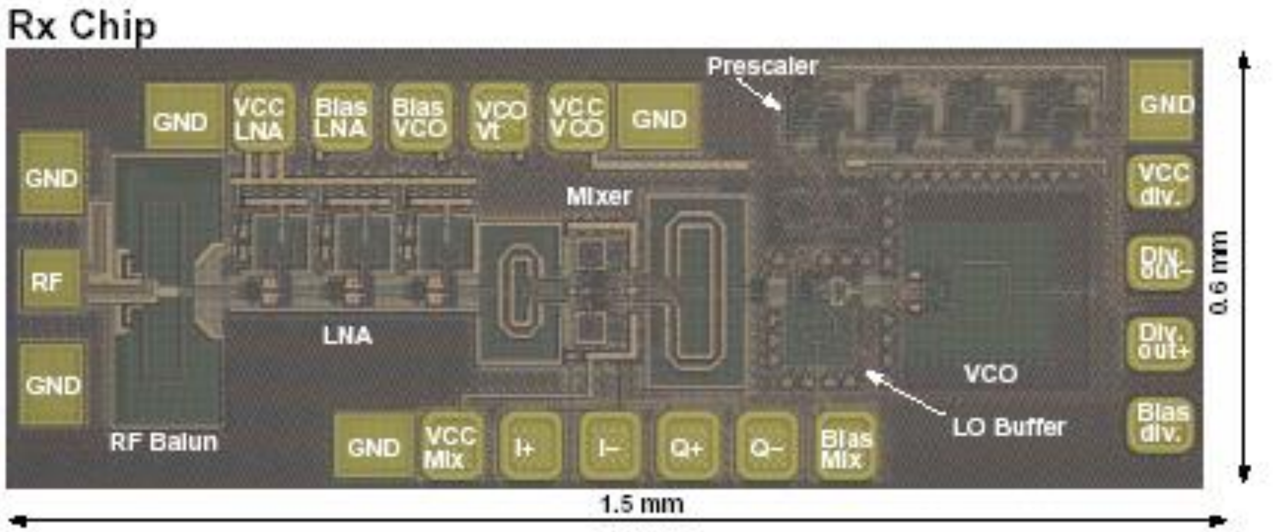
At 8GHz 90deg LO is optimal (11.7 dB variation)
At 80GHz phase is less importnet (7.7dB variation, 130deg is optimum due to parasitic phase shifts in quads)

Chip Micrographs

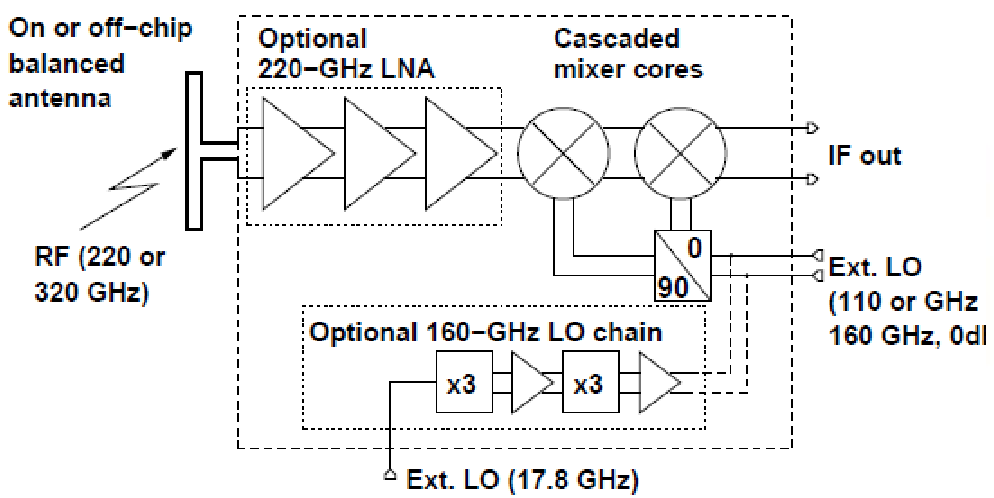
Tx:

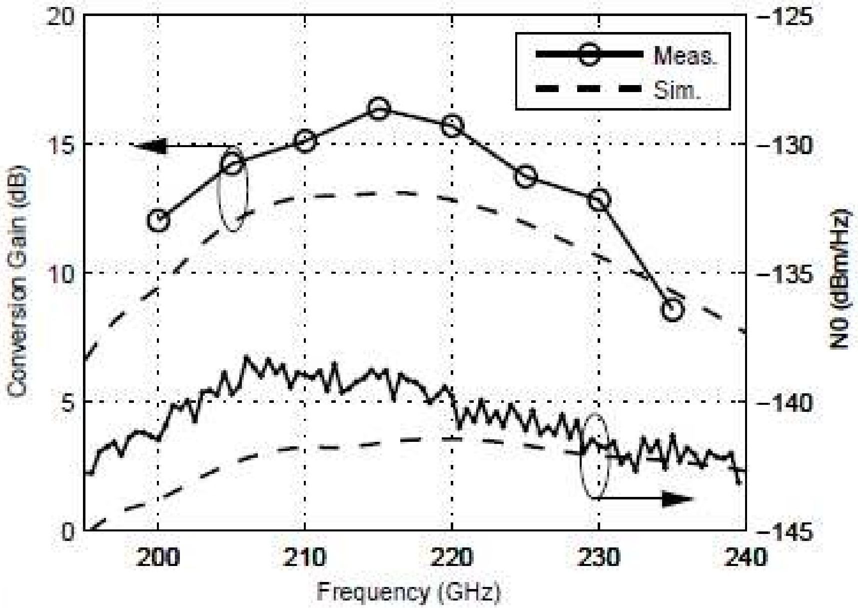


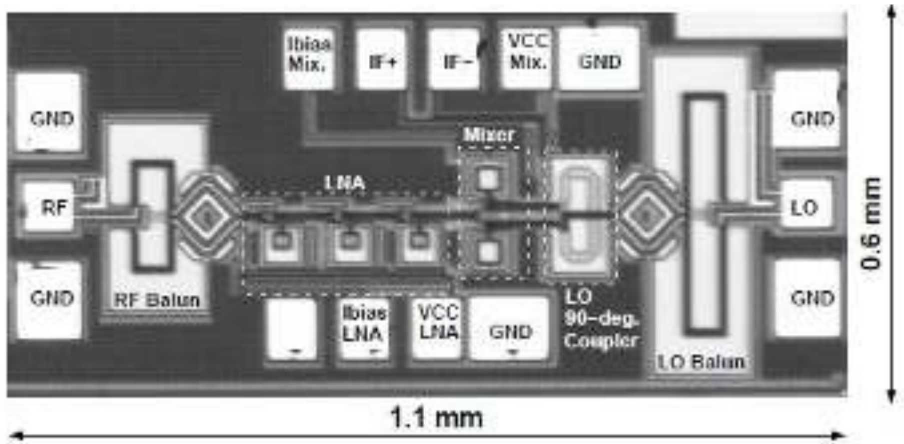
Rx:



220GHz Sub-harmonic Receiver



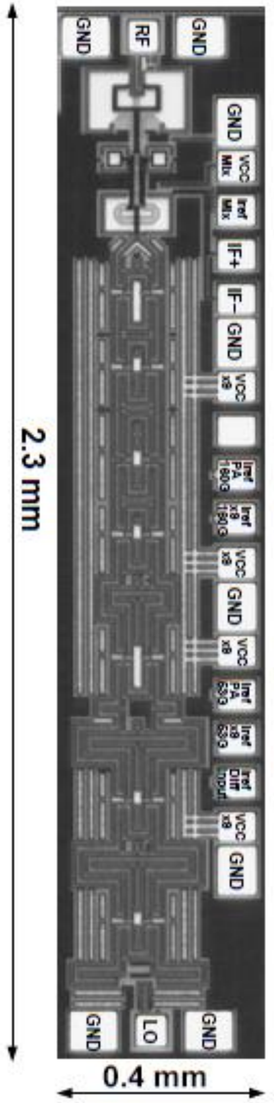


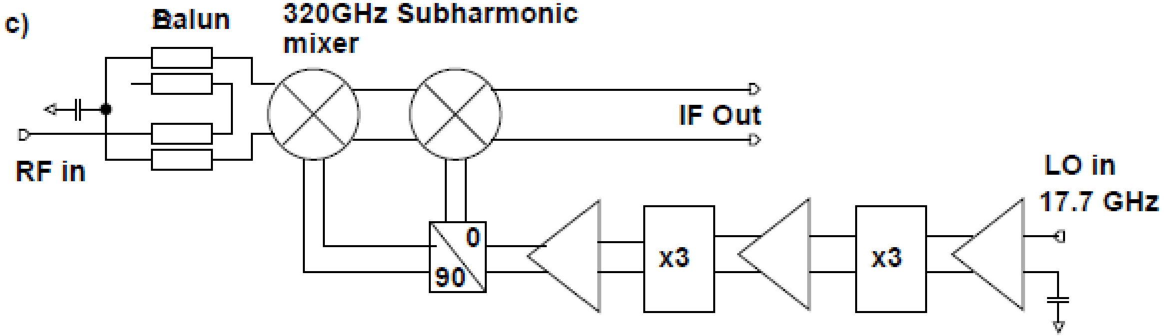


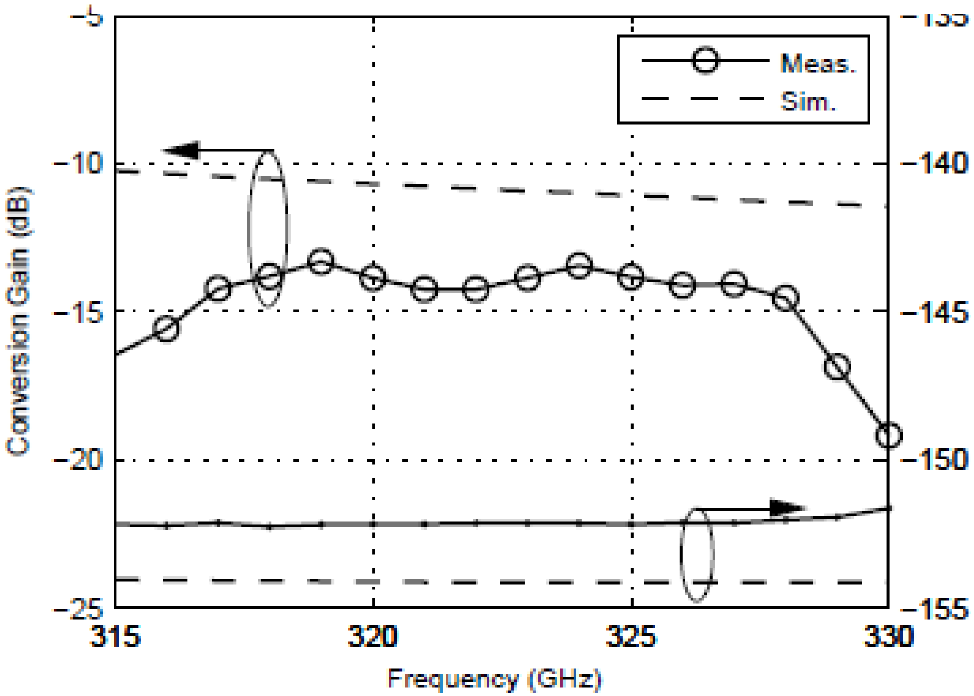
Similar concept at 220GHz (110GHz LO)
16dB CG
18dB SSB NF

[1] E. Öjefors et al, RFIC 2011

320GHz Sub-harmonic Front-End







[1] E. Öjefors et al, RFIC 2011

Similar concept at 320GHz (160GHz LO)

No LNA!!!
-13dB CG
32dB SSB NF

Circuits for Communication Fundamentally operated 240 GHz IQ Tx and Rx Chip-Set

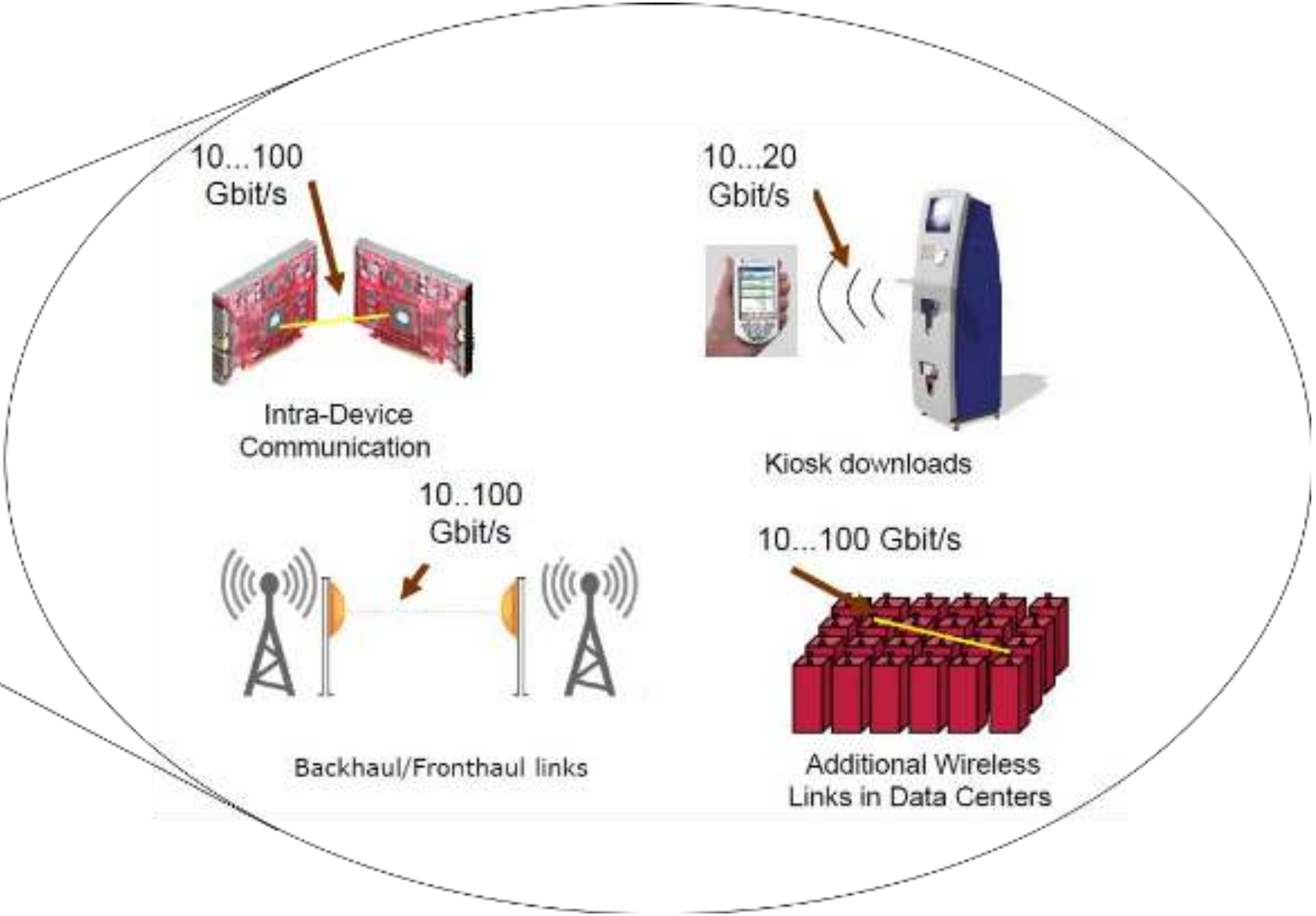
Communication Towards 100Gbps

High-speed Communication

- 60GHz, E-band, 5G, 6G, …
- IEEE 802.15.3d-2017 252.72-321.84GHz
- Towards 100GBit/s
- Interconnects
- Data servers
- Networking and protocols

- **Commercially available wireless standards, e.g. WLAN can deliver theoretical data rates of 600 Mbps (802.11n).**
- **The limited data rate is related to the very limited available bandwidth (hundreds of MHz) in the frequency band of 2-5 GHz. Hence, towards realizing data rates approaching 100 Gbps, frequency up-scaling is inevitable.**
- **Above the licensed bands, e.g. at frequencies beyond 300 GHz excessive bandwidth is available and provides a feasible alternative towards 100 Gbps wireless links.**

Usecases adressed by IEEE 802.15.3d-2017



240GHz link-budget estimation (QPSK)

$$FSPL_{max} = 10log_{10}(kT \cdot BW) + NF + SNR_{min} - P_{TX} - G_{AntTX} - G_{AntRX} + 10dB$$

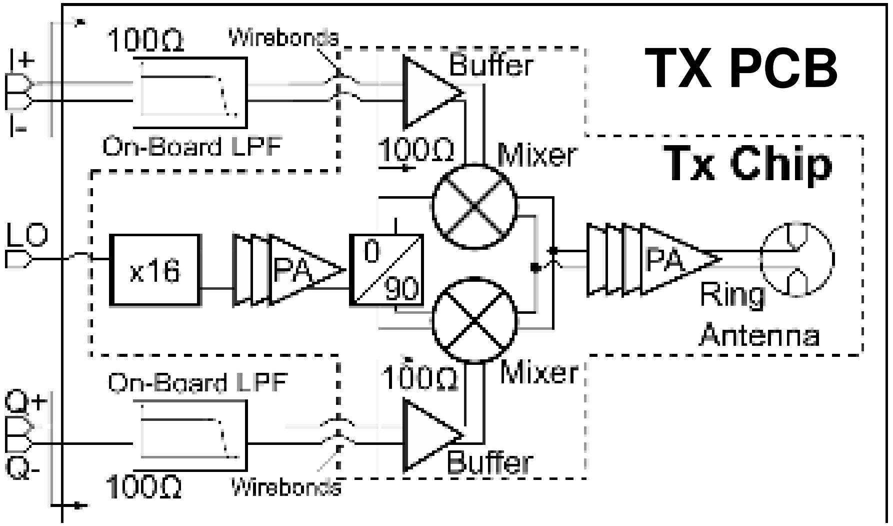
Tx power	NF	Number of channels	Band width	Minimum required receive power	Tx antenna gain	Rx antenna gain	Maximum path loss	Achievable range
0 dBm	20 dB	1	50 GHz	-39,84 dBm	0 dBi	0 dBi	29,84 dB	0,003 m
3 dBm	10 dB	1	50 GHz	-49,84 dBm	25 dBi	5 dBi	72,84 dB	0,44 m
6 dBm	10 dB	2	25 GHz	-52,85 dBm	25 dBi	5 dBi	78,85 dB	0,87 m
6 dBm	10 dB	2	25 GHz	-52,85 dBm	25 dBi	25 dBi	98,85 dB	8,71 m

Circuit Design Challenge:
trade-off Pout, NF, BW, range, ant. gain, packaging

220-260 GHz TX/RX Chip Block Diagrams

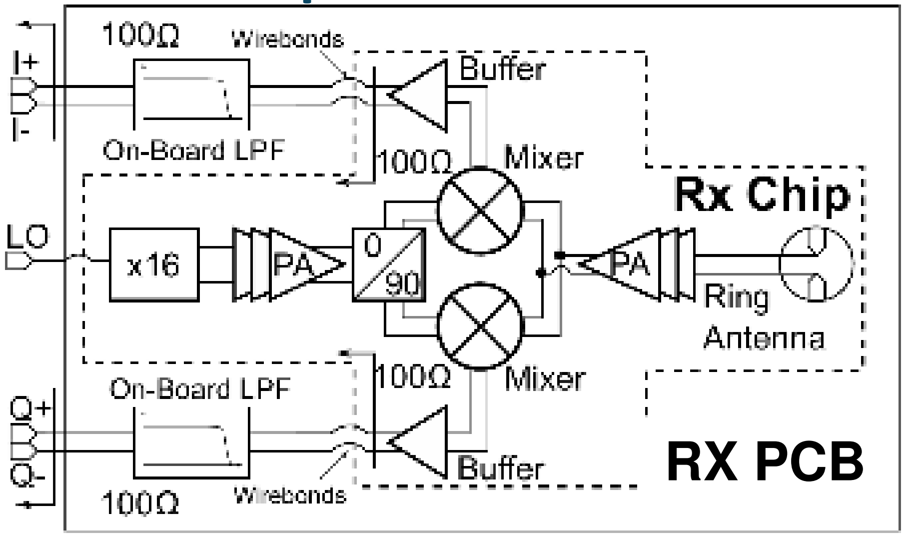
- Direct conversion I/Q Rx/Tx chip set
- In run 2, an improved hybrid is used and LNA replaced by 3-stage PA for BW and center frequency alignment
- Run 1 optimized for RF bandwidth and Run 2 optimized for RF and IF bandwidth

Transmitter

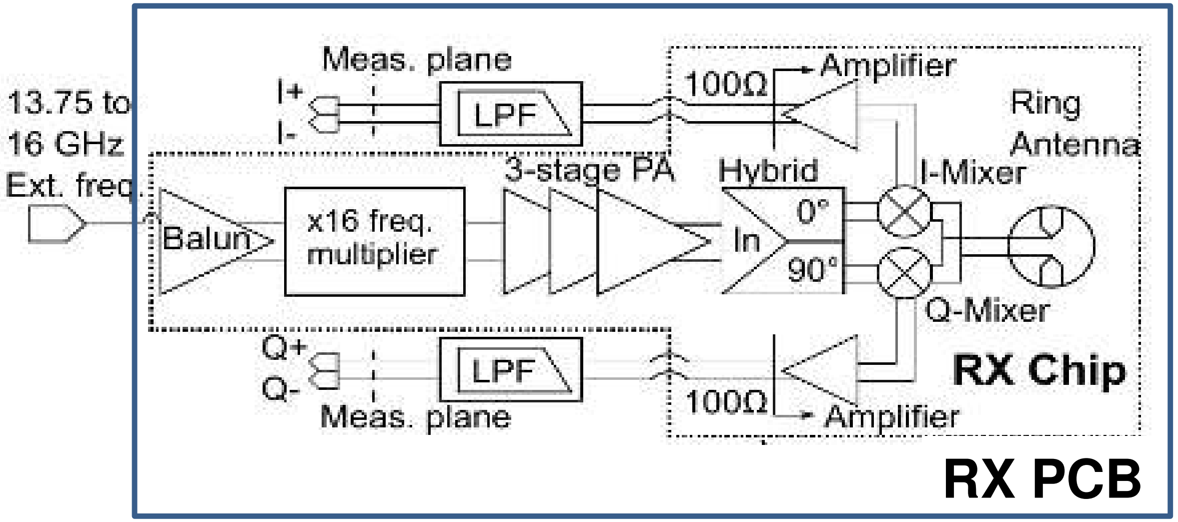


[1] N. Sarmah et al, TMTT 2015 run 1
[2] N. Sarmah et al, EUMIC 2016 run 2

Amplifier First



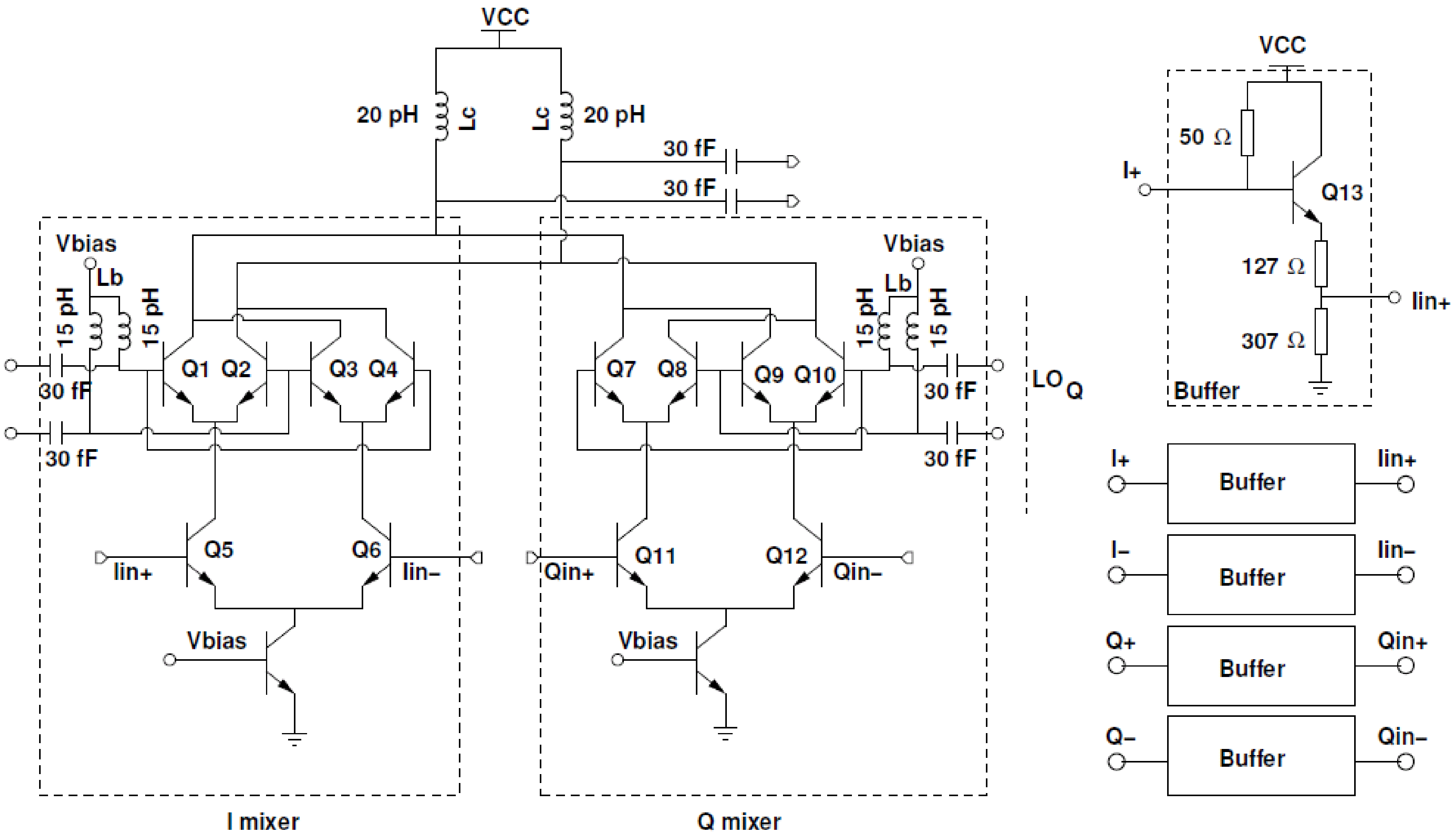
Mixer First



[3] P. R. Vazquez et al, Int. J. of Microw. and Wireless Tech.

