Radio Front-Ends for 100 Gbps and beyond

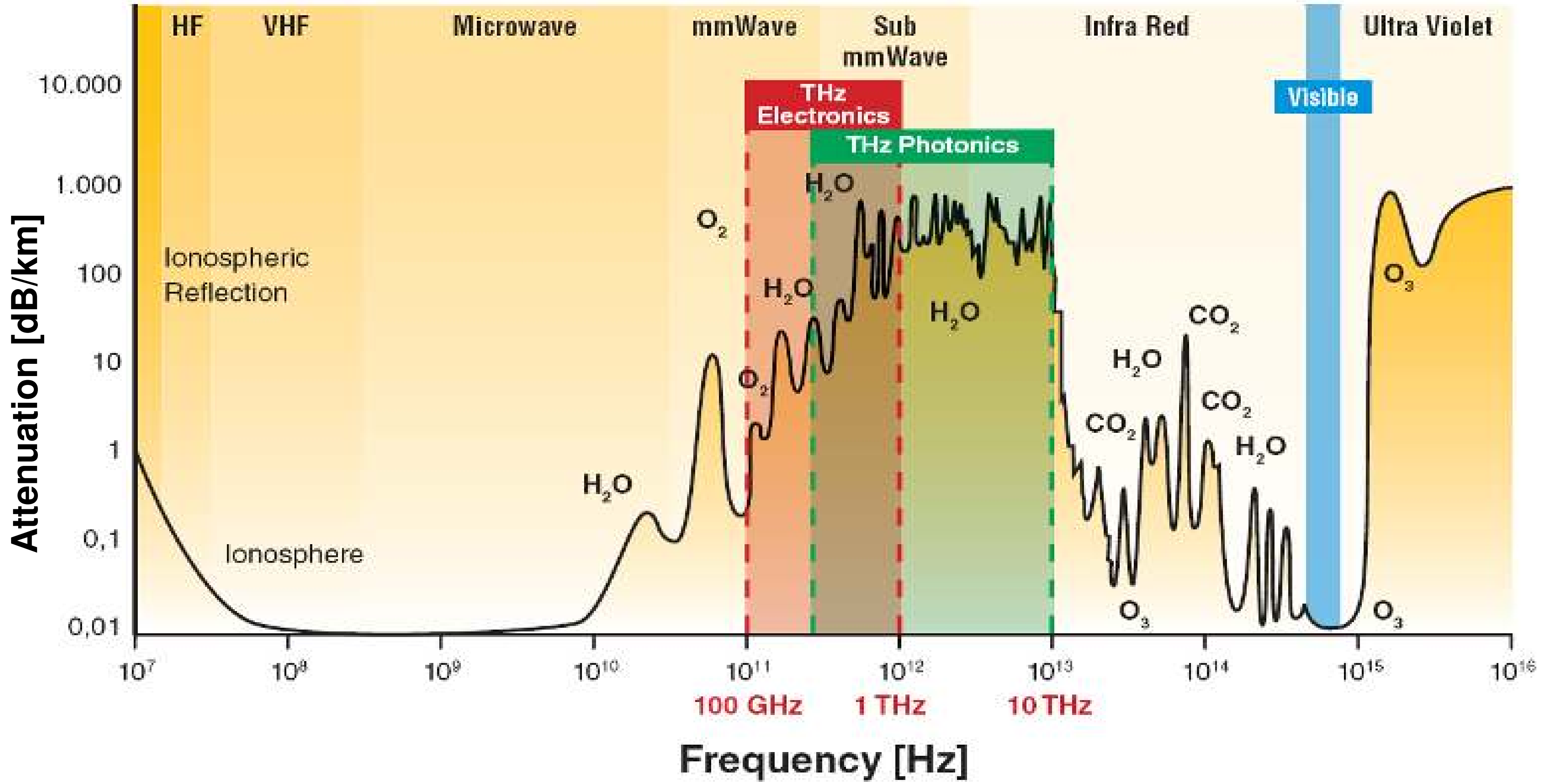
Ullrich Pfeiffer
ullrich@ieee.org
High-Frequency and Communication Technology (IHCT)
University of Wuppertal, Germany

6G WIRELESS SUMMIT
Levi · Lapland · Finland
24-26 March 2019

BERGISCHE UNIVERSITÄT WUPPERTAL

Institute for High-Frequency & Communication Technology
IHCT

The Pursuit to Unlimited Bandwidth



mmWave/THz Application Scenarios

mmWave, THz Imaging and Sensing

- Non-destructive testing
- Security
- Bio-medical
- Space
- Material characterization
- Spectroscopy
- Super-Resolution Imaging

Radar Applications

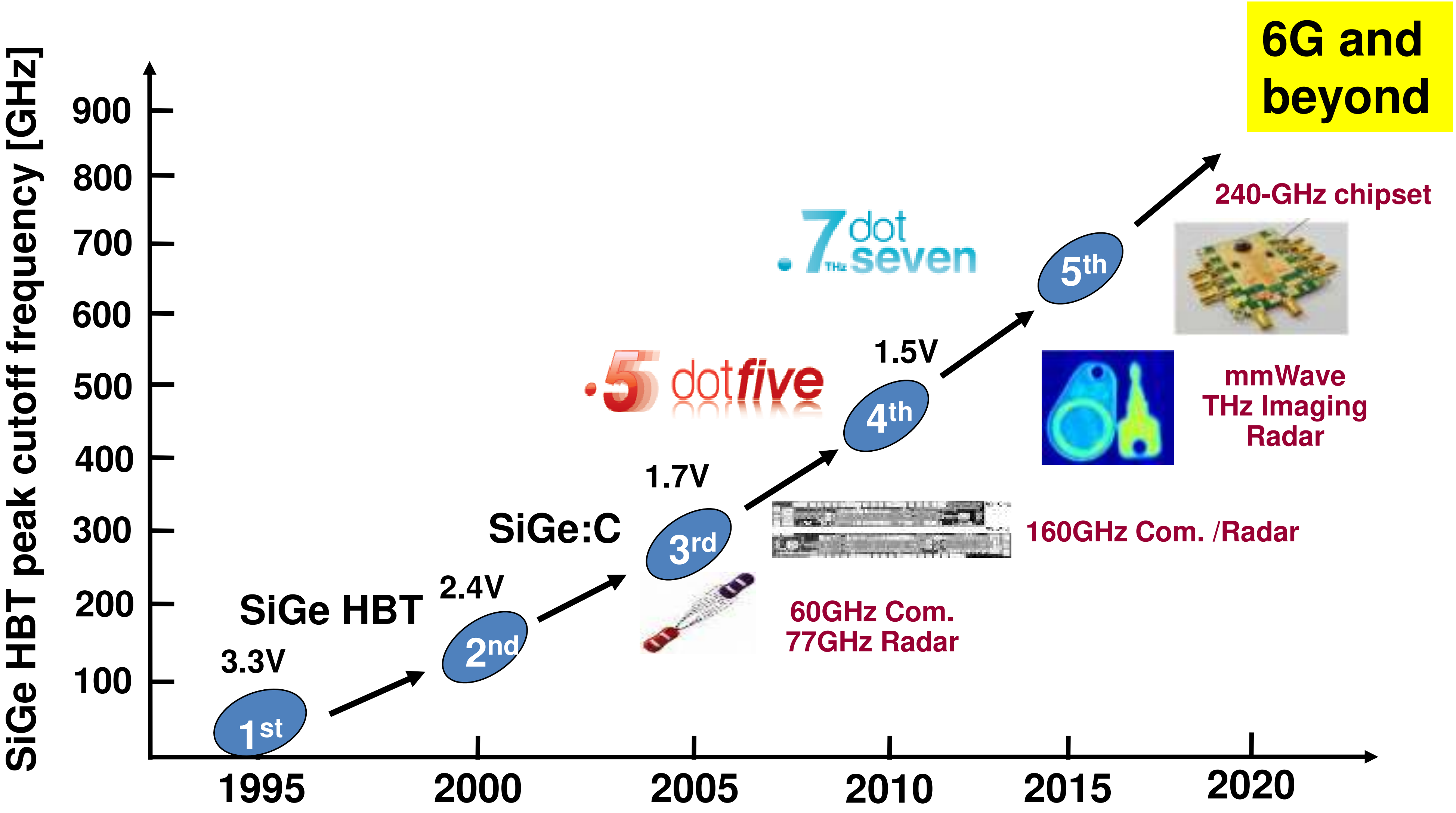
- 77GHz, 120GHz, 240GHz
- Automotive
- Remote control
- Gesture recognition
- Process control
- 3-D Imaging
- Patient monitoring

High-speed Communication

- 60GHz, E-band, 5G, 6G and beyond
- **IEEE 802.15.3d-2017 252-322 GHz**
- Towards 100GBit/s
- Interconnects
- Data servers
- Networking and protocols

Can we use silicon to implement THz Radio Front-Ends?

