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Abstract: The architecture, implementation and performance of active MMIC-based transmit and receive frontends for sub-mmW communication are presented. A focus is on the generation of local oscillator signals for up- and down-conversion by frequency multiplication up to 480 GHz. Transmission experiments at a center frequency of 220 GHz achieve up to 25 Gbit/s data rate.

Purpose: Review of current progress on the implementation of active electronics-based transmitters and receivers for terahertz communication.

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MMIC Chip Sets for Wireless Communication up to 480 GHz

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Abstract

The architecture, implementation and performance of active MMIC-based transmit and receive frontends for sub-mmW communication are presented.

A focus is on the generation of local oscillator signals for up- and down-conversion by frequency multiplication up to 480 GHz.

Transmission experiments at a center frequency of 220 GHz achieve up to 25 Gbit/s data rate.
Generic Millimeter-Wave Analog Frontend

BB or IF signal processing → D/A

D/A

generic analogue frontend

frequency generation and/or multiplication

LO
e.g. VCO (comm.) DDS (radar)

IF/BB

frequency translation (up-conversion)

Rx amplification

IF/BB

frequency translation (down-conversion)

Tx amplification

distribution network

switches

filters

phase shift

antennas
MMIC-based sub-mmW frequency generation

- Frequency generation < 20 GHz
- Frequency platform in W-band
- Single-chip cascade of multiplication and amplification stages

Waveform generation (arbitrary architecture)

- Oscillator (OSC)
- Phase detector (PD)
- Voltage-controlled oscillator (VCO)
- Divider (1/n)
- Direct digital synthesizer (DDS)
- Local oscillator (LO)
- Frequency multipliers: 6, 8, 9, 12
- Frequency range:
  - 6.25 - 9.17 GHz (×12)
  - 8.3 - 12.2 GHz (×9)
  - 9.4 - 13.8 GHz (×8)
  - 12.5 - 18.3 GHz (×6)

- W-band frequency multiplier
- f₀ = 75 - 110 GHz
- fWR-10 = (150 - 220 GHz)
- fWR-2 = (300 - 440 GHz)
- fWR-3 = (225 - 330 GHz)
- fWR1.5 = (450 - 600 GHz)
FET Frequency Multipliers

Power compression

Conduction angle (class A-C)

output power [dBm]

input power @ f₀ [dBm]

Fourier coefficients [Iₙ/Iₘₐₓ]

Gate voltage [V]
Frequency Multiplier Figures of Merit

- Multiplication factor $N$
- Output power $P_{out}$
- Conversion Gain $G_C$
- Suppression of unwanted harmonics $S$
- Degradation of phase noise $\geq 20 \cdot \log N$
- DC power

Phase / amplitude modulation

$$\begin{bmatrix} \theta_2 \\ m_2 \end{bmatrix} = \begin{bmatrix} T_{pp} & T_{pa} \\ T_{ap} & T_{aa} \end{bmatrix} \begin{bmatrix} \theta_1 \\ m_1 \end{bmatrix} = \begin{bmatrix} N & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \theta_1 \\ m_1 \end{bmatrix}$$
W-Band Multiplier-by-Twelve
MMIC and Waveguide Module

Kallfass et. al. EuMIC 2011

DC supply board
WR10-waveguide
50 µm MS quartz transition
W-Band Multiplier-by-Twelve Module Performance

- Range: 78 – 100 GHz
- Bandwidth: 22 GHz (25%)
- Spectral purity: >12 dBc

- Output power: -1.5 dBm
- Conversion gain: 2.5 dB

![Graph showing harmonic frequencies and output power]
(X to) W-Band Multiplier-by-Nine

Lewark et. al. GeMIC 2011
(X to) W-Band Multiplier-by-Nine

Optimized BW and spectral purity by DDS controlled bias and Pin

- DDS generation
- Constant bias and $P_{in}$

Output Power [dBm]