[1] N. Sarmah et al, TMTT 2015 run 1
[2] N. Sarmah et al, EUMIC 2016 run 2

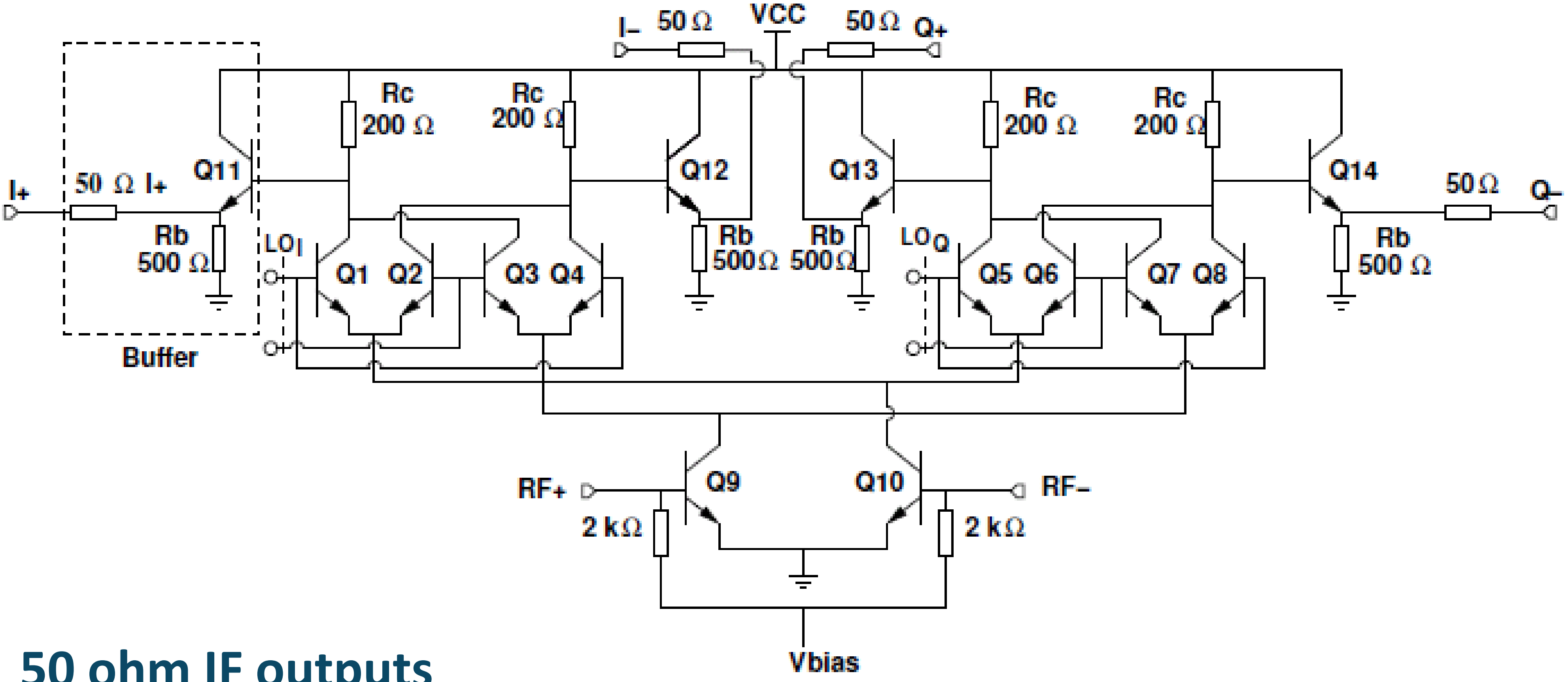
Up-conversion mixer (run 2)



- **50 ohm IF inputs**
- **Up-conversion mixer: CG -0.2 dB@240 GHz, Psat=-5 dBm (simulated)**

[1] N. Sarmah et al, EUMIC 2016 run 2

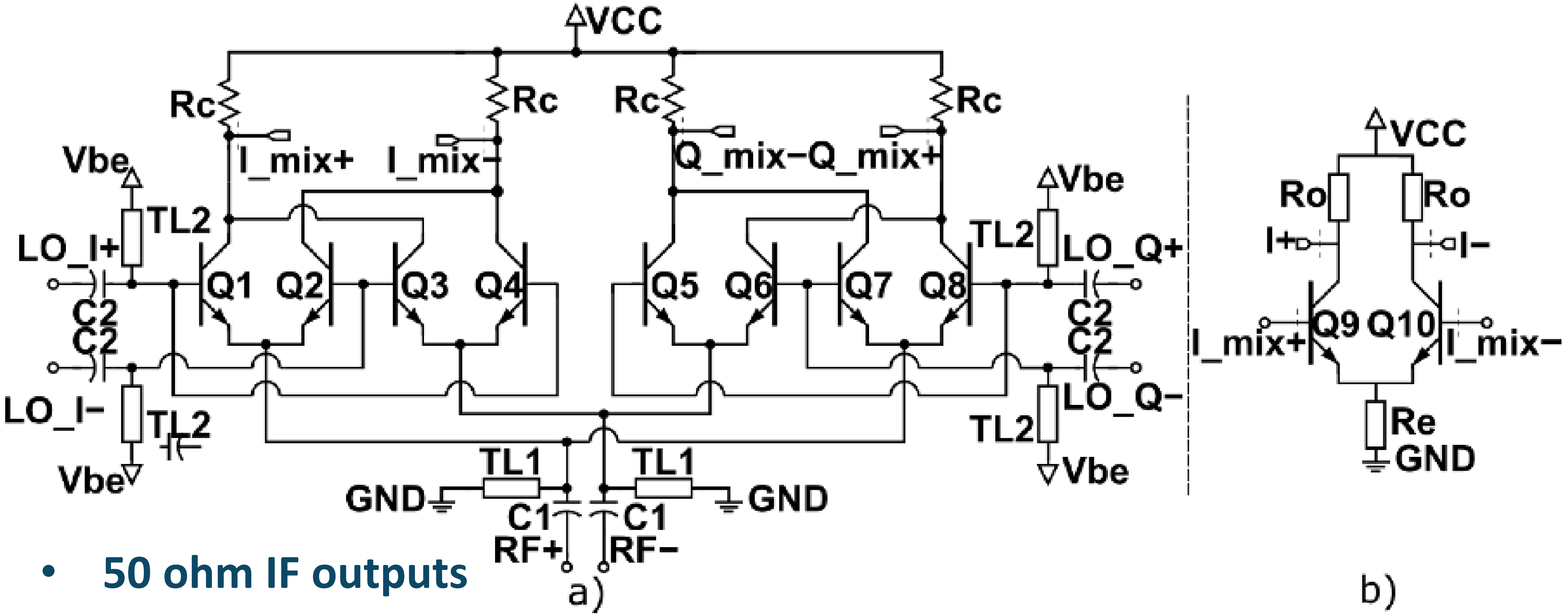
Down-conversion mixer (Amplifier first, run 2)



- 50 ohm IF outputs
- Down-conversion mixer: CG -0.2 dB@240 GHz, SSB NF 14.2 (simulated)

[1] N. Sarmah et al, EUMIC 2016 run 2

Mixer-first Circuit Schematic (no LNA)

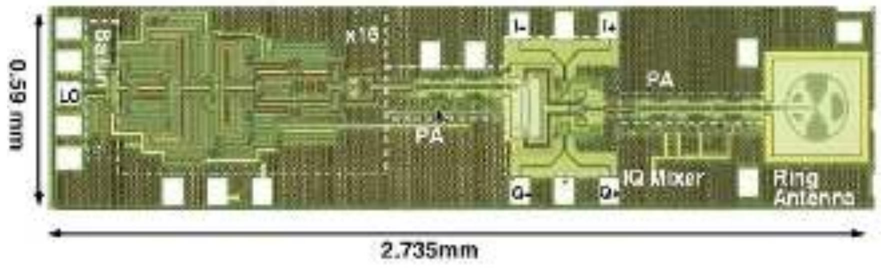


- 50 ohm IF outputs
- Down-conversion mixer: CG 0dB@240 GHz, SSB NF 11dB (simulated)

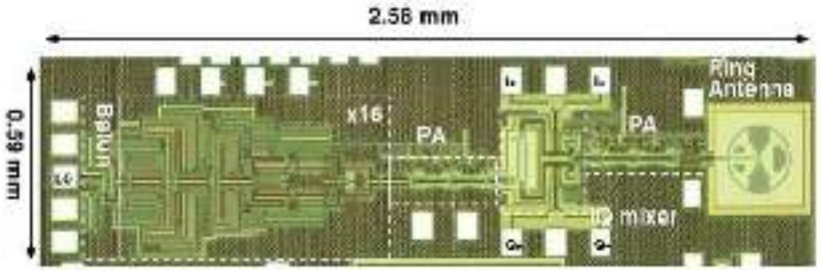
[3] P. R. Vazquez et al, Int. J. of Microw. and Wireless Tech.

Chip Micrographs and Packaging

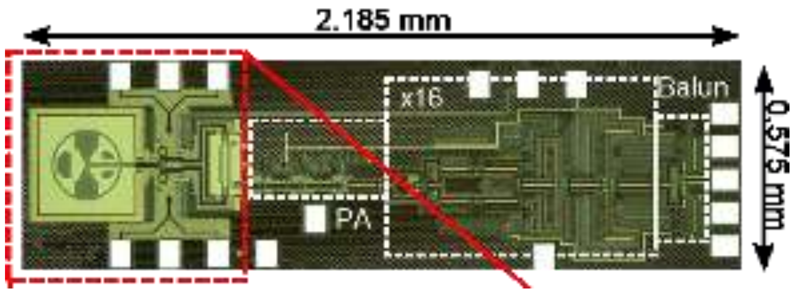
Transmitter

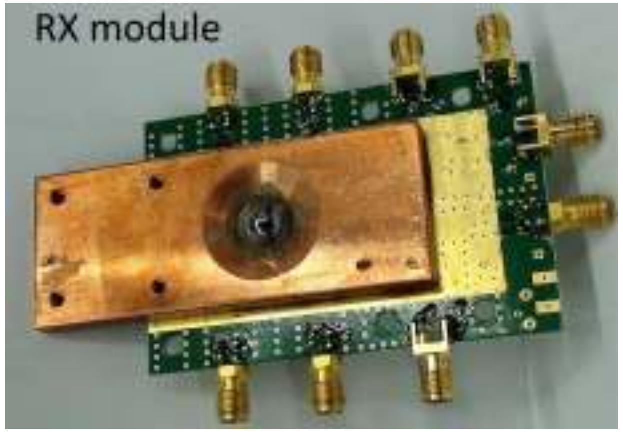


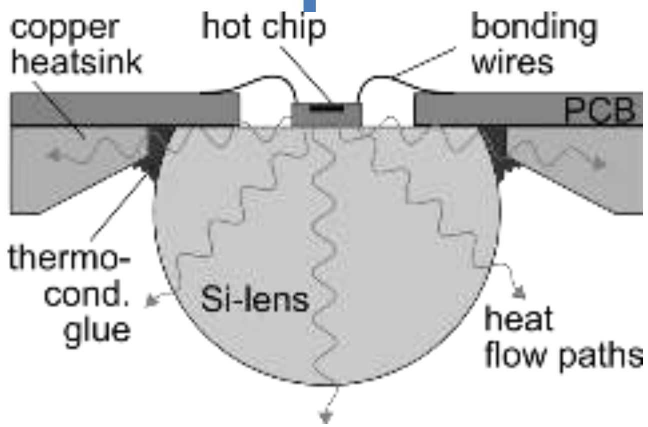
Amplifier First RX

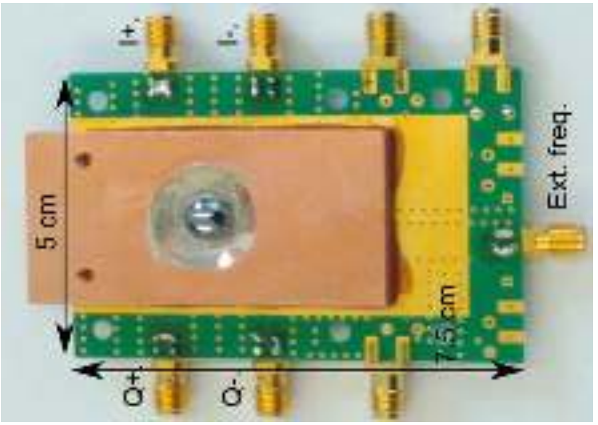


Mixer First RX

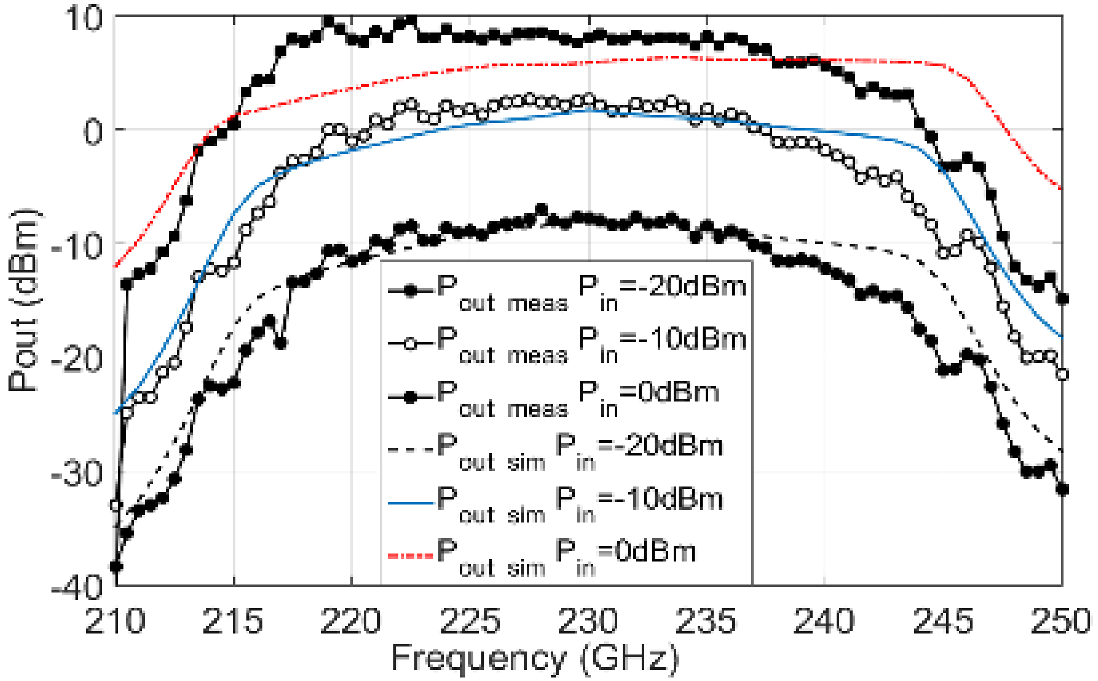


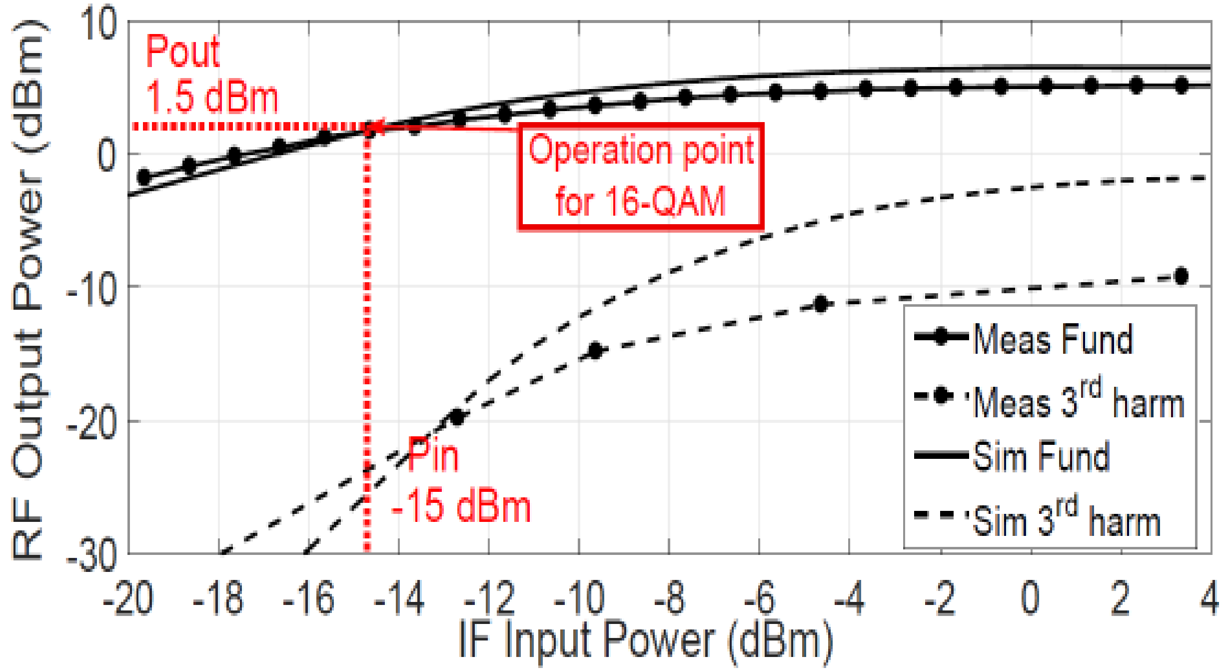






Transmitter RF Front-End Performance

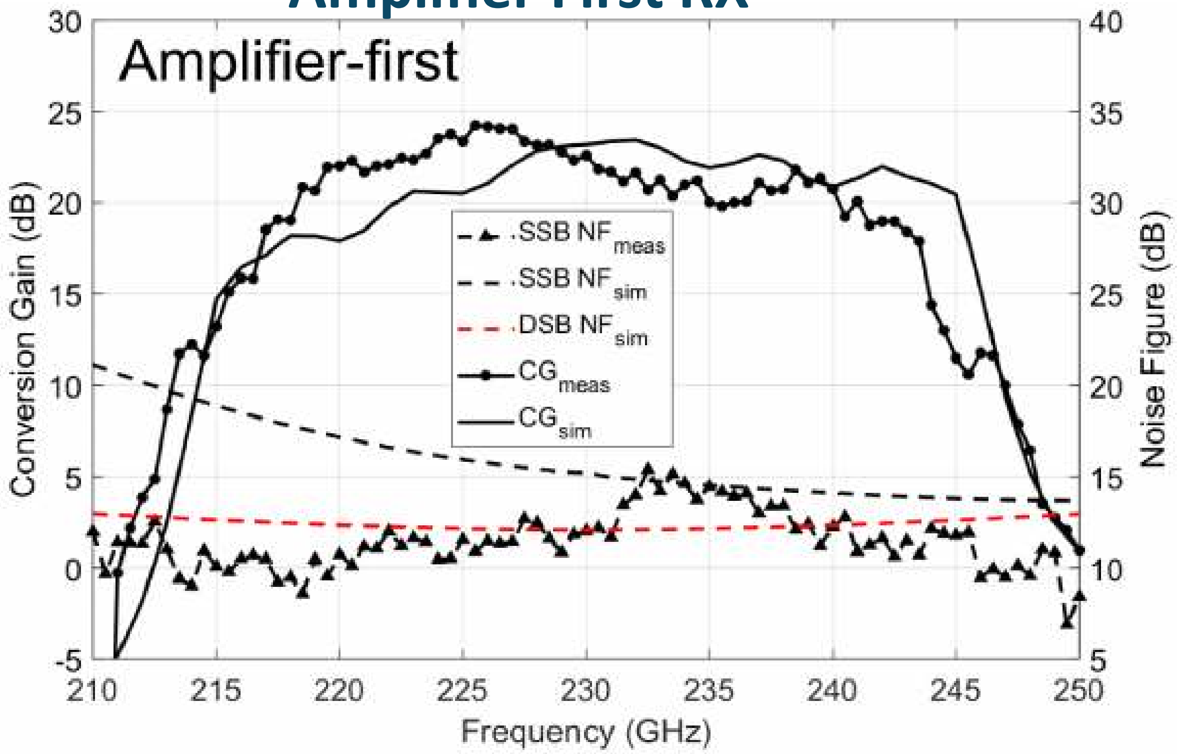




- **For LO = 220-260 GHz; Psat= -2 to 9.5 dBm**
- **3dB RF BW: 25GHz at 230GHz LO**
- **IP1dB = -15 to -5 dBm and additionally varies across IF frequency**
- **IQ Amp. Imb. < 0.5 dB for IF up to 17 GHz, IQ phase Imb. < 2 deg**

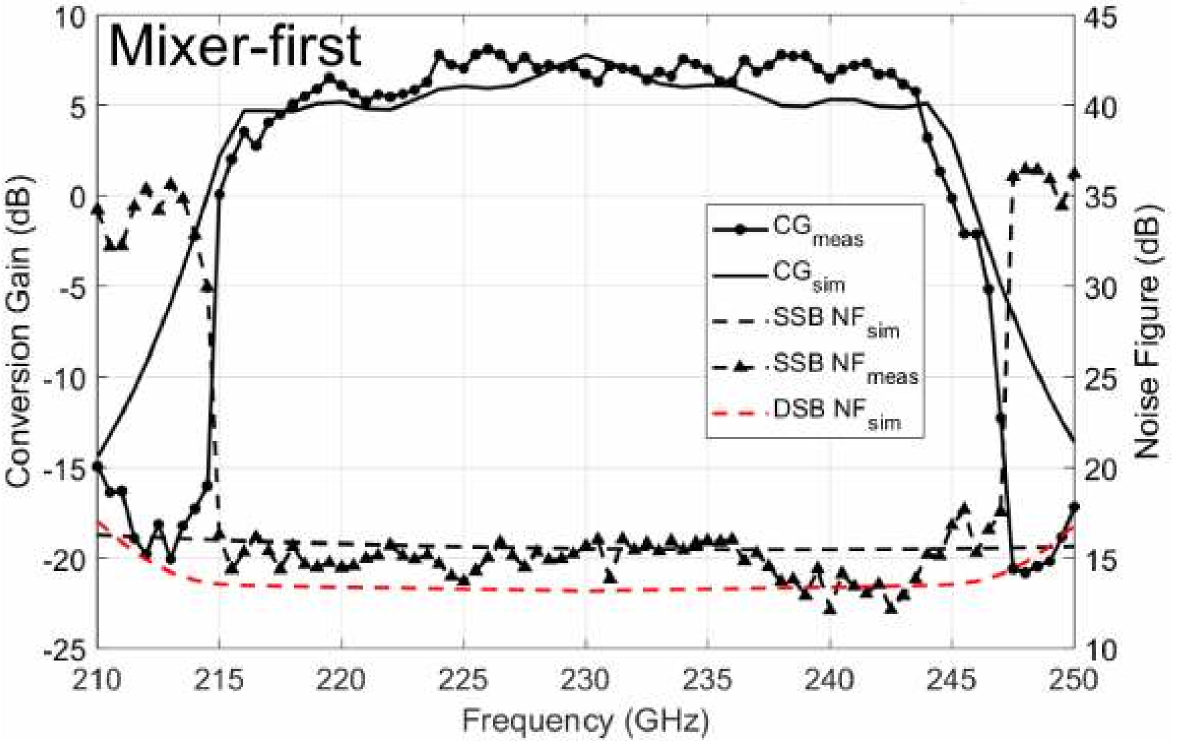
Receiver RF Front-End Performance

Amplifier First RX



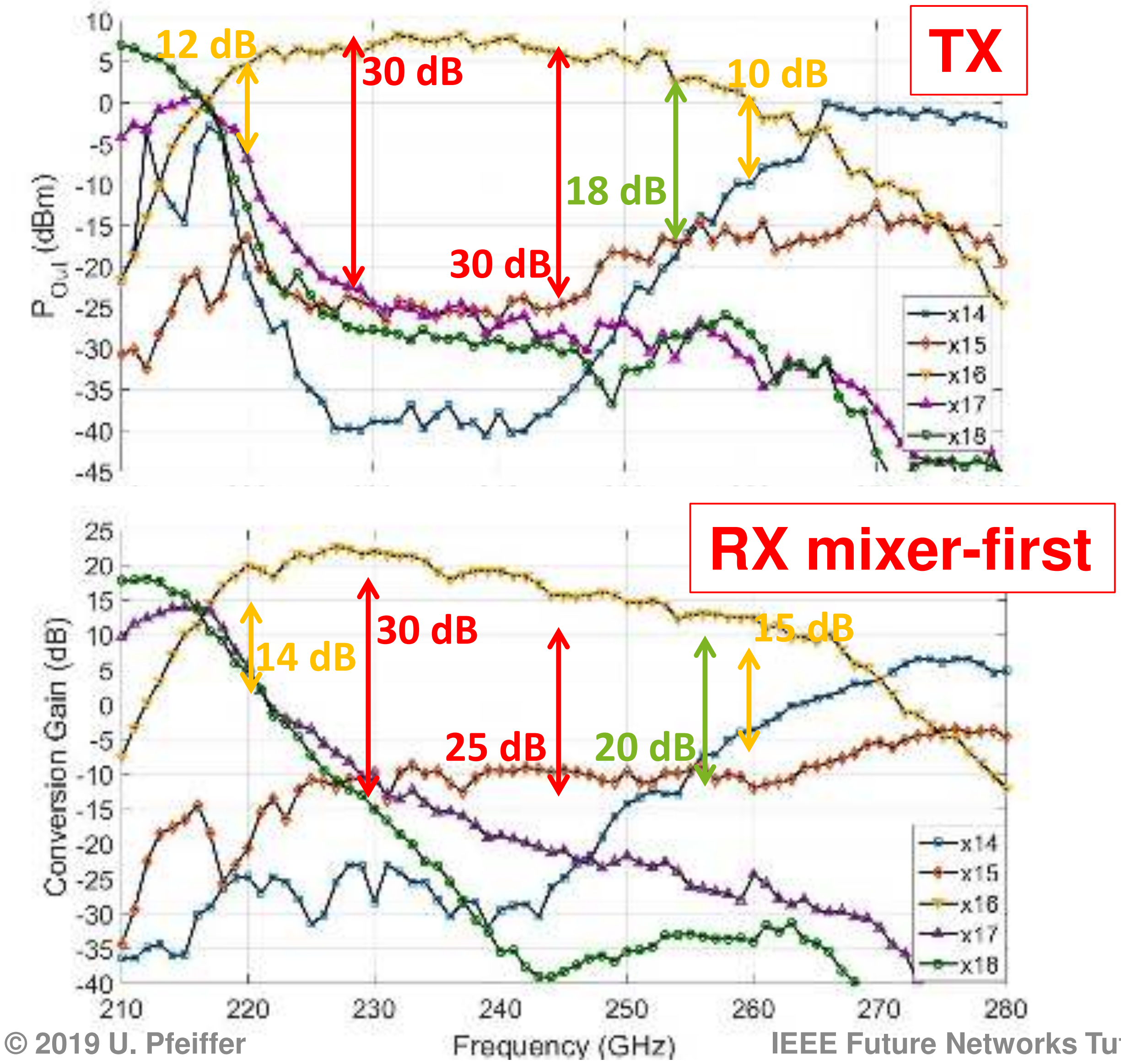
- For LO = 220-260 GHz:
  - CG = 12 to 24 dB, SSB NF = 9 to 16 dB
- 3dB RF/IF BW = 23/11.5 GHz
- IQ Amp. Imb. < 0.5 dB for IF up to 17 GHz

Mixer First RX



- For LO = 220-260 GHz:
  - CG = 7.8 dB, SSB NF = 13.5 to 14 dB
- 3dB RF/IF BW = 28/14 GHz
- IQ Amp. Imb. < 1 dB for IF up to 17 GHz

