A 64-QAM 60GHz CMOS Transceiver with 4-Channel Bonding

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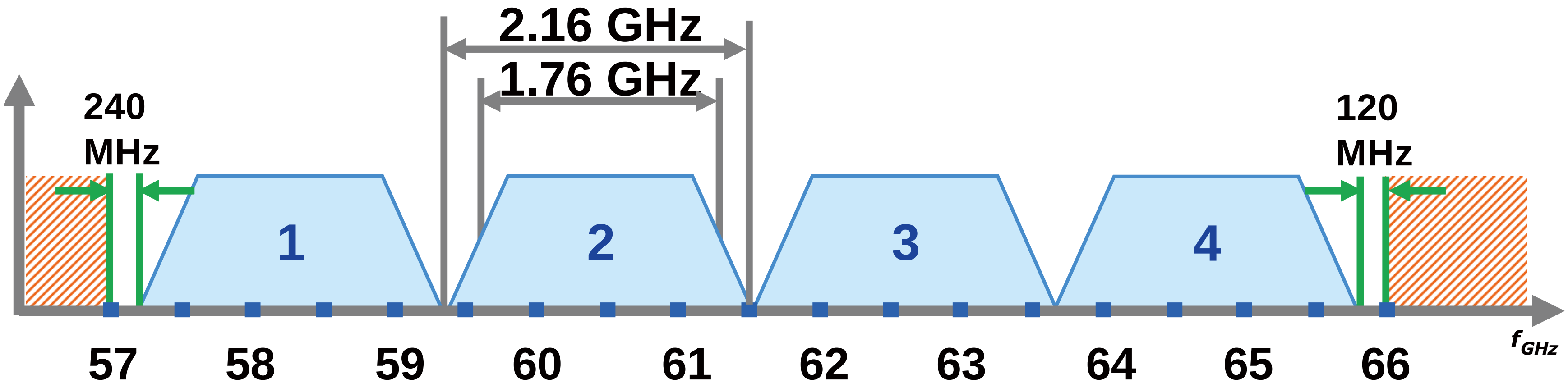
Outline

- Motivation
- Transmitter
  - Mixer-first transmitter
- Receiver
  - Open-loop FVF-based amp.
- Measurement and Comparison
- Conclusion

60GHz-Band Capability

- QPSK ➔ 3.52Gbps/ch
- 16QAM ➔ 7.04Gbps/ch
- 64QAM ➔ 10.56Gbps/ch (not reported yet)

- 16QAM
  - 2-ch bonding ➔ 14.08Gbps
  - 3-ch bonding ➔ 21.12Gbps (not reported yet)
  - 4-ch bonding ➔ 28.16Gbps (not reported yet)



from IEEE802.11ad/WiGig

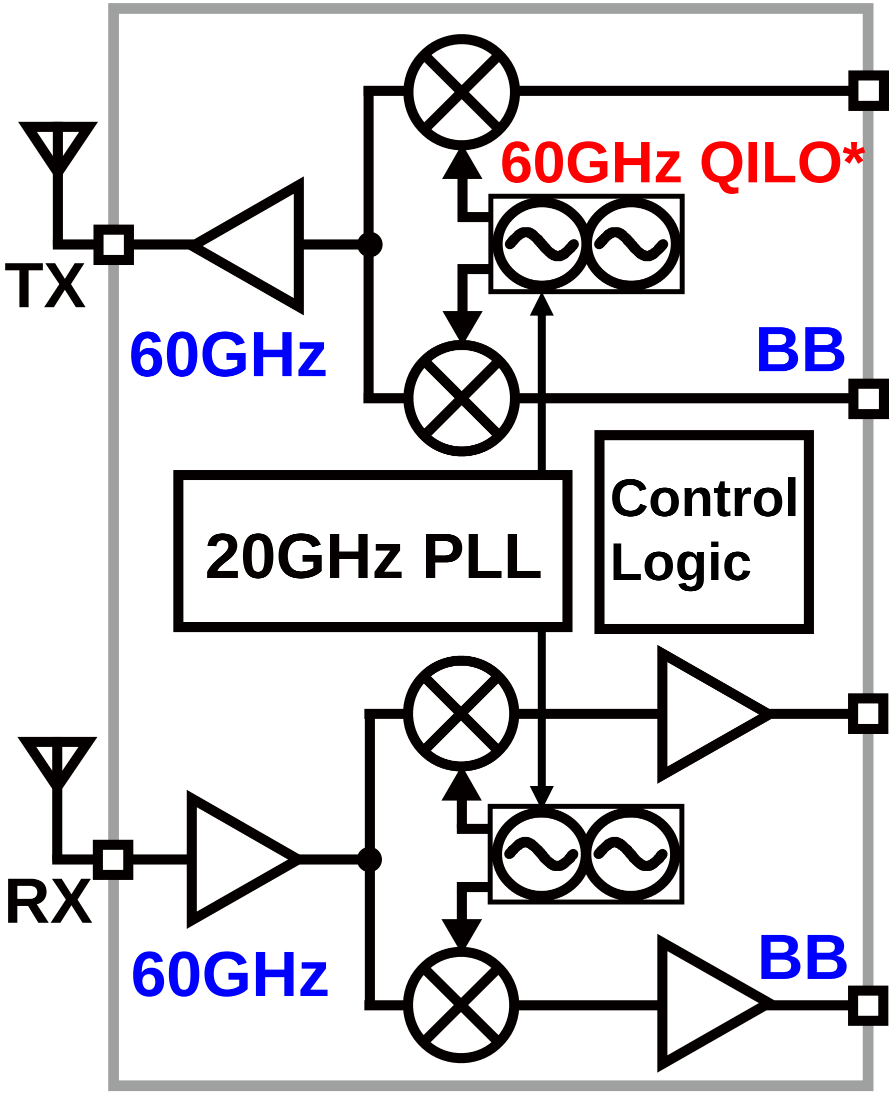
Design Considerations

- Wideband gain characteristics
  - RF: 57-66GHz
  - BB: 1.2GHz(1ch), 5GHz(4-ch bonding)
- Wide dynamic range
  - Linearity & Sensitivity
  - RX SNDR >40dB
- Low phase noise (performance limiter)*
  - -96dBc/Hz@1MHz (64QAM)
- I/Q mismatch & LO leakage**
  - Image rejection ratio <-40dBc

*K. Okada, *et al*., JSSC 2013

**S. Kawai, *et al*., RFIC 2013

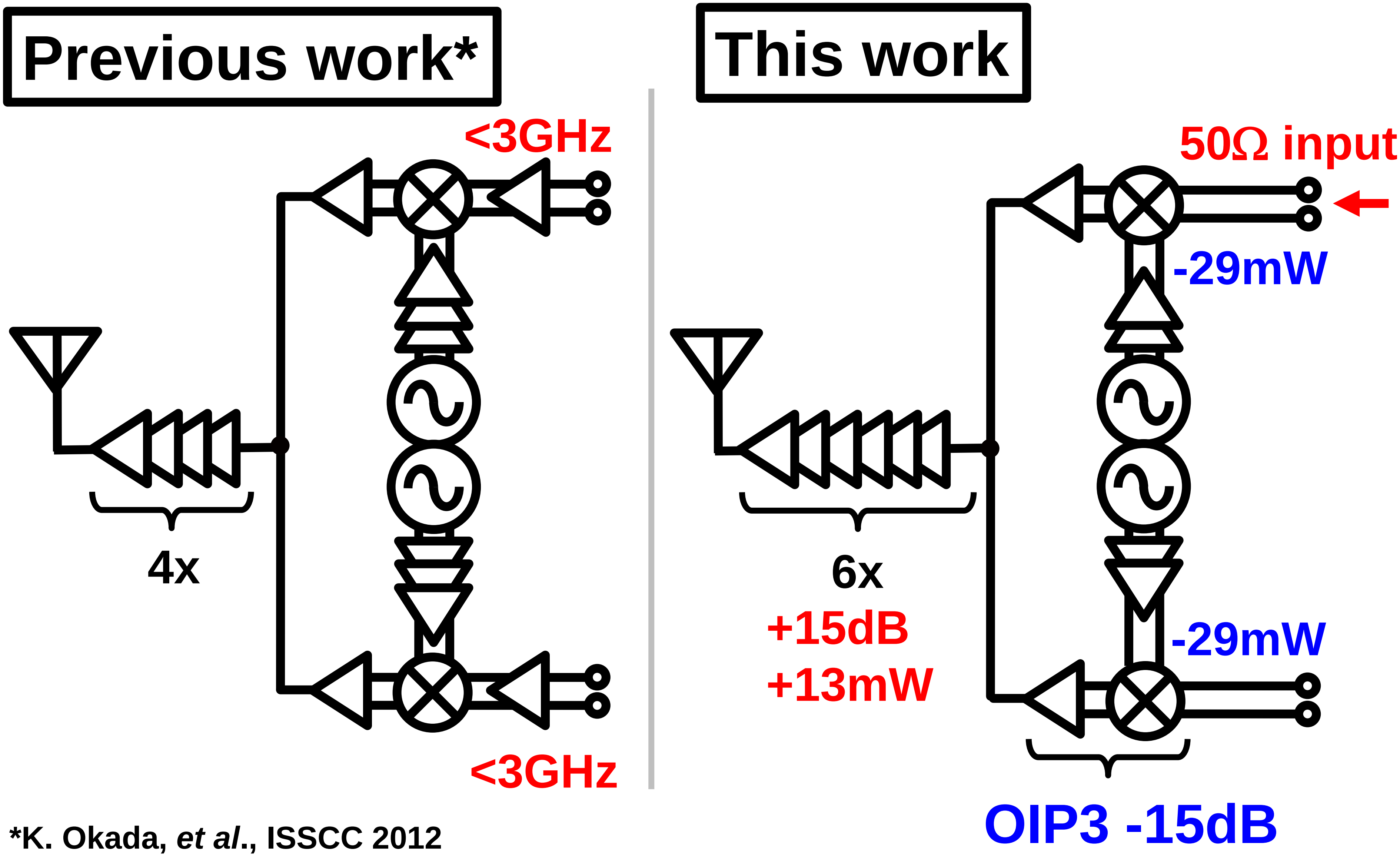
Block Diagram



- Direct-conversion
- TX
  - Mixer-first topology
- RX
  - FVF BB amp.
  - Current-bleeding mixer
- LO
  - Injection-lock
  - 60GHz QILO* +20GHz PLL

