Integrated Circuit Design for Terahertz Applications

Ullrich Pfeiffer
ullrich@ieee.org
High-Frequency and Communication Technology (IHCT)
University of Wuppertal, Germany
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 \([\text{Wm}^{-2} \text{ Hz}^{-1} \text{ rad}^{-2}]\)
  \[ B_\nu = \frac{2h\nu^3}{c^2\left(e^{h\nu/k_BT} - 1\right)} \]

• **Stefan-Boltzmann law**
  - Total brightness
  \[ \int B_\nu d\nu = \sigma T^4 \]
  - Planck's const.
  - Boltzmann's const.

• **Rayleigh – Jeans approx.**
  \[ h\nu \ll k_BT \]
  \[ B_\nu \approx \frac{2k_BT}{\lambda^2} \]

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

• **1 THz (λ= ⅓ mm):**
  – $E = 4 \text{ meV}$
  – 1THz = Blackbody Radiation at 17K!

• **X-Ray:**
  – $E = \sim 10 \text{ keV}$
  – $\sim 10.000.000$, 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

- Biotech/Medical
  - Histopathology

- Security
  - Airports

- Communication
  - Wireless

- Process control
  - Plastics, Cardboards

- Space
  - Background radiation

- Terahertz Applications

- Art conservation
  - Frescos
  - Paint analysis
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

Solid-State THz Sources (CW)

- **Electronics**
  - HBTs
  - Impatt
  - Gunn

- **Photonics**
  - Multipliers
  - Lasers, LEDs
  - QC Lasers

- **Cryogenic Cooling**

20dB/decade

[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 Keating)
  – 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

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

Primary use: Calibrated absolute power measurements

Photo-acoustic power-meter head
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 waveguide 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)
Noise Figure – Cryogenic Standards

• Hot/cold (Y-factor) method
  – Cold: Absorber in liquid N2
  – Hot: Absorber in room temp.
• Physics-based standard, much more accurate
• 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

- High performance
- Low performance
- Low cost
- High cost

THz “Nobel Prize”
Emerging THz markets
New applications!
Today’s THz Systems
No business here!
FEL

Today’s THz Systems
High performance
Low performance
Low cost
High cost
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, $f_{\text{max}}=1.5\text{THz}$, 9dB >1THz amp
  - GaN, $f_{\text{max}}=0.58\text{THz}$
  - InP-GaAsSb DHBT, $f_{\text{max}}=1.18\text{THz}$
- **Silicon substrates**
  - CMOS bulk/SOI/FinFETs, $f_{\text{max}}\approx 300-350\text{GHz}$
  - SiGe BiCMOS/SiGe HBT, $f_{\text{max}}=700\text{GHz}$
- **Heterogeneous integration**
  - InP + SiGe
- **Electronic-Photonic integration**
  - Modulators, WG, Ge photo-diodes + Silicon

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

- **SiGe HBT peak cutoff frequency [GHz]**
  - 1995: 3.3V
  - 2000: 2.4V
  - 2005: 1.7V
  - 2010: 1.5V
  - 2015: 1.2V
  - 2020: 240-GHz chipset

- **SiGe:C**
  - 2015: 60GHz Com. /Radar
  - 2016: 77GHz Radar
  - 2018: 160GHz Com. /Radar

Circuit Frequency Planning

**below f\text{max}**

- 220/240GHz
- 2\times \text{(320GHz)}

**beyond f\text{max}**

- 4\times \text{650GHz}
- 5\times \text{825GHz}
- 6\times \text{1THz}

- Fundamentally operated
- Sub-harmonically operated

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Value</th>
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<tbody>
<tr>
<td>DC</td>
<td>~1/10 \text{f\text{max}} (PVT robust)</td>
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<tr>
<td></td>
<td>1/3 \text{f\text{max}} (165GHz)</td>
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<tr>
<td></td>
<td>1/2 \text{f\text{max}} (250GHz)</td>
</tr>
<tr>
<td>f\text{max}</td>
<td>(500GHz)</td>
</tr>
<tr>
<td>2\times f\text{max}</td>
<td>(1THz)</td>
</tr>
</tbody>
</table>

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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

### Table:

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

Consider circuit design trade-offs!
OK, let’s compare DOTSEVEN vs. DOTFIVE on power amplifiers.

