Optical Wireless Laboratory (OWL) @ HKUST

Recent Developments in Transceiver SoC Design for Next Generation Optical Networks

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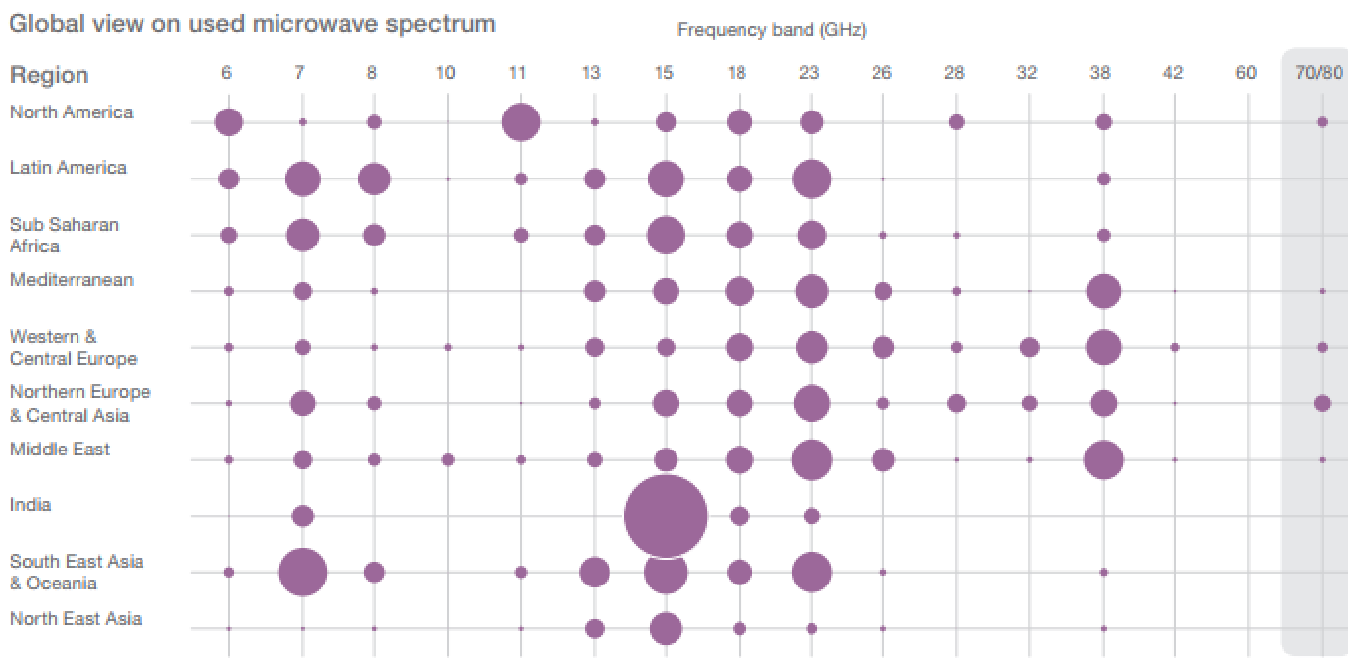
Outline

- Motivation
- BoF circuit and system design
- Measured results
- Summary and future work

Motivation

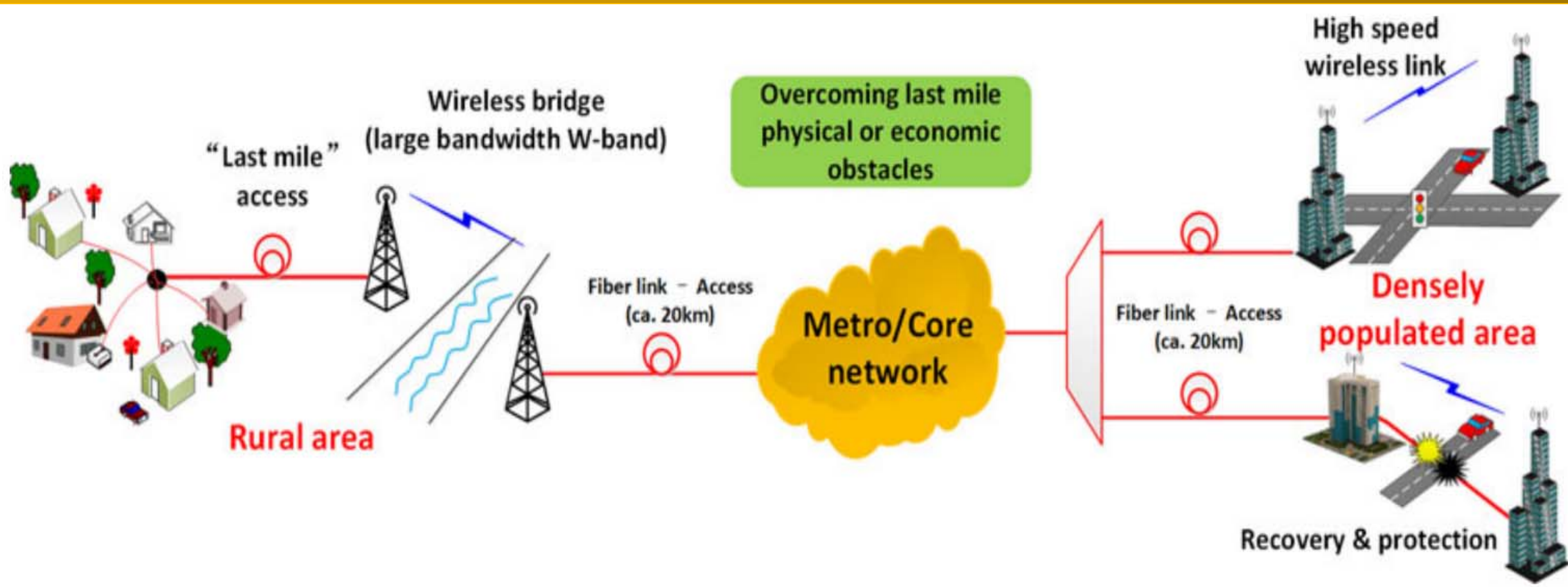
- Mobile data to grow >1000x over 2010 to 2020 [1]
- Expected 5G initial deployment in 2020 [1]



- New emerged mm-wave spectrum for 5G [2]
  - 26GHz, 28GHz, 32GHz, 38GHz, 70/80GHz…

[1] NTT NOCOMO 5G White Paper [2] Ericsson Mobility Report

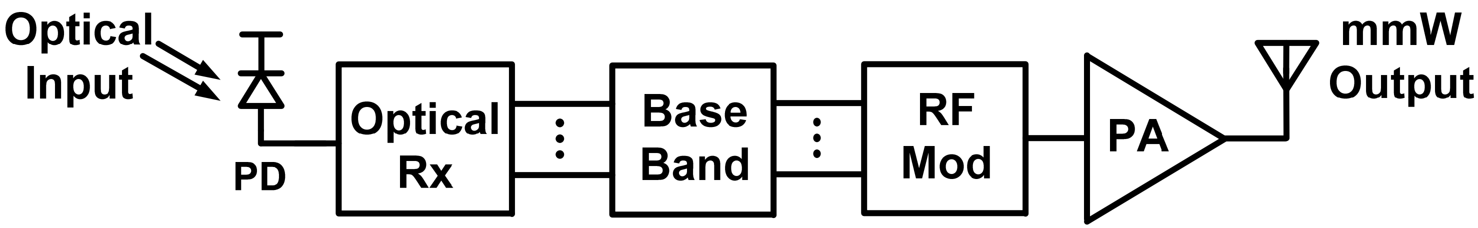
Motivation



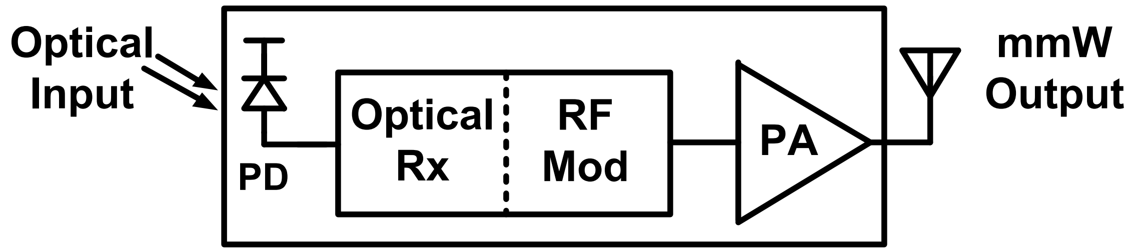
- **Macro/pico cells widely used to extend coverage and data throughput capacity in 4G LTE and 5G cellular network**
- **Wired connection sometimes physically impractical or costly**
- **Hybrid fiber-wireless network: flexible and high performance solution for short-range backhaul links deployment**

Motivation

Conventional Solution:



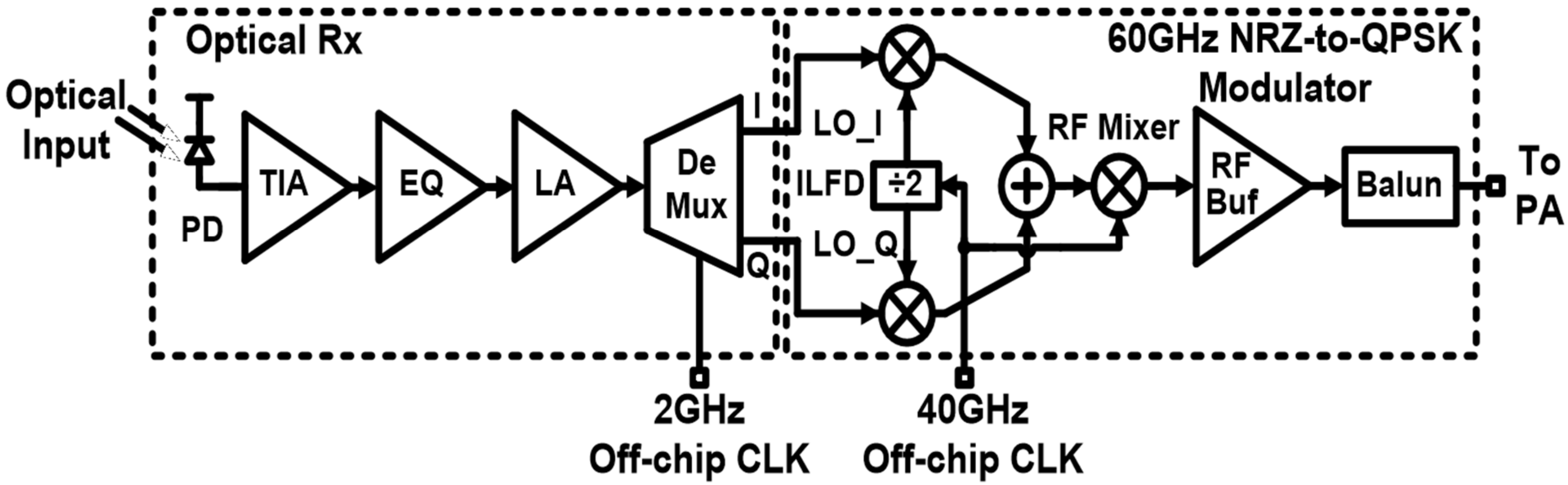
Proposed Solution:



- **Conventional fiber-wireless network composed of discrete O/E and RF components is costly and power hungry**
- **Redundant baseband digital processing introduces large overhead and latency**

Previous Work

❑ 60GHz 4Gb/s NRZ to QPSK Modulator [1]



- **Work at 60GHz**
- **No power amplifier integrated -> external PA needed**
- **No IQ calibration -> may suffer from image tone**
- **No on-chip demodulation -> difficult to measure BER**

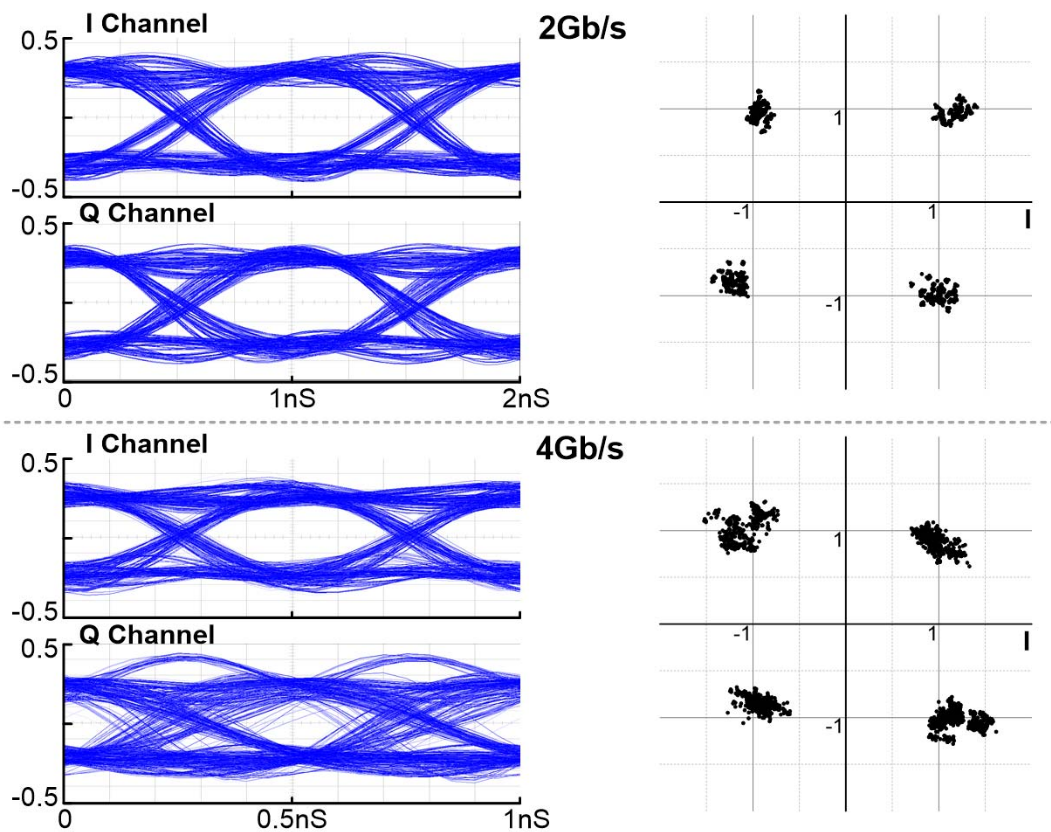
[Y. Wang, ESSCIRC 2015]

Previous Work

- 60GHz 4Gb/s NRZ to QPSK Modulator [1]
  - Data rate limited to 4Gb/s
  - Unbalance I/Q performance -> May be IQ mismatch

