High Density Silicon Photonics with integrated III-V EAMs for Coherent Optical Engines

QRock FY22 ENLITEND Annual Review

Roshanak Shafiiha, Guomin Yu, Aaron Zilkie
Rockley Photonics Inc.

Grad Students: Yujie Xia, Xinhong Du, Viviana Arrunategui-Norvick

Faculty: James Buckwalter, Larry Coldren, Adel Saleh, Clint Schow

UC Santa Barbara

Overview

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1. Rockley Si Photonics Platform Differentiations
2. Overview of QRock ENLITENED approach, challenges and differentiations
   - QPSK modulation implemented with III-V EAMs integrated in low-loss Si Photonics platform
   - Simplified driver requirements yield substantial power savings
   - >10X footprint reduction compared to Mach-Zehnder implementations
3. Accomplishments so far: Gen1 Characterization Results
4. Remaining Work: Gen 2 Schedule and Deliverables
   i. EAM, driver, and packaging improvements
5. Summary and Transition Plans

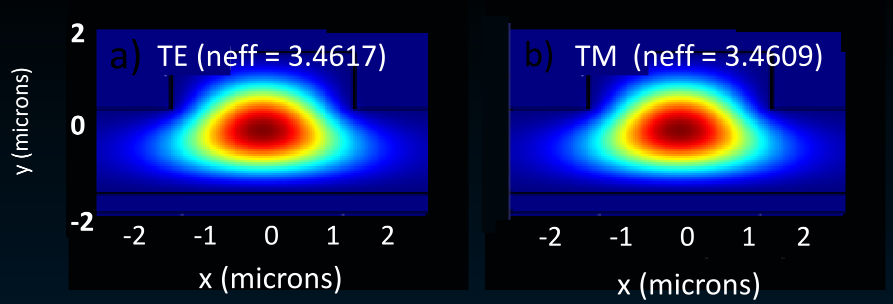
System level goals

Metric	State of the Art	Proposed	QRock Achievable
System Energy Efficiency	baseline	2X improvement	4-6X improvement (based on INTREPID)
TX+RX Energy Efficiency	20 - 40 pJ/bit (400ZR)	18 pJ/bit with 13dB link budget	< 10 pJ/bit
PIC Footprint	Baseline	10x footprint reduction	> 30x footprint reduction

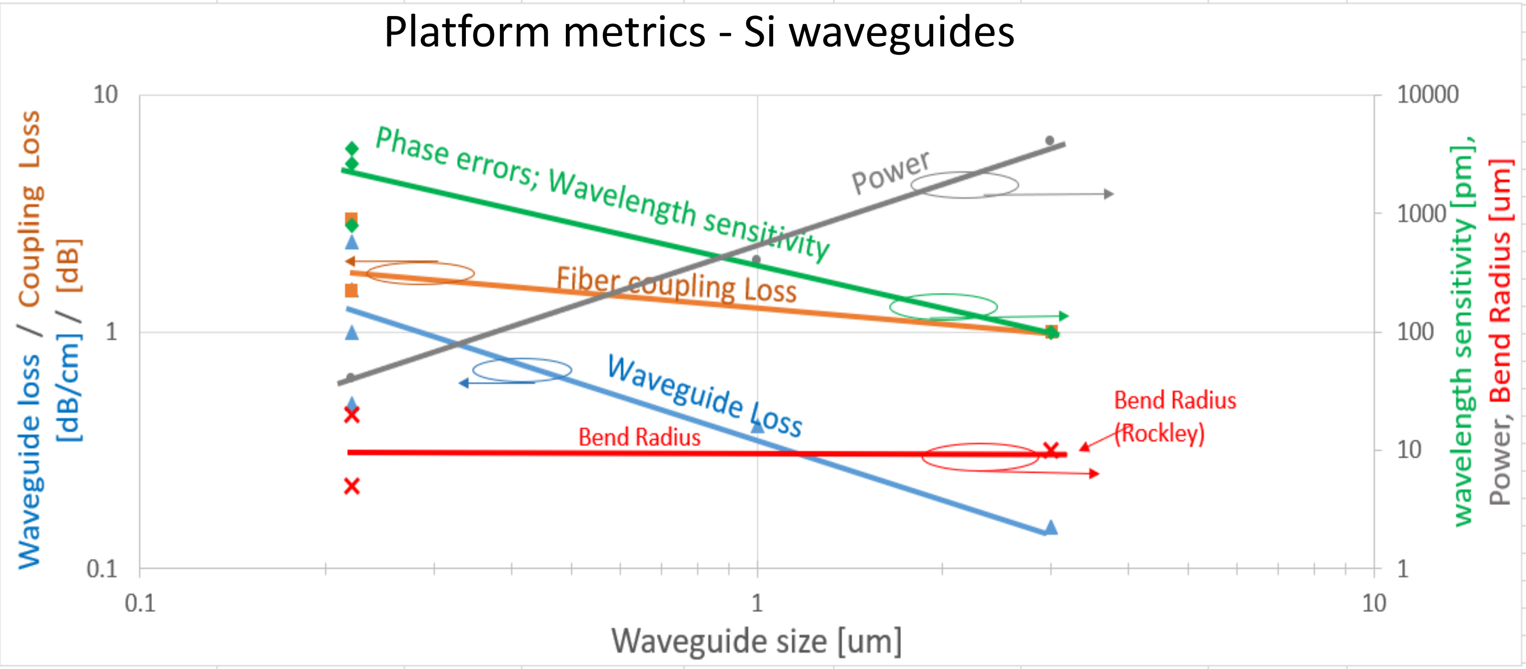
Rockley Photonics Platform Performance Advantages

Unique Benefits

- ✓ Low loss: (< 0.2 dB/cm)
- ✓ Large-scale PIC capability, high levels of integration
- ✓ Strong confinement: Tight packing and turns as well as dense layout capability
  - Low loss compact bends < 10-100 um R_{eff}
- ✓ Low polarization dependent loss (PDL)
- ✓ Low loss, passive align fiber couplers
- ✓ Low wavelength sensitivity, accurate WDM filters
  - filters have 25x reduced λ sensitivity and variations
- ✓ KGD III-V integration for high yield actives



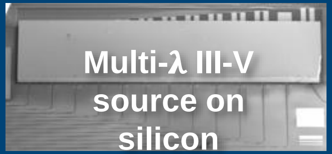
TE and TM polarizations have near-degenerate n_{eff} and mode profiles



Rockley Platform Technology Elements

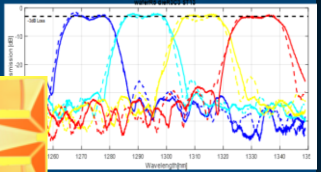
Wide Range of Platform Technology Elements to Address Multiple Market Verticals

Integrated Lasers
- High-density WDM lasers
- DFB, DBR lasers
- Tunable lasers, broadband sources

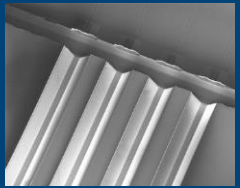


Modulators
- High-speed EAMs: Heterogeneous III-V 1310nm, monolithic SiGe 1550nm
- Carrier injection/depletion phase modulators

Mux / Demux / Filter Technologies
- AWG
- Echelle Grating
- Mach Zehnder Interferometers
- λ stable, process tolerant

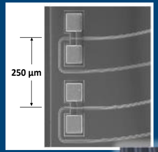


Fiber Edge-couplers
- Integrated V-groove mode matched to SMF

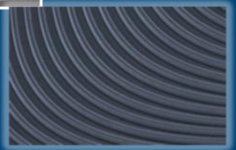


Other Passives
- Splitters, taps, combiners, …

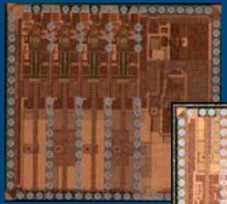
Photodetectors
- Monolithic Ge PD

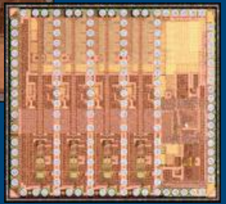


Euler Bends
- Tight waveguide bends for compact layouts



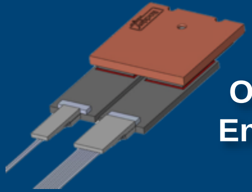
Analog Front End Electronics
- TX: Modulator & laser driver ICs
- RX: Transimpedance amplifier ICs

