Optica

Co-packaged SiPh based optical transceivers for high-speed data-center interconnects

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Acknowledgment

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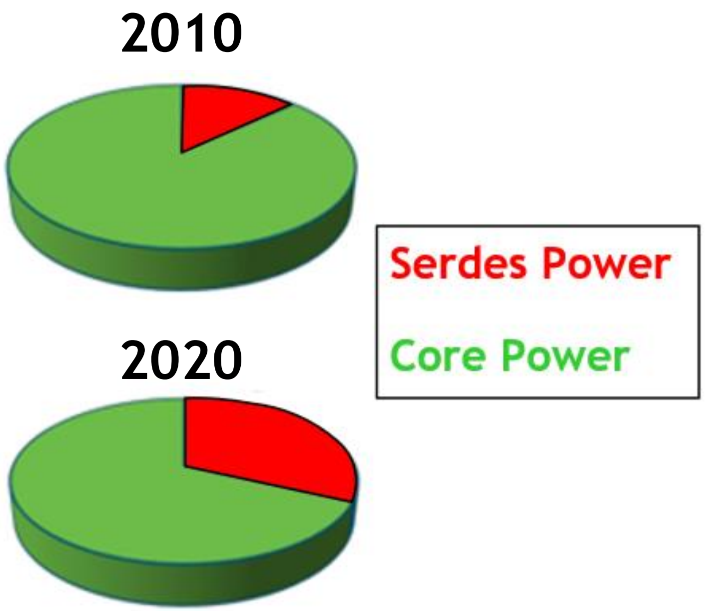
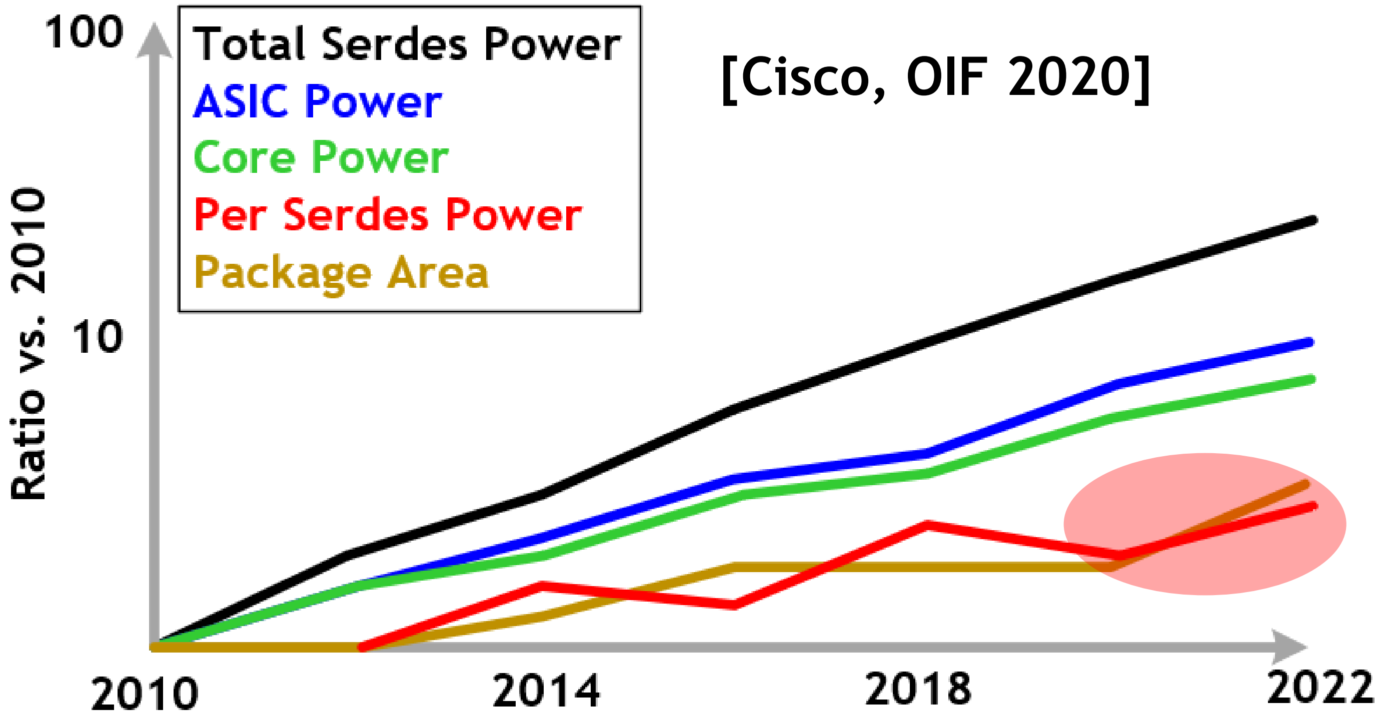
- Intel PHY Research Lab
- Intel Silicon Photonics Product Division (SPPD)
- Intel Assembly and Test Technology Development (ATTD)

Outline

- **<u>SiPh platform for high-speed DCI</u>**
- IMDD optical links
- Photonic devices
- CMOS electronics for single-λ links
- Wavelength-division multiplexing
- Future directions and conclusion

Introduction: Limits of Electrical I/O

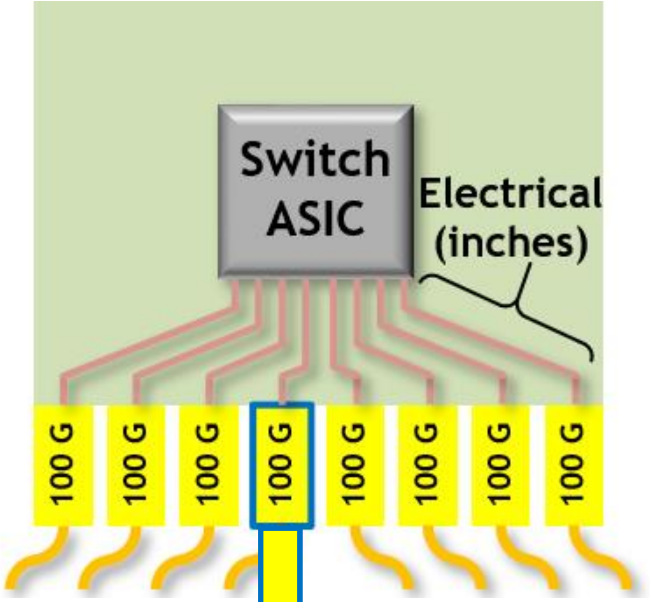


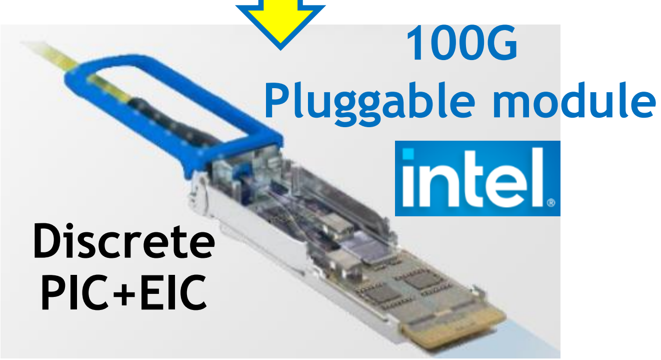


- Bandwidth limitation: Frequency-dependent channel loss.
- Power limitation: I/O power can exceed package limit.
- Package limitation: Pin count and package size scaling are unsustainable.

Optical I/O Pluggable Module

HVM product

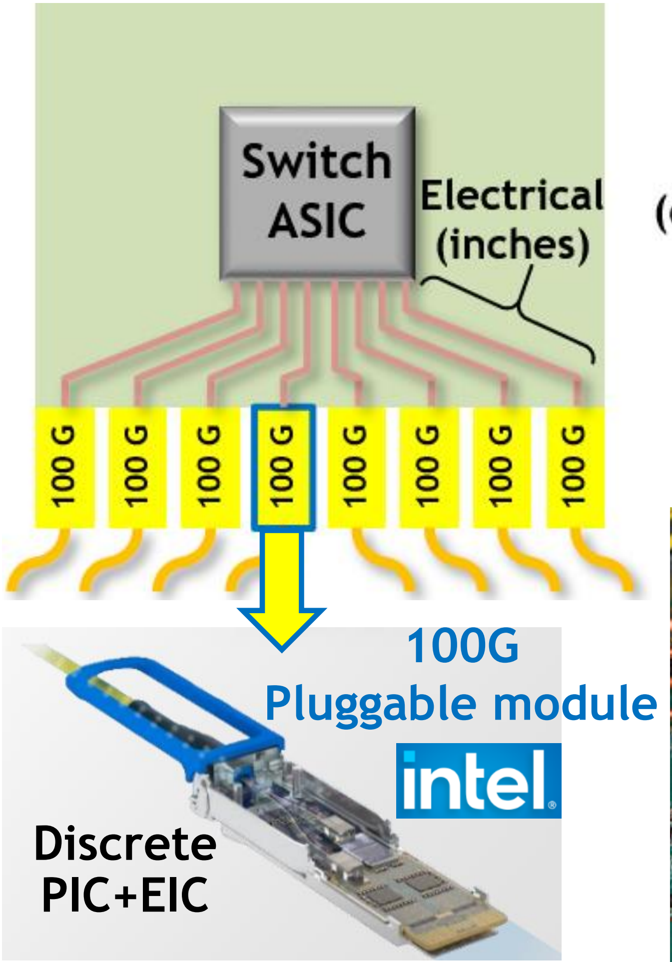




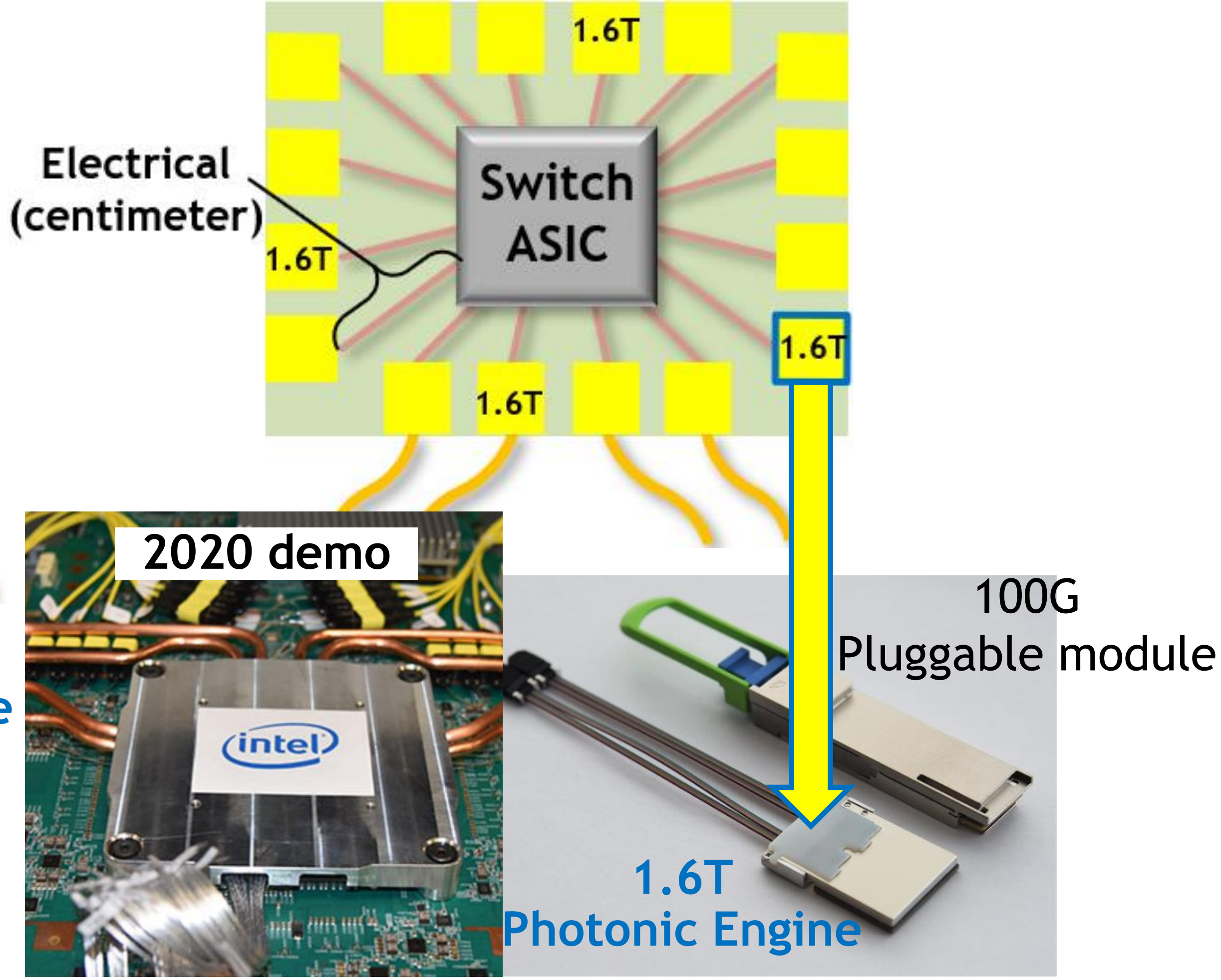
Current high-volume product is an I/O module that plugs into a rack.

Co-packaged SiPh Optical I/O

HVM product



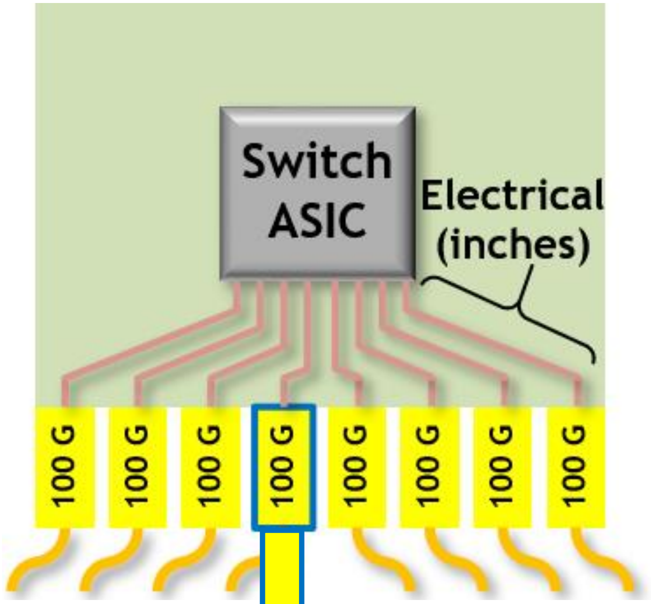
2020 Demo

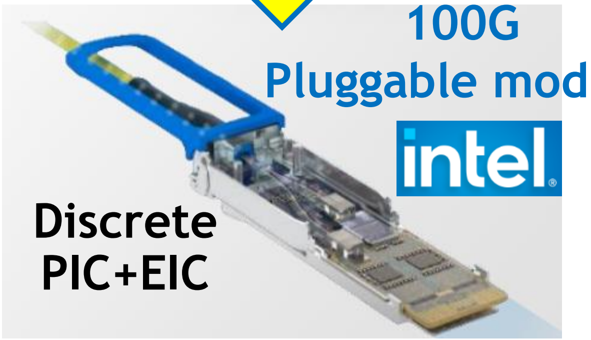


Silicon photonics brings optics closer to ASIC.