EVM = –14dB

EVM = –12dB

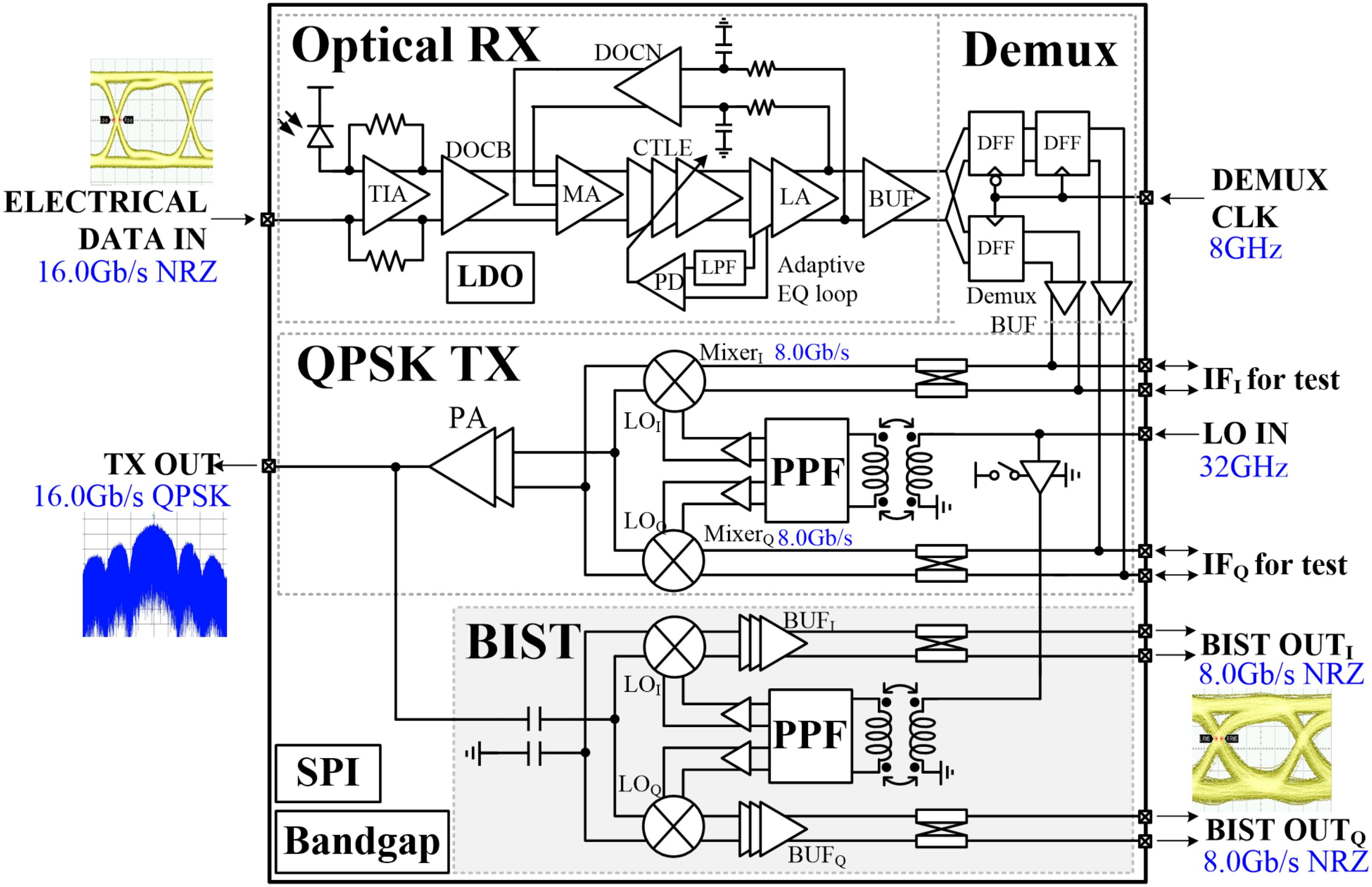


[Y. Wang, ESSCIRC 2015]

Outline

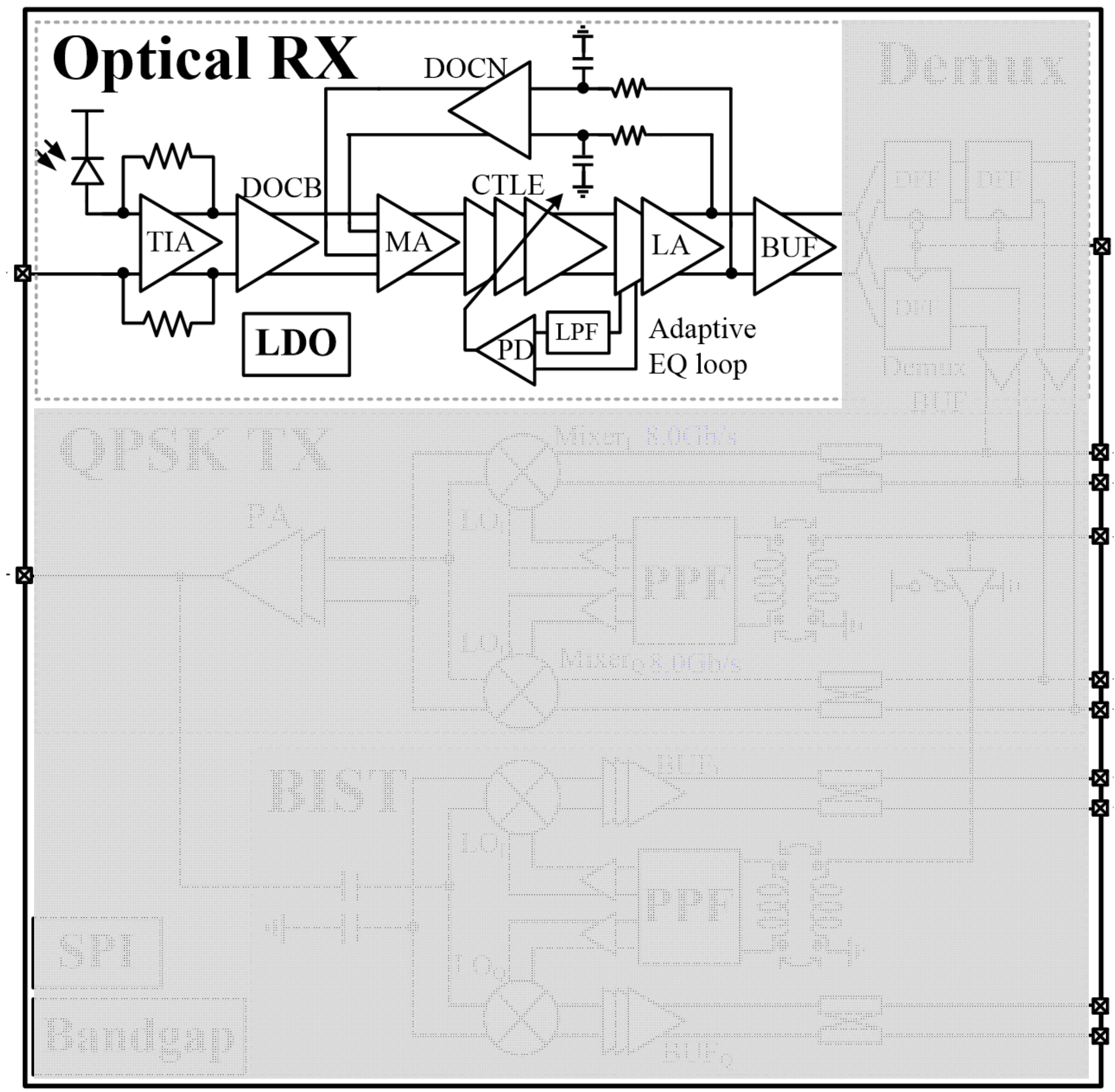
- Motivation
- BoF circuit and system design
  - Optical RX with integrated PD
  - Wideband QPSK TX
  - Built-in-self-test
- Measured results
- Summary and future work

The BoF System Architecture



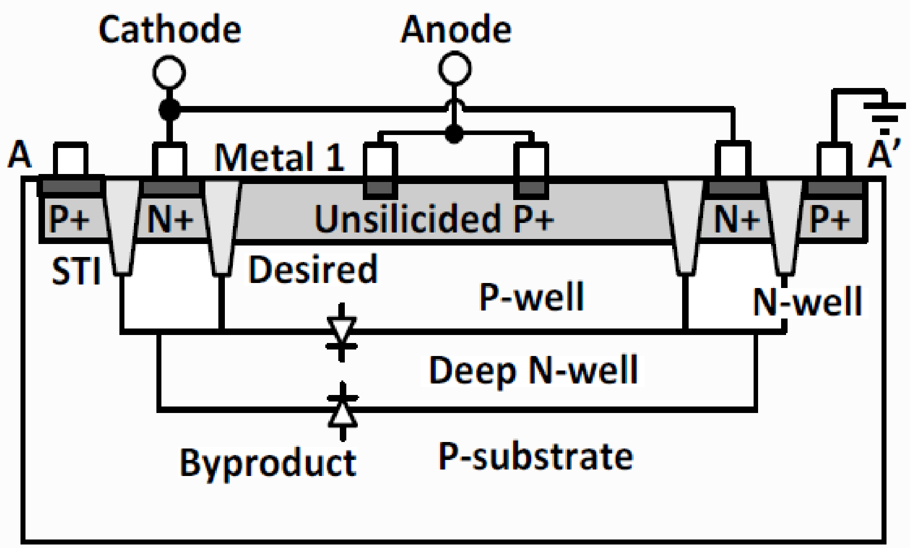
Optical Receiver

- Optical RX
  - on-chip PD
  - inv-based TIA
  - 3-Stage CTLE
  - MA/LA

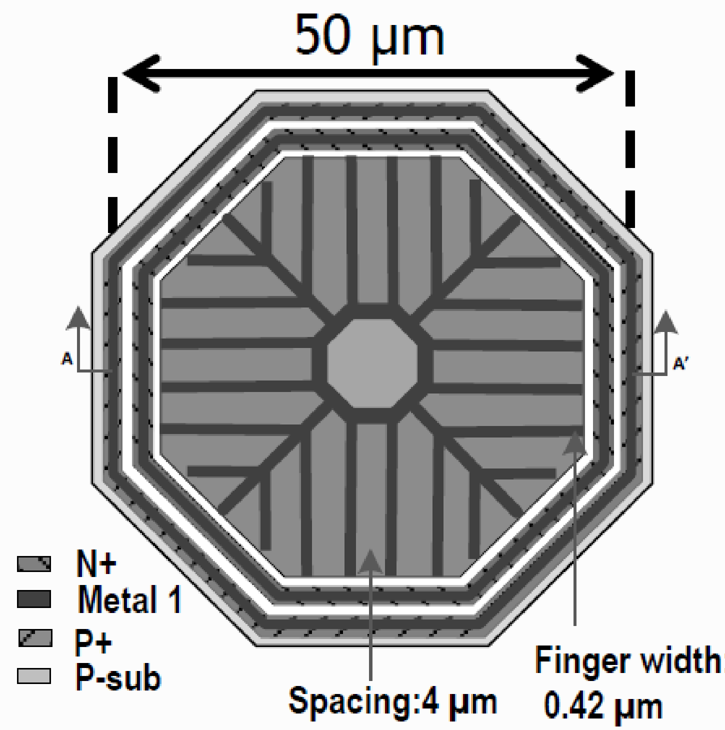


[Q. Pan, VLSI 2014]

P-well/Deep N-well PD Structure



Cross-section view

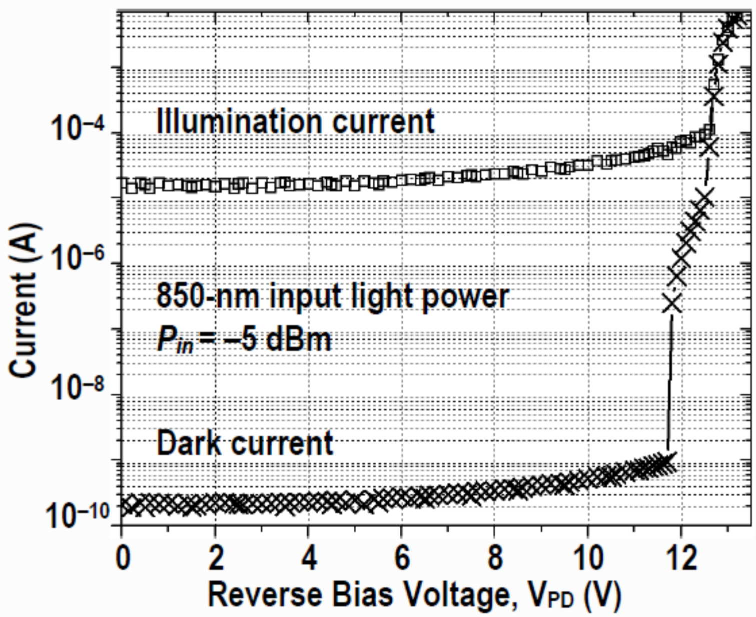


Top-down view

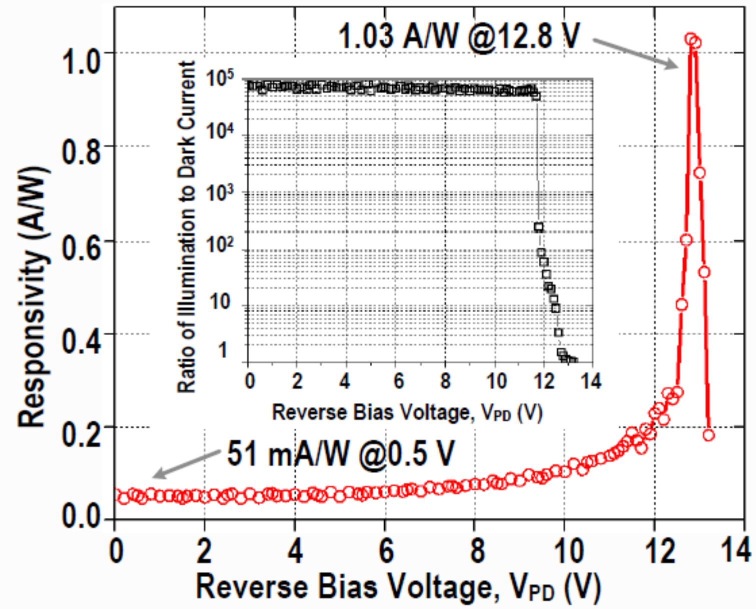
- Eliminate the slow substrate diffusion current
- Deeper junction depth and lighter doping concentration
- Compatible with optical receiver design when operating in the avalanche mode

P-well/Deep N-well PD Structure

❑ Measured Responsivity



Measured illumination and dark currents of the PW/DNW PD

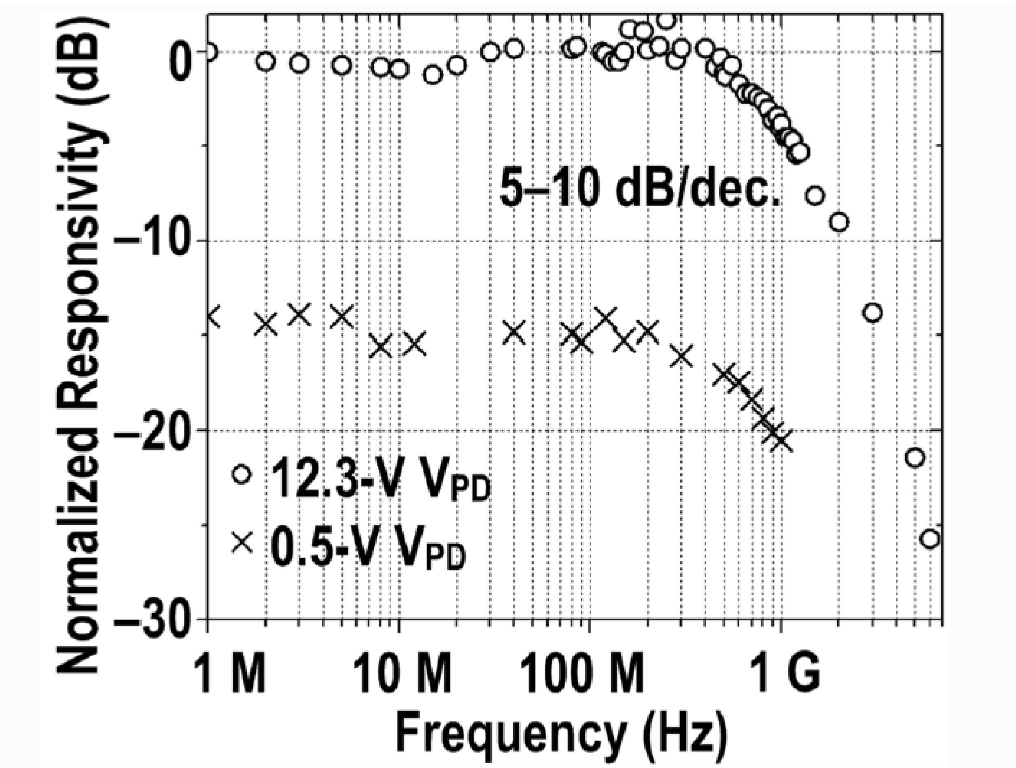


Measured bias dependency of the PW/DNW PD responsivity

- **Input light power (-5dBm) is chosen according to sensitivity to work in the linear region**
- **51mA/W @0.5V; 272mA/W @12.3V (optimal); 1.03A/W @ 12.8V (maximum)**

