Fully Integrated Radio Front-End Module for Wireless 100 Gbps Communications

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Motivation

<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 (kiosk)</th>
<th>Rx antenna gain (mobile)</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>

\[ R_{\text{max}} = \frac{\lambda}{4\pi} \sqrt{\frac{P_{\text{tx}} G_{\text{tx}} G_{\text{rx}}}{P_{\text{rx,min}}}} \]
State-of-the-Art – On-Chip Antennas

- **[JPB13] SiGe technology**
  - 240 GHz radar sensor, range: 0.8 m
  - Differential fed patch antenna
  - 24 GHz gain bandwidth (3 dB), return loss -3 dB
  - Small distance between patch and ground plane → poor bandwidth-efficiency product

- **[SWB13] 0.13 μm SiGe:C BiCMOS technology**
  - Double folded dipole at 240 GHz, microstrip feed
  - Localized backside etching (LBE) technology → decrease of surface wave modes
  - Ground plane distance: 200μm
  - 11 GHz bandwidth (return loss < -10 dB)

- **[GRY15] 0.13 μm SiGe:C BiCMOS technology**
  - 240 GHz radar sensor
  - Integrated lens antenna, circularly polarized
  - Antenna bandwidth > 100 GHz

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State-of-the-Art – Power Amplification

- **[Yu14] GaN power amplifier**
  - 40 dBm output power @ 30 GHz
  - Power added efficiency: 15%
  - 3.5 x 3.4 mm²
  - 8 parallel amplifier chains

- **[Cam14] 35 nm InAlAs/InGaAs**
  - 14 mW output power @ 200 GHz
  - 20 dB small signal gain
  - 12.9 dB small signal gain from 185 to 215 GHz
  - 2.5 x 1 mm²
  - 8 parallel 3 stage amplifiers
  - Measured losses of 2 dB for tandem coupler
  - Simulated losses 1.5 dB for 1:4 combiner

- **[Ate11] Free-space power-combining**
  - EIRP 33-35 dBm @ 90-98 GHz
  - on-chip power: 21-23 dBm
  - ~100 % free space power combining efficiency
  - 3x3 antenna array (λ₀/2 spacing)
  - Chip-size: 7.3 x 6.6 mm²

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Different Types of Power Combining

- Parallel amplifiers with power combiner and antenna
  - Losses of coupler feed lines and antenna after the amplifiers
  - Coupler has to match the output impedance of the power matched amplifiers

- Use of an antenna array
  - Minimum distance between the antenna elements necessary → increase of chip size

- Feeding of one antenna element with several amplifiers.
  - → this new approach
Integrated Lens Antenna - Principle of Operation

- No ground plane as reflector
- Planar monopole antenna as primary radiator
  \[ \frac{P_{\text{dielectric}}}{P_{\text{total}}} \approx 1 - \frac{1}{\varepsilon_r^{3/2}} \]
- Principle of Integrated Lens Antenna (ILA)
  - Surface waves negligible
  - E.g. 6 mm lens diameter
  - 200 µm matching layer with \( \varepsilon_r = 2.82 \)

![Diagram of an integrated lens antenna with labels for silicon, high resistivity silicon lens, and Antenna-on-Chip (BEOL).]

![Graph showing directivity vs lens diameter at 240 GHz, with a point indicating 6 mm, 22.4 dBi.]

Farfield pattern
Primary Radiator – Impedance Matching

- Slot antenna including 4 monopoles [Ada10]
- Advantage
  - Small dimensions (slot diameter < 0.25\(\lambda_0\))
  - Matching of antenna input impedance (per monople)

Primary Radiator – Polarization

- Different polarizations by applying different phases

Dual polarized (2 channels)
e.g.
port 1 and port 3 Tx
port 2 and port 4 Rx
or
port 1 and port 3 Tx1 and
port 2 and port 4 Tx2

Same signal, but phase shifted
⇒ in-antenna power combining

Same signal, but 45° phase shifted
⇒ power combining with circularly polarized wave

Extended power-combining: more than one feed-line per monopole possible
Primary Radiator – Extended Power Combining

Extended power-combining: more than one feed-line per monopole possible

4 x 70Ω
8 x 70Ω
16 x 70Ω
32 x 70Ω
Primary Radiator – Extended Power Combining

Extended power-combining: more than one feed-line per monopole possible

4 x 70Ω
8 x 70Ω
16 x 70Ω
32 x 70Ω

![Graph showing total efficiency vs. frequency for different number of feed-lines: 4, 8, 16, 32 feed-lines.](image)
Ultra-Compact Power-Splitters