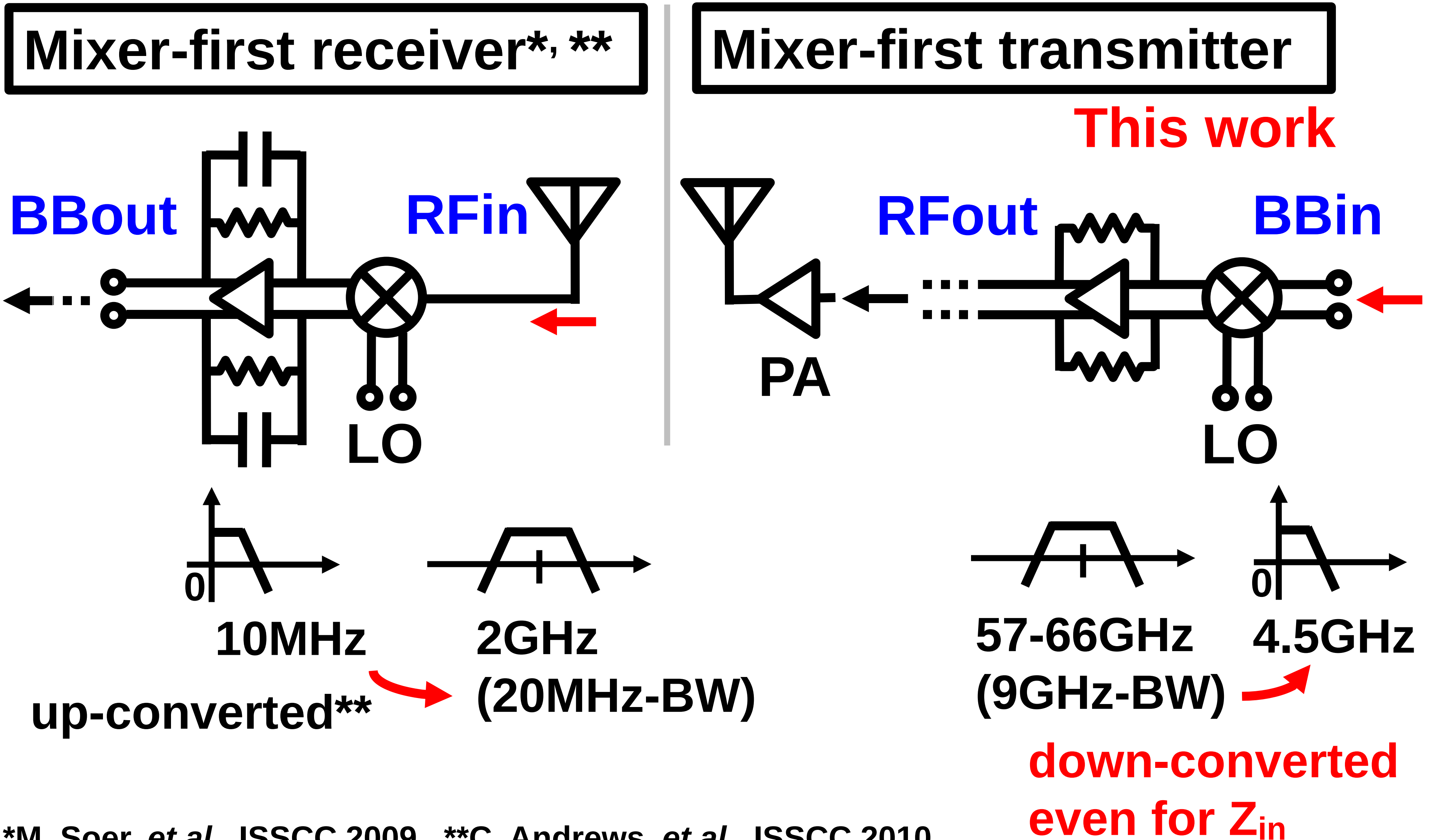
*K. Okada, *et al*., ISSCC 2011

TX Design Considerations



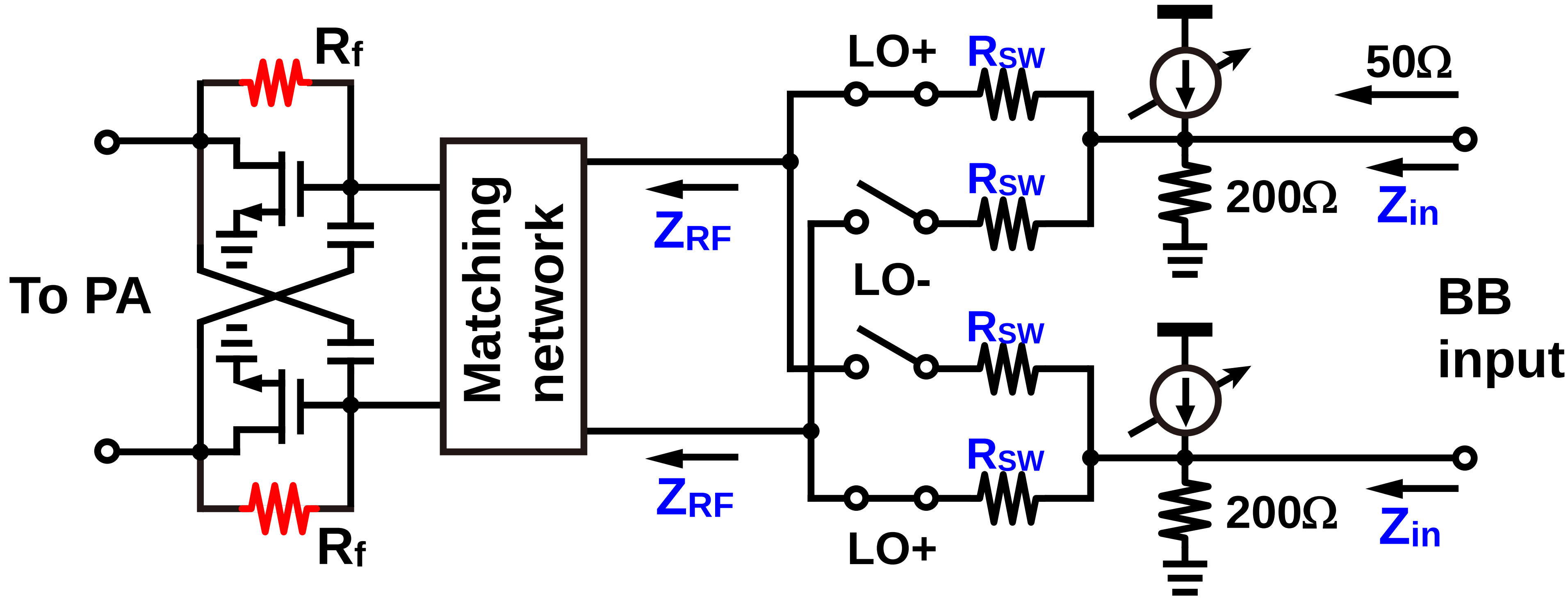
*K. Okada, *et al*., ISSCC 2012

Mixer-First Transmitter



*M. Soer, *et al*., ISSCC 2009 **C. Andrews, *et al*., ISSCC 2010

Input Impedance and Leakage Cancel



$$Z_{\text{in}}(\omega_{\text{BB}}) = 200\Omega /\!/ \left[R_{\text{sw}} + \frac{4}{\pi^2} \{ Z_{\text{RF}}(\omega_{\text{BB}} + \omega_{\text{LO}}) + Z_{\text{RF}}(\omega_{\text{BB}} - \omega_{\text{LO}}) \} \right]$$

Wideband Z_{RF} is realized by R_f-feedback.

*C. Andrews, *et al*., ISSCC 2010

TX Measurement Result

Lower-side-band gain including RF path

LO=61.56GHz

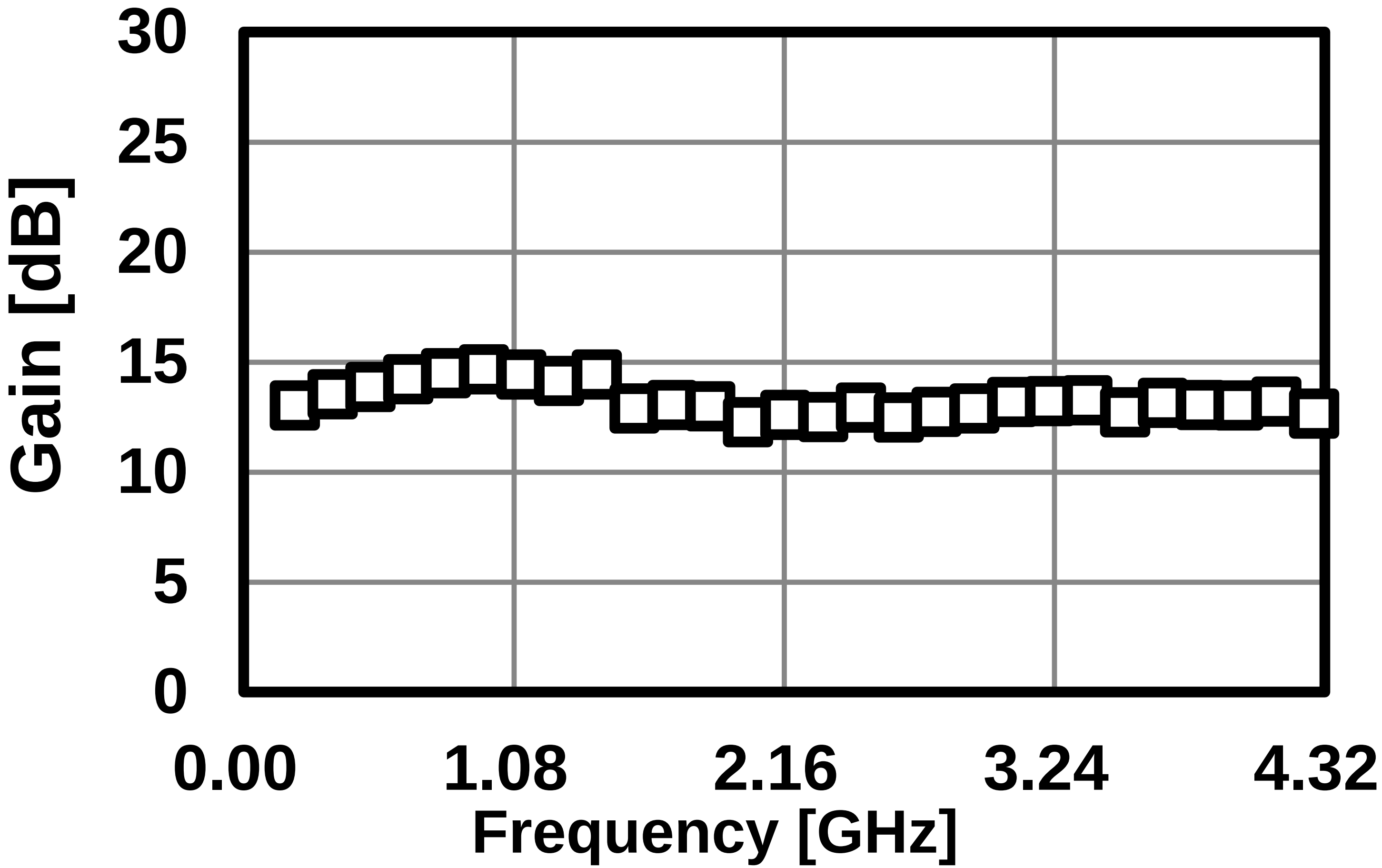
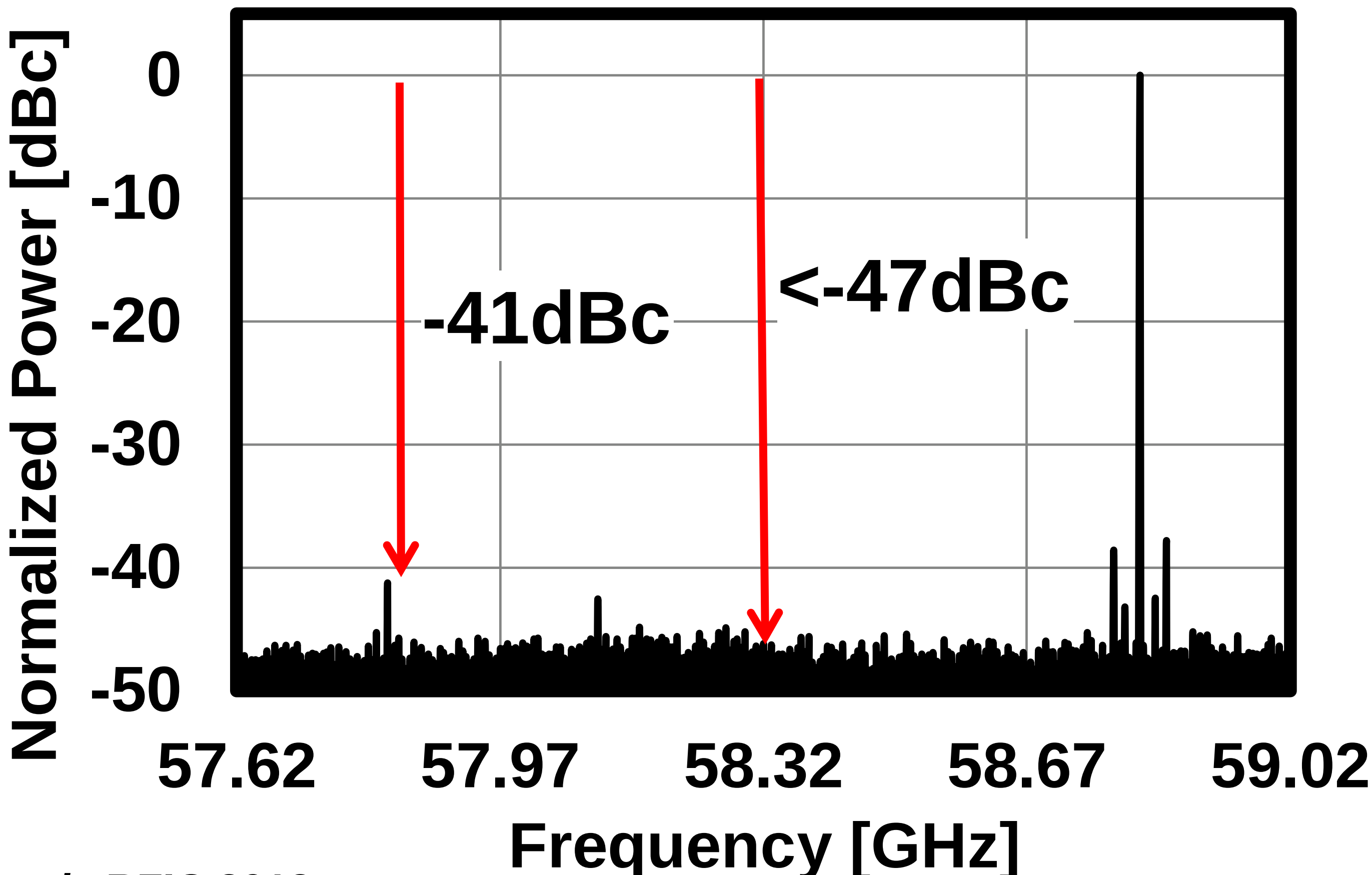