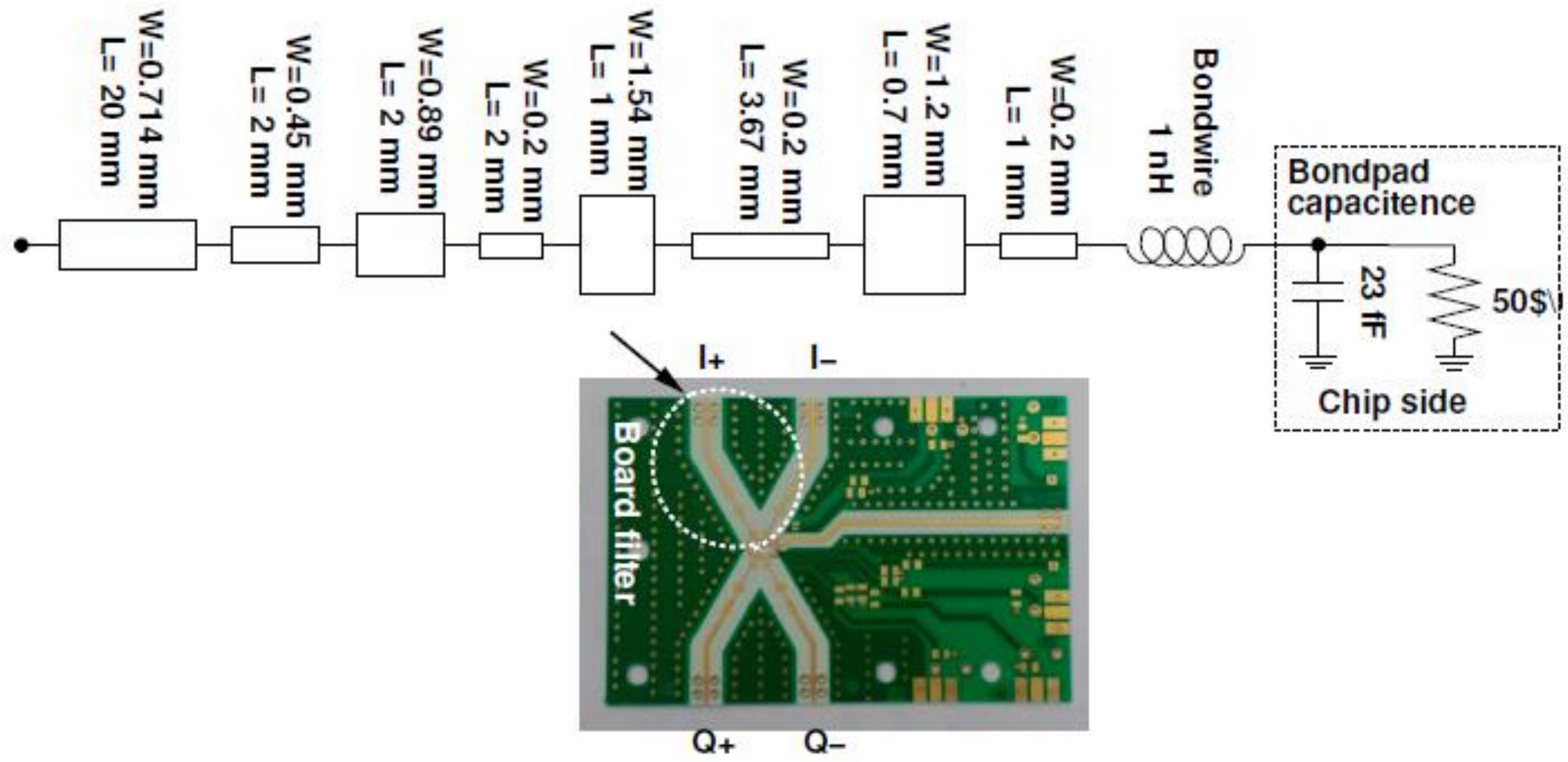
Harmonic Spurs From the Mult. chain



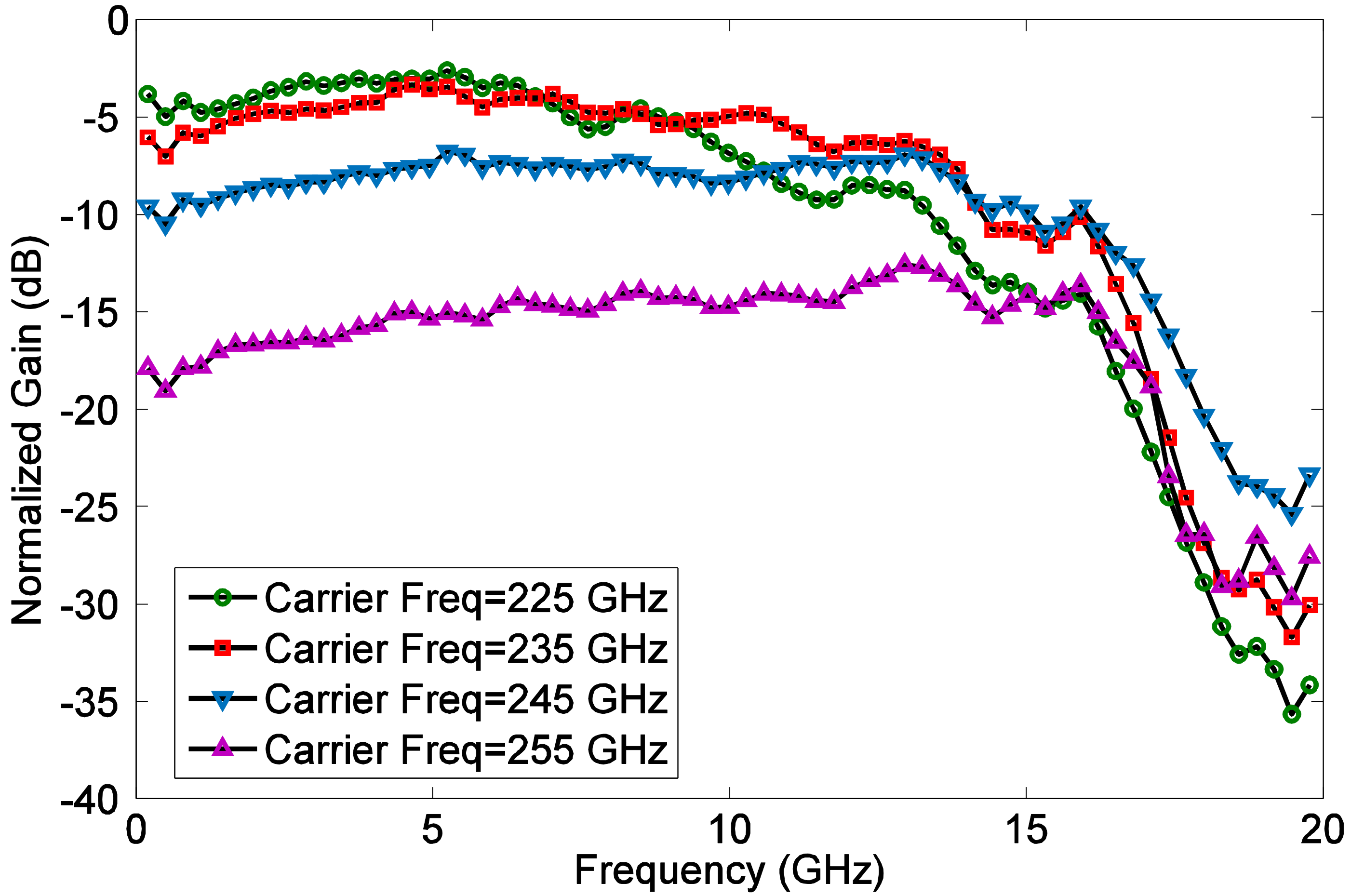
- Harmonic power was measured in the Tx and Rx for multiple LOs
- In the operation center (225-245 GHz), the spur content under 25 dB for the Odd harmonics.
- Between 245-255 GHz, the suppression is better than 18 dB.
- At 220 and 260 GHz (edges of the band), the harmonic suppression is worse than 15 dB.
- Odd harmonics are particularly harmful to this system

How to get wideband IF off chip?

- **Broadband low-pass filter based on the Rogers 4350B PCB material**
- **Microstrip line based stepped impedance filter implementation**



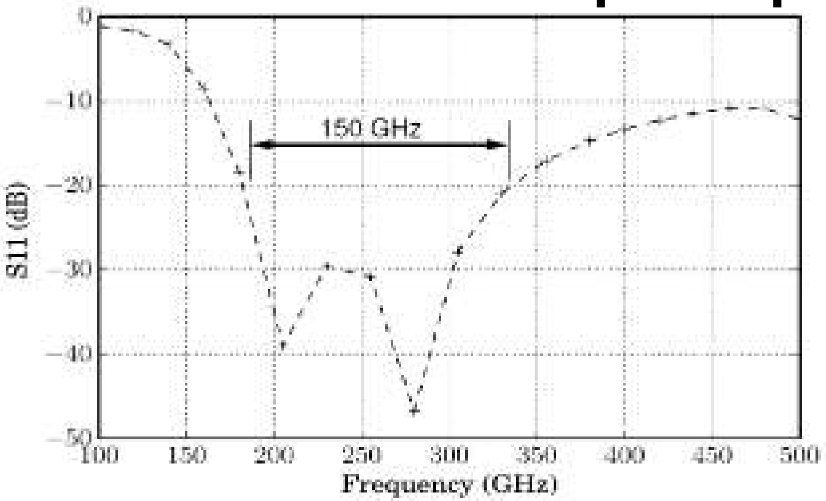
Tx/Rx IF Characterization



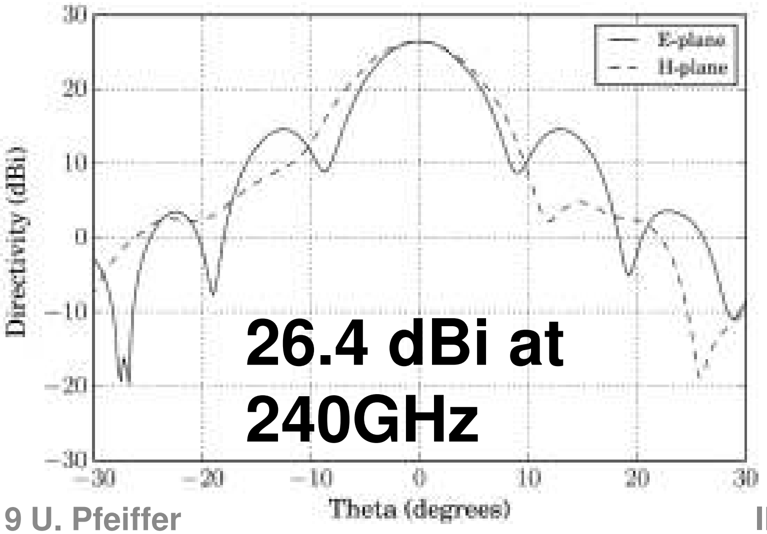
- **IF bandwidth characterization from back to back Tx-Rx measurement (saturated Tx)**
- **Link distance 90cm**
- **I/Q imbalance for the link< 1dB**
- **6-dB IF bandwidth is 15GHz**

Antenna Design/Packaging

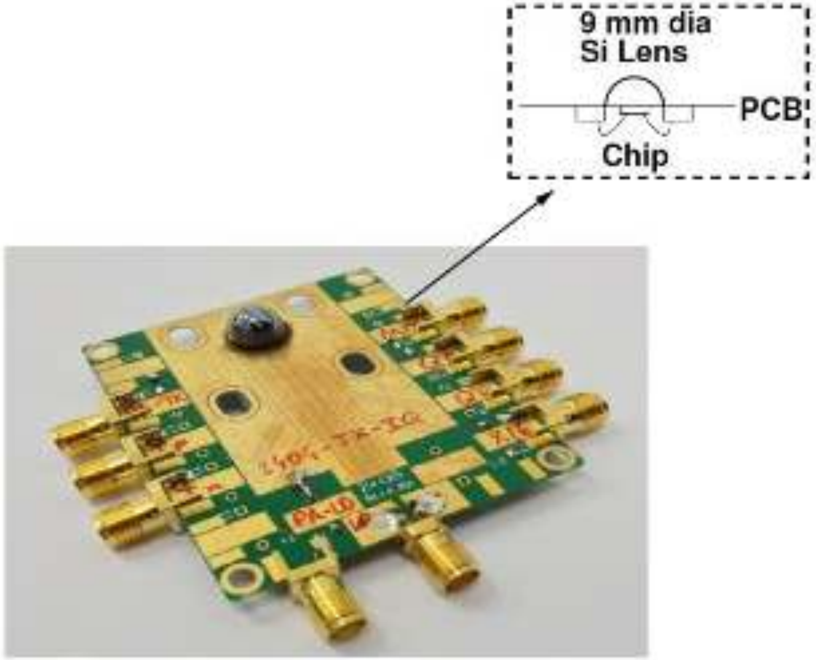
Simulated Antenna Input Impedance

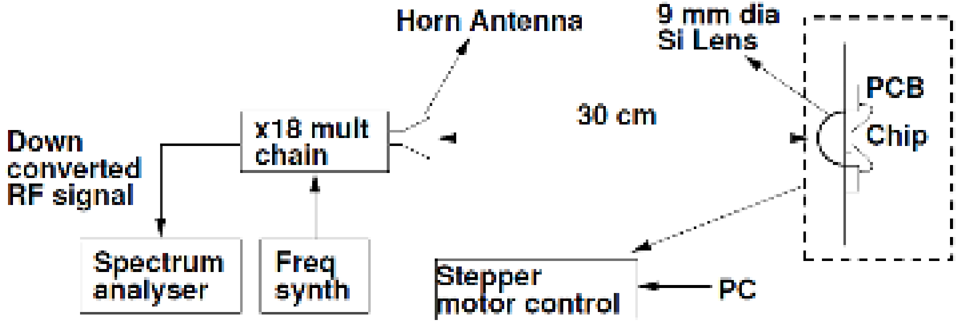


Measured Radiation Pattern



26.4 dBi at 240GHz





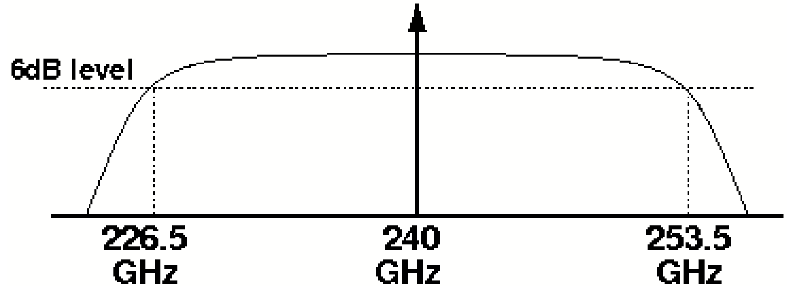
Estimated measured gain at 240 GHz: 26.4 dBi

Wireless Link Tests
240 GHz IQ Tx and Rx Chip-Set

Communication Link Tests

Approach 1: Full bandwidth

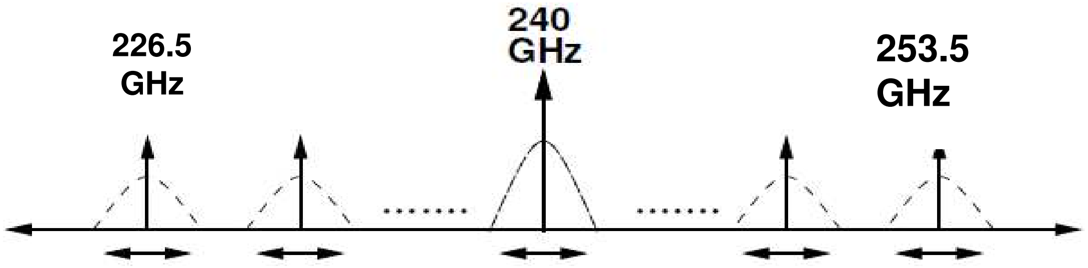
- Performance evaluation.
- Requires fastest test equipment (Scope/ADC) available on the market.
- Too costly/bulky for commercial applications.



Requires ultra fast test and measurement equipment

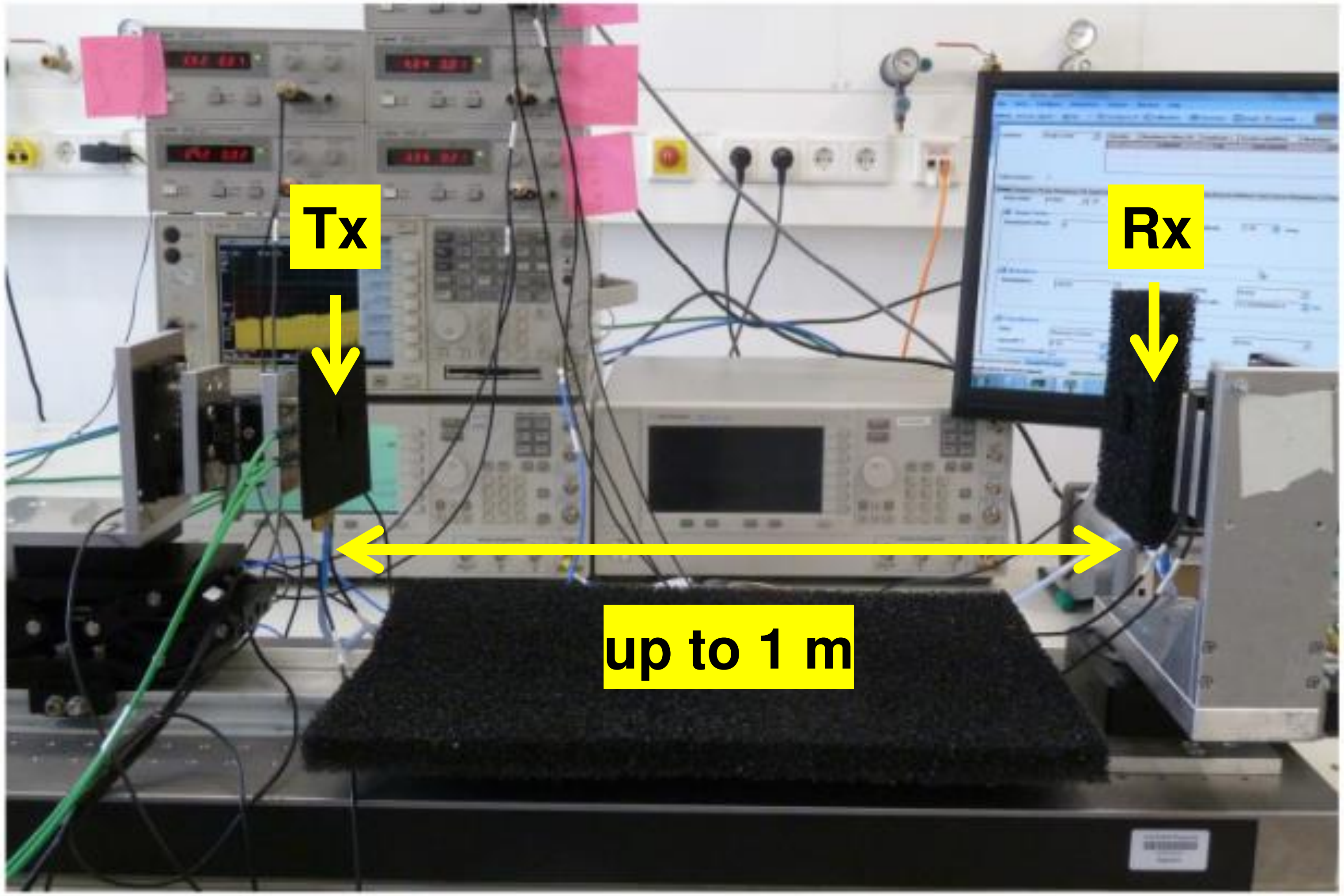
Approach 2: Multi-carrier

- Multiple carriers share the full bandwidth.
- Scalable data-rates possible
- Commercially viable due to commercial baseband/ADC hardware, e.g. from broadcom.



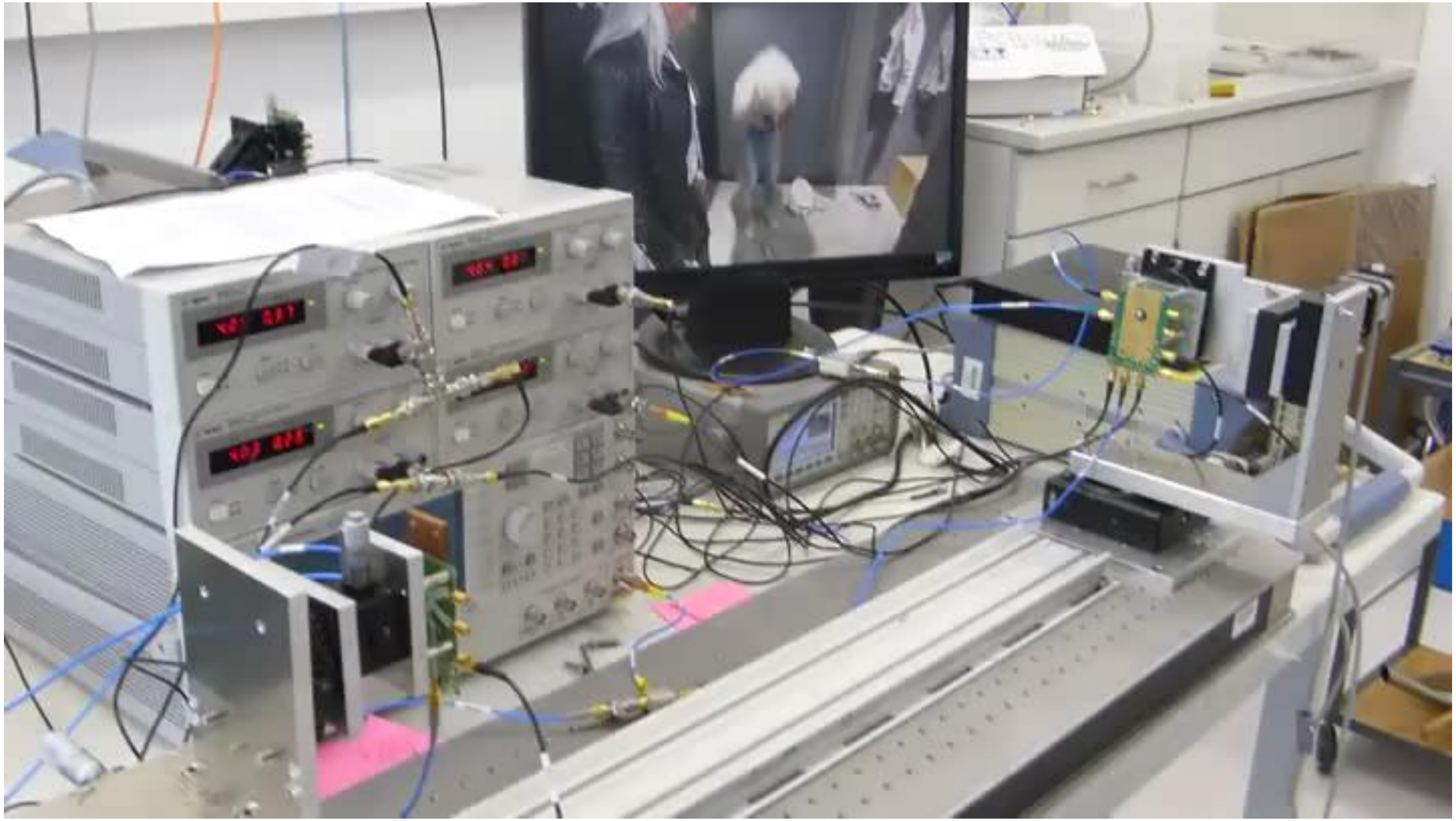
Commercial viable, but IF filters required

Communication Link Tests

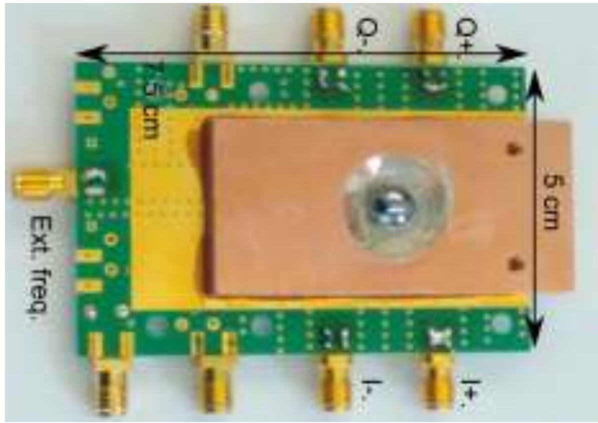


- Absorbers cover PCB and rail
- LoS alignment
- RF Phase alignment

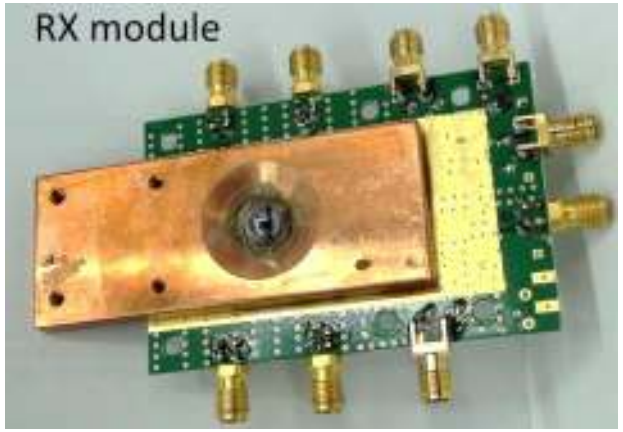
Simple Communication Demo



Approach 1: 1-Meter Wireless Comm Link

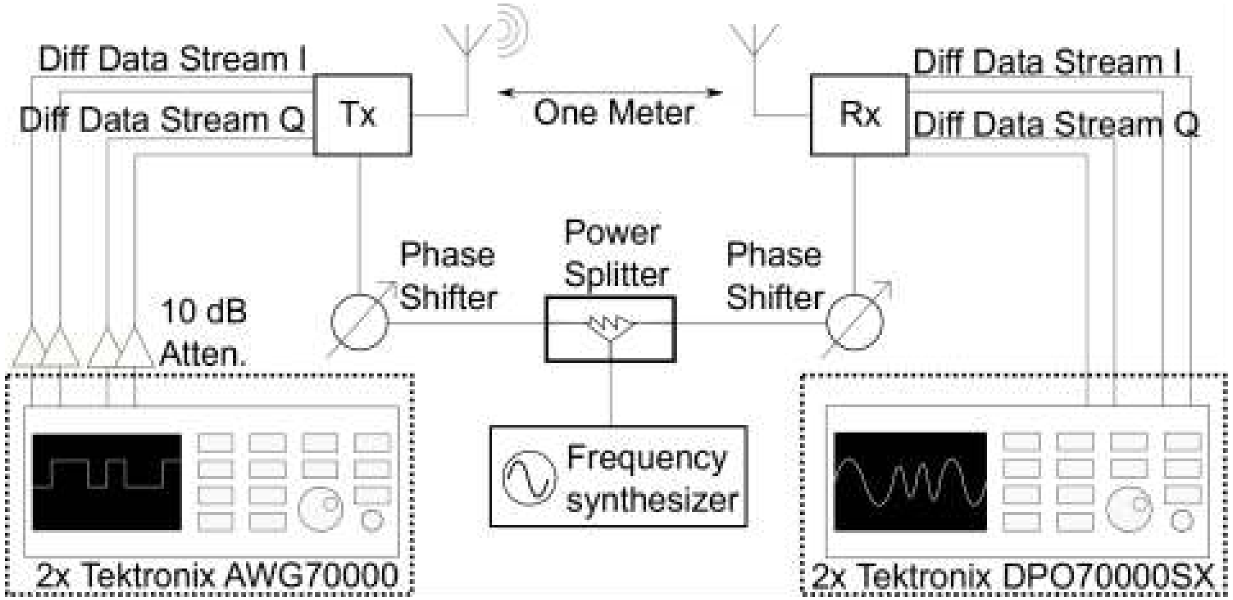


- 1 meter line-of-sight
- No free space optics or mirrors
- LO Phase-shifters for phase alignment
- 10 dB IF attenuators for linear TX



AWG:

- RRC filter (0.1-0.7)
- Pre-compensation
- 50 GS/s and 10-bit
- 20 GHz analog BW
- Eff. BW 16QAM:
  - 12.4 GHz, 90 Gbps, -8.2 dBm, 2.5% EVM



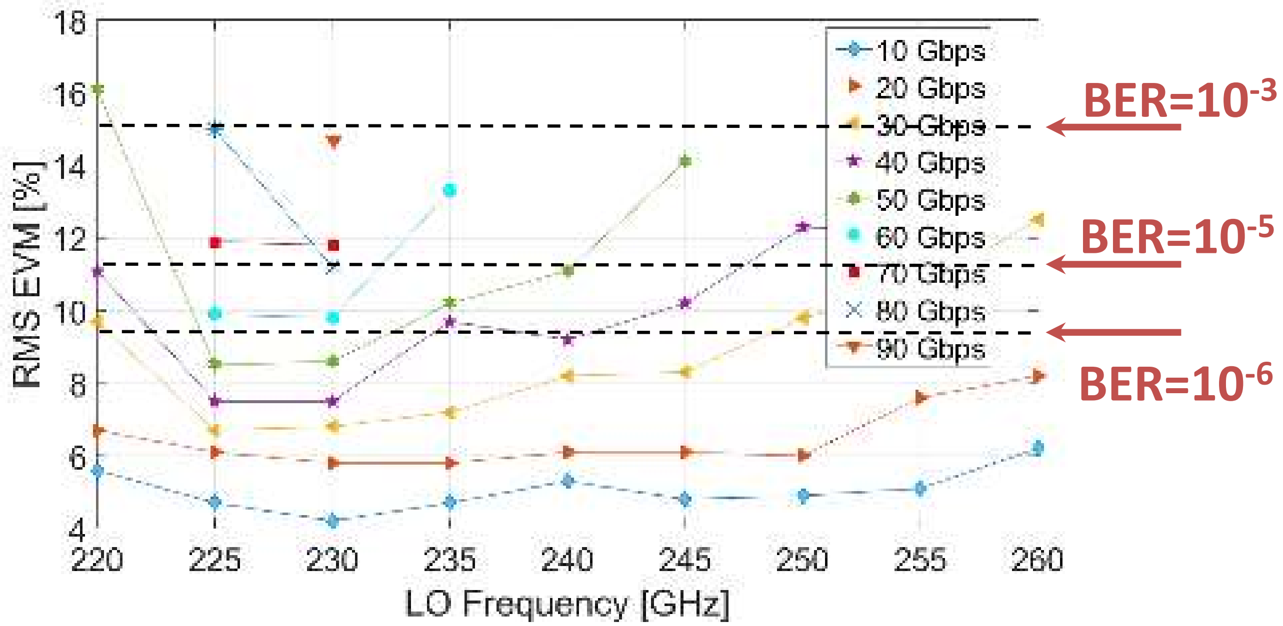
[1] P. R. Vazquez et.al. “Towards 100 Gbps: A Fully Electronic 90 Gbps One Meter Wireless Link at 230 GHz”, European Microwave Conference (EuMC) 2018, :1389-1392 November 2018

Scope:

