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Submission Title: Active MMIC Technology for 240 GHz Wireless Data Links
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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

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Outline

- Introduction
- Frontend Architecture
- Enabling MMIC Technology
- MMICs for Broadband Communication
- First 220 GHz Link Demonstrations

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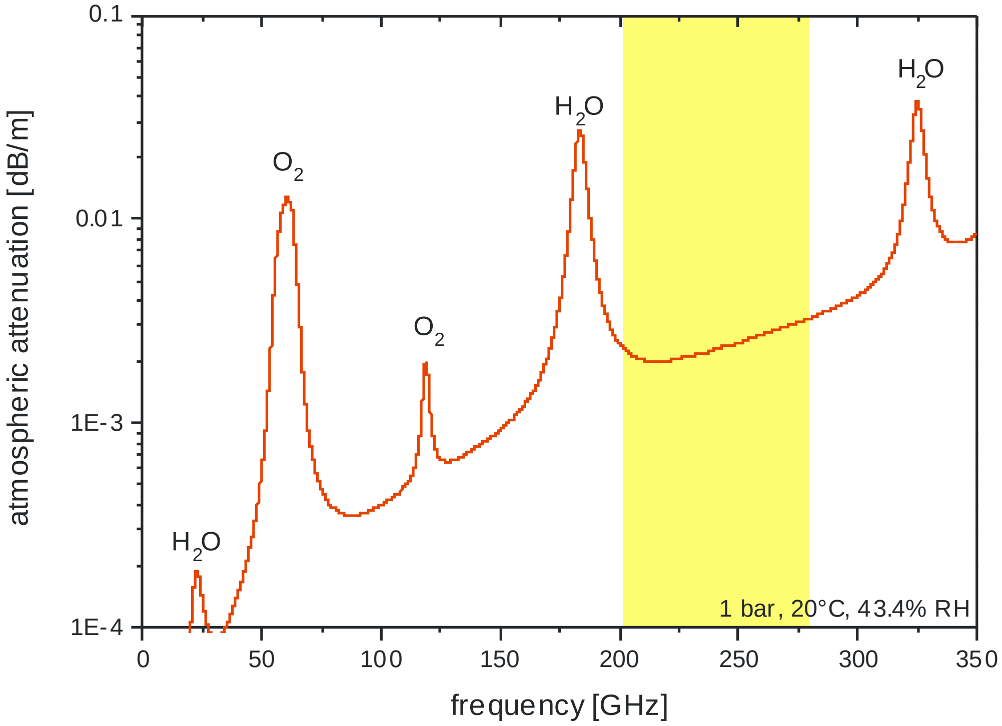
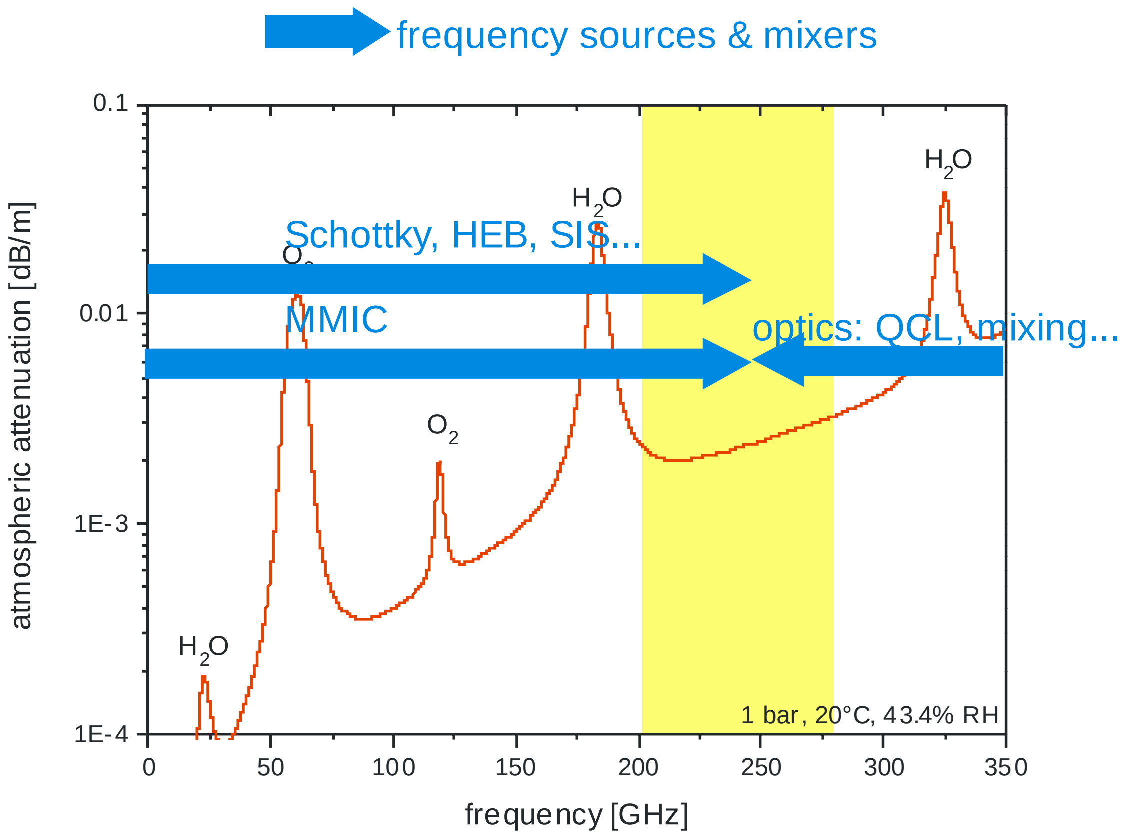
Motivation for 200 – 300 GHz Communication

- 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



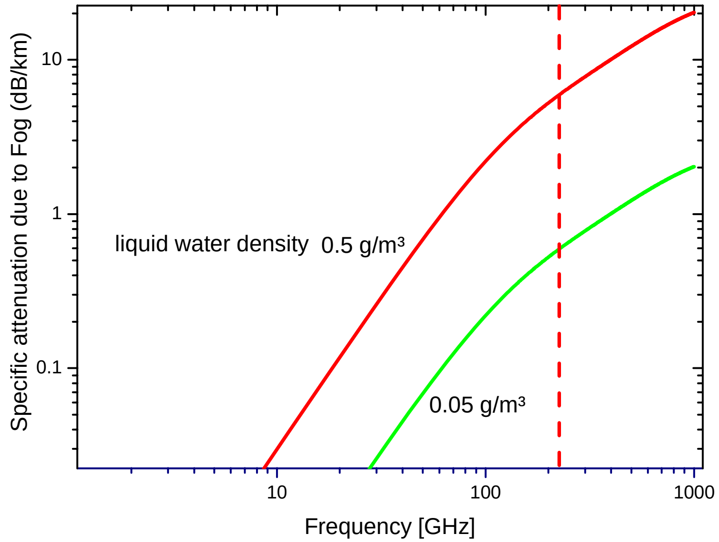
Technologies for 200 – 300 GHz Communication

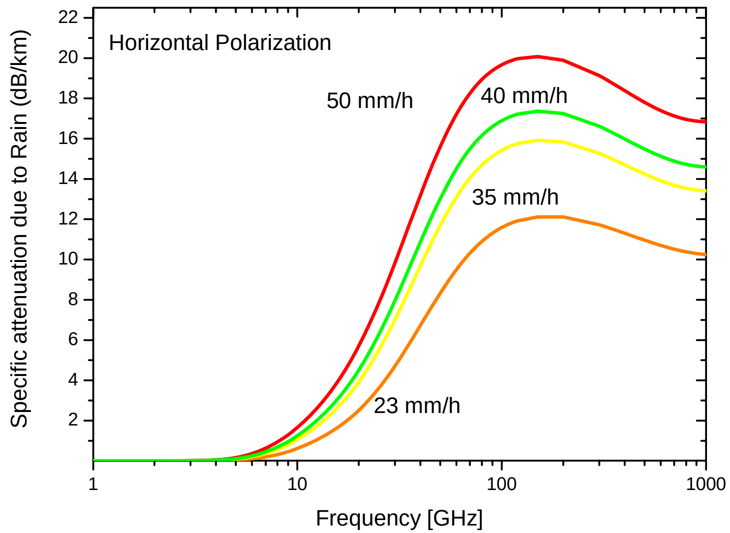
- Passives/diodes: e. g. Schottky
- Nonlinear optical
- **Active MMIC**
  - **Multi-functional**
  - **Highly compact**
  - **Easy-to-deploy**
  - **Cost efficient**