Silicon (SiGe) HBT Technology Evolution



240GHz link-budget estimation (QPSK)

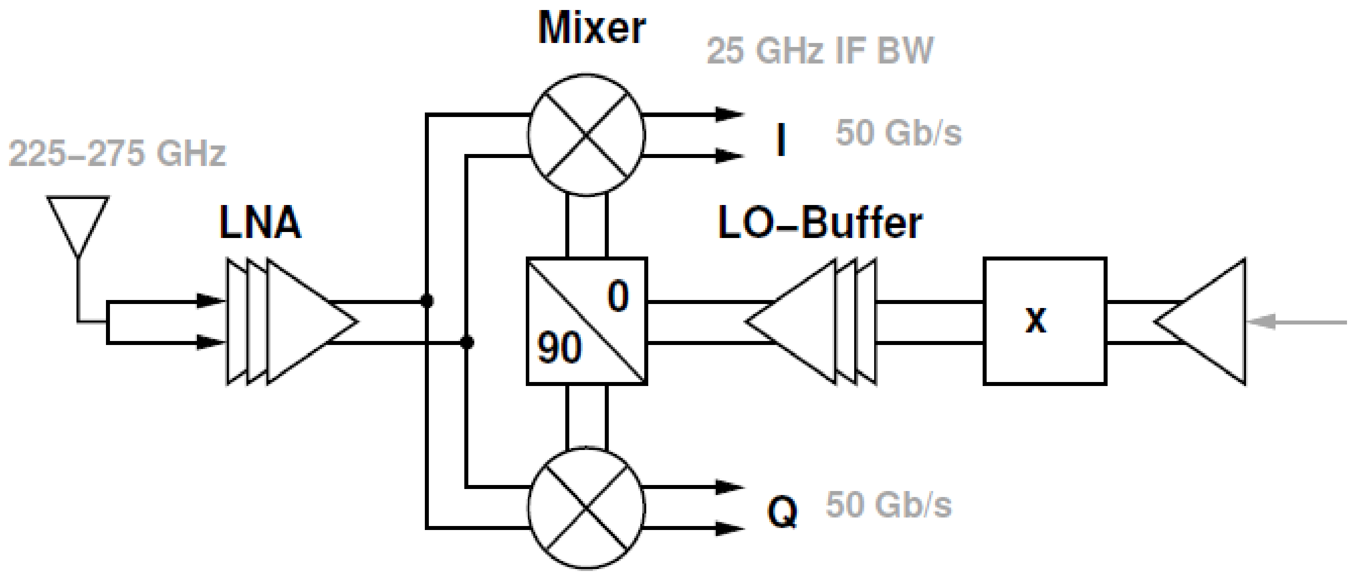
$$FSPL_{max} = 10log_{10}(kT \cdot BW) + NF + SNR_{min} - P_{TX} - G_{AntTX} - G_{AntRX} + 10dB$$

Tx power	NF	Number of channels	Band width	Minimum required receive power	Tx antenna gain	Rx antenna gain	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**

Circuit Design Challenge:
trade-off Pout, NF, BW, range, antenna gain, packaging

Can we build a generic THz I/Q transceiver?

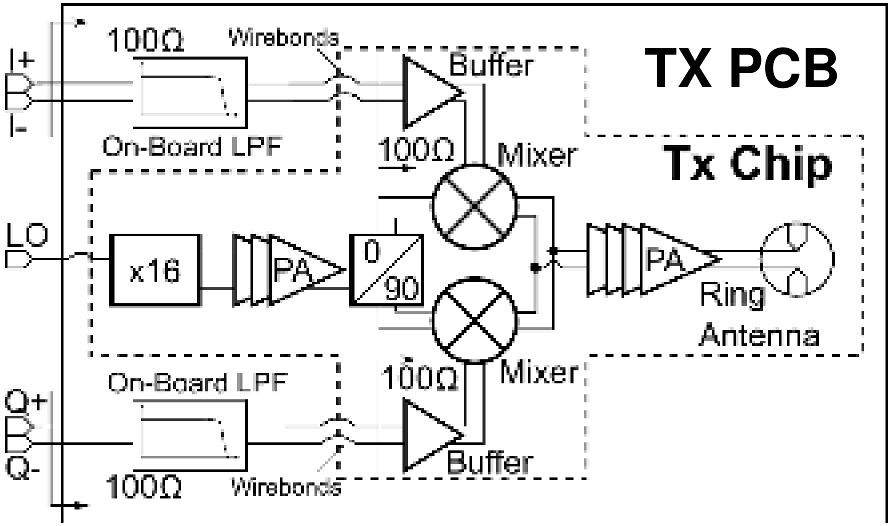
- **Circuit approach: generic wideband I/Q radios with spectral efficiencies of 2-3 bit/s/Hz at 240 GHz**



  - Challenges: limitations in transmit power, receiver noise figure, IF/RF bandwidth, linearity and I/Q imbalance over a very wide bandwidth
  - Approach: apply wide-band circuit matching techniques

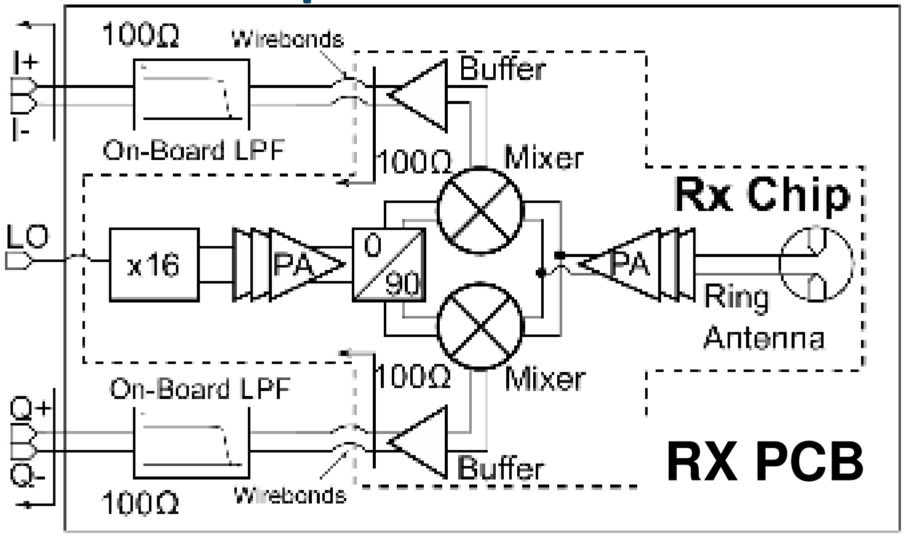
220-260 GHz TX/RX Chip Block Diagrams

Transmitter



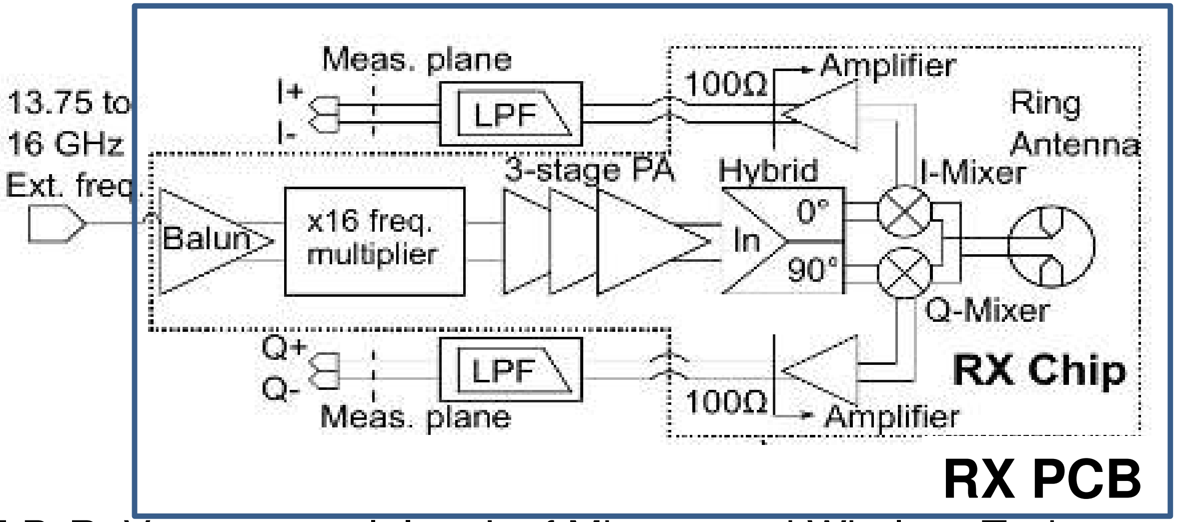
[1] N. Sarmah et al, TMTT 2015 run 1
[2] N. Sarmah et al, EUMIC 2016 run 2