<table>
<thead>
<tr>
<th>Input Frequency [GHz]</th>
<th>86</th>
<th>88</th>
<th>90</th>
<th>92</th>
<th>94</th>
<th>96</th>
<th>98</th>
<th>100</th>
<th>102</th>
</tr>
</thead>
<tbody>
<tr>
<td>DDS generation</td>
<td>-30</td>
<td>-25</td>
<td>-20</td>
<td>-15</td>
<td>-10</td>
<td>-5</td>
<td>0</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Constant bias and $P_{in}$</td>
<td>-25</td>
<td>-20</td>
<td>-15</td>
<td>-10</td>
<td>-5</td>
<td>0</td>
<td>5</td>
<td>10</td>
<td>15</td>
</tr>
</tbody>
</table>

Output Frequency (9th harmonic) [GHz]

- 8 $f_0$
- 9 $f_0$
- 10 $f_0$
- 11 $f_0$

Phase Noise [dBc]

- E8257D + multiplier MMIC
- E8247C (15.55GHz)
- E8257D (10.45GHz)
- E8257D (10.45GHz) + 20 Log(9)
- E8247C (15.55GHz) + 20 Log(6)

Phase noise degradation = 20 log 9

[Diagram showing DDS generation, constant bias, and output power vs. input frequency, with phase noise graph showing various curves for different frequencies and multipliers.]
Chip Set for 220 GHz Transmission

- $f_{RF,c}$: 220 GHz
- $B_{RF}$: 34 GHz
- $f_{LO}$: 9.17 GHz
- $f_{LO}$: 110 GHz ($n = 12$)
- $B_{BB}$: 17 GHz
- $P_{tx}$: ca. 0 dBm
- $NF_{rx}$: ca. 6.8 dB
- $G_{rx/Gtx}$: ca. 15 dB
## 220 GHz Transmission Coherent LO

<table>
<thead>
<tr>
<th>Setup</th>
<th>Rate</th>
<th>Dist.</th>
<th>Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coherent LO</td>
<td>25 Gbit/s</td>
<td>10 m</td>
<td>Q &gt;3</td>
</tr>
<tr>
<td></td>
<td>15 Gbit/s</td>
<td>20 m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Full DVB-S</td>
<td>20 m</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>30 Gbit/s</td>
<td>n/a</td>
<td>BER &lt; 10(^{-3})</td>
</tr>
<tr>
<td></td>
<td>16 Gbit/s</td>
<td>2 m</td>
<td>Q^2 &gt; 13.9</td>
</tr>
</tbody>
</table>

![Graph showing bit rate vs. quality factor Q](image)

- **Bit rate** in Gbit/s
- **Distance** measured in meters
- **Quality** metrics include Q, BER, Q^2

![Image of transmission setup](image)
Optical – 220 GHz Wireless – Optical Link

16 Gbit/s NRZ-OOK after 2x20 km fiber span
($P_{RX1} = P_{RX2} = -12$ dBm)

König et. al. OFC 2012
220 GHz Transmission Incoherent LO

<table>
<thead>
<tr>
<th>Symbol rate</th>
<th>Data rate</th>
<th>EVM</th>
<th>BER[^1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>QPSK</td>
<td>1 GBd</td>
<td>12.4 %</td>
<td>&lt; 10^{-10}</td>
</tr>
<tr>
<td></td>
<td>2 GBd</td>
<td>18.1 %</td>
<td>10^{-8}</td>
</tr>
<tr>
<td>8PSK</td>
<td>1 GBd</td>
<td>10.7 %</td>
<td>10^{-6}</td>
</tr>
<tr>
<td>16APSK</td>
<td>1 GBd</td>
<td>9.7 %</td>
<td>-</td>
</tr>
<tr>
<td>16QAM</td>
<td>1 GBd</td>
<td>10.5 %</td>
<td>10^{-3}</td>
</tr>
</tbody>
</table>