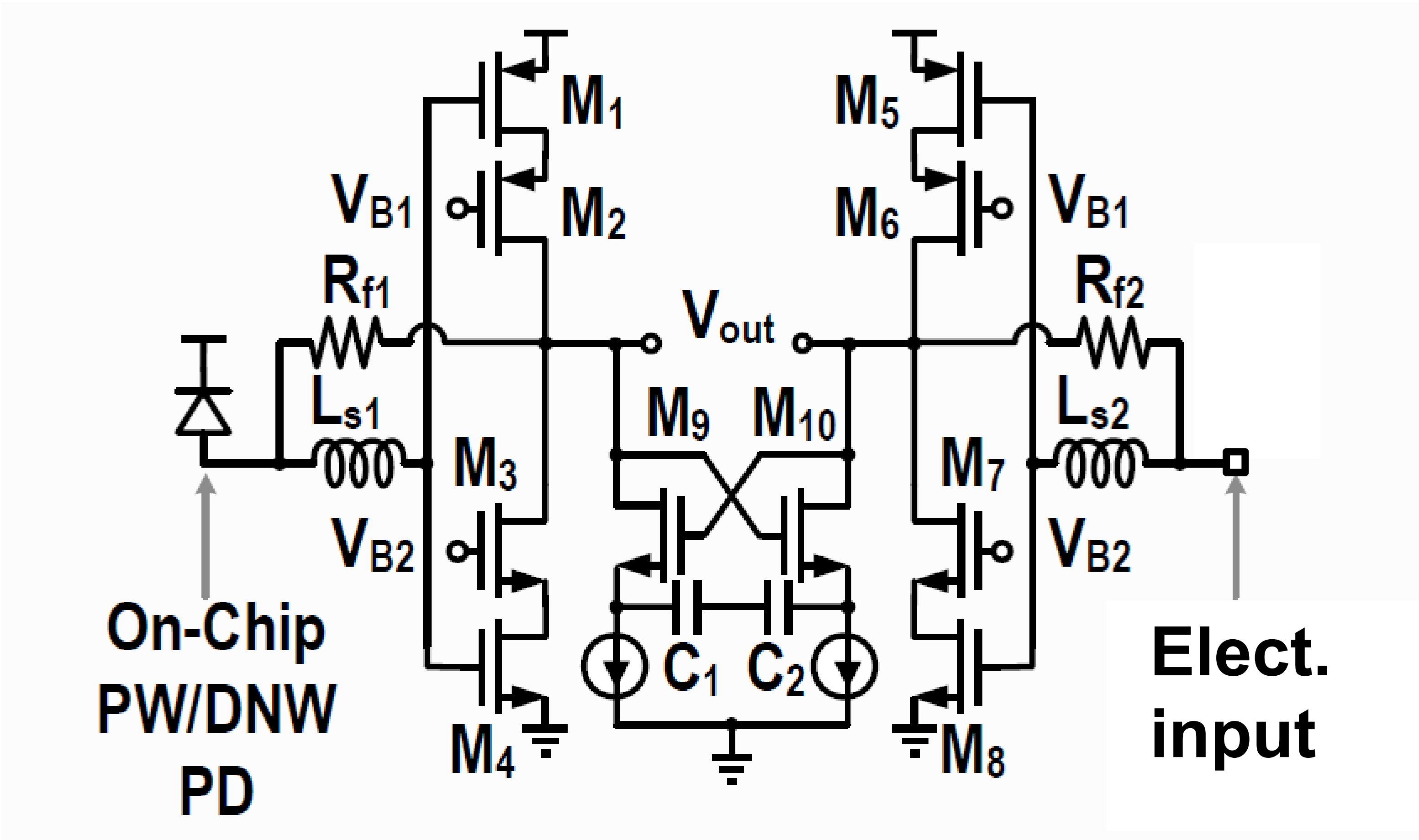
P-well/Deep N-well PD Structure

❑ Measured Optical Frequency Response



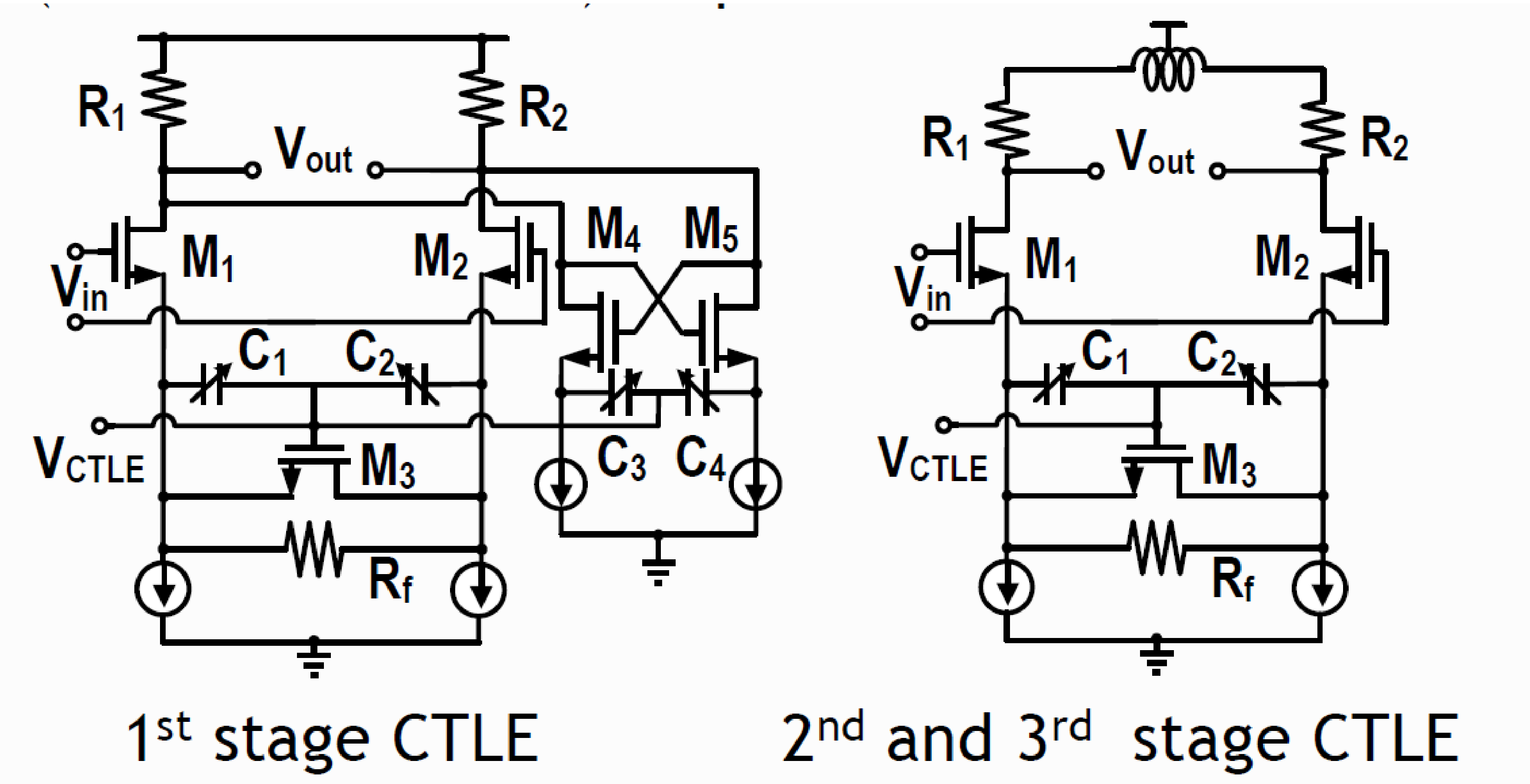
- **Normalized to DC responsivity @ avalanche mode**
- **Slow roll-off frequency response**
- **Fitting -3dB bandwidth: 500MHz**

Inductive Cascode Inverter-Based TIA



- Given a 480-fF PD capacitance, boost the bandwidth and minimize the input referred noise (IRN)

Slow Roll-Up 3-Stage Cascaded CTLE

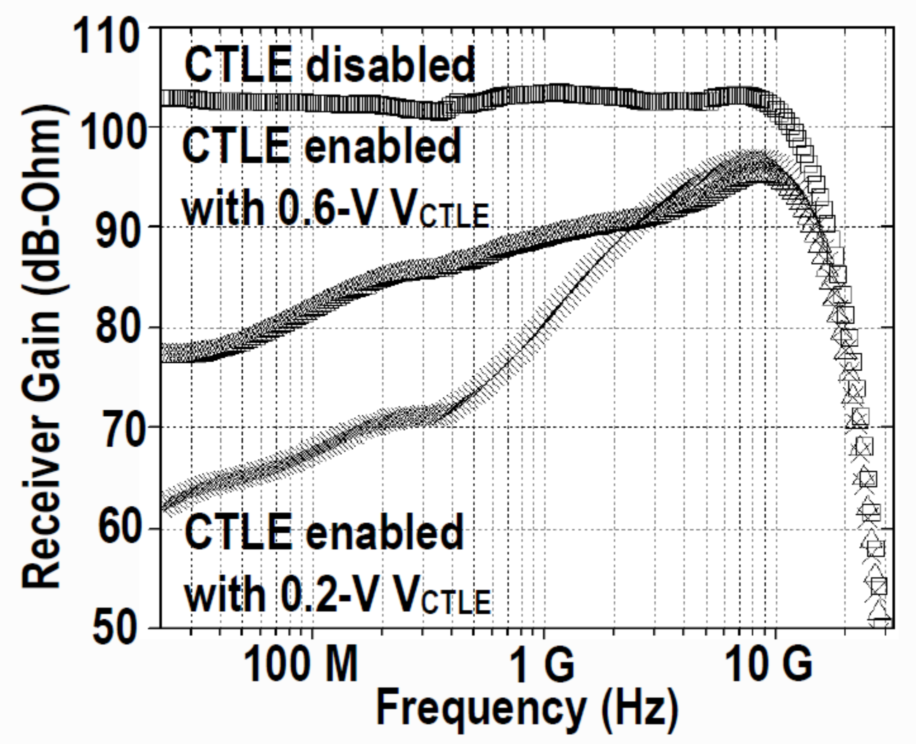


- **By interpolating the poles and zeros, a slow roll-up (5~10dB/decade) response can be achieved**