Amplifier First



[1] N. Sarmah et al, TMTT 2015 run 1
[2] N. Sarmah et al, EUMIC 2016 run 2

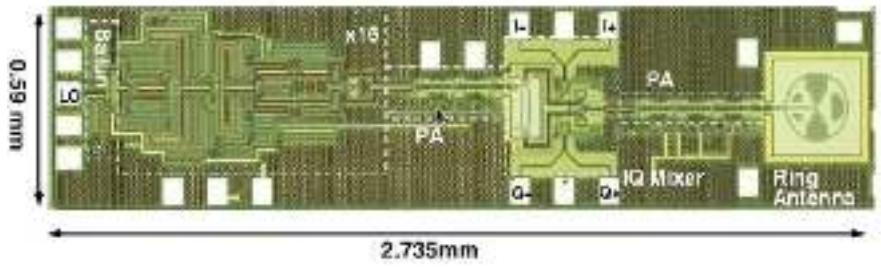
Mixer First



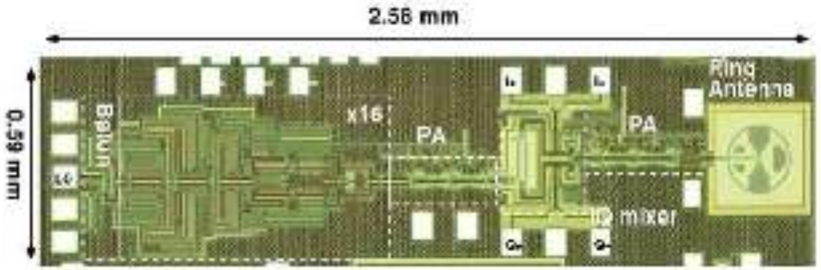
[3] P. R. Vazquez et al, Int. J. of Microw. and Wireless Tech.