<table>
<thead>
<tr>
<th>Circuit</th>
<th>DOTFIVE</th>
<th>DOTSEVEN</th>
<th>Performance</th>
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</thead>
<tbody>
<tr>
<td>mmWave PAs</td>
<td>Run 3</td>
<td>Run 1</td>
<td>Run 2</td>
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<tr>
<td>RF</td>
<td>160 GHz</td>
<td>240 GHz</td>
<td>240 GHz</td>
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<tr>
<td>Psat</td>
<td>10 dBm</td>
<td>5 dBm</td>
<td>7.5 dBm</td>
</tr>
<tr>
<td>$G_T$</td>
<td>20 dB</td>
<td>10 dB</td>
<td>25 dB</td>
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<tr>
<td>BW</td>
<td>7 GHz</td>
<td>30 GHz</td>
<td>40 GHz</td>
</tr>
<tr>
<td>Tech</td>
<td>ST</td>
<td>IHP</td>
<td>IHP</td>
</tr>
</tbody>
</table>

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

• **Heterodyne 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**

Voltage Responsivity: \( R_v = \frac{U_{out}}{P_{in}} \) [V/W]

Noise equivalent power: \( NEP = \frac{V_N}{R_v} \) [W/√Hz]

Total NEP: \( NEP_{\text{total}} = \frac{V_N \sqrt{BW_{IF}}}{R_v} \) [W]
What NEP or NF are we looking for?

a) Active Direct Detection

\[ \text{SNR} = \frac{P_{\text{sig}}}{\text{NEP} \sqrt{f_{\text{ps}}}} \]

\[ \tau = 1/f_{\text{ps}} \]

b) Active Heterodyne Detection

\[ \text{SNR} = \frac{P_{\text{sig}}}{k_B T F f_{\text{ps}}} \]

\[ \tau = 1/f_{\text{ps}} \]
Comparison of Direct versus Heterodyne Detection

\[ P_{\text{sig}} = 10\text{nW} \ @ 25\text{fps} \]

\[ 20\text{pW/}\sqrt{\text{Hz}} \]

\[ 90\text{dB} \]
THz Imaging Systems

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?
Add extra capacitance to enhance self-mixing!

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

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

\[
I_{IF} \propto V_{RF}^2
\]

\[
g_{ds} \propto V_{LO}
\]

-> Square law detector converts RF power to DC current / voltage
Let's take a closer look...

- 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 a Partial Differential Equation:

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

Note, PDE is identical to over-damped plasma wave dynamics:

Continuity eqn.
Simplified Euler eqn.
Gradual channel approx.
Decay of Channel Voltage (Charge Density) Modulation

6 GHz \( \omega_T = 0.0018 \)  

600 GHz \( \omega_T = 0.18 \)

Detector design considerations

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

- a) RF Filter and RF Block with RL
- b) RF Filter and RF Block with RL
- c) RF Filter and RF Block with RL
- d) RF Filter and RF Block with RL and V_B
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

**2010:** 65nm SOI

**2011:** 65nm SOI

**2011:** 65nm Bulk

**2012:** 65nm Bulk

**2018:** 22FDX

<table>
<thead>
<tr>
<th>Year</th>
<th>Technology</th>
<th>Frequency</th>
<th>Sensitivity</th>
<th>Noise</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>65nm SOI</td>
<td>650 GHz</td>
<td>1.1 kV/W</td>
<td>50 pW/√Hz</td>
<td>[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</td>
</tr>
<tr>
<td>2018</td>
<td>22FDX</td>
<td>0.65-1.1 THz</td>
<td>1.2kV/W</td>
<td>12 pW/√Hz</td>
<td>[6] R. Jain, A Terahertz Direct Detector in 22nm FD-SOI CMOS, EUMIC 2018</td>
</tr>
</tbody>
</table>

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IEEE Future Networks Tutorials (Invited Tutorials)
How does this compare with heterodyne RX?

