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

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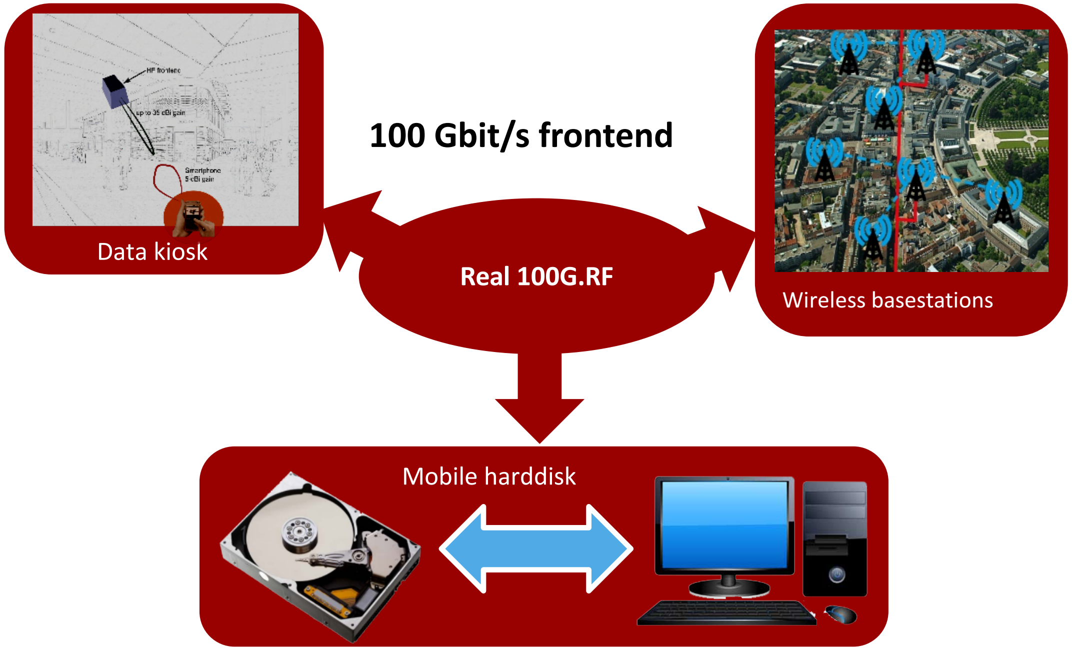
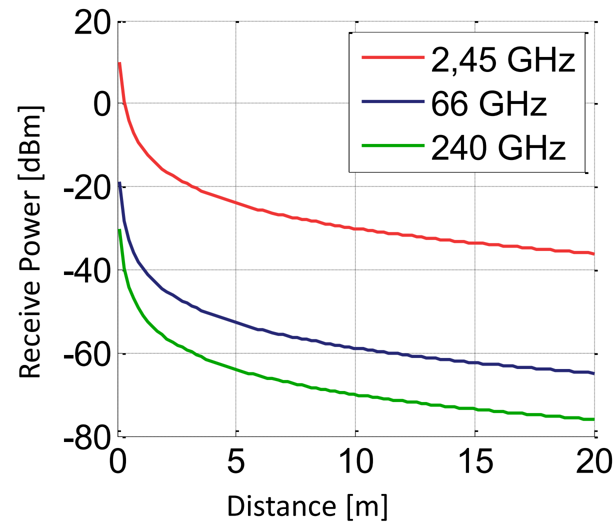
Motivation

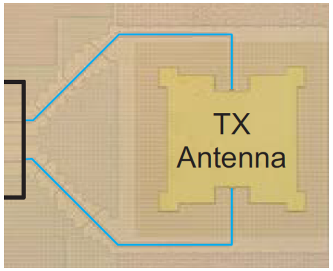


$$R_{\text{max}} = \frac{\lambda}{4\pi}\sqrt{\frac{P_{\text{tx}}G_{\text{tx}}G_{\text{rx}}}{P_{\text{rx,min}}}}$$

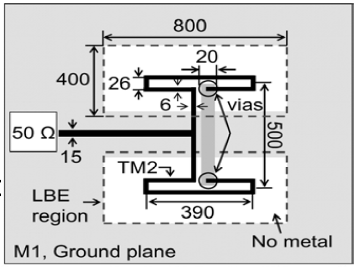


Tx power	NF	Number of channels	Band width	Minimum required receive power	Tx antenna gain (kiosk)	Rx antenna gain (mobile)	Maximum path loss	Achievable range
0 dBm	20 dB	1	50 GHz	-39,84 dBm	0 dBi	0 dBi	29,84 dB	0,003 m
3 dBm	10 dB	1	50 GHz	-49,84 dBm	25 dBi	5 dBi	72,84 dB	0,44 m
6 dBm	10 dB	2	25 GHz	-52,85 dBm	25 dBi	5 dBi	78,85 dB	0,87 m
6 dBm	10 dB	2	25 GHz	-52,85 dBm	25 dBi	25 dBi	98,85 dB	8,71 m

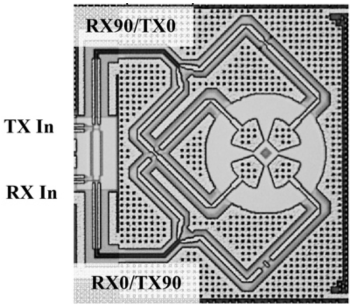
State-of-the-Art – On-Chip Antennas

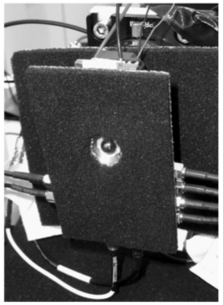


- [JPB13] SiGe technology
  - 240 GHz radar sensor, range: 0.8 m
  - Differential fed patch antenna
  - 24 GHz gain bandwidth (3 dB), return loss -3 dB
  - Small distance between patch and ground plane → poor bandwidth-efficiency product



- [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 moc
  - Ground plane distance: 200µm
  - 11 GHz bandwidth (return loss < -10 dB)





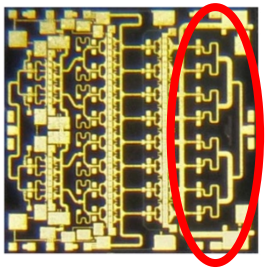
- [GRY15] 0.13 µm SiGe:C BiCMOS technology
  - 240 GHz radar sensor
  - Integrated lens antenna, circularly polarized
  - Antenna bandwidth > 100 GHz

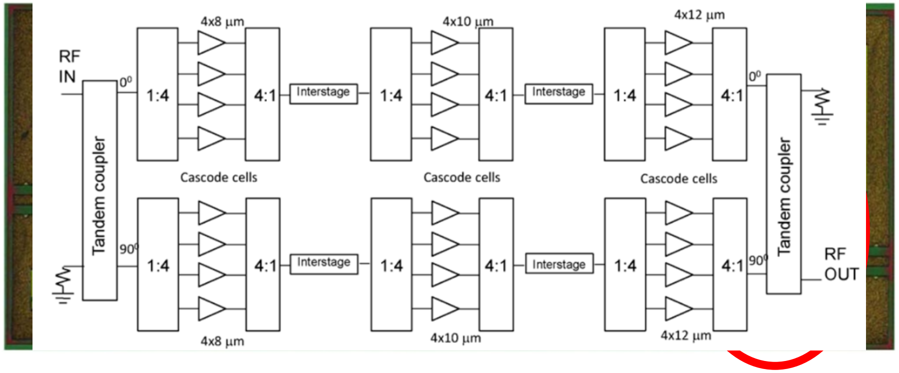
[JPB13] Jaeschke, T et al., "A 240 GHz ultra-wideband FMCW radar system with on-chip antennas for high resolution radar imaging," *Microwave Symposium Digest (IMS), 2013 IEEE MTT-S International* , vol., no., pp.1,4, 2-7 June 2013

[SWB13] K. Schmalz et al., "245 GHz SiGe transmitter with integrated antenna and external PLL," *Microwave Symposium Digest (IMS), 2013 IEEE MTT-S International* , vol., no., pp.1,3, 2-7 June 2013

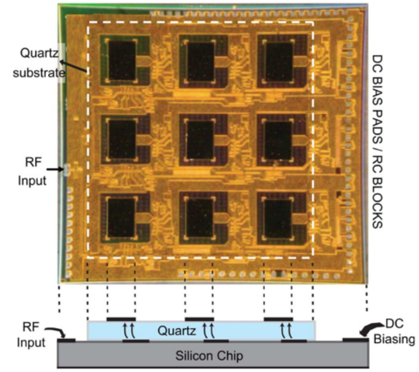
[GRY15] J. Grzyb et al., „A wideband 240 GHz lens-integrated circularly polarized on-chip annular slot antenna for a FMCW radar transceiver module in SiGe technology“, Microwave and Optoelectronics Conference (IMOC), 2015 SBMO/IEEE MTT-S International, pp. 1-4, 2015.