Chip Micrographs and Packaging

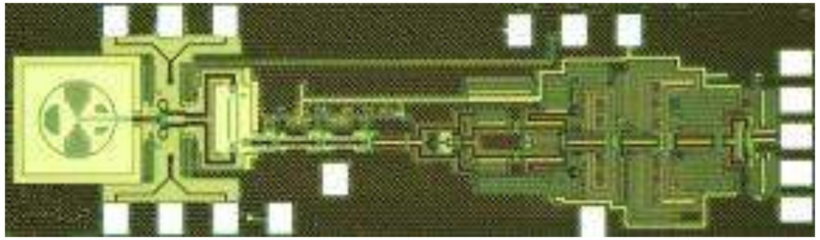
Transmitter

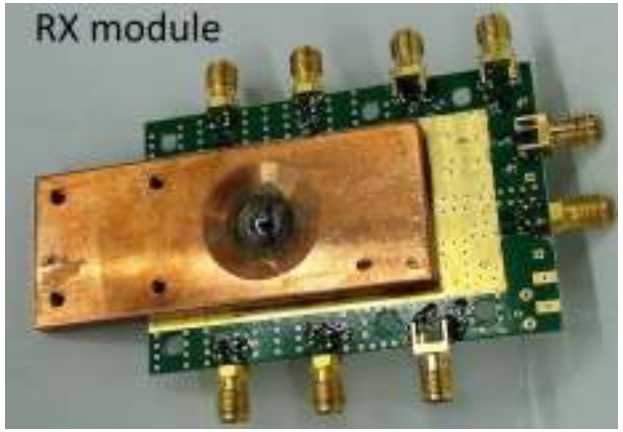


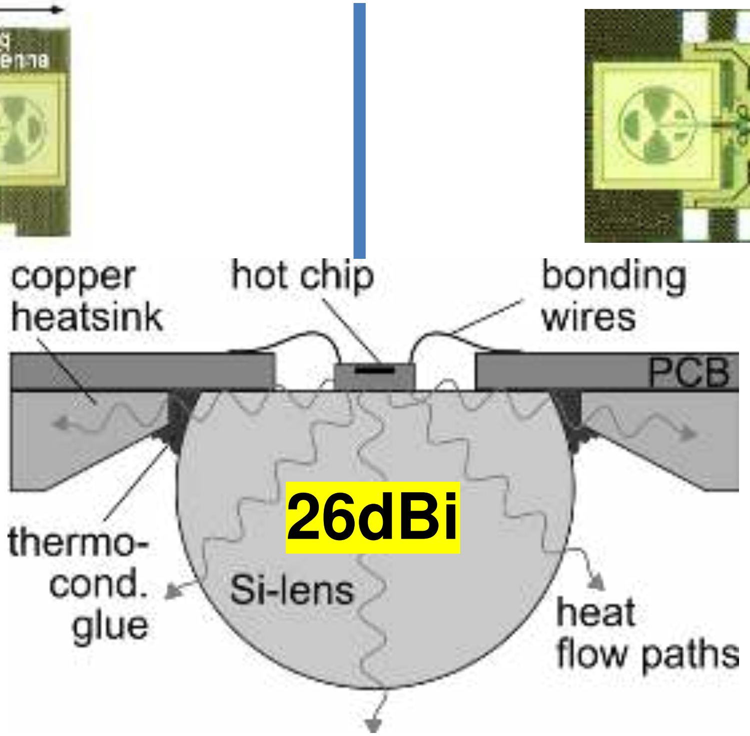
Amplifier First RX

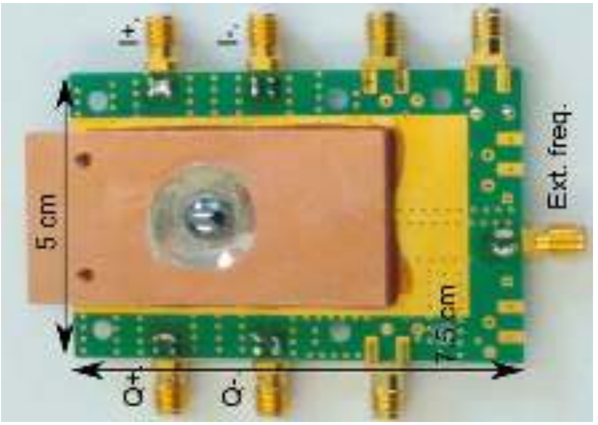


Mixer First RX

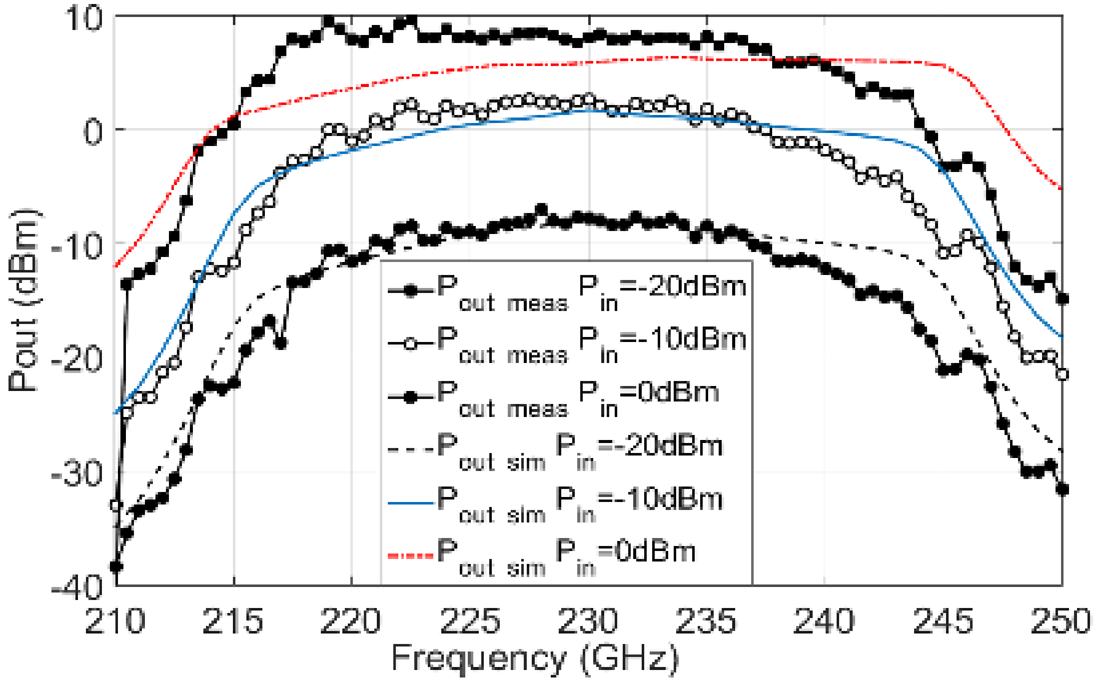


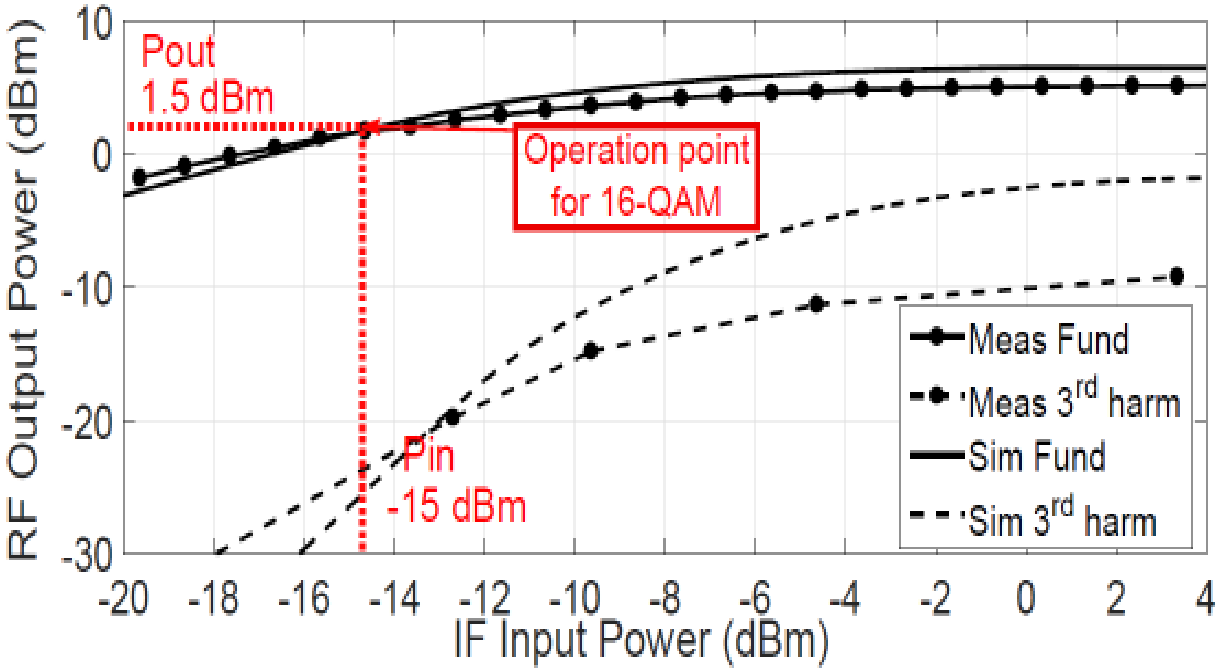






Transmitter RF Front-End Performance

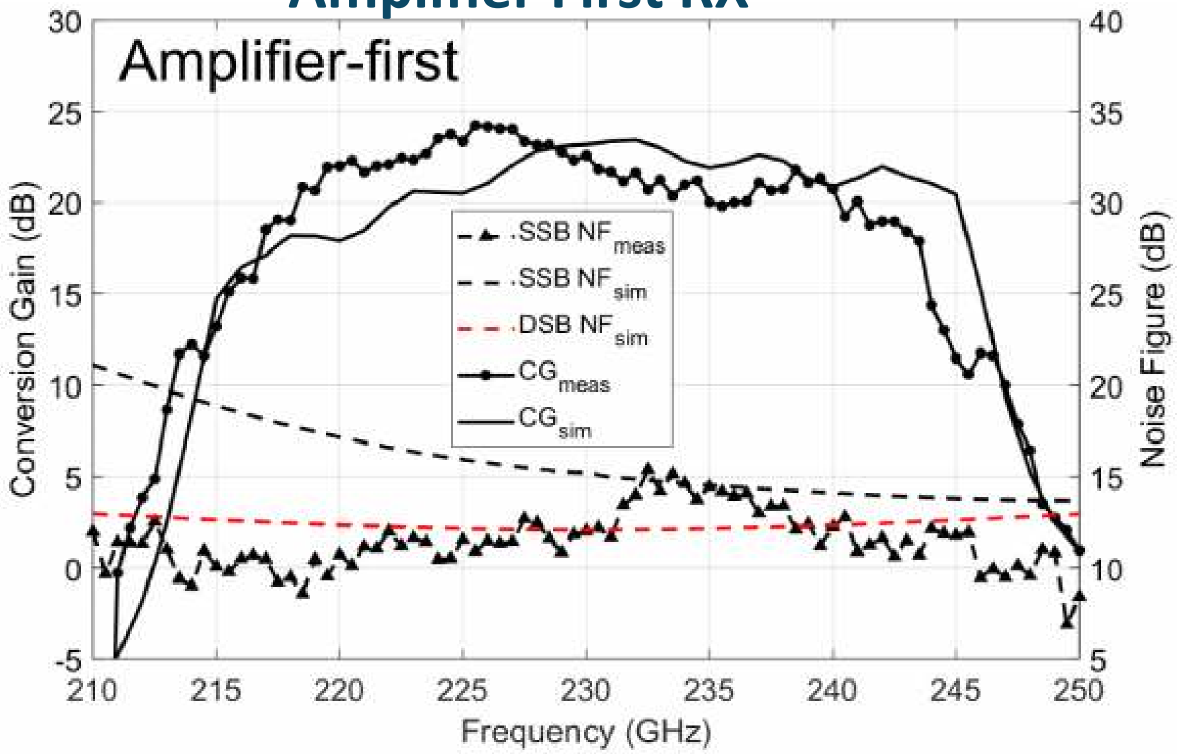




- For LO = 220-260 GHz; Psat= -2 to 9.5 dBm
- 3dB RF BW: 25GHz at 230GHz LO
- IP1dB = -15 to -5 dBm and additionally varies across IF frequency
- IQ Amp. Imb. < 0.5 dB for IF up to 17 GHz, IQ phase Imb. < 2 deg

