Submission Title: Active MMIC Technology for 240 GHz Wireless Data Links
Date Submitted: 8 November, 2010
Source: Ingmar Kallfass, Fraunhofer Institute for Applied Solid-State Physics
Address: Tullastrasse 72, D-79108 Freiburg, Germany
Voice: +49 761 5159 486, FAX: +49 761 5159 71486, E-Mail: ingmar.kallfass@iaf.fraunhofer.de

Re: doc.: 15-10-0824-00-0thz

Abstract: Active Monolithic Millimeter-wave Integrated Circuits are today covering the entire millimeter-wave frequency range and enable highly compact and cost-efficient analog frontends. This contribution presents MMIC technology and components dedicated to broadband wireless communication between 200 and 300 GHz. First link demonstrations based on multi-functional MMIC transmitters and receivers are shown.

Purpose: Proof of concept of broadband active transmit and receive MMIC components for wireless data transmission in the frequency range from 200 to 300 GHz.

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Active MMIC Technology for 240 GHz Wireless Data Links

Ingmar Kallfass\textsuperscript{1,2}, Daniel Lopez-Diaz\textsuperscript{1}, Sebastian Diebold\textsuperscript{2}, Jochen Antes\textsuperscript{2}
Axel Tessmann\textsuperscript{1}, Arnulf Leuther\textsuperscript{1}

\textsuperscript{1} Fraunhofer Institute for Applied Solid-State Physics, Freiburg, Germany
\textsuperscript{2} Karlsruhe Institute of Technology, Karlsruhe, Germany
Outline

• Introduction
• Frontend Architecture
• Enabling MMIC Technology
• MMICs for Broadband Communication
• First 220 GHz Link Demonstrations
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• Frontend Architecture
• Enabling MMIC Technology
• MMICs for Broadband Communication
• First 220 GHz Link Demonstrations
Motivation for 200 – 300 GHz Communication

- Multi Gbit/s wireless capability

- **Point-to-point**
  - Fiber-over-radio
  - Radio-over-fiber (e.g. TV)

- Telecom base stations
  - Backhaul
  - Pico-cells
  - Last mile / fiber to the home

- **Intra-machine communication**
  - Sensor readout
  - Board-to-Board

![Graph showing atmospheric attenuation vs. frequency with peaks at different frequencies for H2O and O2. The graph indicates the reduced attenuation at 200 GHz to 300 GHz due to water vapor absorption.](image)
Technologies for 200 – 300 GHz Communication

- Passives/diodes: e. g. Schottky
- Nonlinear optical
- Active MMIC
  - Multi-functional
  - Highly compact
  - Easy-to-deploy
  - Cost efficient
Atmospheric Attenuation

- Broad atmospheric window from 200 to 300 GHz
- Clear sky: 2 – 4 dB/km
- Adverse weather
  - Fog: 1 - 6 dB/km
  - Rain: 10 - 20 dB/km

Source: ITU-Recommendation ITU-R P.676-8
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System Considerations

- Goal: incoherent transmission of APSK and >10 Gbit/s OOK signals
- Direct detection (only OOK) or zero-IF (a) with IQ receiver and rectification/summation
- Super-heterodyne (b): Single-ended and IQ mixers are possible
- Coherent detection: challenging due to probably inadequate carrier phase noise
MMIC Frontend Architecture (1)

- Use broadband (~55-65 GHz) VCOs which will become available for 60 GHz Wireless
MMIC Frontend Architecture (2)

- Use commercially available 10 GHz or 20 GHz VCOs in combination with a frequency multiplier-by-twelve or -by-six

![MMIC Frontend Architecture Diagram]
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MMIC Technology Candidates

![Graph showing atmospheric attenuation vs frequency for different technologies. The graph includes data points for Si CMOS, SiGe HBT, InP HBT, and InP HEMT. The frequency range is from 0 to 350 GHz, and the atmospheric attenuation is in dB/km. The graph highlights the suitability of these technologies for various applications such as wireless communication, automotive radar, imaging, and atmospheric sensing/spectroscopy.]
State-of-the-Art
InP HEMTs / GaAs mHEMTs

- **LNAs**
  - Amplifiers up to 550 GHz
  - NF 4.8 dB at 210 GHz (on-wafer)
  - NF 8.4 dB at 340 GHz (waveguide module)

- **PAs**
  - 17 dBm at 220 GHz (module)
  - 10 dBm at 338 GHz (module)
Why metamorphic?