State-of-the-Art – Power Amplification





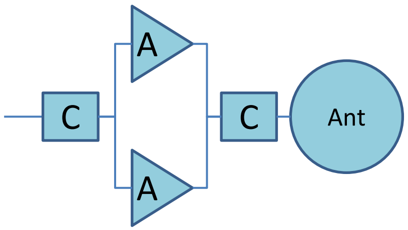
- [Yu14] GaN power amplifier
  - 40 dBm output power @ 30 GHz
  - Power added efficiency: 15 %
  - 3.5 x 3.4 mm²
  - **8 parallel amplifier chains**
- [Cam14] 35 nm InAlAs/InGaAs
  - 14 mW output power @ 200 GHz
  - 20 dB small signal gain
  - 12.9 dB small signal gain from 185 to 215 GHz
  - 2.5 x 1 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 ($\lambda_0/2$ spacing)
    →**Chip-size: 7.3 x 6.6 mm²**



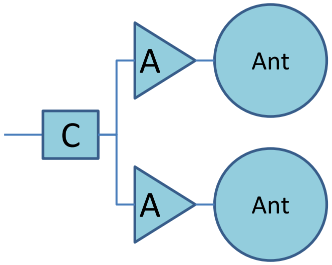
[Yu14] Yu, X. et al., "A Millimeter Wave 11W GaN MMIC Power Amplifier," *Antennas and Propagation (APCAP), 2014 3rd Asia-Pacific Conference on, pp. 1342 – 1344, 2014.*
[Cam14] Campos-Roca, Y. et al., "A 200 GHz Medium Power Amplifier MMIC in Cascode Metamorphic HEMT Technology," *IEEE Microwave and Wireless Components Letters*, 2014.
[Ate11] Y. A. Atesal et al., "Millimeter-Wave Wafer-Scale Silicon BiCMOS Power Amplifiers Using Free-Space Power Combining", IEEE Transactions on Microwave Theory and Techniques, 2011

Different Types of Power Combining

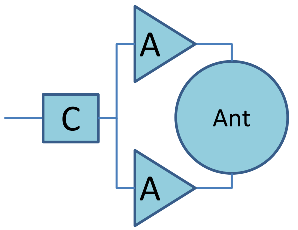
- Parallel amplifiers with power combiner and antenna
  - Losses of coupler feed lines and antenna after the amplifiers
  - Coupler has to match the output impedance of the power matched amplifiers



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

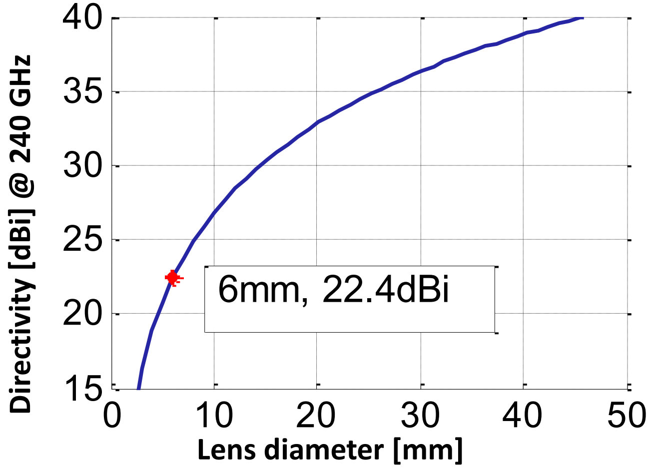


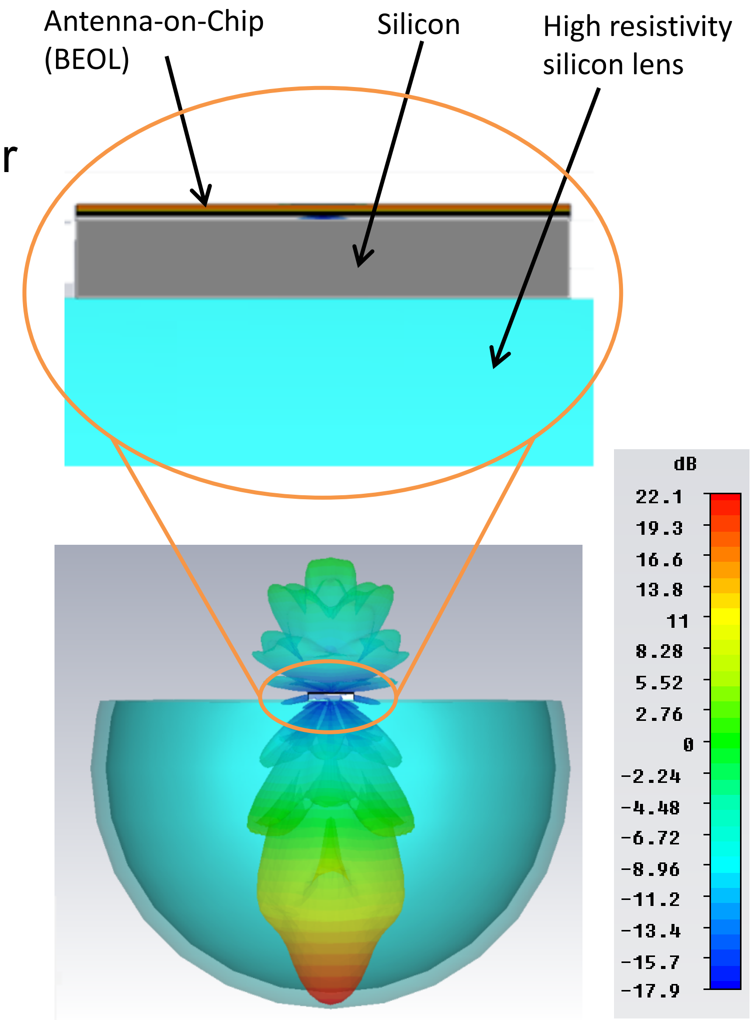
- Feeding of one antenna element with several amplifiers.
  - → this new approach



Integrated Lens Antenna - Principle of Operation

- No ground plane as reflector
- Planar monopole antenna as primary radiator
- $\frac{P_{\text{diel}}}{P_{\text{total}}} \approx 1 - \frac{1}{\varepsilon_{\text{r}}{}^{3/2}}$
- Principle of Integrated Lens Antenna (ILA)
  - Surface waves neglectible
  - E.g. 6 mm lens diamter
  - 200 µm matching layer with ε_r = 2,82