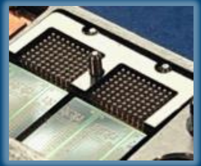




Receiver Architectures
- Direct-detect
- Coherent detection
- Large arrays, high integration densities

Packaging
- Wafer-level packaging
- Integrated fanout
- 2.5D/3D integration
- Passive fiber attach





III-V EA Modulators for Ultra High Density I/O

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- Electrical switch size limited by BGA package, sets requirements on data density
  - XSR interconnects allows substrate up to double size substrate to host CPO optical chips
- For 51Tb/s and 102 Tb/s switch ASICs with perimeter-integration:
  - **Densities of 200 Gb/s/mm and 400 Gb/s/mm are needed for optical I/O components**
  - Need compact modulators and detectors with pitches of ≤250 µm, channel rates of 100 Gb/s, and scaling to <125 µm and 200 Gb/s

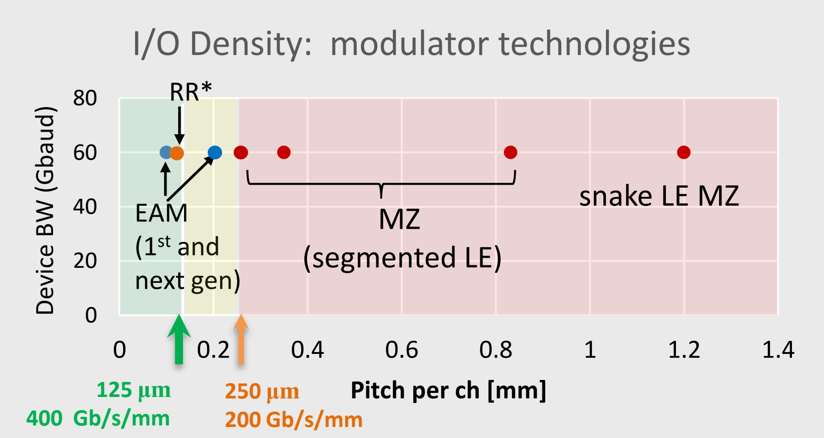
Electrical				Optical				
Switch				CPO	Faceplate Pluggable			
# lanes	Serdes rate (Gb/s)	capacity (Tb/s)	Electrical Data Density (Gb/s/mm)	Min Optical Data Density for XSR (Gb/s/mm)	lanes	capacity	modules	Faceplate size
256	50	12.8	100	50	8	400G	32	1RU
512	50	25.6	200	100	8	400G	64	2RU
256	100	25.6	200	100	8	800G	32	1RU
512	100	51.2	400	200	8	800G	64	2RU
1024	100	102.4	800	400	8	800G	256	4RU
1024	100	102.4	800	400	16	1.6T	128	2RU
512	200	102.4	800	400	8	1.6T	128	2RU

Choose InP EAMs for high density Si Photonics for CPO

- Si MZMs can not meet the integration densities needed for future CPO generations
- Rockley half-ring EAM and Si RR modulators meet the density requirements, and are roughly the same size
- RRs are very sensitive to temperature and fabrication variations and require more control pads
- EAMs have wide operating bandwidth allowing open loop operation over 30C operating T range, 0-70C with T control

Rockley U-bend EAM

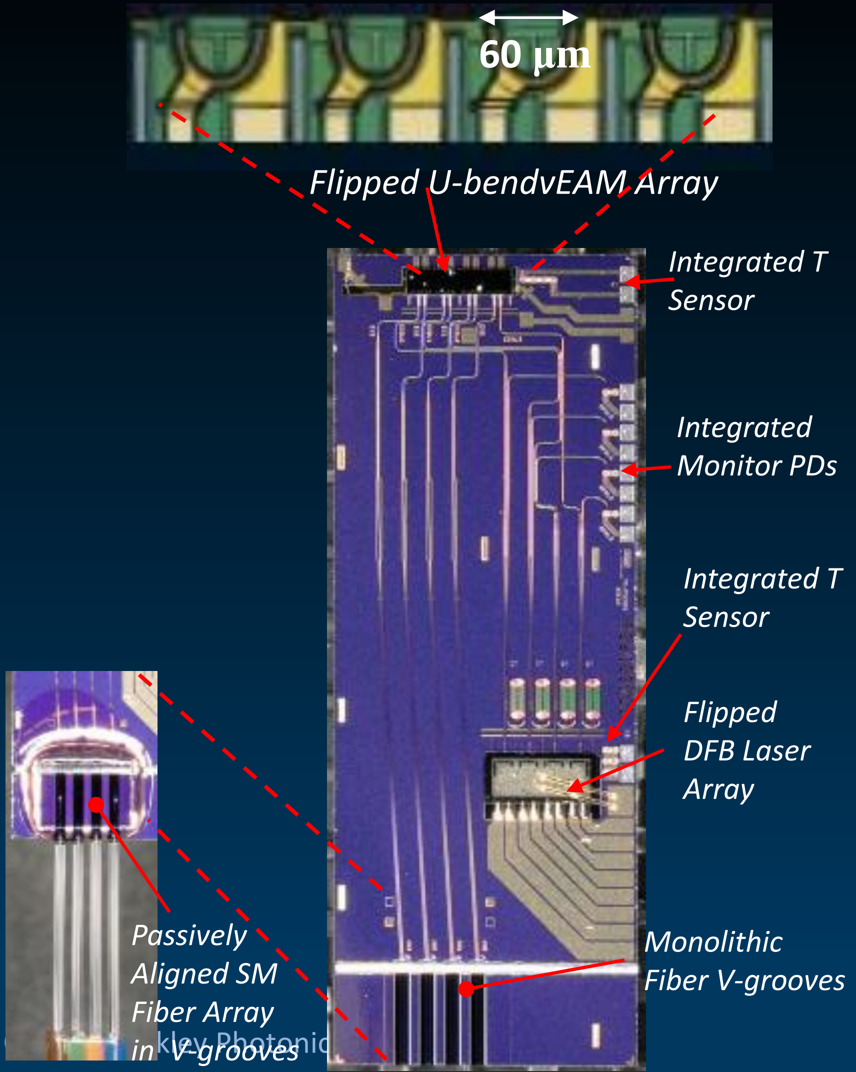
60 µm



*RRs are bigger in area when consider more drive + control pads needed

400G Tx and 400G/800G Rx Chipsets

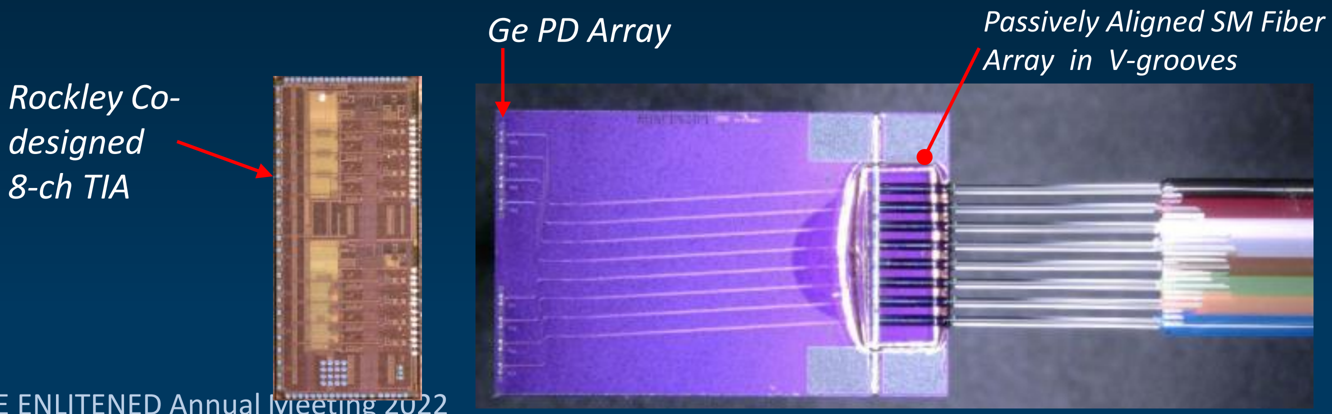
400G Tx PIC + Driver chipset



- Rockley DR4 400 Gb/s Tx and Rx PIC + Bi-CMOS Driver/TIA chipset
- Tx: Advanced planar coupon integration technology for EAMs and lasers scales to 3D integration and ultra-high throughput III-V integration for OEs and CPO
- Rx: PIC based on Rockley monolithic Ge PDs and compact passives supports high data densities needed for CPO