Image Rejection & LO Leakage

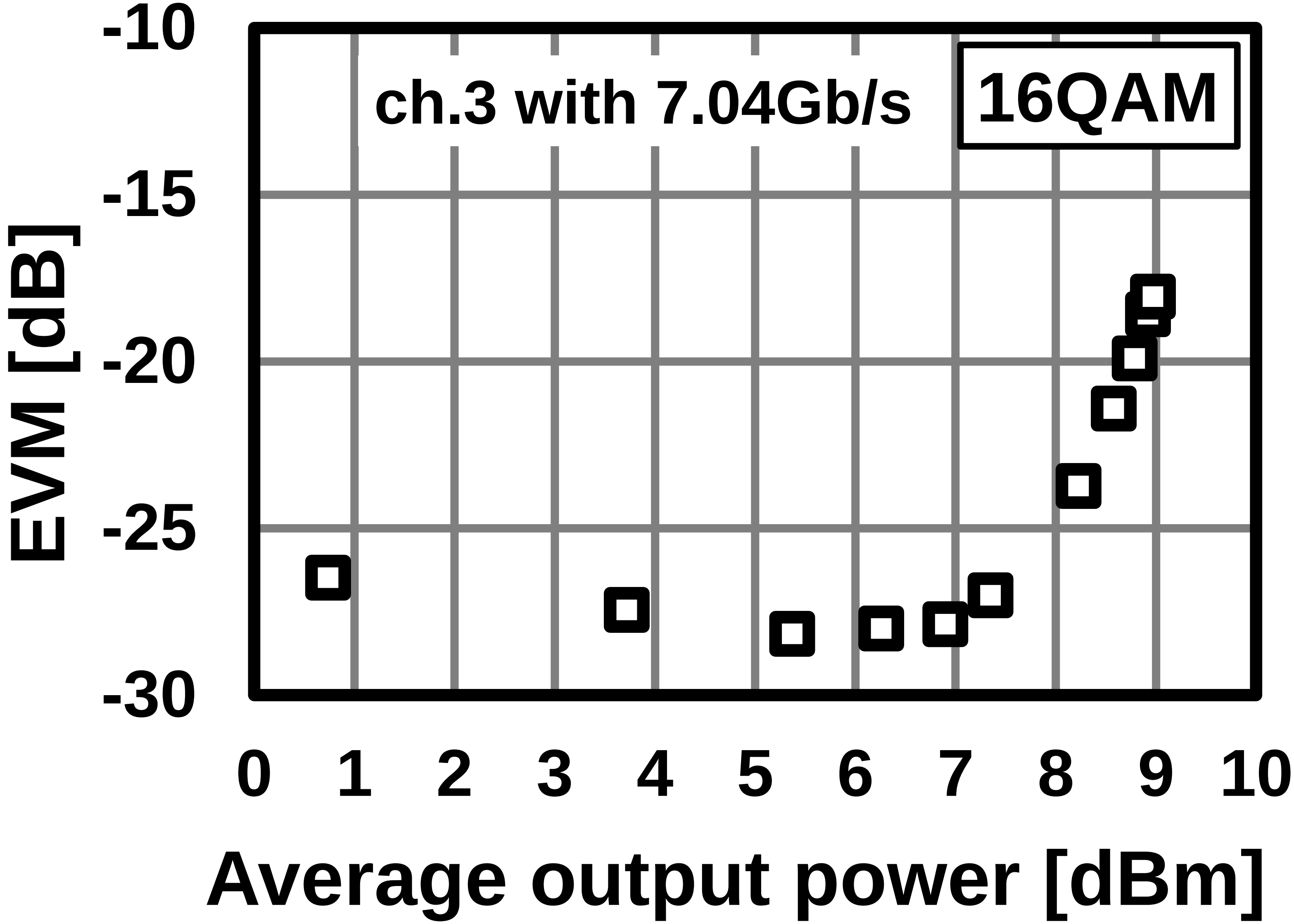
I/Q mismatch calibration* is applied.

RF VGA & QILO phase adjustment

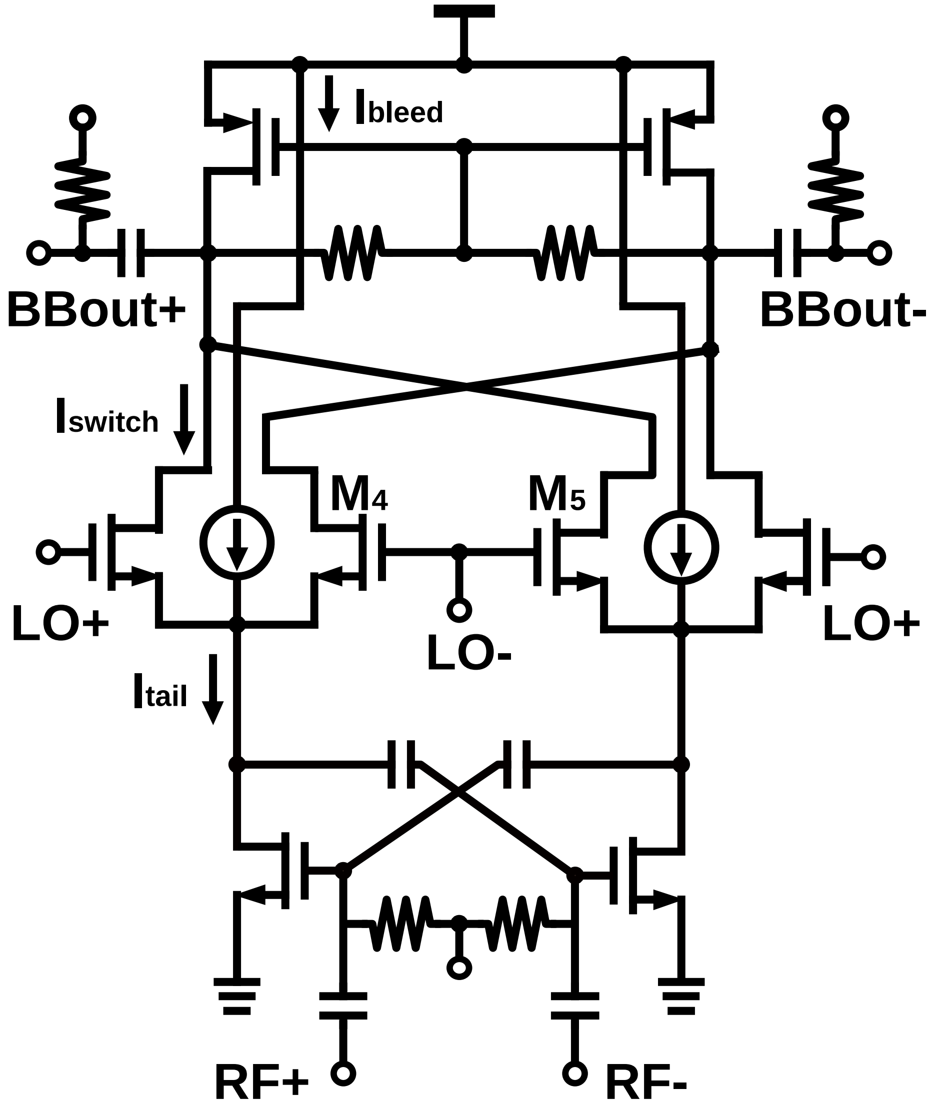


*S. Kawai, *et al*., RFIC 2013

TX EVM Measurement



RX Mixer



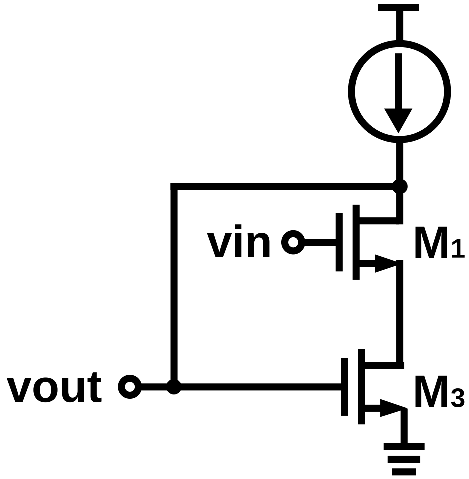
- Current-bleeding to reduce LO power
- CCC at RF input