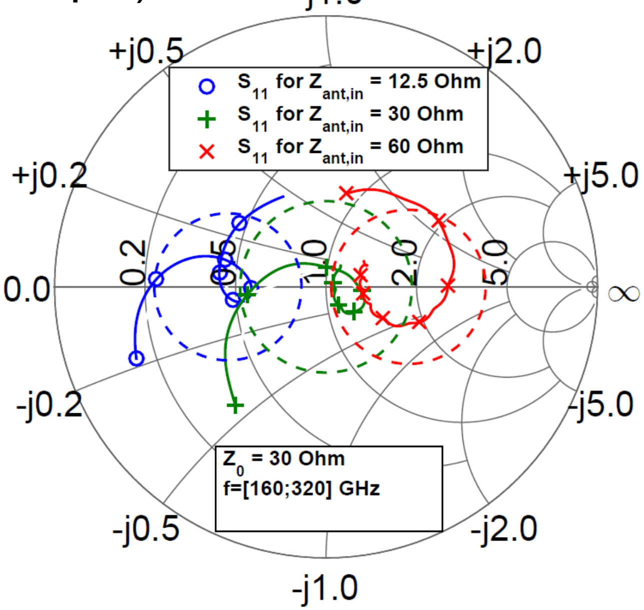


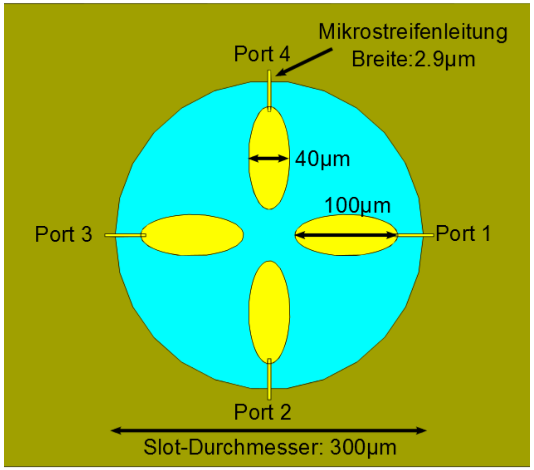


Farfield pattern

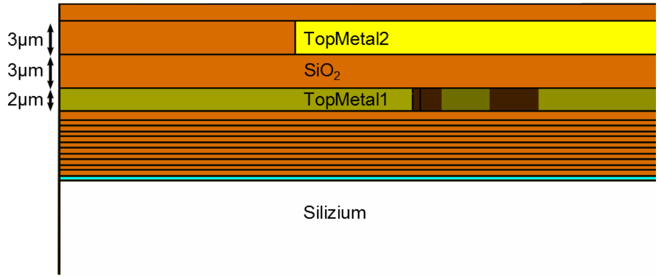
Primary Radiator – Impedance Matching

- Slot antenna including 4 monopoles [Ada10]
- Advantage
  - Small dimensions (slot diameter < 0,25 λ_0)
  - Matching of antenna input impedance (per monople)





Top view

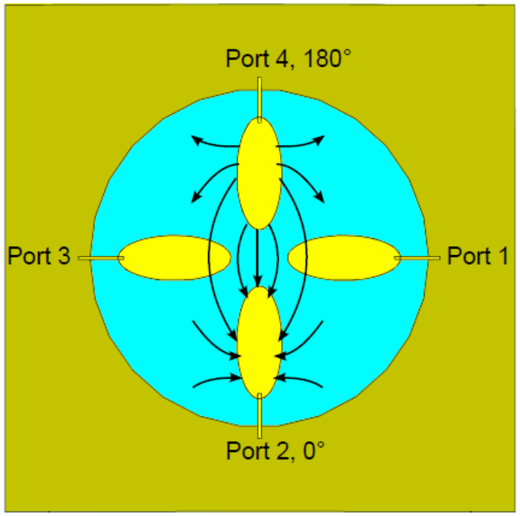


Cross section through metal layers

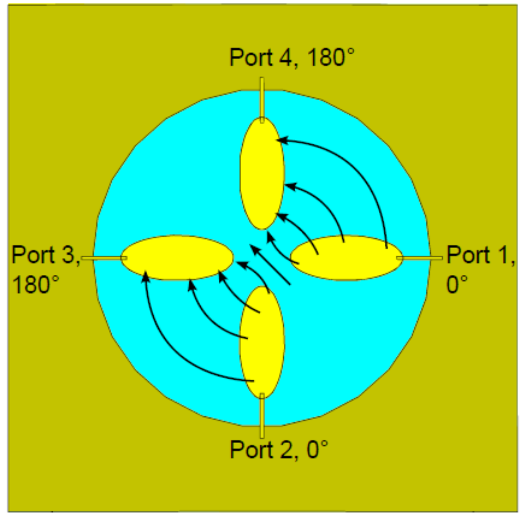
[Ada10] Grzegorz Adamiuk. „Methoden zur Realisierung von dual-orthogonal, linear polarisierten Antennen für die UWB-Technik“. Karlsruhe, KIT, Diss., 2010.

Primary Radiator – Polarization

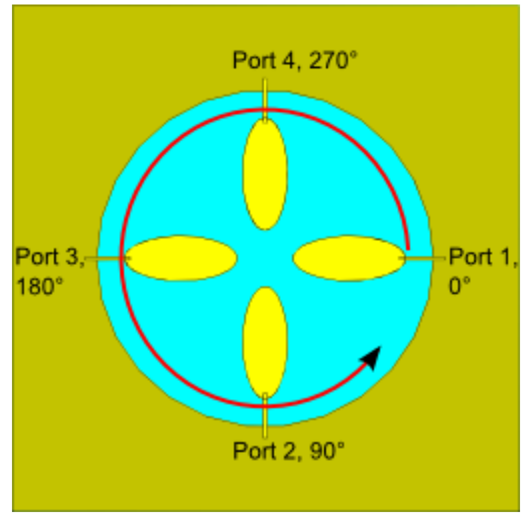
- Different polarizations by applying different phases



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

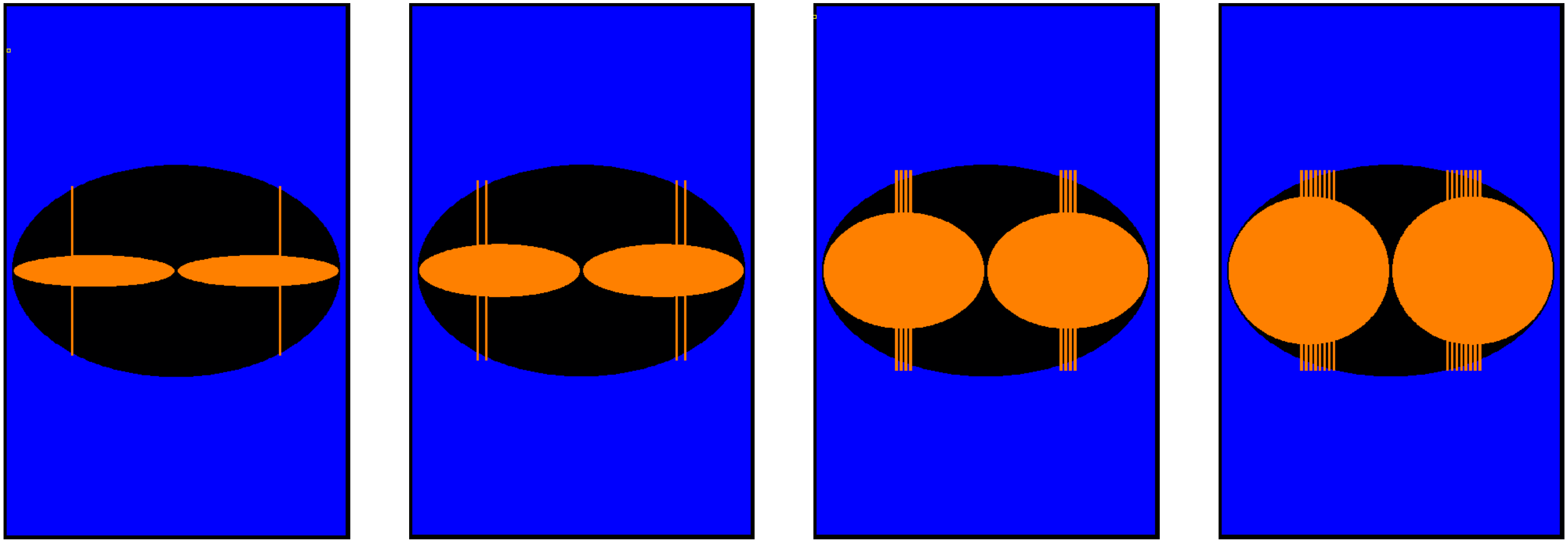


Same signal, but 45 °phase shifted
→ power combining with circularly polarized wave