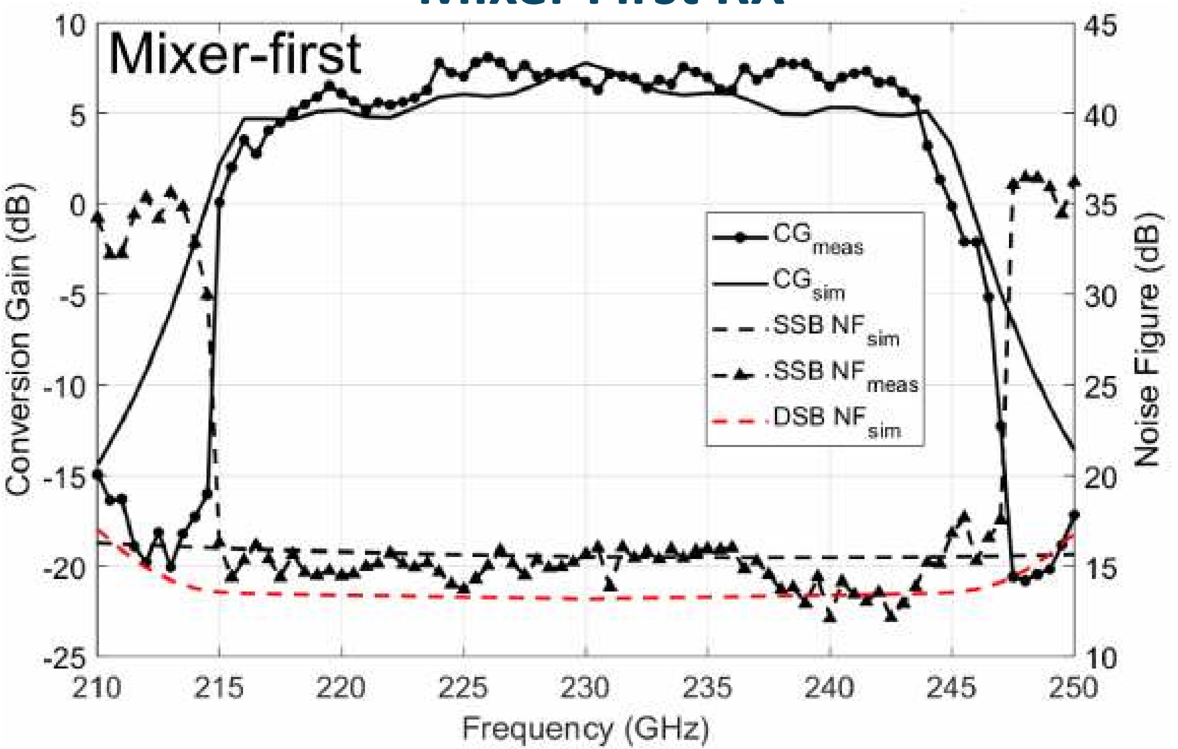
Receiver RF Front-End Performance

Amplifier First RX



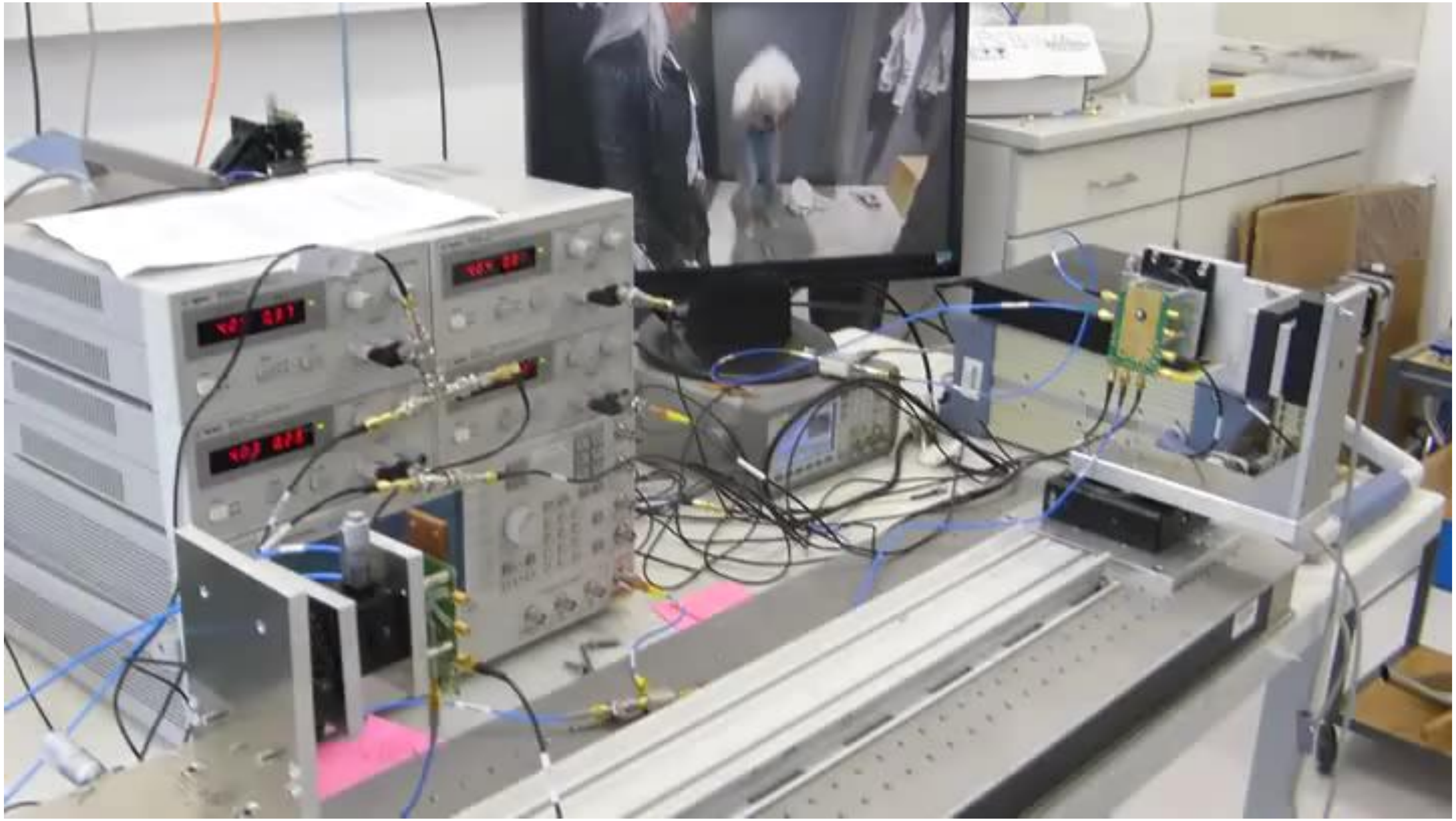
- **For LO = 220-260 GHz:**
  - **CG = 12 to 24 dB, SSB NF = 9 to 16 dB**
- **3dB RF/IF BW = 23/11.5 GHz**
- **IQ Amp. Imb. < 0.5 dB for IF up to 17 GHz**

Mixer First RX

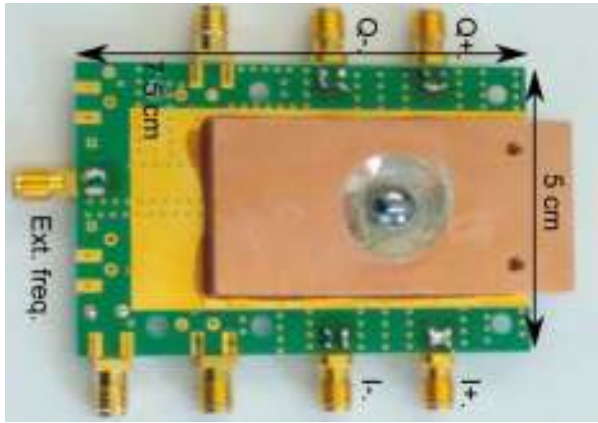


- **For LO = 220-260 GHz:**
  - **CG = 7.8 dB, SSB NF = 13.5 to 14 dB**
- **3dB RF/IF BW = 28/14 GHz**
- **IQ Amp. Imb. < 1 dB for IF up to 17 GHz**

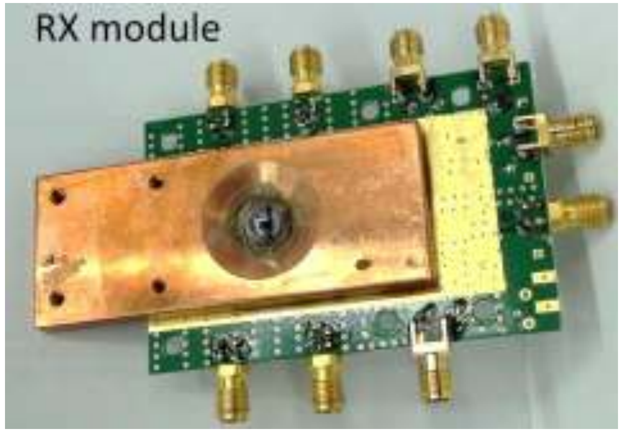
Simple Communication Demo



Testbed for 100 Gbps and Beyond?

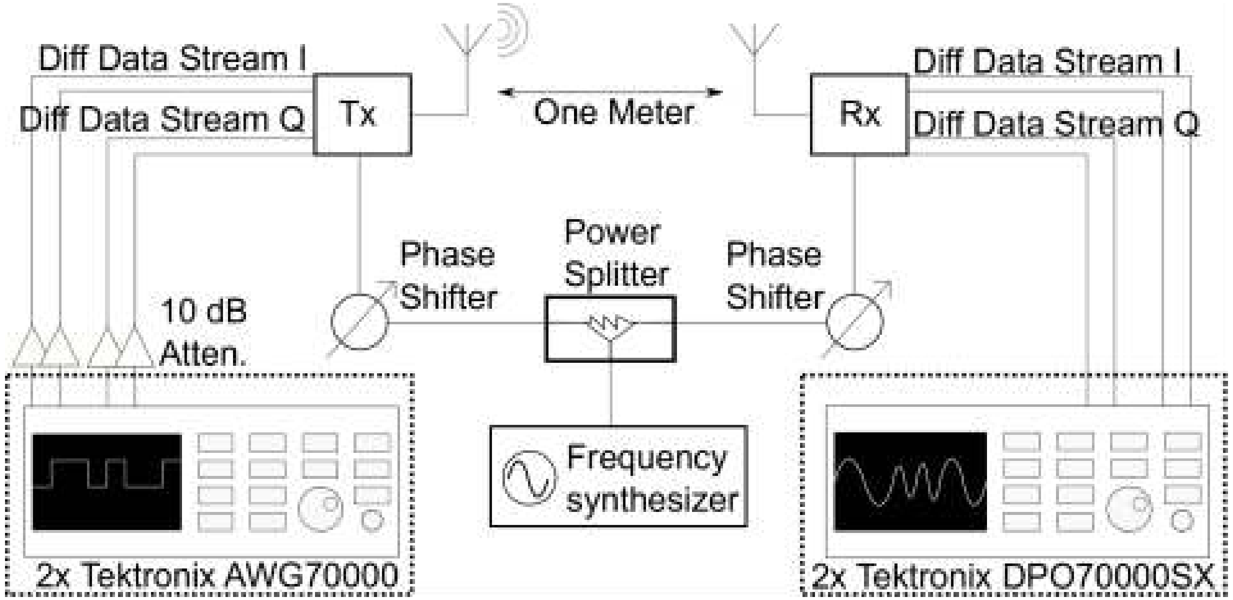


- 1 meter line-of-sight
- No free space optics or mirrors
- LO Phase-shifters for phase alignment
- 10 dB IF attenuators for linear TX



AWG:

- RRC filter (0.1-0.7)
- Pre-compensation
- 50 GS/s and 10-bit
- 20 GHz analog BW
- Eff. BW 16QAM:
  - 12.4 GHz, 90 Gbps, -8.2 dBm, 2.5% EVM