- Pdc: 11mW
- CG: -7dB
- f_{low}: 0.27MHz
- f_{high}: >4GHz

RX Baseband Amplifier

- **Wide bandwidth (>5GHz)**
- **High gain and high linearity**
- **Low power consumption**

  ⇨ **Open-loop FVF-based amplifier**

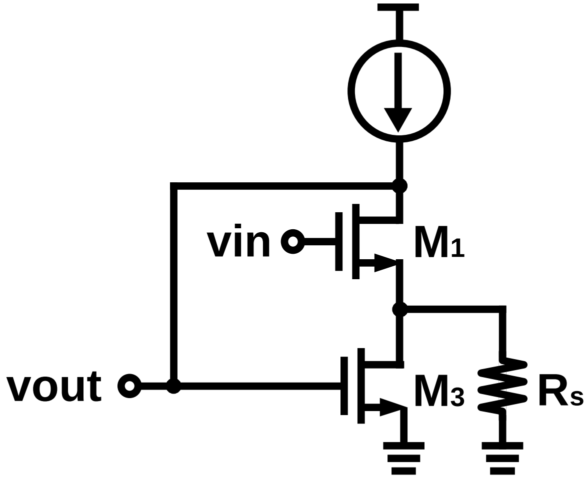


$$A_V \cong -\frac{g_{ds3}}{g_{m3}}$$

Flipped Voltage Follower* (FVF)

*R. Carvajal, *et al.*, TCAS-I 2005

RX Baseband Amplifier (*Cont.*)