Chip Set for 240 GHz Transmission

- $f_{RF,c}$: 240 GHz
- $B_{RF}$: 80 GHz
- $f_{LO}$: 55–65 GHz
- $f_{LO}$: 110-130 GHz ($n = 2$)
- $B_{BB}$: 40 GHz
- $P_{tx}$: 0 dBm (excl. PA)
- $NF_{rx}$: ca. 6.8 dB
- $G_{rx/Gtx}$: n/a

Additional notes:
- $RF$ 200 - 280 GHz
- IFI, IFQ: 0 - 40 GHz
- LO: 110 - 130 GHz
- LO: 55 - 65 GHz
- MPA: doubler
- VCO: 55 - 65 GHz
240 GHz Rx MMIC

LNA – fund. Mixer – LO doubler
IQ channels
Also as Tx

50 nm mHEMT, 2.5 x 1 mm²

Conversion gain (dB)

PLO (dBm)

Conversion gain (dB)

IF frequency (MHz)
240 GHz Tx MMIC

LNA (Tx) – subharm. Mixer
IQ channels
Also as Rx

50 nm mHEMT, 2.5 x 1 mm²
300 GHz Source and Receiver

- **Source**
  - LO \(\sim 100 \text{ GHz} \)
  - tripler
  - LNA
  - RF \(290 \rightarrow 320 \text{ GHz} \)

- **Heterodyne Detector**
  - LNA
  - mixer
  - buffer
  - tripler
  - LO \(\sim 100 \text{ GHz} \)
  - IF

**Input Frequency in GHz**

**Output Power (dBm)**
- \(P_i = 14 \text{ dBm} \)
- without buffer

**Conversion Gain (dB)**
- \(\text{IF} = 100 \text{ MHz} \)
- \(P_{LO} = 8 \text{ dBm} @ \text{freq/3} \)
- \(V_m = 0 \text{ V} \)

Lewark et. al. EuMIC 2011
Tessmann et. al. CSICS 2011

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480 GHz Frequency Quadrupler

**Doubler**
balanced (Marchand) class-B cascode FETs

**Amplifier**
Cascode FETs

**Doubler**
single-ended class-B FET λ/4 fund. suppression

[Diagram of the 480 GHz Frequency Quadrupler with labeled components such as \( V_{GN} \), \( V_D \), \( V_G \), \( V_C \), and \( V_{D2} \).]
480 GHz Frequency Quadrupler

**Doubler**
- balanced (Marchand)
- class-B cascode FETs

**Amplifier**
- Cascode FETs
- ca. 2 dBm Psat
- input power backoff
- reduced load/source pulling

**Doubler**
- single-ended class-B FET
- $\lambda/4$ fund. suppression

\[ P_{\text{DC}} \text{ 50 mW (w/ } P_{\text{RF}}) \]

\[ P_{\text{DC}} \text{ 60 mW} \]

\[ P_{\text{DC}} \text{ 11 mW (w/ } P_{\text{RF}}) \]
480 GHz Frequency Quadrupler

Output power:
-14.3 dBm

Bandwidth:
>45 GHz
435...>480 GHz

-22 -20 -18 -16 -14
-22 -20 -18 -16

P_{in} = 8 dBm
Four-Stage 480 GHz Amplifier S-MMIC

- Reactively matched common source stages
- Gate width: 2 × 5 µm
- 13.4 dB @ 476 GHz
- >10.5 dB @ 440...481 GHz
- 32 mW (Vd = 1.2 V, Id = 27 mA)
- Simulated NF = 9.9 dB @ 480 GHz
State-of-the-Art: Multipliers

Frequency Multipliers

- diode
- InP HEMT
- pHEMT
- SiGe HBT

Output power [dBm] vs. Output frequency [GHz]

excl. amp incl. amp
Chip Set Overview

- W-Band x9 & x12
- 200 – 280 Tx & Rx
- 280 - 320 x3 & Rx
- 440 - 480 x4 & Rx

- 200 – 240 Tx & Rx

![Graph showing atmospheric attenuation vs. frequency with O2, H2O, and various weather conditions.]