Co-packaged SiPh Optical I/O

HVM product

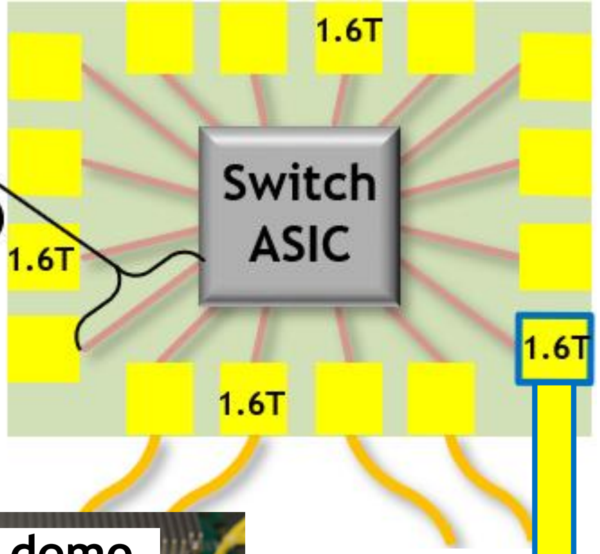


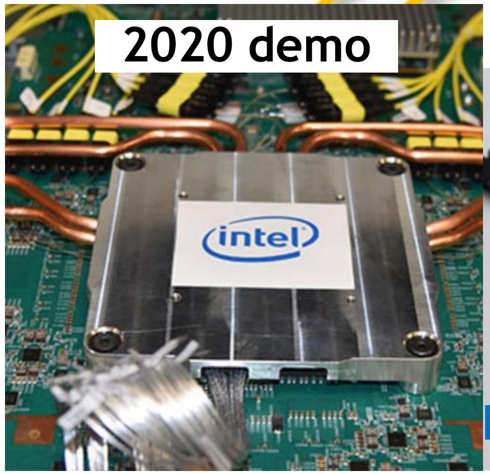


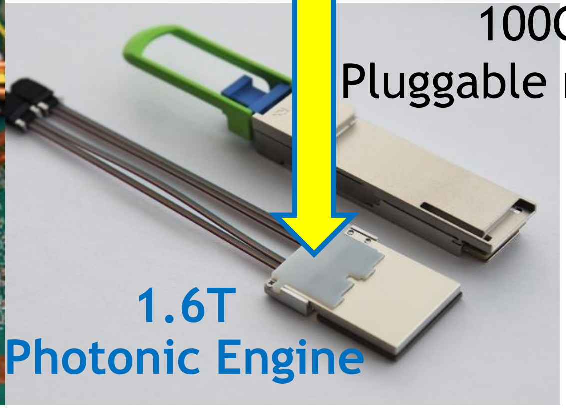
100G
Pluggable module

Discrete
PIC+EIC

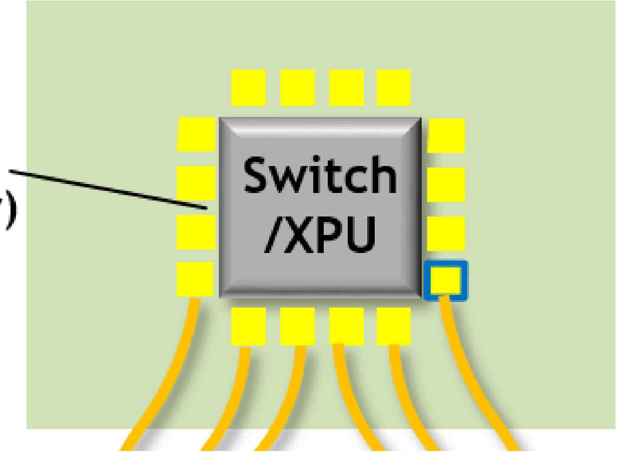
2020 Demo







Future



Silicon photonics brings optics closer to ASIC.

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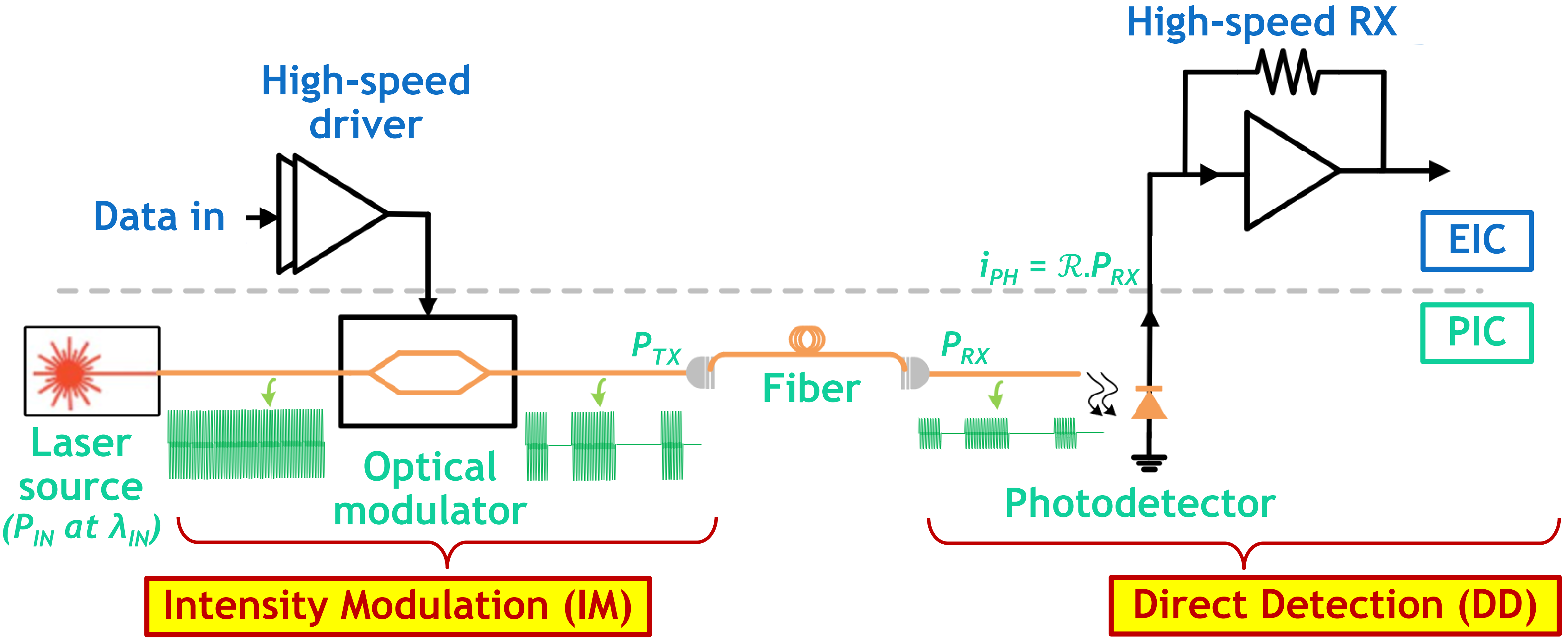
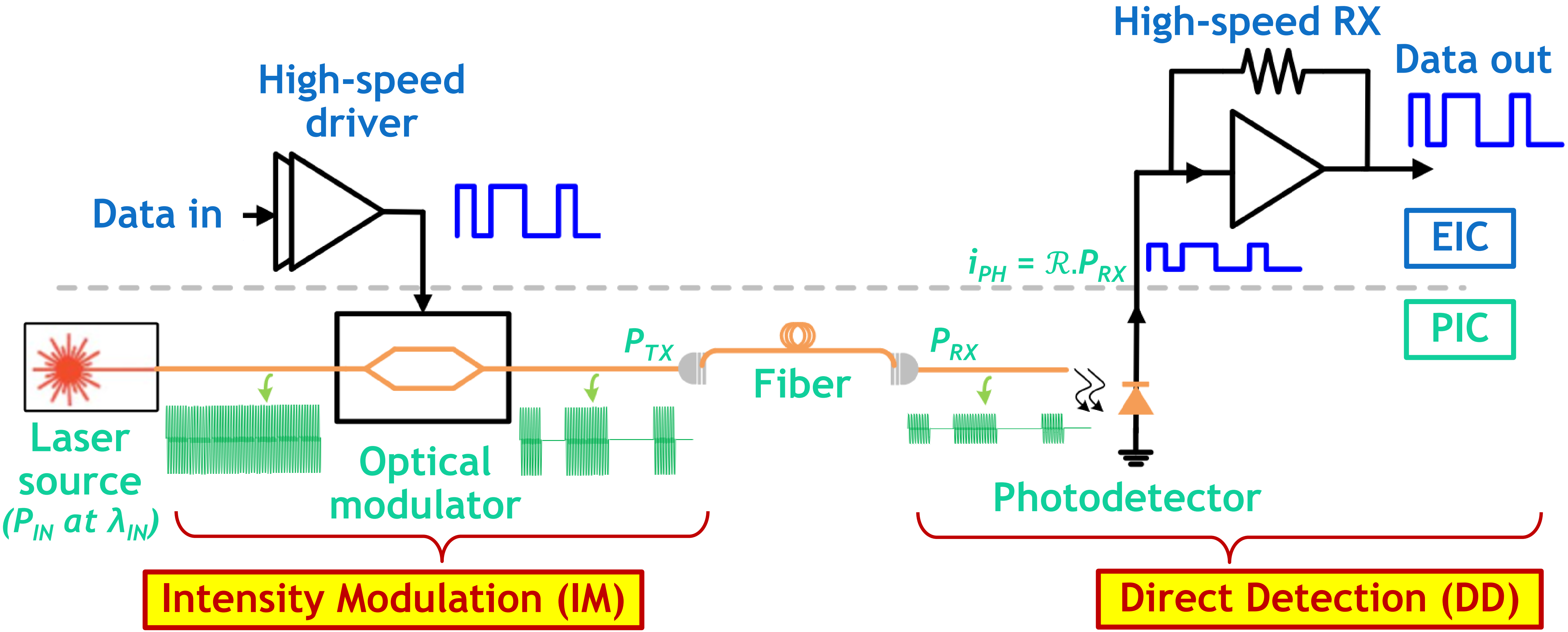
- SiPh platform for high-speed DCI
- **IMDD optical links**
- Photonic devices
- CMOS electronics for single-λ links
- Wavelength-division multiplexing
- Future directions and conclusion

IMDD Optical Links



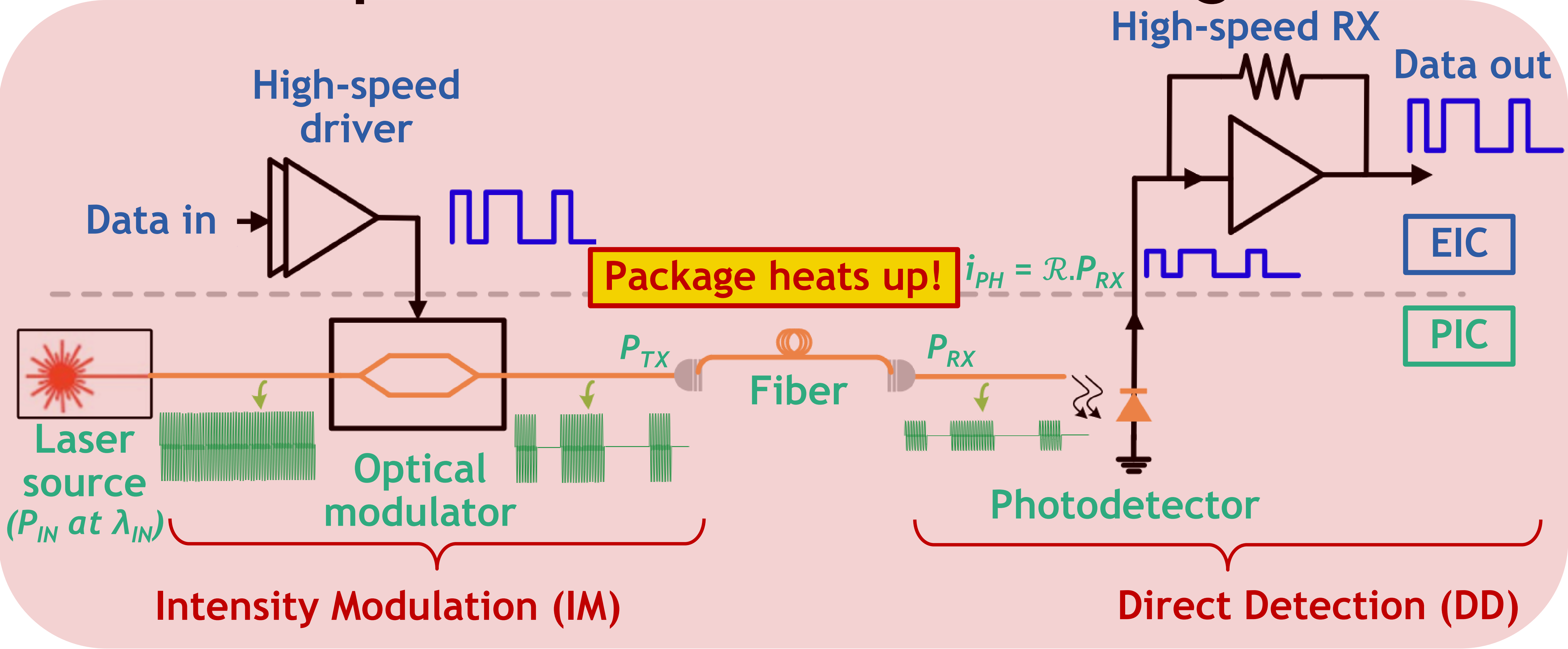
High-speed links require advances in SiPh optical devices and CMOS electronics.