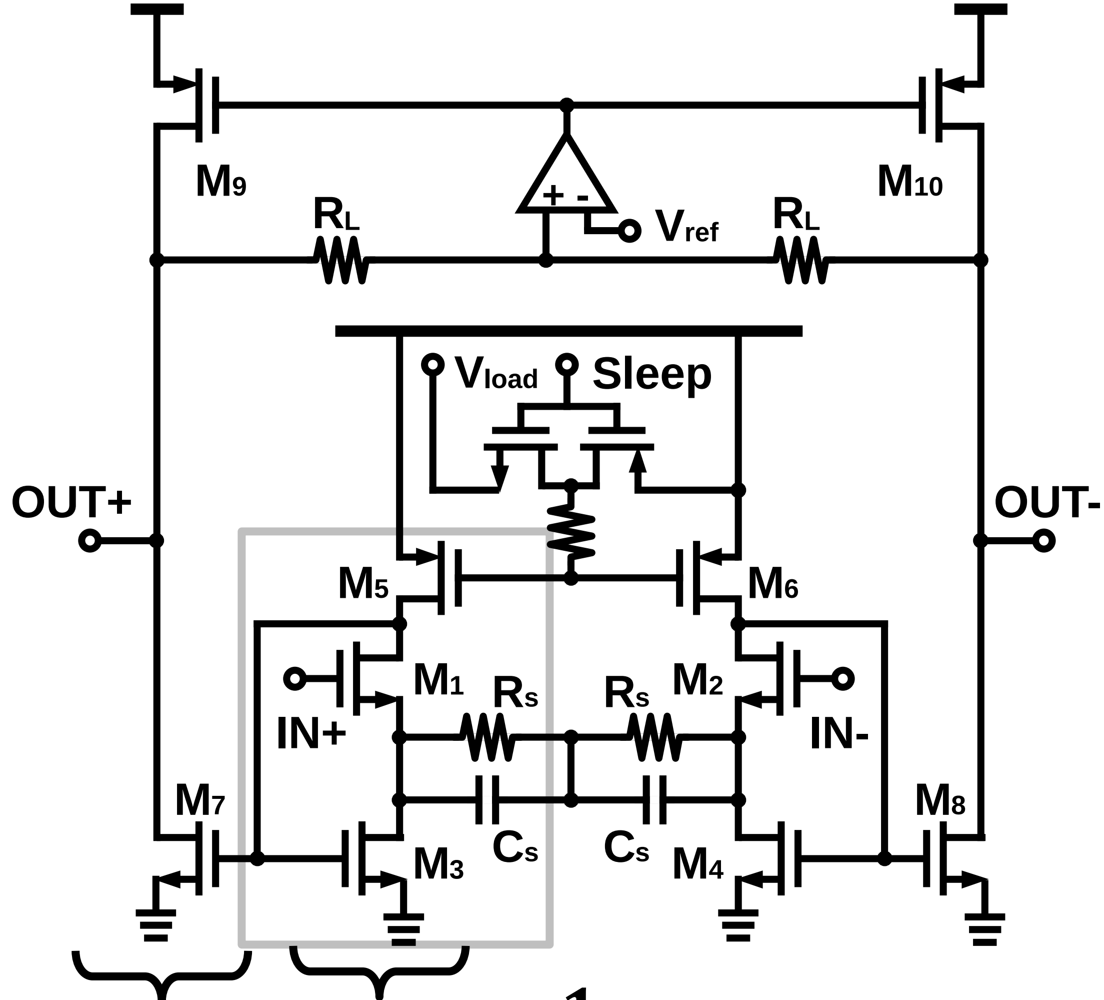


$$A_V \cong -\frac{1}{g_{m3} R_S}$$

modified FVF

$$A_V \cong \frac{g_{m7}}{g_{m3}} \frac{R_L}{R_S}$$

by 6mW

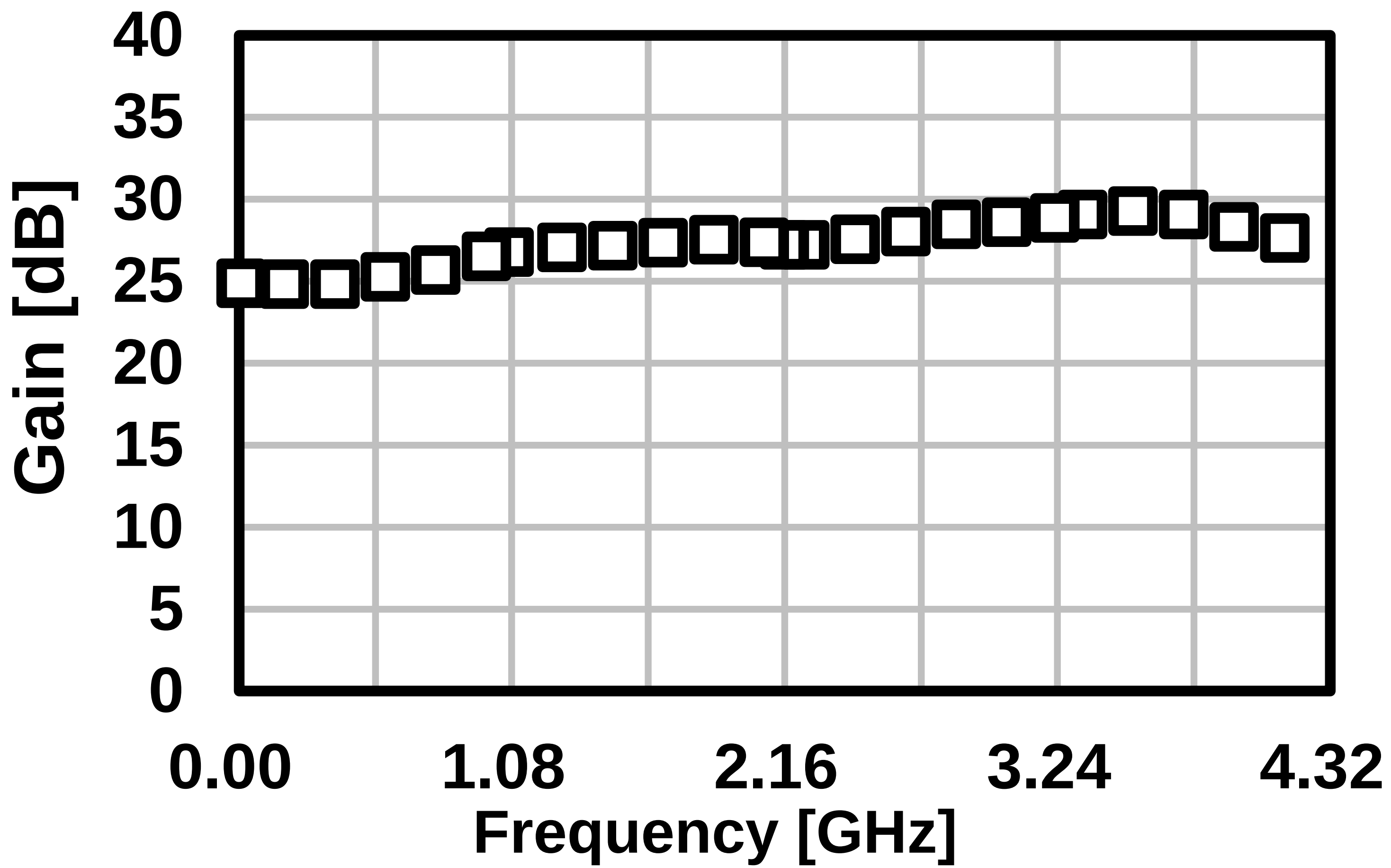


$$-g_{m7} R_L \qquad -\frac{1}{g_{m3} R_S // (1/j\omega C_S)}$$

RX Measurement Result

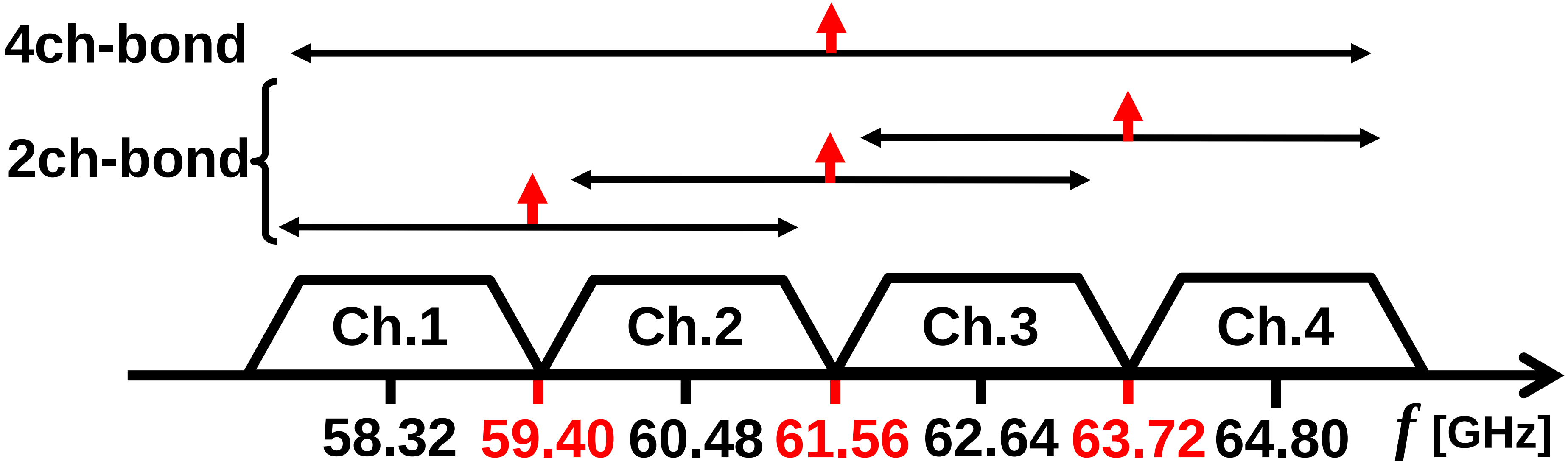
Lower-side-band gain including RF path

LO=61.56GHz



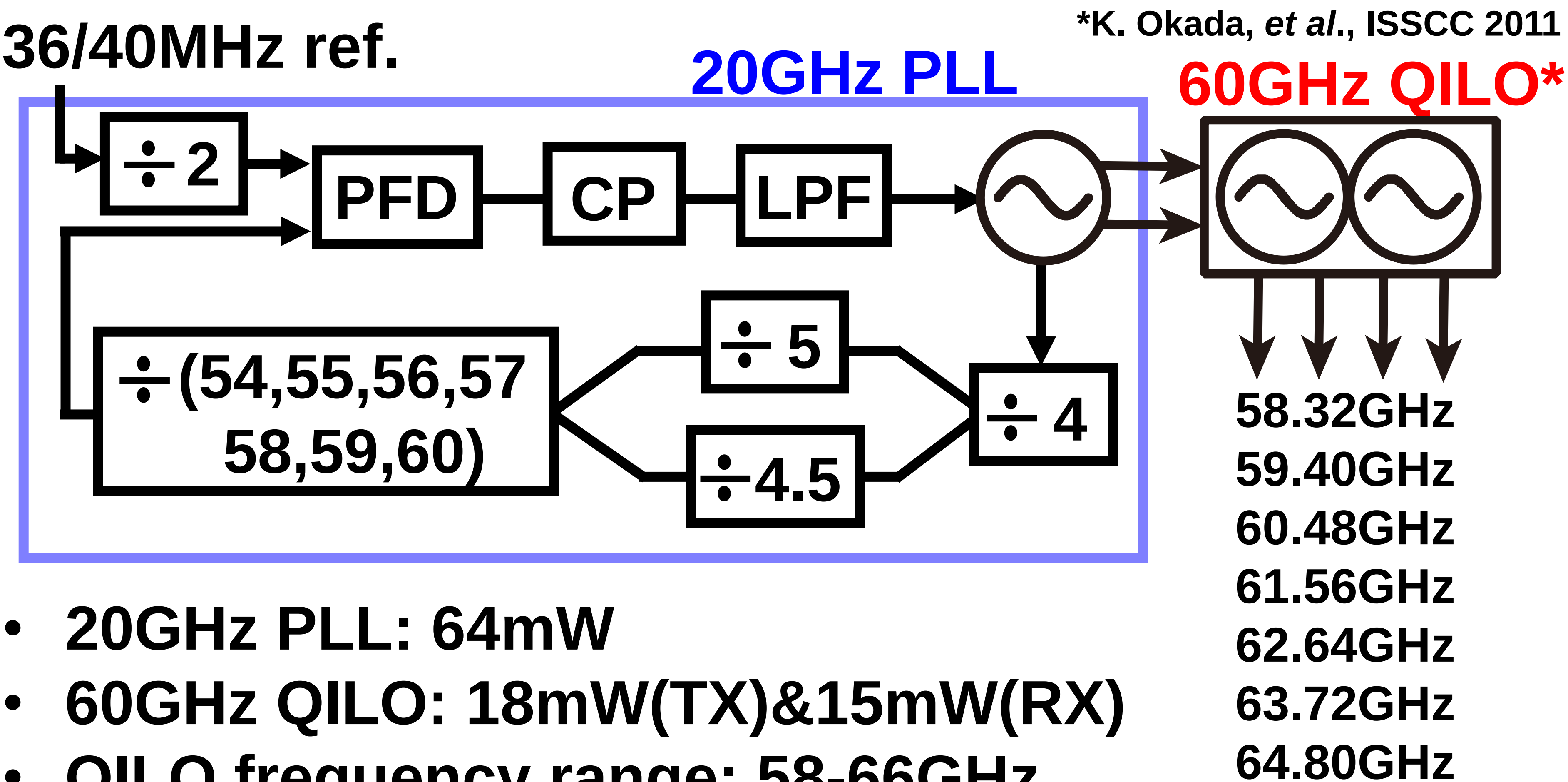
60GHz LO Considerations

- -96dBc/Hz@1MHz for 64QAM
  - ➔ 60GHz Quadrature Injection Locked Oscillator*
- Channel bonding
  - ➔ 7 carrier frequencies



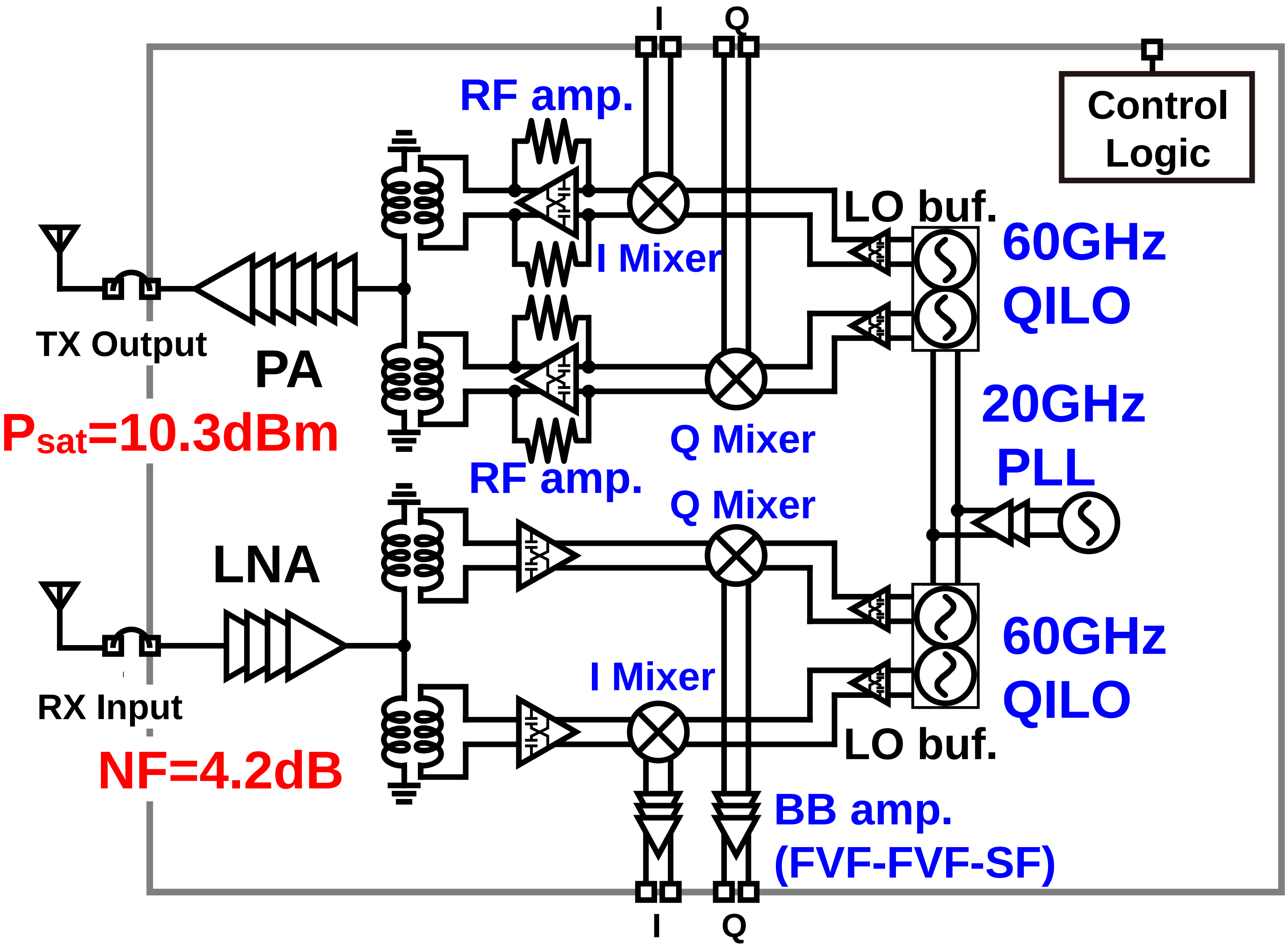
*K. Okada, *et al*., JSSC 2013

60GHz Quadrature LO Design



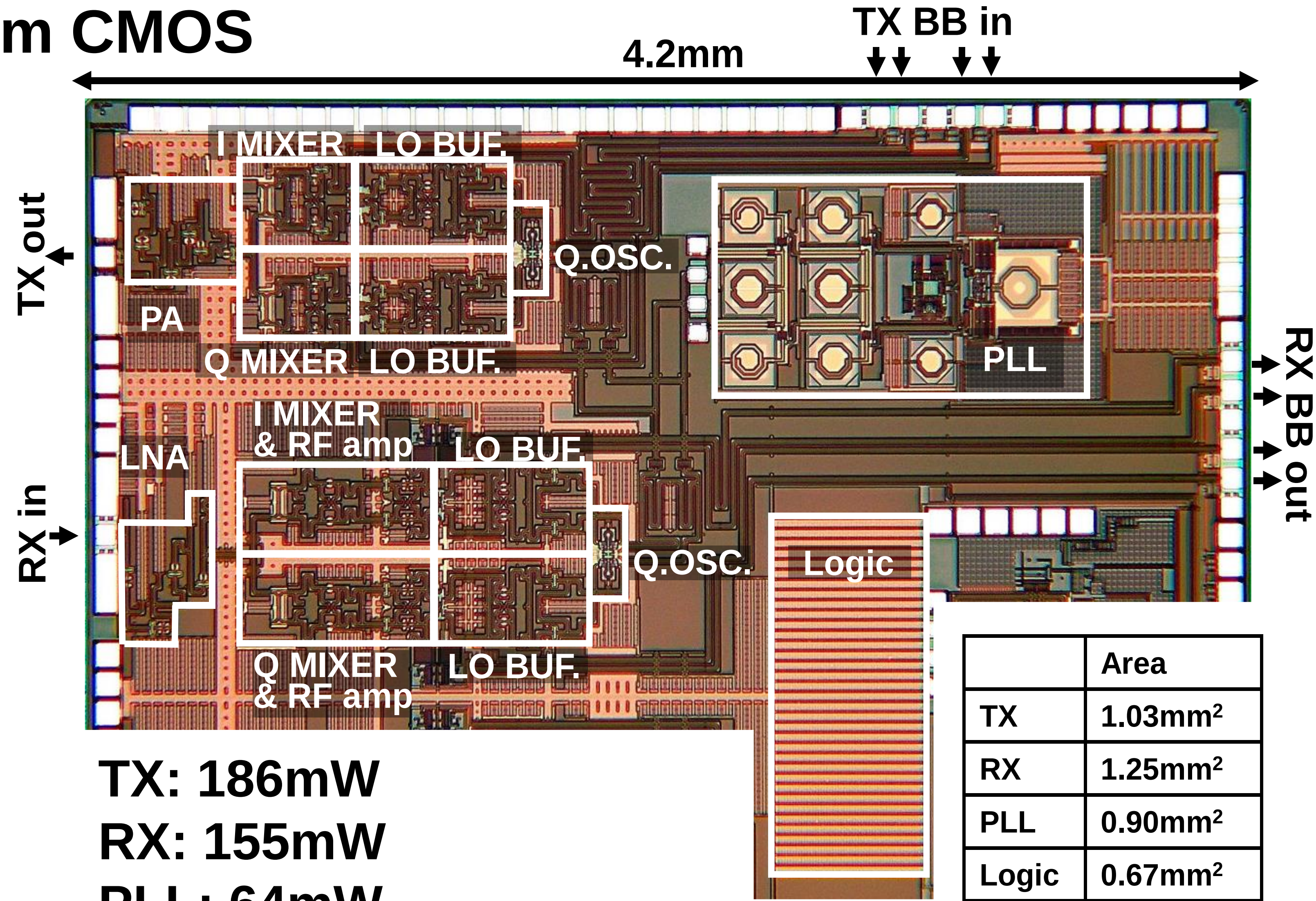
- 20GHz PLL: 64mW
- 60GHz QILO: 18mW(TX)&15mW(RX)
- QILO frequency range: 58-66GHz
- Phase noise improvement by injection locking*
- -96.5dBc/Hz @ 1MHz at 61.56GHz