See also: A. Zilkie et al., JSTQE, 25 (5), p. 8200713, 2019
P. Srinivasan et al., ECOC 2019, 2019, pp. 1-3

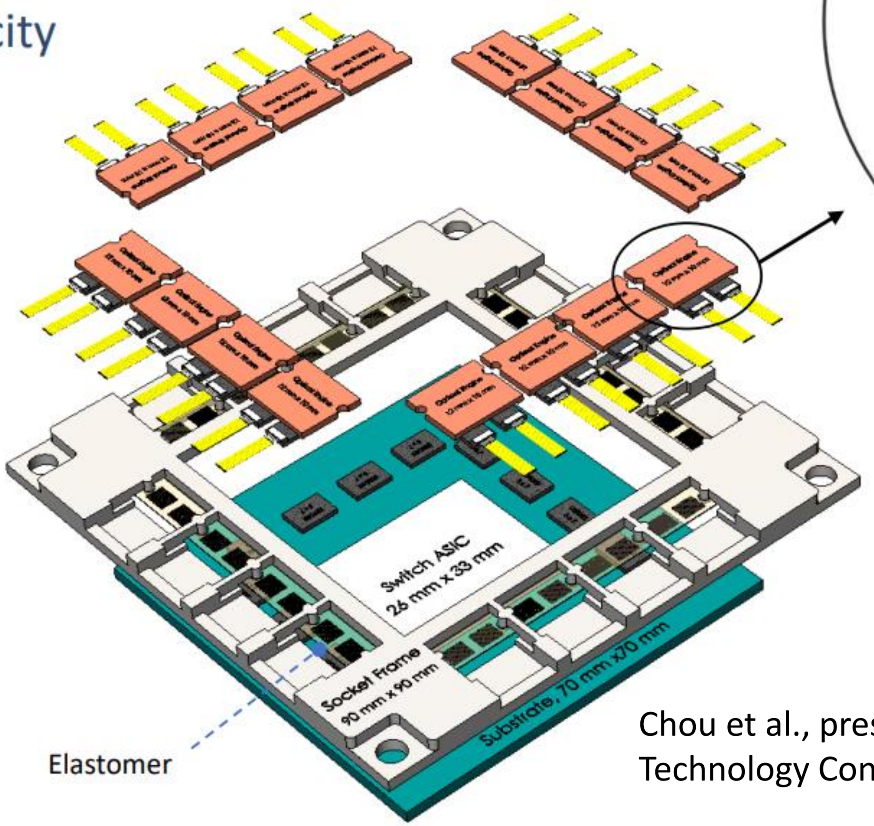
800G Rx PIC + Driver chipset

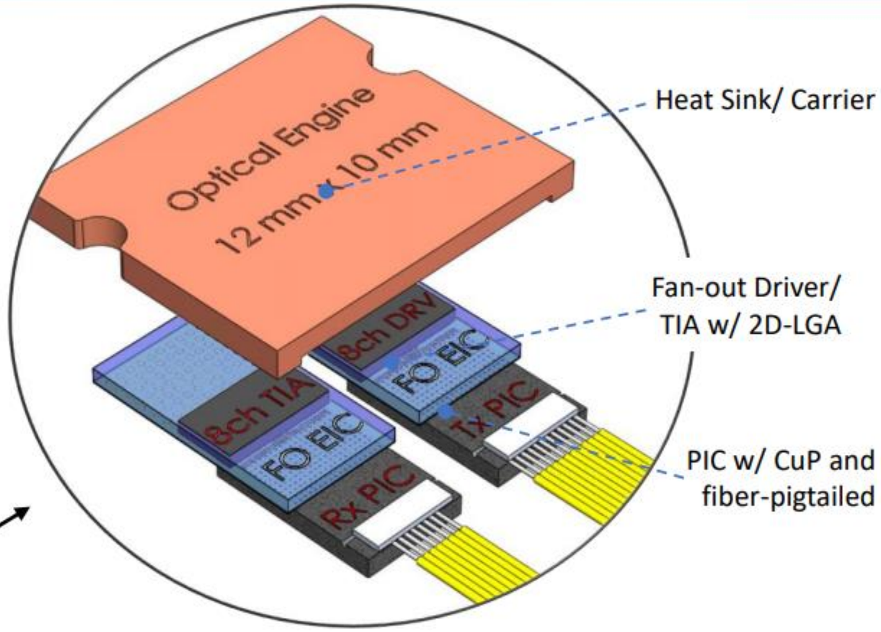


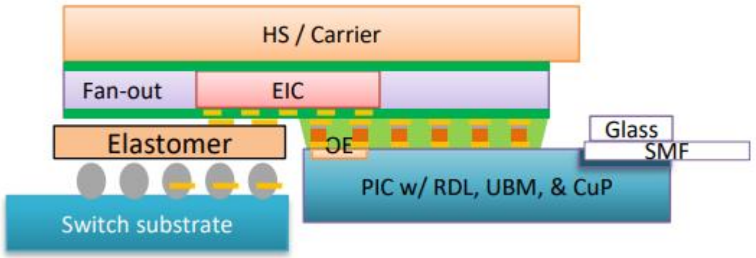
Rockley Optical Engine for CPO

- RP PIC platform (to be discussed next)
- Flip-chip of PIC on Fan-out EIC
- 8 channels @ 100 Gbps PAM4 → scalable to 3.2 T Optical Engine
- 16 Engines → 51.2 T capacity

Mechanical model (OFC 2020)







Chou et al., presented at IEEE 72th Electronic Components and Technology Conference (ECTC) , San Diego, CA, May 31, 2022

ENLITENED QRock - Coherent Tx with III-V EAMs

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- ➢ <u>Differentiators</u>

i. At least 10x Higher linear density coherent solution with U-bend III-V EAM compared to MZM solution, path to I/O densities of 10Tb/s with Rockley Compact U-bend EAM and integrated WDM MUXs/DEMUXs
   - up to 30x smaller length, > 2x smaller width (~50x smaller area)

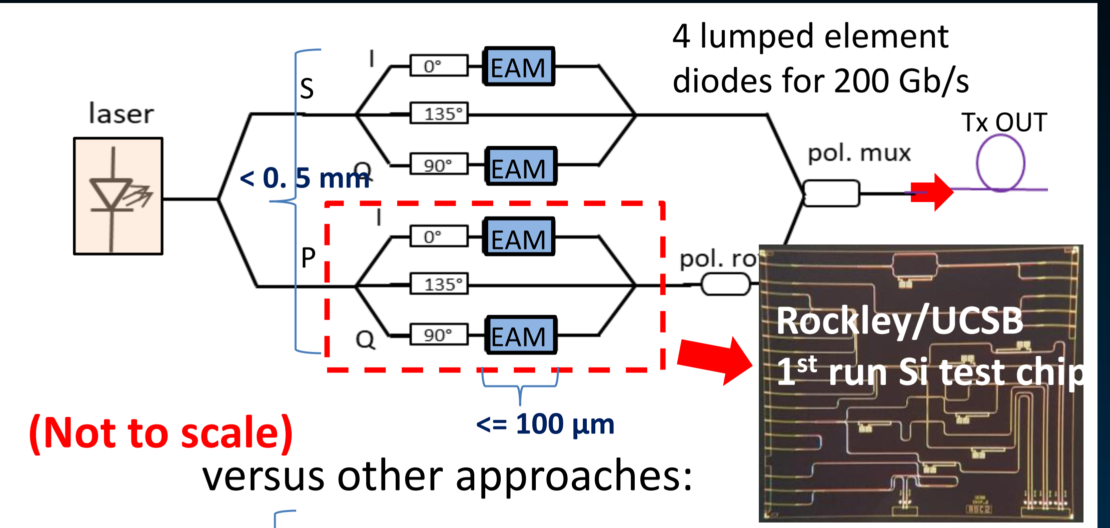
ii. Simpler to control (no phase balancing and impedance matching needed), less phase variations in multi-micron platform