IMDD Optical Links



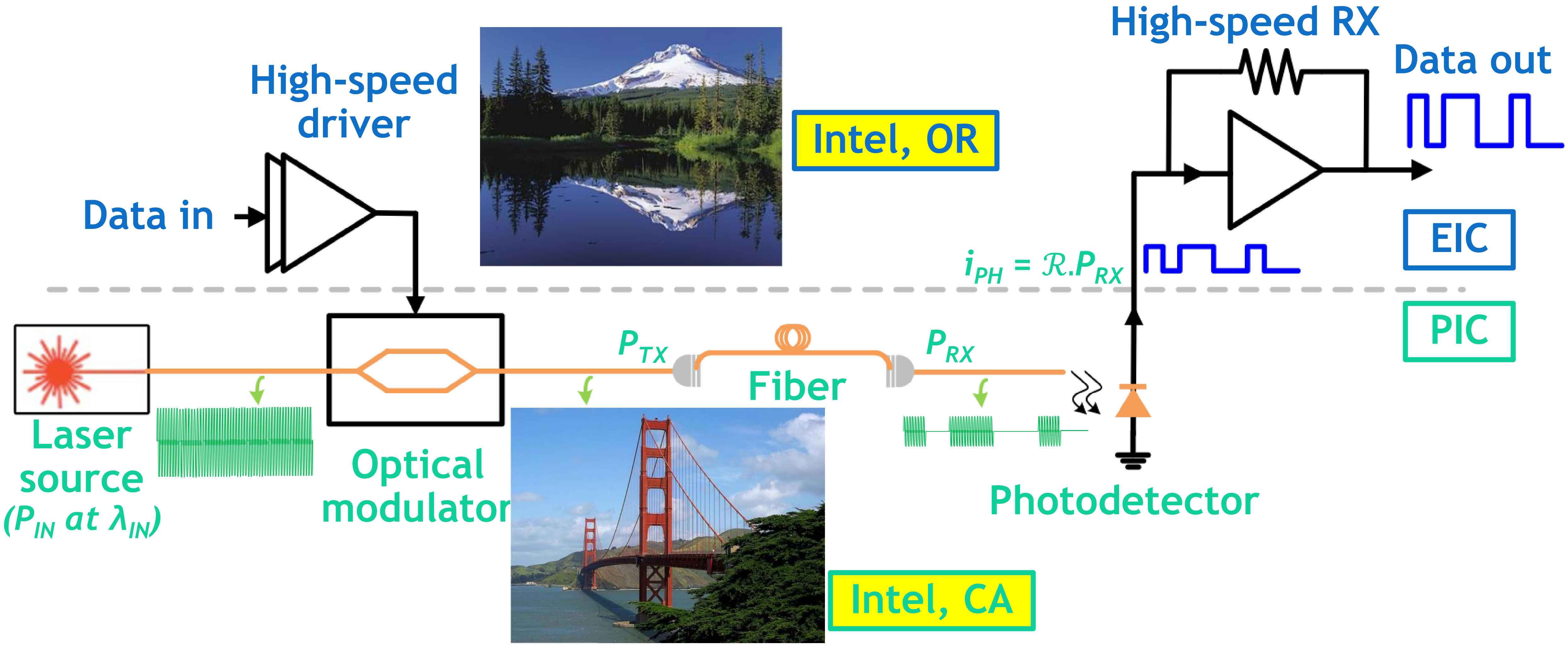
High-speed links require advances in SiPh optical devices and CMOS electronics.

IMDD Optical Links: Thermal Management



Thermal control for photonic devices in co-packaged optics is critical.

IMDD Optical Links at Intel



High-speed links require advances in SiPh optical devices and CMOS electronics.

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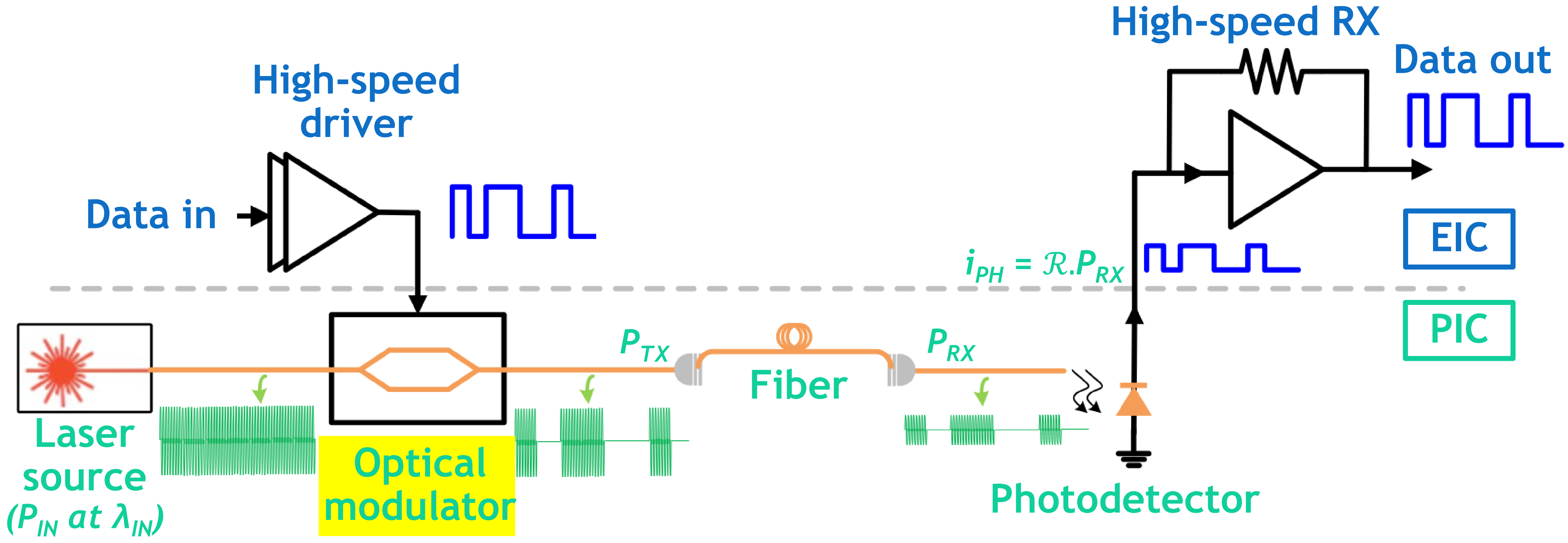
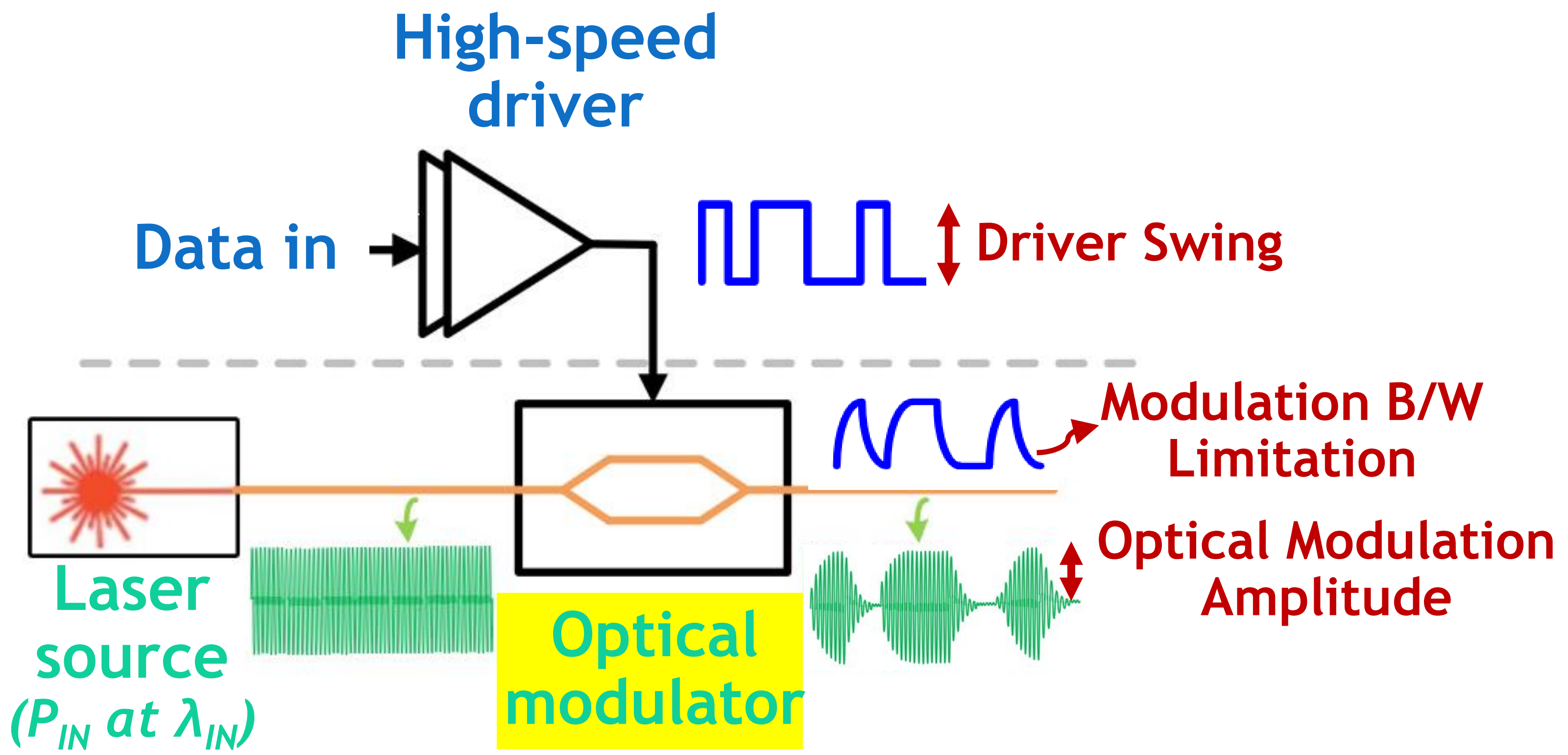
IMDD Optical Links



Optical Modulator: Metrics of Interest



Key metrics of an optical modulator include:

- Driver swing
- Modulator bandwidth

Is this CMOS compatible?

Some Popular Optical Modulators

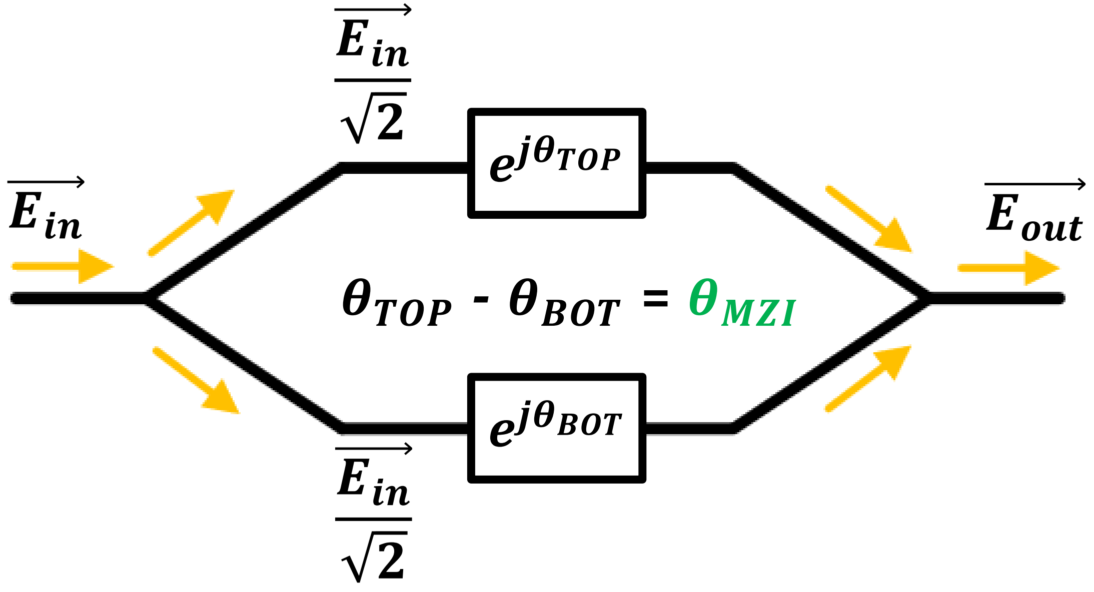
	Driver swing	Modulator B/W
MZM		
EAM		
MRM		

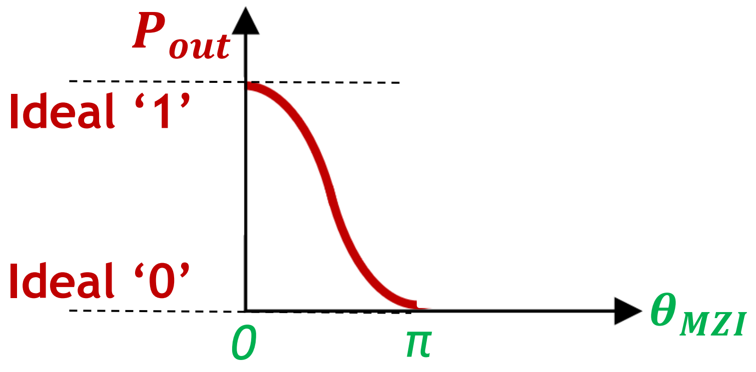
Some Popular Optical Modulators : MZM

MZM: Mach-Zehnder Modulator

	Driver swing	Modulator B/W
MZM		
EAM		
MRM		

MZM: Signal interferes with delayed-version to create intensity modulation.





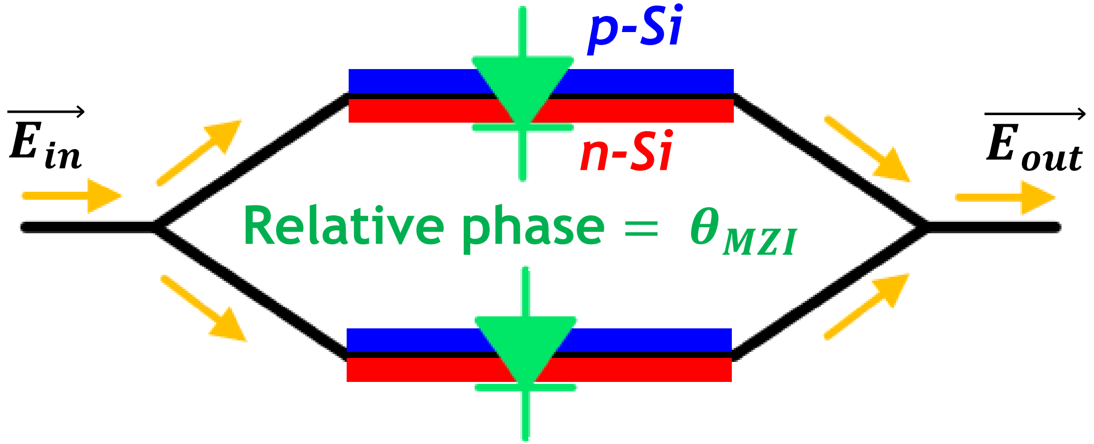
$$P_{out} = \|E_{out}\|^2 = \frac{P_{in}}{2}[1 + \cos(\theta_{MZI})]$$

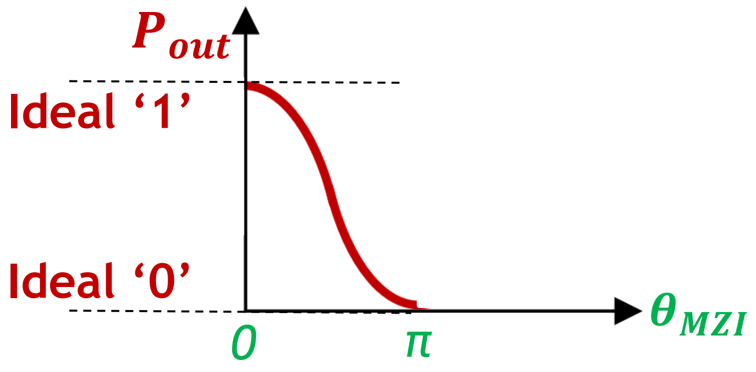
Some Popular Optical Modulators : MZM

MZM: Mach-Zehnder Modulator

	Driver swing	Modulator B/W
MZM		
EAM		
MRM		

Carrier density modulation in the doped waveguide can introduce a phase-shift.