Detailed Block Diagram



Die Photo

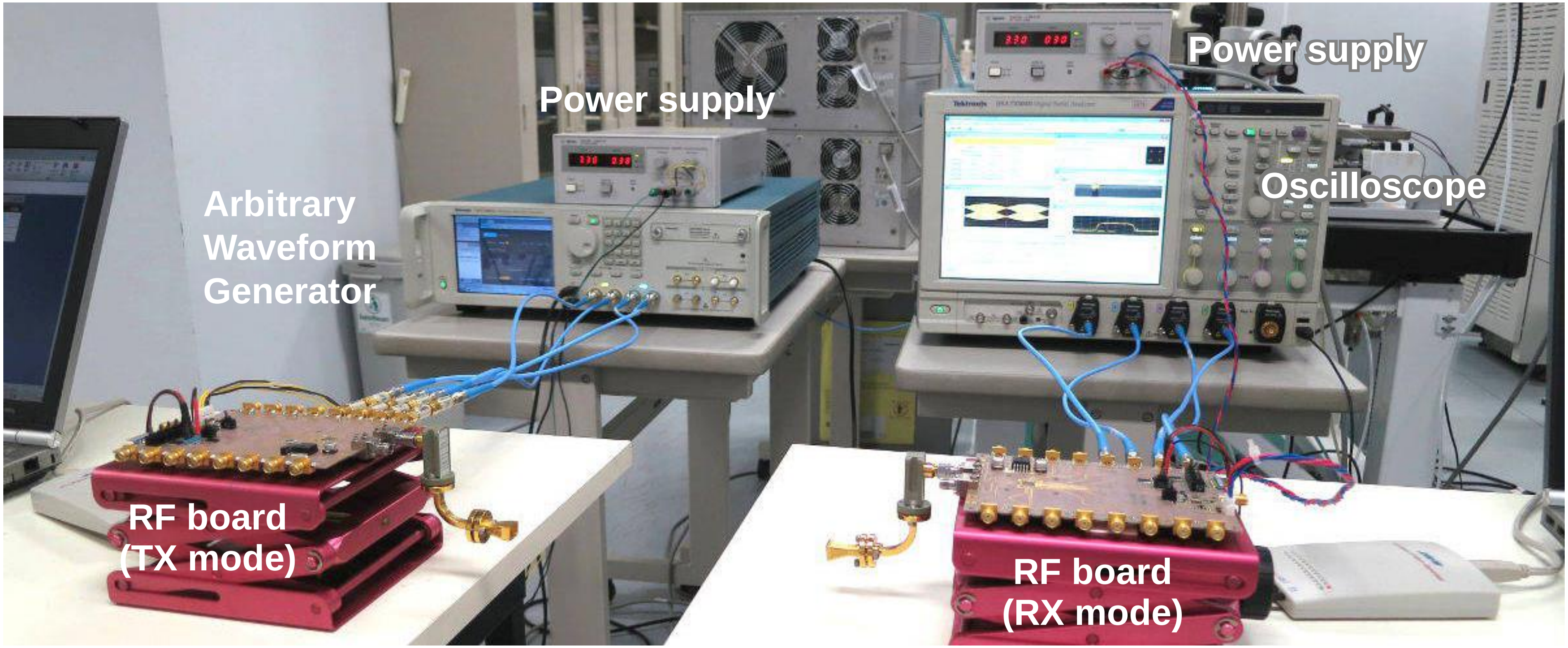
65nm CMOS



	Area
TX	1.03mm^2
RX	1.25mm^2
PLL	0.90mm^2
Logic	0.67mm^2

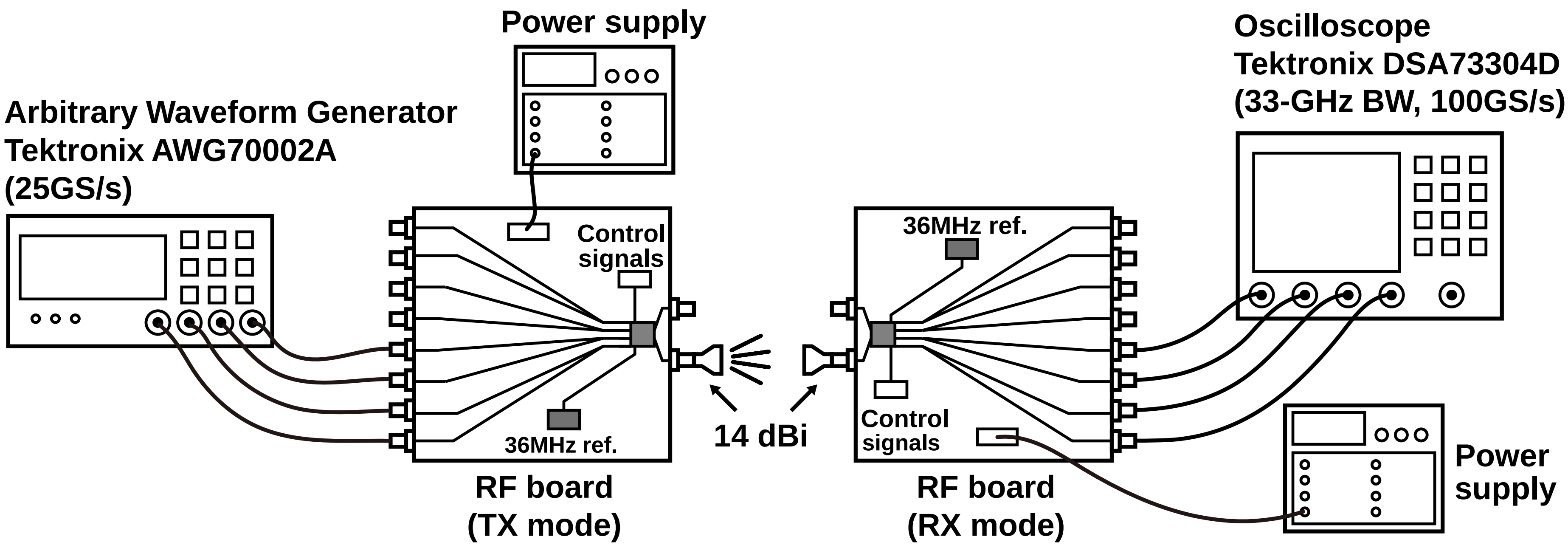
TX: 186mW
RX: 155mW
PLL: 64mW

Measurement Setup



- 25-GS/s AWG
- 100-GS/s oscilloscope (33GHz BW)
- 14-dBi horn antennas

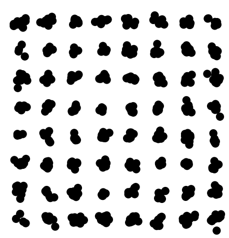
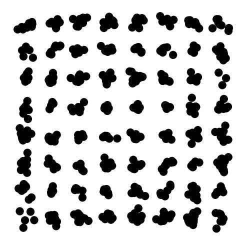
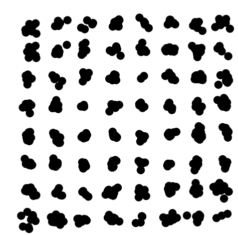
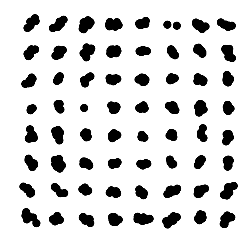
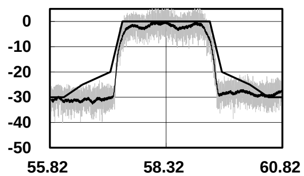
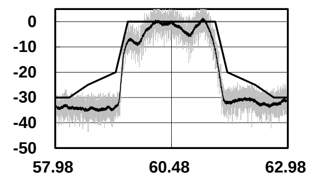
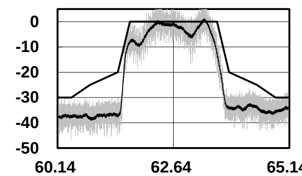
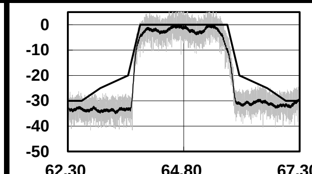
Setup for TX-to-RX Measurement



- Symbol rate: 1.76GS/s (1ch), 7.04GS/s (4ch bonding)
- Roll-off factor: 25% for WiGig spectrum mask
- A maximum distance is defined within a SNR of 9.8dB(QPSK), 16.5dB(16QAM), and 22.5dB(64QAM) for a theoretical BER of 10^{-3}.

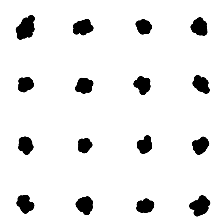
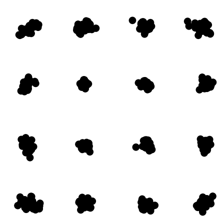
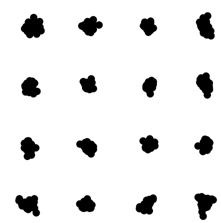
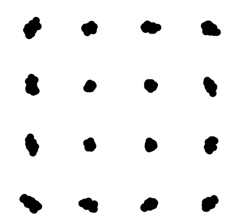
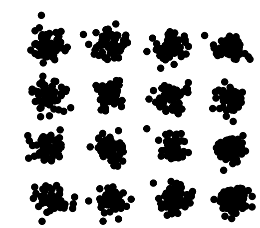
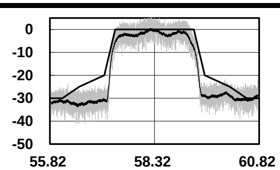
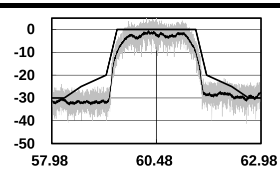
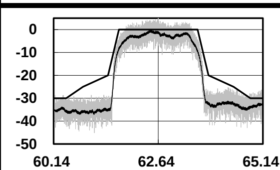
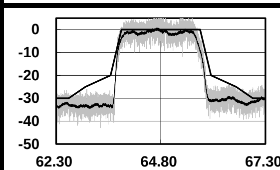
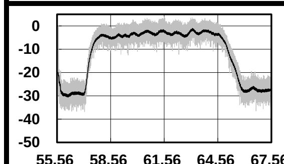
10.56Gb/s 64QAM

64QAM with 10.56Gb/s is achieved for the full 4 channels.