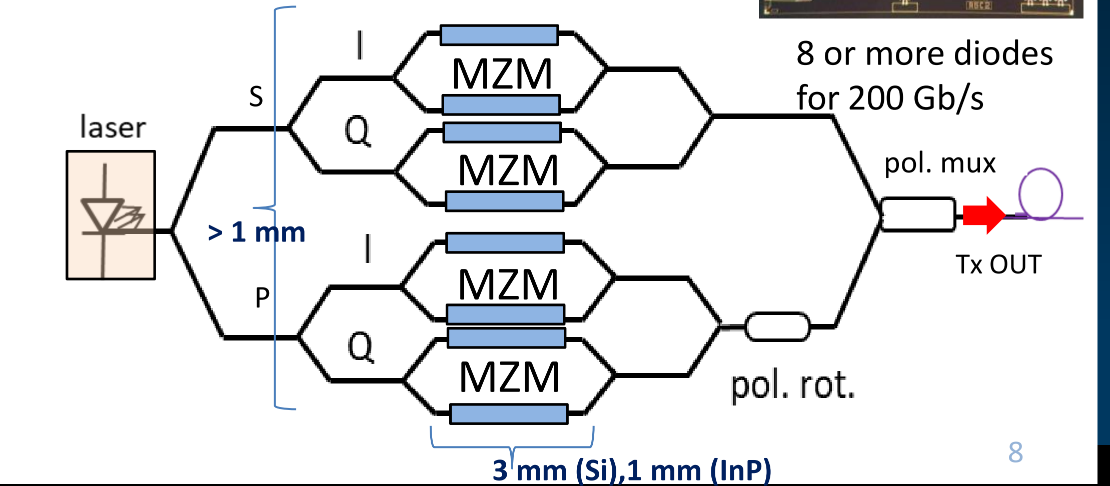
iii. Brings benefits of Rockley platform – CPO optical engine platform, polarization independence, low losses, high integration densities,

iv. Full range of integrated III-V actives allows for integrated III-V lasers and/or MZMs as well as needed

- ➢ Tradeoffs – 6-8 dB higher Tx losses, higher laser power
- ➢ **Further energy-improvement architecture evolution possible with addition of AWGRs, WDM switches and/or fiber switches**

Tx with parallel EAMs concept from Doerr at el. PTL 19 (15) p. 1184 (2007)





Unique design - QPSK Modulator Based on EAMs

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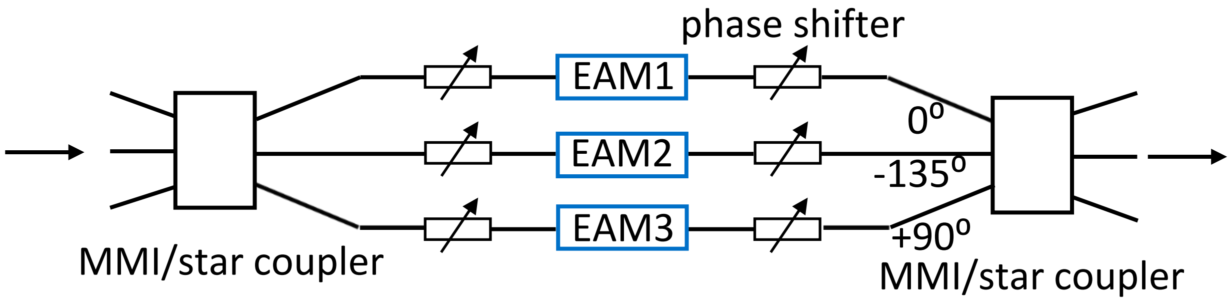

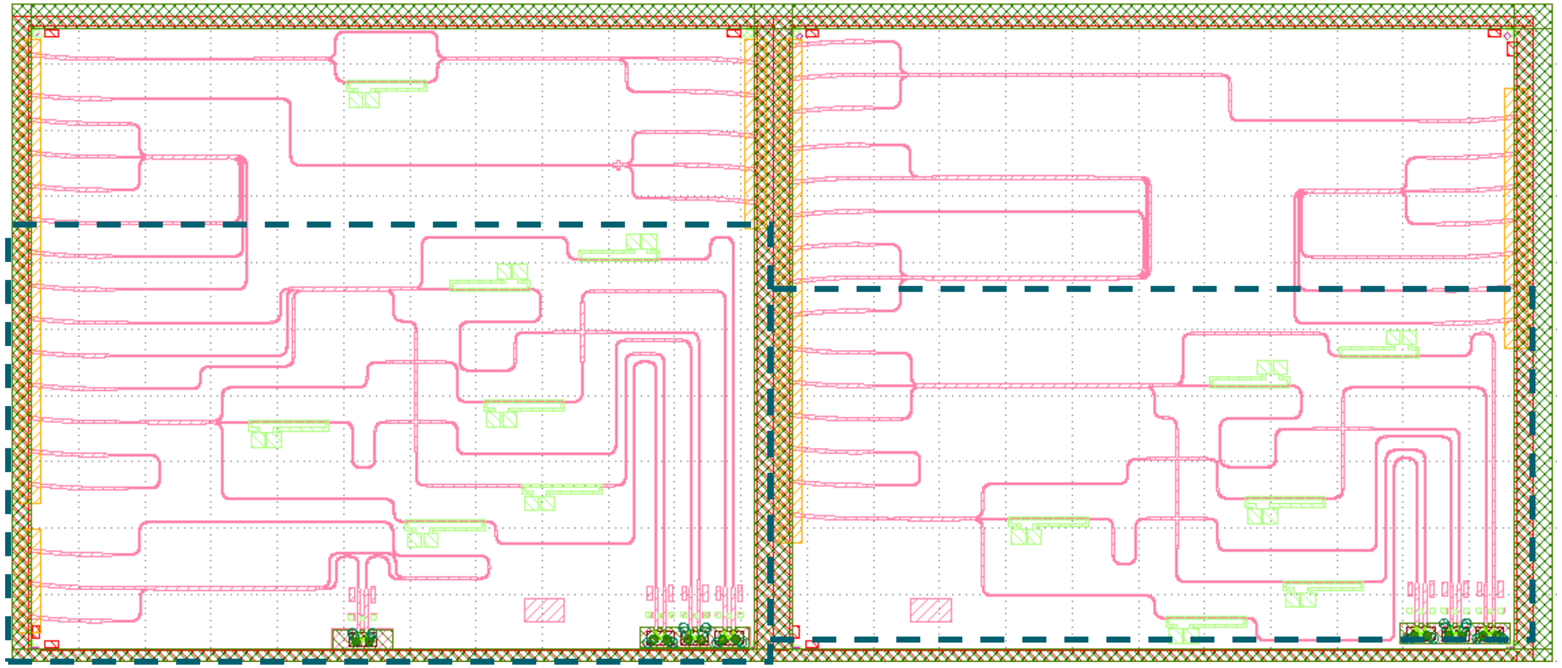

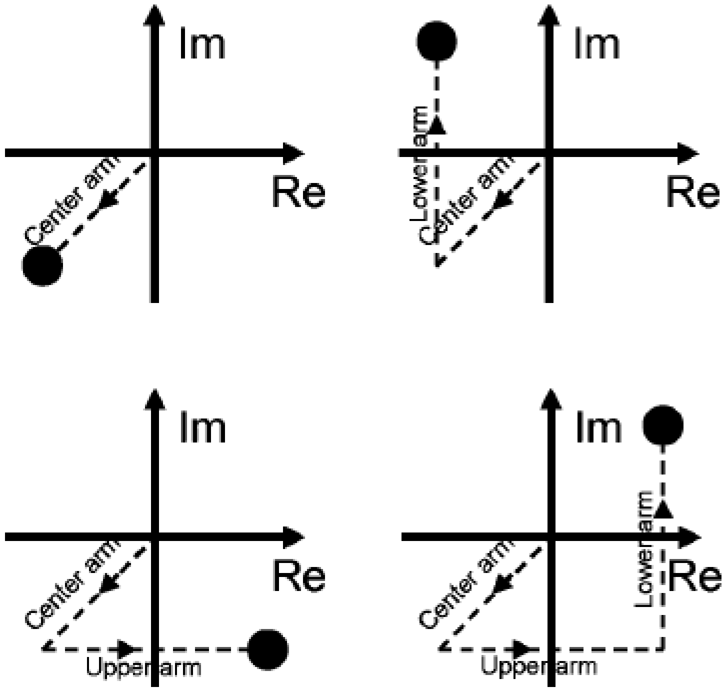

C. R. Doerr *et al.*, "Compact High-Speed InP DQPSK Modulator," in *IEEE Photonics Technology Letters*, vol. 19, no. 15, pp. 1184-1186, Aug.1, 2007