GF 22nm FD-SOI

12 pW/√Hz @ 855 GHz

IHP 130nm SiGe

3 pW/√Hz @ 500 GHz


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

- Multiplied source: 645 GHz, 0.5 mW
- Envelope
- Monolithic array
- XY-scanning
- Ref. signal
- AM-modulation
- Lock-in amplifier
- Data acquisition
Example: Active Imaging at 650GHz


A 825GHz SiGe TX/RX Chipset

LED Flashlight
Visible

Bluetooth Dongle and SD Card
Visible

825GHz, 601x80 pixel image

825GHz, 601x80 pixel image
A 825GHz SiGe TX/RX Chipset

Ceramic Scissors in a Paper Envelope
Visible (excl. envelope.)

Firecrackers in a Paper Envelope

825GHz, 601x80 pixel image
Advanced: Computed Tomography (CT) Imaging

Example: CT Imaging at THz

- 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)  [1] U.R. Pfeiffer, „Sub-millimeter Wave Active Imaging with Silicon Integrated Circuits“, IRMMW-THz, plenary talk, Oct. 2011
Active THz Video Cameras
... the real imagers!
Sensors/ Imaging Cameras

<table>
<thead>
<tr>
<th>Frequency (Energy)</th>
<th>Terahertz</th>
<th>Infrared</th>
<th>Near-infrared</th>
<th>Visible</th>
<th>Ultraviolet</th>
<th>X-ray</th>
<th>Gamma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td><img src="image1" alt="Terahertz" /></td>
<td><img src="image2" alt="Infrared" /></td>
<td><img src="image3" alt="Near-infrared" /></td>
<td><img src="image4" alt="Visible" /></td>
<td><img src="image5" alt="Ultraviolet" /></td>
<td><img src="image6" alt="X-ray" /></td>
<td><img src="image7" alt="Gamma" /></td>
</tr>
</tbody>
</table>
Active THz Video Camera Imaging Setup

• Problem: Source power spread over object 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 Exhibition
Pixel Characterization Essentials (non-video mode)

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

\[ R_v = \frac{U_{\text{out}}}{P_{\text{in}}} \]

\[ \text{NEP} = \frac{V_N}{R_v} \]

\[ \text{NEP}_{\text{total}} = \frac{V_N \sqrt{\text{BW}_{\text{IF}}}}{R_v} \]
Direct-Method of Camera Characterization

Not a chopped lock-in technique!

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

\[ NEP_{total} = \frac{V_{N, total}}{R_v}. \]
Measured RF Bandwidth

- Usable BW > 1 THz
- $BW_{-10dB} = 400$ GHz
- Total NEP = 3 nW
  @820 GHz, $\tau = 34$ s
  (average over 1024 frames), 10-20 nW
  @ 30fps
Responsivity of the camera in video mode (single-pixel)

video-mode at 856 GHz

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


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IEEE Future Networks Tutorials (Invited Tutorials)
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

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

CMOS FPA:
- Bulk resistivity = 15Ω.cm

Si-Lens Resistivity > 10kΩ.cm

$X + Th = 2.75\text{mm}$

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

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

- **4-D Light-Field**
- Common computation method in Optics

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THz Light-Field Example

Separation of two occluded points in space

Coherent vs. Incoherent Methods

- Coherent Methods
  - mmWave
  - Terahertz

- Light-Field Methods
  - IR/Visual

Return on Effort vs. Frequency
THz Illumination
Improve performance (Devices to Components)

ST 65nm bulk CMOS

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

IHP 130nm SiGe

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

[1] P. Hilger, A Lens-Integrated 430 GHz SiGe HBT Source With Up to -6.3 dBm Radiated Power, RFIC 2017
Silicon Source Arrays (Coherent vs. Incoherent)