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

Primary Radiator – Extended Power Combining

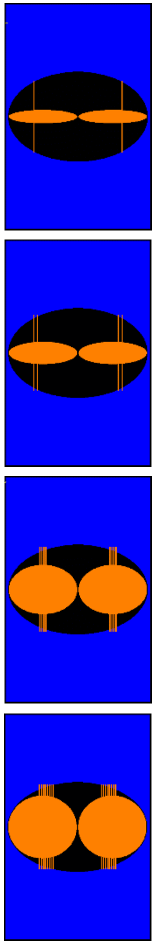
Extended power-combining: more than one feed-line per monopole possible



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

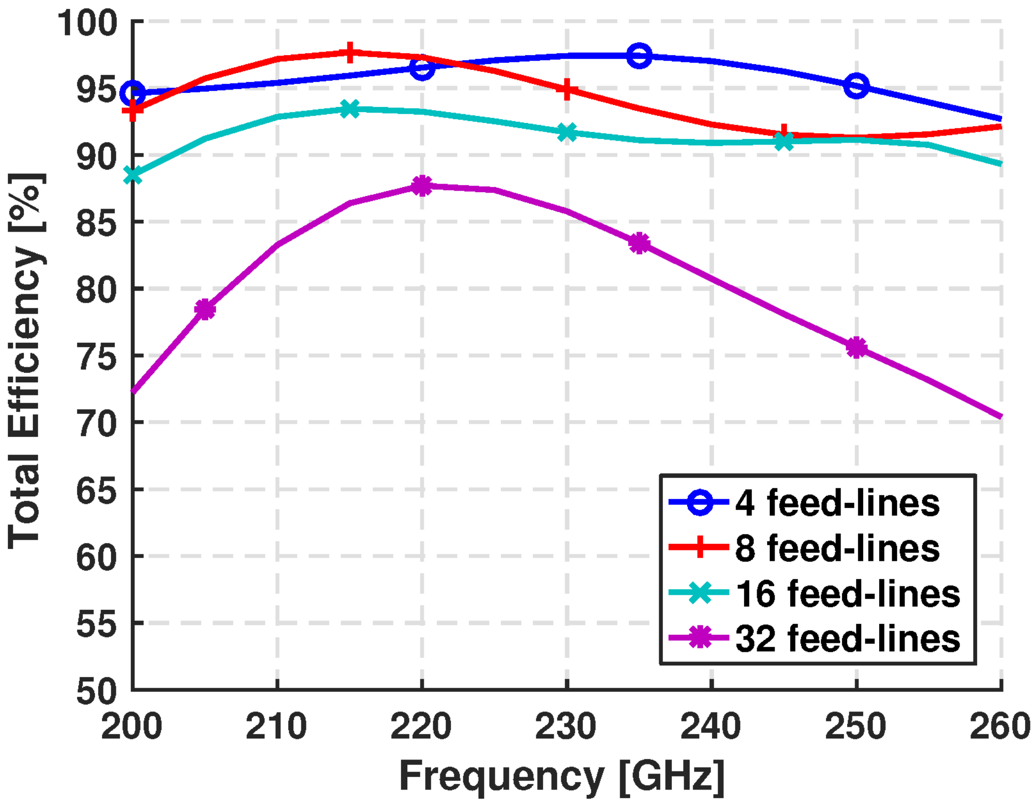


4 x 70Ω

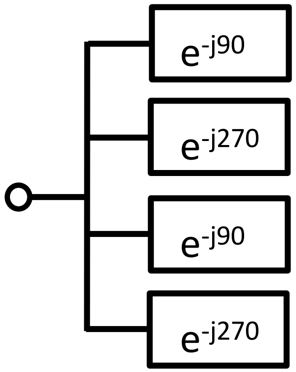
8 x 70Ω

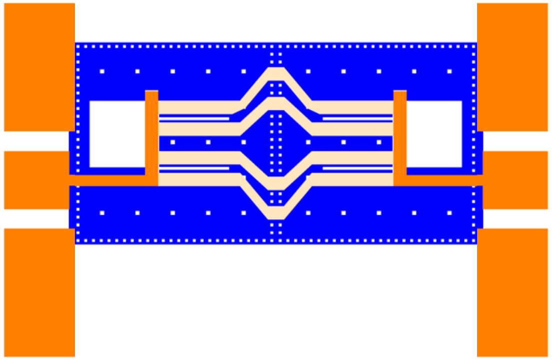
16 x 70Ω

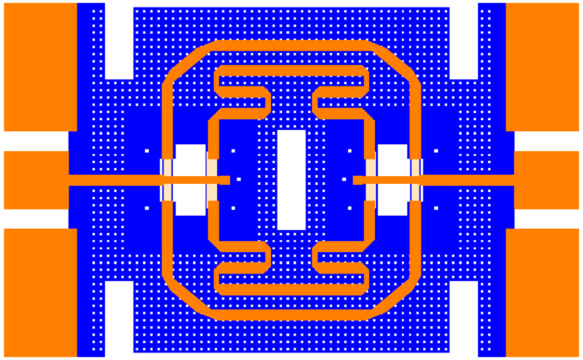
32 x 70Ω



Ultra-Compact Power-Splitters

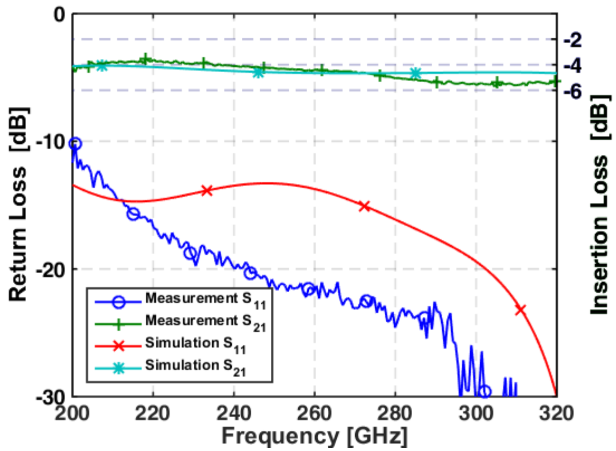




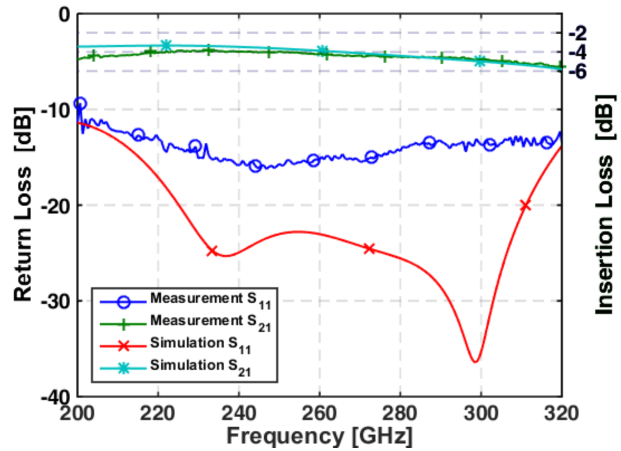


- Distributed transformer (DT) circuit
- Stacked magnetically coupled lines with intrinsic inductance → MIM capacitors for their compensation
- Single-ended input
- Quasi differential outputs
- Ultra-broadband
- Low-loss
- Back-to-back measurements