- EAM1 and EAM3 need RF modulation; EAM2 only needs DC bias for adjusting power ratio

UCSB 130 nm BiCMOS 50-Ω differential driver

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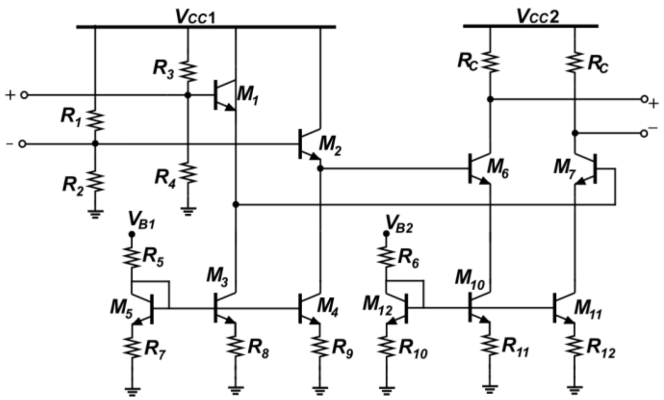
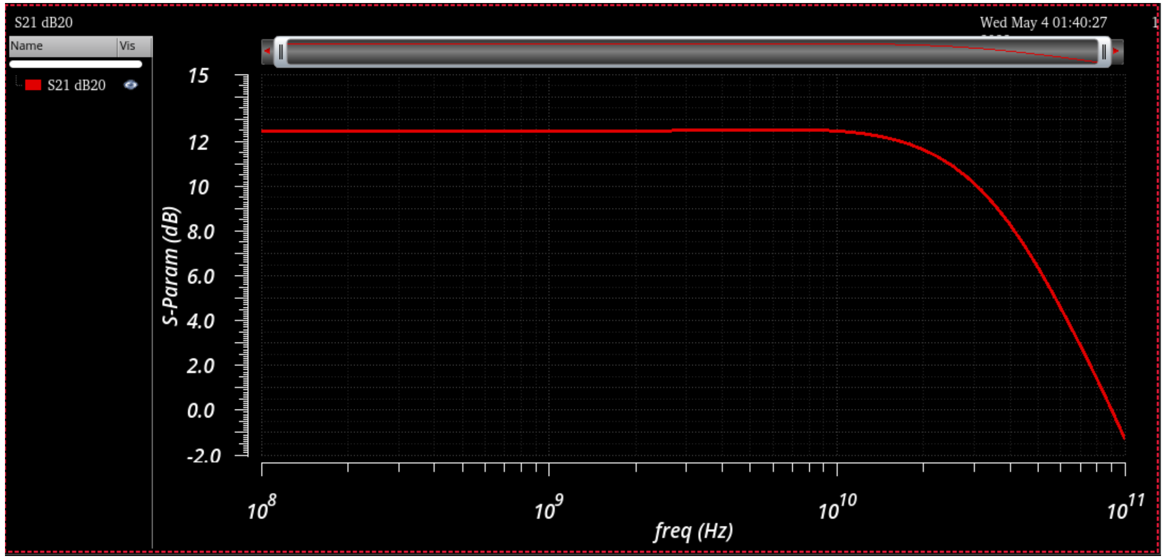
- 2-stage 50-Ω output driver
- 50-Ω input buffer
- Emitter-coupled differential pair output
- 34 GHz BW
- 12.5 dB single-ended gain

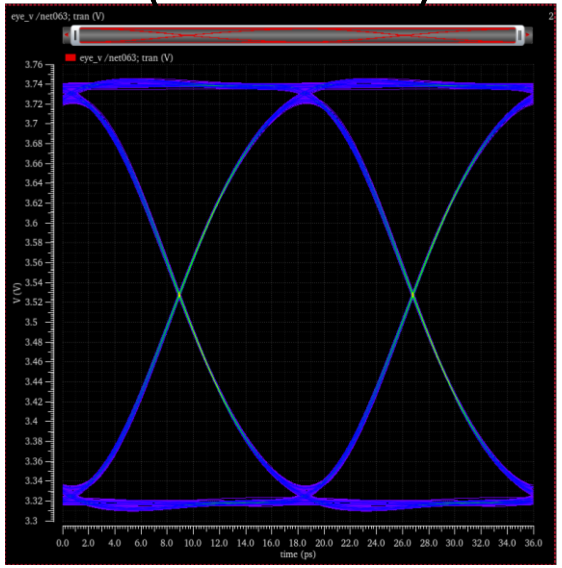


Schematic of one stage

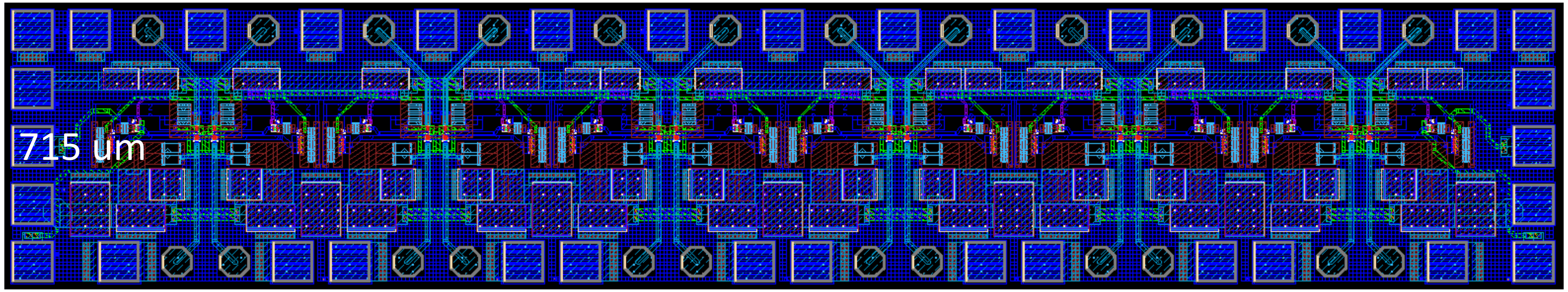
Simulated S_{21}



Simulated 56 Gbps eye (50-Ω load)