- Distributed transformer (DT) circuit
- Stacked magnetically coupled lines with intrinsic inductance → MIM capacitors for their compensation
- Single-ended input
- Quasi differential outputs
- Ultra-broadband
- Low-loss
- Back-to-back measurements

- 4 x 12.5 Ω outputs
  - Max. phase inbalance: 10°
  - Max. amplitude imbalance: 0.9 dB
  - DT size: 90 x 60 μm²

- 4 x 50 Ω outputs
  - Max. phase inbalance: 4°
  - Max. amplitude imbalance: 0.7 dB
  - DT size: 80 x 80 μm²
Passive 4-feed Differential Antenna

- Characterization of the multi-feed passive antenna
- Power-splitter by spiral Klopfenstein taper and DTs
- Antenna input impedance: 50 Ω (per microstrip line)
- Simulated radiation efficiency: > 90 % (without splitter network)
- Small dimensions: antenna slot diameter $\lambda_0/5$ @ 240 GHz

- IC mounted on 12 mm hemispheric silicon lens
- Chip size: 820 x 700 µm²
Active 4-feed Differential Antenna

- IC (1056 x 485 μm²) mounted on 12 mm hemispherical silicon lens serves as heat dissipation
- Small dimensions: antenna slot diameter < $\lambda_0/5$ @ 240 GHz
- Four parallel single-stage differential cascode amplifiers
- Power-splitter consists of:
  - Microstrip T-junction
  - Klopfenstein taper
  - DTs with 4 x 12.5 Ω outputs, 50 Ω inputs

0.9 dB loss

~2 dB loss
Active 4-feed Differential Antenna

- Antenna bandwidth: > 120 GHz
- Four parallel single-stage differential cascode amplifiers
- Recalculated amplifier gain compared to simulations of a single differential amplifier cell
Blockdiagram of the 240-GHz Transmitter

**Carrier generation [1]**
- Local Oscillator (LO) input signal at 15 GHz
- Active balun (single-ended to differential)
- Four cascaded frequency doubler stages
- Three stage power amplifier

**IQ Modulation [1]**
- Differential baseband inputs of inphase and quadrature component
- Double-balanced Gilbert-cell topology

**On-chip Antenna [2]**
- In-antenna power combining approach
- Dielectric 12 mm lens
- Antenna gain around 20 dBi

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240-GHz Transmitter Package

- Single SiGe RF MMIC
  - 0.13 µm Bi-CMOS technology
  - Chip size 1336 x 3006 µm

- 2 x 2 cm alumina board
  - Connectors for differential baseband signal
  - Connector for local oscillator input
  - DC power supply using flat ribbon cable
240-GHz Transmitter Package
240 GHz Communication - Measurement Setup

TX
Fully integrated 240 GHz transmitter

RX
MilliLink receiver modules presented in [3].

AWG M8190A
12 Gsamp/s
12-bit DAC

DC-blocks

Oscilloscope DSOX93204A
80 Gsamp/s
8-bit ADC

Horn-antenna

Baseband-amplifier

Multiplier x6

TX
-10 dBm @ 15 GHz

RX
6 dBm @ 20 GHz

d = 20 cm

240 GHz Communication - Measurement Setup

- MilliLink receiver modules
- 24 dBi horn-antenna
- 240-GHz Transmitter
- Flat ribbon cable for DC power supply

Tripods for antenna alignment
Measurement Results

- Keysight VSA Software as digital receiver
  - Carrier recovery
  - Time synchronization
  - IQ offset and imbalance correction
  - Channel equalization

- EVM and MER estimation
  - Averaging over 100 measurements with each 4096 symbols
  - Pseudo random bit sequence with length of $2^{15}-1$ bits

*EVM and MER curve for increased symbol rates*
240 GHz Transmission Results

EVM curve for increased symbol rates using QPSK and 8-PSK modulated signals.

30 Gbps data transmission at 240-GHz carrier frequency using 8-PSK modulated signals.
Summary & Outlook

- High bandwidth and high efficient on-chip in-antenna power-combining
- Usable for simplex communication transmitters
- Different types of power-splitters (DTs and feed-ring)
- Calibrated gain measurements for verification of passive and active antennas
- Integration to a 240 GHz communication transmitter
- 30Gbps demonstration with integrated transmitter