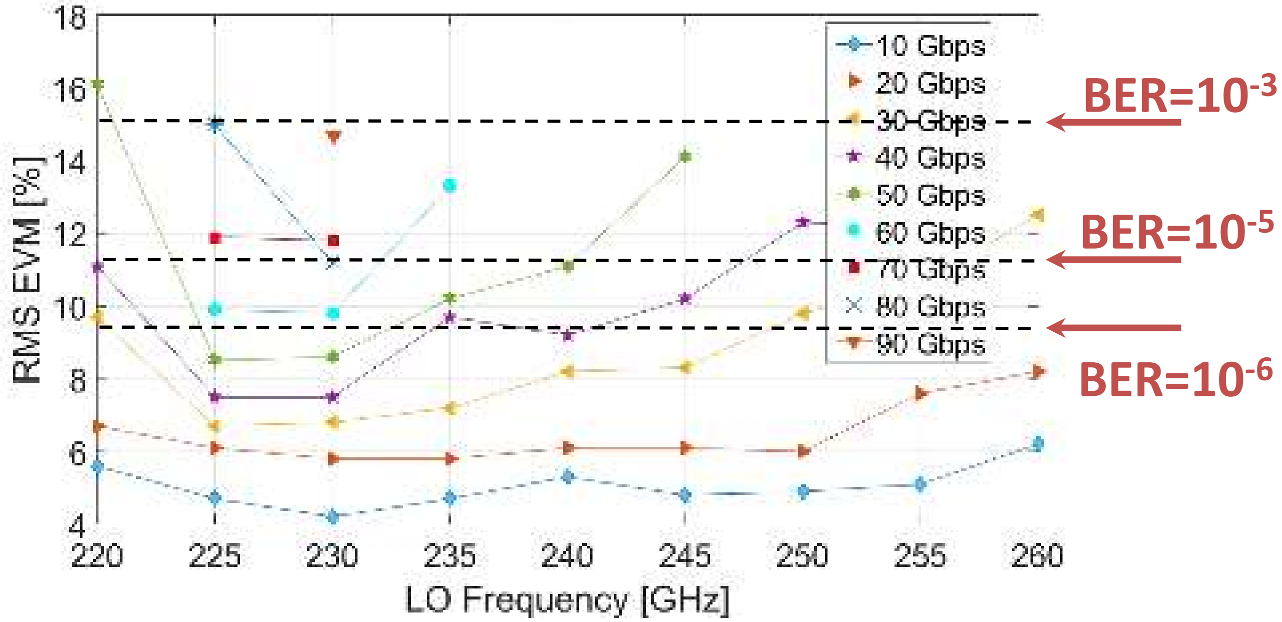
[1] P. R. Vazquez et.al. “Towards 100 Gbps: A Fully Electronic 90 Gbps One Meter Wireless Link at 230 GHz”, European Microwave Conference (EuMC) 2018, :1389-1392 November 2018

Scope:

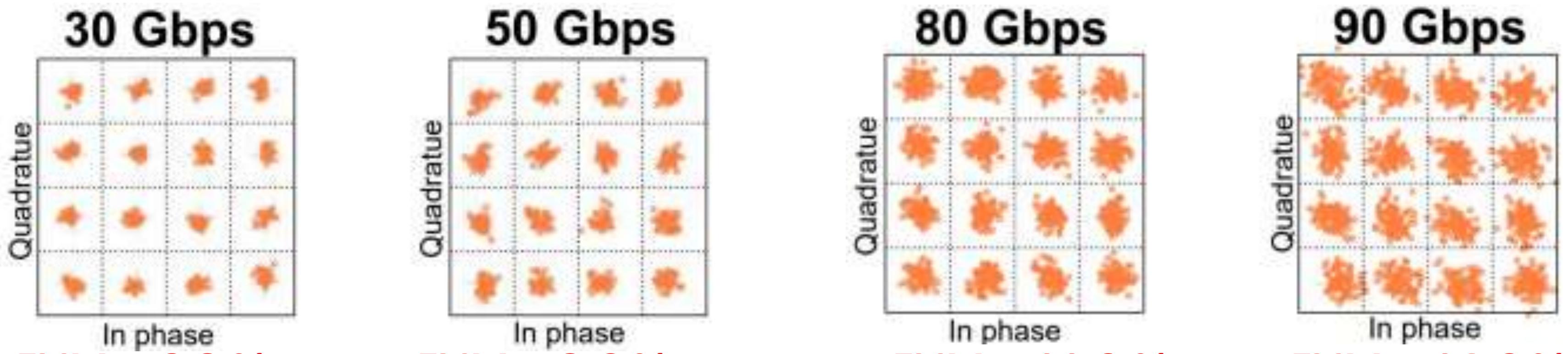
- 2*33 GHz, 100 GS/s
- Vector signal analysis software
- RRC matches AWG
- Feed-forward adaptive equalizer (17 taps)

Link Summary (Amplifier First)

Mod.	Date Rates/ EVM	Range/ max range	Reference
BPSK	35/27.5%	1m/5m	[RWW18]
QPSK	65/30.7%	1m/5m	[RWW18]
16QAM	90/14.7%	1m/1.8m	[EuMC18]
32QAM	90/11.9%	1m/1.6m	[APMC18]
64QAM	81/8.7%	1m/1m	[RWW19]



16QAM



EVM = 6.8 % EVM = 8.6 % EVM = 11.2 % EVM = 14.6 %

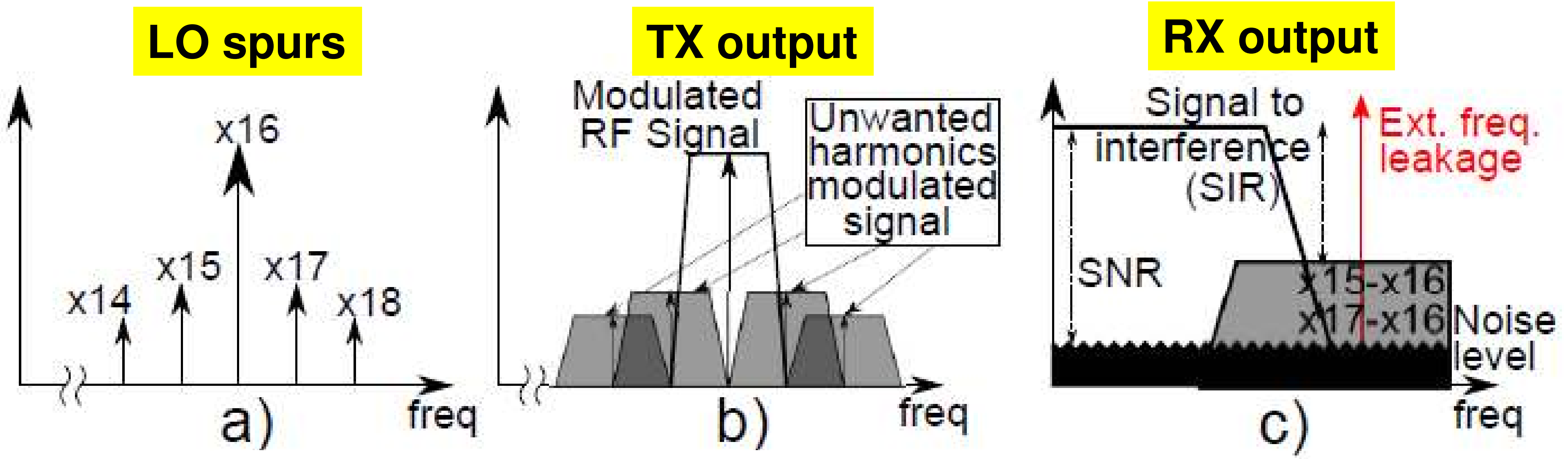
Limits: I/Q correlation, LO SFDR, -55 dB LO-BB feed-through, group delay distortion (package)

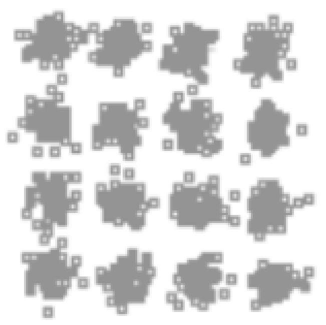
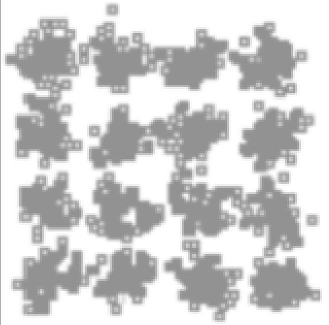
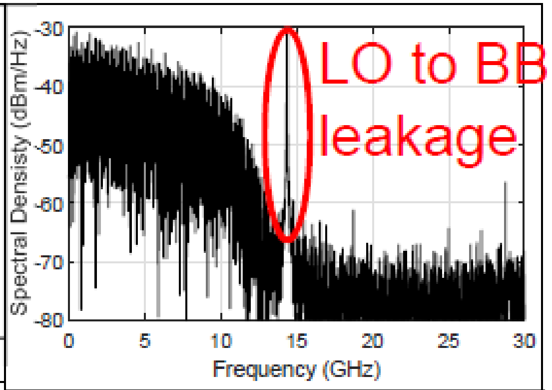
Chip-Set Summary (Tunable Carrier 220-260 GHz)

