Radio Front-Ends for 100 Gbps and beyond

Ullrich Pfeiffer
ullrich@ieee.org
High-Frequency and Communication Technology (IHCT)
University of Wuppertal, Germany
The Pursuit to Unlimited Bandwidth
mmWave/THz Application Scenarios

- Non-destructive testing
- Security
- Bio-medical
- Space
- Material characterization
- Spectroscopy
- Super-Resolution Imaging

Can we use silicon to implement THz Radio Front-Ends?

Radar Applications
- 77GHz, 120GHz, 240GHz
- Automotive
- Remote control
- Gesture recognition
- Process control
- 3-D Imaging
- Patient monitoring

High-speed Communication
- 60GHz, E-band, 5G, 6G and beyond
- IEEE 802.15.3d-2017
- 252-322 GHz
- Towards 100GBit/s
- Interconnects
- Data servers
- Networking and protocols
Silicon (SiGe) HBT Technology Evolution

SiGe HBT peak cutoff frequency [GHz]

- 1995: SiGe HBT, 3.3V
- 2000: 2nd generation, 2.4V
- 2005: 3rd generation, 1.7V
- 2010: 4th generation, 1.5V
- 2015: 5th generation, 1.3V

SiGe:C

- 2015: 60GHz Com. /Radar
- 2016: 77GHz Radar
- 2020: 160GHz Com. /Radar
- 2020: 240-GHz chipset

6G and beyond

© 2019 U. Pfeiffer

6G Wireless Summit
### 240GHz link-budget estimation (QPSK)

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

<table>
<thead>
<tr>
<th>Tx power</th>
<th>NF</th>
<th>Number of channels</th>
<th>Bandwidth</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, antenna gain, packaging*
Can we build a generic THz I/Q transceiver?

- 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
220-260 GHz TX/RX Chip Block Diagrams

[1] N. Sarmah et al, TMTT 2015 run 1
Chip Micrographs and Packaging

Transmitter

Amplifier First RX

Mixer First RX

RX module

copper heatsink
hot chip
bonding wires

Si-lens
thermo-cond. glue
heat flow paths

26dBi

© 2019 U. Pfeiffer
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
- $3\, dB$ 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
- $3\, dB$ RF/IF BW = $28/14$ GHz
- IQ Amp. Imb. < $1$ dB for IF up to $17$ GHz
Testbed for 100 Gbps and Beyond?

- 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>

**Limits:** I/Q correlation, LO SFDR, -55 dB LO-BB feed-through, group delay distortion (package)
## Chip-Set Summary (Tunable Carrier 220-260 GHz)

<table>
<thead>
<tr>
<th>RF front-end performance</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>
<tr>
<td></td>
<td>11.5 dB</td>
<td>220-260 GHz /28 GHz</td>
</tr>
<tr>
<td></td>
<td>7.8 dB</td>
<td>14 dB</td>
</tr>
</tbody>
</table>

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

[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,"  

© 2019 U. Pfeiffer 6G Wireless Summit
Link Impairments (Mixer First)

- **LO spurs**
- **TX output**
- **RX output**

<table>
<thead>
<tr>
<th>Tx to Rx Constellation 16-QAM</th>
<th>[Table with data]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol Rate</td>
<td>23.75 Gbaud</td>
</tr>
<tr>
<td>EVM</td>
<td>15% / -16.4 dB</td>
</tr>
<tr>
<td>Data Rate</td>
<td>95 Gbps</td>
</tr>
</tbody>
</table>

LO to BB leakage

RX Signal Spectrum (95 Gbps)
Q: What do we need to improve data-rates and range?
– Range: Tx power, Rx noise figure, antenna directivity
– Data rates: SNR/PN limit spectral eff., RF BW flatness, PN floor of 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 Estimation

<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 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 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 mW²</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>Doubble 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.
Conclusion and summary

• Vast number of potential applications for Silicon at mmWave/THz
  – THz Video Cameras, 3D radar
  – Near-field imaging and sensing in biomedical applications

• A 100 Gbps wireless communication is possible in SiGe today!
  – 240GHz Chipset and with a inexpensive COB packaging incl. Si lense
  – Up to 100m range with 50dBi antenna gain possible

• Future challenges
  – Improve on RF link impairments
  – Solve the digital base-band gap

Close the 6G and technology gap!
• 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
• Partially funded by the European Commission within the project DOTFIVE and DOTSEVEN (no. 316755 )
• DFG Priority Program SPP 1655 (Real100G), 1857 (ESSENCE), SPP 1798 (CoSIP)
• DFG Collaborative Research Center (MARIE), PF 661/4-1(2)
• DFG Reinhart Koselleck Projekt, PF 661/11-1
• DFG PF 661/6-1, LO 455/22-1, and 661/10-1
References