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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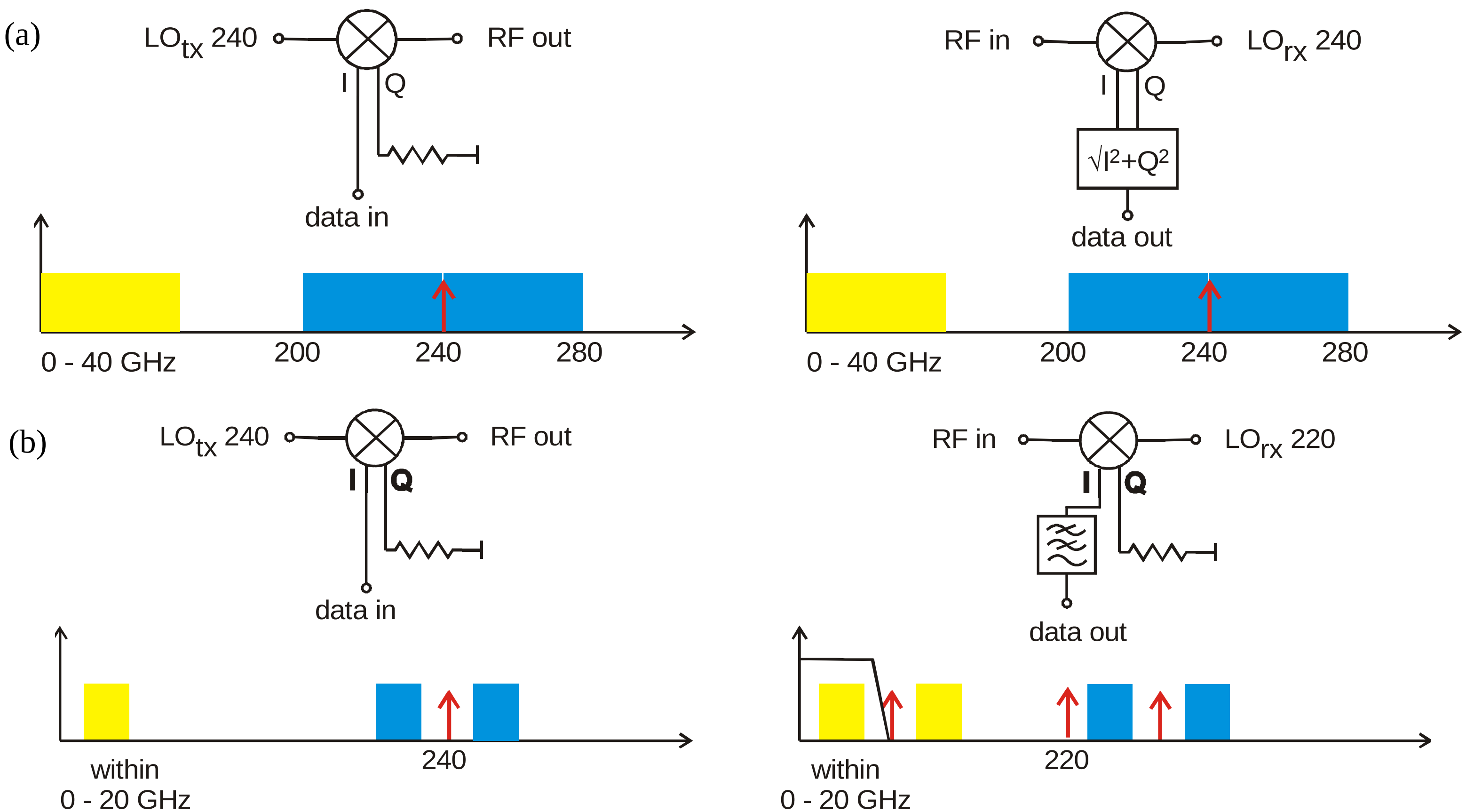
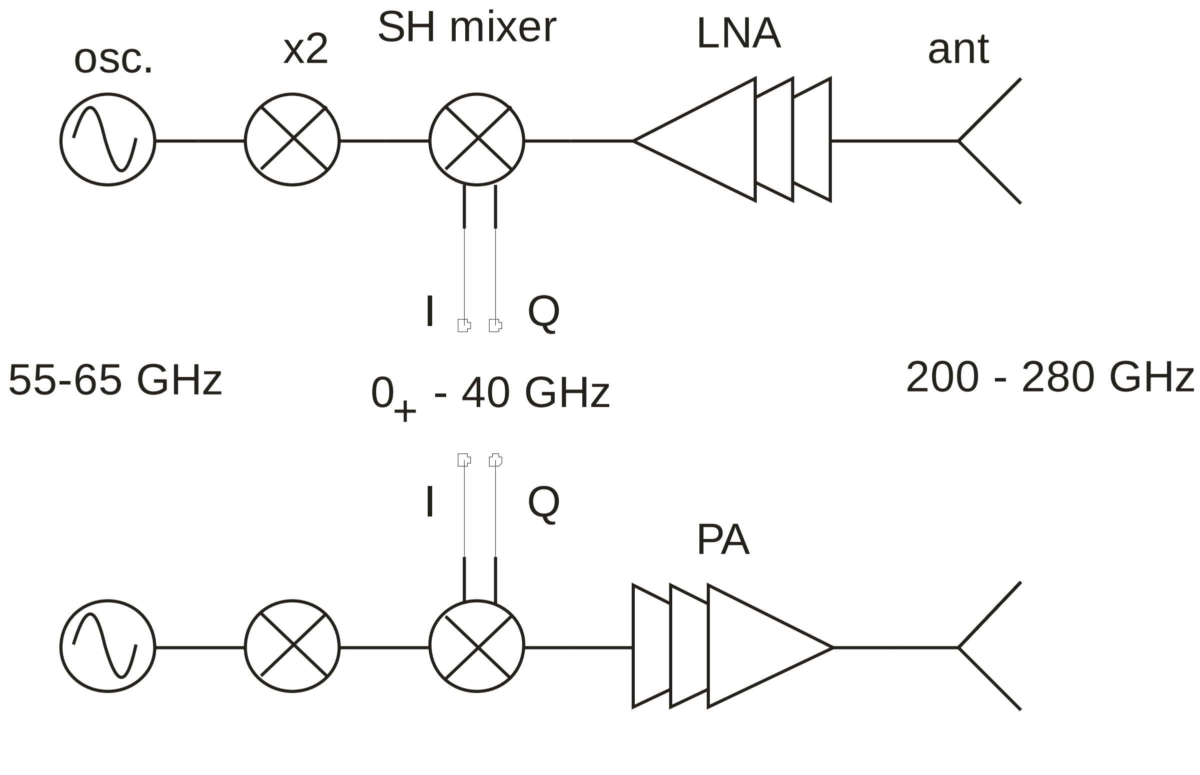
System Considerations

- 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



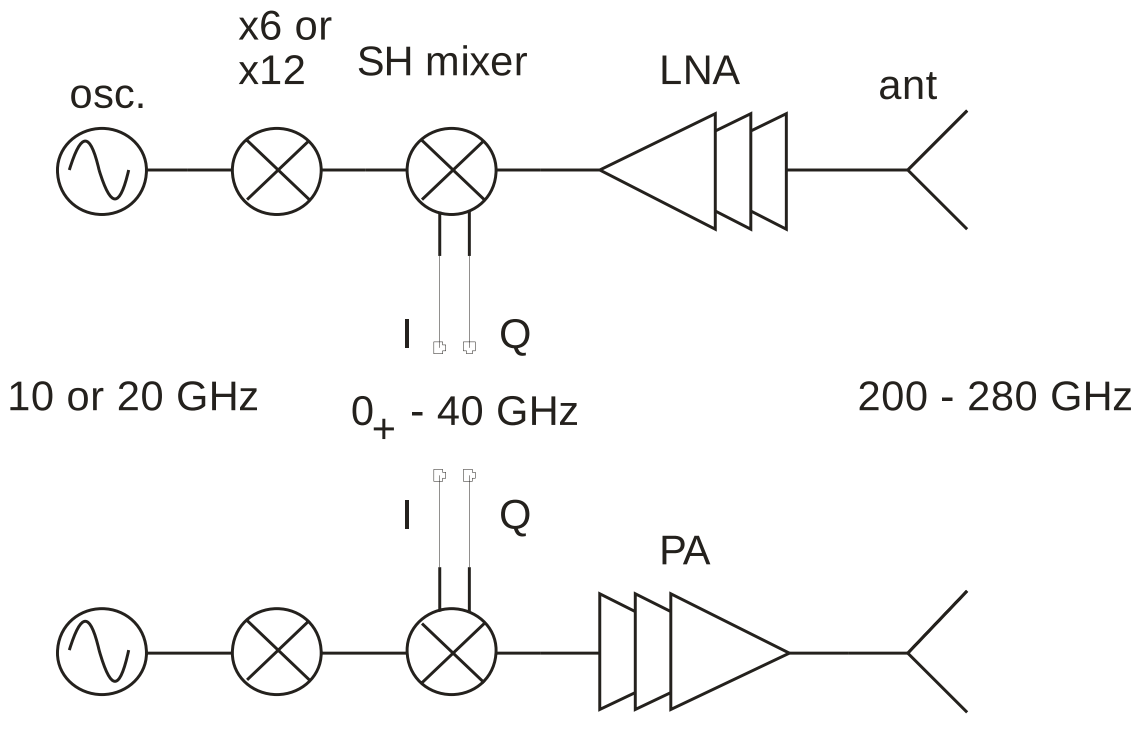
MMIC Frontend Architecture (1)