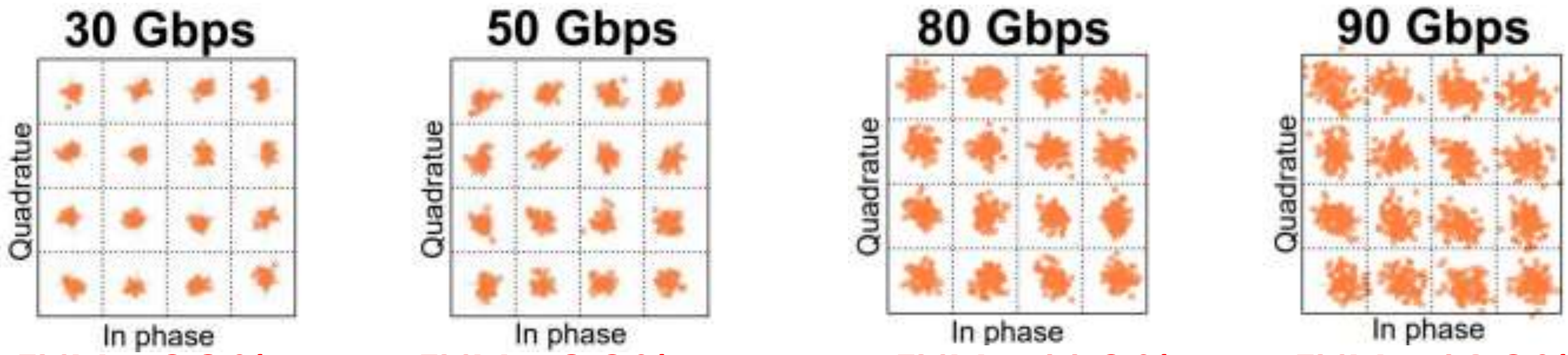
- 2*33 GHz, 100 GS/s
- Vector signal analysis software
- RRC matches AWG
- Feed-forward adaptive equalizer (17 taps)

Link Summary (Amplifier First)

Mod.	Date Rates/ EVM	Range/ max range	Reference
BPSK	35/27.5%	1m/5m	[RWW18]
QPSK	65/30.7%	1m/5m	[RWW18]
16QAM	90/14.7%	1m/1.8m	[EuMC18]
32QAM	90/11.9%	1m/1.6m	[APMC18]
64QAM	81/8.7%	1m/1m	[RWW19]



16QAM



EVM = 6.8 % EVM = 8.6 % EVM = 11.2 % EVM = 14.6 %

Limits: I/Q correlation, LO SFDR, -55 dB LO-BB feed-through, group delay distortion (package)

Chip-Set Summary (Tunable Carrier 220-260 GHz)

	Amplifier First (230GHz carrier)				Mixer First (230GHz carrier)			
RF front-end performance	Carrier/BW	Psat	CG	NFmin	Carrier/BW	Psat	CG	NFmin
	230GHz /24GHz	9dBm	23dB	11.5 dB	220-260 GHz /28 GHz	9dbm	7.8 dB	14 dB
Link performance	Mod.	Date Rates/ EVM	Range/ max range	Reference	Mod.	Data Rates/ EVM	Range/ max range	Reference
	BPSK	35/27.5%	1m/5m	[RWW18]	BPSK	35/27.9%	1m/4m	Not published
	QPSK	65/30.7%	1m/5m	[RWW18]	QPSK	60/26.2%	1m/4m	[IJMWT]
	16QAM	90/14.7%	1m/1.8m	[EuMC18]	16QAM	100/17%	1m/1.8m @ 80Gbps	[MWCL]
	32QAM	90/11.9%	1m/1.6m	[APMC18]	32QAM	90/13.7%	1m/1.6m	Not published
	64QAM	81/8.7%	1m/1m	[RWW19]				

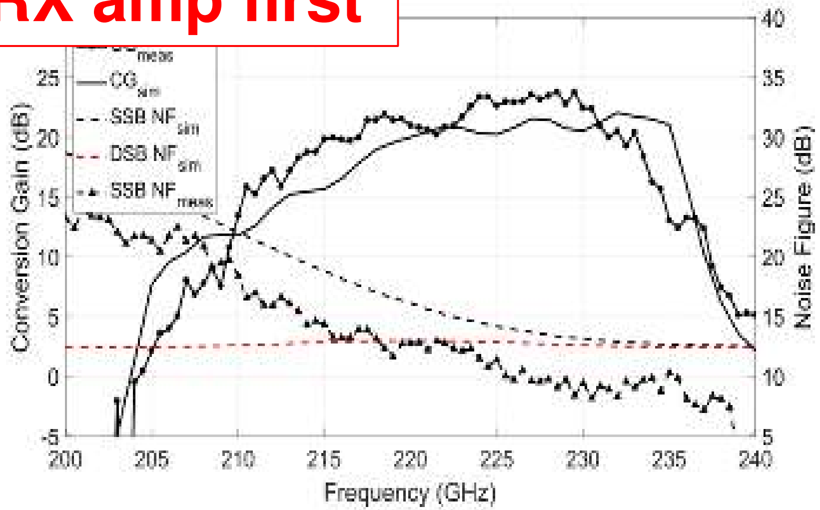
[MWCL] P. Rodríguez-Vázquez, et. al.,"A 16-QAM 100-Gb/s 1-M Wireless Link With an EVM of 17% at 230 GHz in an SiGe Technology,"

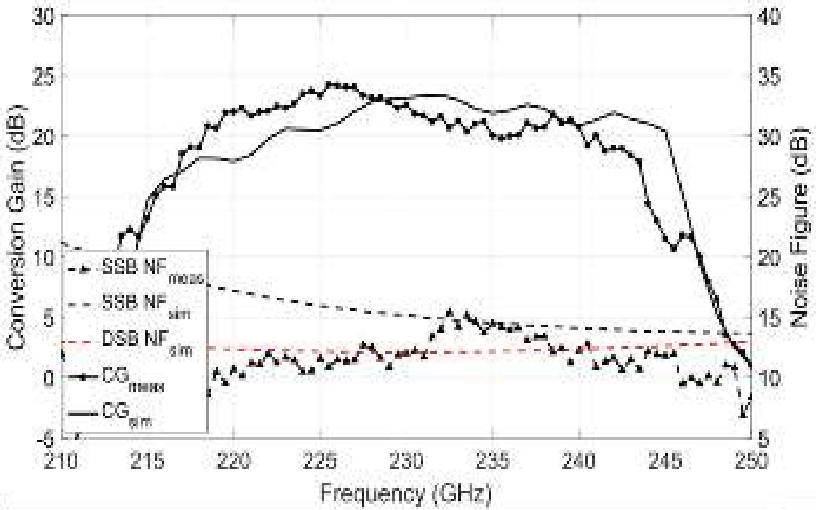
Link Impairments (Mixer First)

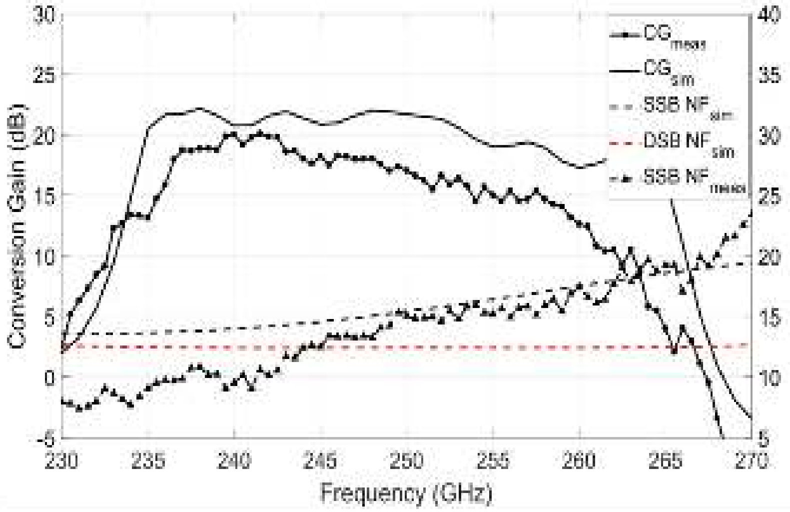
- **IQ channel leakage:**
  - Uneven RF BW cause different USB and LSB transfer functions and cross-talk at BB
- **Broadband phase-noise floor:**
  - Broadband noise floor becomes more relevant
  - PN of the external Synth **(-150 dBc/Hz)** scales by a factor of **20log10(16)=24.1 dB**
  - -> Rms phase error in the LO path scales linearly with the modulation BW
  - The total integrated (BW=13GHz) rms phase error is **4°**
  - Close-carrier PN is 1.8° at 1GHz
- **Harmonic spurs in LO:**
  - odd (×15,×17) and even (×14,×18) harmonics around the desired ×16 tone
  - The odd harmonics (×15,×17) are particularly harmful for the link performance.
  - Mixing with ×16 produces modulated replicas centered at a frequency offset equal to the external LO frequency drive. For data-rates above 50 Gbps, these replicas alias with the main spectrum with no space for filtering at the Rx output.
- **Insufficient isolation from ext. LO:**
  - was measured to be at 50 to -55 dBc. For data-rates >90 Gbps signal quality effected.

USB and LSB transfer function asymmetry

RX amp first





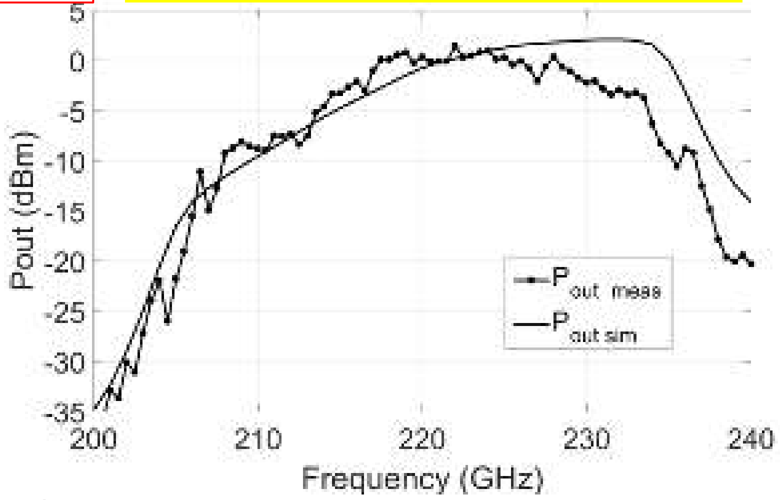


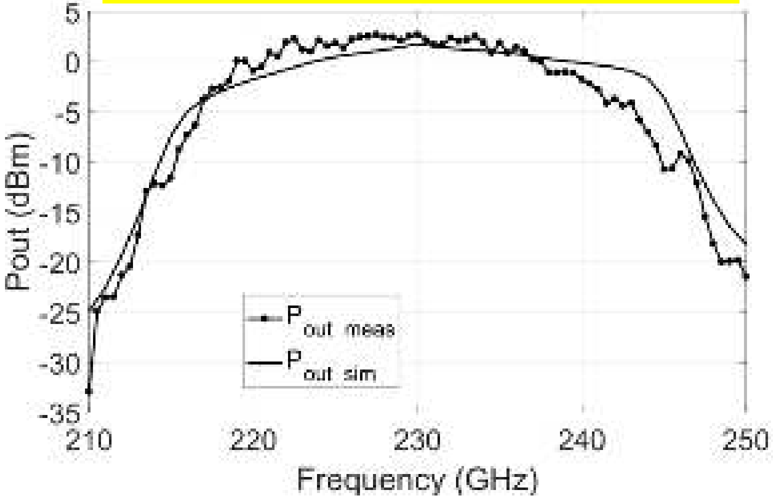
TX

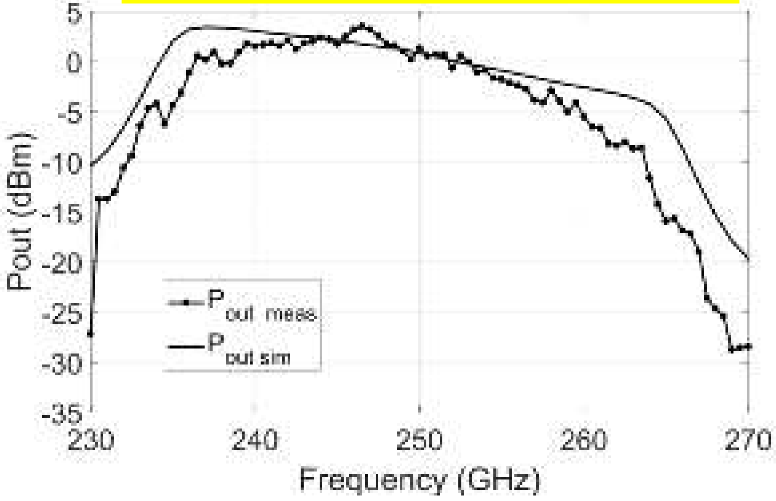
USB >> LSB (8 dB)

LSB > USB (2-3 dB)

LSB >> USB (7 dB)

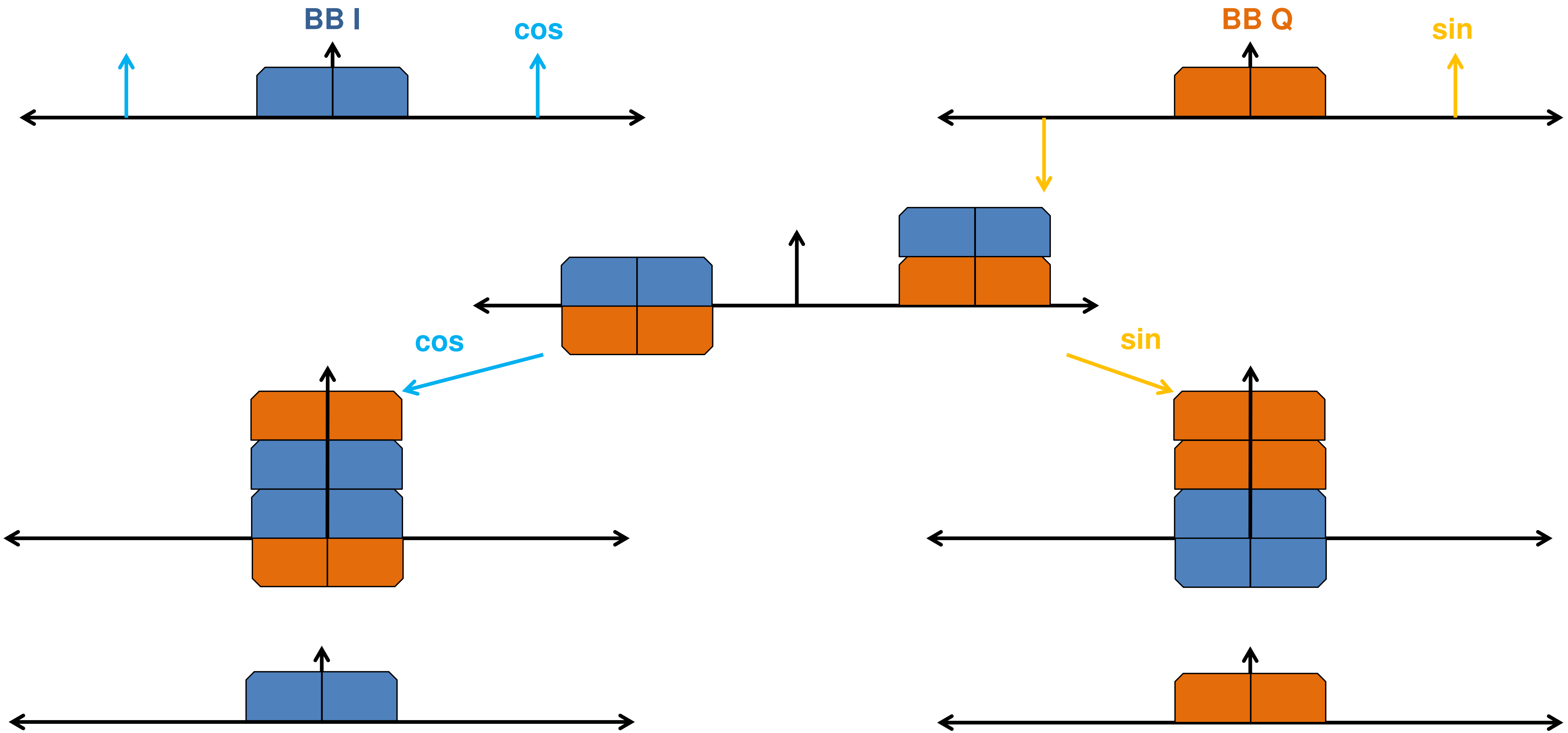




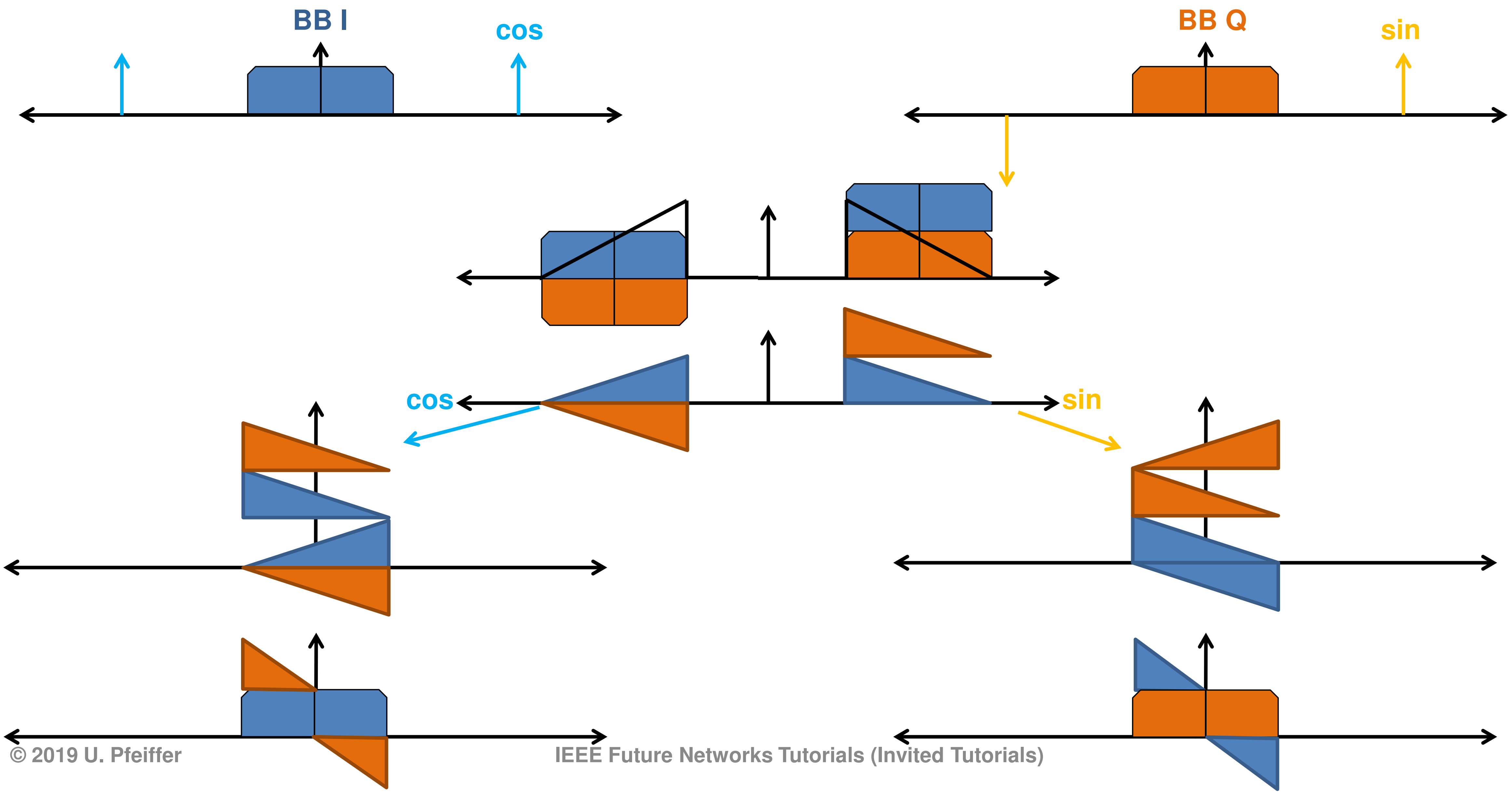


220 GHz **230 GHz** **250 GHz**

IQ channel leakage from amp. distortion

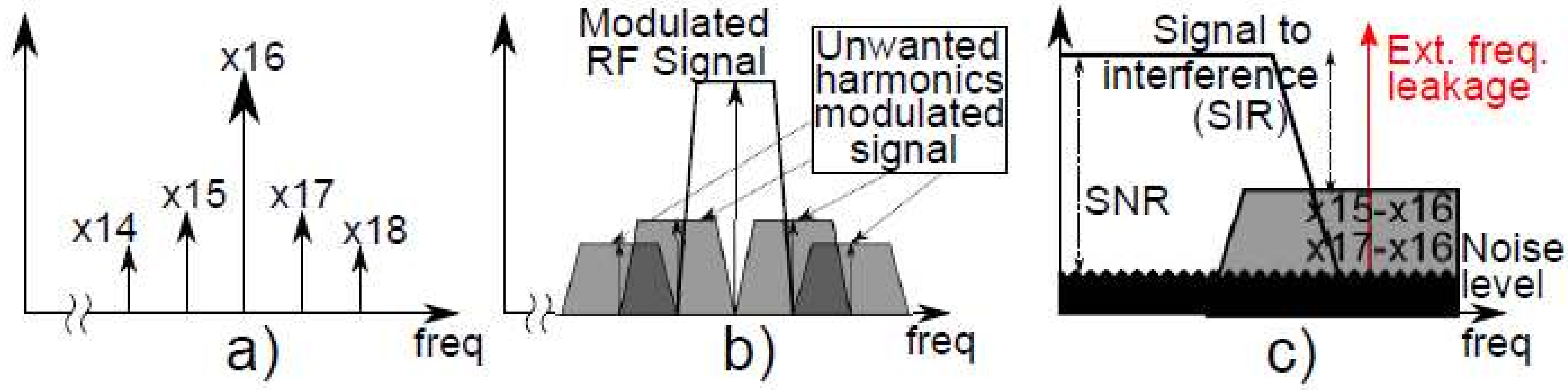


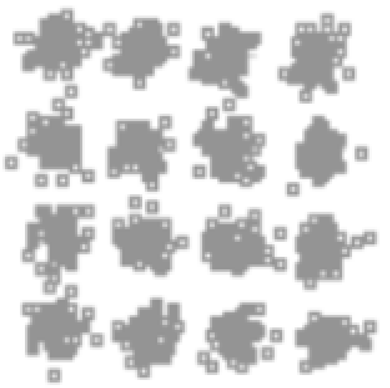
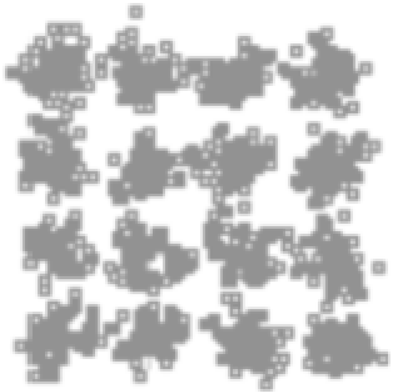
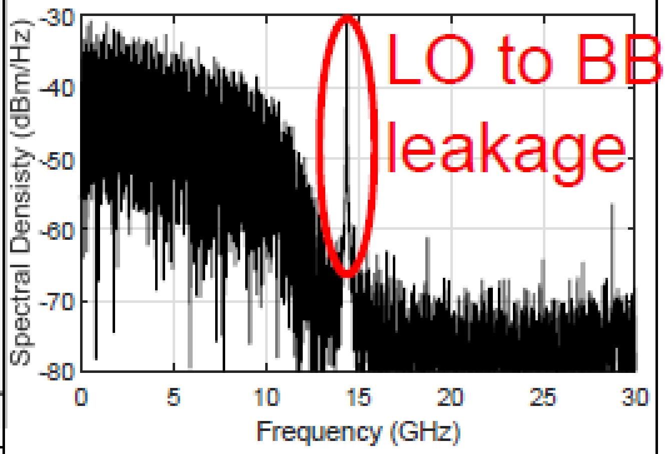
IQ channel leakage from amp. distortion



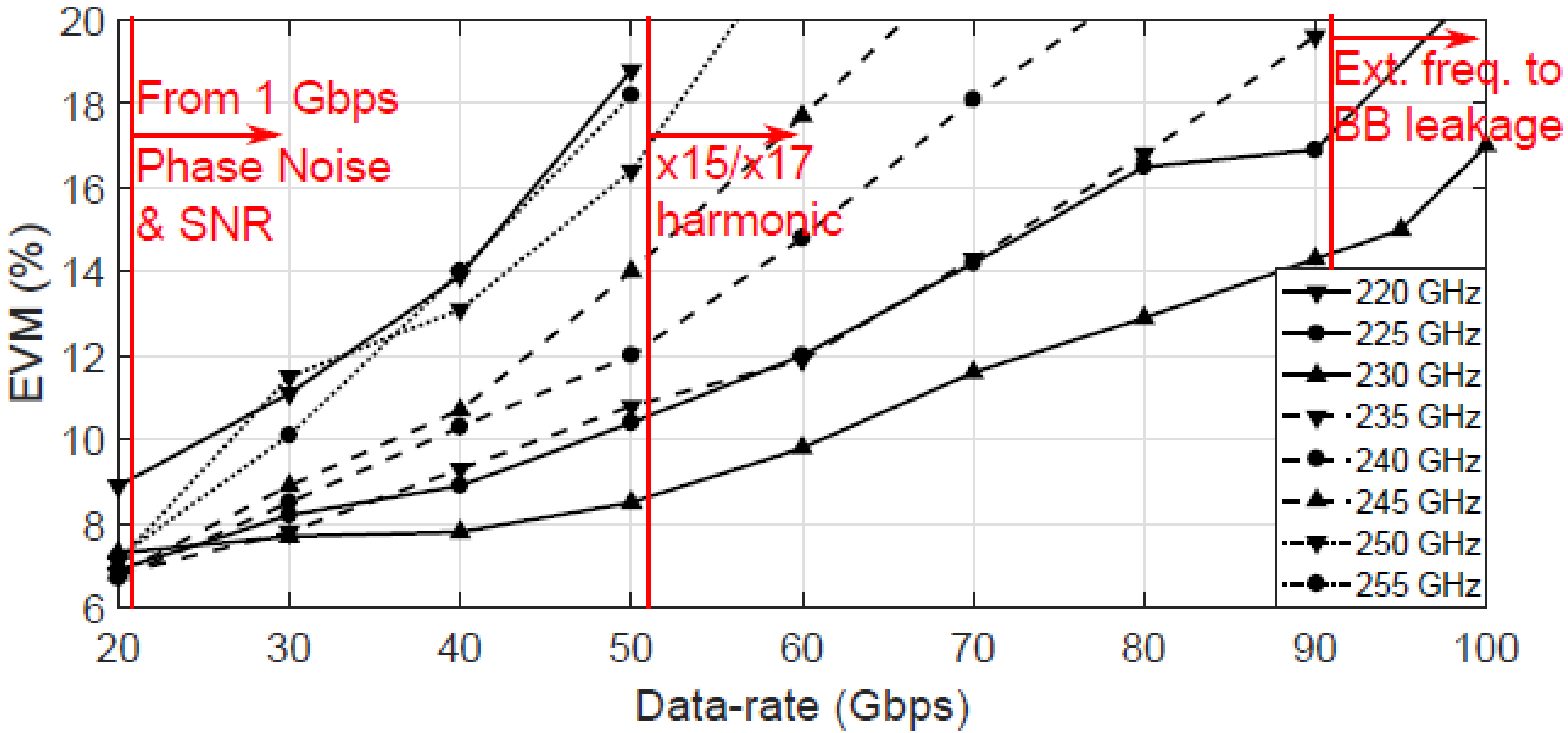
Link Impairments (Mixer First)

LO spurs | **TX output** | **RX output**



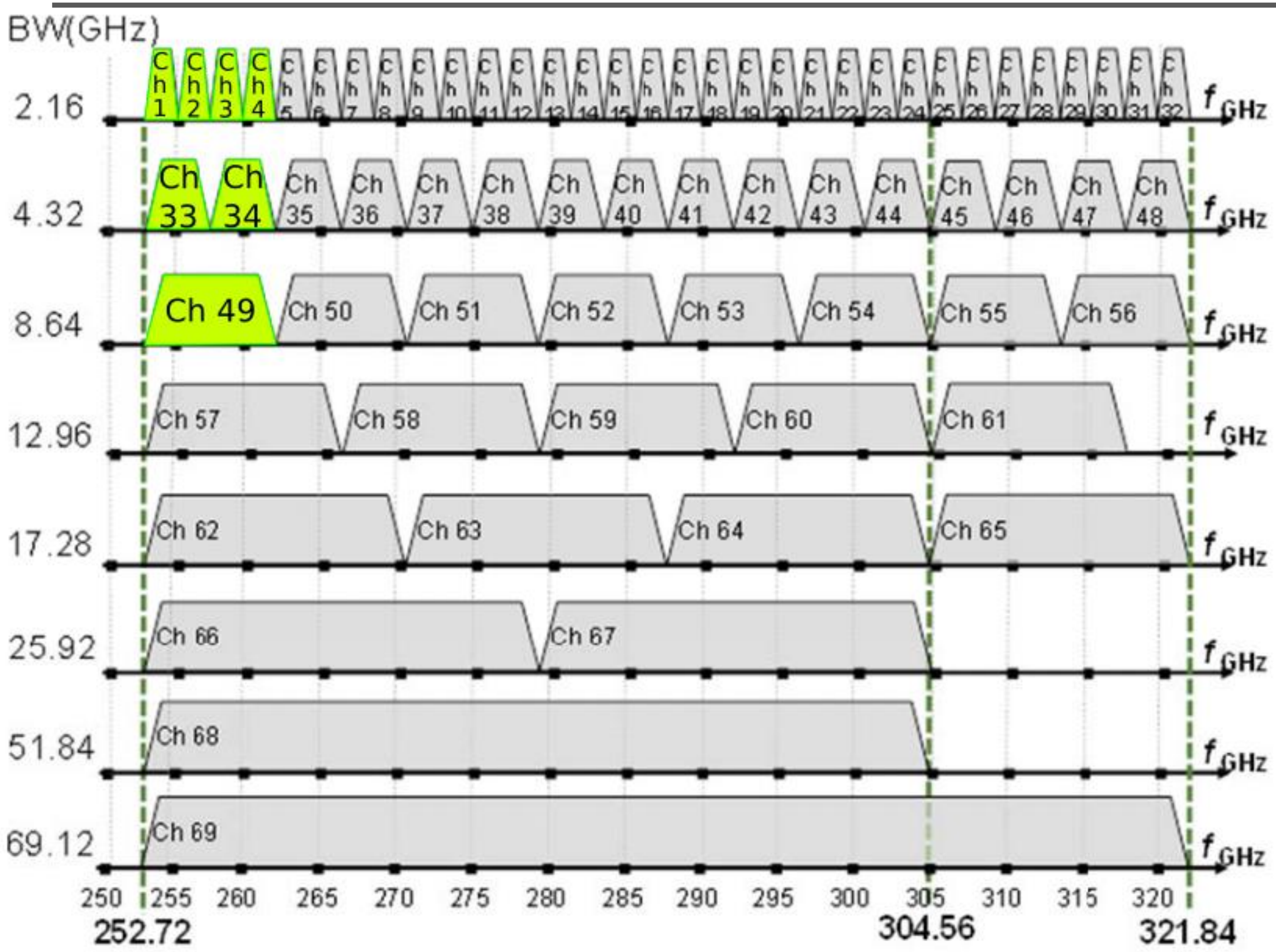
Tx to Rx Constellation 16-QAM			
Symbol Rate	23.75 Gbaud	25 Gbaud	
EVM	15% / -16.4 dB	17% / -15.4 dB	RX Signal Spectrum (95 Gbps)
Data Rate	95 Gbps	100 Gbps	

Link Impairments (Mixer First)



- **Q: What do we need to do to improve data-rates and range?**
  - Range: Tx radiated power, Rx noise figure, antenna directivity
  - Data rates: SNR/PN limit spectral eff., but RF BW flatness, PN floor of ext. ref. Synth, freq. planning

IEEE 802.15.3d-2017 Channel Allocation



- 4 Channels with 2.16 GHz BW @ 253.8, 255.96, 258.12, and 260.28 GHz
- 2 Channels with 4.32 GHz BW @ 254.88 and 259.2 GHz
- 1 Channel with 8.64 GHz BW @ 257.04 GHz

- All this Channels are expected to reach data-rates under 50 Gb/s. We already reached this goal.