Metamorphic and InP HEMTs:
- different substrates
- identical active layers

Advantages
- better mechanical stability
- high quality substrates up to 6"
- different lattice constants

Disadvantage
- additional growth effort
### Epitaxy

#### Material

<table>
<thead>
<tr>
<th>Material</th>
<th>Doping</th>
<th>Remarks</th>
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</thead>
<tbody>
<tr>
<td>$\text{In}<em>{0.53}\text{Ga}</em>{0.47}\text{As}$</td>
<td>Si</td>
<td>cap</td>
</tr>
<tr>
<td>$\text{In}<em>{0.52}\text{Al}</em>{0.48}\text{As}$</td>
<td>n.i.d.</td>
<td>Schottky barrier</td>
</tr>
<tr>
<td>$\text{Si}$</td>
<td></td>
<td>$\delta$-doping</td>
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<tr>
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<td>n.i.d.</td>
<td>spacer</td>
</tr>
<tr>
<td>$\text{In}<em>{x}\text{Ga}</em>{1-x}\text{As}$</td>
<td>n.i.d.</td>
<td>channel</td>
</tr>
<tr>
<td>$\text{Ga}<em>{0.52}\text{Al}</em>{0.48}\text{As}$</td>
<td>n.i.d.</td>
<td>buffer</td>
</tr>
<tr>
<td>$\text{In}<em>{0.52}\text{Al}</em>{0.48}\text{As}$</td>
<td>n.i.d.</td>
<td>metamorphic buffer</td>
</tr>
</tbody>
</table>

- $\text{Al}_{0.48}\text{In}_{0.52}\text{As} \quad a = 5.87 \text{ (InP)}$
- $\text{Al}_{0.48}\text{Ga}_{0.52}\text{As} \quad a = 5.65 \text{ (GaAs)}$

4" si GaAs substrate
Transistor Scaling

100 nm
$f_T / f_{max} = 220/300$ GHz

50 nm
375/600 GHz

35 nm
515/900 GHz

20 nm
Feasibility demonstrated
Ongoing development (epi, gate...)

Fraunhofer IAF
MMIC Process

Frontside
- Passives: MIM, resistors, etc.
- SiN passivation
- Microstrip or grounded coplanar
- 50 µm and 14 µm ground-to-ground spacing

Backside
- substrate mode suppression
- 50 µm wafer thinning
- 20 µm via holes
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• Introduction
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• MMICs for Broadband Communication
  – Low Noise Amplification
  – Frequency Multiplication
  – Frequency Conversion
  – Receivers and Transmitters
• First 220 GHz Link Demonstrations
Towards an all-MMIC-based 300 GHz Receiver

4-stage LNA
\[ G_{\text{MMIC}} > 15 \text{ dB} \]
\[ BW = 268-306 \text{ GHz} \]

Doubler and Mixer
\[ L_{\text{conv.}} < 12 \text{ dB} \]
\[ BW = 260-308 \text{ GHz} \]

3-stage PA
\[ G_{\text{MMIC,lin}} > 17 \text{ dB} \]
\[ BW = 133-147 \text{ GHz} \]
\[ P_{\text{out, sat}} = 13 \text{ dBm} \]

Active Sixtupler
\[ BW = 110-164 \text{ GHz} \]
\[ P_{\text{out, H6}} = -2 \text{ dBm} \]
D-Band Frequency Multiplier-by-Six

Balanced Tripler
2-stage
class A FETs in compression
Broadband HP and TP-type matching
Even-order rejection

Balanced Doubler
Class-B push-push FETs
Cascode topology

Active UNBAL
Differential stage

Balanced Tripler
2-stage
class A FETs in compression
Broadband HP and TP-type matching
Even-order rejection

Balanced Doubler
Class-B push-push FETs
Cascode topology

![Diagram of the D-Band Frequency Multiplier-by-Six](image)
D-Band Frequency Multiplier-by-Six