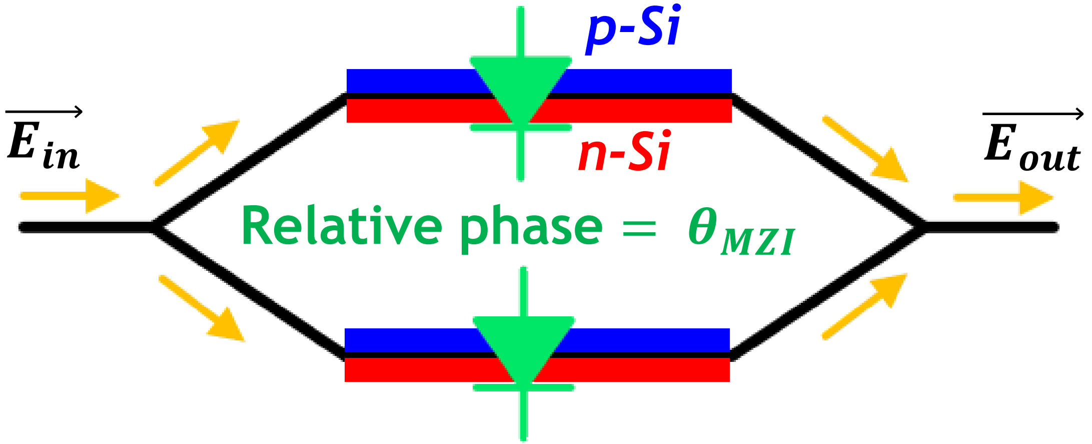




Some Popular Optical Modulators : MZM

MZM: Mach-Zehnder Modulator

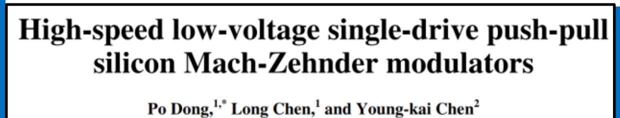
	Driver swing	Modulator B/W
MZM		
EAM		
MRM		



Carrier density modulation in the doped waveguide can introduce a phase-shift.

Forward-bias	Reverse-bias
Carrier-injection	Carrier-depletion
Low swing	High swing
Low bandwidth	High bandwidth

[Bell Labs, Opt. Exp. 2012]

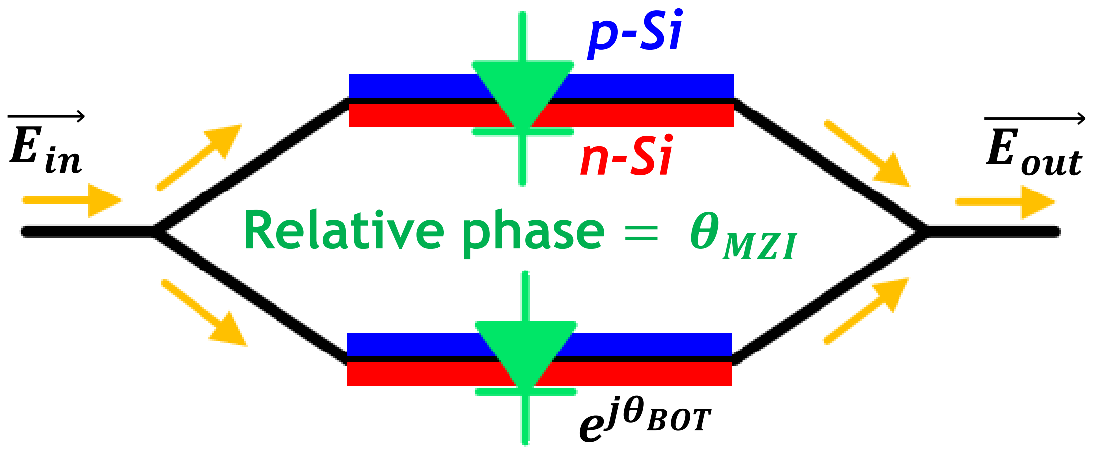

High-speed low-voltage single-drive push-pull silicon Mach-Zehnder modulators

Po Dong,[1,*] Long Chen,[1] and Young-kai Chen[2]

Some Popular Optical Modulators : MZM

MZM: Mach-Zehnder Modulator

	Driver swing	Modulator B/W
MZM	High	High
EAM		
MRM		



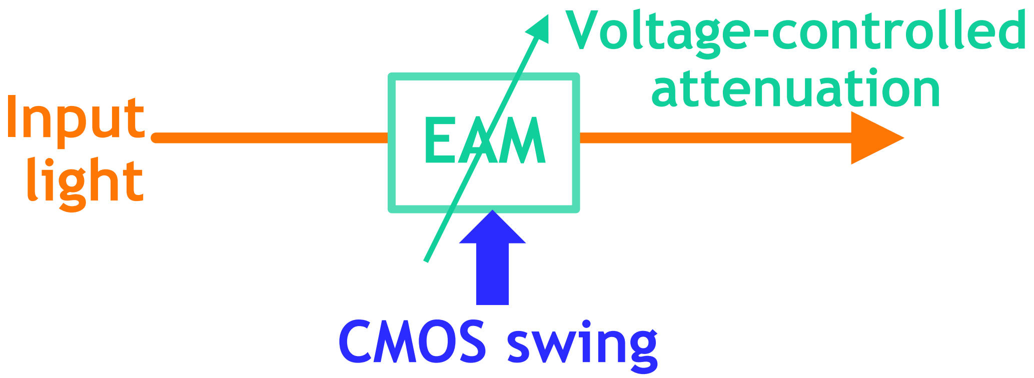
Carrier density modulation in the doped waveguide can introduce a phase-shift.

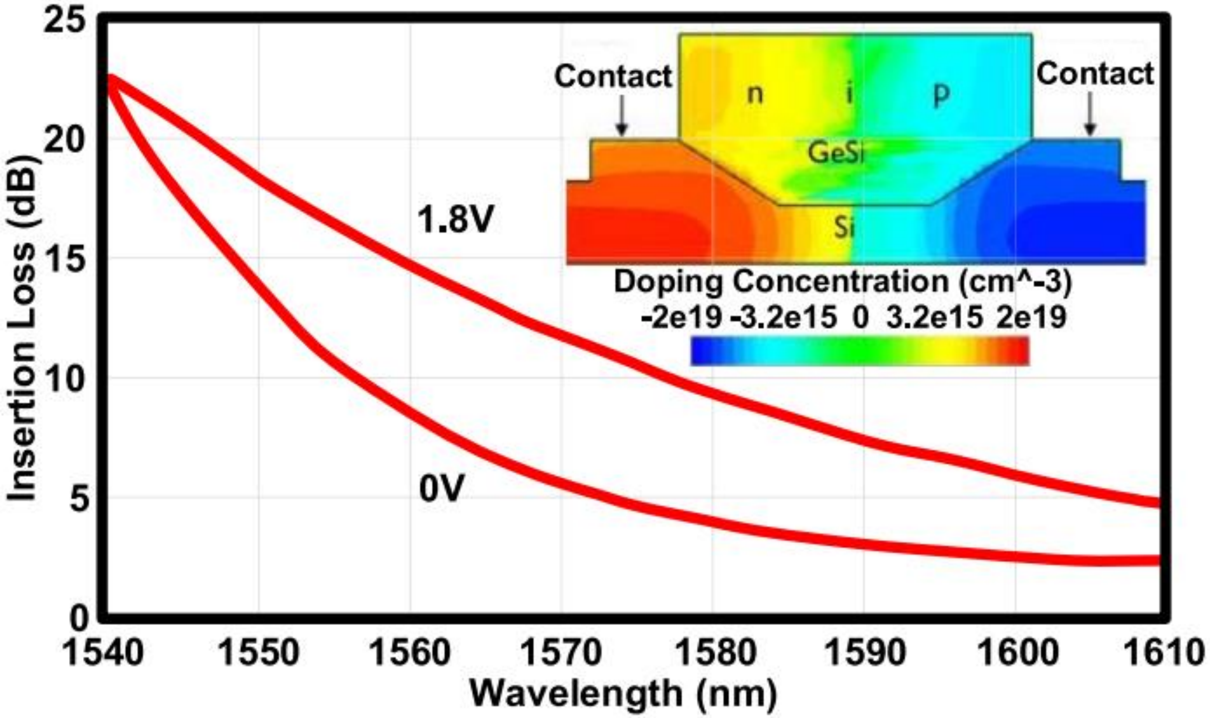
Forward-bias	Reverse-bias
Carrier-injection	Carrier-depletion
Low swing	High swing
Low bandwidth	High bandwidth

Some Popular Optical Modulators : EAM

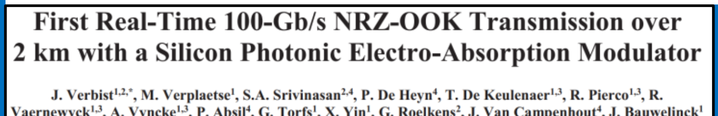
EAM: Electro-Absorption Modulator

	Driver swing	Modulator B/W
MZM	High	High
EAM	Low	High
MRM		





Modulator: [Ghent U/IMEC: OFC 2017]
OTRX: [Xilinx/IMEC: JSSC 2020]



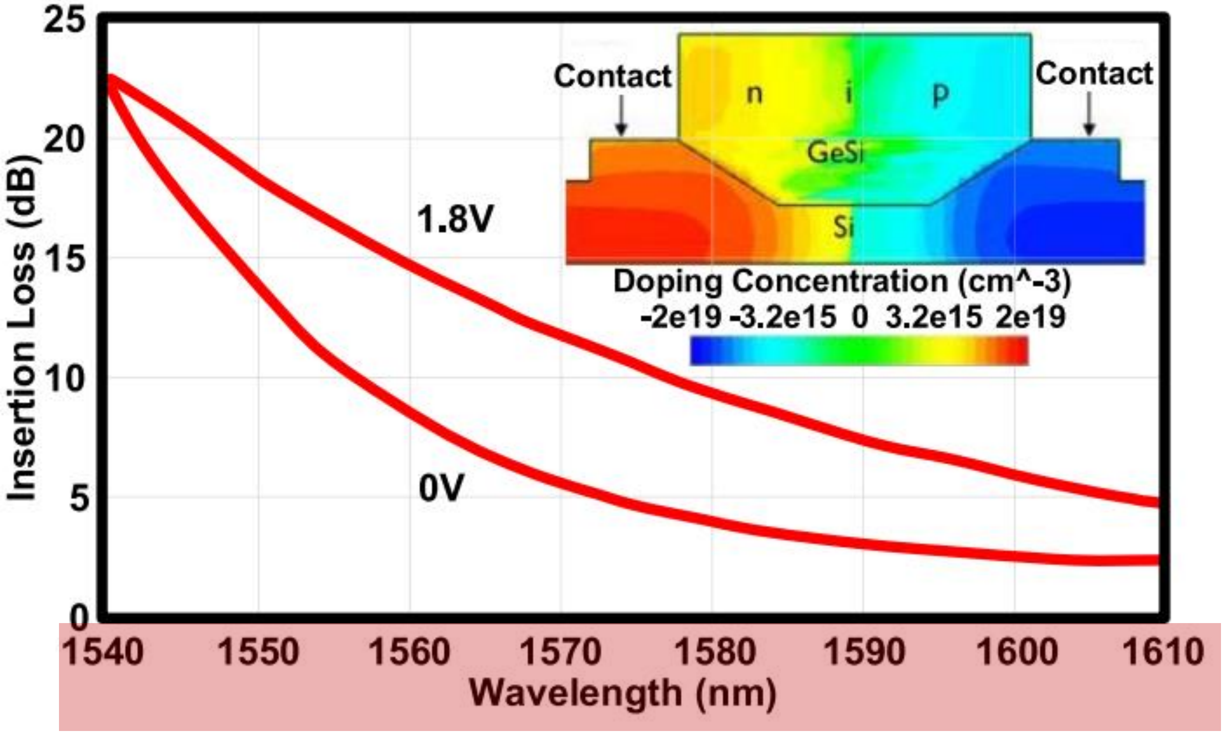
First Real-Time 100-Gb/s NRZ-OOK Transmission over 2 km with a Silicon Photonic Electro-Absorption Modulator

J. Verbist[1,2,*], M. Verplaetse[1], S.A. Srivinasan[2,4], P. De Heyn[4], T. De Keulenaer[1,3], R. Pierco[1,3], R. Vaernewyck[1,3], A. Vyncke[1,3], P. Absil[4], G. Torfs[1], X. Yin[1], G. Roelkens[2], J. Van Campenhout[4], J. Bauwelinck[1]