- Link distance remains a problem:
  1. Pout 10 mW not 1 W
  2. Antennas 25 dBi not 40 dBi

More directivity is required (50 dBi to compensate for the reduced Pout)

Link Budget Estimations

Freq.	Tx Pout	RF BW	Data -rate	NF	Mod.	SNR for BER = 10^{-3} +16 dB loss	Antenna Gain (Tx & RX)	Power required in Rx	Maximum Distance	Notes
230 GHz	5 dBm	30 GHz	100 Gbps	14 dB	16-QAM	32.5 dB	26 dBi	-29 dBm	1 meters	Measured
230 GHz	5 dBm	30 GHz	100 Gbps	14 dB	16-QAM	32.5 dB	50 dBi	-29 dBm	100 m	With a second 6.5 cm lens

100m range coverage expected for 50dBi lens gain

SoA for all-electronic wireless links < 200 GHz

Reference	Technology	Frequency	Channel BW	Modulation	Data-rate	P_{DC}	Distance	On- chip antenna	Fully-packaged?
[Kang15], [Thyagarajan15]	65 nm CMOS	240 GHz	-	QPSK	16[1] Gbps	480 mW	2 cm	2 Ring	No (on wafer)
[Fritsche17]	130 nm SiGe	190 GHz	20 GHz	BPSK	50 Gbps	154 mW[2]	0.6 cm	Monopole	No (on wafer)
[Lee19]	40 nm CMOS	300 GHz	20 GHz	16-QAM	80 Gbps	1.79 W	3 cm	No	No (on wafer)
[Kallfass15]	35 nm InP	300 GHz	22 GHz	QPSK	64 Gbps	-	2 meters	No	Wave-guide
[Boes13]	35 nm InP	240 GHz	-	8-PSK	64 Gbps	-	40 meters	No	Wave-guide + Horn
[Hamada18]	80 nm InP	270 GHz	-	16-QAM	100 Gbps	-	2.2 meters	No	Wave-guide + Horn + Lens
[Eisa18]	130 nm SiGe	240 GHz	<15 GHz	BPSK	25 Gbps	950 mW	15 cm	Doulble folded dipole	PCB + plastic lens
[EUMC18]	130 nm SiGe	220-260 GHz	13 GHz	16/32-QAM	90 Gbps	1.96 W	1 meter	Ring	PCB + silicon lens
[MWCL19]	130 nm SiGe	220-255 GHz	13 GHz	16-QAM	100 Gbps	1.41 W	1 meter	Ring	PCB + silicon lens

[1] Tx without baseband interface: PRBS generator on chip.
[2] No LO generation path implemented on chip.

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[Kang15] S. Kang, S. V. Thyagarajan and A. M. Niknejad, "A 240 GHz Fully Integrated Wideband QPSK Transmitter in 65 nm CMOS," in *IEEE Journal of Solid-State Circuits*, vol. 50, no. 10, pp. 2256-2267, Oct. 2015.

[Thyagarajan15] S. V. Thyagarajan, S. Kang and A. M. Niknejad, "A 240 GHz Fully Integrated Wideband QPSK Receiver in 65 nm CMOS," in IEEE Journal of Solid-State Circuits, vol. 50, no. 10, pp. 2268-2280, Oct. 2015.

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[Hamada18] H. Hamada et al., "300-GHz. 100-Gb/s InP-HEMT Wireless Transceiver Using a 300-GHz Fundamental Mixer," 2018 IEEE/MTT-S International Microwave Symposium - IMS, Philadelphia, PA, 2018, pp. 1480-1483.

[Eisa18] M. H. Eissa et al., "Wideband 240-GHz Transmitter and Receiver in BiCMOS Technology With 25-Gbit/s Data Rate," in IEEE Journal of Solid-State Circuits, vol. 53, no. 9, pp. 2532-2542, Sept. 2018.

[RWW18] P. Rodríguez-Vázquez, J. Grzyb, N. Sarmah, B. Heinemann and U. R. Pfeiffer, "A 65 Gbps QPSK one meter wireless link operating at a 225–255 GHz tunable carrier in a SiGe HBT technology," 2018 IEEE Radio and Wireless Symposium (RWS), Anaheim, CA, 2018, pp. 146-149.

[EUMC18] P. Rodríguez- Vázquez, J. Grzyb, N. Sarmah, B. Heinemann and U. R. Pfeiffer, "Towards 100 Gbps: A Fully Electronic 90 Gbps One Meter Wireless Link at 230 GHz," 2018 48th European Microwave Conference (EuMC), Madrid, 2018, pp. 1389-1392.

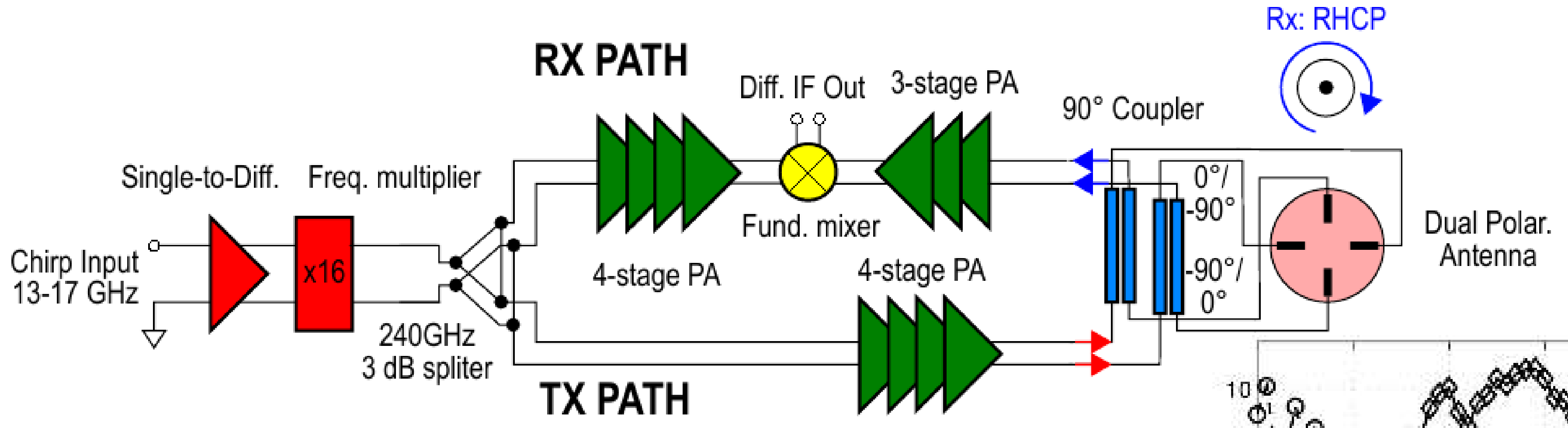
[APMC18] P. Rodríguez-Vázquez, J. Grzyb, B. Heinemann and U. R. Pfeiffer, "Performance Evaluation of a 32-QAM 1-Meter Wireless Link Operating at 220–260 GHz with a Data-Rate of 90 Gbps," 2018 Asia-Pacific Microwave Conference (APMC), Kyoto, 2018, pp. 723-725.

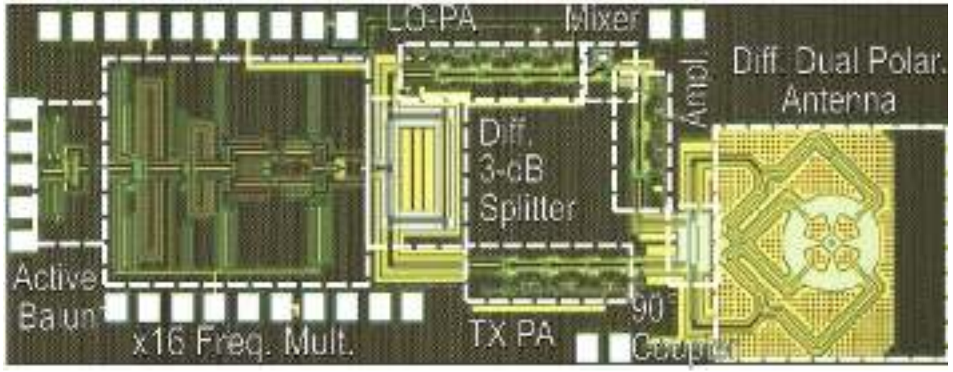
[RWW19] P. Rodríguez-Vázquez, J. Grzyb, B. Heinemann and U. R. Pfeiffer, "Optimization and Performance Limits of a 64-QAM Wireless Communication Link at 220-260 GHz in a SiGe HBT Technology, " 2019 IEEE Radio and Wireless Symposium (RWS), Orlando, FL, 2019.

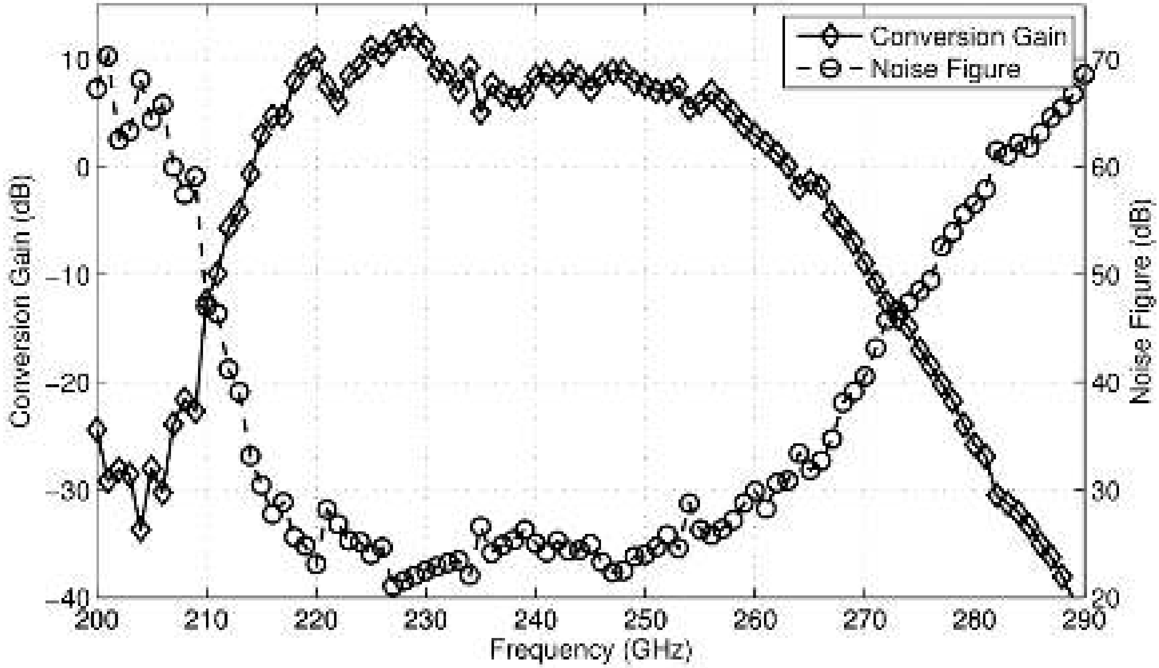
[MWCL19] P. Rodríguez-Vázquez, J. Grzyb, B. Heinemann and U. R. Pfeiffer, "A 16-QAM 100-Gb/s 1-M Wireless Link With an EVM of 17% at 230 GHz in an SiGe Technology," in IEEE Microwave and Wireless Components Letters.

240GHz Radar Transceiver

3D-Imaging (210–270-GHz Radar Transceiver)



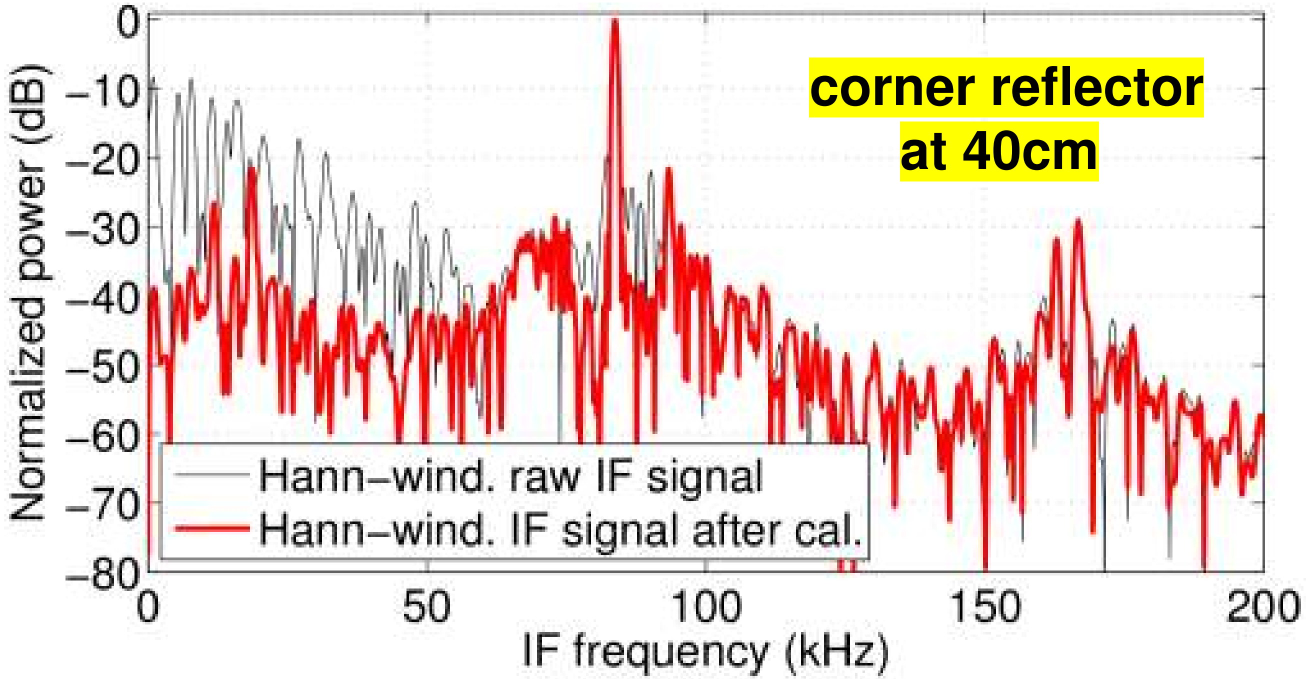




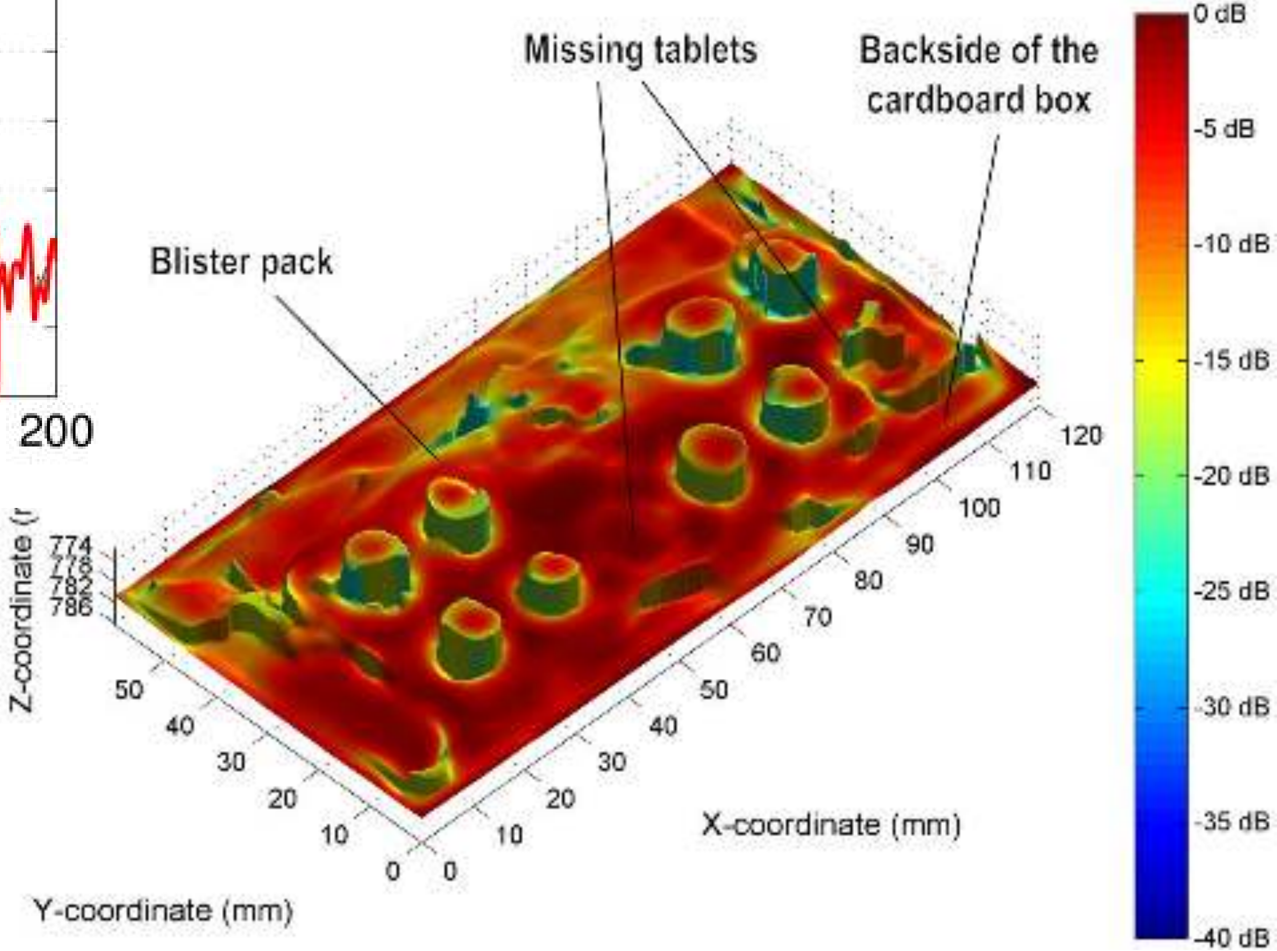
[1] J. Grzyb et.al., A 210–270-GHz Circularly Polarized FMCW Radar With a Single-Lens-Coupled SiGe HBT Chip, T-TST 2016

RX CG=12.1dB, NFmin=21.1dB, -10dB-BW=46.3GHz

3D Imaging and Non-Destructive Imaging Results



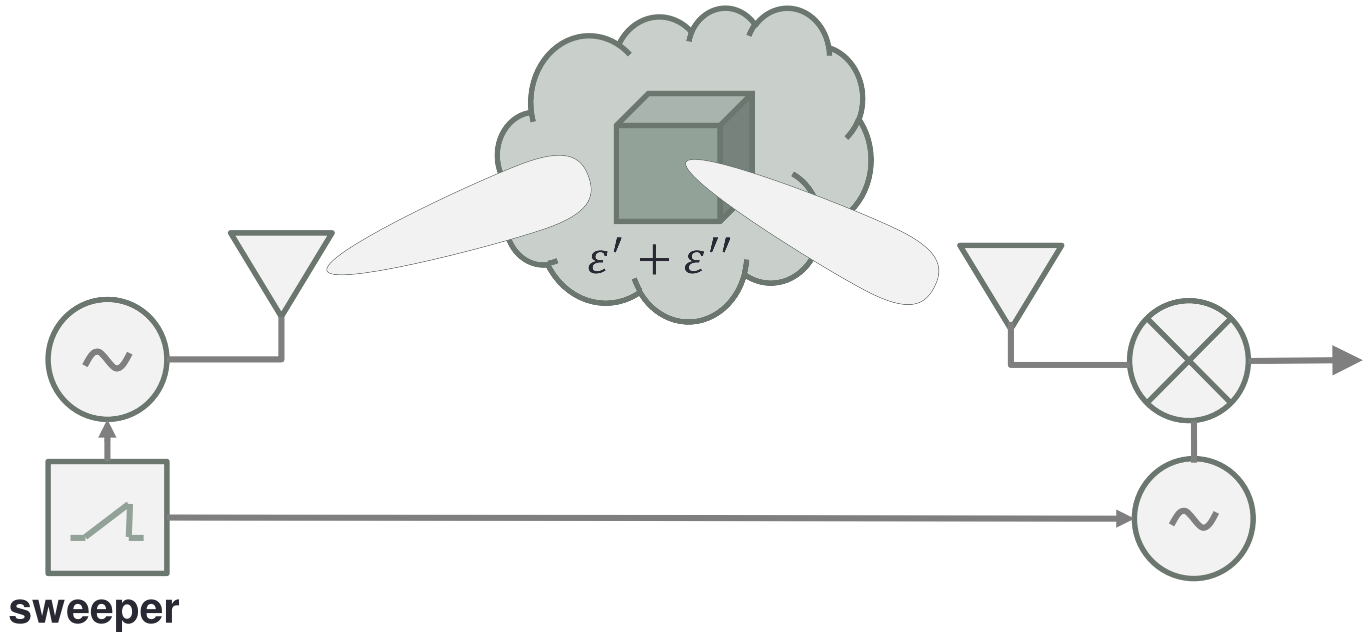
- Measured range resolution = 2.75mm

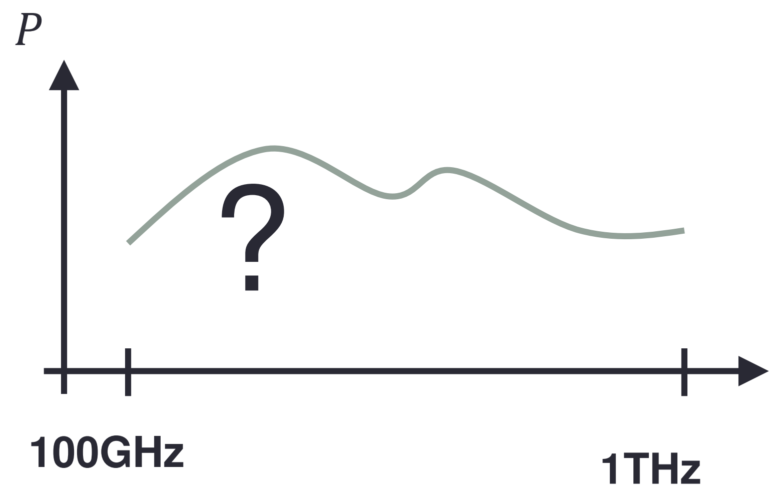


Multi-Color Imaging

How about hyper spectral imaging and sensing?

Wanted: Materials spectral fingerprint
\+
Polarization-diversity for ellipsometry

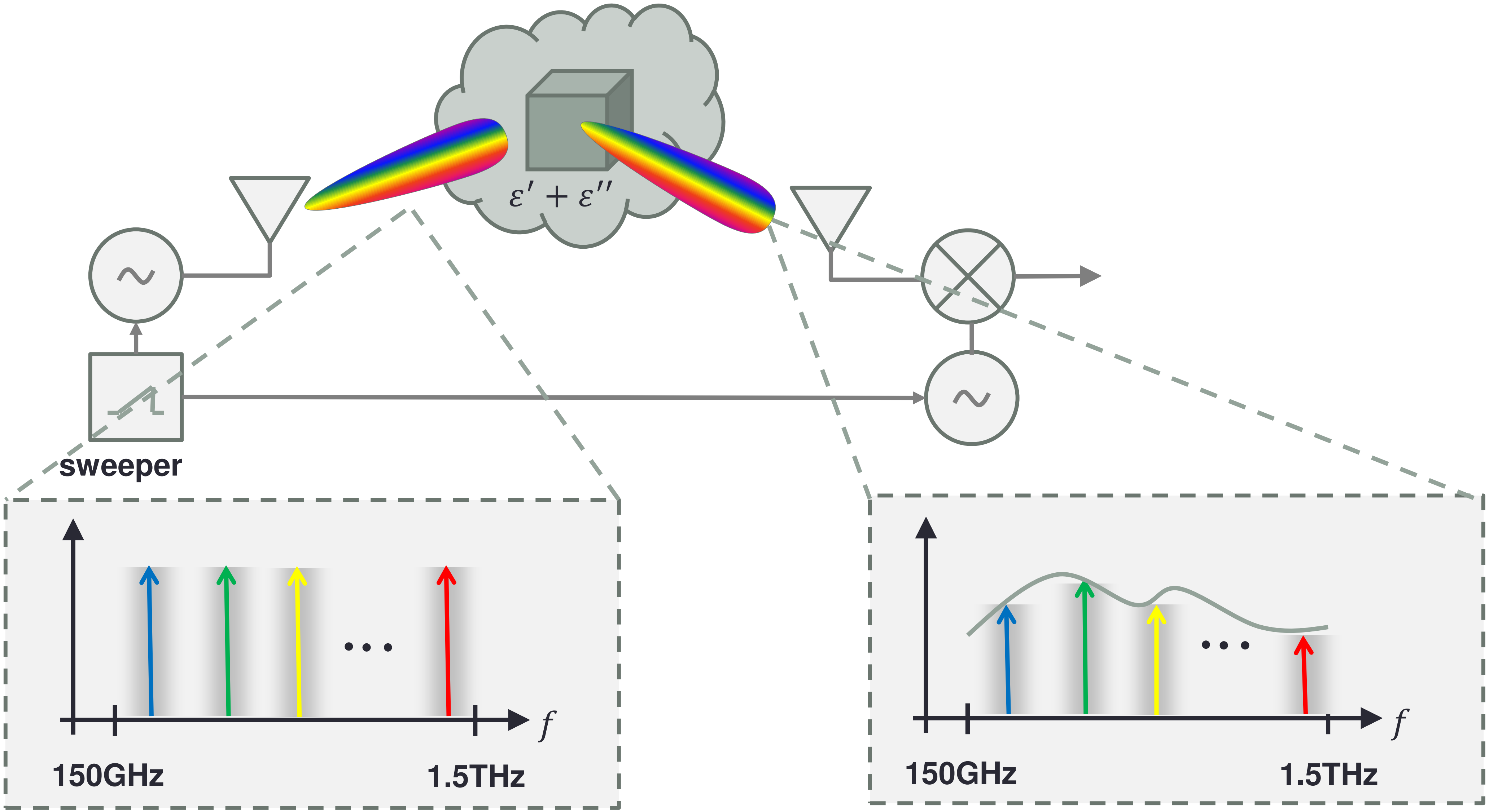




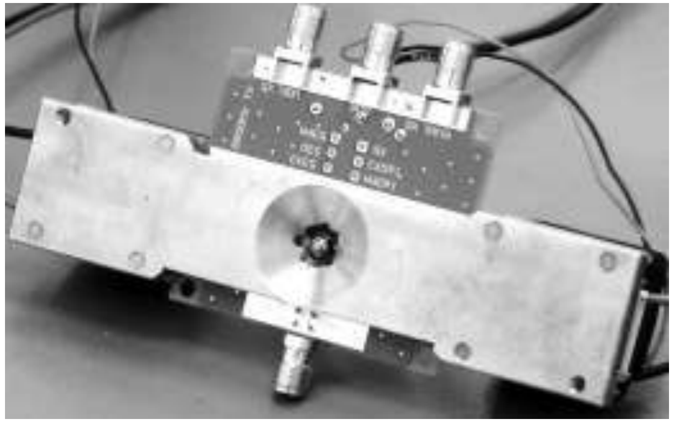
at least a decade of bandwidth!