4 mm



Gen 1: Progess on QPSK signal generation

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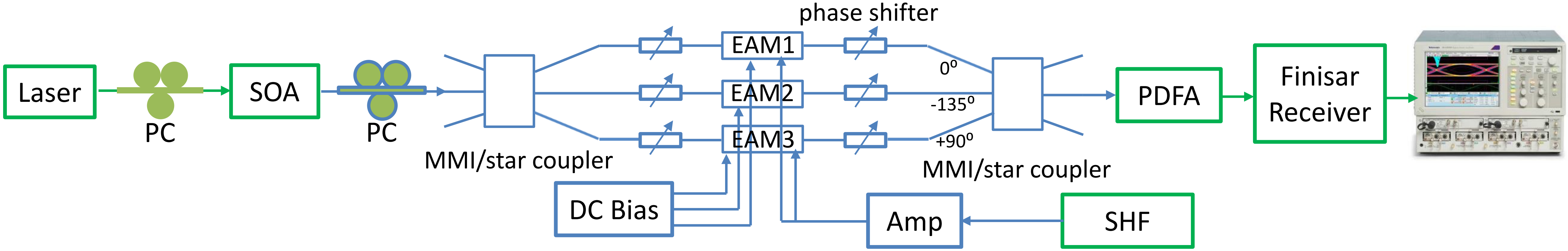
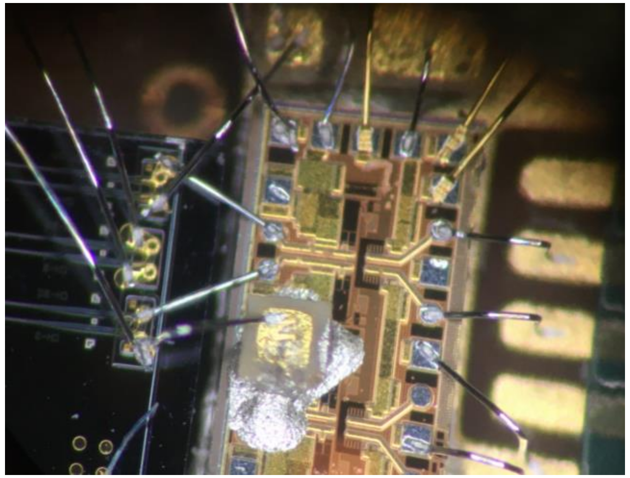
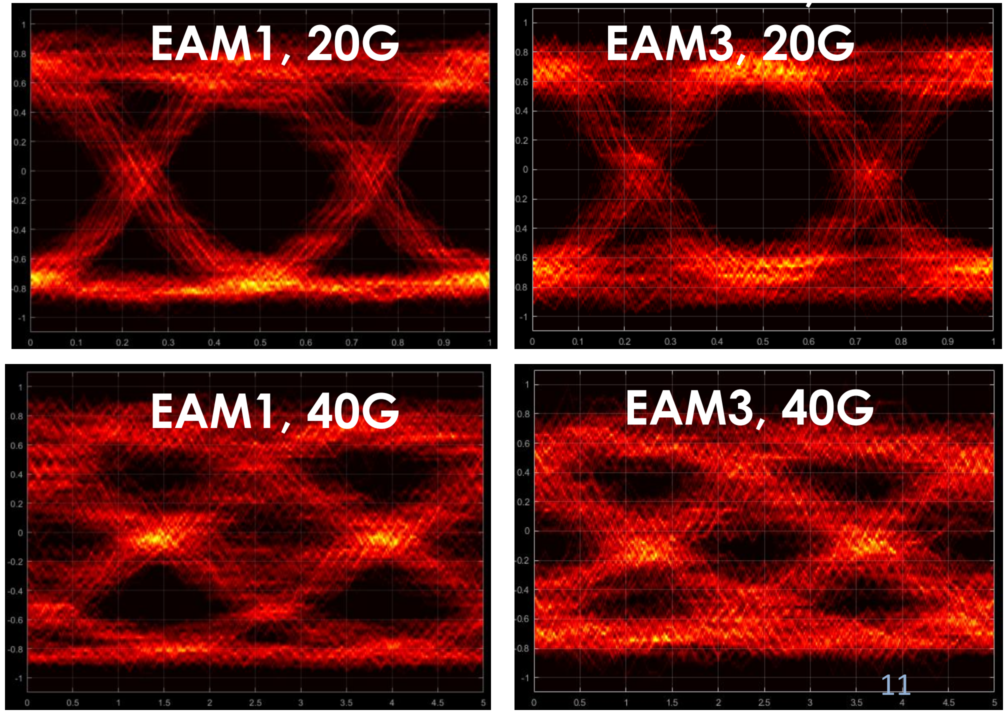


- Bandwidth limited by long wire bond at EAM cathode
- OOK 20G and 40G eyes are indicative of QPSK modulation
- Verified that phase shifters provide sufficient tuning range to set a QPSK operating point
- To be verified with constellation measurements



PIC Driver Board



ENLITENED QRock - High Density Coherent Rx

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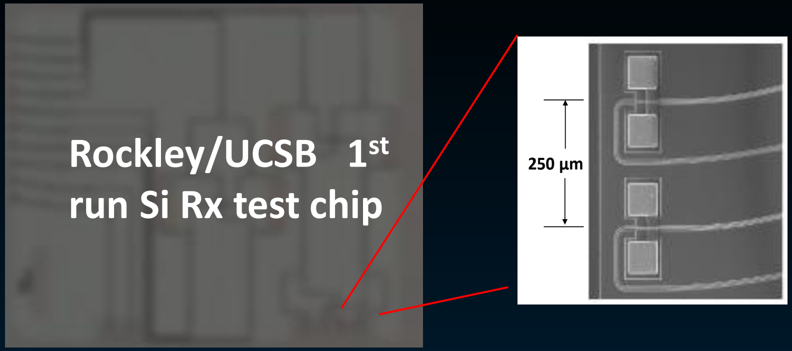
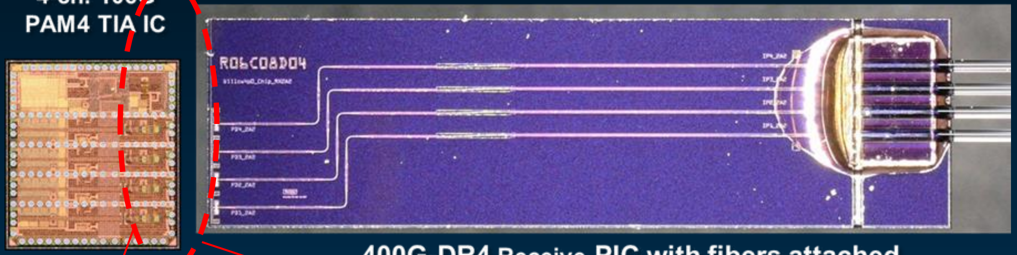
- Monolithic Ge detectors in multi-micron platform ideal for coherent Rx:
  - Unique advantages:
    1. Accurate MMI splitters for Coherent Hybrids with low variability
    2. Reduced phase imbalances
    3. Natively polarization independent
    4. Inherently broad band
- Rockley's TIA co-designed with 3-Terminal differential PD pair gives ultra-low balanced receiver dark current performance
- Rx PIC based on Rockley monolithic Ge PDs and compact passives supports data densities needed for Coherent solutions and CPO