Some Popular Optical Modulators : EAM

	Driver swing	Modulator B/W
MZM	High	High
EAM (not O-band)	Low	High
MRM		

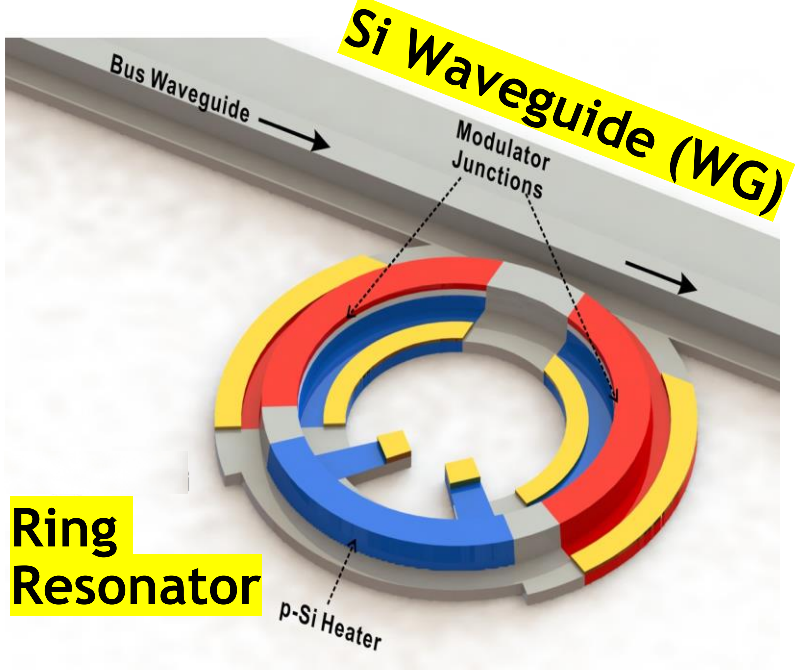
O-band: 1260 to 1360 nm (lowest dispersion)
C/L-band: 1530 to 1625 nm (lowest loss)

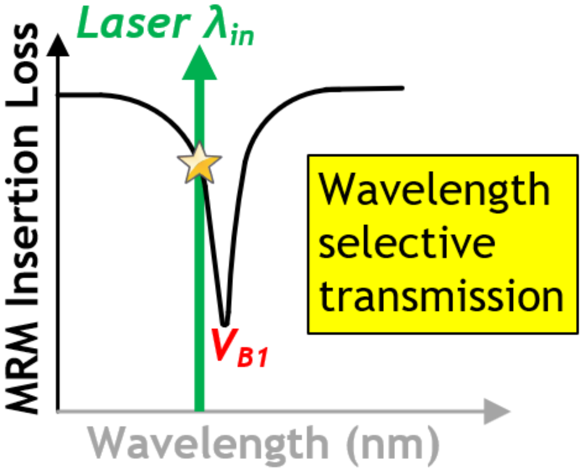


Modulator: [Ghent U/IMEC: OFC 2017]
OTRX: [Xilinx/IMEC: JSSC 2020]

EAM: Electro-Absorption Modulator

Optical modulator: Micro-Ring modulator (MRM)

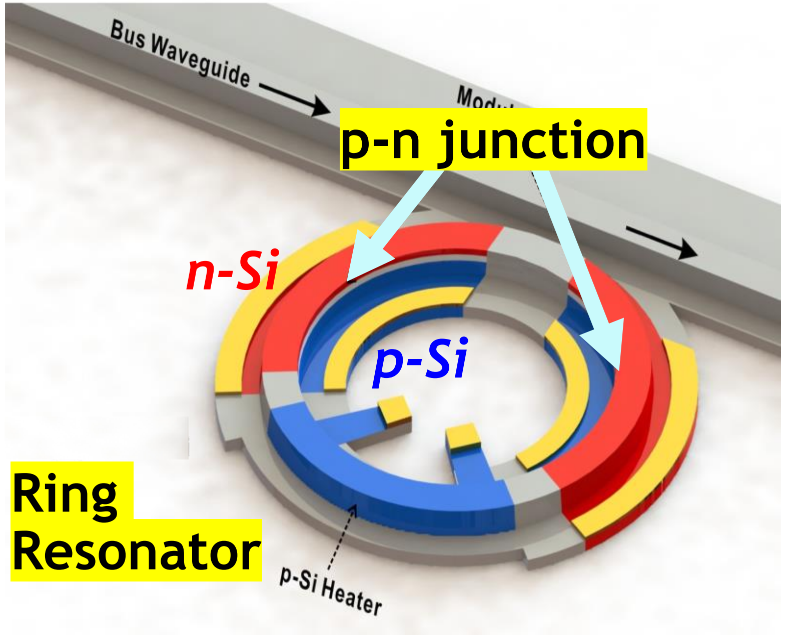




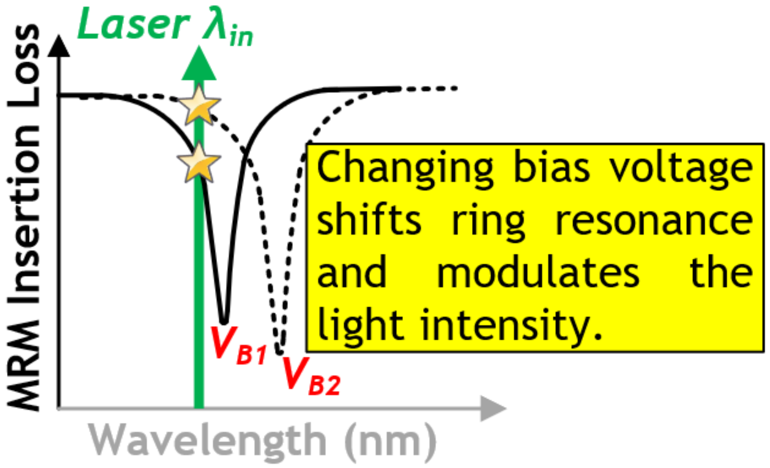
MRM: Micro-Ring Modulator

WG coupled to a ring-resonator exhibits wavelength-selective transmission.

MRM: Operation

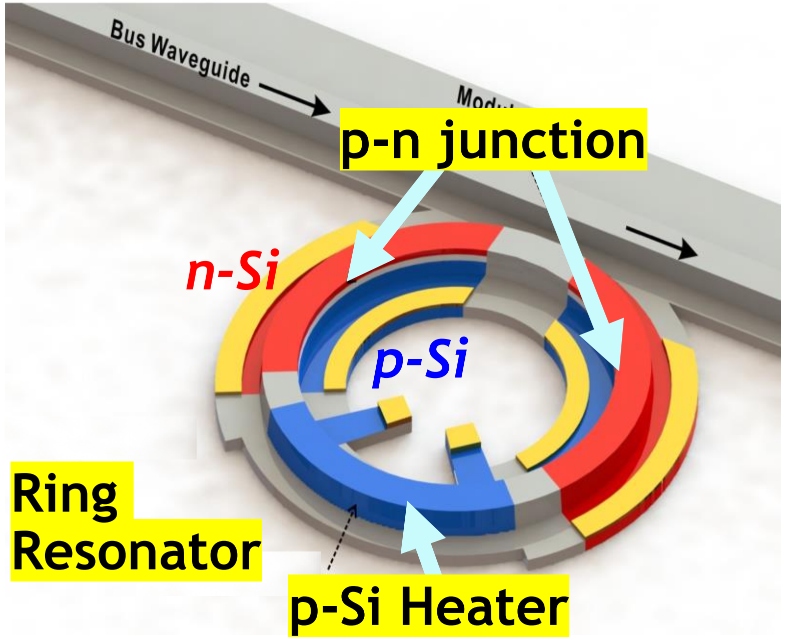


MRM: Micro-Ring Modulator

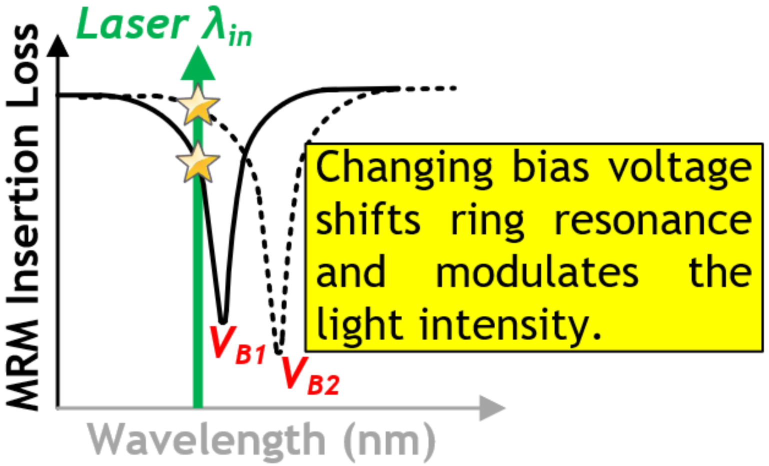


Voltage swing applied to the MRM can intensity modulate the incident light.

MRM: Thermal Sensitivity



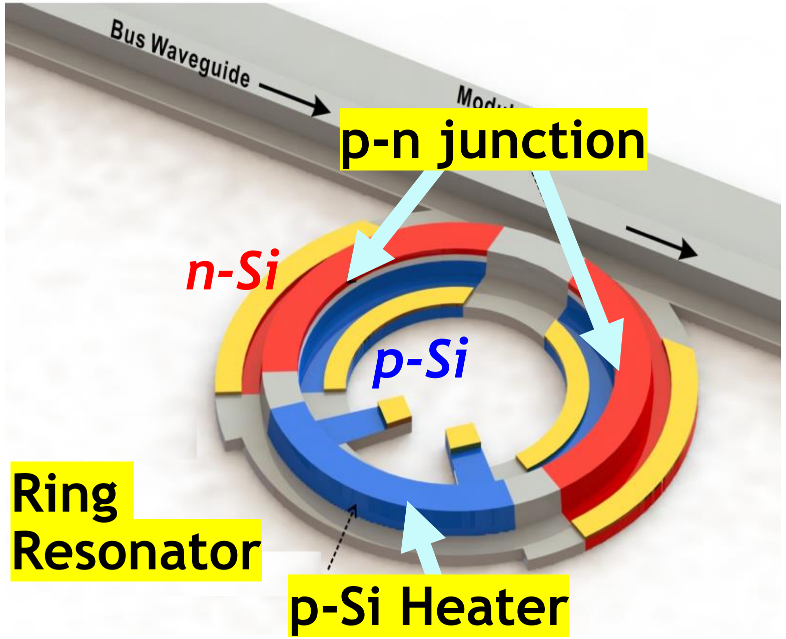
MRM: Micro-Ring Modulator



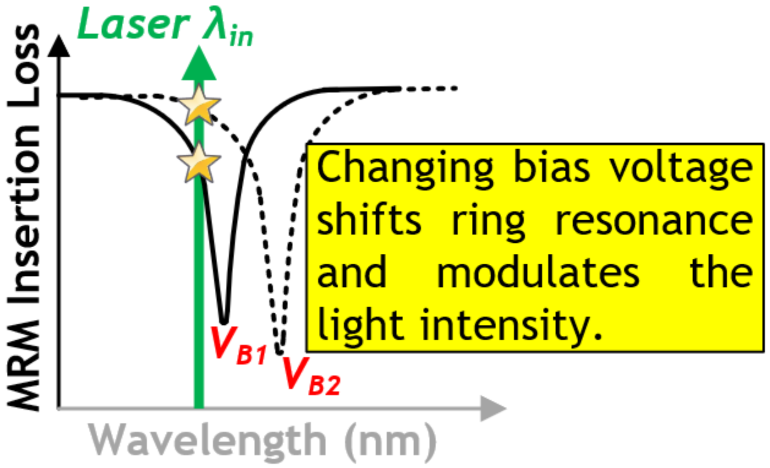
Local heater stabilizes the ring spectrum in the presence of thermal drift.

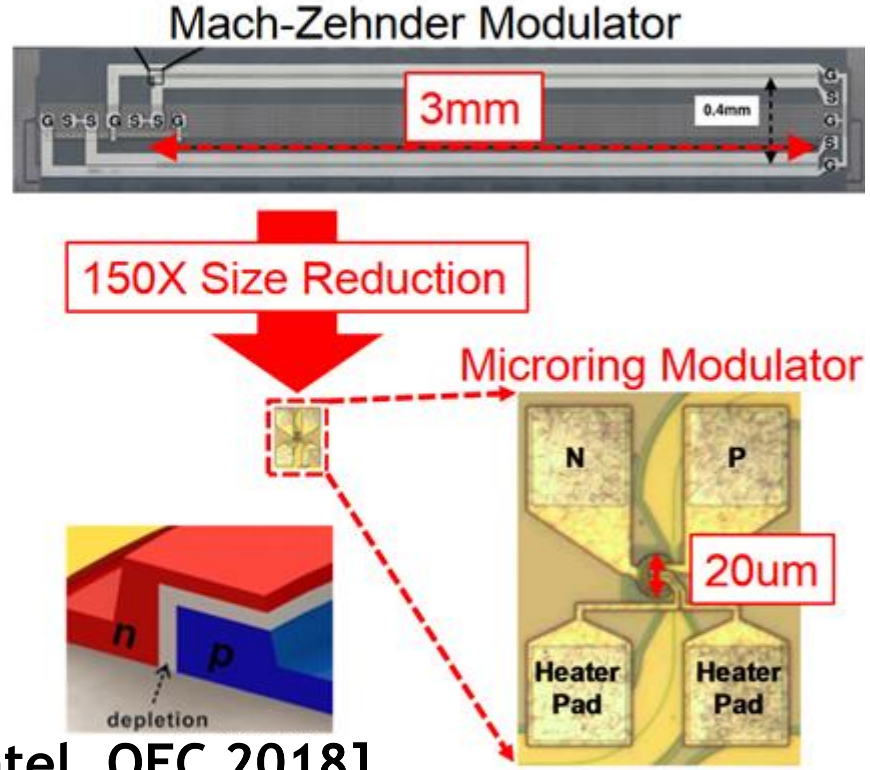
MRM: Compact Size

[R. Ding, Optcomm 2014]