- 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



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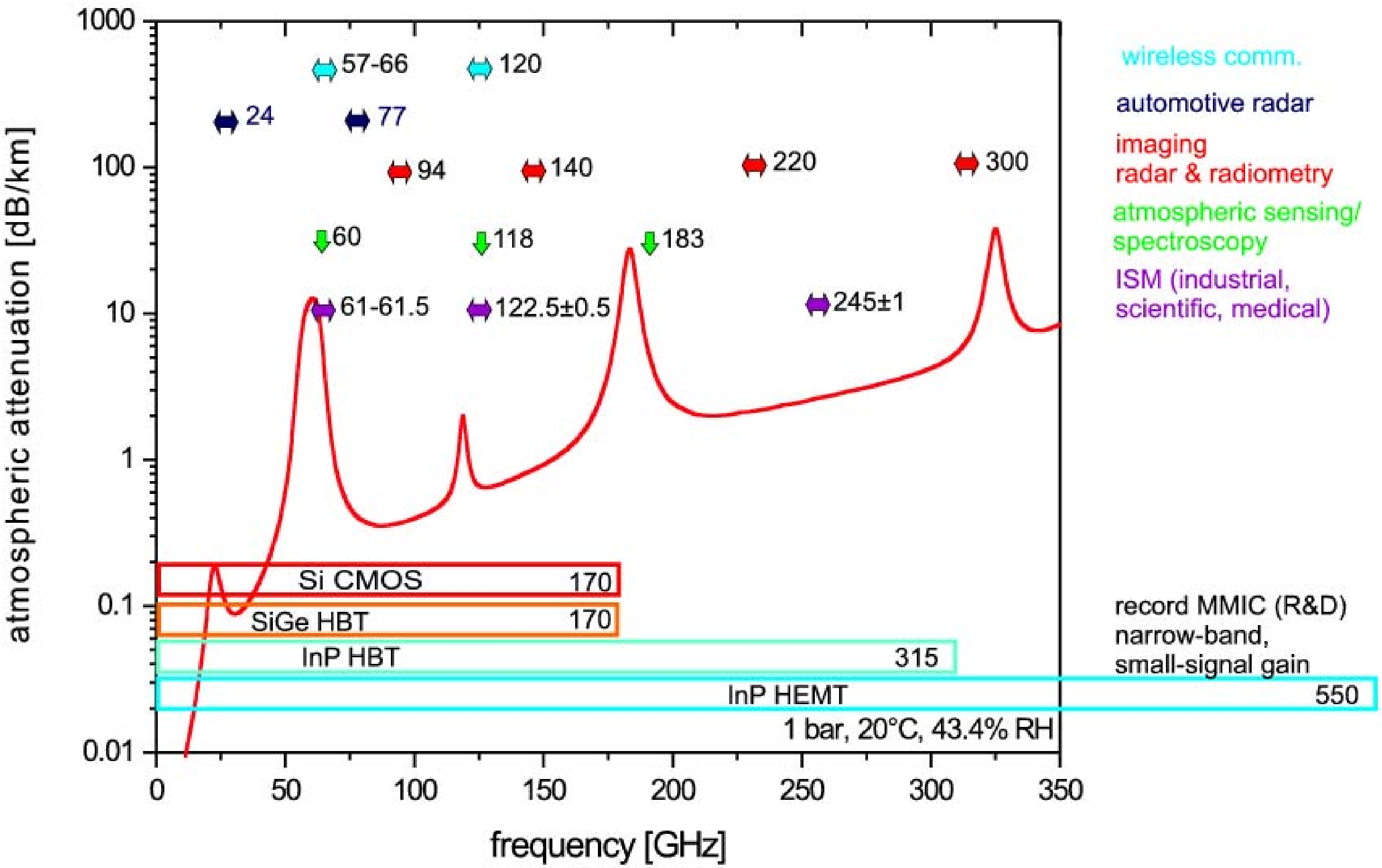
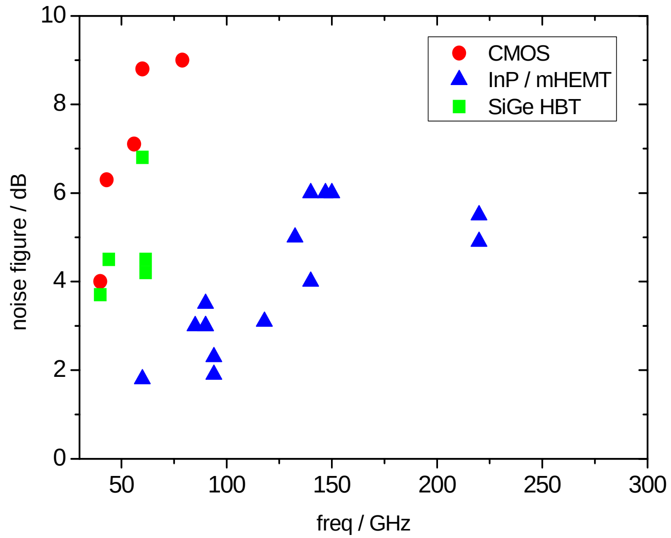
MMIC Technology Candidates

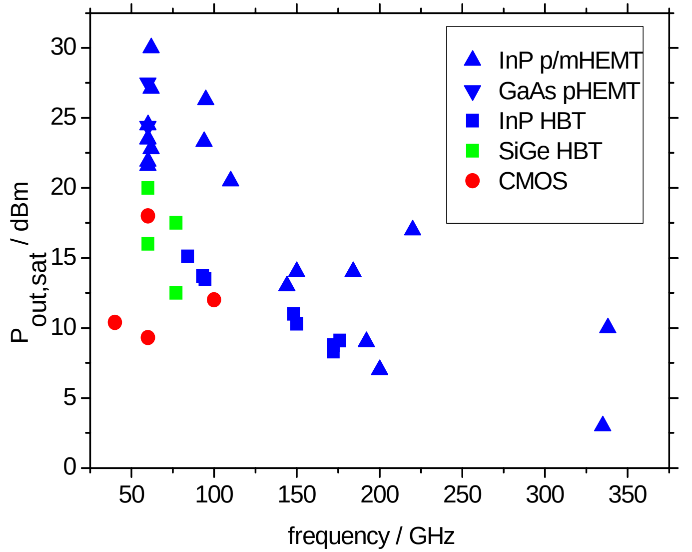


State-of-the-Art
InP HEMTs / GaAs mHEMTs

- 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 :

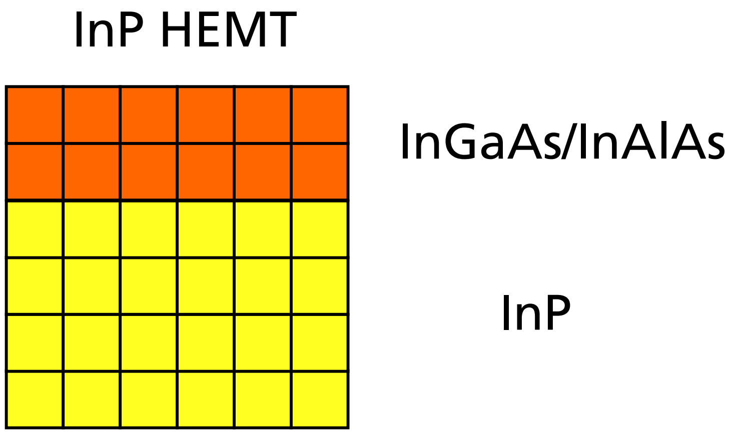
- different substrates
- identical active layers

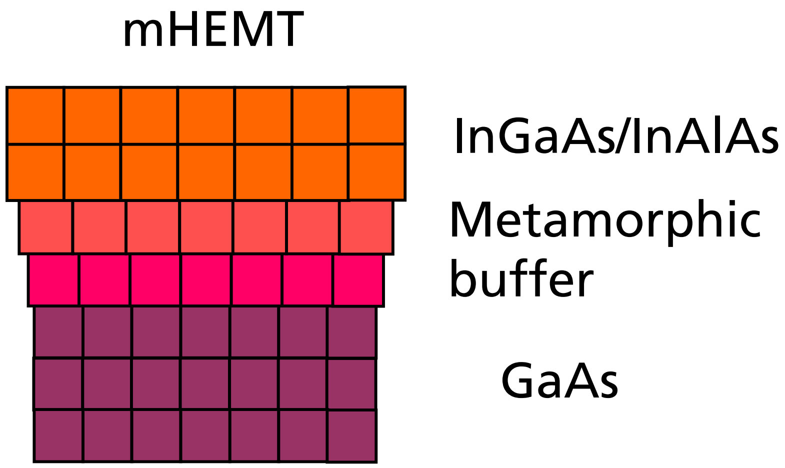
Advantages

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

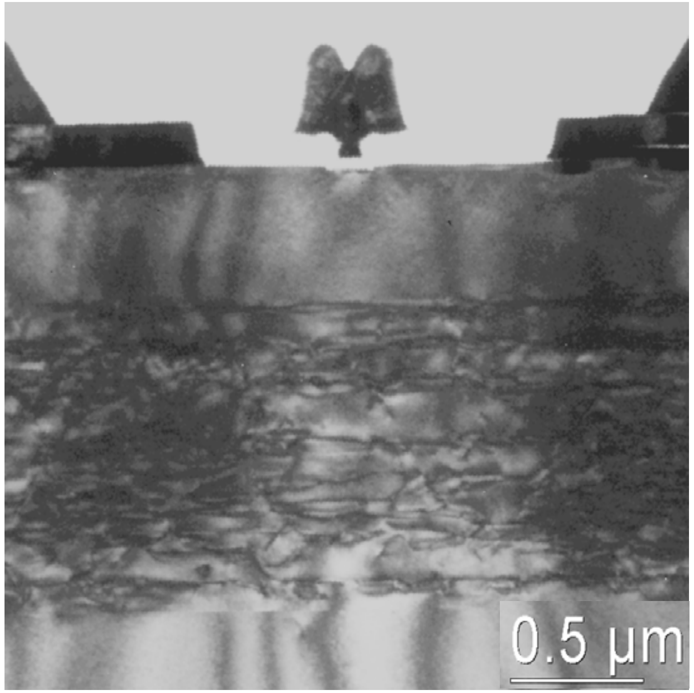
Disadvantage

- additional growth effort





Epitaxy



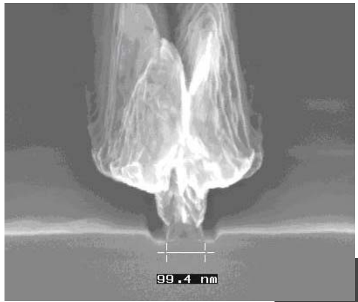
$Al_{0.48}In_{0.52}As$ a = 5.87 (InP)

$Al_{0.48}Ga_{0.52}As$ a = 5.65 (GaAs)