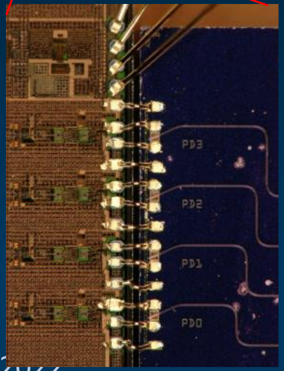


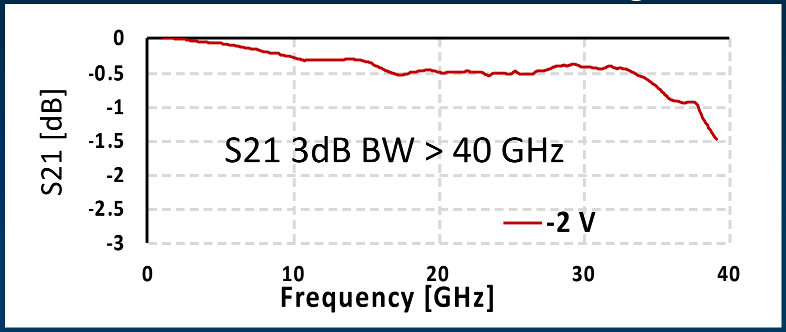
4-ch. 106G PAM4 TIA IC



400G-DR4 Receive PIC with fibers attached

SMF fibers passively aligned in V-grooves





Gen 1: 1 pJ/bit Coherent Rx demonstrated

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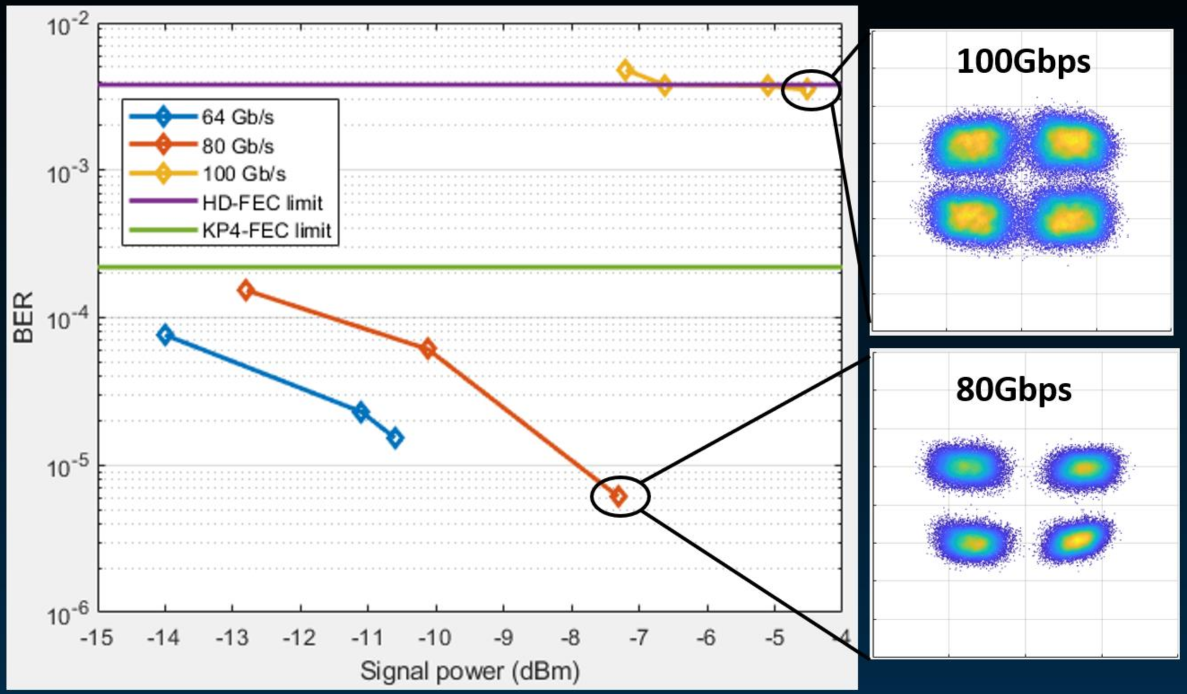
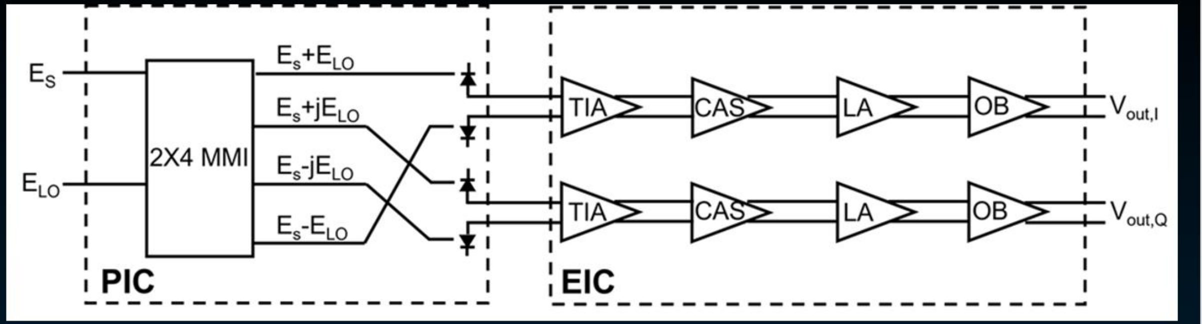
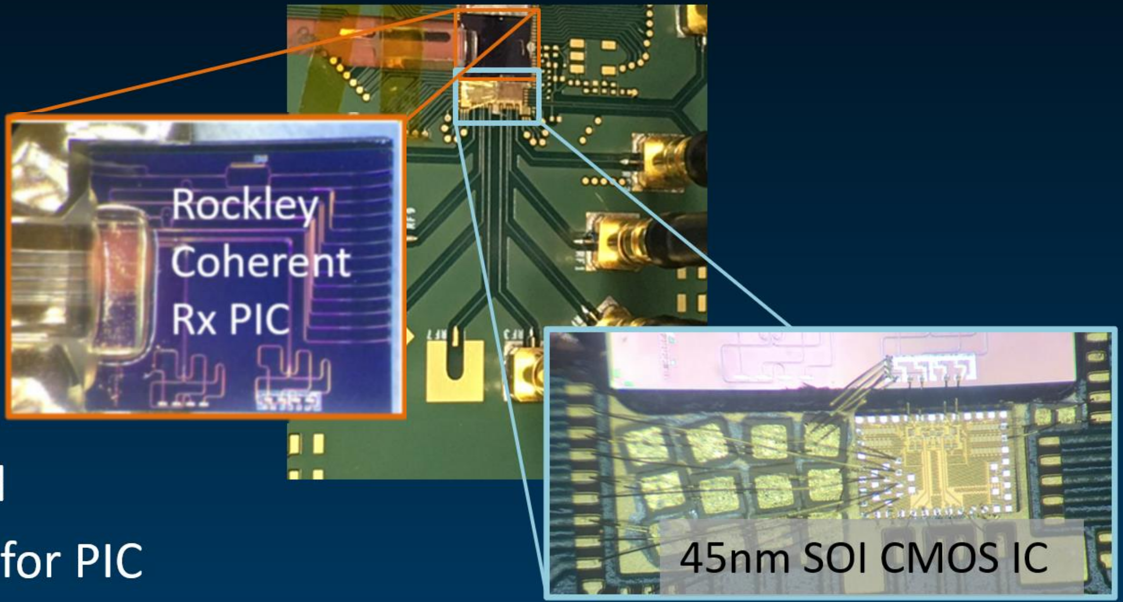


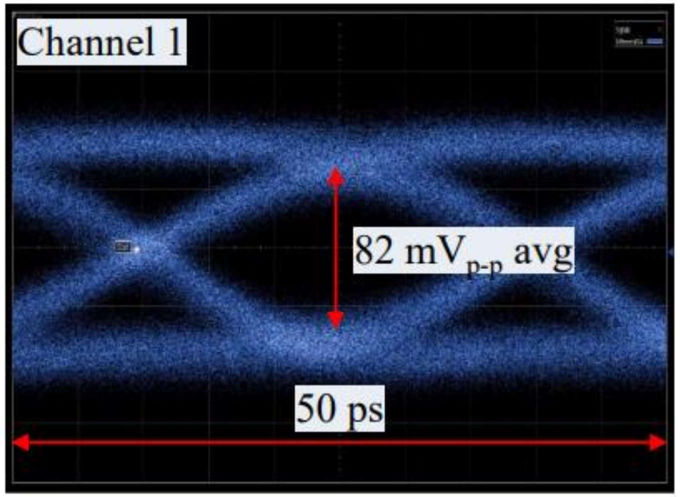


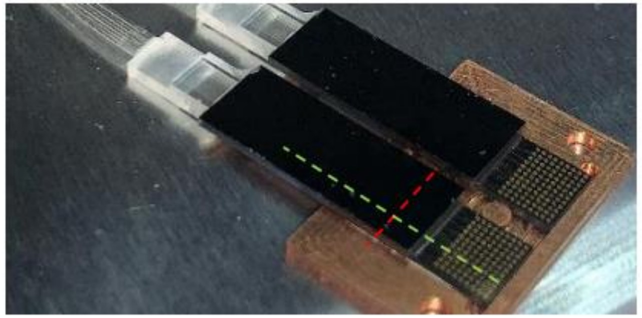


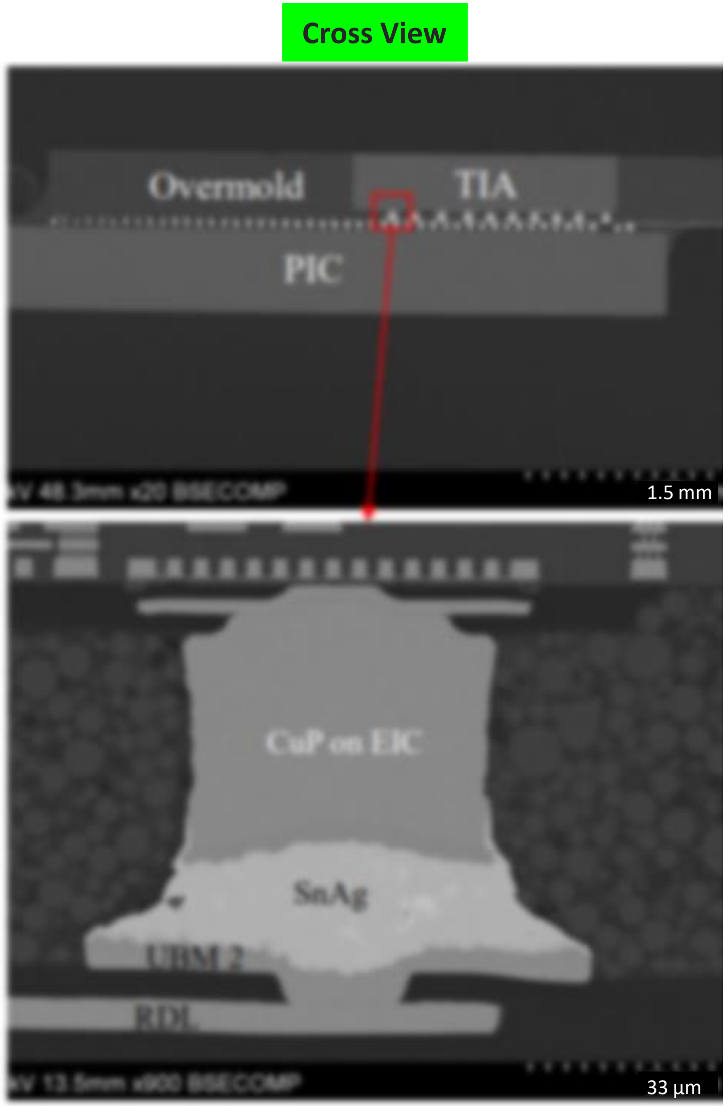
- 100 Gb/s operation below HD-FEC BER limit demonstrated
- 98 mW EIC power consumption, no tuning power needed for PIC
- High 0.5 A/W responsivity of PIC measured from fiber facet to PD