MRM: Micro-Ring Modulator

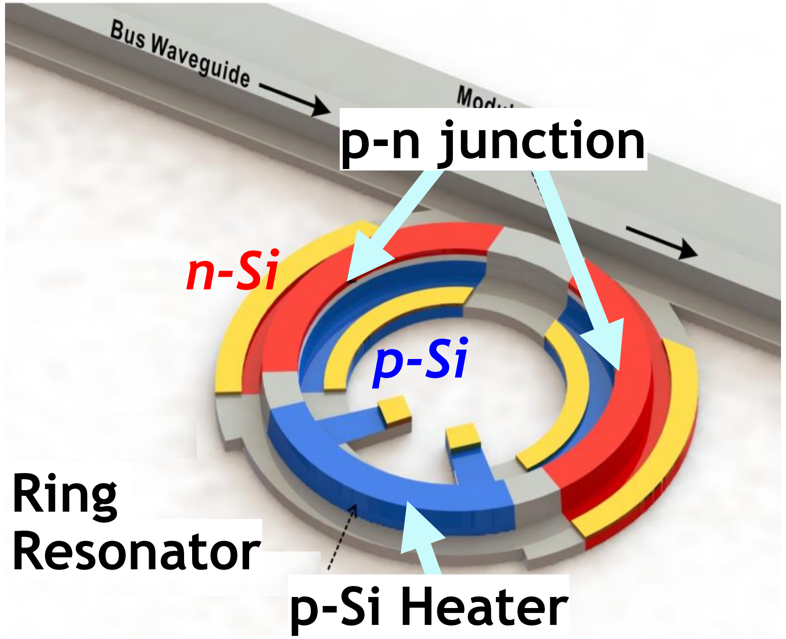


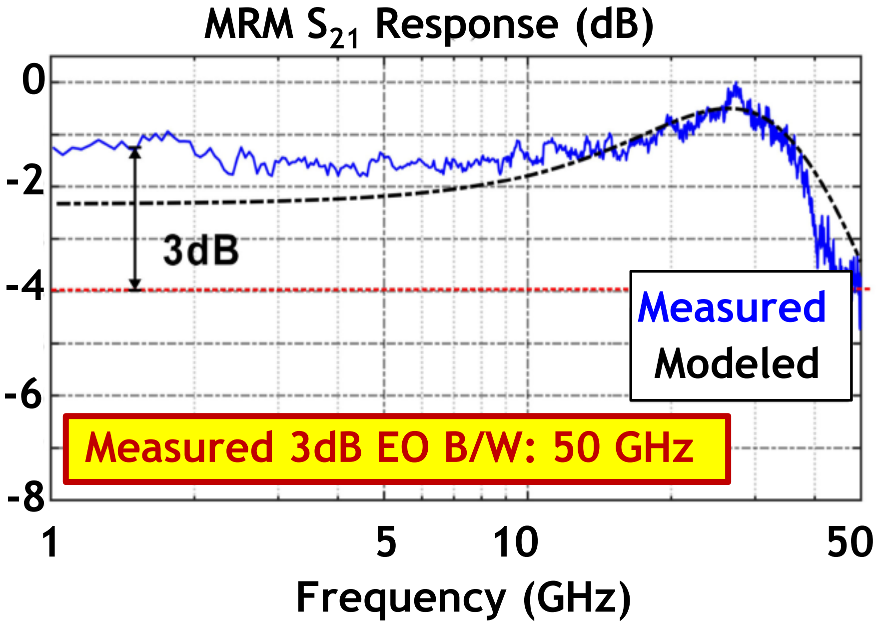


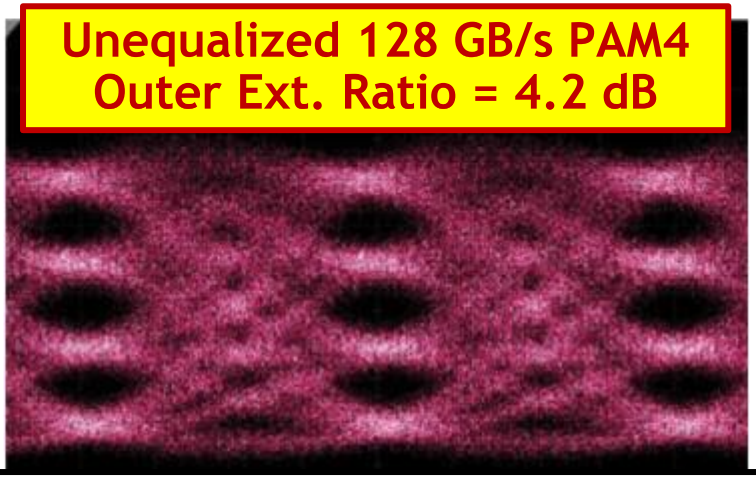
[Intel, OFC 2018]

MRMs are ultra-compact and have high electro-optic bandwidths.

MRMs at Intel: Performance Highlight







MRM Reverse Bias: 4 V
Laser detuning (λ_L - $\lambda_{ring\ resonance}$): 6 dB

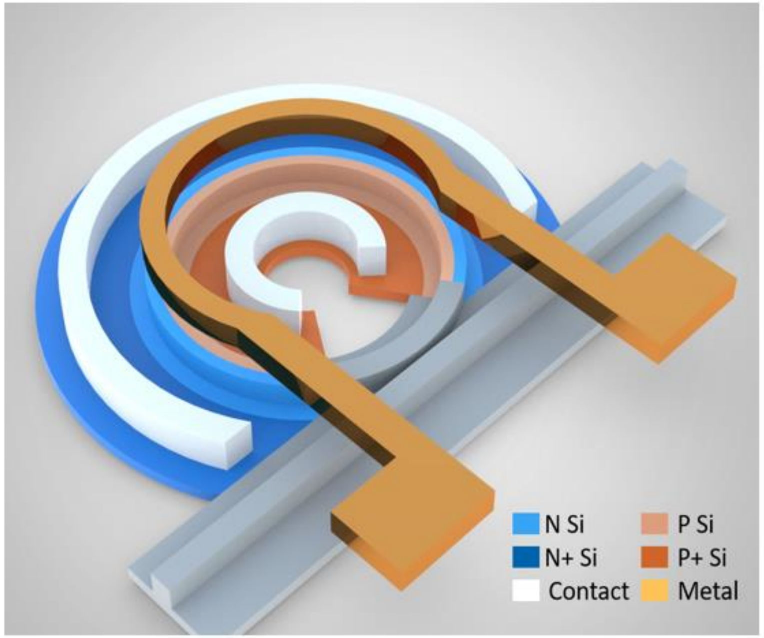
[Intel, JLT 2019]

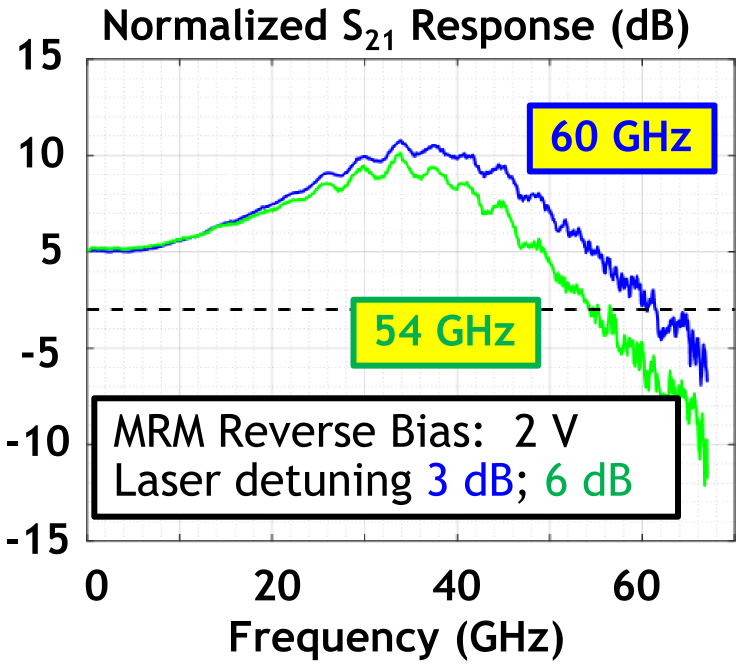
- MRM with 10 µm radius has a modulator bandwidth of 50 GHz.
- Open eye at 128 Gb/s PAM4 ***without*** equalization and 2.4V_{pp} electrical swing.

A 128 Gb/s PAM4 Silicon Microring Modulator With Integrated Thermo-Optic Resonance Tuning

Jie Sun, Ranjeet Kumar, Meer Sakib, Jeffrey B. Driscoll, Hasitha Jayatilleka, and Haisheng Rong

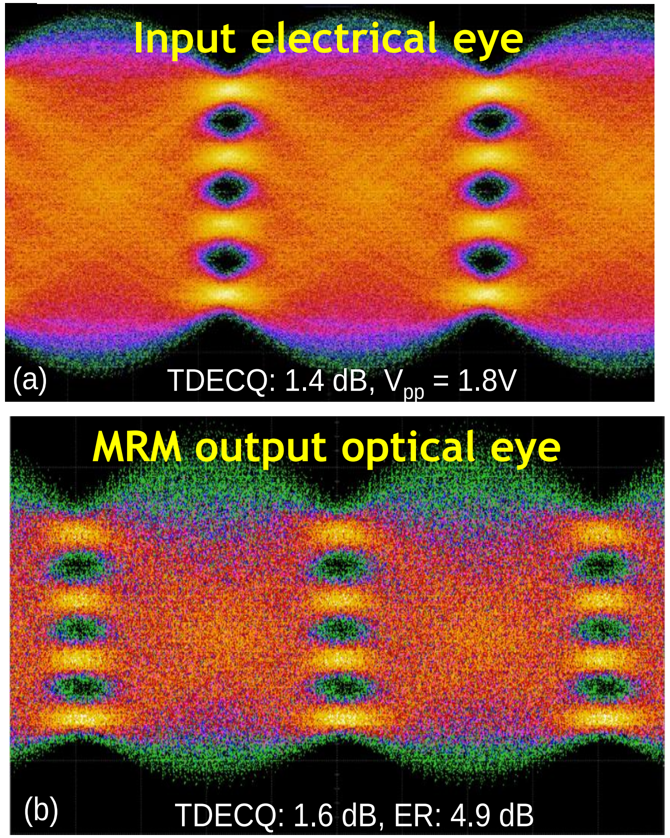
MRMs at Intel: Performance Highlight #2





[Intel, OFC 2021]

224Gb/s PAM4 performance



- **MRM with 4 μm radius has a modulator bandwidth of 60 GHz.**
- **Open eye at 224 Gb/s PAM4 *with* scope equalization and 1.8V_{pp} electrical swing.**

Popular Optical Modulators: Comparison

	Driver swing	Modulator B/W	Thermal sensitivity	Area	O-band
MZM	High	High	Low	High	Yes
EAM	Low	High	Low	Low	No
MRM	Low	High (improved)	High	Very low	Yes

MRM: A low swing, high-bandwidth and compact modulator for integrated SiPh.

Popular Optical Modulators: Comparison

	Driver swing	Modulator B/W	Thermal sensitivity	Area	O-band
MZM	High	High	Low	High	Yes
EAM	Low	High	Low	Low	No
MRM	Low	High (improved)	High (temp control)	Very low	Yes

MRM: A low swing, high-bandwidth and compact modulator for integrated SiPh.

A sub-400 fJ/bit thermal tuner for optical resonant ring modulators in 40 nm CMOS

Philip Amberg, Eric Chang, Frankie Liu, Jon Lexau, Xuezhe Zheng, Guoliang Li, Ivan Shubin, John E. Cunningham, Ashok V. Krishnamoorthy and Ron Ho

[Oracle, ASSCC 2012]

A 45 nm CMOS-SOI Monolithic Photonics Platform With Bit-Statistics-Based Resonant Microring Thermal Tuning

Chen Sun, *Member, IEEE*, Mark Wade, Michael Georgas, Sen Lin, Luca Alloatti, Benjamin Moss, Rajesh Kumar, Amir H. Atabaki, Fabio Pavanello, Jeffrey M. Shainline, Jason S. Orcutt, Rajeev J. Ram, *Fellow, IEEE*, Miloš Popović, *Member, IEEE*, and Vladimir Stojanović, *Member, IEEE*

[Berk/U Colorado/MIT, JSSC 2016]

Wavelength Locking of a Si Ring Modulator Using an Integrated Drop-Port OMA Monitoring Circuit

Saurabh Agarwal, Mark Ingels, *Member, IEEE*, Marianna Pantouvaki, *Member, IEEE*, Michiel Steyaert, *Fellow, IEEE*, Philippe Absil, and Joris Van Campenhout, *Member, IEEE*

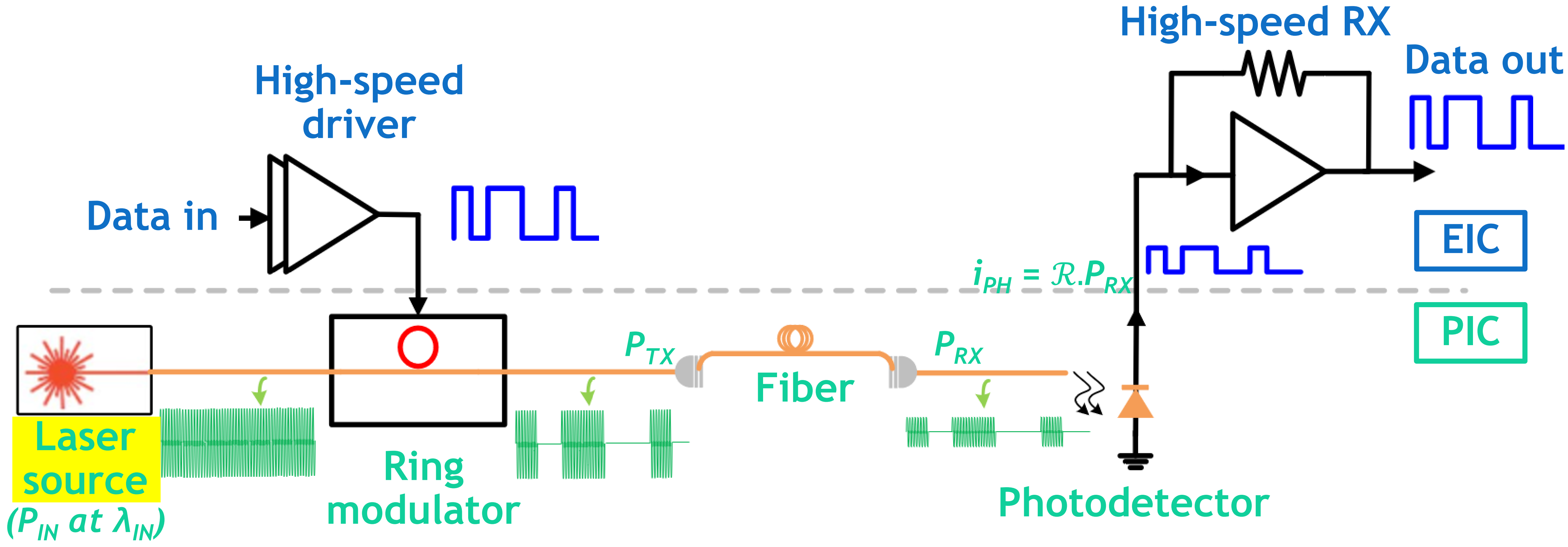
[IMEC/KU Leuven, JSSC 2016]

A 3-D-Integrated Silicon Photonic Microring-Based 112-Gb/s PAM-4 Transmitter With Nonlinear Equalization and Thermal Control

Hao Li, *Member, IEEE*, Ganesh Balamurugan, *Member, IEEE*, Taehwan Kim, *Member, IEEE*, Meer N. Sakib, *Member, IEEE*, Ranjeet Kumar, *Member, IEEE*, Haisheng Rong, *Senior Member, IEEE*, James Jaussi, *Member, IEEE*, and Bryan Casper, *Member, IEEE*