**Coherent Radiators**
- 91 elements
- OSC 4-push
- -10.9dBm @ 1.01 THz
- DC to RF: 0.0073%
- IHP 130nm SiGe

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

**Incoherent Radiators**
- 16 elements
- OSC 3-push
- 0dBm@530GHz
- DC to RF: 0.04%
- IHP 130 nm SiGe

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

Stochastically independent source pattern destroys illumination phase coherence

530GHz
**Circuit Block Diagram**

- 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 triple-push oscillator
Core TPO Circuit Schematic

CC Colpitts topology

Impedance matching network

Ring Antenna

Two TPOs locked 180deg out of phase to drive antenna
Illustration of the Locking Method

Fundamental Phase Diagrams

TPO1

120°

0°

180°

+180°

60°

TPO2

240°

3rd Harmonic Phase Diagrams

differential to antenna
Chip Micrograph

- Honeycomb tessellation to save die area
- Total die area of 2x2.1mm² for all 16 source pixel
- 510µm pitch
Tapered line used for impedance matching at 3\textsuperscript{rd} harmonic

Locking cap (Ce)

Le (RF choke)

TPO output nodes
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
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Recorded Illumination

Single beams

Diffused background
Diffused Illumination

1 mW $\frac{1}{2}$ THz diffuse illumination

1 mW THz source

$d = 150 \text{mm}$

$\Phi = 50 \text{mm}$

$\pm 10^\circ \text{ fov}$

$f_\# = 1$

two plano-convex PTFE lenses

object plane

$d = 50 \text{mm}$

$\Phi = 50 \text{mm}$

THz Camera

$\pm 23^\circ \text{ fov}$

$f_\# = 3$

[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

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

\[ A = \frac{|V_2|}{|V_1|} \quad \phi = \angle \frac{V_2}{V_1} \quad G_m|_{\text{max}} \quad \Theta(A_{opt}, \phi_{opt}) \]

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

Drawback: single-ended output

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

Chip Micrographs

Single oscillator

Balanced oscillator (core: 120x150µm²)

Balanced Source incl. ant. (500x570µm²) (no pads)
Max Pout on wafer: 700 $\mu$W (-1.5 dBm)

Max Pout (free space): 390 $\mu$W (-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)

325GHz Doubler Schematic (push-push)

- Class-B biased amplifier
- Driven into compression
- Differential drive
Simulated Doubler Performance Power Contour Plots

\[ V_{\text{bias}} \text{ (V)} \]
\[ \text{Input power (dBm)} \]
\[ \text{Output power (dBm)} \]

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

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

160 GHz input power
Output Power Compression

220GHz doubler

-1dBm @220GHz

x18 Multiplier

-3dBm @325GHz

110 GHz input power

18 GHz input power

PA drive sufficient for 320GHz doubler (reaches -3 dBm of breakout)
Measured Output Power vs Frequency

Tuning range is about 20 GHz (limited by driver)

Q: Can we do better than this?
x16 Frequency Multiplier Chain

- 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.

x16 Measurement Results

Chip-micrograph

• Identical circuits in run 1 and run 2.

• Higher output power due to process improvement

<table>
<thead>
<tr>
<th>Technology</th>
<th>Multiplication factor</th>
<th>Psat (dBm)</th>
<th>3dB BW (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IHP run 1</td>
<td>X16</td>
<td>0 @ 250 GHz</td>
<td>30</td>
</tr>
<tr>
<td>IHP run 2</td>
<td>X16</td>
<td>6.4 @ 230 GHz</td>
<td>50</td>
</tr>
</tbody>
</table>
Broadband 240 GHz power source

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

Module assembly with a 7-mm silicon lens

2.2 x 1.45 mm²
Measured results

- 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

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

Class-A save operation region
Single SiGe HBT Output Power Limits

Class-A, no power combining:

- Assumes: class-A, $x = 50\%$ above $BV_{ceo}$, load-line
  $R_{in} = 10 \Omega$ ($r = 5$, $R_{load} = 50 \Omega$)

- Note, other values may shift this data within 3 dB or more but its trend remains

- Johnson limit SiGe:
  $BV_{ceo} + f_T = 200 \text{ GHz V}$

$THz \text{ gap} \equiv \text{Transistor can not be switched}$
Practical Limitation for THz PA design

Issues with frequency upscaling

Output resistance decreases with frequency

Dimensions of tuning elements decrease with emitter width

Limits device size

Limited output power

Recap: Load-line Impedance Match

How does $R_o$ limit $P_{out}$?
Ananlysis of Device Parasitics

Which are the key elements which limit $R_o$?