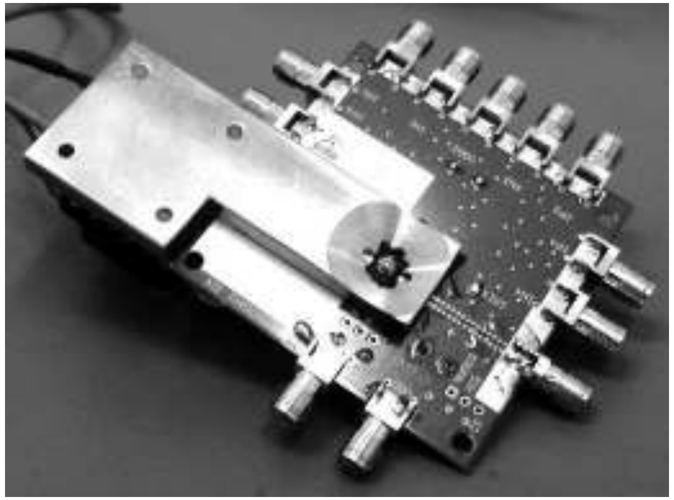
Can we do this in a compact silicon-based coherent imager?

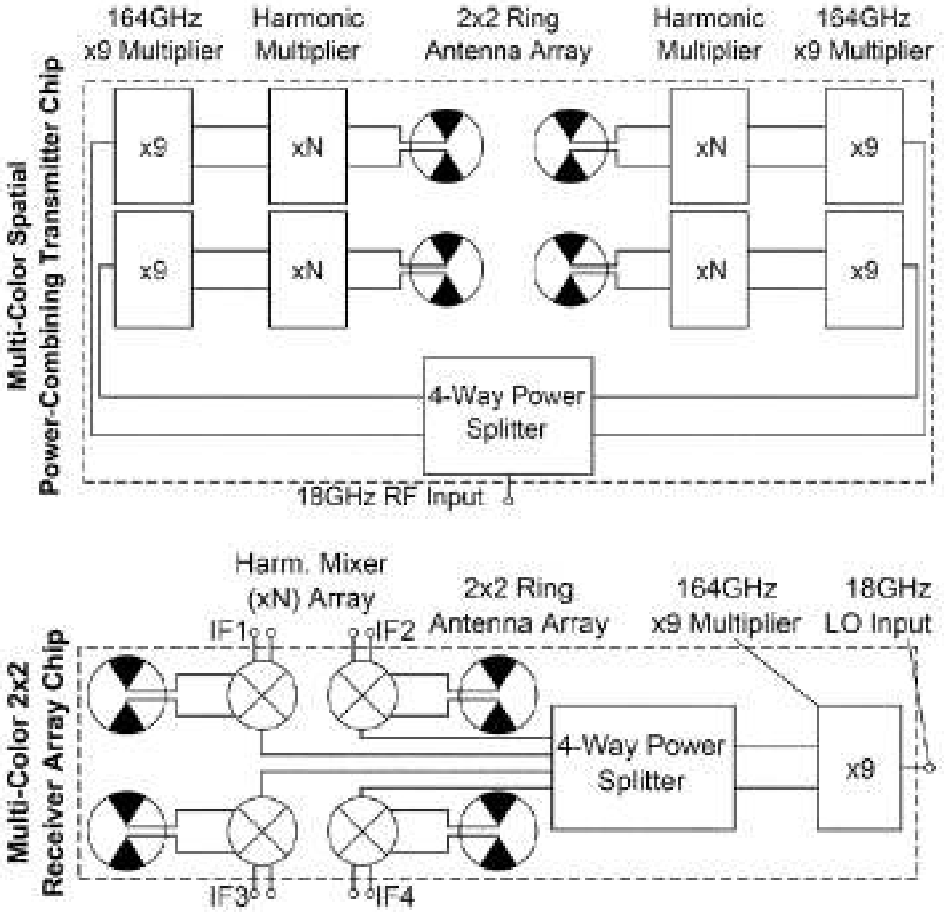
Hyper Spectral Imaging



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



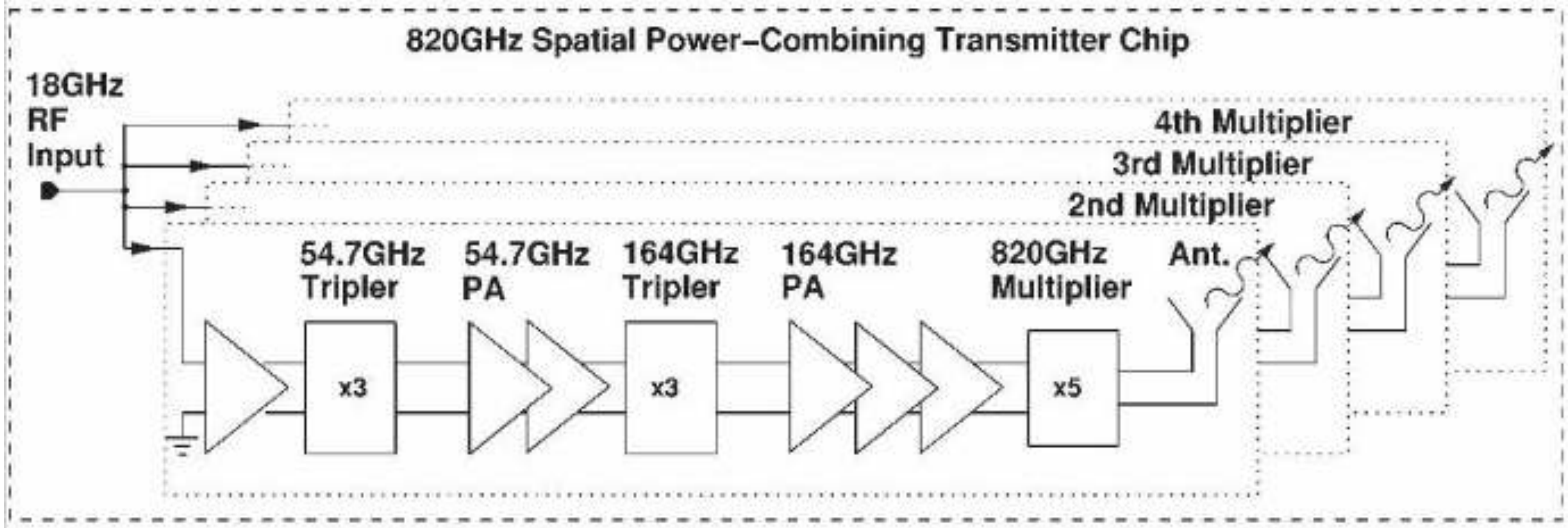


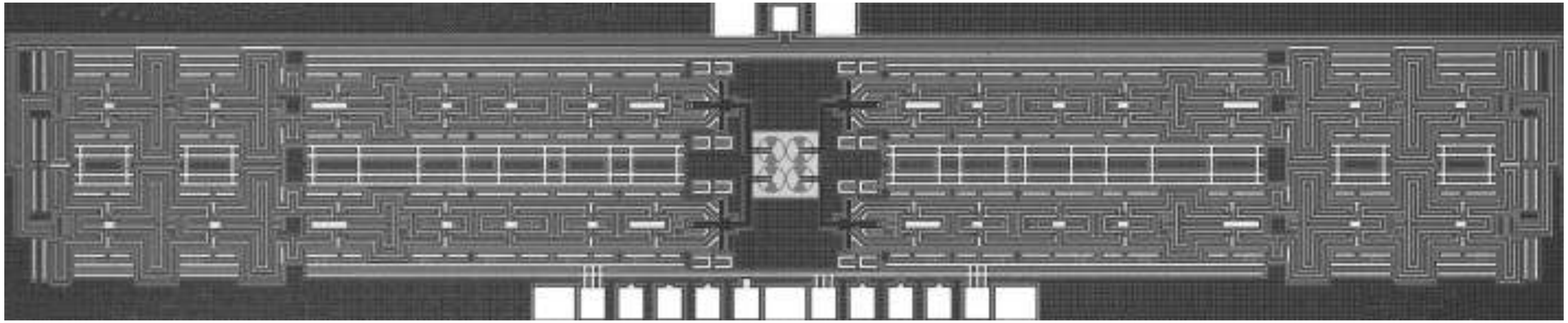


- Differential 825-GHz RF mixes with the 5th harmonic of a 162GHz LO
- CG= -15dB
- 4 freq. mult. Stages
- 4 ring antennas for spatial power combining
- 4.0 x 0.8 mm²

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

THz Harmonic Generator



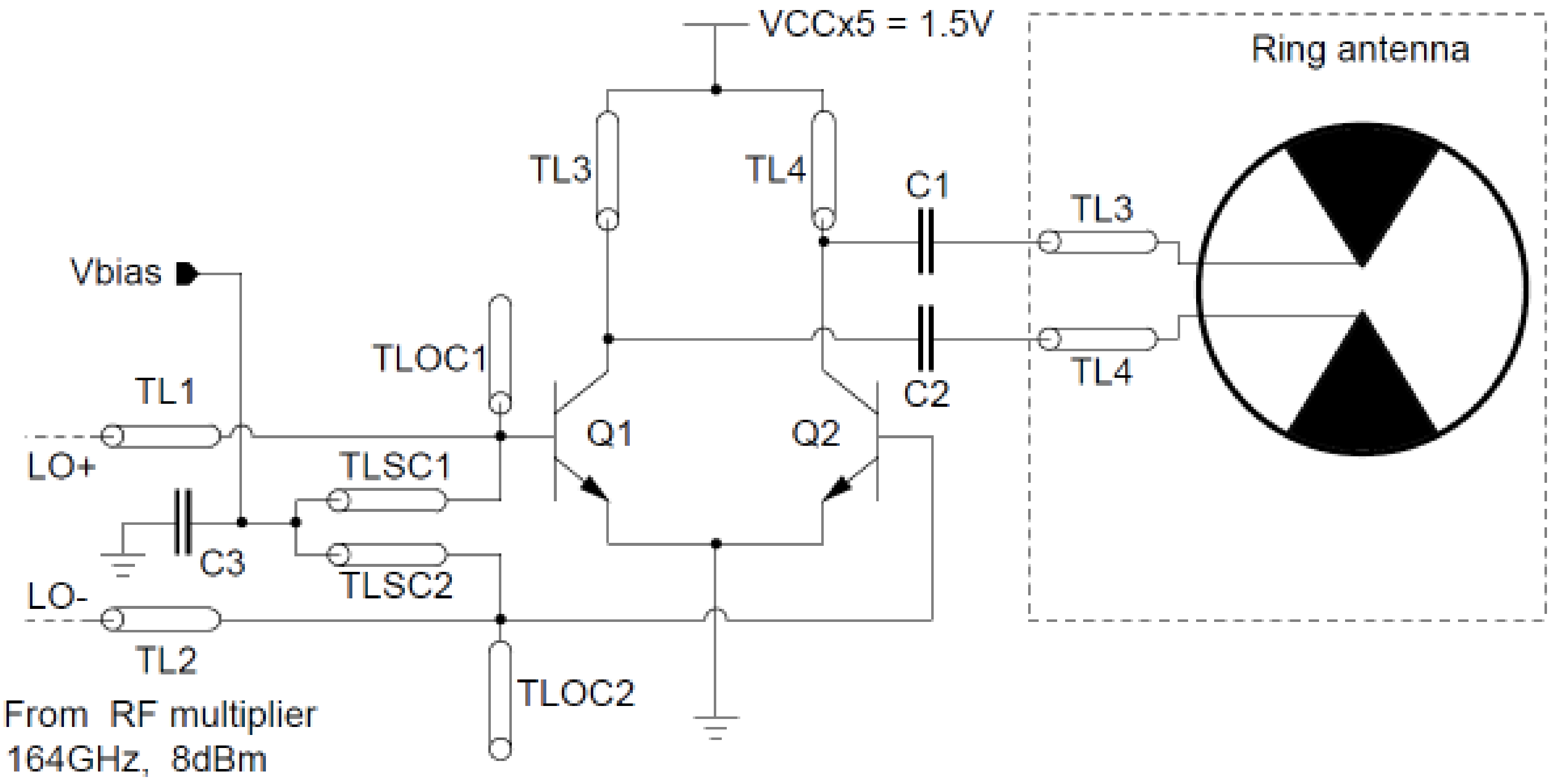


- 4.0 x 0.8 mm² TX chip
- 4 freq. mult. Stages
- 4 ring antennas for spatial power combining

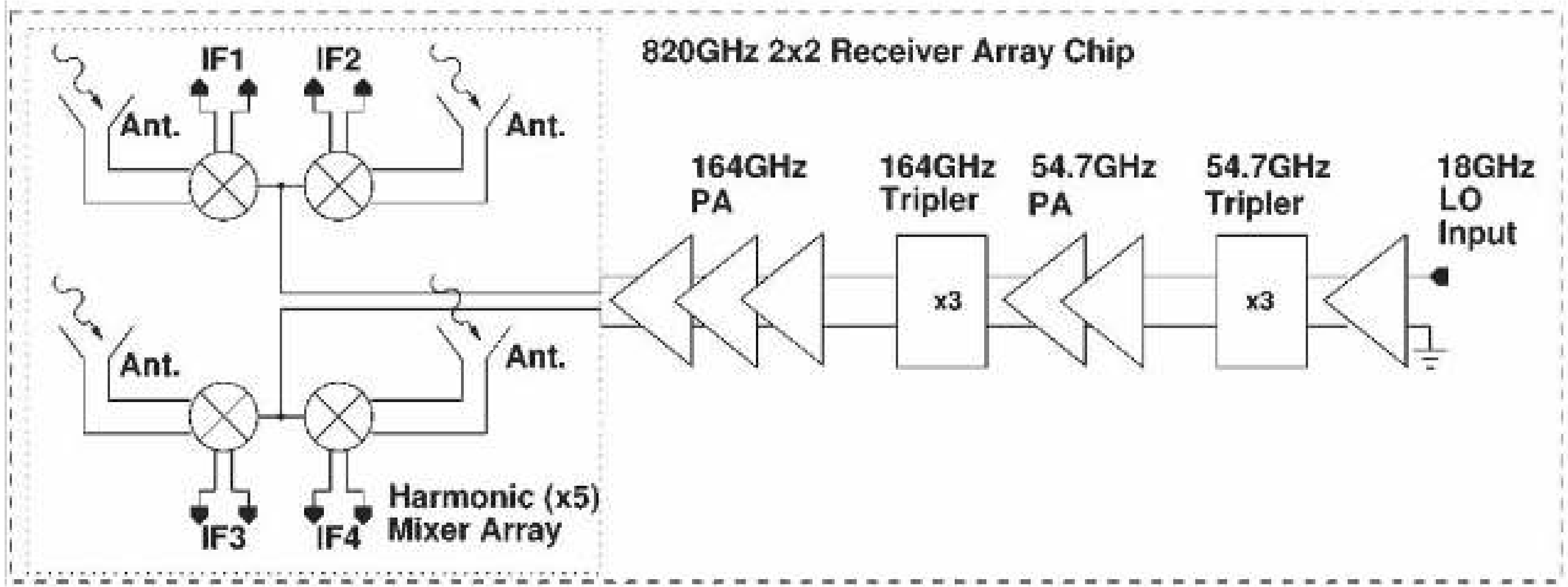
[1] K. Statnikov et al, „160GHz to 1THz Multi-Color Active Imaging with a Lens-Coupled SiGe HBT Chip-Set", TMTT Dec. 2014

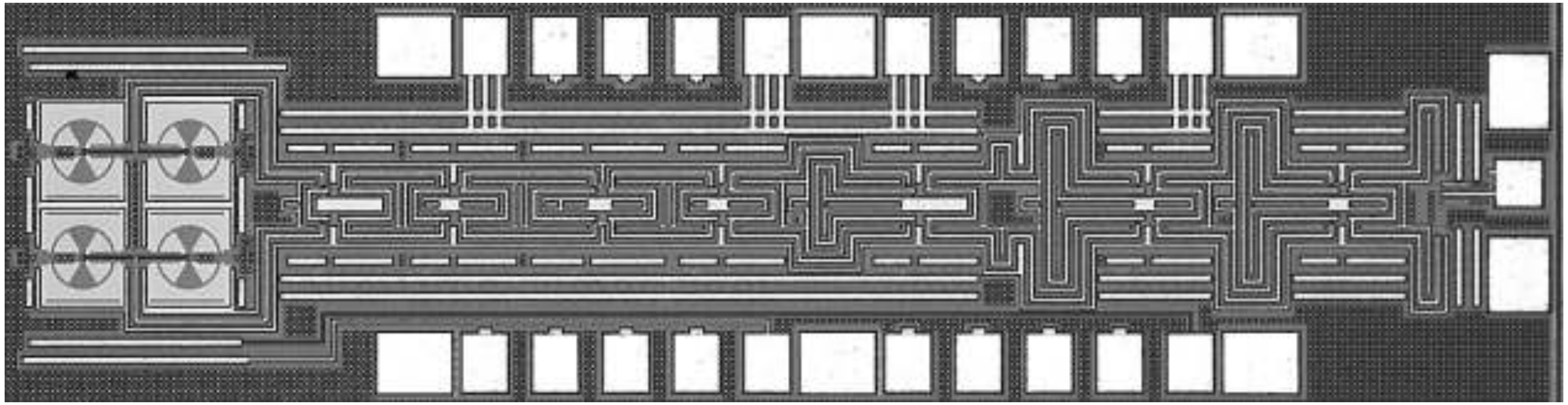
TX: harmonic generator circuit

- Differential stage Q1/Q2 pumped with a 164GHz RF signal
- Output tank L1/L2 and C1/C2 tuned to 825GHz center frequency
- Simulated output power -25dBm with an 8dBm input signal



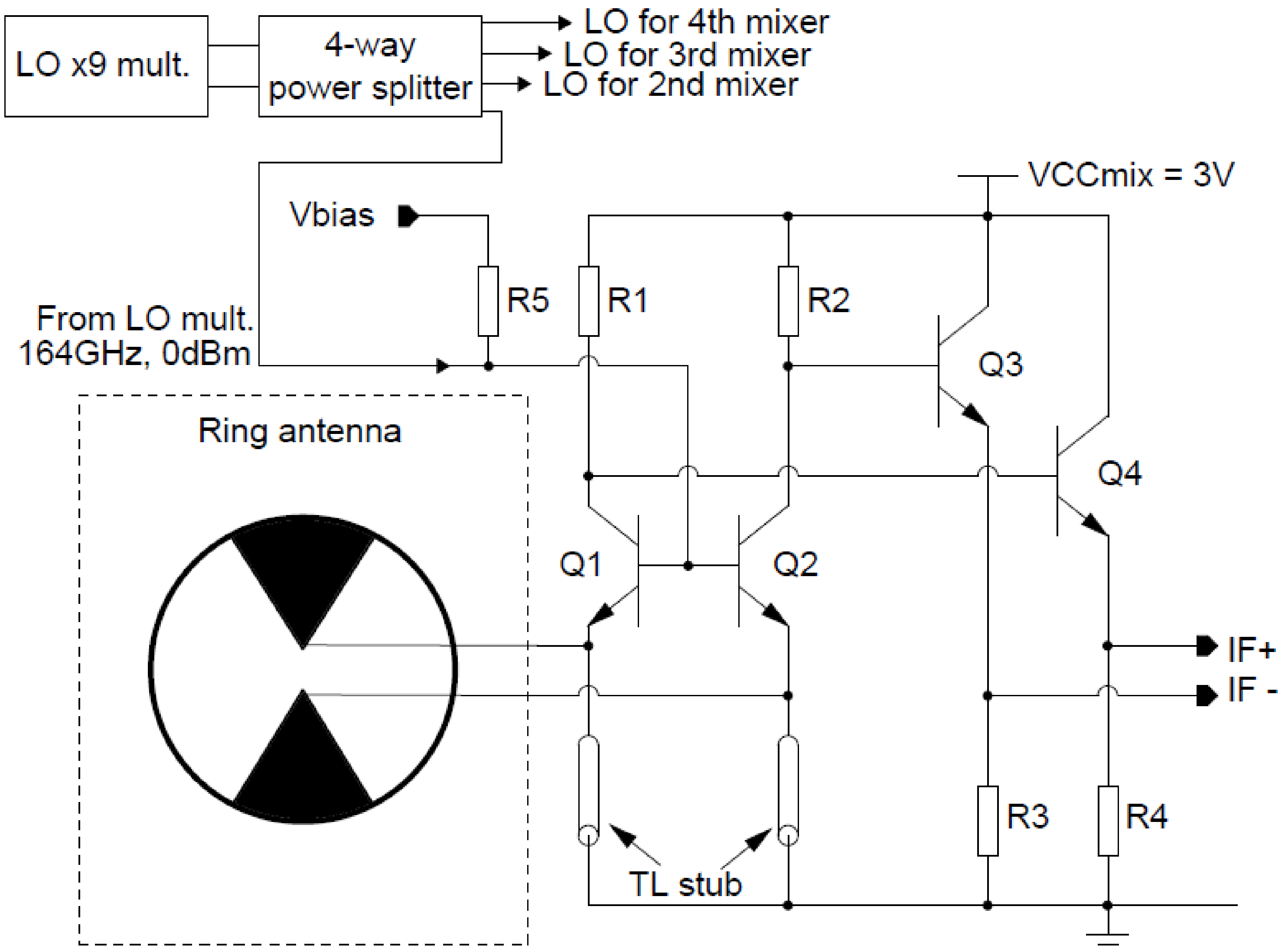
Rx Harmonic receiver array





- 2.3 x 0.6 mm^2 RX chip
- 2x2 receiver array
- Angular diversity / Multiple beams

RX: Harmonic mixer front-end circuit

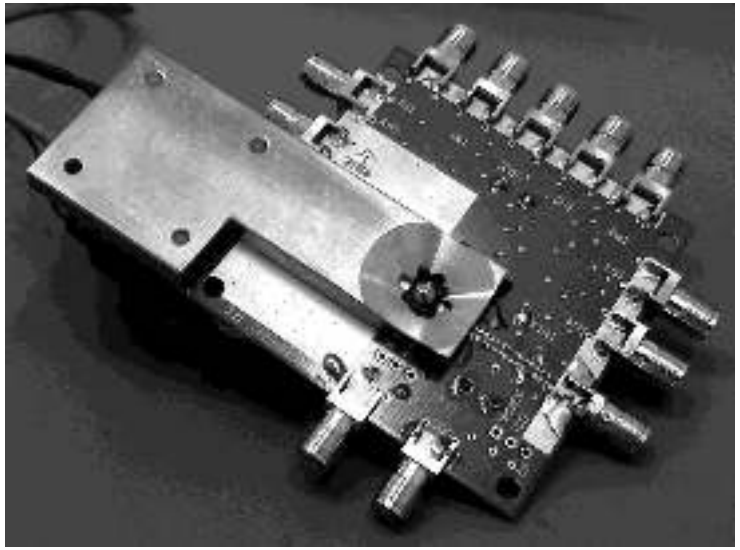


- Differential 825-GHz RF from antenna mixes in Q1/Q2 with the 5th harmonic of the 162-GHz common-mode LO signal
- Simulated conversion gain = -15 dB (0dBm LO)