RF front-end performance	Amplifier First (230GHz carrier)				Mixer First (230GHz carrier)			
	Carrier/BW	Psat	CG	NFmin	Carrier/BW	Psat	CG	NFmin
	230GHz /24GHz	9dBm	23dB	11.5 dB	220-260 GHz /28 GHz	9dbm	7.8 dB	14 dB
Link performance	**Mod.**	**Date Rates/ EVM**	**Range/ max range**	**Reference**	**Mod.**	**Data Rates/ EVM**	**Range/ max range**	**Reference**
	BPSK	35/27.5%	1m/5m	[RWW18]	BPSK	35/27.9%	1m/4m	Not published
	QPSK	65/30.7%	1m/5m	[RWW18]	QPSK	60/26.2%	1m/4m	[IJMWT]
	16QAM	90/14.7%	1m/1.8m	[EuMC18]	16QAM	**100/17%**	1m/1.8m @ 80Gbps	[MWCL]
	32QAM	90/11.9%	1m/1.6m	[APMC18]	32QAM	90/13.7%	1m/1.6m	Not published
	64QAM	81/8.7%	1m/1m	[RWW19]				

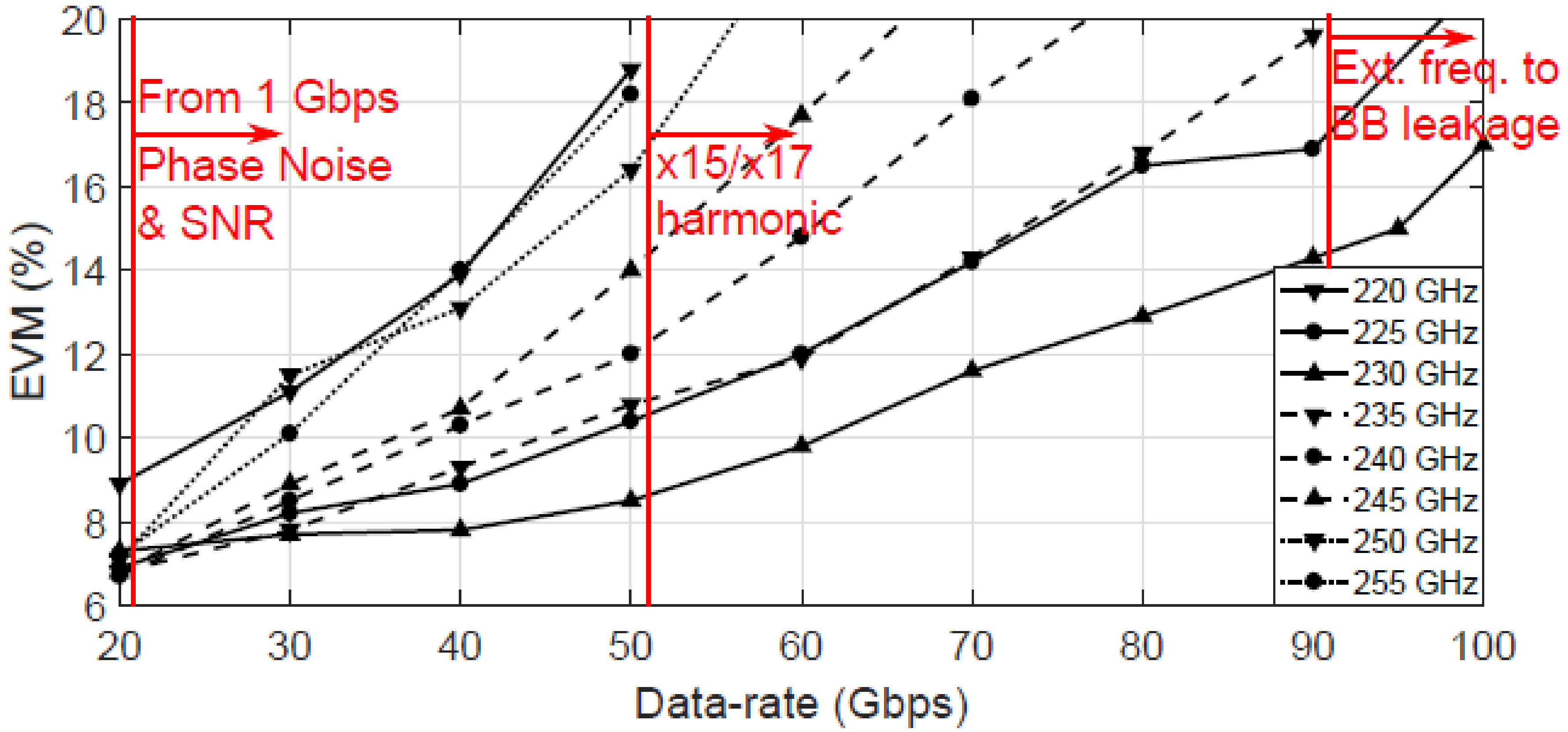
[MWCL] P. Rodríguez-Vázquez, et. al.,"A 16-QAM 100-Gb/s 1-M Wireless Link With an EVM of 17% at 230 GHz in an SiGe Technology,"

Link Impairments (Mixer First)



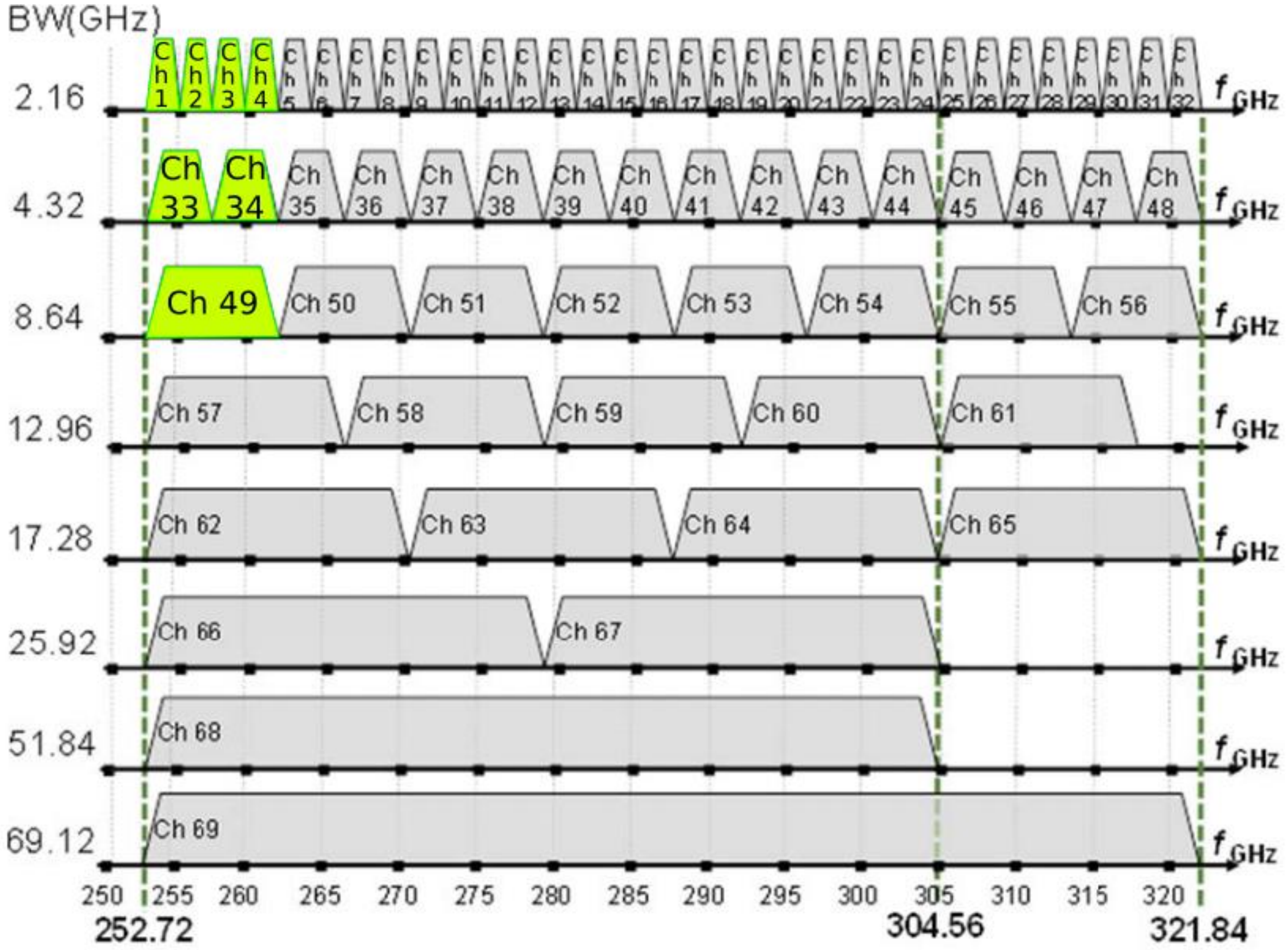
Tx to Rx Constellation 16-QAM			
Symbol Rate	23.75 Gbaud	25 Gbaud	RX Signal Spectrum (95 Gbps)
EVM	15% / -16.4 dB	17% / -15.4 dB	
Data Rate	95 Gbps	100 Gbps	

Link Impairments (Mixer First)



- **Q: What do we need to improve data-rates and range?**
  - Range: Tx power, Rx noise figure, antenna directivity
  - Data rates: SNR/PN limit spectral eff., RF BW flatness, PN floor of ref. Synth, freq. planning

IEEE 802.15.3d-2017 Channel Allocation



- 4 Channels with 2.16 GHz BW @ 253.8, 255.96, 258.12, and 260.28 GHz
- 2 Channels with 4.32 GHz BW @ 254.88 and 259.2 GHz
- 1 Channel with 8.64 GHz BW @ 257.04 GHz

- All this Channels are expected to reach data-rates under 50 Gb/s. We already reached this goal.