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

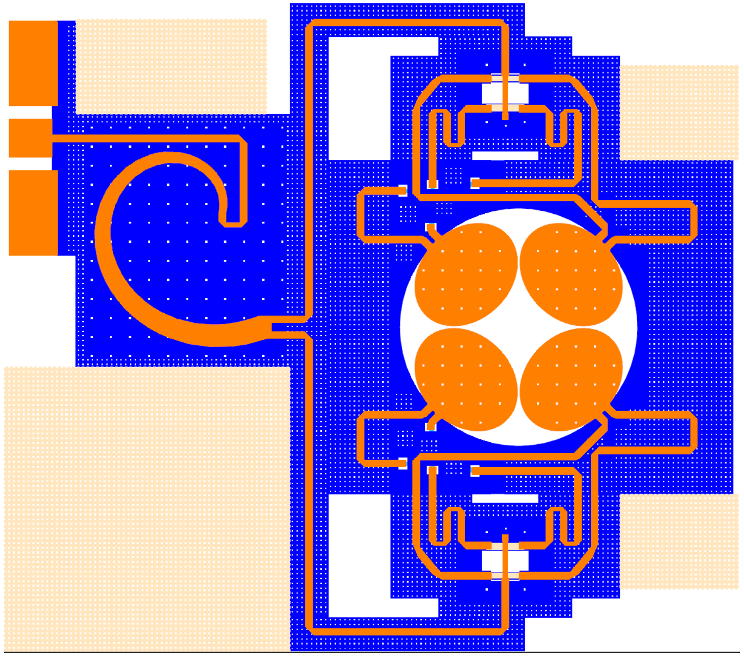


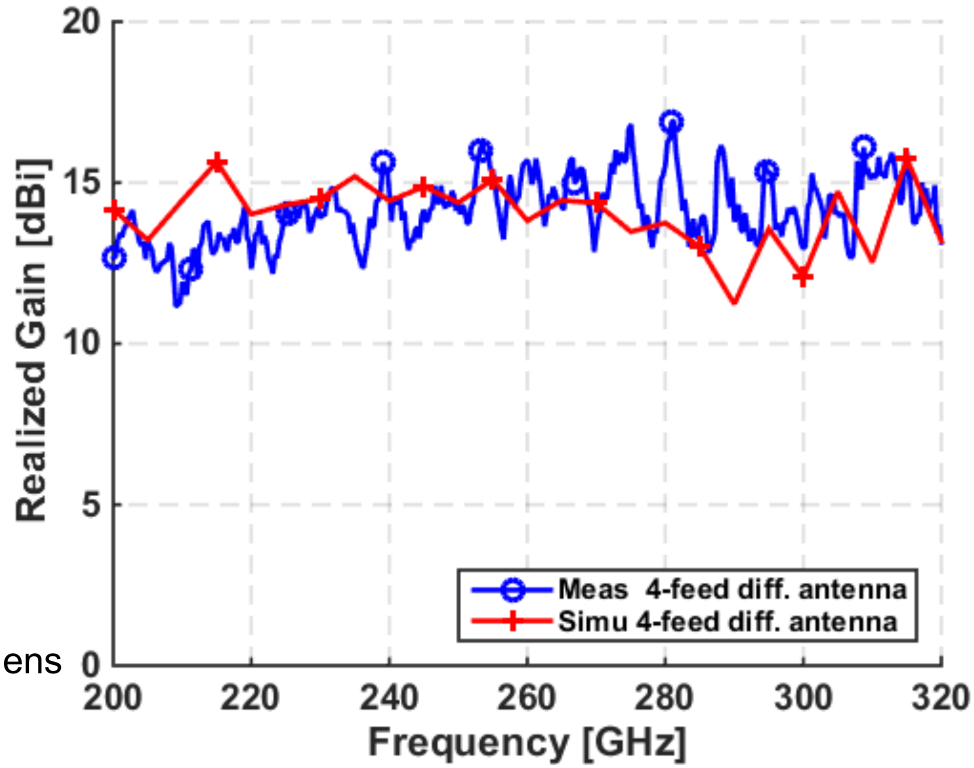
- **4 x 50 Ω outputs**
- **Max. phase inbalance: 4°**
- **Max. amplitude imbalance: 0.7 dB**
- **DT size: 80 x 80 µm²**