Channel/ Carrier freq.	ch.1 58.32GHz	ch.2 60.48GHz	ch.3 62.64GHz	ch.4 64.80GHz
Modulation	64QAM			
Data rate	10.56Gb/s	10.56Gb/s	10.56Gb/s	10.56Gb/s
Constellation				
Spectrum				
TX EVM	-27.1dB	-27.5dB	-28.0dB	-28.8dB
TX-to-RX EVM	-24.6dB	-23.9dB	-24.4dB	-26.3dB
Distance	0.08m	0.08m	0.13m	0.06m

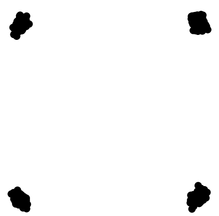
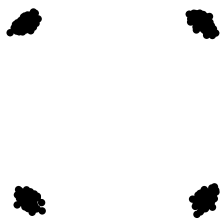
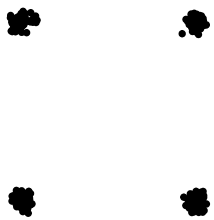
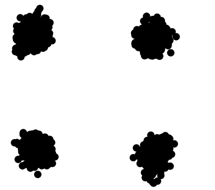
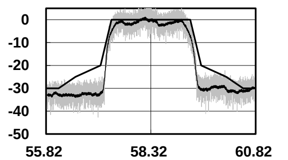
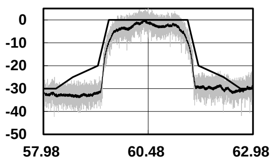
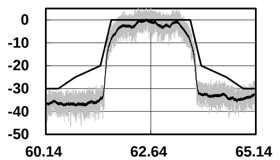
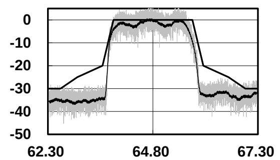
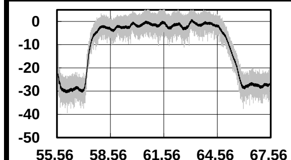
7.04Gb/s 16QAM (max 28.16Gb/s)

28.16Gb/s is achieved by using 4-bonded channel.

Channel/ Carrier freq.	ch.1 58.32GHz	ch.2 60.48GHz	ch.3 62.64GHz	ch.4 64.80GHz	ch.1-ch.4 Channel bond
Modulation	16QAM				
Data rate	7.04Gb/s	7.04Gb/s	7.04Gb/s	7.04Gb/s	28.16Gb/s
Constellation					
Spectrum					
TX EVM	-27.8dB	-27.6dB	-28.4dB	-28.8dB	-20.0dB
TX-to-RX EVM	-24.6dB	-24.1dB	-24.6dB	-27.0dB	-17.2dB
Distance	0.7m	0.6m	0.8m	0.4m	0.07m

3.52Gb/s QPSK (max 14.08Gb/s)

14.08Gb/s is achieved by using 4-bonded channel.

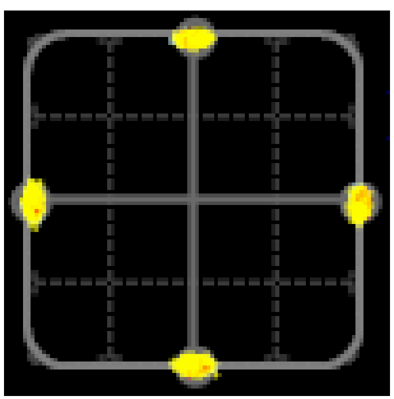
Channel/ Carrier freq.	ch.1 58.32GHz	ch.2 60.48GHz	ch.3 62.64GHz	ch.4 64.80GHz	ch.1-ch.4 Channel bond
Modulation	QPSK				
Data rate	3.52Gb/s	3.52Gb/s	3.52Gb/s	3.52Gb/s	14.08Gb/s
Constellation					
Spectrum					
TX EVM	-28.1dB	-27.7dB	-29.0dB	-29.7dB	-20.1dB
TX-to-RX EVM	-25.3dB	-24.5 dB	-24.5dB	-26.6dB	-17.9dB
Distance	2.4m	2.0m	2.6m	0.9m	0.3m

Performance Comparison of 60GHz TRX

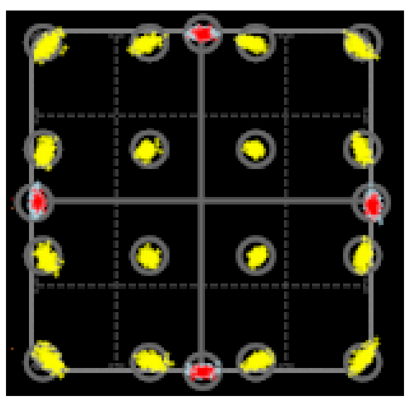
	Data rate / Modulation	TX-to-RX EVM	Power consumption
SiBeam [3]	7.14Gb/s(16QAM)	-19dB	TX: 1,820mW RX: 1,250mW
Tokyo Tech [4, 5]	16Gb/s(16QAM) 20Gb/s(16QAM)[5]	-21dB	TX: 319mW RX: 223mW
IMEC [6]	7Gb/s(16QAM)	-18dB	TX: 167mW RX: 112mW
Panasonic [9]	2.5Gb/s(QPSK)	-22dB	TX: 347mW RX: 274mW
This work	10.56Gb/s(64QAM) 28.16Gb/s(16QAM)	-26dB	TX: 251mW RX: 220mW

Measurement for IEEE802.11ad/WiGig

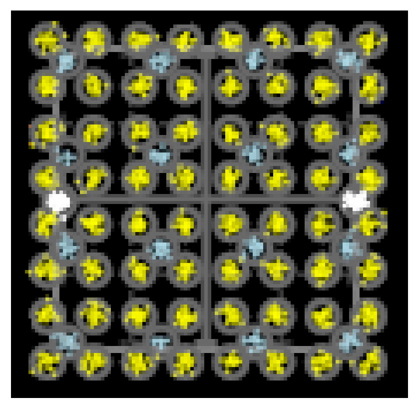
MCS	Modulation		Data rate [Mb/s]	TX EVM [dB]	
				Spec.	Meas.
9	QPSK	SC	2502.5	-15	-27.1
12	16QAM	SC	4620	-21	-27.0
24	64QAM	OFDM	6756.75	-26	-26.5



MCS9



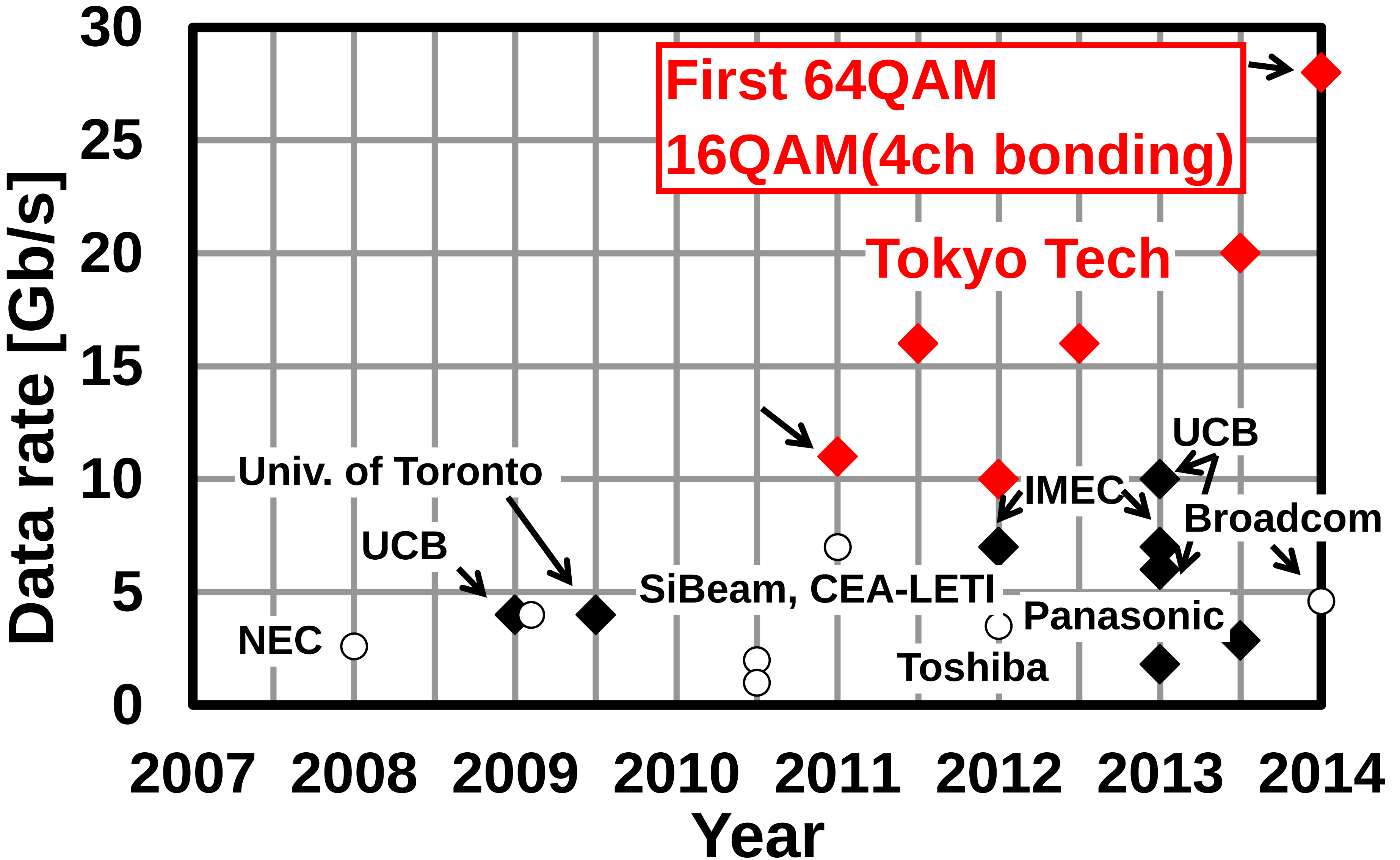
MCS12



MCS24

Measured by Agilent AWG + Osc. + VSA + 81199A in ch.3

60GHz CMOS Transceiver



Conclusion

- A 60GHz direct-conversion transceiver in 65nm CMOS
- The first 64QAM transceiver (10.56Gbps/ch)
  - IEEE802.11ad/WiGig conformance: MCS1-MCS24(64QAM/OFDM)
- The first transceiver capable of 4-channel bonding (28.16Gbps by 16QAM) realized by
  - Mixer-first transmitter
  - Open-loop FVF-based baseband amplifier
  - Quadrature injection-locked oscillator

Acknowledgement

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References

[1] K. Okada, *et al*., “A 60GHz 16QAM/8PSK/QPSK/BPSK Direct-Conversion Transceiver for IEEE 802.15.3c,” *IEEE ISSCC*, pp. 160-161, Feb. 2011.

[2] A. Siligaris, *et a*l., “A 65nm CMOS Fully Integrated Transceiver Module for 60GHz Wireless HD Applications,” *IEEE ISSCC*, pp.162-163, Feb. 2011.