Slow Roll-Up 3-Stage Cascaded CTLE

❑ Measured Electrical Frequency Response

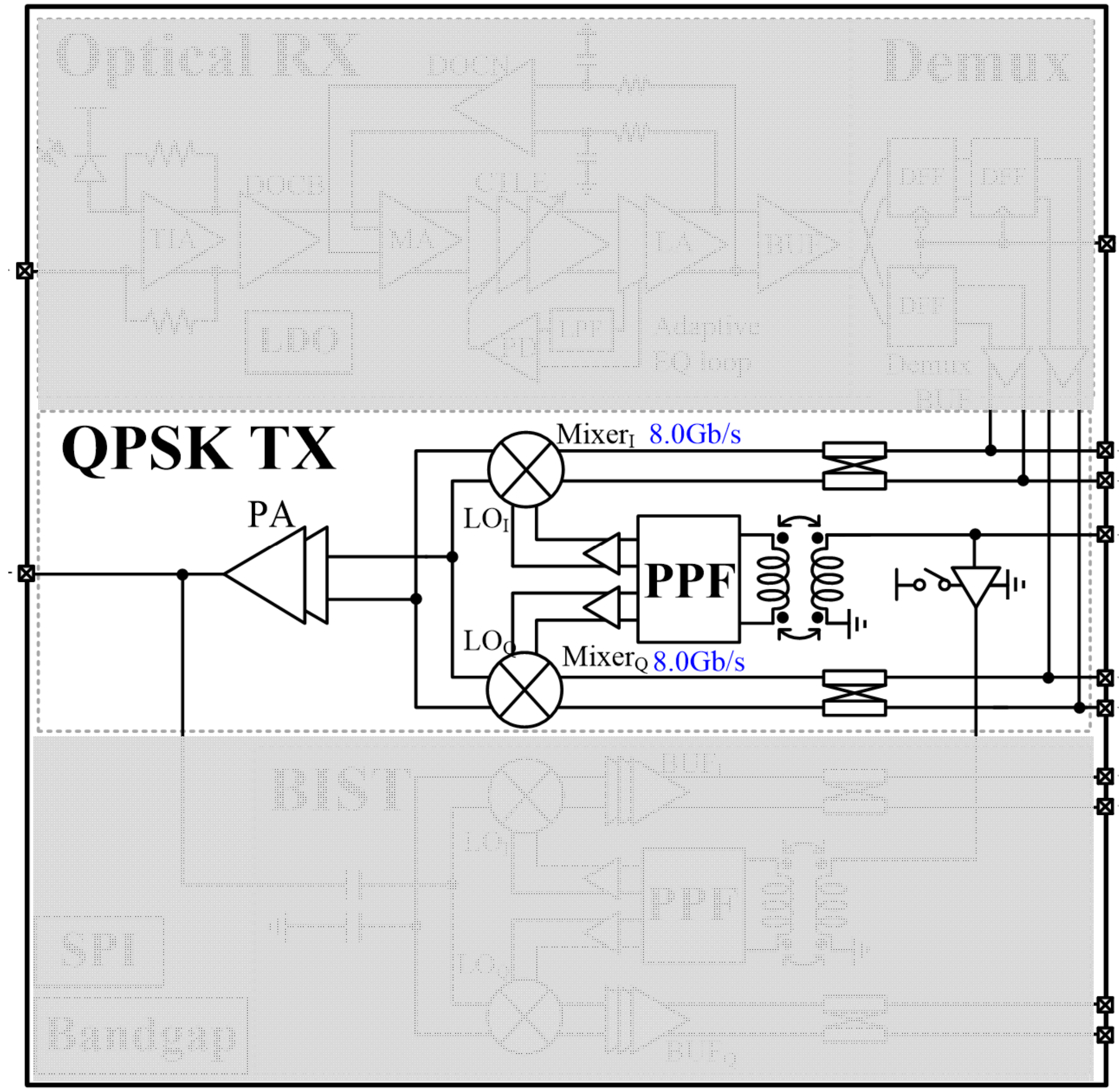
➢ The gain of optical RX



- Tested by direct probing without the on-chip PD
- 33-dB CTLE tuning range

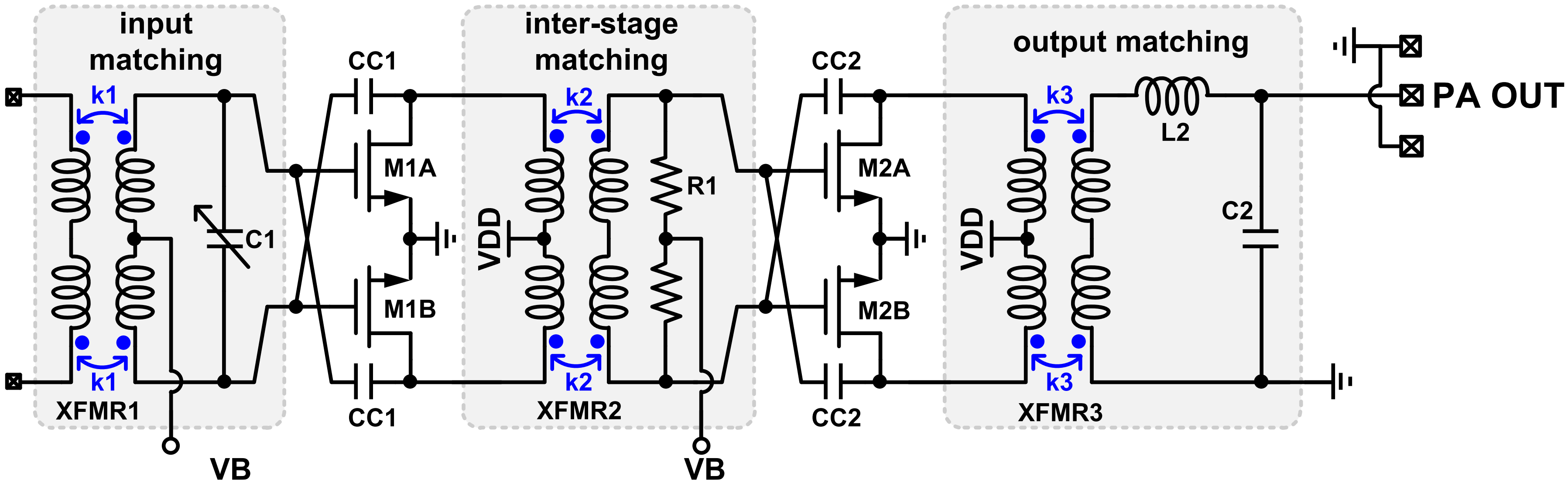
QPSK Transmitter

- QPSK TX
  - 2-stage PPF
  - Wideband PA
  - Gilbert mixer
  - Ripple cancel



Wideband Power Amplifier

❑ Wideband Power Amplifier

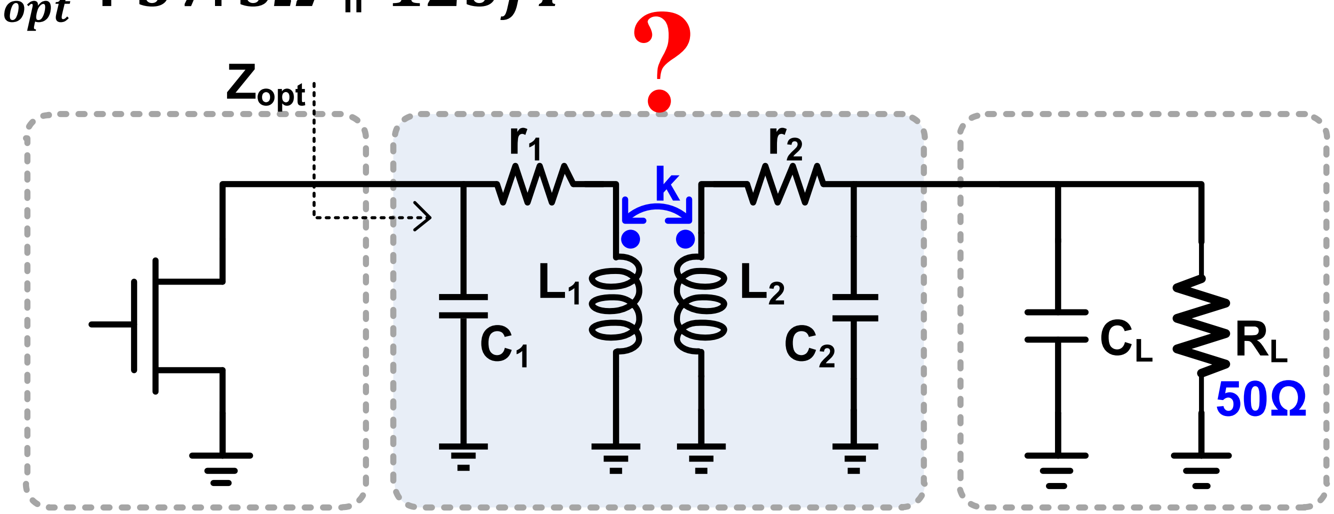


M1A/M1B	CC1	M2A/M2B	CC2
64µm/60nm	23fF	128µm/60nm	45fF

- Two amplification stages with neutralization cap
- Coupled resonator wideband matching network

Wideband Power Amplifier

- **Coupled Resonator based Wideband Matching**
  - **Transform the loading to Z_{opt} obtained from load pull simulation**
  - $R_L = 50\Omega$, $C_L = 25fF$ **(PAD capacitance)**
  - Z_{opt}^*: $37.5\Omega \parallel 123fF$

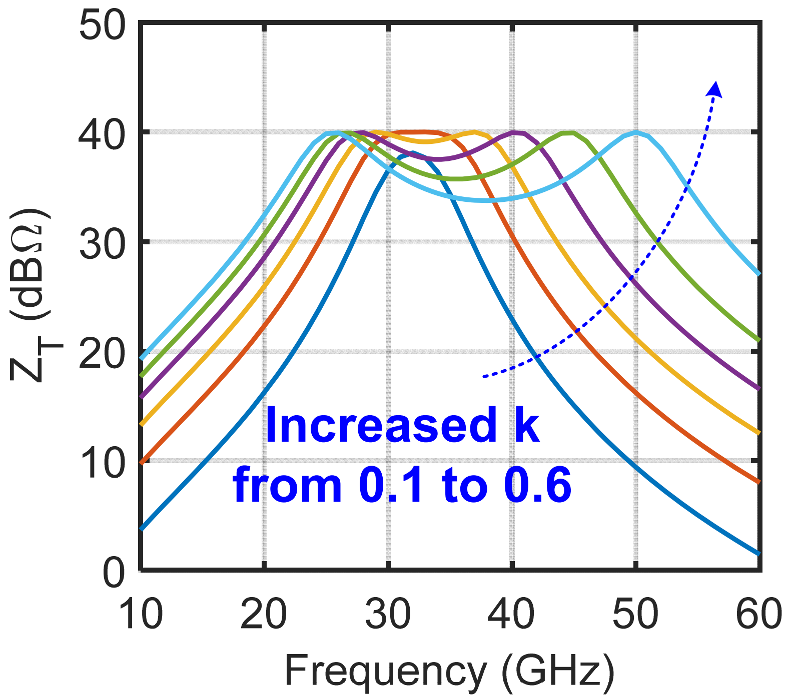


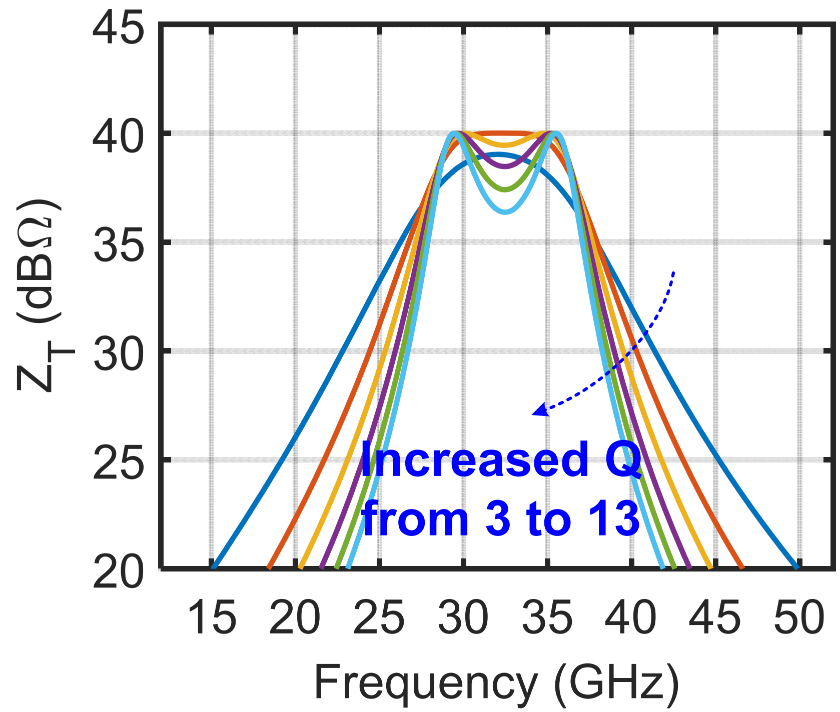
How to achieve wideband impedance transformation with low insertion loss?

Wideband Power Amplifier

❑ Coupled Resonator based Wideband Matching

➢ The effect of k and Q



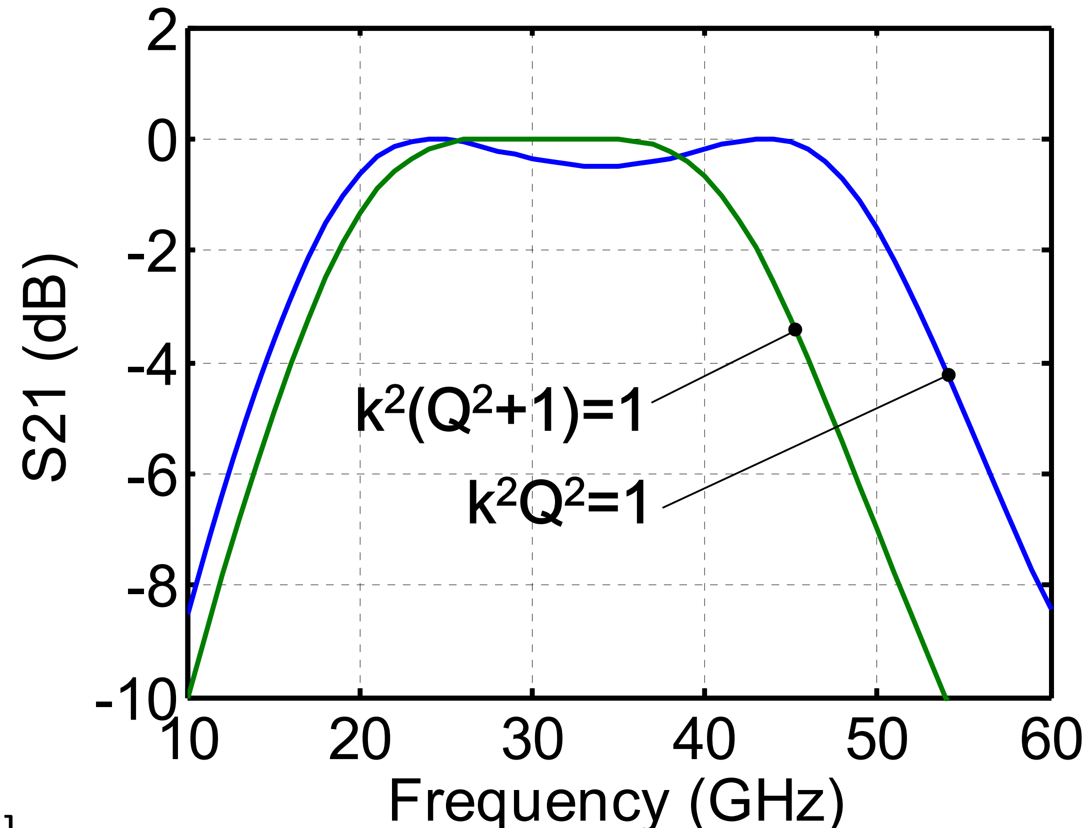


- large k pushes two poles away
- central freq increases with k
- When is the flattest response?

- large Q leads to large ripple
- Q has little influence on peak magnitude

Wideband Power Amplifier

- **Coupled Resonator based Wideband Matching**
  - **Minimal gain ripple condition:** $k^2(Q^2+1)=1$
  - **More accurate than previous mentioned** $k^2Q^2=1$ **[1]**



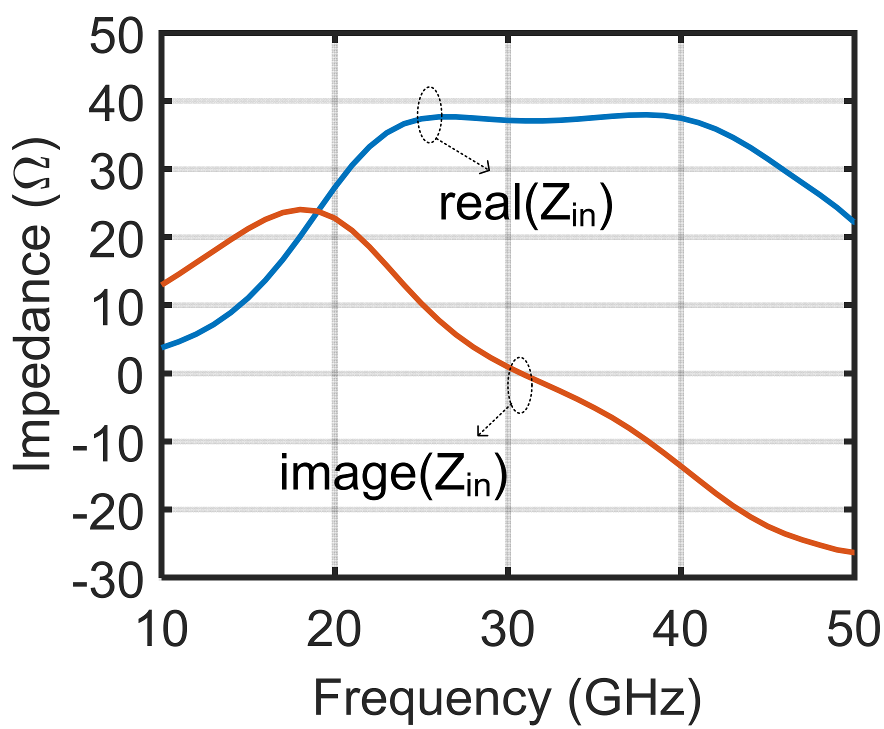
[C. Li, TMTT 2012]

Wideband Power Amplifier

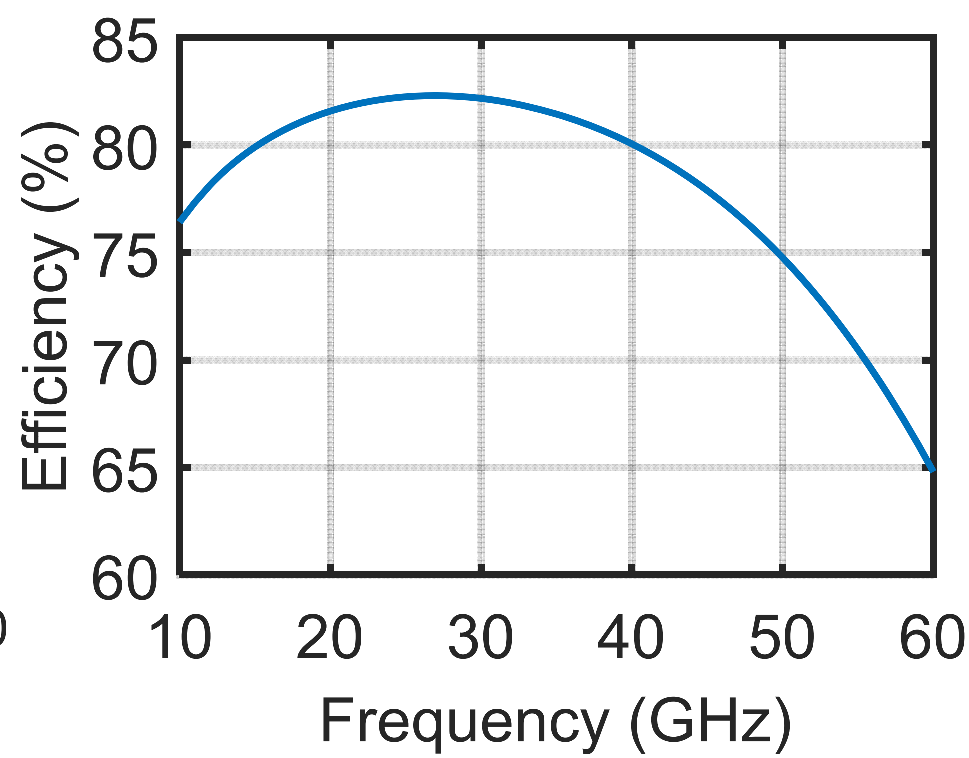
❑ Coupled Resonator based Wideband Matching