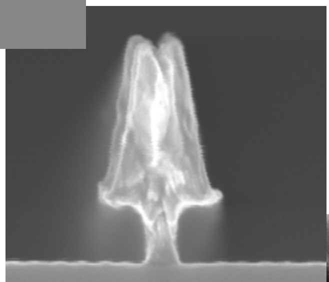
Material	Doping	Remarks
$In_{0.53}Ga_{0.47}As$	Si	cap
$In_{0.52}Al_{0.48}As$	n.i.d.	Schottky barrier
	Si	δ-doping
$In_{0.52}Al_{0.48}As$	n.i.d.	spacer
$In_xGa_{1-x}As$	n.i.d.	channel
$I_{0.52}Al_{0.48}As$	n.i.d.	buffer
$In_{0.52}Al_{0.48}As$ – $Ga_{0.52}Al_{0.48}As$	n.i.d.	metamorphic buffer

4“ si GaAs substrate

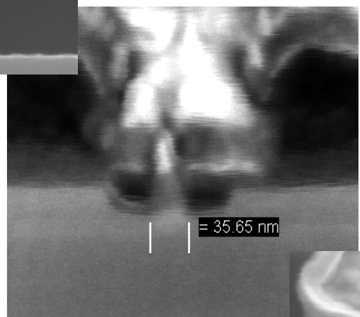
Transistor Scaling



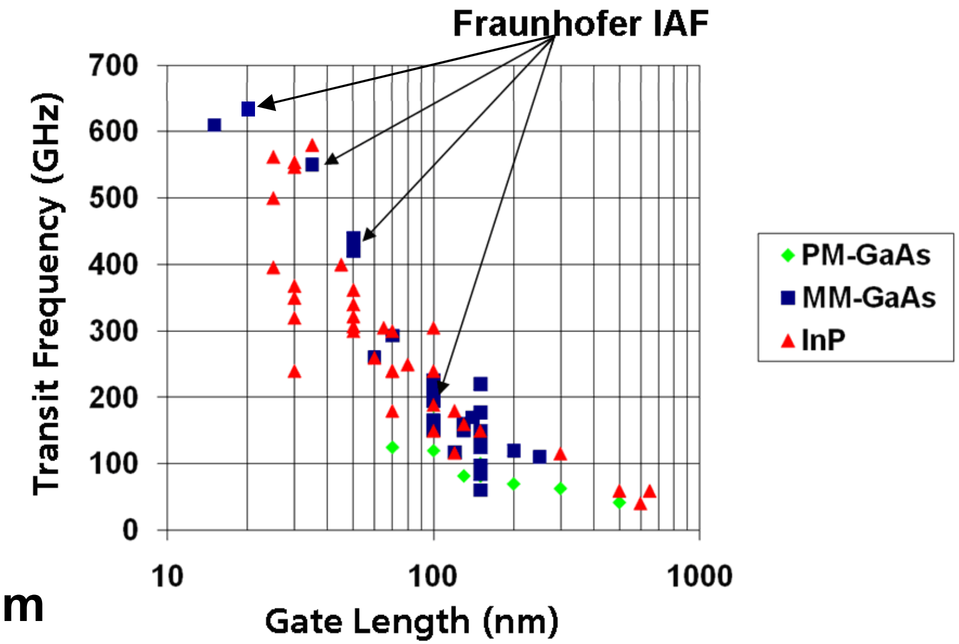
100 nm
f_T / f_{max} = 220/300 GHz

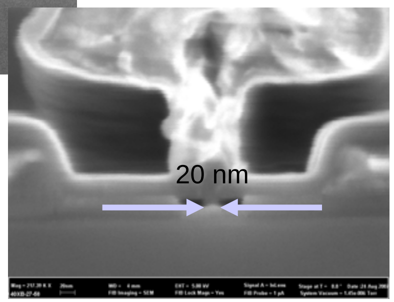


50 nm
375/600 GHz



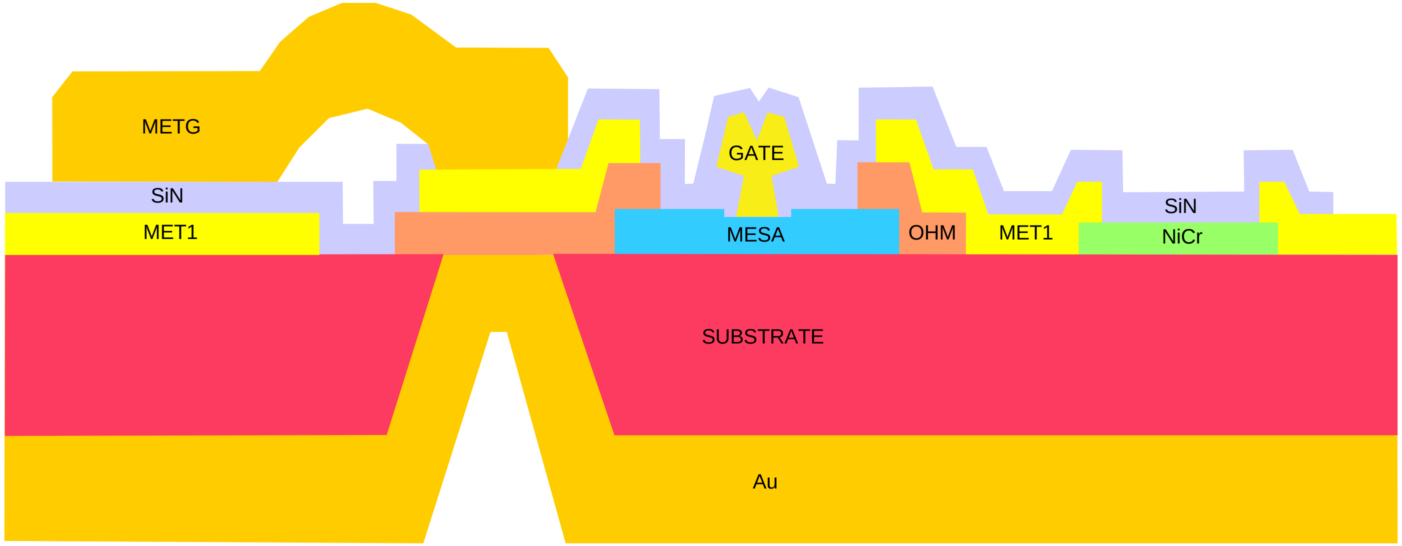
35 nm
515/900 GHz

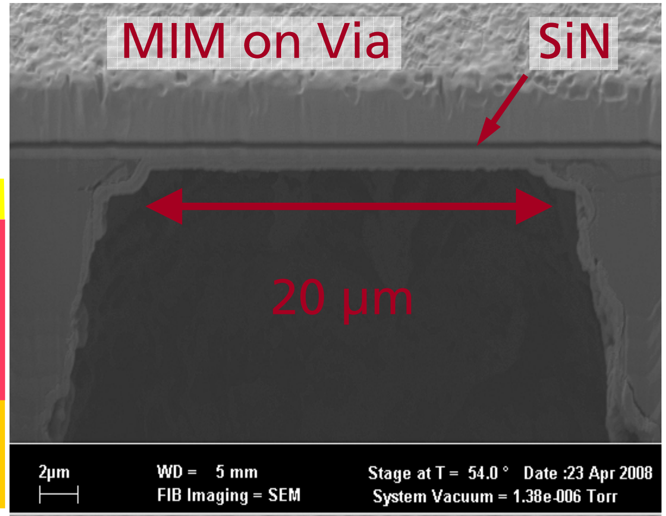




20 nm
Feasibility demonstrated
Ongoing development (epi, gate…)

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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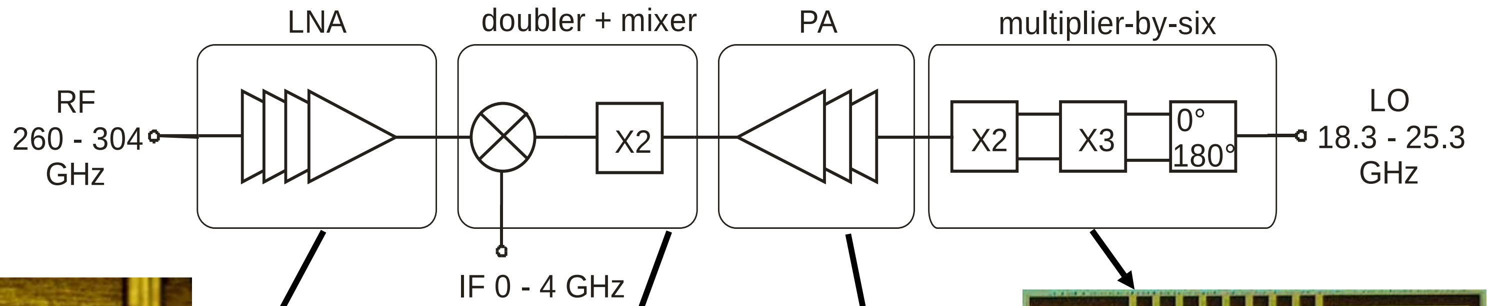
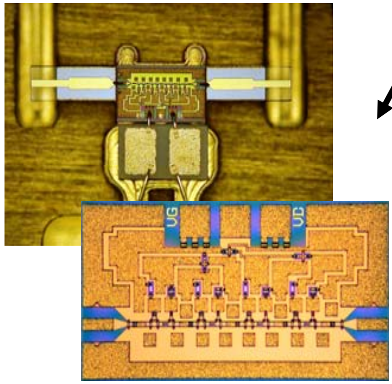
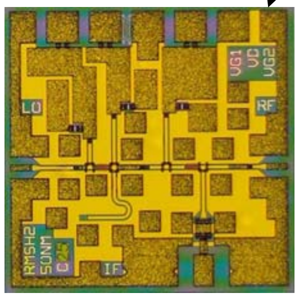
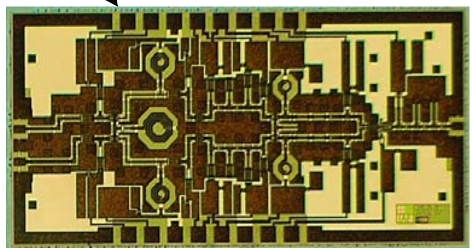
- MMICs for Broadband Communication
  - Low Noise Amplification
  - Frequency Multiplication
  - Frequency Conversion
  - Receivers and Transmitters
- First 220 GHz Link Demonstrations