- 100 nm mHEMT technology
  - $f_T / f_{\text{max}} = 220 / 300$ GHz
- Grounded coplanar TRL environment
D-Band Frequency Multiplier-by-Six

- Operating range: <110 – 164 GHz
- Bandwidth: 54 GHz (39 %)
- Output power: -2 dBm @140 GHz
- Conversion loss: 10 dB
- Spectral purity: > 20 dBc
- Supply
  - drain voltage: 2.2 V
  - current: 180 mA
  - power: 396 mW
300 GHz Frequency Doubler and Mixer

- **Doubler**
  - 50 nm mHEMT
  - 2x20 µm Class-B FET
  - Fundamental λ/4 stub
  - Also as stand-alone MMIC

- **Mixer**
  - 50 nm mHEMT
  - Resistive FET
300 GHz Frequency Doubler and Mixer

Doubler
- Output power: -6 dBm
- Frequency range: 260 – 300 GHz

Doubler + Mixer
- Conversion gain
  - @ 0 dBm PLO (w/o PA): -20 dB
  - @ 3 dBm PLO (w/ PA): -12 dB
  - w/ LNA: 3 dB
200-300 GHz Mixers

Subharmonic IQ

Conv. Loss 18.4 dB @ 2dBm P_{LO}
Phase imbalance +/-5° @ 188-220 GHz

Fundamental balanced

RF 160-260 GHz, IF 0-50 GHz
Conv. Loss <20 dB @ 0 dBm P_{LO}
H-Band Cascode mHEMT Amplifier S-MMIC

- 50nm mHEMT technology
- cascode mHEMT
- gate width: 2 × 10 µm
- chip size: 0.6 mm²

- reactively matched
- GCPW line impedance = 50 Ω
H-Band Cascode mHEMT Amplifier S-MMIC

- gain: 19.5 dB @ 320 GHz
- gain: > 15.0 dB @ 240...320 GHz
- simulated NF = 7.3 dB @ 300 GHz
- power consumption: 90 mW (Vd = 2.0 V, Id = 45 mA)
Four-Stage 300 GHz Amplifier Module
(Lg = 50 nm)

- power consumption: 530 mW (V = 5.0 V, I = 106 mA)
- gain: >19 dB @ 295…320 GHz
- max. gain: 21 dB @ 300 GHz
- matching: -10 dB @ 285…320 GHz
Multifunctional Integration

- Wideband IF
- Mirrored LNA in Transmitter
- Identical chip interface for packaging
- Receive conversion gain: 3.5 dB
- RF transmit power: up to -1.5 dBm (LNA saturation)
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DVB-C Transmission at 220 GHz

- Carrier @ 220 GHz (LO @ 110 GHz)
- DVB-C media stream @ 64 QAM
- IF amplification 33 dB
DVB-C Transmission at 220 GHz
Summary & Outlook

• Fully MMIC-based wireless transmission at 220 GHz demonstrated
• Broadband, high performance MMIC components based on metamorphic HEMTs are available in the frequency range 200 – 300 GHz

Ongoing activities target
• Fully integrated wideband transmit and receive MMICs featuring
  – Subharmonic IQ mixers
  – PA stages in transmitters (goal: wideband 10 dBm $P_{out}$)
• Experiments for
  – Coherent OOK transmission (eye diagrams)
  – Incoherent super-heterodyne transmission
Thank you for your attention!

Ingmar Kallfass
Prof. Dr.-Ing.

Fraunhofer Institute for Applied Solid State Physics
Tullastraße 72
D-79108 Freiburg/Germany
Phone: +49 (0)761 5159 486
Fax: +49 (0)761 5159 71486
Email: ingmar.kallfass@iaf.fraunhofer.de
Web: www.iaf.fraunhofer.de

Karlsruher Institut für Technologie (KIT)
Institut für Hochfrequenztechnik und Elektronik
Kaiserstraße 12
76131 Karlsruhe
Tel.: +49-(0)721-608-2525
Fax: +49-(0)721-691865
E-Mail: ingmar.kallfass@kit.edu
Web: www.kit.edu ; www.ihe.kit.edu