- ➢ The imp transformation achieved when $\frac{L_2}{L_1} = \frac{R_L}{R_s}$

Simulated impedance



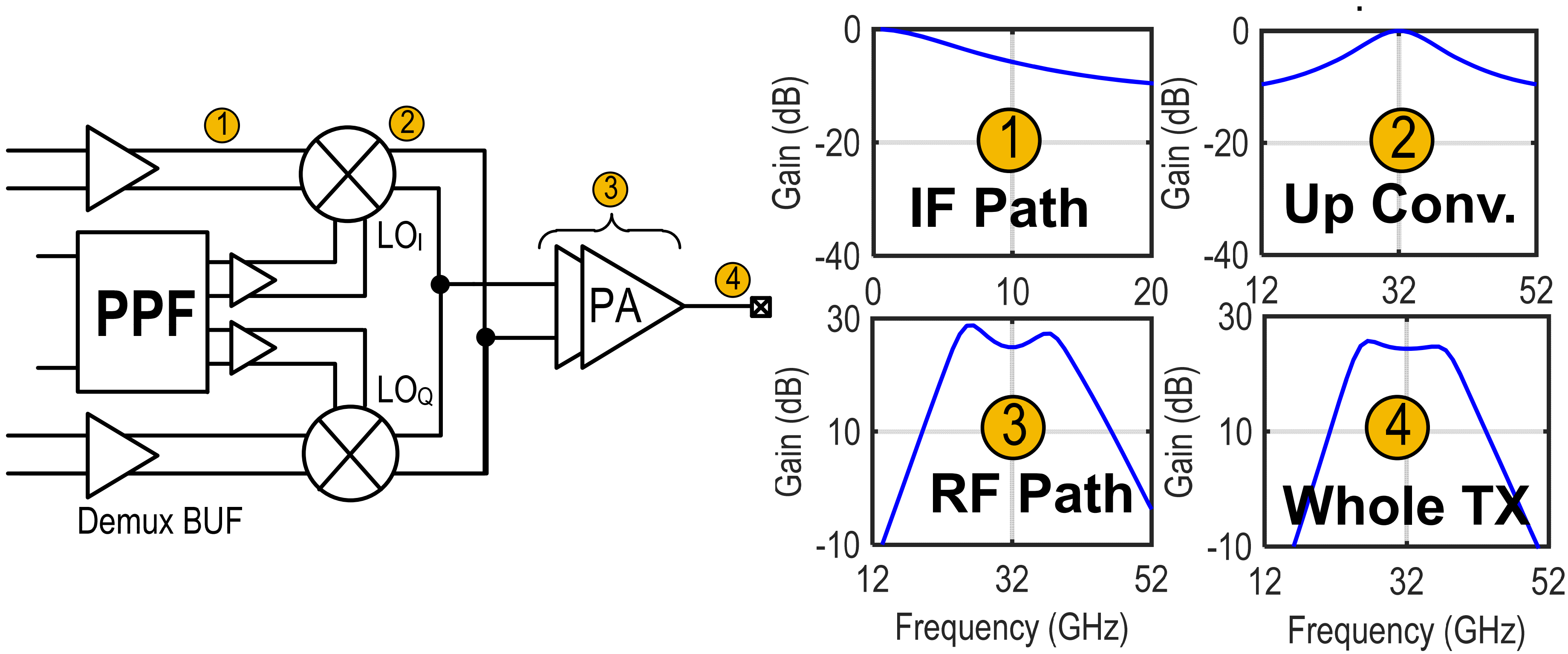
Simulated efficiency



[H. Jia, A-SSCC 2016]

Wideband Power Amplifier

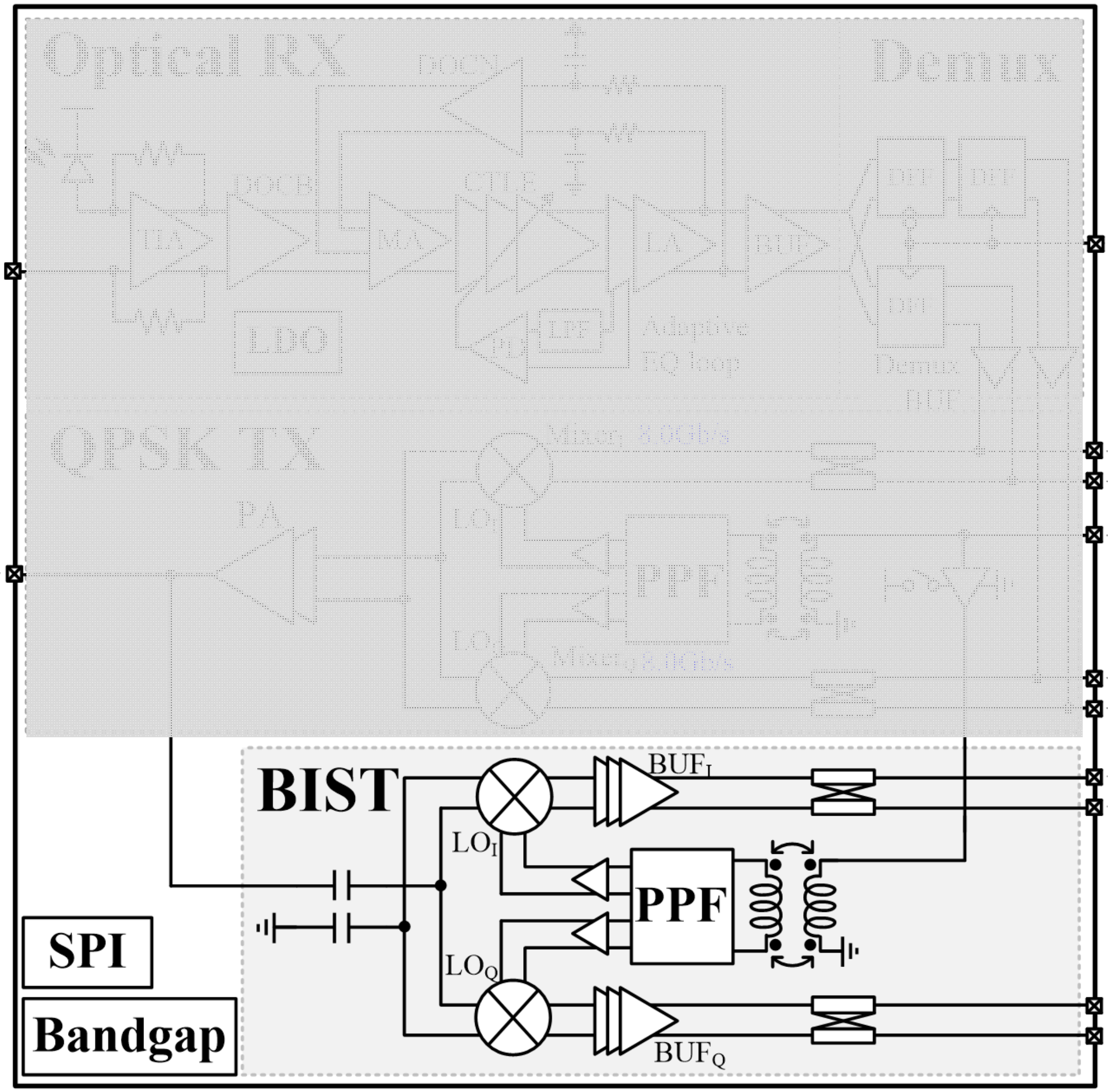
- PA Input/Inter-Stage Matching Network
  - Take advantage of gain ripple & bandwidth trade-off
  - Use the IF low pass feature to compensate ripple



- Simulated gain ripple reduces from 3.8dB to 1.3dB

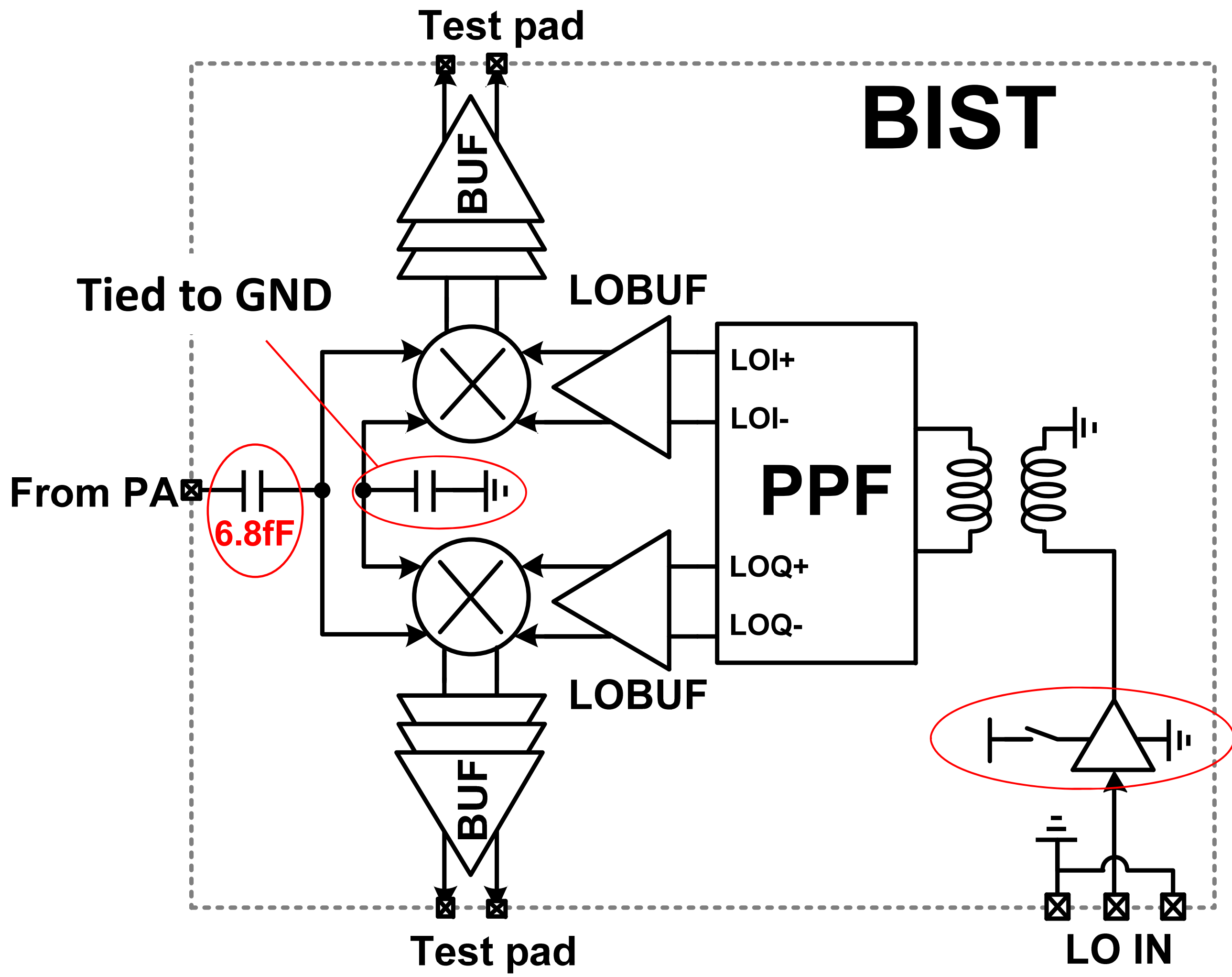
Built-In-Self-Test (BIST)

- BIST
  - 2-stage PPF
  - Cap coupling
  - Current bleeding mixer
  - CML driver



Built-In-Self-Test

- On Chip Demodulator to support BER test

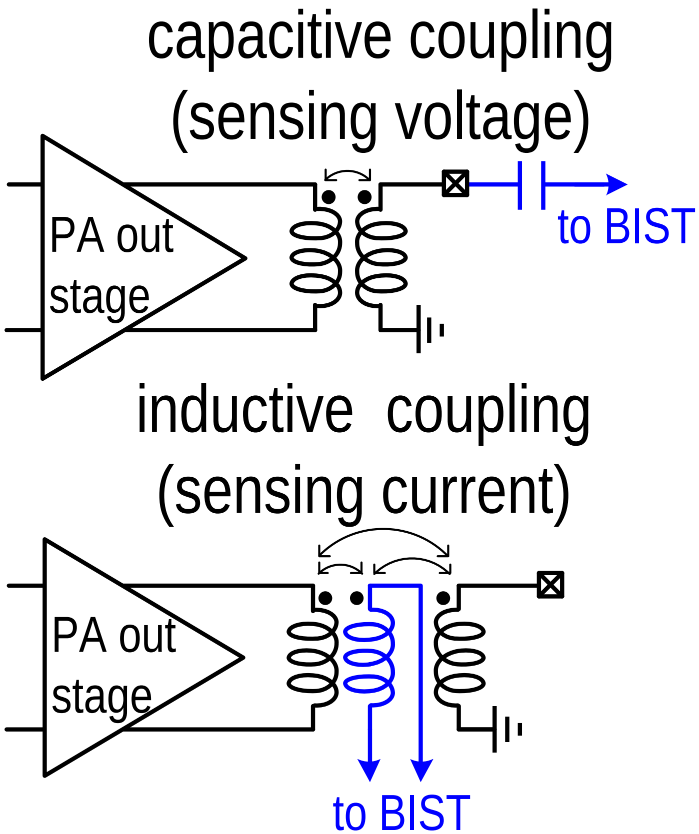


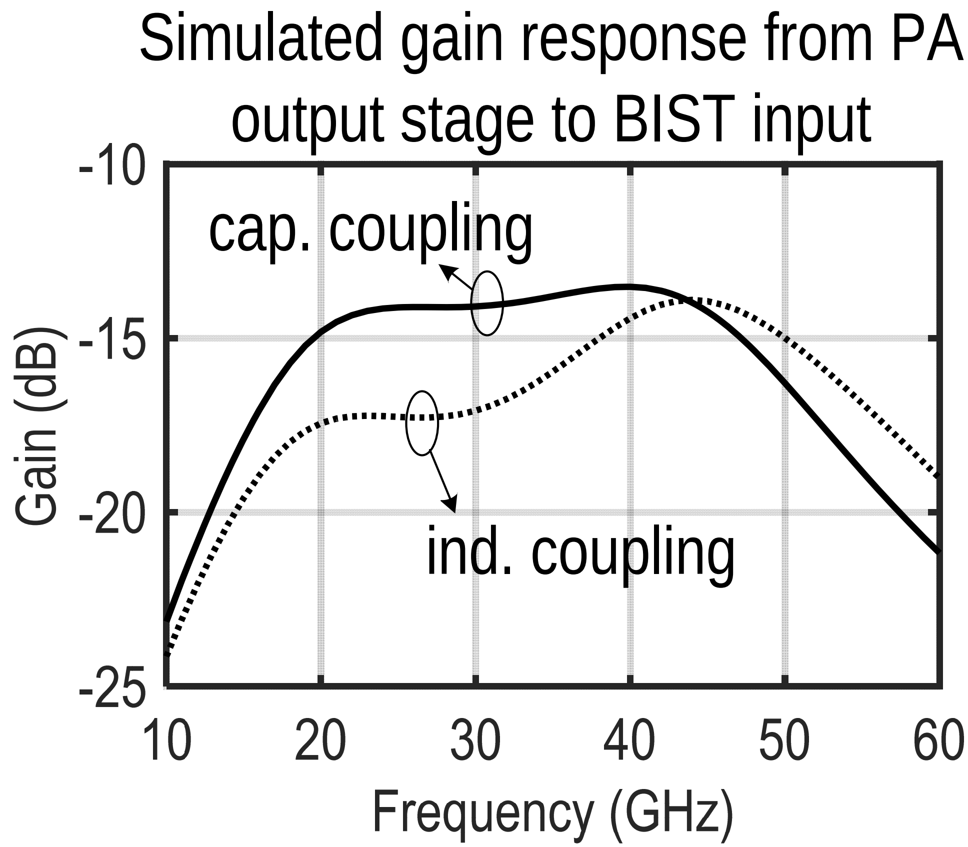
- On-chip demod.
- Cap coupled
- Sharing the same LO with QPSK Tx