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

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

Overall $R_{out}$ scales down with frequency as:

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

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

Infineon & IHP Amplifier

- **Infineon 212 GHz 4-stage Amplifier**
  - $f_T/f_{\text{max}} = 250/360$ GHz
  - Gain: 19.5 dB
  - BW: 21 GHz
  - NF: 14 dB (sim)
  - 65 mA @ 3.3 V

- **IHP 230 GHz 4-stage LNA**
  - $f_T/f_{\text{max}} = 300/450$ GHz
  - Gain: 22.5 dB
  - BW: 10 GHz
  - NF: 12.5 dB (sim.)
  - 17 mA @ 4 V
Infineon & IHP Measurement Results

- Both amplifiers show $\geq 20$ 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

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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 heterodyne mixer with same LO

Why use trig. identity:
\[ \sin(2x) = 2 \cos(x) \times \sin(x) \]
and not:
\[ 1 + \sin(2x) = 2 \sin(x) \times \sin(x) \]

[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)!

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How close to $F_{\text{max}}$ can we operate?

We are here!
(no square-waves)

Large-signal HB simulation

**Quadrature LO**

**In-phase LO**
Optimum LO phase shift

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

Tx Chip

Rx Chip
220GHz Sub-harmonic Receiver

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

320GHz Sub-harmonic Front-End

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

• 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 upscaling 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.
Use cases addressed by IEEE 802.15.3d-2017

- Intra-Device Communication: 10...100 Gbit/s
- Backhaul/Fronthaul links: 10...100 Gbit/s
- Kiosk downloads: 10...20 Gbit/s
- Additional Wireless Links in Data Centers: 10...100 Gbit/s
## 240GHz link-budget estimation (QPSK)

The formula for calculating the maximum required receive power (FSPL\(_{\text{max}}\)) is given by:

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

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

**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

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

Up-conversion mixer (run 2)

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

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)

Mixer-first Circuit Schematic (no LNA)

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

Chip Micrographs and Packaging

Transmitter

Amplifier First RX

Mixer First RX

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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

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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.

![Graph showing 6dB level across 226.5 GHz to 253.5 GHz]

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.

![Graph showing 226.5 GHz, 240 GHz, and 253.5 GHz with IF filters required]

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

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

## Link Summary (Amplifier First)

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

**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)

## RF front-end performance

<table>
<thead>
<tr>
<th></th>
<th>Amplifier First (230GHz carrier)</th>
<th>Mixer First (230GHz carrier)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier/BW</td>
<td>Psat</td>
<td>CG</td>
</tr>
<tr>
<td>230GHz/24GHz</td>
<td>9dBm</td>
<td>23dB</td>
</tr>
</tbody>
</table>

## Link performance

<table>
<thead>
<tr>
<th>Mod.</th>
<th>Data Rates/Range/Max range</th>
<th>Reference</th>
<th>Mod.</th>
<th>Data Rates/Range/Max range</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK</td>
<td>35/27.5% 1m/5m</td>
<td>[RWW18]</td>
<td>BPSK</td>
<td>35/27.9% 1m/4m</td>
<td>Not published</td>
</tr>
<tr>
<td>QPSK</td>
<td>65/30.7% 1m/5m</td>
<td>[RWW18]</td>
<td>QPSK</td>
<td>60/26.2% 1m/4m</td>
<td>[IJMWT]</td>
</tr>
<tr>
<td>16QAM</td>
<td>90/14.7% 1m/1.8m</td>
<td>[EuMC18]</td>
<td>16QAM</td>
<td>100/17% 1m/1.8m @ 80Gbps</td>
<td>[MWCL]</td>
</tr>
<tr>
<td>32QAM</td>
<td>90/11.9% 1m/1.6m</td>
<td>[APMC18]</td>
<td>32QAM</td>
<td>90/13.7% 1m/1.6m</td>
<td>Not published</td>
</tr>
<tr>
<td>64QAM</td>
<td>81/8.7% 1m/1m</td>
<td>[RWW19]</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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[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 \((-150 \text{ dBC/Hz})\) scales by a factor of \(20\log_{10}(16)=24.1 \text{ dB}\)
  – \(\rightarrow\) Rms phase error in the LO path scales linearly with the modulation BW
  – The total integrated (BW=13GHz) rms phase error is \(4^\circ\)
  – Close-carrier PN is \(1.8^\circ\) at 1GHz