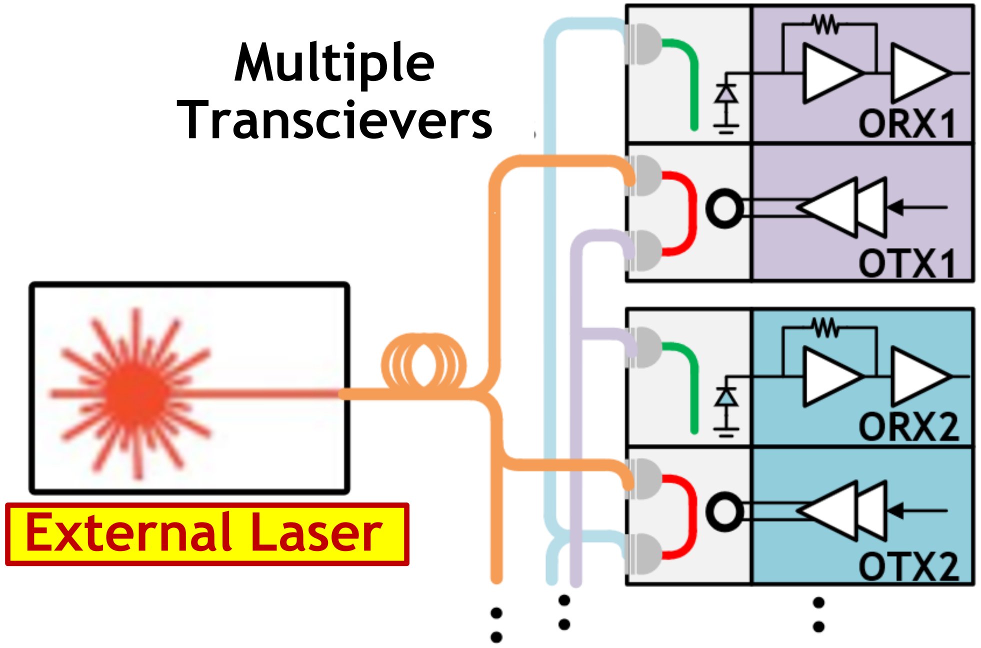
[Intel, JSSC 2021]

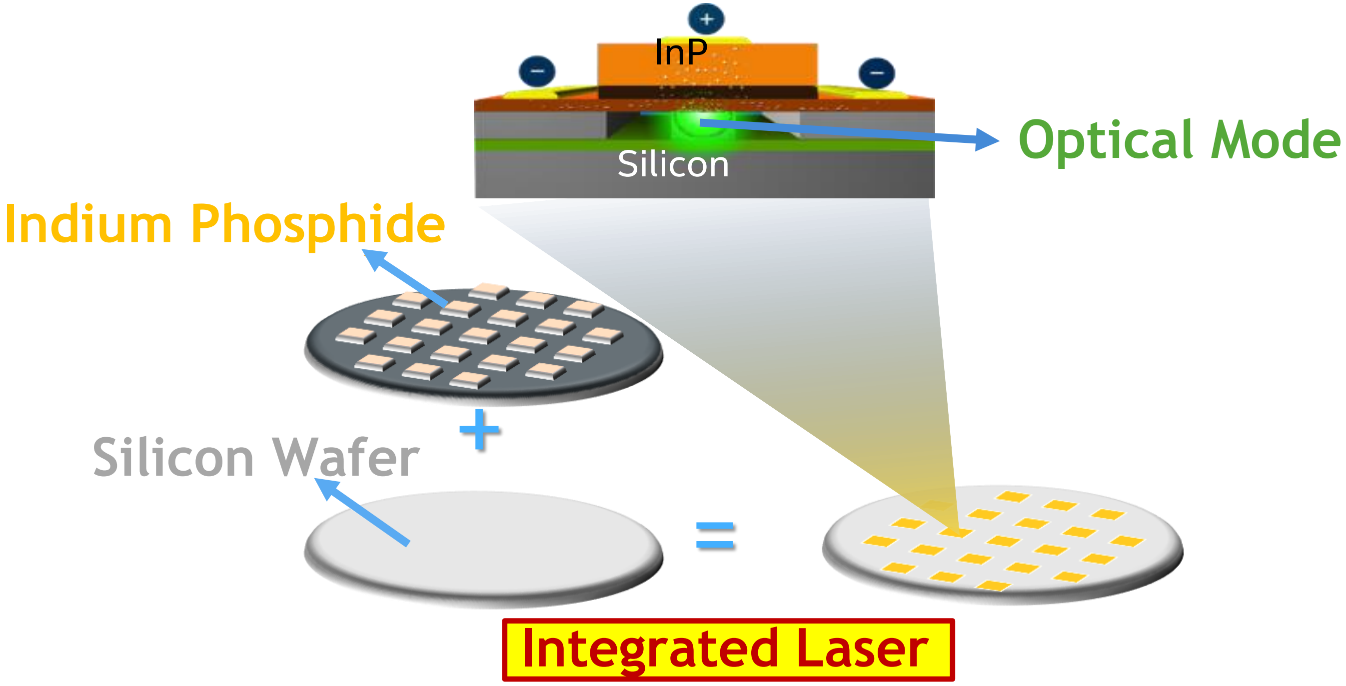
IMDD Optical Links



Laser technology: External vs Integrated

	Thermal variation	Coupling loss	Alignment	Amplification
External	Low	High	Costly fiber alignment	Required
Integrated	High	Low	Wafer-bonded	Architecture-based requirement

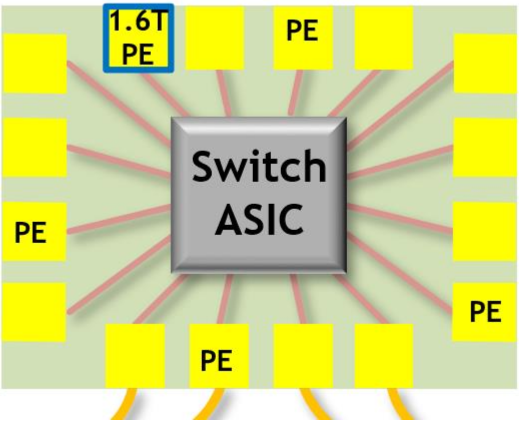


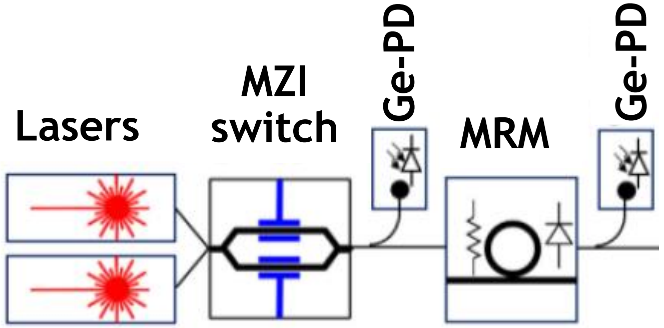


- External: Thermally stable but additional coupling loss.
- Integrated: Can see greater thermal variation but directly coupled.

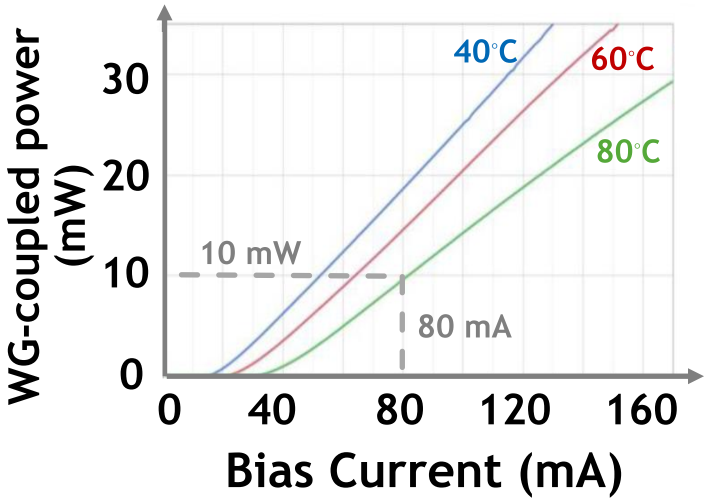
Intel's Integrated Laser: Performance

Each 1.6T PE: 16 channels @ 100 Gb/s!





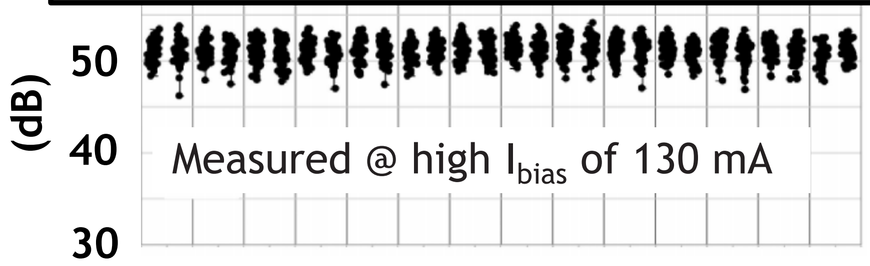
Redundant laser per channel at no cost



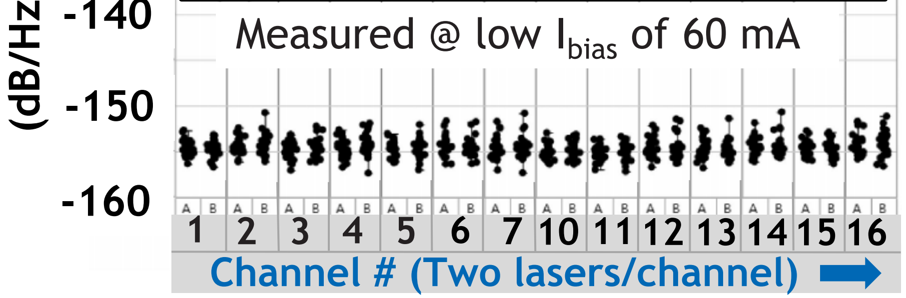
High-power

[Intel, OFC 2020]

Side-mode Suppression Ratio (SMSR)
Better than 55 dB



Relative Intensity Noise (RIN)
Better than -150 dB/Hz



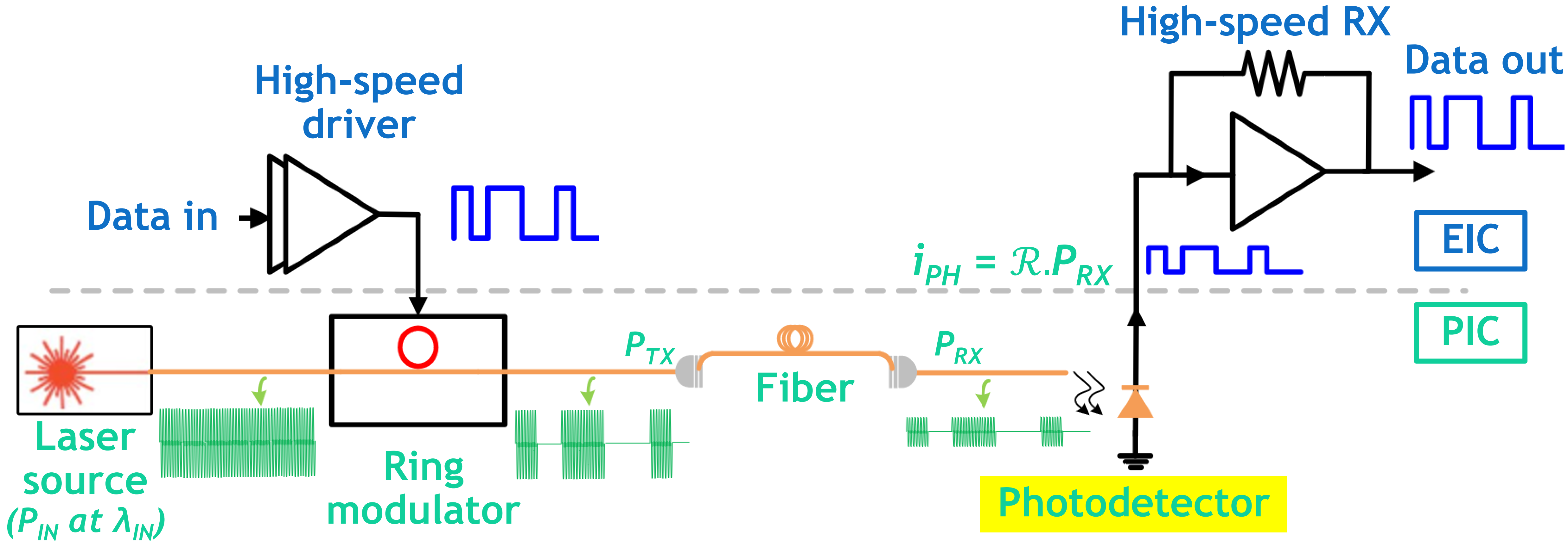
Low spurious content and noise

Integrated O-band laser provides high power with a clean spectrum for SiPh optical I/O.