Powered off when not in use

Built-In-Self-Test

❑ Cap. Couple Instead of Ind. Couple





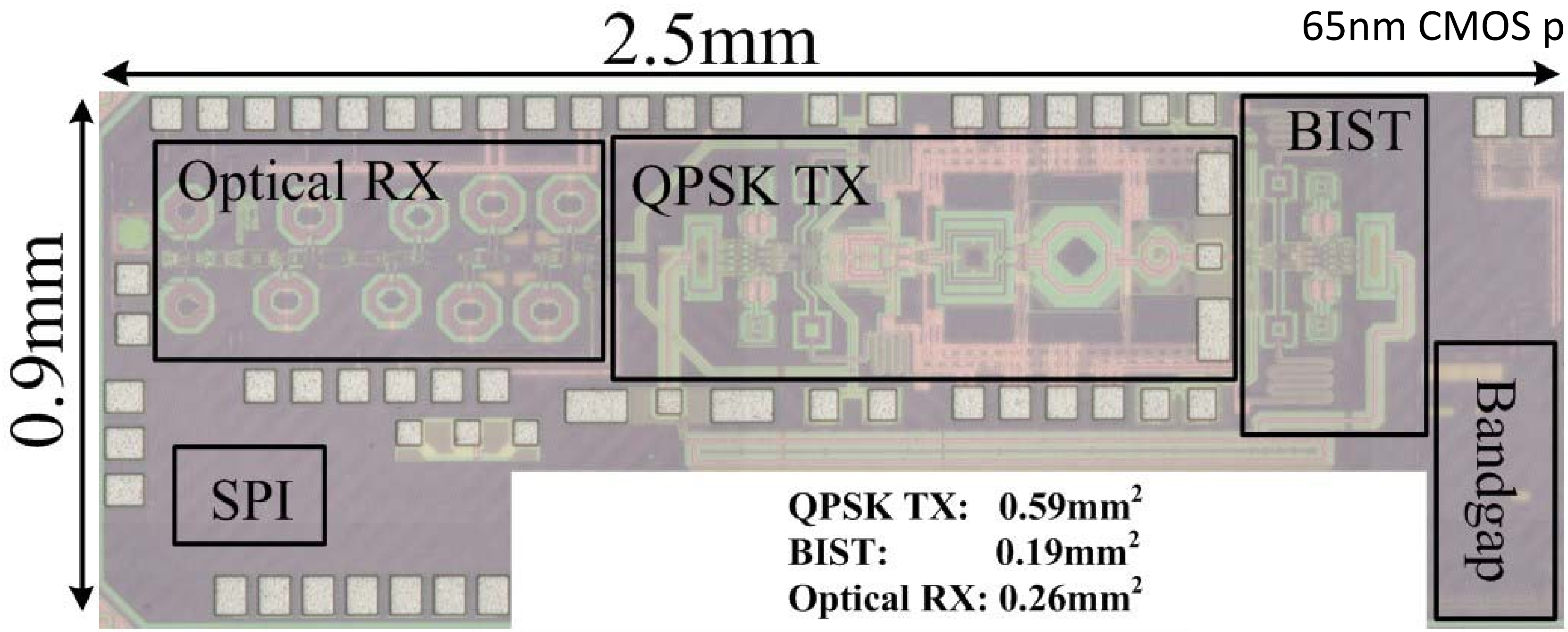
- **Cap coupling maintains the TX's wideband property**

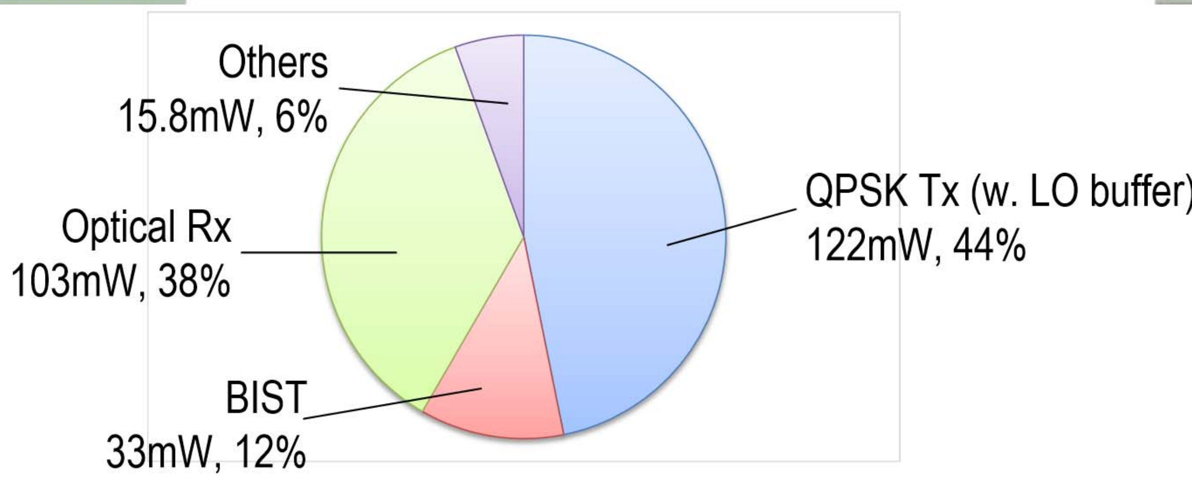
Outline

- ❑ Motivation
- ❑ BoF circuit and system design
- ❑ **Measured results**
- ❑ Summary and future work

Chip Photo and Power Consumption

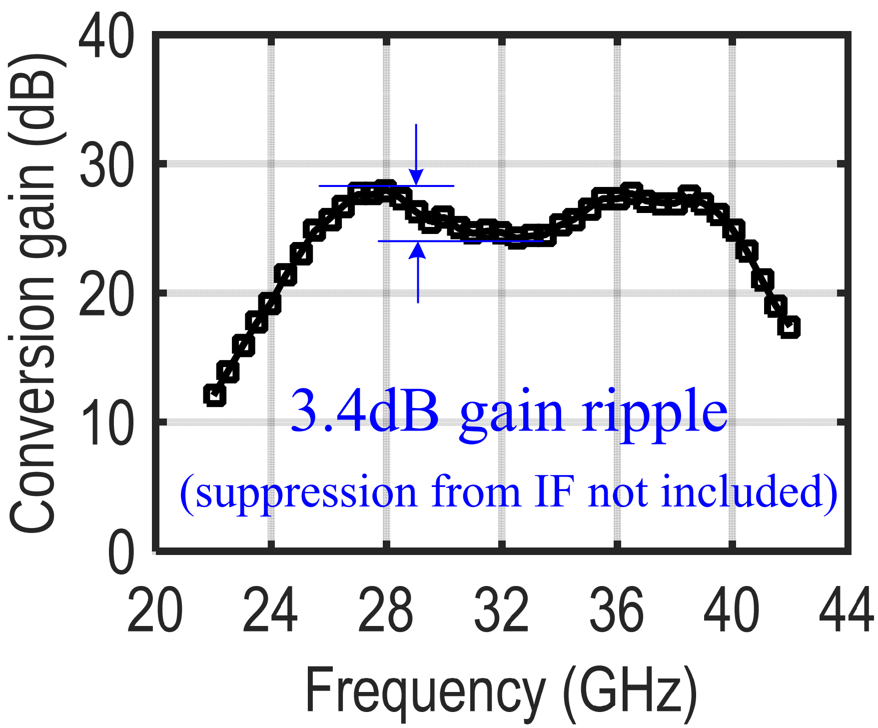
65nm CMOS process

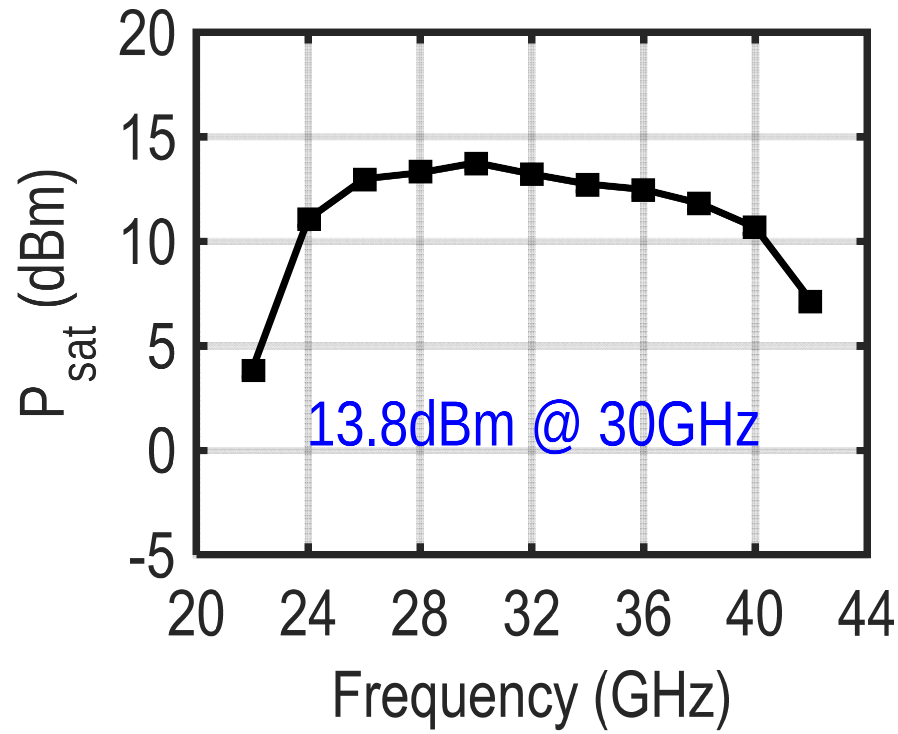




Continuous Wave Measured Results

❑ The QPSK TX Conversion Gain

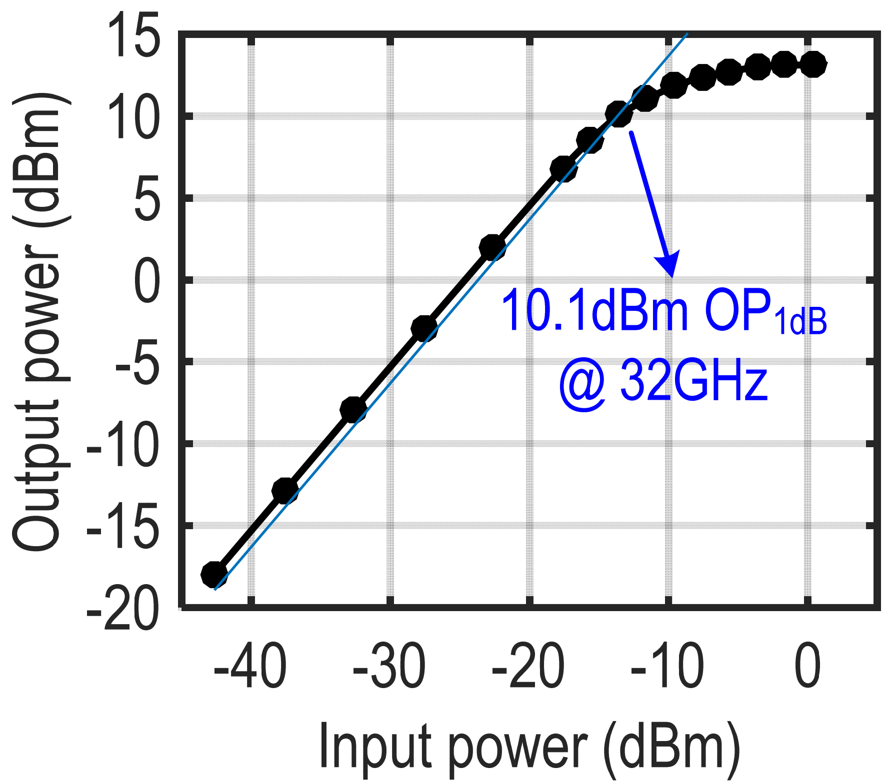


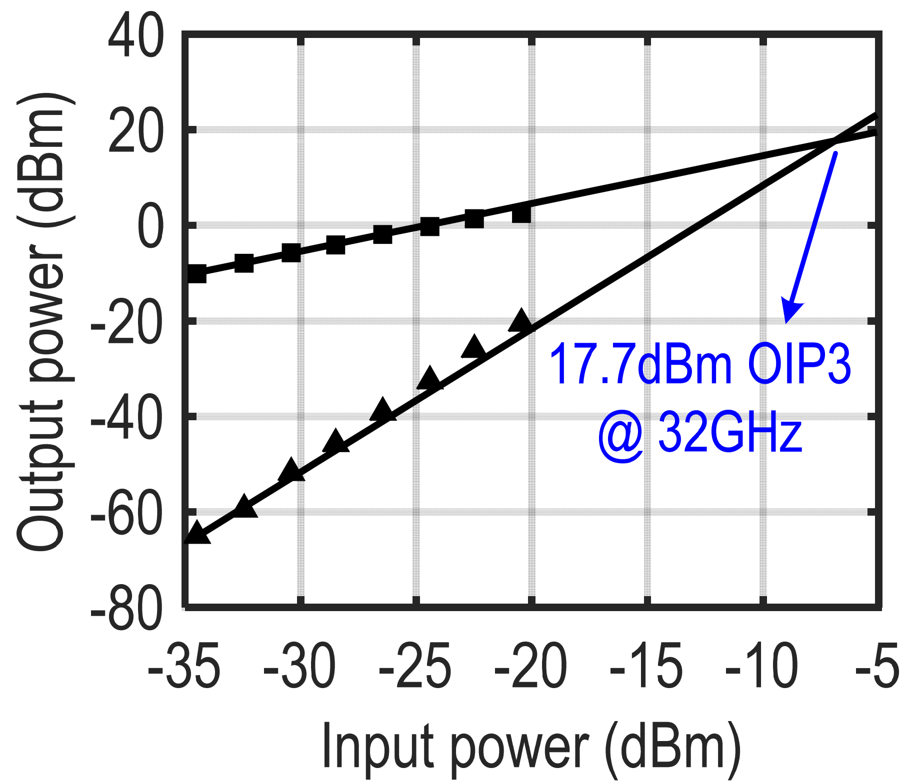


- **24.7dB at 32GHz, >24dB from 25.3 to 40.3GHz**
- **3.4dB gain ripple (no include IF path LPF)**
- **13.8dBm Psat at 30GHz**