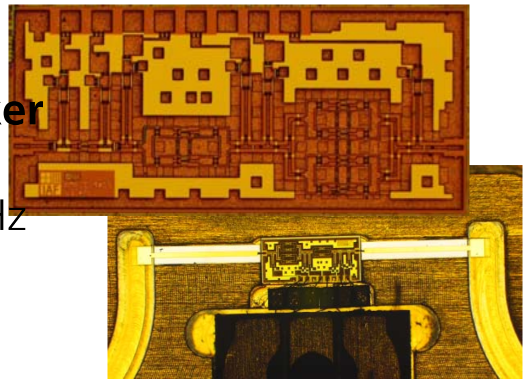
Towards an all-MMIC-based 300 GHz Receiver











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

Doubler and Mixer
$L_{conv.}$ < 12 dB
BW = 260-308 GHz

Active Sixtupler
BW = 110-164 GHz
$P_{out,H6}$ = -2 dBm

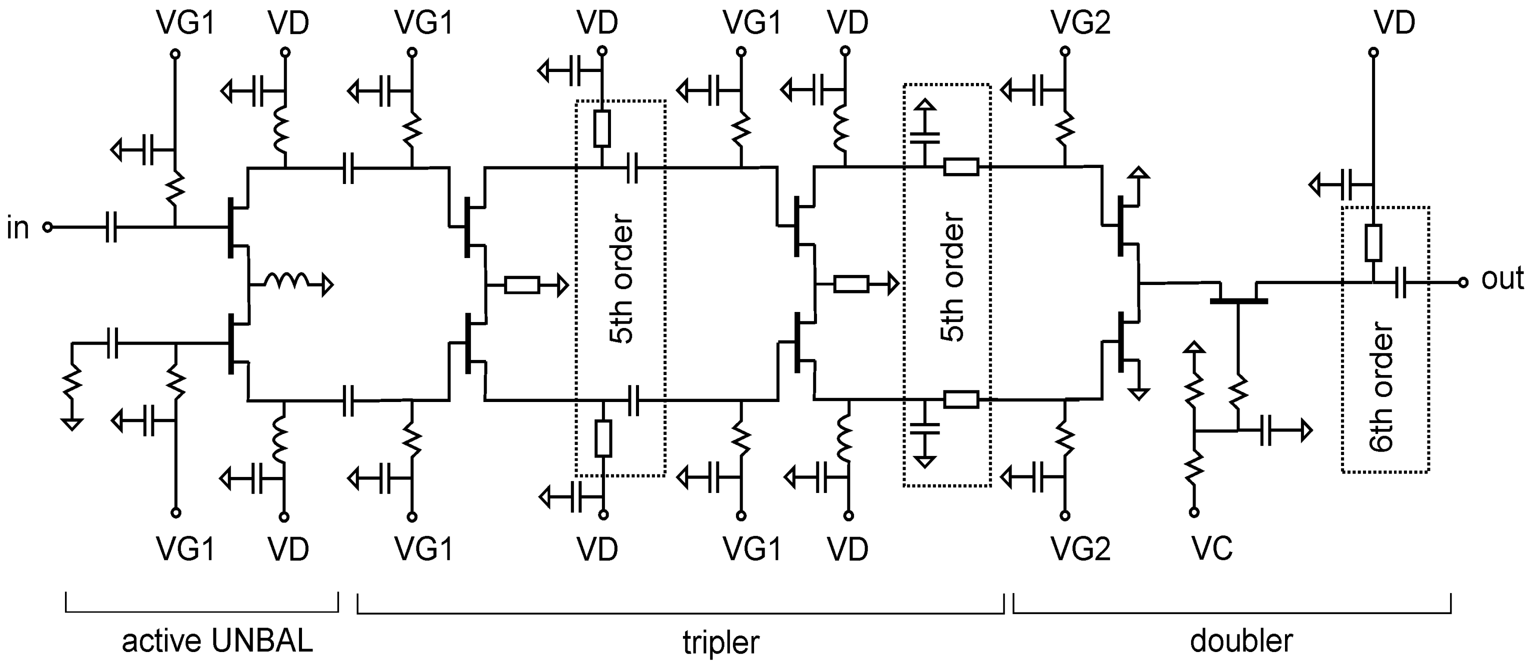
3-stage PA
$G_{MMIC,lin}$ > 17 dB
BW = 133-147 GHz
$P_{out,sat}$ = 13 dBm

D-Band Frequency Multiplier-by-Six

Active UNBAL
Differential stage

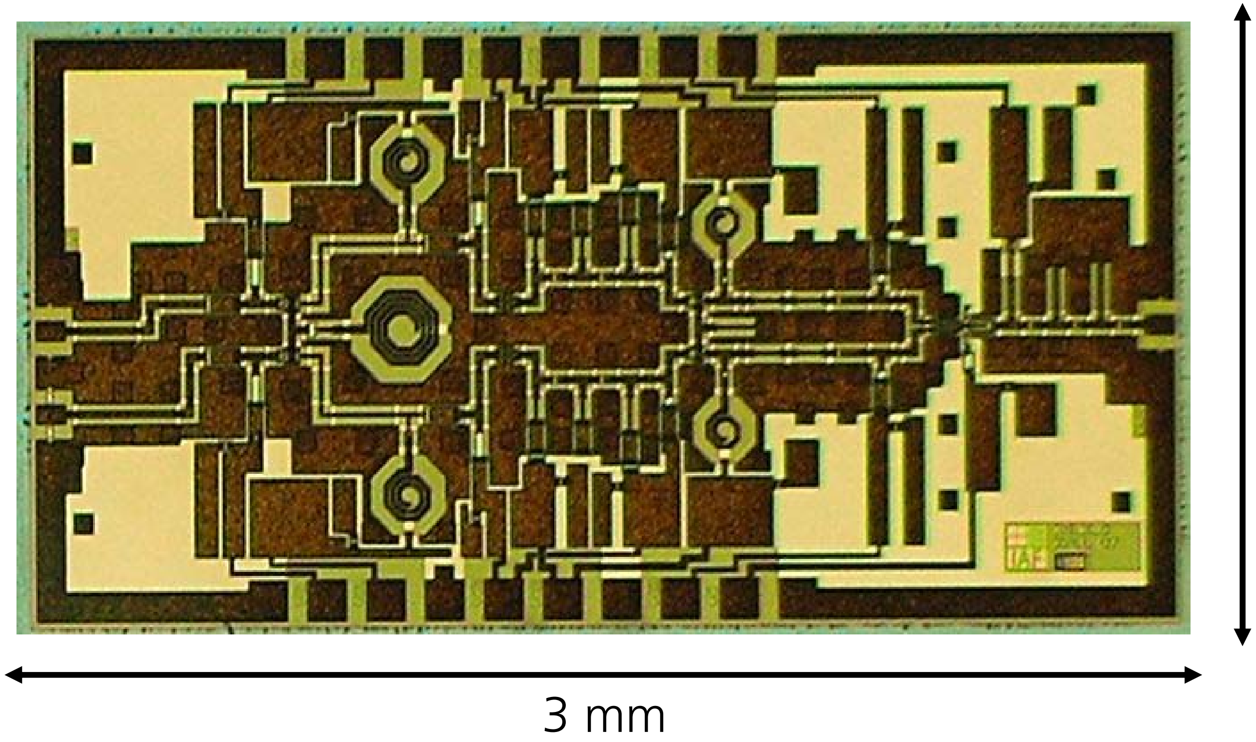
Balanced Tripler
2-stage
class A FETs in compression
Broadband HP and TP-type matching
Even-order rejection

Balanced Doubler
Class-B push-push FETs
Cascode topology



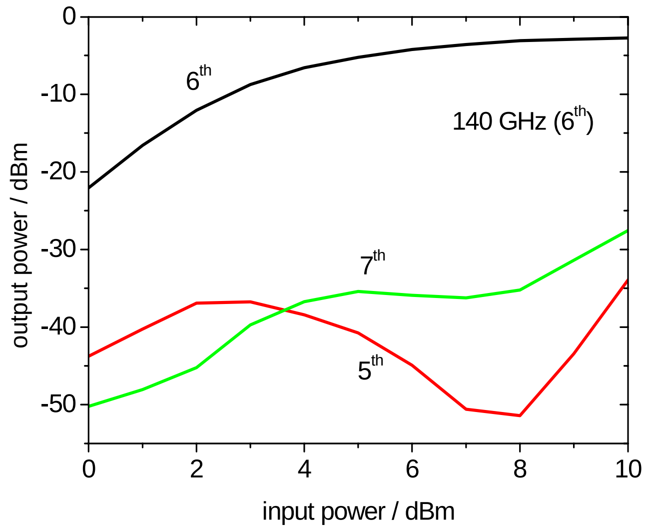
D-Band Frequency Multiplier-by-Six

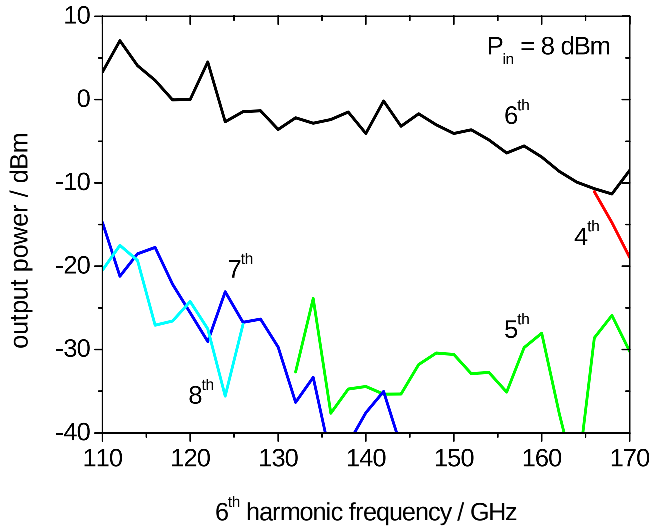
- 100 nm mHEMT technology
  - f_T / f_{max} = 220 / 300 GHz
- Grounded coplanar TRL environment