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

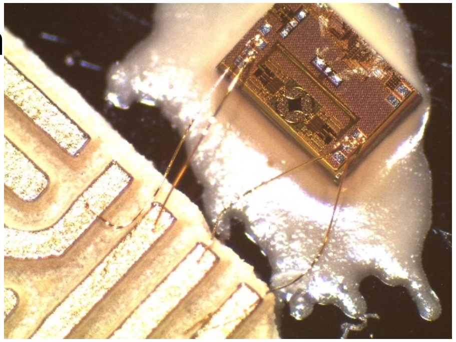


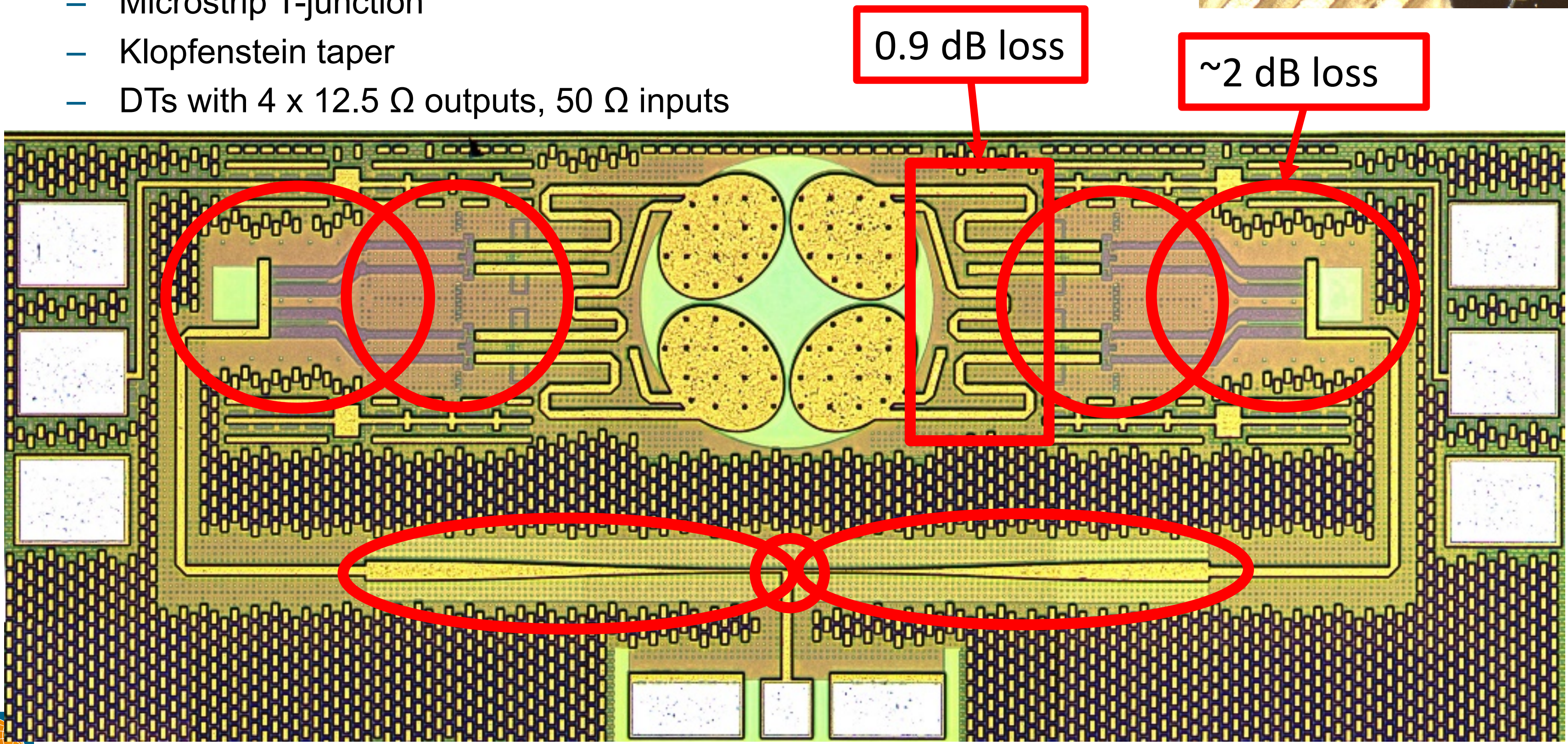


- IC mounted on 12 mm hemispheric silicon lens
- Chip size: 820 x 700 µm²

Active 4-feed Differential Antenna

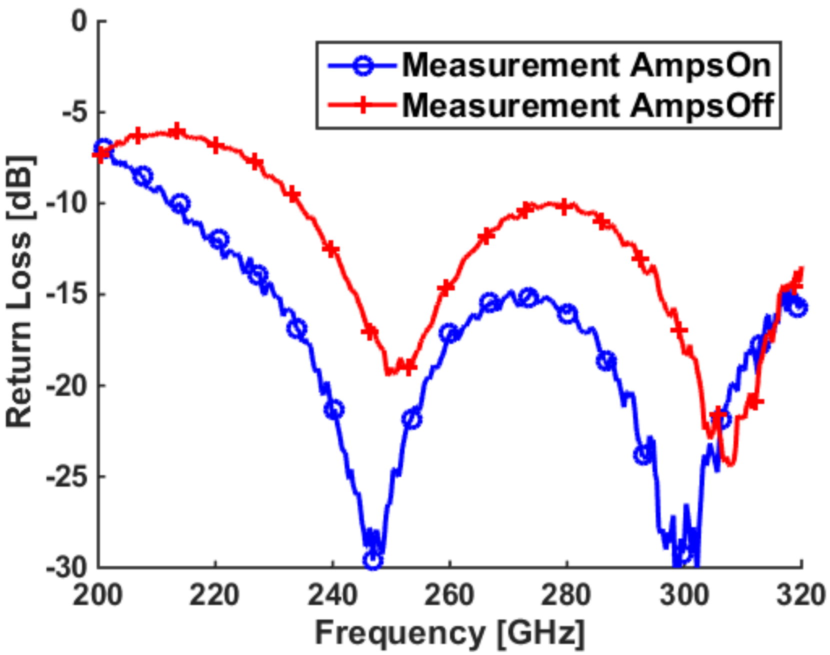
- IC (1056 x 485 µm²) mounted on 12 mm hemispherical silicon len serves as heat dissipation
- Small dimensions: antenna slot diameter < $\lambda_0/5$ @ 240 GHz
- Four parallel single-stage differential cascode amplifiers
- Power-splitter consists of:
  - Microstrip T-junction
  - Klopfenstein taper
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

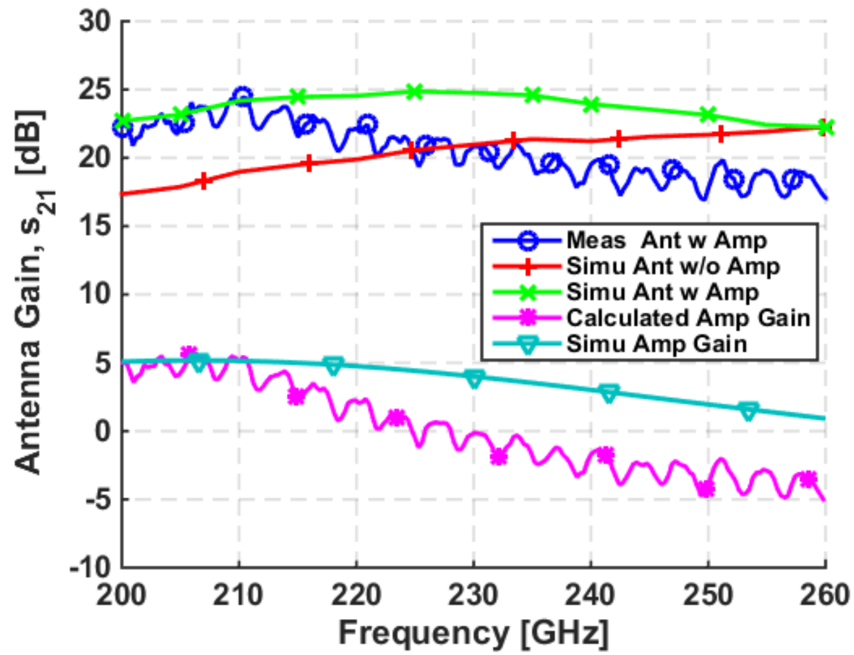




Active 4-feed Differential Antenna

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

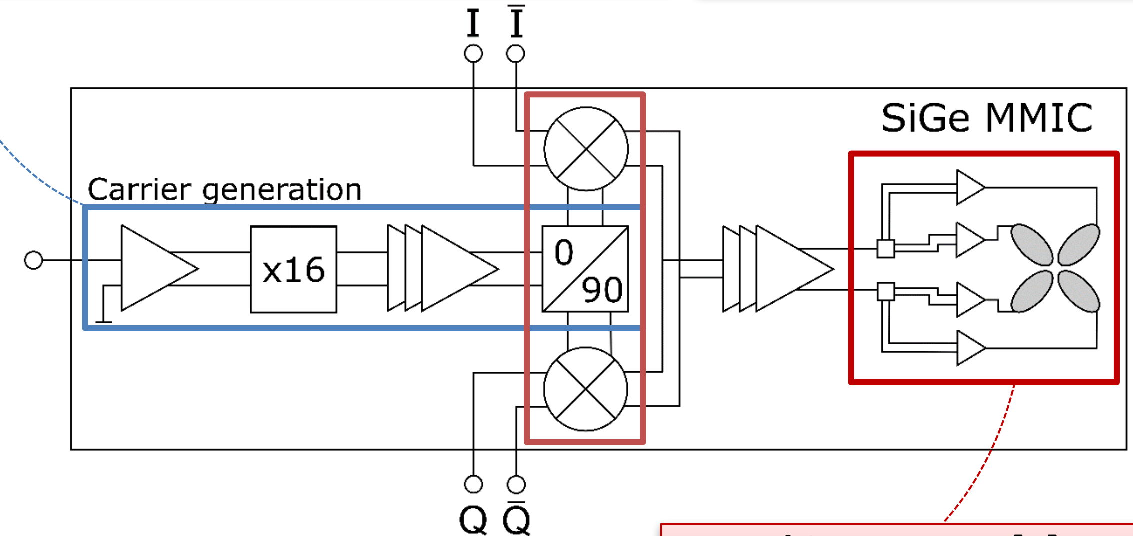




Blockdiagram of the 240-GHz Transmitter

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



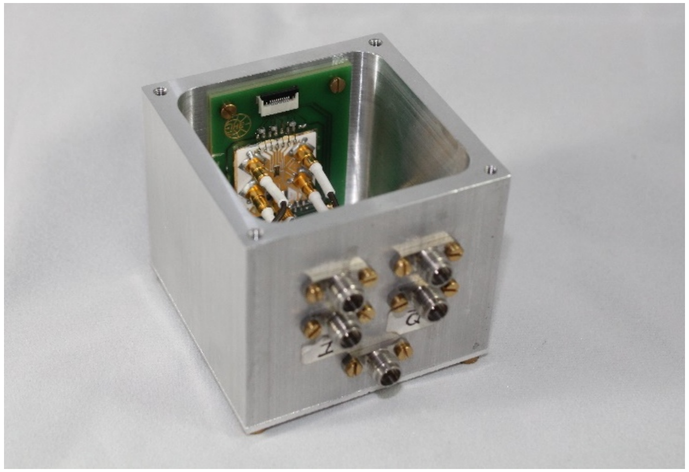
On-chip Antenna [2]
- In-antenna power combining approach
- Dielectric 12 mm lens
- Antenna gain around 20 dBi