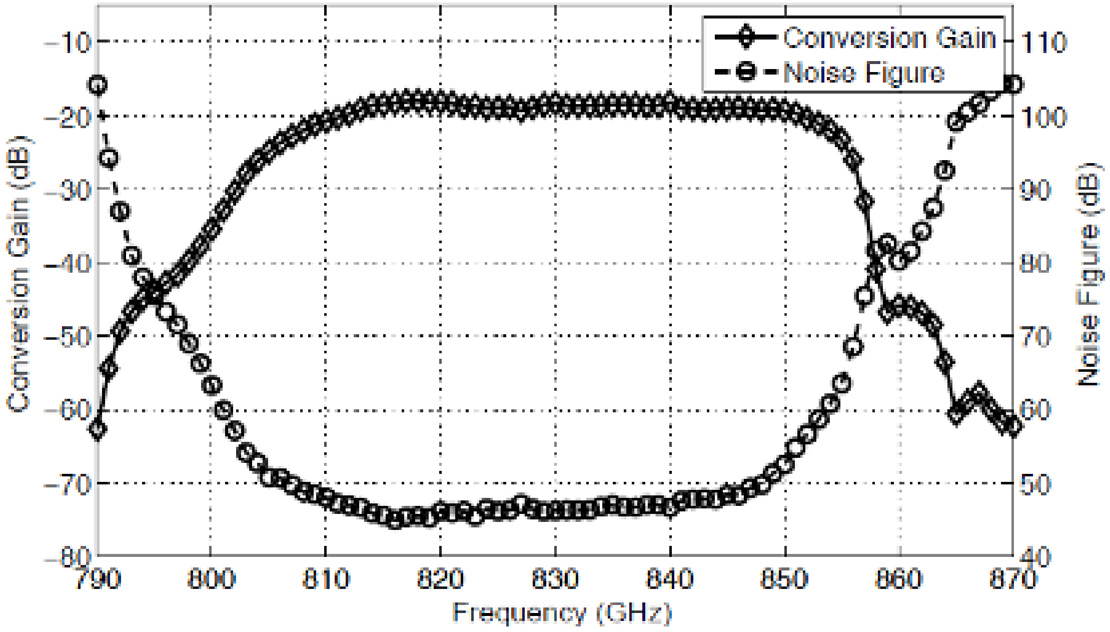
Measured Rx Results

- <10% fractional RF BW, but at multiple harmonics!
- 45 dB SSB NF

RX board



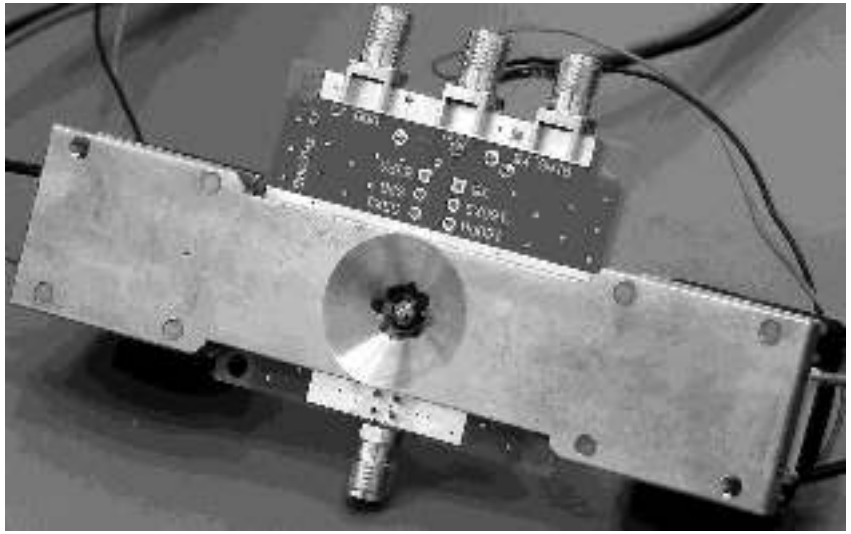
10cm



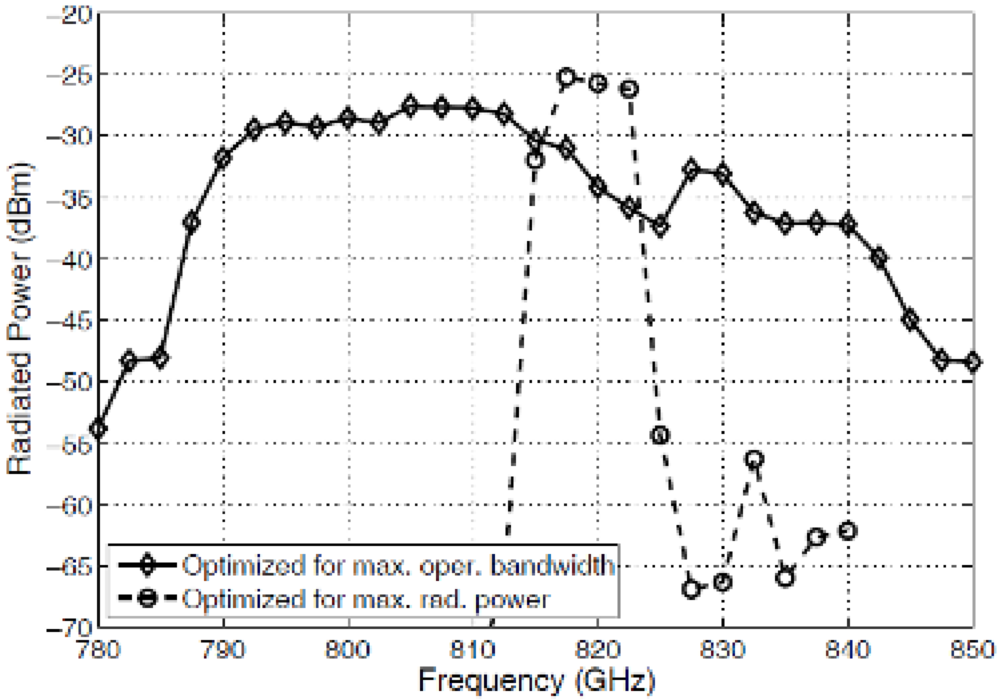
Measured Tx Results

- <10% fractional RF BW, but at multiple harmonics!
- 0dBm EIRP, -25dBm Prad

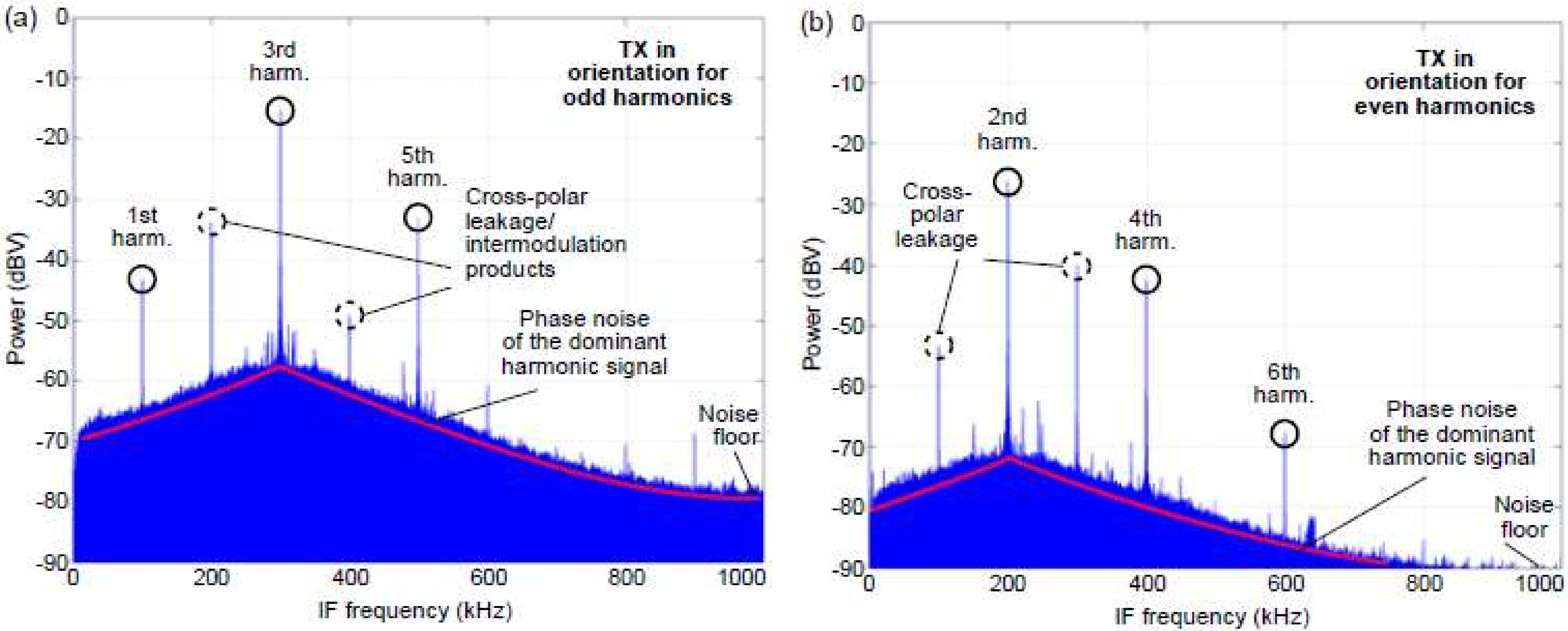
Transmitter board



10cm

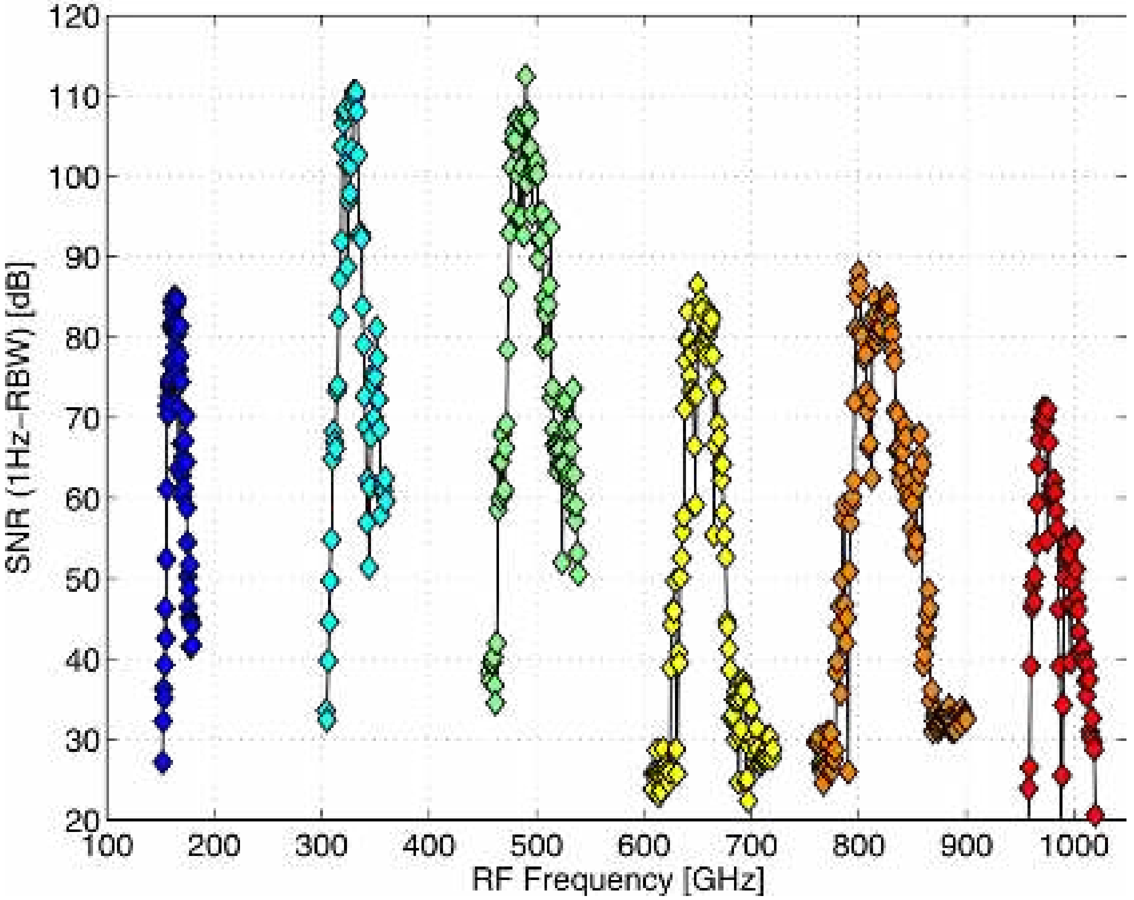


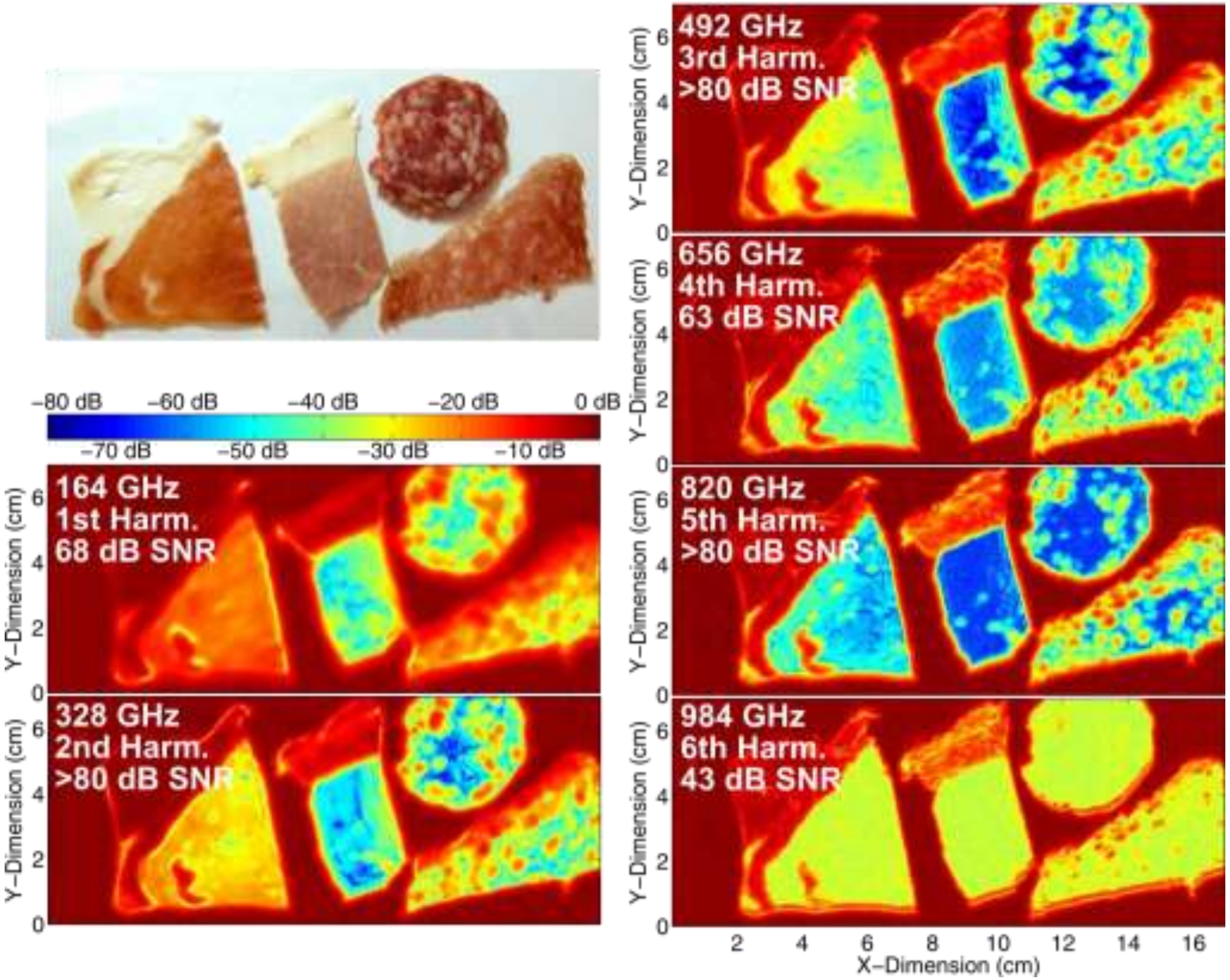
IF Spectrum



- **Only one image scan required to capture odd harmonics at 0.16, 0.48, and 0.82 THz**
- **Cross-polarization is also available at 0.32, 0.64, 0.96 THz**

Imaging Results

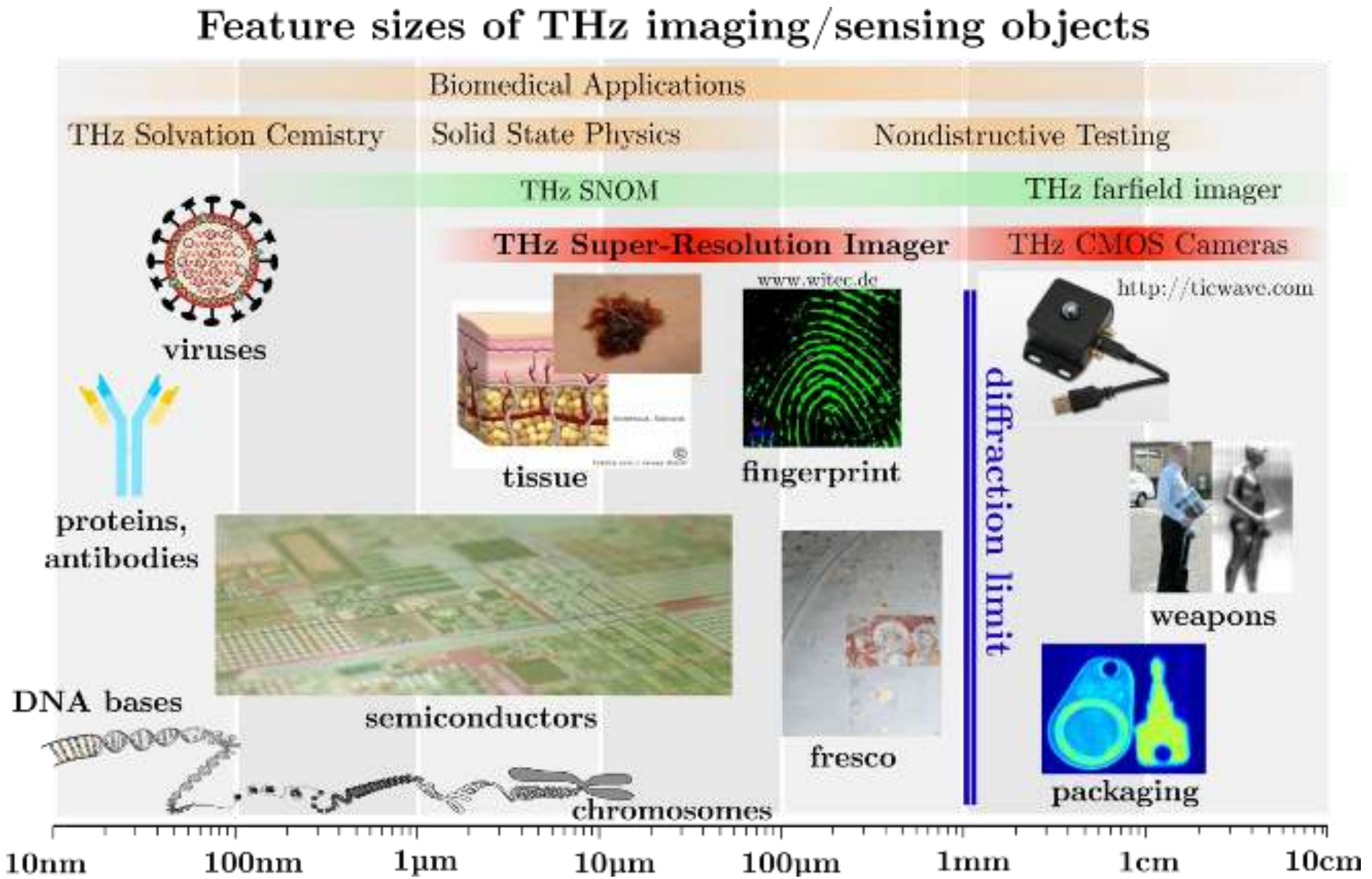


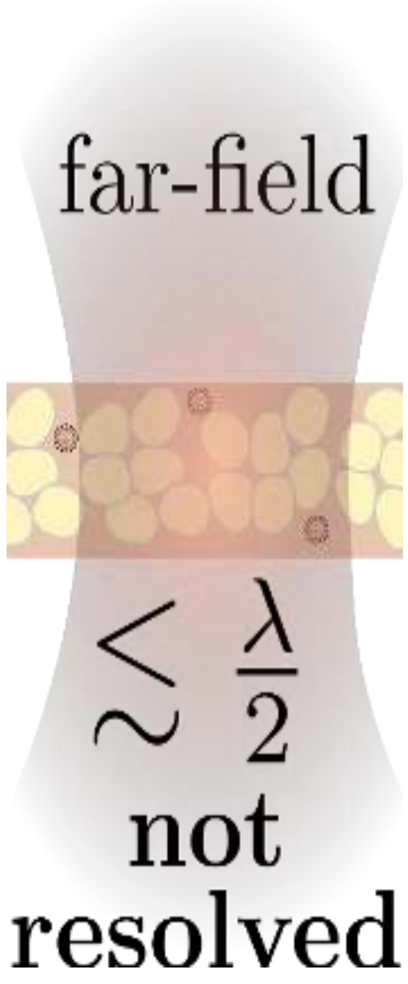


Coherent System: High imaging SNR even at 1THz possible!

THz Near-Field Imaging

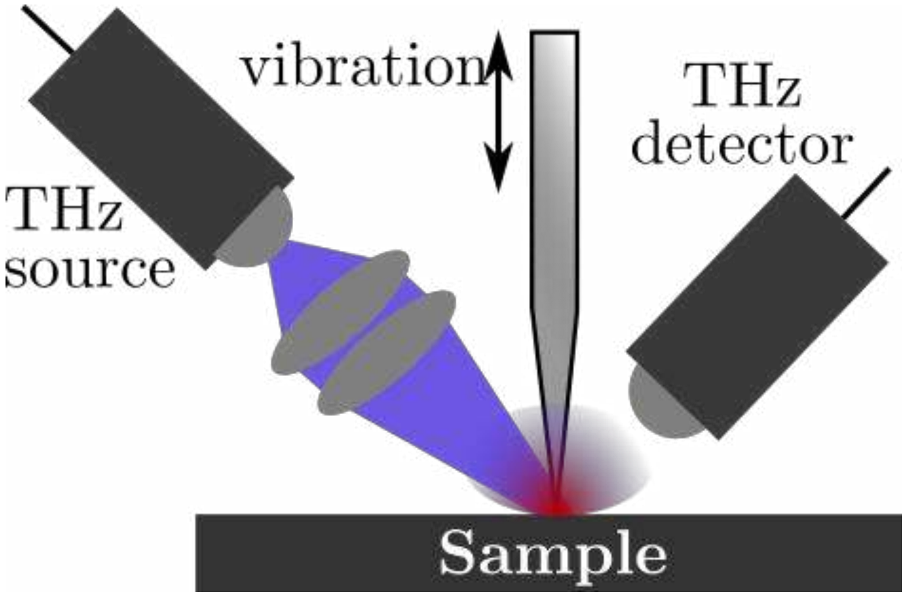
However, resolution is diffraction limited…





SoA Near-Field Imaging

Near-Field Scanning Optical Microscopy (NSOM)



µm/nm-range resolution

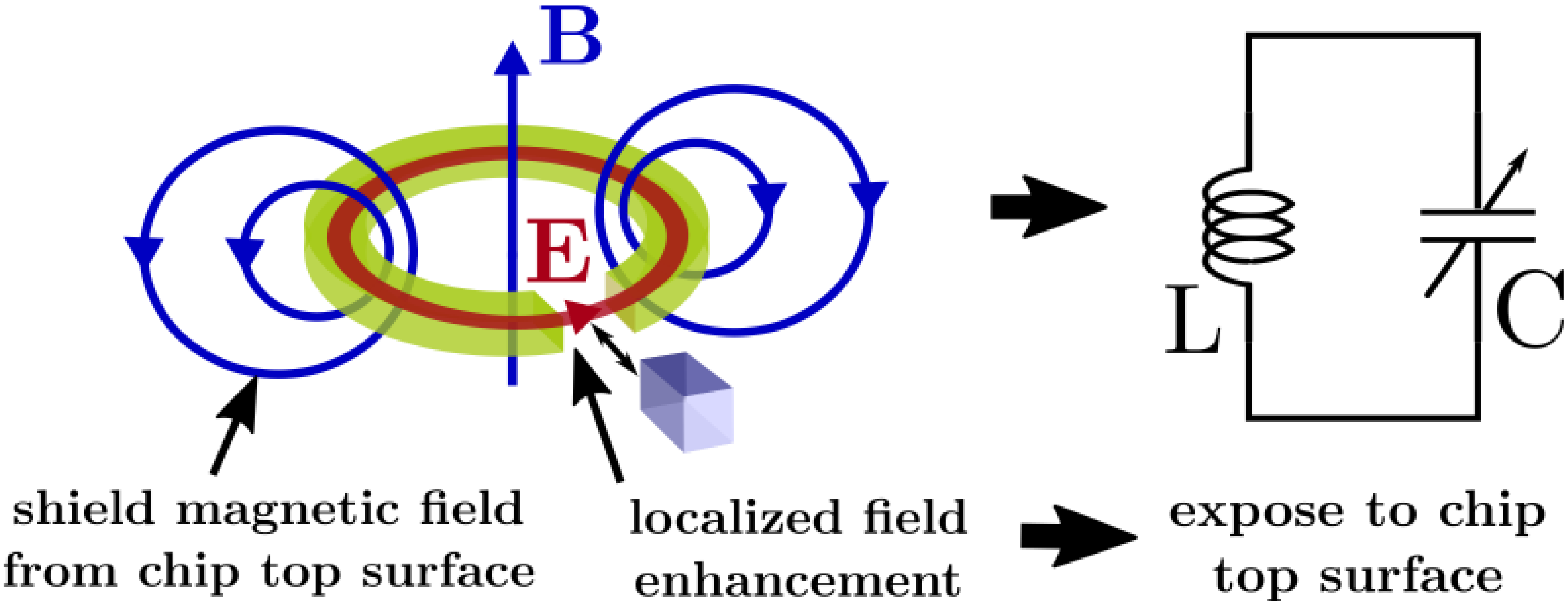
Source or detector placed remotely

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

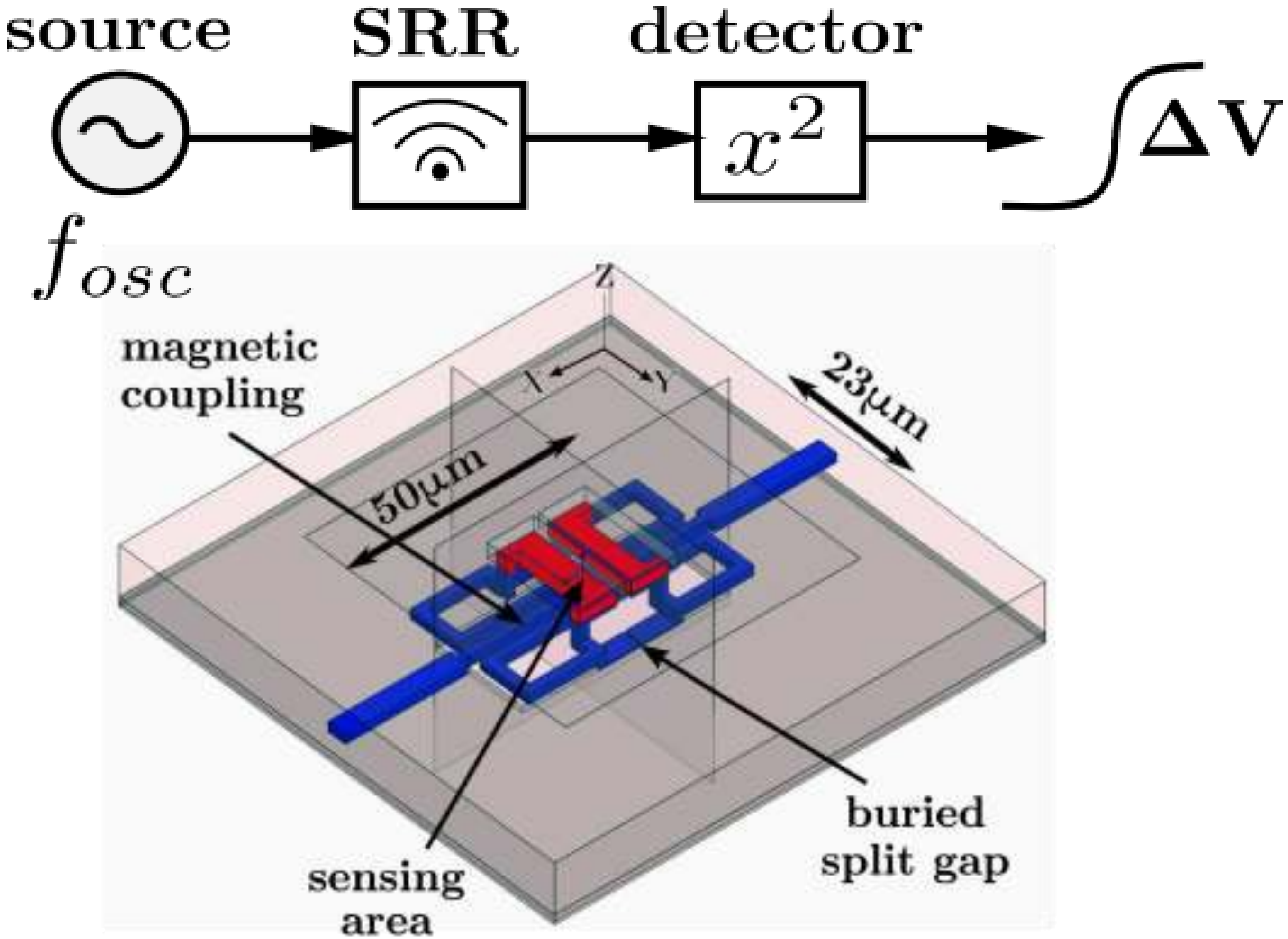
Laboratory technique

Sensing Mechanism

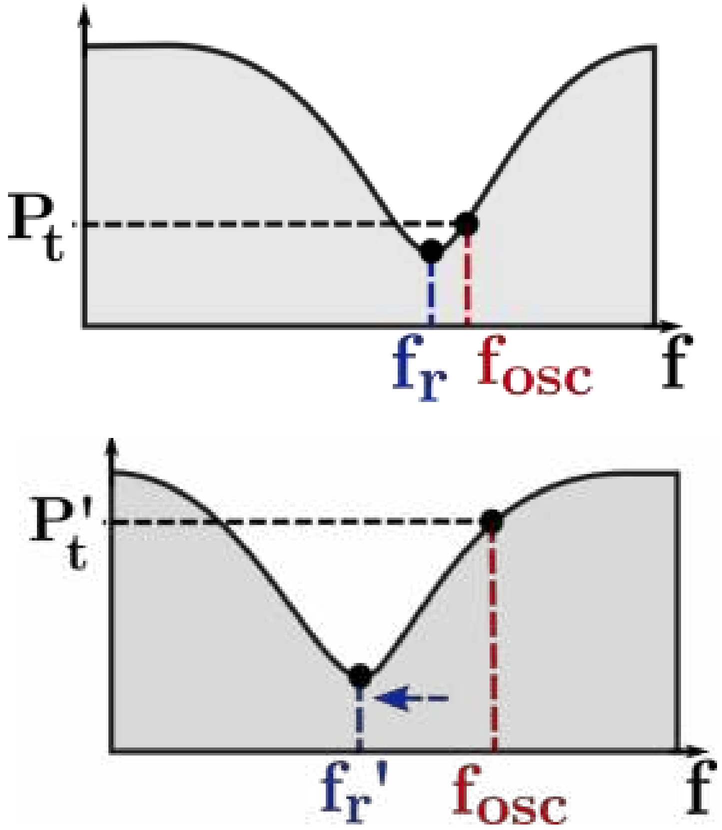
Split-ring resonator (SRR)