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

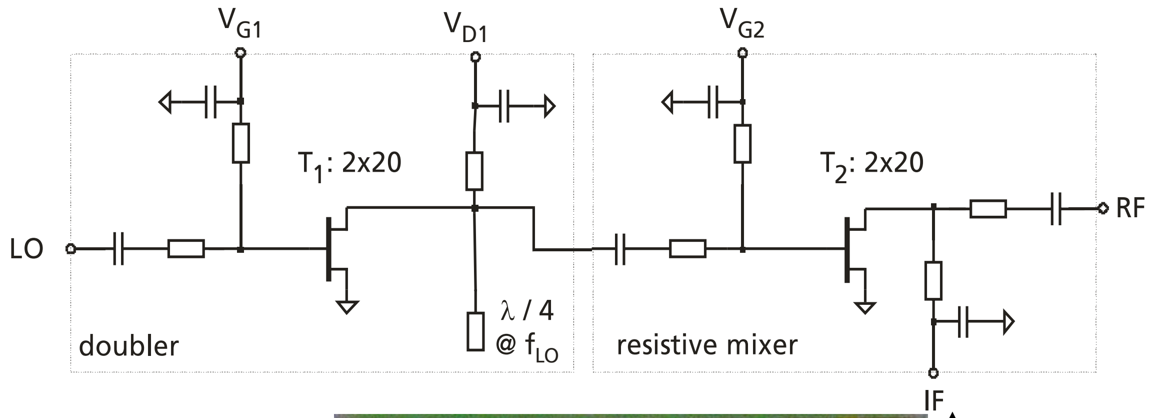


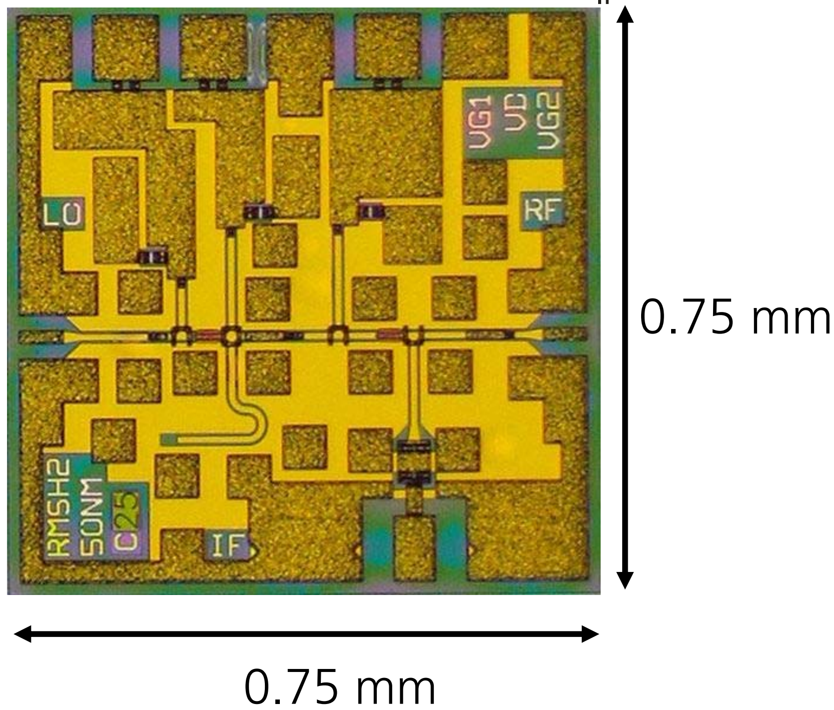


300 GHz Frequency Doubler and Mixer

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

- Mixer
  - 50 nm mHEMT
  - Resistive FET





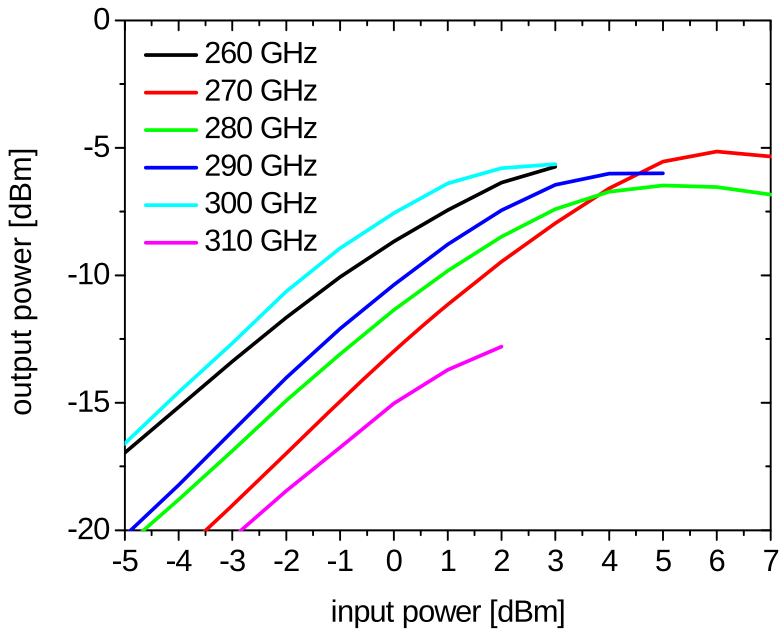
300 GHz Frequency Doubler and Mixer

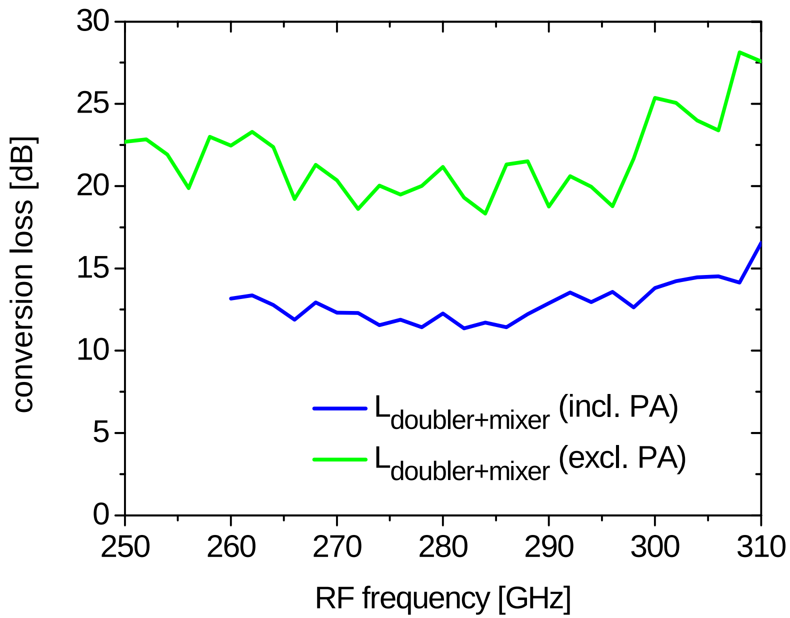
Doubler

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

Doubler + Mixer

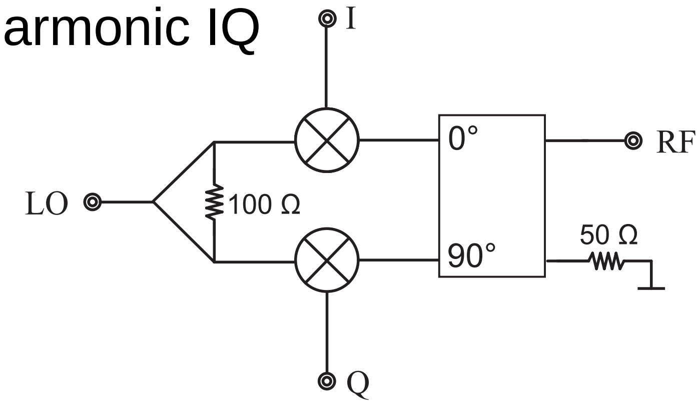
- Conversion gain
  - @ 0 dBm PLO (w/o PA): -20 dB
  - @ 3 dBm PLO (w/ PA): -12 dB
  - w/ LNA: 3 dB