Rx Optical Engine Results – 25 GHz NRZ

- Demo Rx Optical Engine built using QRock PDs and 25 Gbps NRZ TIA
- Short electrical connection from OE to EIC (TIA) confirmed by cross-section
  - 50 um CuP x 2, 120 um combined RDL, 220 um total
- 25 Gbps/ch NRZ open eyes successfully demonstrated, error free operation
- 100 Gbps PAM4 did not result in clean eyes with Gen 1 chipset
  - Rockley internal Gen2 chipset has demonstrated 100 G PAM4







Gen 2 EAM and Driver - Optimized Co-Design

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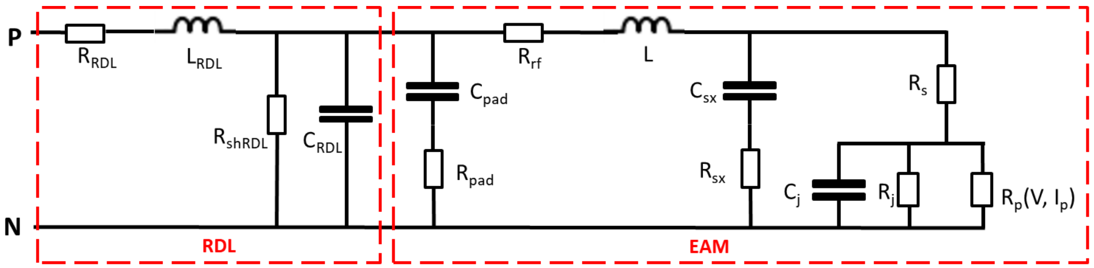
➢ Gen 2 EAM - new waveguide shape and new RF electrode driven either from N side or P side

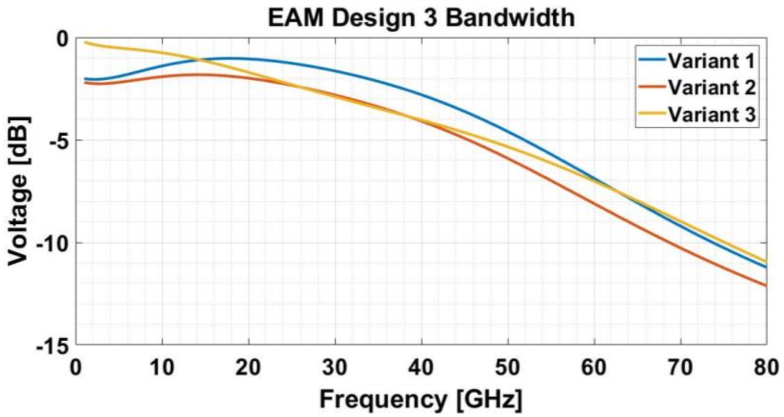


		RDL				EAM											
Temp (°C)	Bias Voltage (V)	L_{RDL} (nH)	C_{RDL} (pF)	R_{RDL} (ohm)	Rsh_{RDL} (ohm)	Pad-Resistance Rpd (ohm)	Pad-Cap Cpd (fF)	RF Trace Eq Resist Rrf (ohm)	Inductance L (pH)	Sub-Resist Rsx (ohm)	Sub-BOX Cap Csx (fF)	Series Resist Rs (ohm)	Junction Resist Rj (ohm)	Junction Cap Cj (fF)	Bias Photocur Ip (mA)	Bias Photocur Eq Resist Rp(ohm)	BW (50Ω driver and 50Ω termed probe) (GHz)
															0.0	-	
	1	0.0496	0.0293	3.79	889	0.1	10	8.52	87.7	5	11.8	24.0	6.00E+08	46.6	0.5	2000	~40 GHz
															0.79	1266	

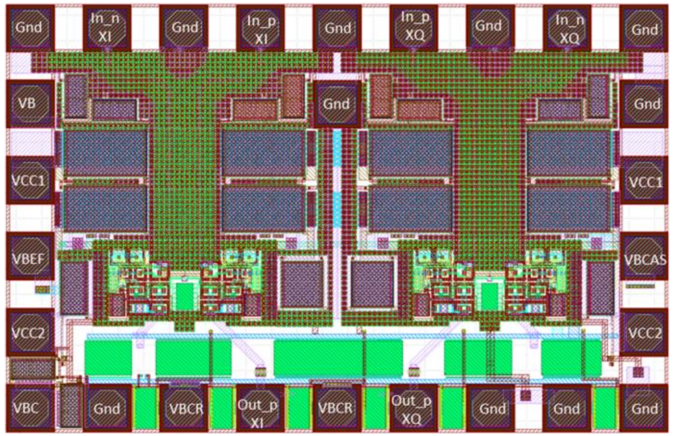
➢ Gen 2 Driver - Custom Flip-Chip Layout

Driver optimized using EAM model

- 150 um pitch
- 75 um x 75 um bondpads
- Three variants taped out with different load and anode resistors



	Variant 1 60Gb/s	Variant 3 60Gb/s
Power [pJ/bit]	10.27	6.33



System-level power benchmarking and conclusions

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1. Parallel EAM approach has the lowest power consumption
   - significantly lower modulator + driver power consumption,
   - laser power needs to be higher to overcome the additional passive splitter losses associated with the scheme architecture.

2. The InP MZM analog coherent scheme is also competitive, lower power consumption than the Si MZM analog coherent scheme
   - InP phase modulators more efficient (have a lower Vpi*L
   - better modulation factor and lower link budget penalty
   - lower laser powers, as well as less drive voltage.
   - may have the potential to have further reductions in power consumption if CMOS drivers to be used.

3. 200 Gb/s/λ PAM-4 parallel EAMs scheme has competitive power consumption to the lowest-power analog coherent approaches

-	**Power Consumption**					
Component	**200 Gb/s Si MZM Analog Coherent**	**200 Gb/s InP MZM Analog Coherent**	**200 Gb/s parallel EAM Analog Coherent**	**200 Gb/s parallel EAM PAM-4 (next gen)**	**100 Gb/s Si MZM PAM-4 DR4**	**100 Gb/s EAM PAM-4 DR4**
Tx Laser [mW]	100	50	330	315	50	79
Rx LO [mW]	100	50	50	0	0	0
SOA [mW]	100	100	0	0	0	0
Modulator + Driver [mW]	1000	680	180	600*	800*	400*
TIA [mW]	664	664	664	540	166	270
OPLL [mW]	186	186	186	0	0	0
Total Power [W]	2.15	1.73	1.41	1.46	1.02	0.75
pJ/b	**10.8**	**8.7**	**7.1**	**7.3**	**10.2**	**7.5**
* Includes power consumption for FFE equalization required to meet equivalent BER						

Conclusions and Transition Plan

- Rockley Photonics offers a versatile silicon photonics platform that uses III-V U-bend EAMs and monolithic Ge PDs providing advantages for integration density and power efficiency
- Rockley Photonics has developed a 400-800G DR4 TRx technology that can be used for traditional pluggable transceivers as well as a socketable OE version w/ FOWLP for CPO
- QRock Approach - Silicon Photonics with integrated III-V EAMs for Coherent Optical Engines:
  1. A Tx PIC concept with parallel EAMs that can have lowest power consumption and most compact size compared to other coherent Tx PIC solutions (characterization results to be reported in future)
  2. Demonstrated Rx PIC which has excellent performance and is simple to operate