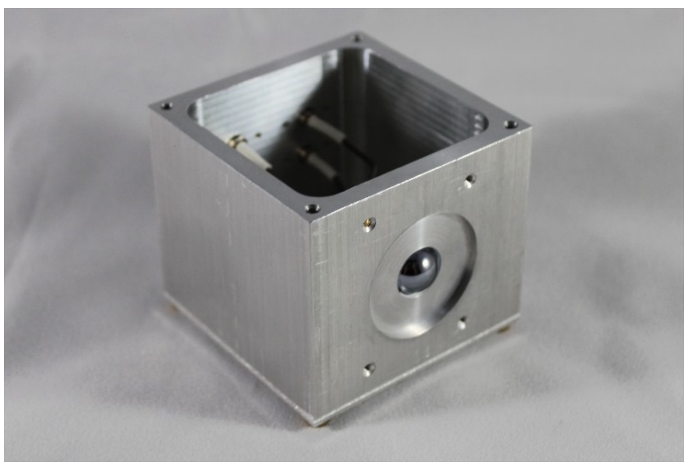
[1] N. Sarmah et al., “A Fully Integrated 240-GHz Direct-Conversion Quadrature Transmitter and Receiver Chipset in SiGe Technology,” IEEE Transactions on Microwave Theory and Techniques, vol. 64, no. 2, pp. 562–574, feb 2016.
[2] B. Goettel et al., “Active Multiple Feed on-Chip Antennas with Efficient In-Antenna Power Combining Operating at 200 - 320 GHz,” submitted to Transaction on Antennas and Propagation, pp. 1–8, 2016.

240-GHz Transmitter Package

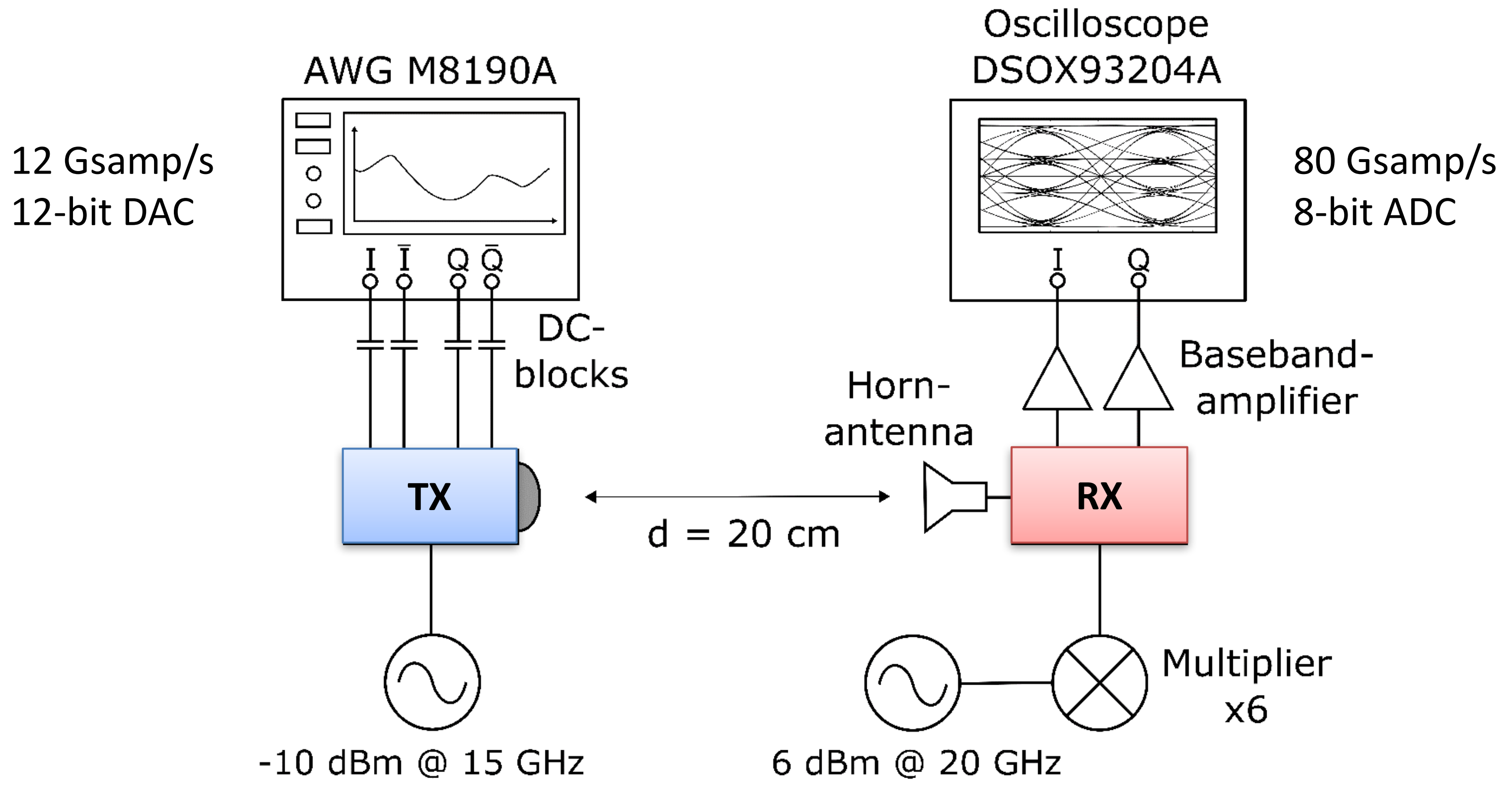
- Single SiGe RF MMIC
  - 0.13 µm Bi-CMOS technology
  - Chip size 1336 x 3006 µm
- 2 x 2 cm alumina board
  - Connectors for differential baseband signal
  - Connector for local oscillator input
  - DC power supply using flat ribbon cable

240-GHz Transmitter Package





240 GHz Communication - Measurement Setup



TX

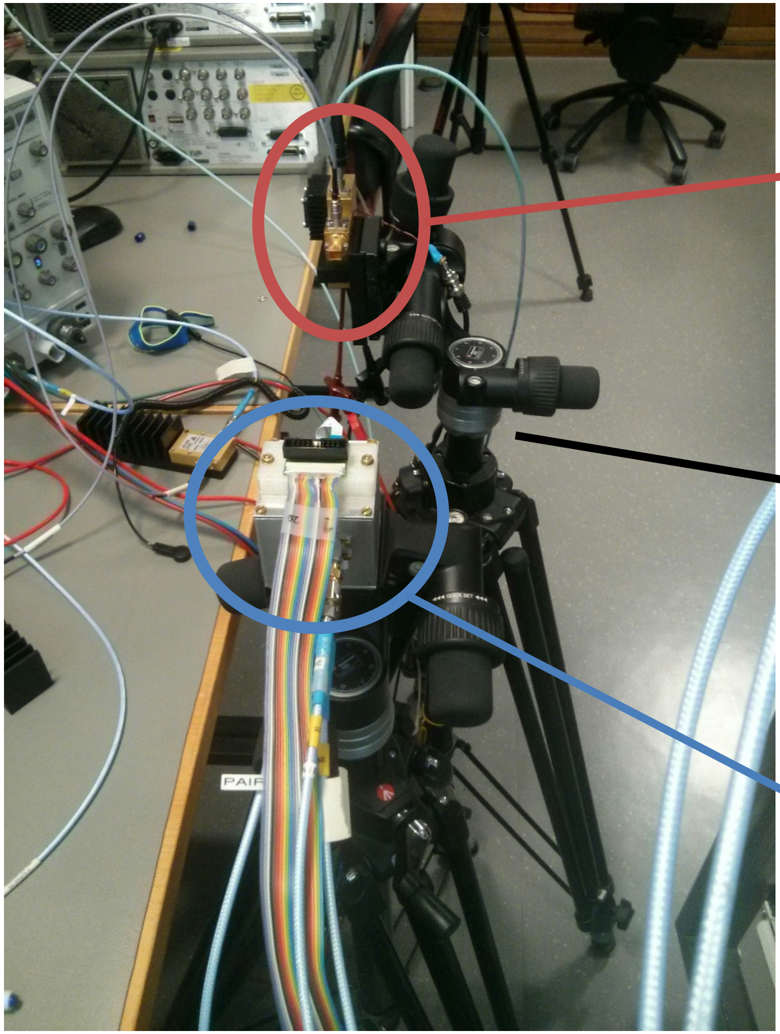
Fully integrated 240 GHz transmitter

RX

MilliLink receiver modules presented in [3].