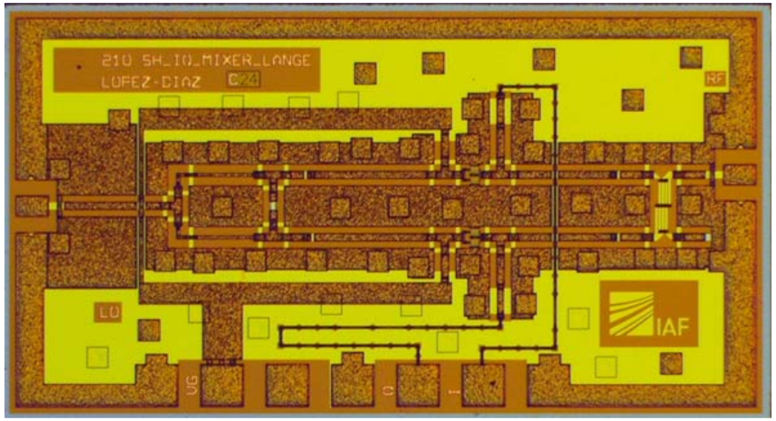




200-300 GHz Mixers

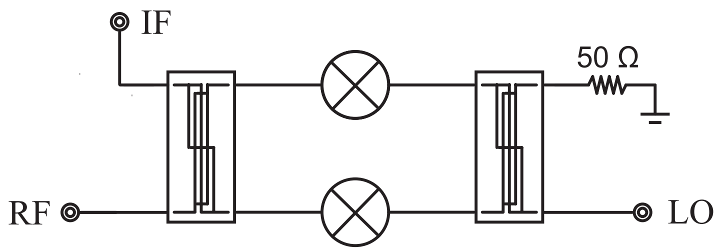
Subharmonic IQ

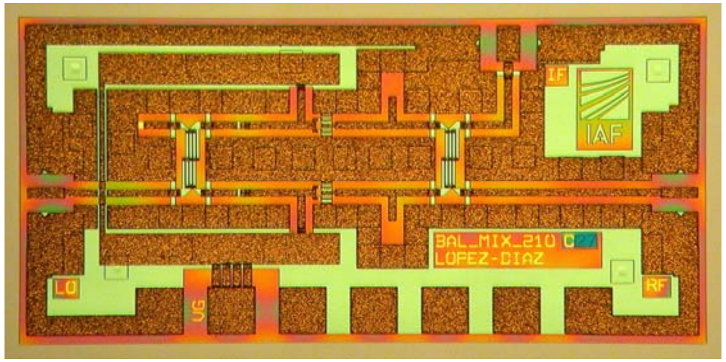




Conv. Loss 18.4 dB @ 2dBm P_{LO}
Phase imbalance +/-5° @ 188-220 GHz

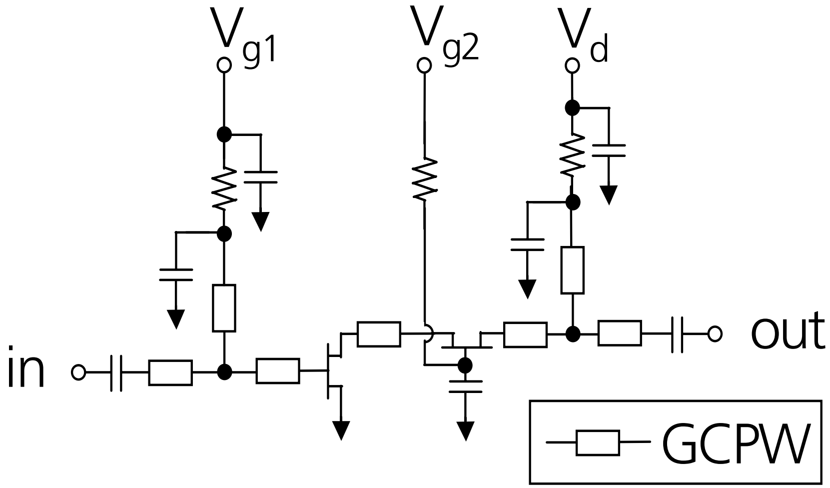
Fundamental balanced

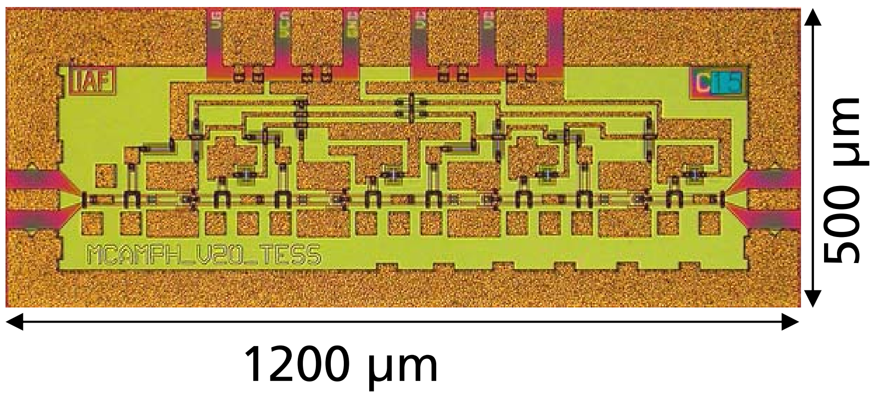




RF 160-260 GHz, IF 0-50 GHz
Conv. Loss <20 dB @ 0 dBm P_{LO}

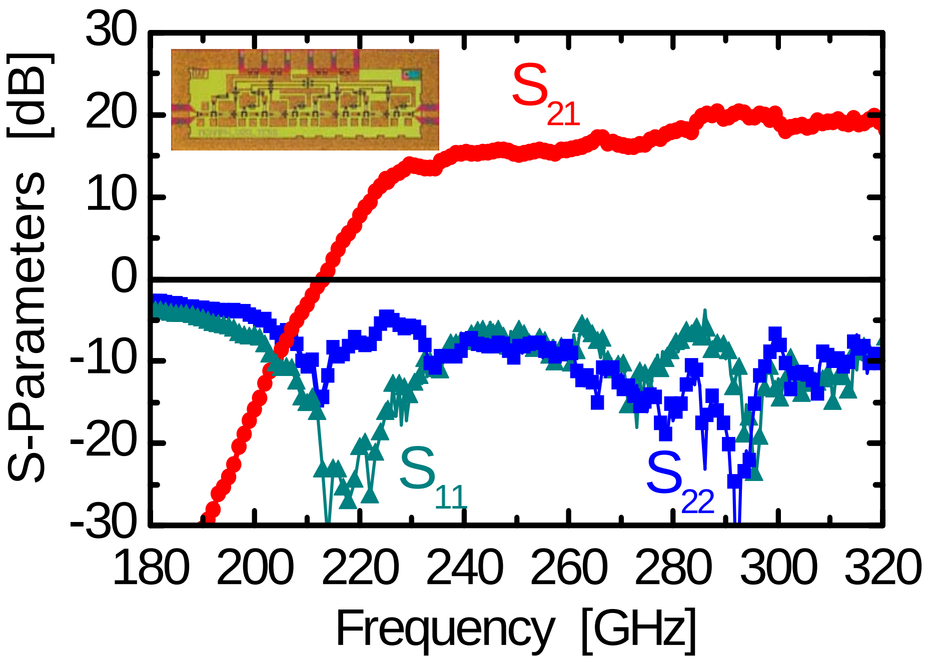
H-Band Cascode mHEMT Amplifier S-MMIC





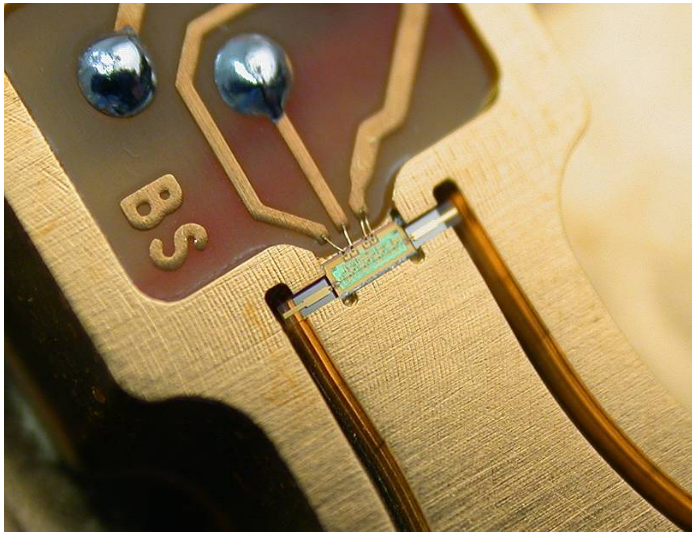
- 50nm mHEMT technology
- cascode mHEMT
- gate width: 2 × 10 µm
- chip size: 0.6 mm²
- reactively matched
- GCPW line impedance = 50 Ω

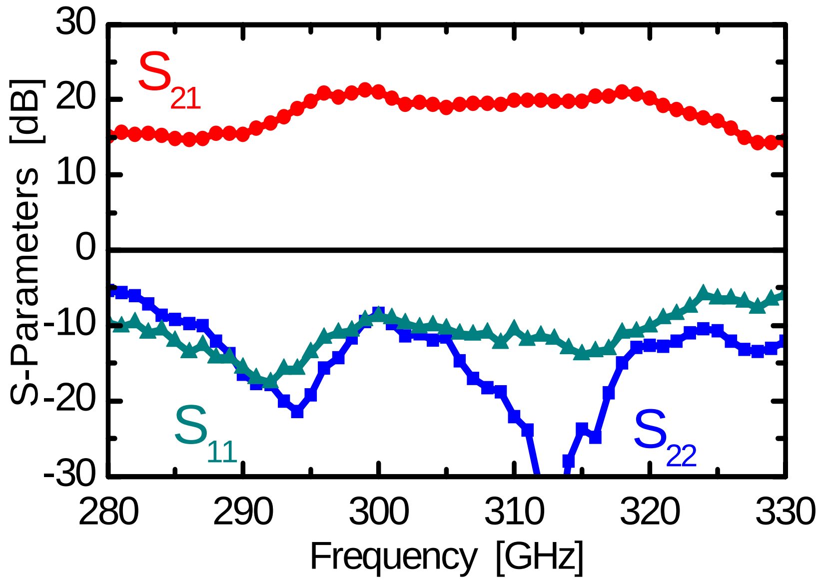
H-Band Cascode mHEMT Amplifier S-MMIC



- 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 (L_g = 50 nm)