Continuous Wave Measured Results

❑ The QPSK TX Large Signal Performance



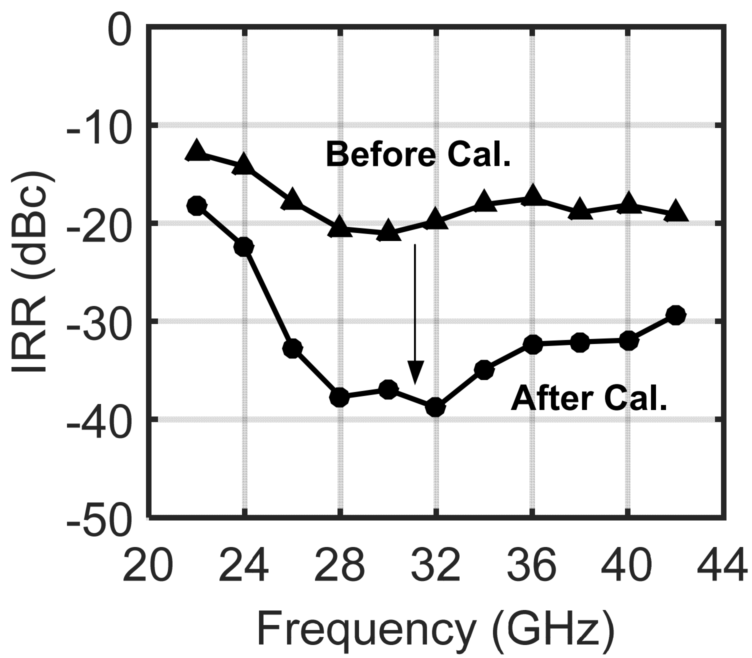


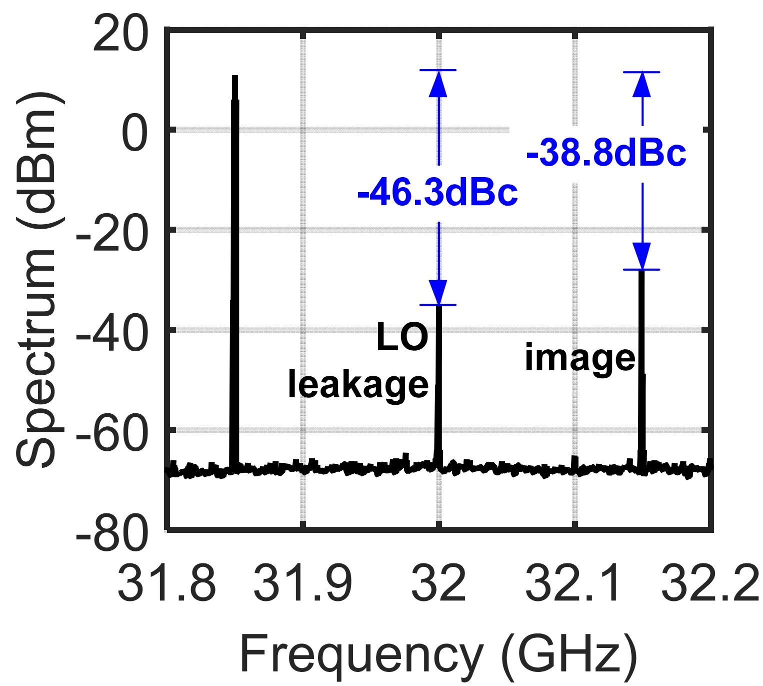
- **Measured 10.1dBm output 1dB point**
- **Measured 17.7dBm output IP3 point**

Continuous Wave Measured Results

❑ The QPSK TX Image Rejection Ratio (IRR)

➢ **Improved by manually tuning the PPF res array**



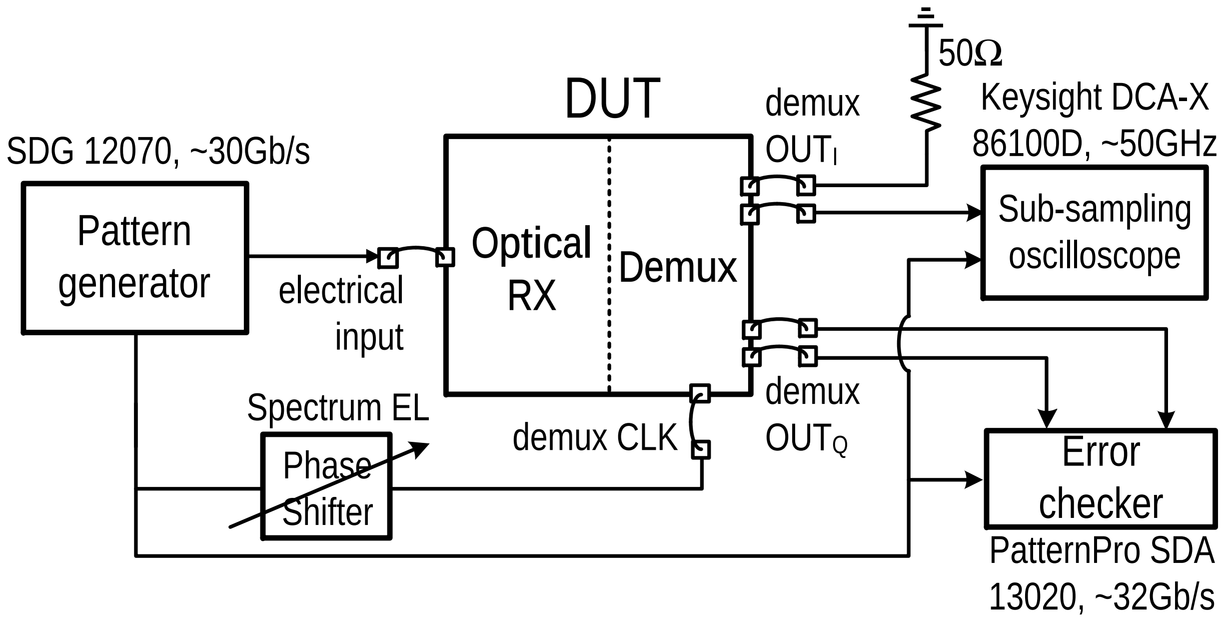


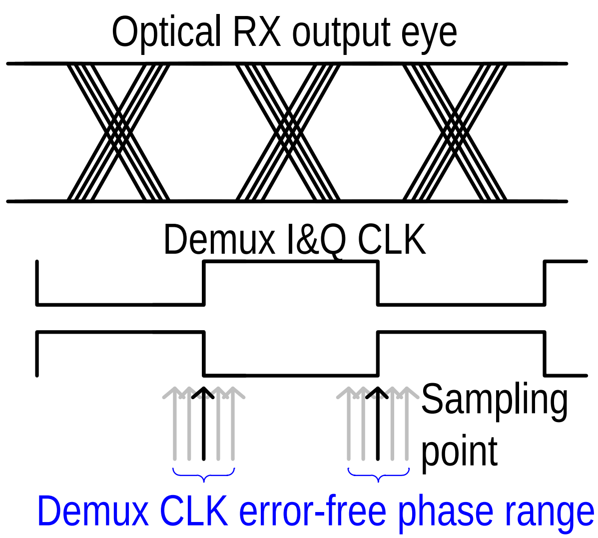
- **IRR improved from -19.8dBc to -38.8dBc**
- **-38.8dBc image rejection and -46.3dBc LO rejection**

Optical RX Measured Results

❑ Measurement Setup

➢ External phase shifter

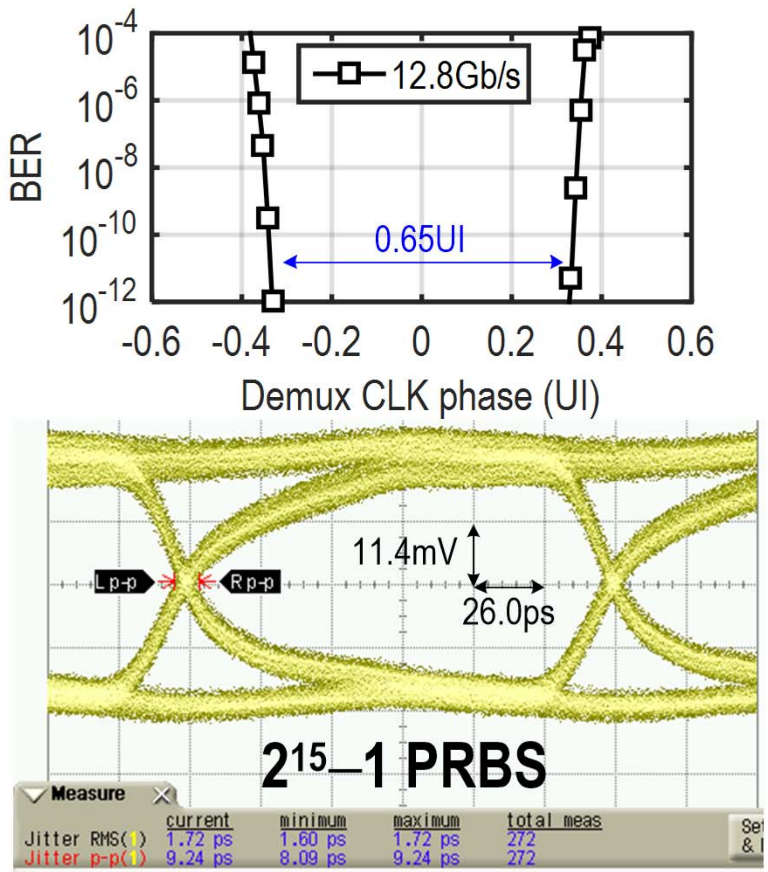


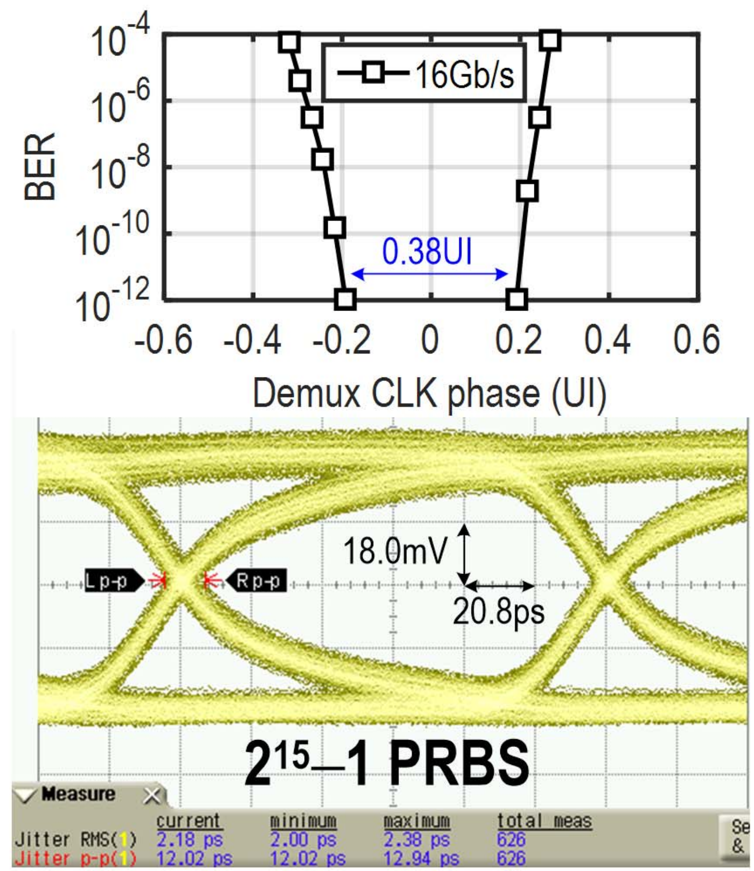


- **Manually tuning the phase for optimal sampling**
- **The error free sampling phase range is measured**