[3] S. Koenig, D. Lopez-Diaz, J. Antes, F. Boes, R. Henneberger, A. Leuther, A. Tessmann, R. Schmogrow, D. Hillerkuss, R. Palmer, T. Zwick, C. Koos, W. Freude, O. Ambacher, J. Leuthold, and I. Kallfass, “Wireless sub-THz communication system with high data rate,” Nature Photonics, vol. 7, no. 12, pp. 977–981, oct 2013.

240 GHz Communication - Measurement Setup



- MilliLink receiver modules
- 24 dBi horn-antenna

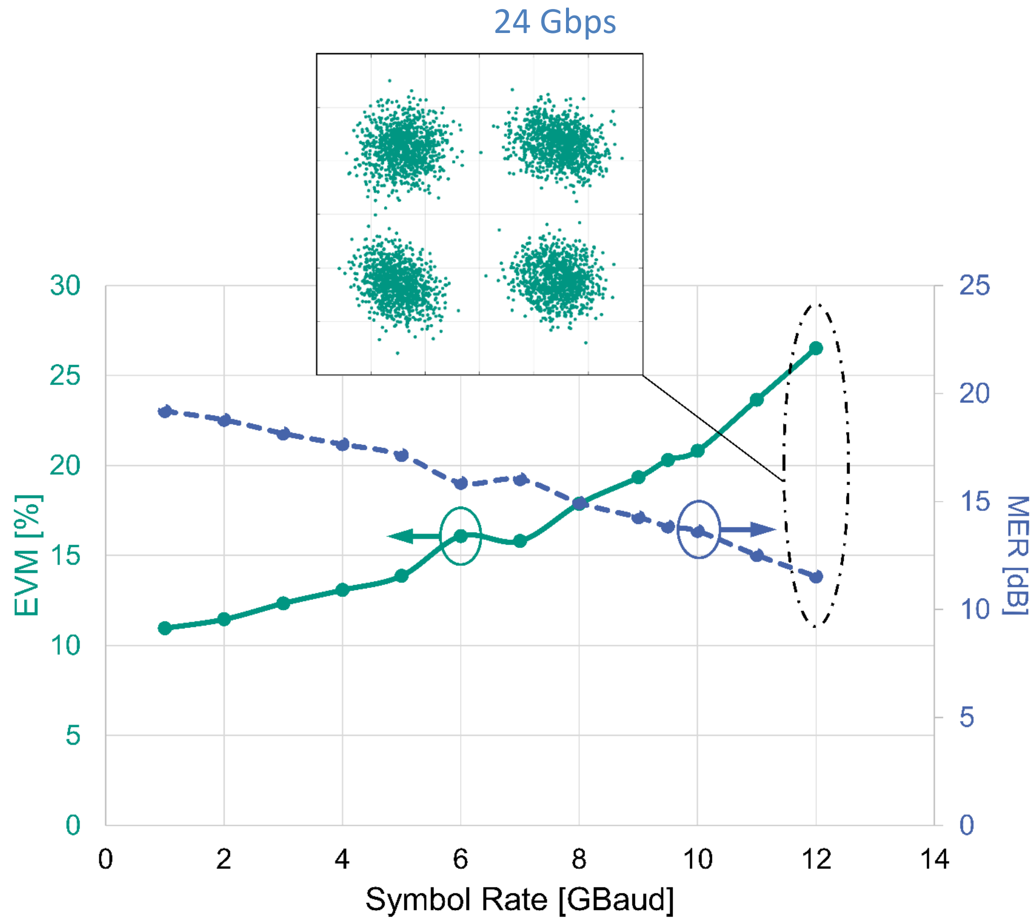
Tripods for antenna alignment

- 240-GHz Transmitter
- Flat ribbon cable for DC power supply

Measurement Results

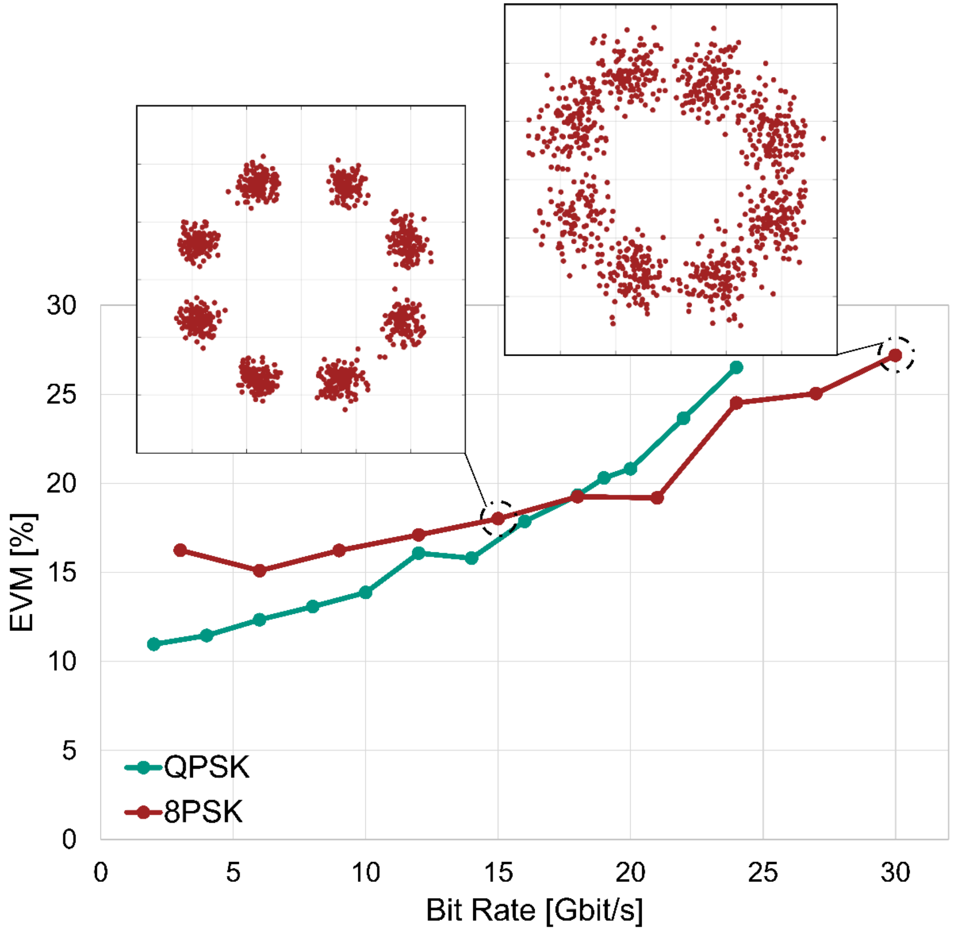
- Keysight VSA Software as digital receiver
  - Carrier recovery
  - Time synchronization
  - IQ offset and imbalance correction
  - Channel equalization

- 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