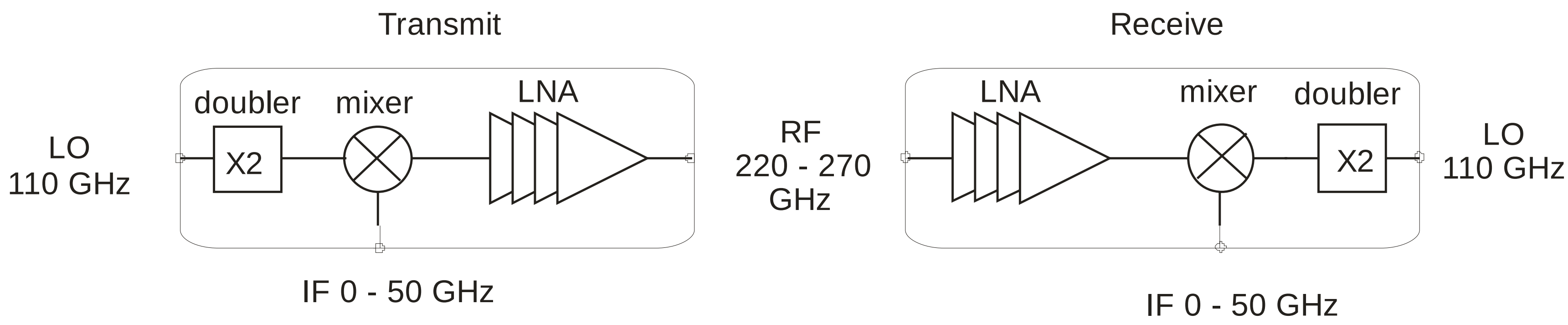


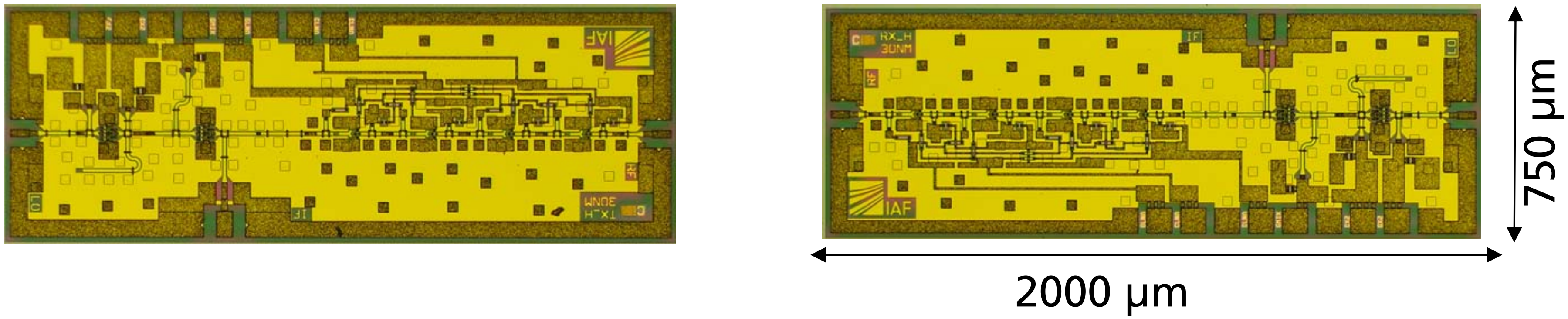


- power consumption: 530 mW (V = 5.0 V, I = 106 mA)

- 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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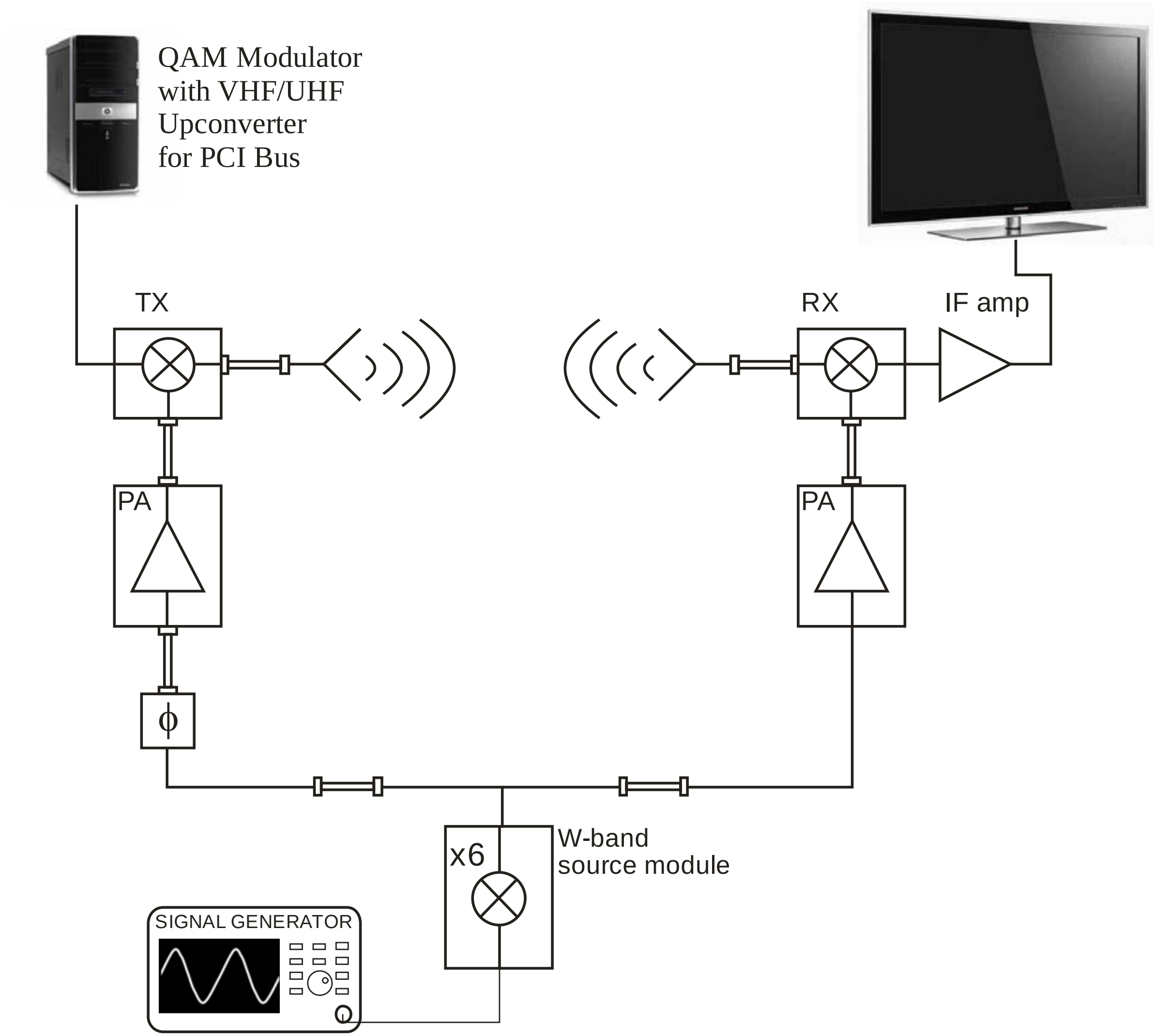
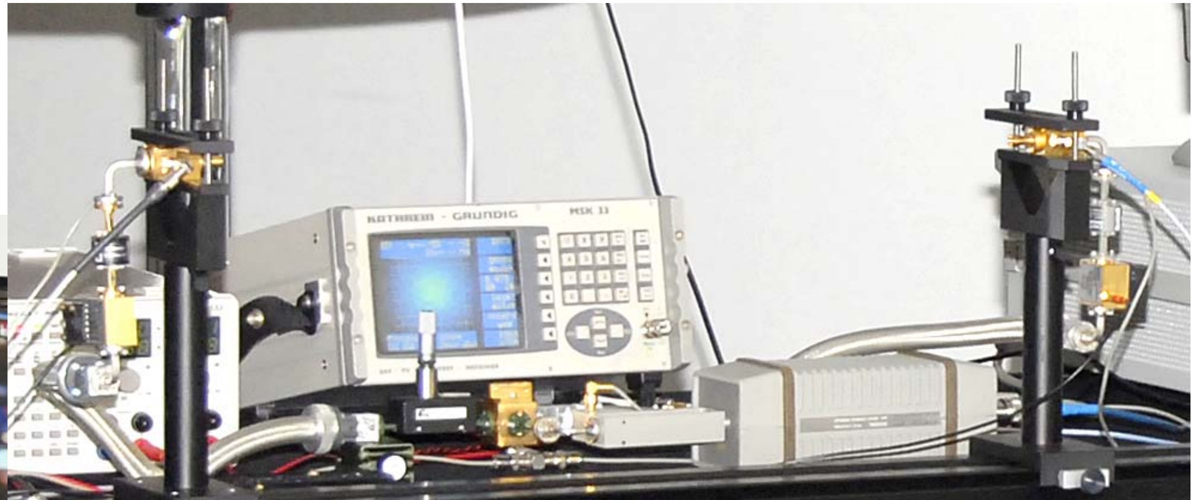
DVB-C Transmission at 220 GHz

- 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!

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