[3] S. Emami, *et al*., “A 60GHz CMOS Phased-Array Transceiver Pair for Multi-Gb/s Wireless Communications,” *IEEE ISSCC*, pp.164-165, Feb. 2011.

[4] K. Okada, *et al*., “A Full 4-Channel 6.3Gb/s 60GHz Direct-Conversion Transceiver with Low-Power Analog and Digital Baseband Circuitry,” *IEEE ISSCC*, pp. 218-219, Feb. 2012.

[5] S. Kawai, *et al*., “A Digitally-Calibrated 20Gb/s 60GHz Direct-Conversion Transceiver in 65-nm CMOS,” *IEEE RFIC Symp*., pp.137-140, June 2013.

[6] V. Vidojkovic, *et al*., “A Low-Power 57-to-66GHz Transceiver in 40nm LP CMOS with -17dB EVM at 7Gb/s,” *IEEE ISSCC*, pp. 268-269, Feb. 2012.

[7] T. Mitomo, *et al*., “A 2Gb/s-Throughput CMOS Transceiver Chipset with In-Package Antenna for 60GHz Short-Range Wireless Communication,” *IEEE ISSCC*, pp. 266-267, Feb. 2012.

[8] V. Vidojkovic, *et al*., “ A Low-Power Radio Chipset in 40nm LP CMOS with Beamforming for 60GHz High-Data-Rate Wireless Communication,” *IEEE ISSCC*, pp. 236-237, Feb. 2013.

References

[9] T. Tsukizawa, *et al*., “A Fully Integrated 60GHz CMOS Transceiver Chipset Based on WiGig/IEEE802.11ad with Built-in Self-Calibration for Mobile Applications,” *IEEE ISSCC*, pp. 230-231, Feb. 2013.

[10] M. Soer, *et al*., "A 0.2-to-2.0GHz 65nm CMOS Receiver Without LNA Achieving >11dBm IIP3 and <6.5dB NF," *IEEE ISSCC*, pp.222-223, Feb. 2009.

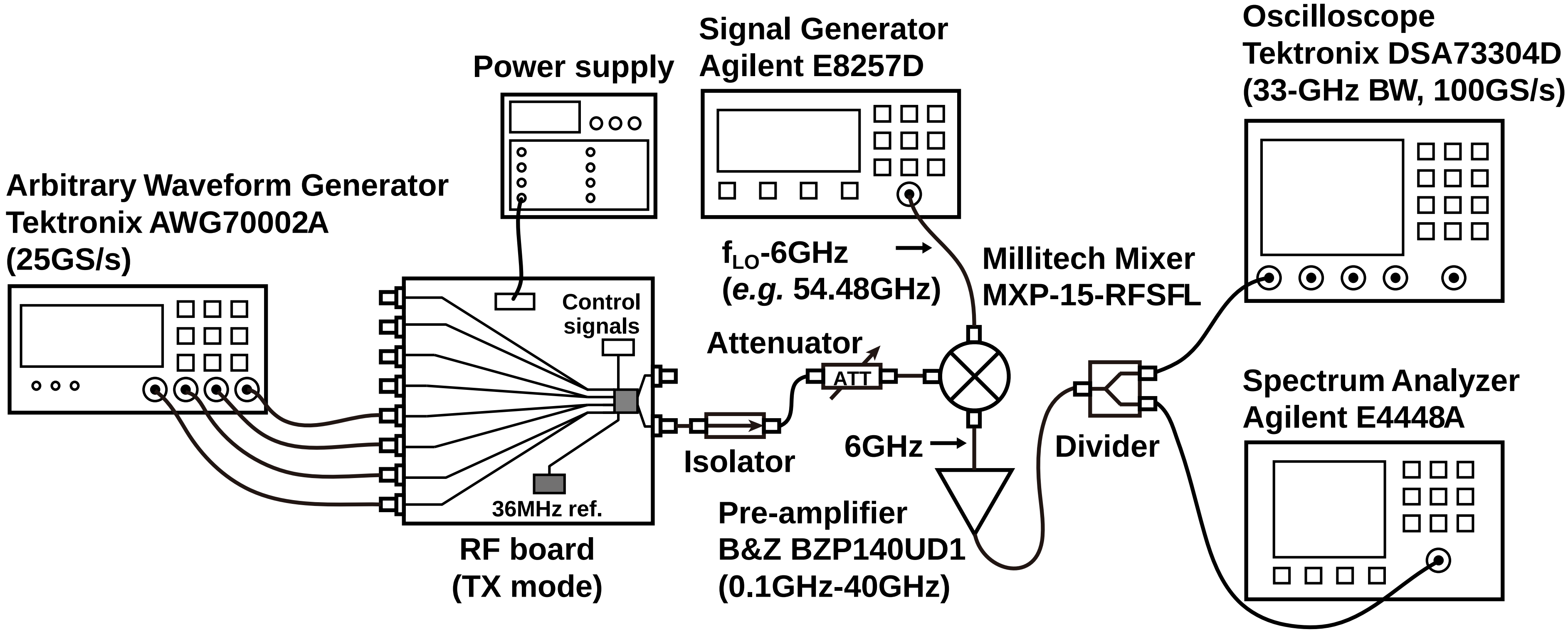
[11] C. Andrews, and A.C. Molnar, "A Passive-Mixer-First Receiver with Baseband-Controlled RF Impedance Matching, < 6dB NF, and > 27dBm Wideband IIP3," *IEEE ISSCC*, pp. 46-47, Feb 2010.

[12] R. Carvajal, *et al*., “The Flipped Voltage Follower: A Useful Cell for Low-Voltage Low-Power Circuit Design,” *IEEE Trans. CAS-I*, Vol. 52, No. 7, pp. 1276-1291, July 2005.

[13] K. Okada, *et al*., “Full Four-Channel 6.3-Gb/s 60-GHz CMOS Transceiver with Low-Power Analog and Digital Baseband Circuitry,” *IEEE JSSC*, Vol. 48, No. 1, pp.46-65, Jan. 2013.

Backup slides

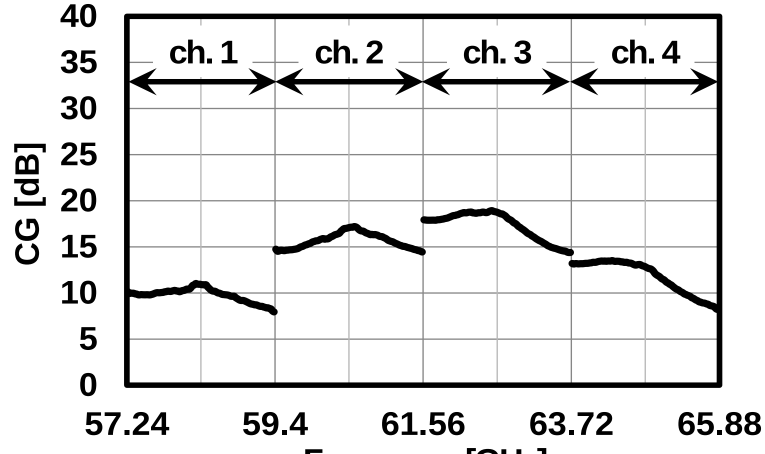
Setup for TX Measurement



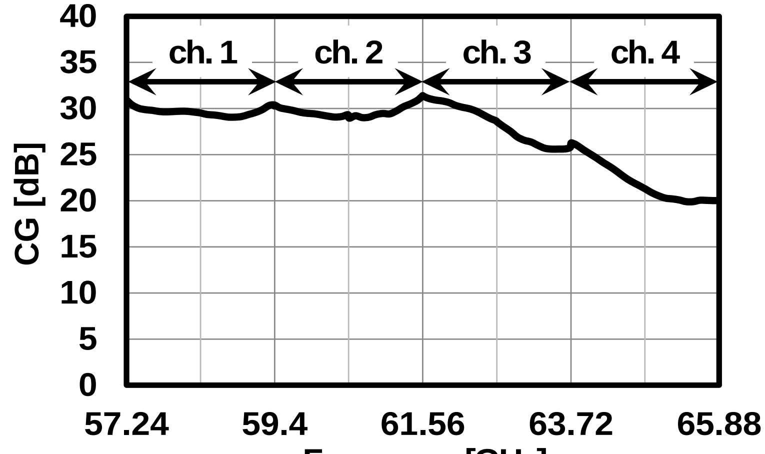
Symbol rate: 1.76GS/s (1ch), 7.04GS/s (4ch bonding)

Roll-off factor: 25% for WiGig spectrum mask

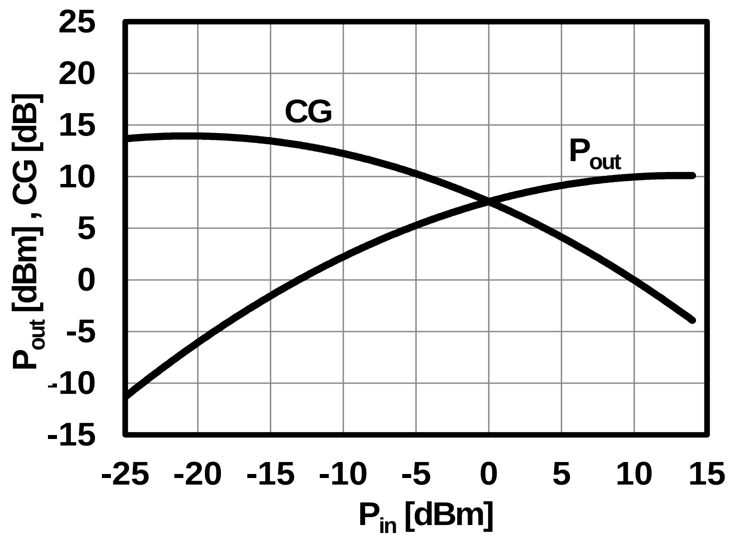
Measurement Results



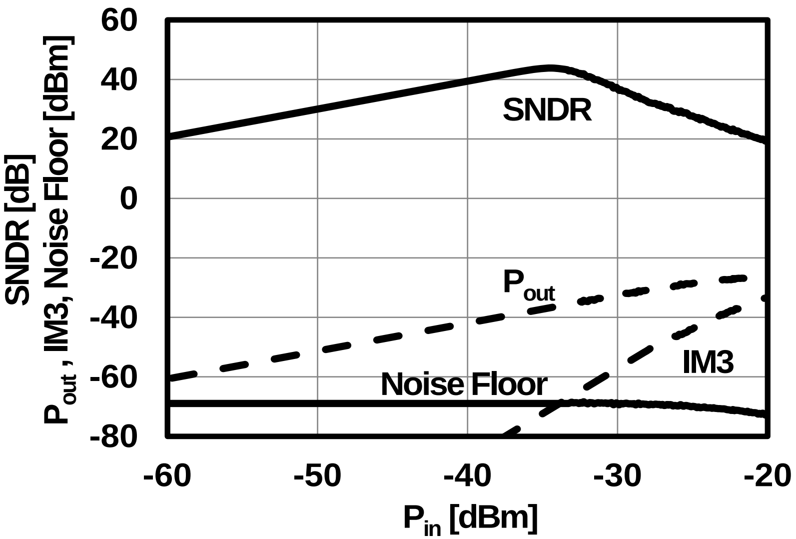
Conversion gain of Tx



Conversion gain of Rx



Output power of Tx



Output power of Rx