• Harmonic spurs in LO:
  – odd \((\times15, \times17)\) and even \((\times14, \times18)\) harmonics around the desired \(\times16\) tone
  – The odd harmonics \((\times15, \times17)\) are particularly harmful for the link performance.
  – Mixing with \(\times16\) 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

**USB >> LSB (8 dB)**

**LSB > USB (2-3 dB)**

**LSB >> USB (7 dB)**

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IQ channel leakage from amp. distortion

BB I

BB Q

\[ \cos \]

\[ \sin \]

\[ \cos \]

\[ \sin \]
IQ channel leakage from amp. distortion
Link Impairments (Mixer First)

LO spurs

TX output

RX output

<table>
<thead>
<tr>
<th>Tx to Rx Constellation 16-QAM</th>
<th>23.75 Gbaud</th>
<th>25 Gbaud</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol Rate</td>
<td>95 Gbps</td>
<td>100 Gbps</td>
</tr>
<tr>
<td>EVM</td>
<td>15% / -16.4 dB</td>
<td>17% / -15.4 dB</td>
</tr>
<tr>
<td>Data Rate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

LO to BB leakage.
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

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

100m range coverage expected for 50dBi lens gain
SoA for all-electronic wireless links < 200 GHz

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

\(^1\) Tx without baseband interface: PRBS generator on chip.
\(^2\) No LO generation path implemented on chip.


240GHz Radar Transceiver
3D-Imaging (210–270-GHz Radar Transceiver)


RX CG=12.1dB, NFmin=21.1dB, -10dB-BW=46.3GHz
3D Imaging and Non-Destructive Imaging Results

- Measured range resolution = 2.75mm

**Graph:**
- Normalized power (dB) vs. IF frequency (kHz)
- Hann–wind. raw IF signal
- Hann–wind. IF signal after cal.

**Diagram:**
- Opaque blister pack containing drugs
- Missing tablets
- Blister pack
- Backside of the cardboard box

**Image:**
- Corner reflector at 40cm
Multi-Color Imaging
How about hyper spectral imaging and sensing?

**Wanted:**

Materials spectral fingerprint

+ Polarization-diversity for ellipsometry

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

\[ \varepsilon' + \varepsilon'' \]

at least a decade of bandwidth!
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

THz Harmonic Generator

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

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 mm² 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

![Image of RX board with 10cm scale]

![Graph showing conversion gain and noise figure vs frequency]
Measured Tx Results

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

Transmitter board
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)

- Source or detector placed remotely
  - Poor power coupling efficiency
  - High-power sources & cooled detectors
  - Low dynamic range & contrast in far-field clutter

**µm/nm-range resolution**

Laboratory technique
Sensing Mechanism

Split-ring resonator (SRR)

shield magnetic field from chip top surface
localized field enhancement
expose to chip top surface
Resonator Design

Source → SRR → Detector

Resonator Design

Free-running oscillator and power detector

128-pixel Near-field Imager (THz SoC)

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

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

2.5mm distance to bondpads

Bondpads to bondpads

ASIC

Refgen

BP + Lock-In

ADC 6.10mm

110μm

split-ring resonator

1.75mm

Epoxy resin
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…

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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)
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