Resonator Design

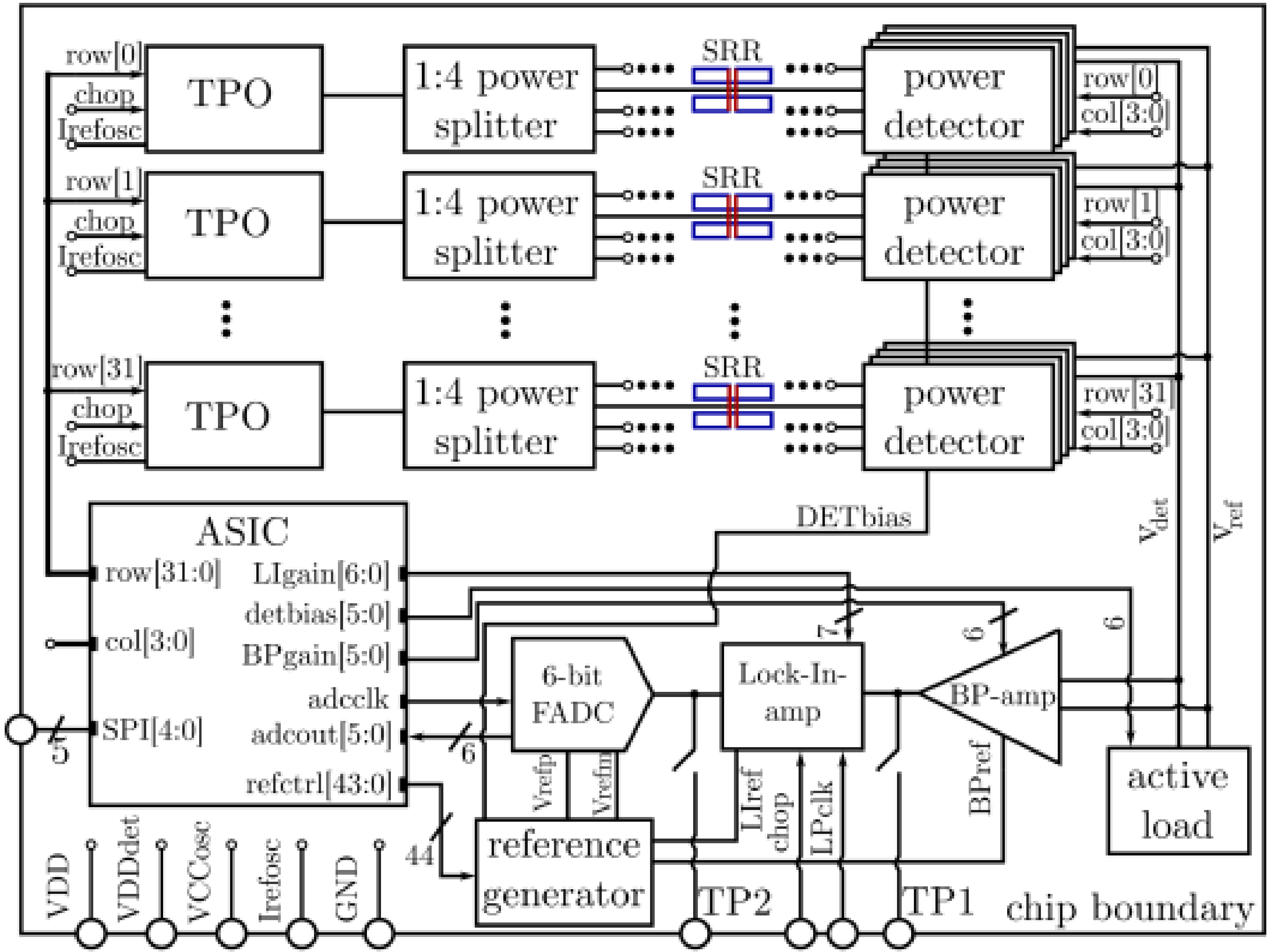


Free-running oscillator and power detector



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

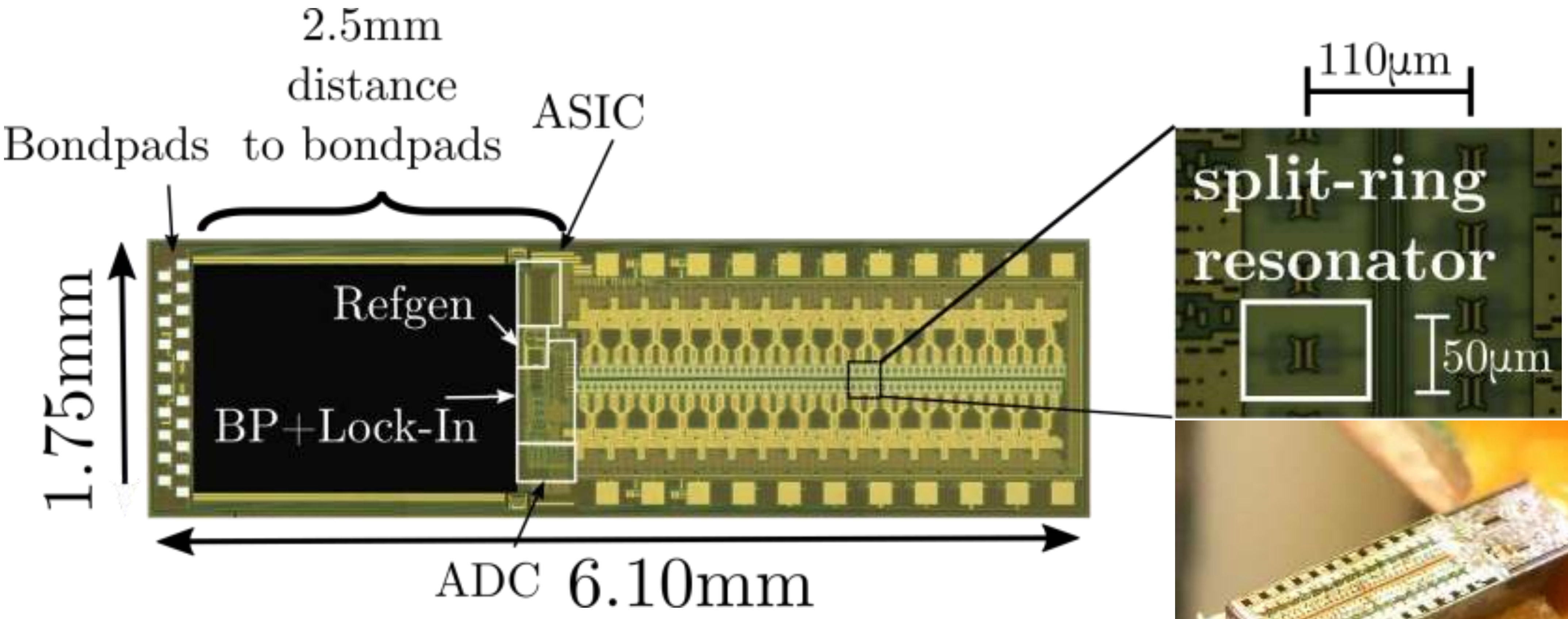
128-pixel Near-field Imager (THz SoC)

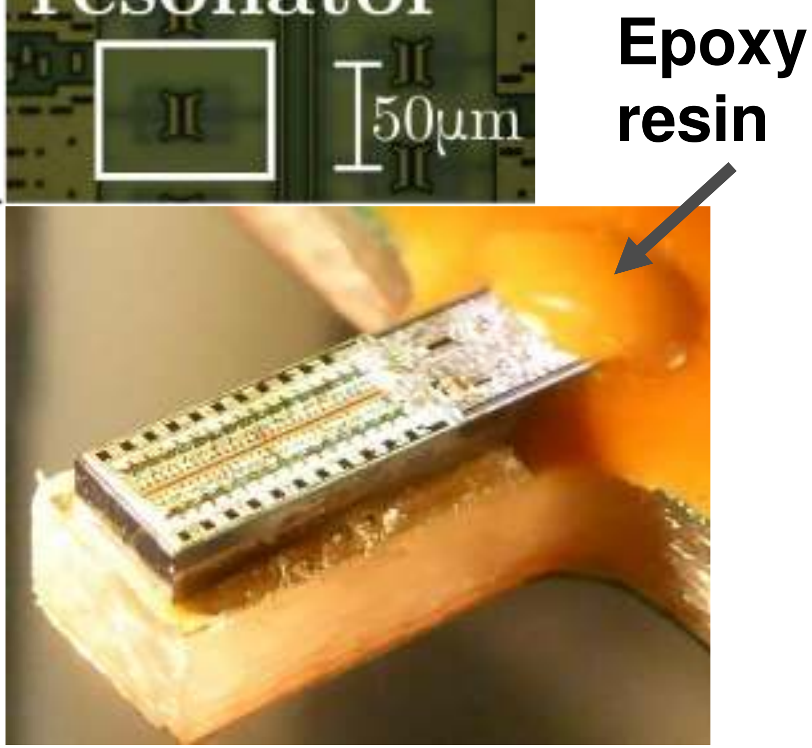


[1] P. Hillger et.al. , A 128-pixel 0.56THz sensing array for real-time near-field imaging in 0.13 µm SiGe BiCMOS, ISSCC 2018

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

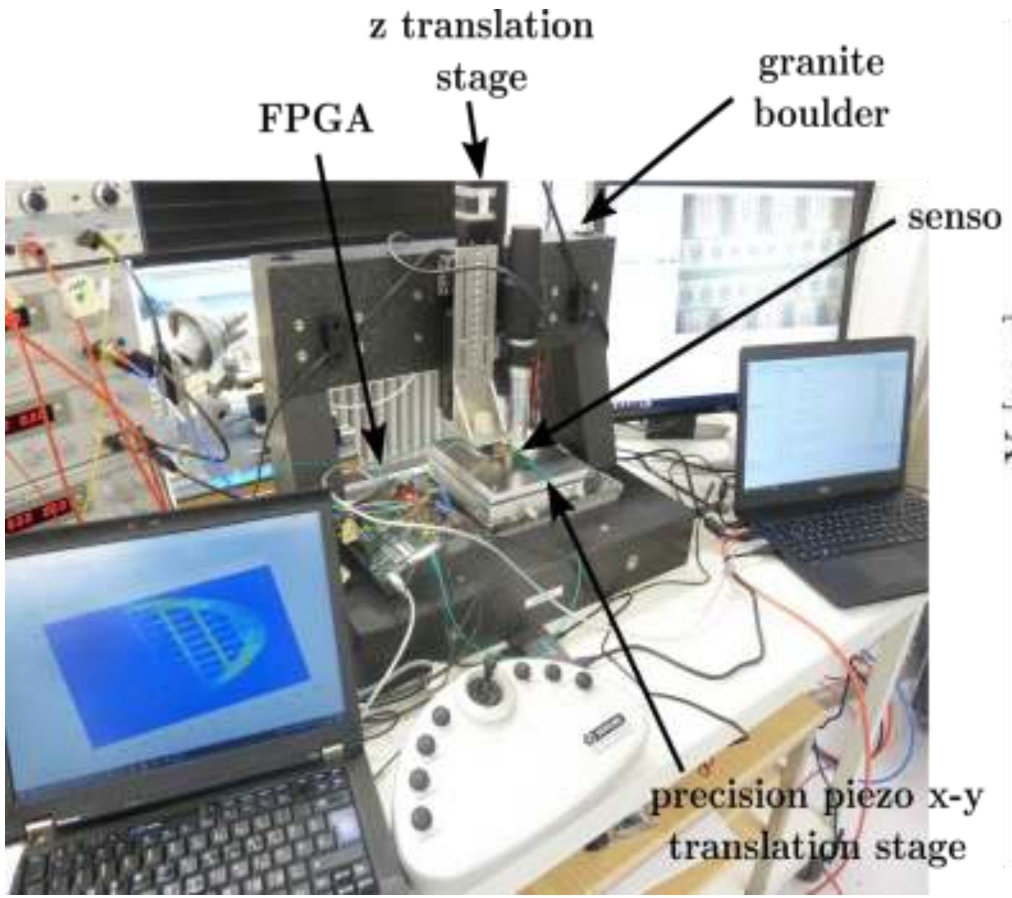
Chip Micrograph and Packaging

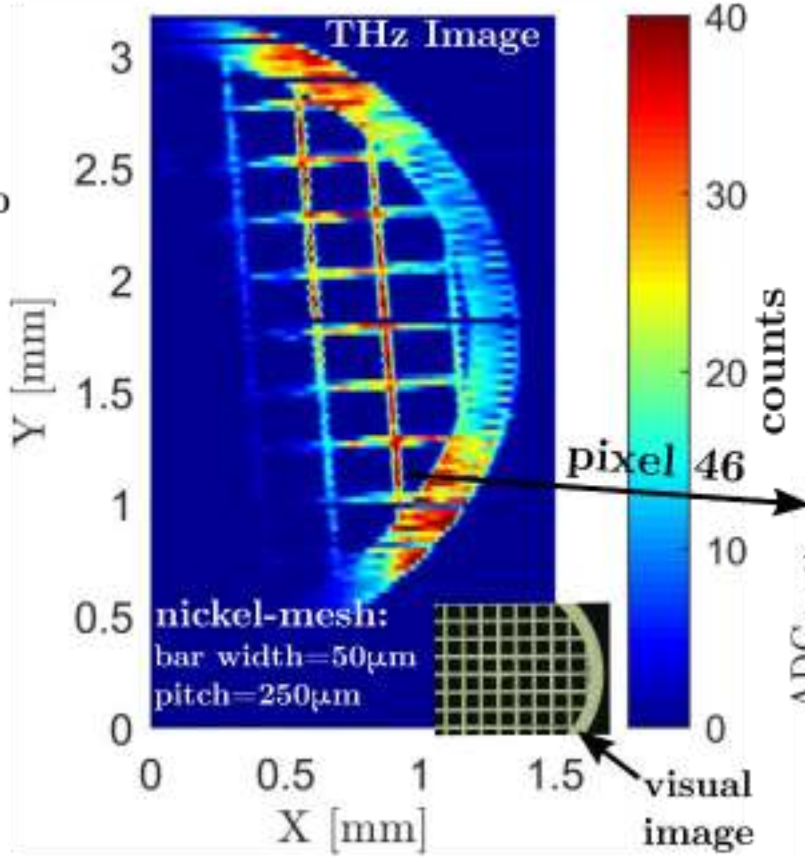


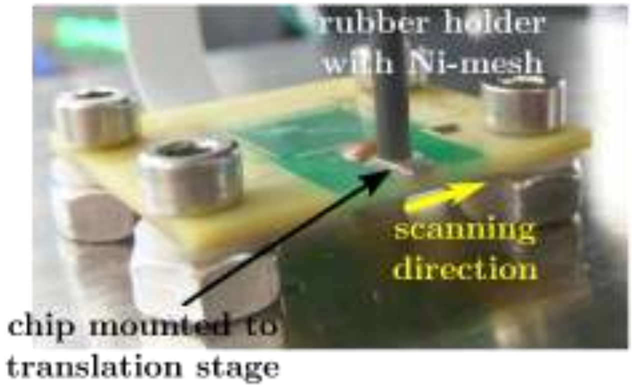


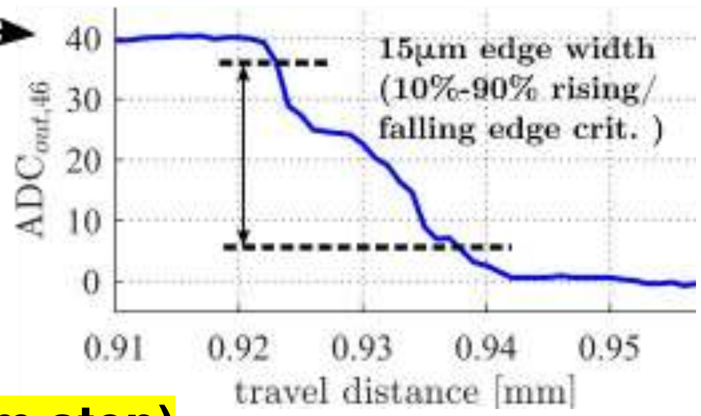
Imaging Results

Main Challenge: Mechanical stability / accuracy



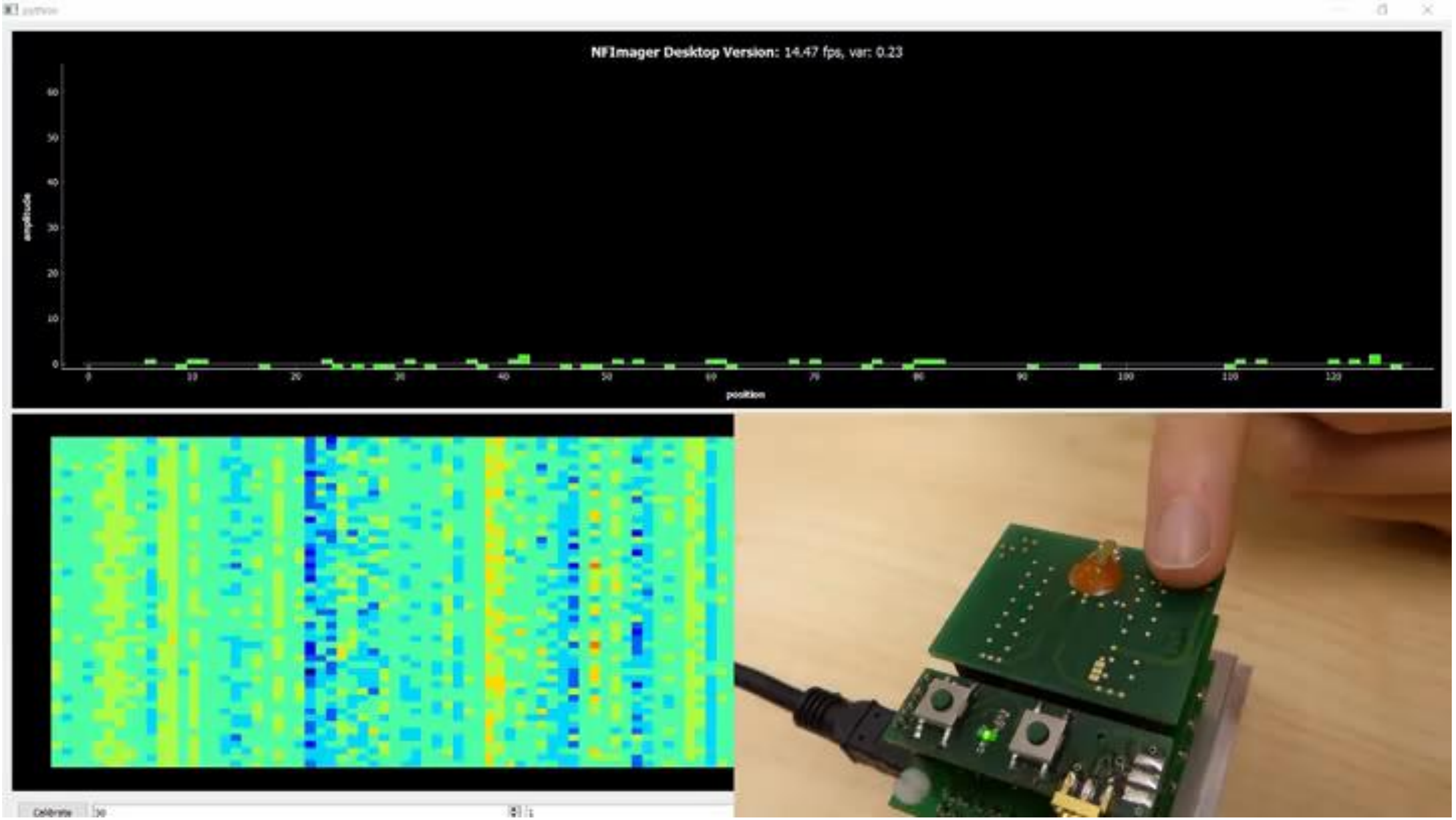


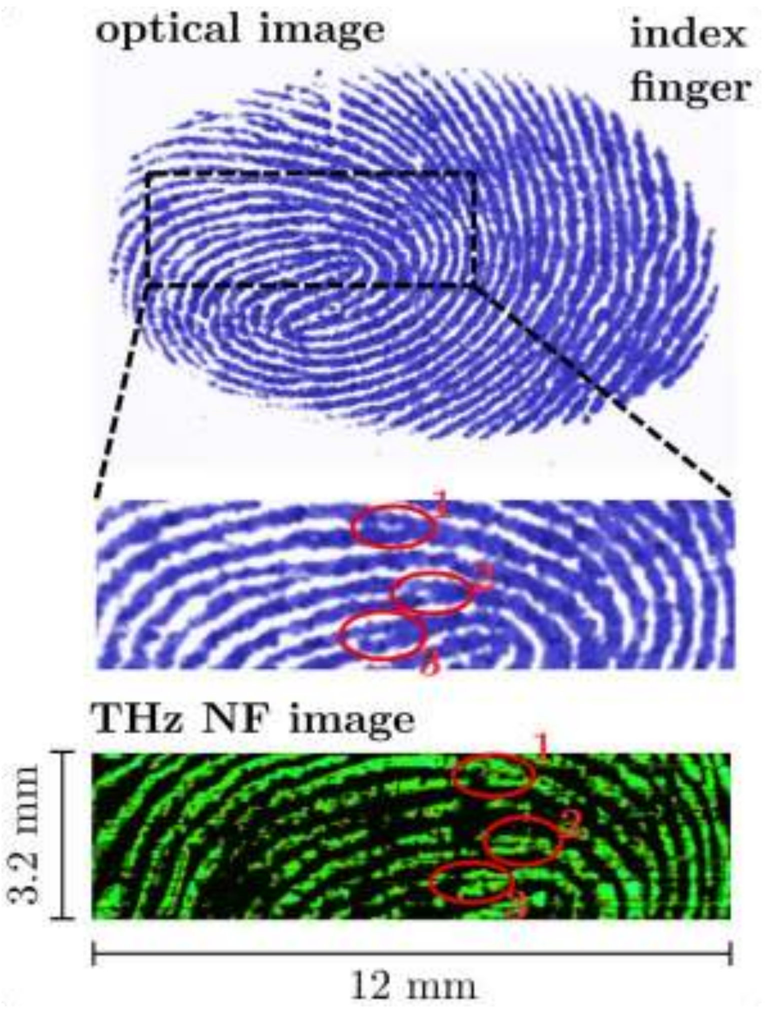




128x1500 pixel (1-D scan, 1µm step)
Tscan=6min 45 sec !

Real-time Near-field Imaging



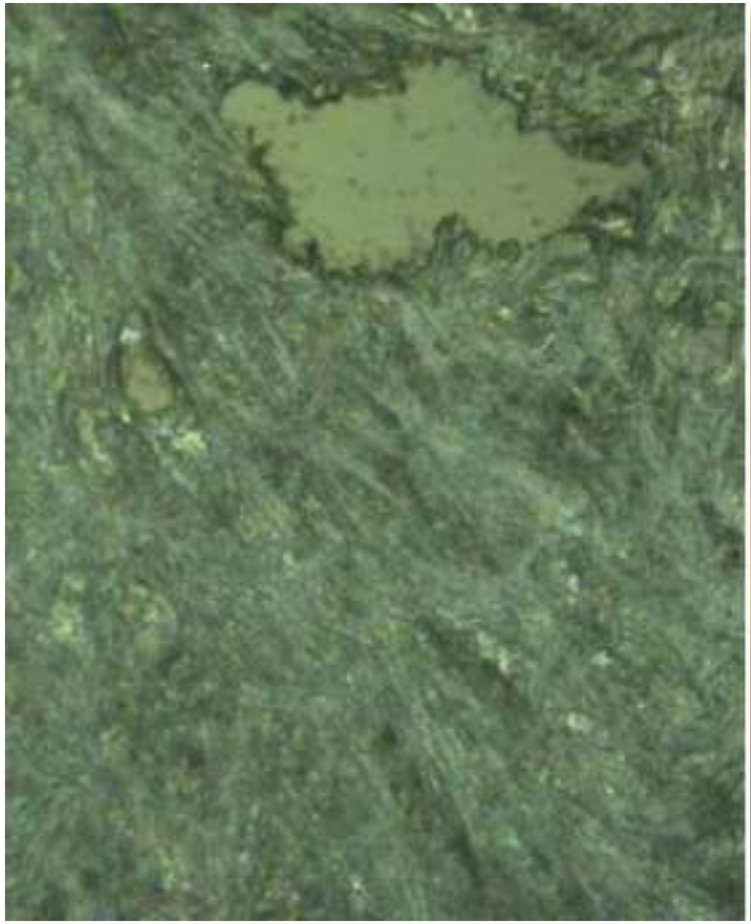


842x128 pixel Tscan=30 sec !

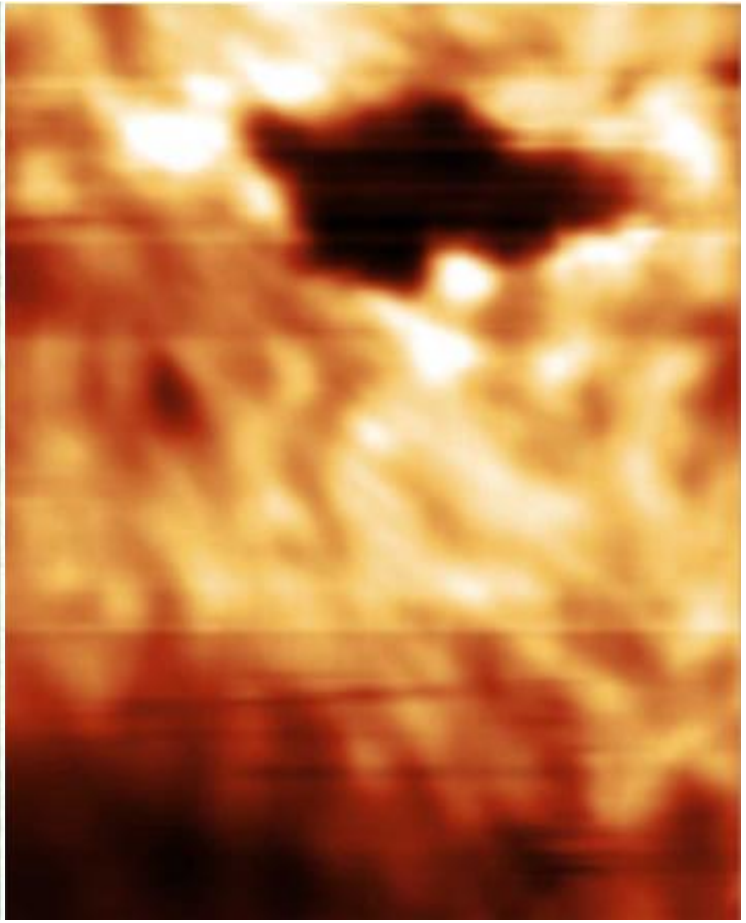
Outlook – Biomedical Applications

Paraffinized tissue slice (5µm thick)

Microscopic Image



THz NF Image



- 250 x 200 pixel
- 500µm x 400µm
- 100ms step time

More results to come…

Summary and Conclusion

- **THz applications with SiGe and CMOS possible!**
  - Vast number of potential applications for Silicon at mmWave and THz frequencies
    - Heterodyne und direct-detection imaging up to 1THz
    - 3D Imaging: Terahertz tomography, 3D radar, Focal-plane imaging with THz Video Camera beyond 1THz
    - Near-field imaging and sensing in biomedical applications
- **Misconception: One can implement THz electronics in Silicon process technologies and circuits work at room temperature!**
  - SiGe HBT:
    - Direct Detector: 3pW/√Hz at ½ THz
    - SiGe HBT power capabilities: 12dBm, -1dBm, -3dBm, -29dBm at 160GHz, 220GHz, 320GHz, 820GHz respectively
    - source arrays up to 0dBm at ½ THz
  - CMOS competitors:
    - Direct detector: 17pW/√Hz (650GHz) demonstrated in 65nm SOI
    - 1k-pixel 500 fps real-time THz video camera demonstrated
    - CMOS capabilities: -1.5dBm (-4dBm rad.) at 288 GHz
- **100 Gbps wireless communication possible now!**
  - Fully-integrated 240GHz RF front-ends up to 1m (100m with mirrors possible)

Thanks

- PhD students and research staff at IHCT: Stefan Malz, Konstantin Statnikov, Neelanjan Sarmah, Pedro Rodriguez Vazquez, Thomas Bücher, Utpal Kalita, Ritesh Jain, Philipp Hillger, Wolfgang Förster, Hans Keller, and Janusz Grzyb
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- DFG Reinhart Koselleck Projekt, PF 661/11-1
- DFG PF 661/6-1, LO 455/22-1, and 661/10-1