- Link distance remains a problem:
  1. Pout 10 mW not 1 W
  2. Antennas 25 dBi not 40 dBi

More directivity is required (50 dBi to compensate for the reduced Pout)

Link Budget Estimation

Freq.	Tx Pout	RF BW	Data -rate	NF	Mod.	SNR for BER = 10^{-3} +16 dB loss	Antenna Gain (Tx & RX)	Power required in Rx	Maximum Distance	Notes
230 GHz	5 dBm	30 GHz	100 Gbps	14 dB	16-QAM	32.5 dB	26 dBi	-29 dBm	1 meters	Measured
230 GHz	5 dBm	30 GHz	100 Gbps	14 dB	16-QAM	32.5 dB	**50 dBi**	-29 dBm	**100 m**	With a second 6.5 cm lens

100m range expected for 50dBi lens gain

SoA for all-electronic wireless links < 200 GHz

Reference	Technology	Frequency	Channel BW	Modulation	Data-rate	P_{DC}	Distance	On- chip antenna	Fully-packaged?
[Kang15], [Thyagarajan15]	65 nm CMOS	240 GHz	-	QPSK	16[1] Gbps	480 mW	2 cm	2 Ring	No (on wafer)
[Fritsche17]	130 nm SiGe	190 GHz	20 GHz	BPSK	50 Gbps	154 mW[2]	0.6 cm	Monopole	No (on wafer)
[Lee19]	40 nm CMOS	300 GHz	20 GHz	16-QAM	80 Gbps	1.79 W	3 cm	No	No (on wafer)
[Kallfass15]	35 nm InP	300 GHz	22 GHz	QPSK	64 Gbps	-	2 meters	No	Wave-guide
[Boes13]	35 nm InP	240 GHz	-	8-PSK	64 Gbps	-	40 meters	No	Wave-guide + Horn
[Hamada18]	80 nm InP	270 GHz	-	16-QAM	100 Gbps	-	2.2 meters	No	Wave-guide + Horn + Lens
[Eisa18]	130 nm SiGe	240 GHz	<15 GHz	BPSK	25 Gbps	950 mW	15 cm	Doulble folded dipole	PCB + plastic lens
[EUMC18]	130 nm SiGe	220-260 GHz	13 GHz	16/32-QAM	90 Gbps	1.96 W	1 meter	Ring	PCB + silicon lens
[MWCL19]	130 nm SiGe	220-255 GHz	13 GHz	16-QAM	**100 Gbps**	1.41 W	1 meter	Ring	PCB + silicon lens

[1] Tx without baseband interface: PRBS generator on chip.
[2] No LO generation path implemented on chip.

Conclusion and summary

- **Vast number of potential applications for Silicon at mmWave/THz**
  - THz Video Cameras, 3D radar
  - Near-field imaging and sensing in biomedical applications
- **A 100 Gbps wireless communication is possible in SiGe today!**
  - 240GHz Chipset and with a inexpensive COB packaging incl. Si lense
  - Up to **100m** range with 50dBi antenna gain possible
- **Future challenges**
  - Improve on RF link impairments
  - Solve the digital base-band gap

Close the 6G and technology gap!

Thanks

- PhD students and research staff at IHCT: Stefan Malz, Konstantin Statnikov, Neelanjan Sarmah, Pedro Rodriguez Vazquez, Thomas Bücher, Utpal Kalita, Ritesh Jain, Philipp Hillger, Wolfgang Förster, Hans Keller, and Janusz Grzyb
- Partially funded by the European Commission within the project DOTFIVE and DOTSEVEN (no. 316755)
- DFG Priority Program SPP 1655 (Real100G), 1857 (ESSENCE), SPP 1798 (CoSIP)
- DFG Collaborative Research Center (MARIE), PF 661/4-1(2)
- DFG Reinhart Koselleck Projekt, PF 661/11-1
- DFG PF 661/6-1, LO 455/22-1, and 661/10-1

References

[Kang15] S. Kang, S. V. Thyagarajan and A. M. Niknejad, "A 240 GHz Fully Integrated Wideband QPSK Transmitter in 65 nm CMOS," in *IEEE Journal of Solid-State Circuits*, vol. 50, no. 10, pp. 2256-2267, Oct. 2015.

[Thyagarajan15] S. V. Thyagarajan, S. Kang and A. M. Niknejad, "A 240 GHz Fully Integrated Wideband QPSK Receiver in 65 nm CMOS," in IEEE Journal of Solid-State Circuits, vol. 50, no. 10, pp. 2268-2280, Oct. 2015.

[Fritsche17] D. Fritsche, P. Stärke, C. Carta and F. Ellinger, "A Low-Power SiGe BiCMOS 190-GHz Transceiver Chipset With Demonstrated Data Rates up to 50 Gbit/s Using On-Chip Antennas," in IEEE Transactions on Microwave Theory and Techniques, vol. 65, no. 9, pp. 3312-3323, Sept. 2017.

[Lee19] S. Lee et al., "9.5 An 80Gb/s 300GHz-Band Single-Chip CMOS Transceiver," 2019 IEEE International Solid- State Circuits Conference - (ISSCC), San Francisco, CA, USA, 2019, pp. 170-172.

[Kallfass15] I. Kallfass et al., "Towards MMIC-Based 300GHz Indoor Wireless Communication Systems", The Institute of Electronics, Information and Communication Engineers Transactions on Electronics, vol.E98-C, no.12, pp.1081-1090, Dec. 2015.

[Boes13] F. Boes et al., "Ultra-broadband MMIC-based wireless link at 240 GHz enabled by 64GS/s DAC," 2014 39th International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz), Tucson, AZ, 2014, pp. 1-2.

[Hamada18] H. Hamada et al., "300-GHz. 100-Gb/s InP-HEMT Wireless Transceiver Using a 300-GHz Fundamental Mixer," 2018 IEEE/MTT-S International Microwave Symposium - IMS, Philadelphia, PA, 2018, pp. 1480-1483.

[Eisa18] M. H. Eissa et al., "Wideband 240-GHz Transmitter and Receiver in BiCMOS Technology With 25-Gbit/s Data Rate," in IEEE Journal of Solid-State Circuits, vol. 53, no. 9, pp. 2532-2542, Sept. 2018.

[RWW18] P. Rodríguez-Vázquez, J. Grzyb, N. Sarmah, B. Heinemann and U. R. Pfeiffer, "A 65 Gbps QPSK one meter wireless link operating at a 225–255 GHz tunable carrier in a SiGe HBT technology," 2018 IEEE Radio and Wireless Symposium (RWS), Anaheim, CA, 2018, pp. 146-149.

[EUMC18] P. Rodríguez- Vázquez, J. Grzyb, N. Sarmah, B. Heinemann and U. R. Pfeiffer, "Towards 100 Gbps: A Fully Electronic 90 Gbps One Meter Wireless Link at 230 GHz," 2018 48th European Microwave Conference (EuMC), Madrid, 2018, pp. 1389-1392.

[APMC18] P. Rodríguez-Vázquez, J. Grzyb, B. Heinemann and U. R. Pfeiffer, "Performance Evaluation of a 32-QAM 1-Meter Wireless Link Operating at 220–260 GHz with a Data-Rate of 90 Gbps," 2018 Asia-Pacific Microwave Conference (APMC), Kyoto, 2018, pp. 723-725.

[RWW19] P. Rodríguez-Vázquez, J. Grzyb, B. Heinemann and U. R. Pfeiffer, "Optimization and Performance Limits of a 64-QAM Wireless Communication Link at 220-260 GHz in a SiGe HBT Technology, " 2019 IEEE Radio and Wireless Symposium (RWS), Orlando, FL, 2019.

[MWCL19] P. Rodríguez-Vázquez, J. Grzyb, B. Heinemann and U. R. Pfeiffer, "A 16-QAM 100-Gb/s 1-M Wireless Link With an EVM of 17% at 230 GHz in an SiGe Technology," in IEEE Microwave and Wireless Components Letters.