Optical RX Measured Results

❑ The eye and BER from RX's output

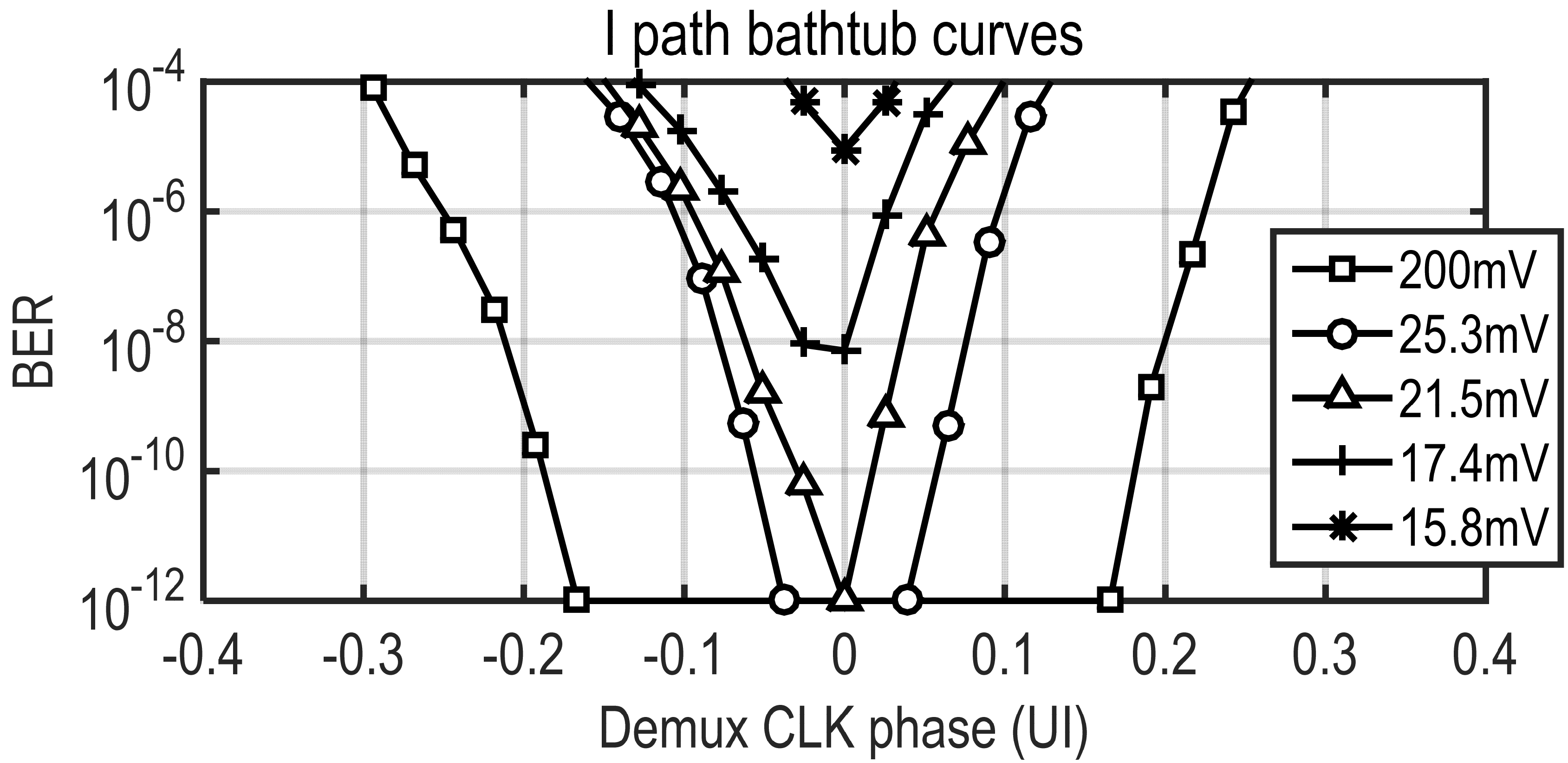




- **0.38UI error free sampling CLK phase range**

Optical RX Measured Results

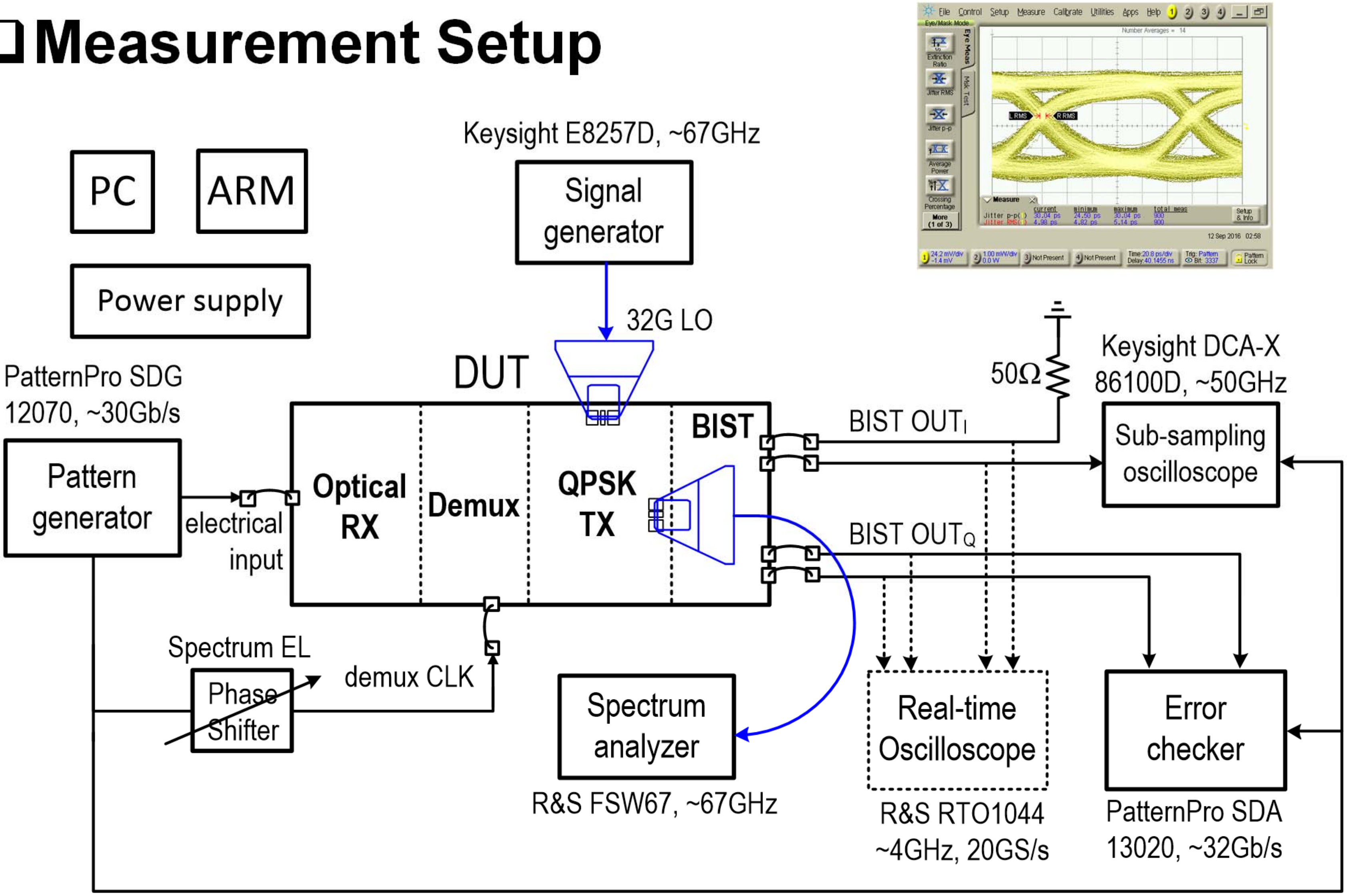
❑ Optical RX sensitivity



- **The minimal error free input amplitude is 21.5mVp-p**
- **Converts to 165uAp-p using a 80Ω input impedance**

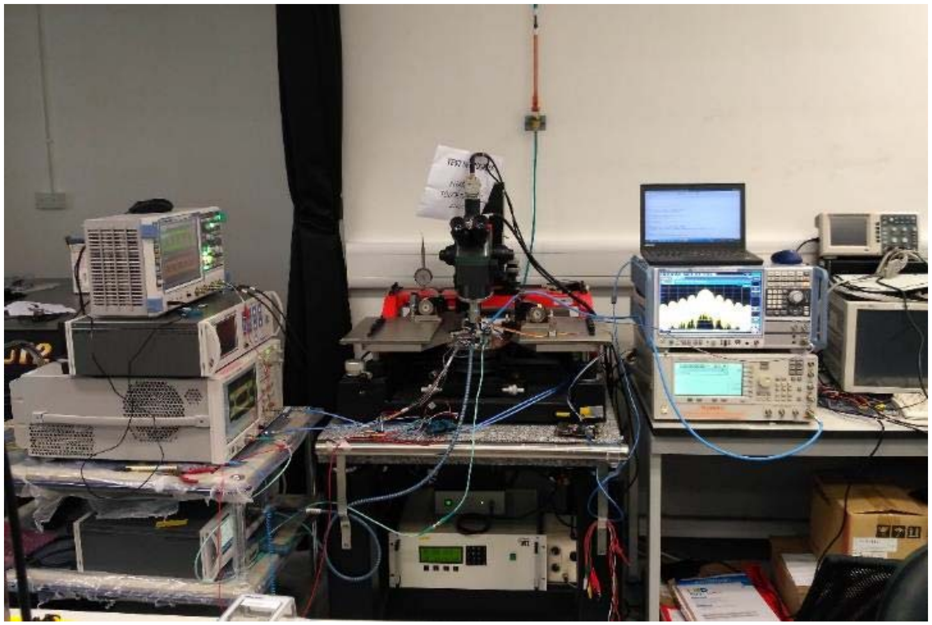
BoF Data Measured Results

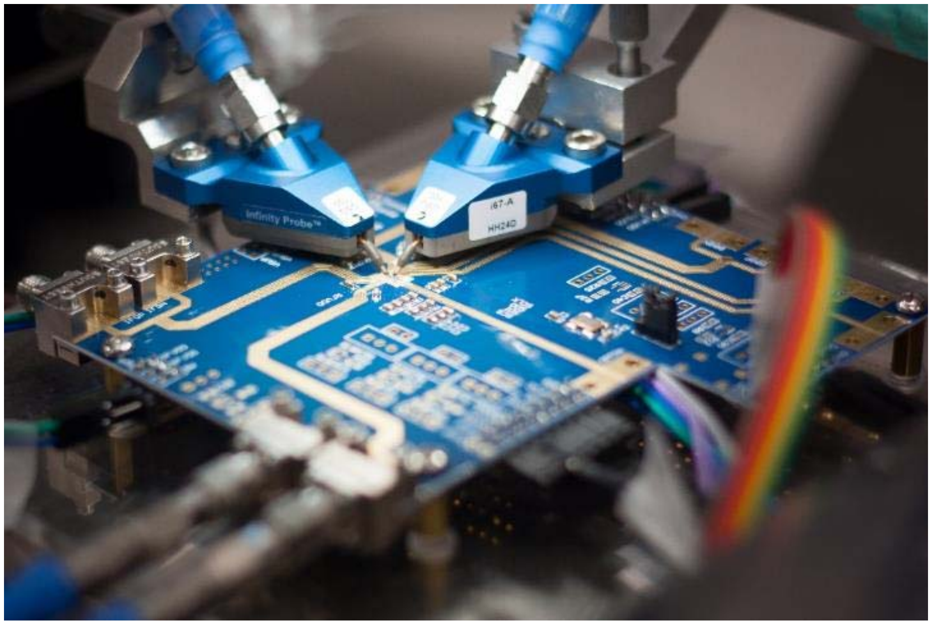
❑ Measurement Setup



BoF Data Measured Results

❑ Measurement Setup



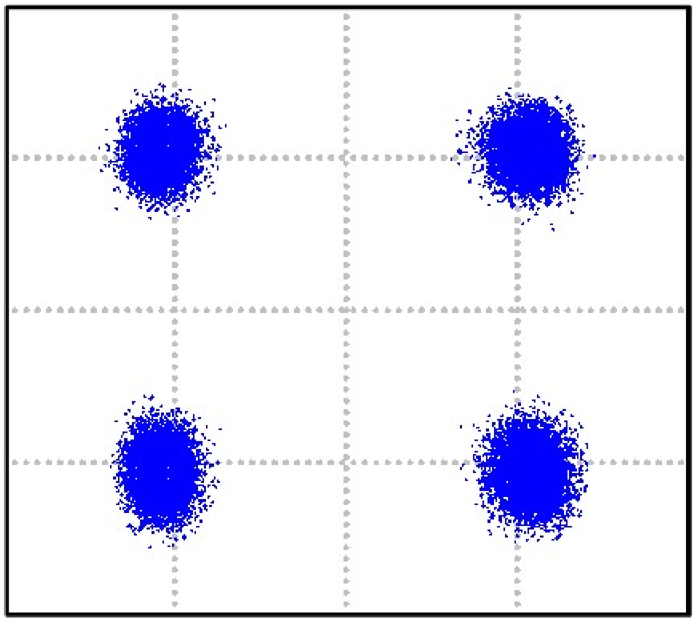


- On-chip probing for high speed signals
- BERT system, signal gen, subsampling osc, real time osc

BoF Data Measured Results

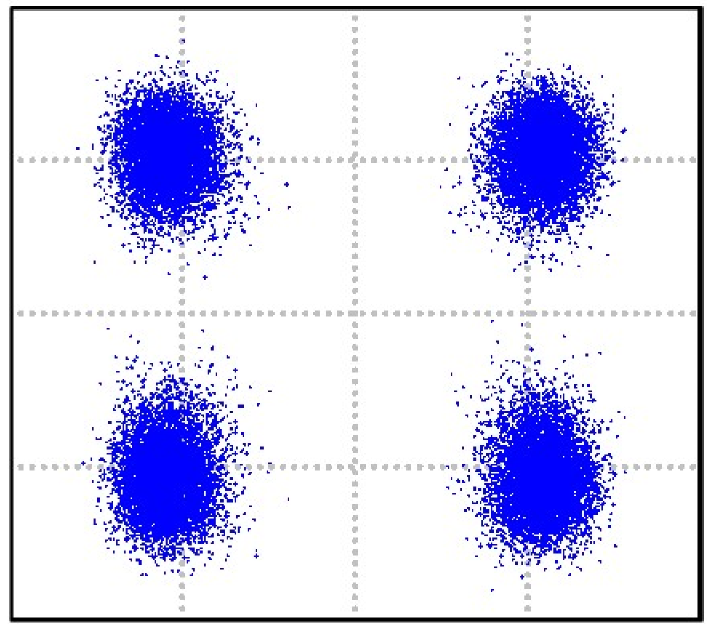
❑ The EVM of TX's output

6.4Gb/s QPSK



EVM=–18.8dB
(32767 symbols)

12.8Gb/s QPSK



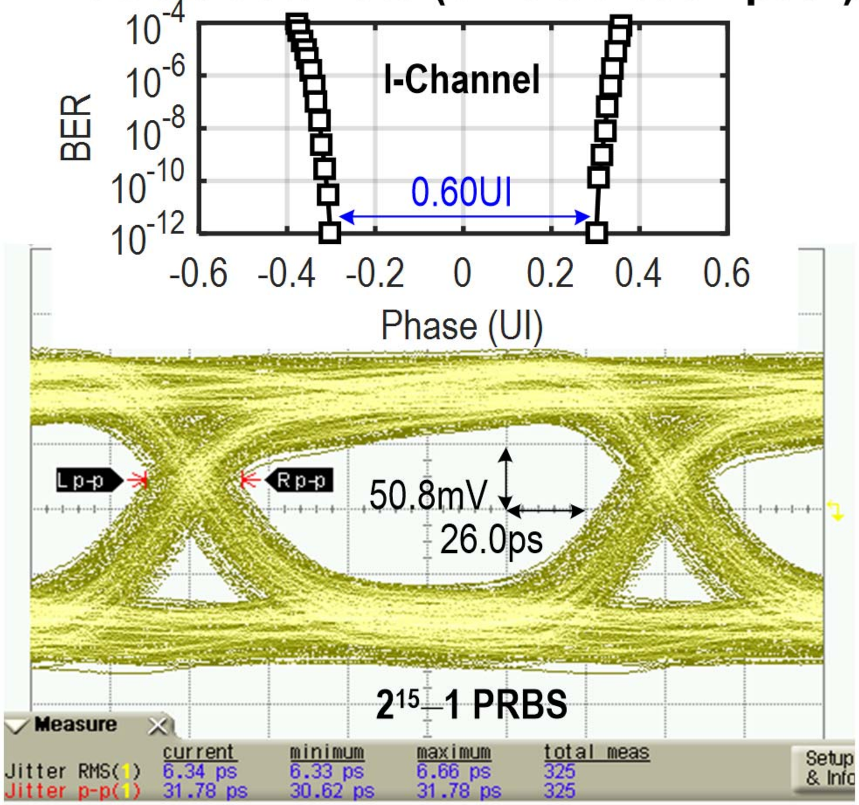
EVM=–15.6dB
(32767 symbols)

- Using 2^{15}-1 PRBS pattern, 32767 symbols collected
- Degraded due to insufficient OSC's BW

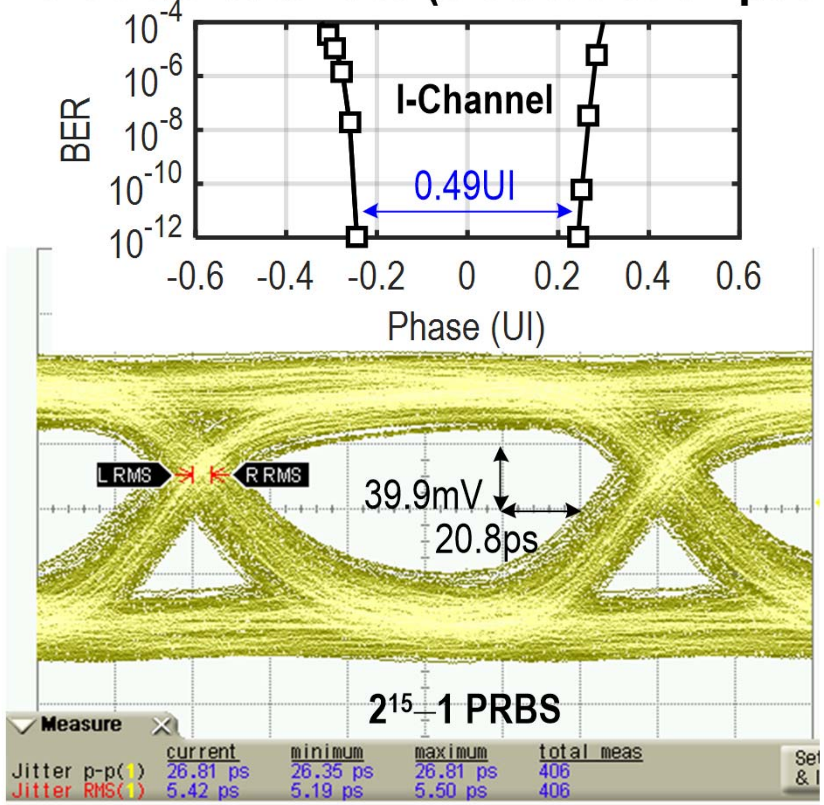
BoF Data Measured Results

❑ The eye and BER from BIST's output

12.8Gb/s data rate (6.4Gb/s each path)



16.0Gb/s data rate (8.0Gb/s each path)



- **0.49UI error free range at 16.0Gb/s data rate**

Performance Summary and Comparison

	This work	ISSCC15 [2]	ISSCC14 [3]	ISSCC13 [4]
Process	65nm CMOS	65nm CMOS	65nm CMOS	40nm LP CMOS
Freq. (GHz)	32	60	60	60
DR (Gb/s) (Mod.)	16.0 (QPSK)	7 (16QAM)	14.08/28.16 (QPSK/16QAM)	3.5/7 (QPSK/16QAM)
TX EVM (dB)	-15.6* (TX-to-BIST)	-21	-20.1/-20.0	-14.8/-15.2 (TX-to-RX)
TX P_{DC} (mW) Excl. LO	138	174	186	181***
TX Eff. (pJ/b)	8.6	24.9	13.2/6.6	78.4/39.2
CG (dB)	24.7	N/A	15	31
P_{-1dB} (dBm)	10.1	6.3	10.3**	10.8***
BIST	Yes	No	No	No
BER	$<10^{-12}$ (TX-to-BIST)	N/A	N/A	$<10^{-4}$ (TX-to-RX at 3.6m)
TX frac. BW (%)	46	N/A	N/A	10
TX Area (mm^2)	0.59	0.79	1.03	1.5*

*EVM at 12.8Gb/s **Saturated output power ***Each TX path

Summary

- Wideband 32GHz QPSK with integrated optical RX and BIST is presented
- Coupled resonator based wideband matching
  - Ripple cancellation using IF intrinsic LPF
- An error-free 16.0Gb/s data rate is achieved at 8.6pJ/b bit efficiency