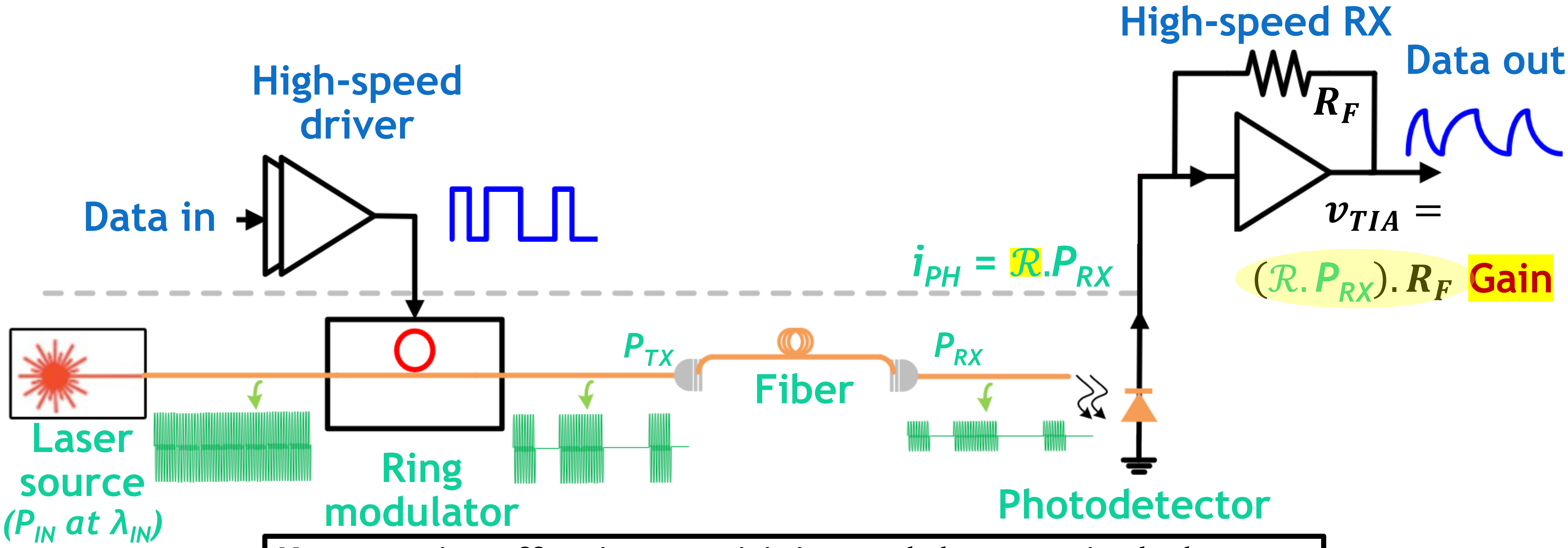
1.6Tbps Silicon Photonics Integrated Circuit for Co-Packaged Optical-IO Switch Applications

Saeed Fathololoumi, Kimchau Nguyen, Hari Mahalingam, Meer Sakib, Zhi Li, Christopher Seibert*, Mohammad Montazeri, Jian Chen, Jonathan K Doylend, Hasitha Jayatilleka, Catherine Jan, John Heck, Ranju Venables, Harel Frish*, Reece A. Defrees*, Randal S. Appleton*, Summer Hollingsworth*, Sean McCargar*, Richard Jones, Daniel Zhu, Yuliya Akulova, and Ling Liao

IMDD Optical Links



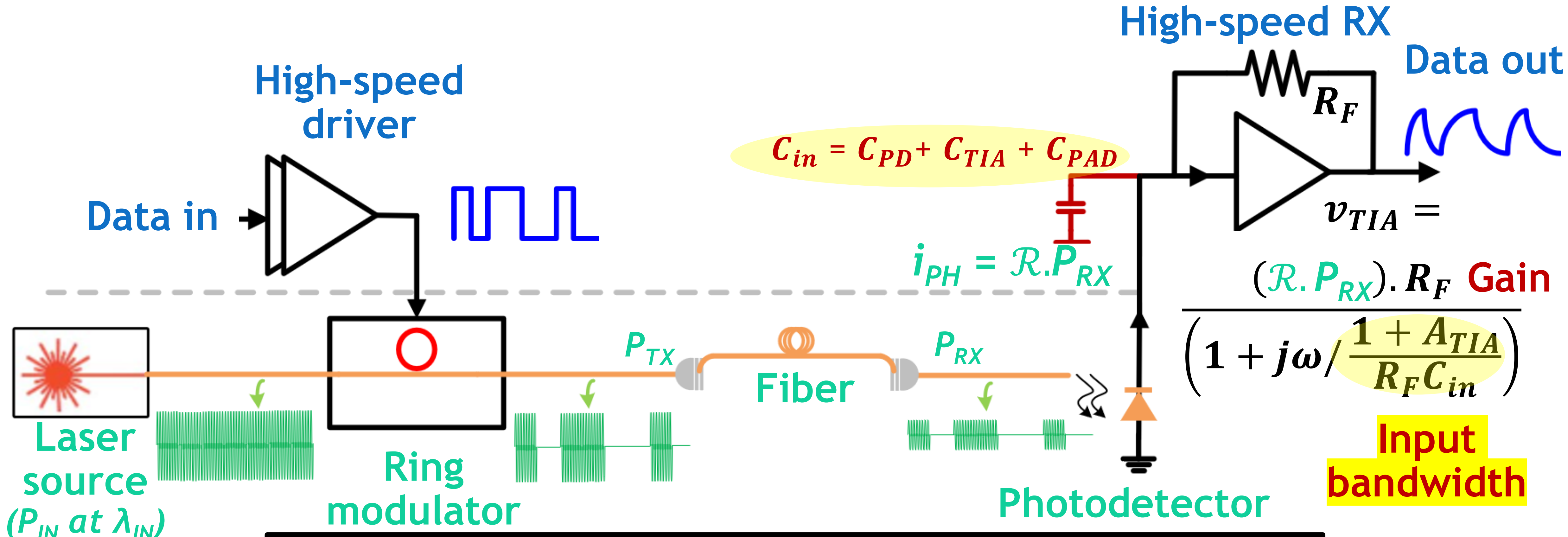
Photodetector: Metrics of Interest



Key metrics affecting sensitivity and datarate include:

- Responsivity ($\mathcal{R}$ in Amp/Watt)

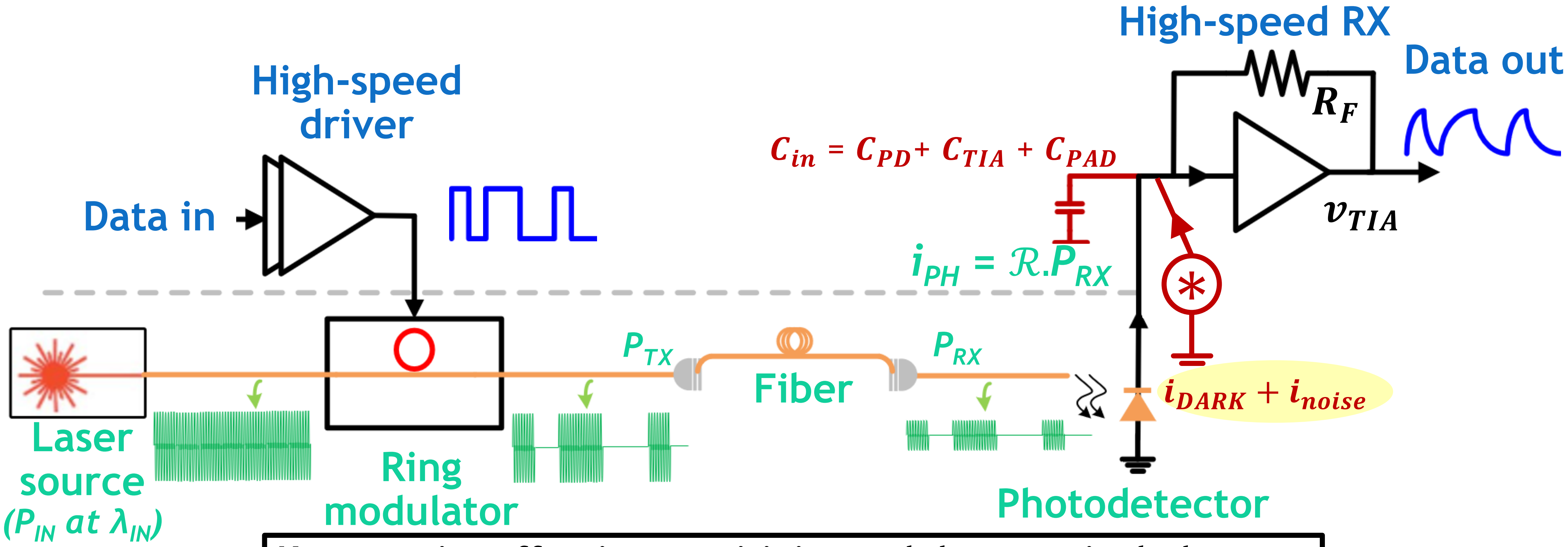
Photodetector: Metrics of Interest



Key metrics affecting sensitivity and datarate include:

- Responsivity ($\mathcal{R}$ in Amp/Watt)
- Photodetector bandwidth (C_{PD})

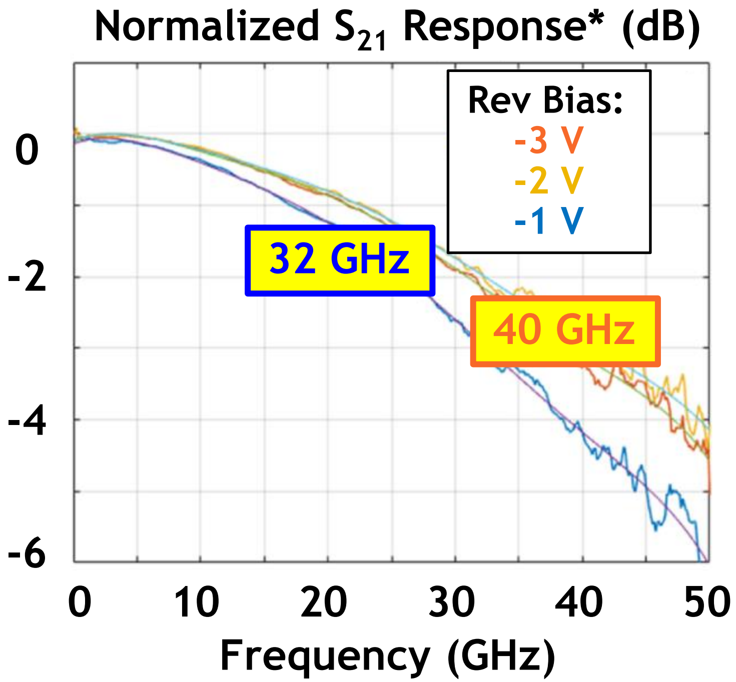
Photodetector: Metrics of Interest



Key metrics affecting sensitivity and datarate include:

- Responsivity ($\mathcal{R}$ in Amp/Watt)
- Photodetector bandwidth (C_{PD})
- Dark current/Shot noise

Ge-based Photodetectors



	Ge-PD		
Resp (A/W)	0.9 @ -1V *saturated*		
Terminated B/W (GHz)	40 @ -2V		
Dark current (nA)	100 @ -2.5		

[Intel, JLT 2021]

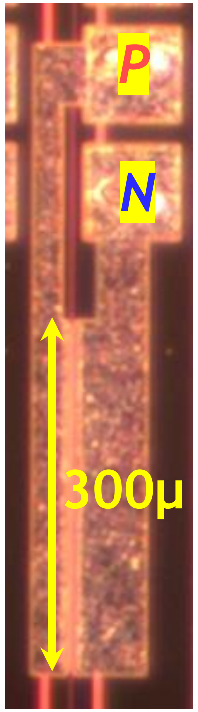
Ge-based PDs show high saturated responsivity, high bandwidth and low dark current at moderate reverse bias.

1.6 Tbps Silicon Photonics Integrated Circuit and 800 Gbps Photonic Engine for Switch Co-Packaging Demonstration

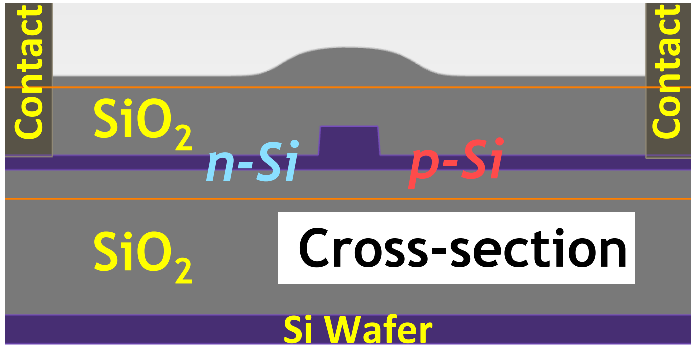
Saeed Fathololoumi, David Hui, Susheel Jadhav, Jian Chen, Kimchau Nguyen, M.N. Sakib, Z. Li, Hari Mahalingam, Siamak Amiralizadeh, Nelson N. Tang, Harinadh Potluri, Mohammad Montazeri, Harel Frish, Reece A. Defrees, Christopher Seibert, Alexander Krichevsky, Jonathan K. Doylend, John Heck, R. Venables, A. Dahal, A. Awujoola, A. Vardapetyan, Guneet Kaur, Min Cen, Vishnu Kulkarni, Syed S. Islam, R. L. Spreitzer, S. Garag, A. C. Alduino, RK Chiou, L. Kamyab, S. Gupta, B. Xie, R. S. Appleton, S. Hollingsworth, S. McCargar, Y. Akulova, K. M. Brown, R. Jones, Daniel Zhu, Thomas Liljeberg, and Ling Liao

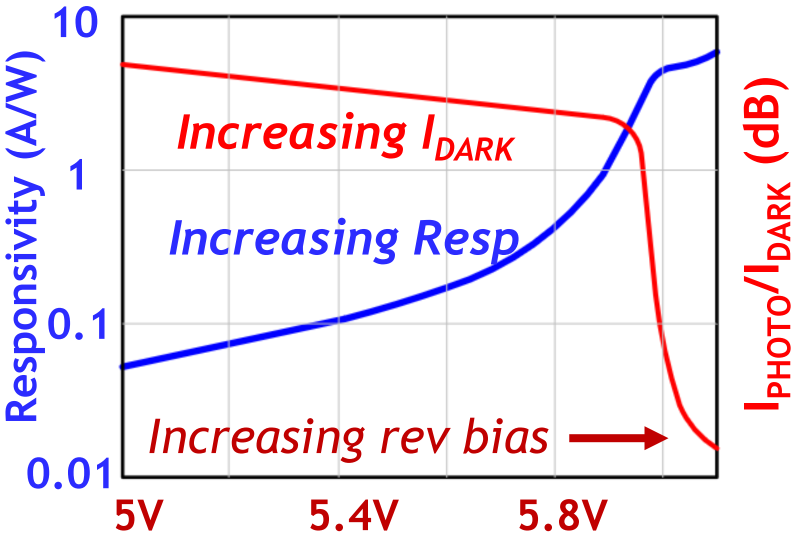
**50 Ω terminated probe*

Si Waveguide Photodetectors (WG PD)



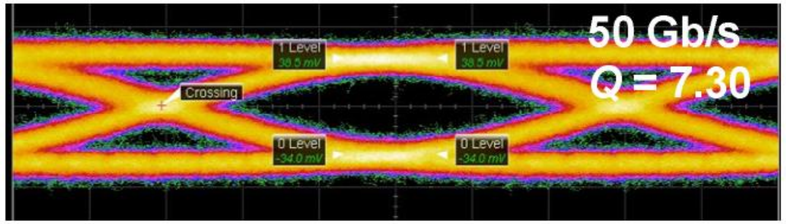
Top view





	Ge-PD	Si WG PD	
Resp (A/W)	0.9 @ -1V *saturated*	0.6 @ -5.8V	
Terminated B/W (GHz)	40 @ -2V	30 @ -5.8	
Dark current (nA)	100 @ -2.5	850† @ -5.8	

†0.45 mW incident power



Si WGPD 50 Gb/s NRZ eye*

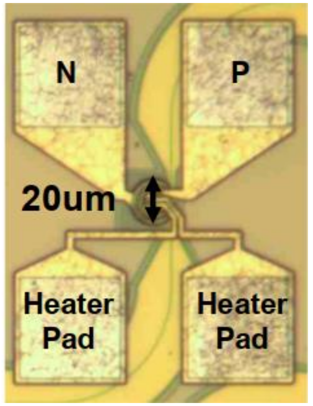
**50 Ω terminated probe* [Intel, CLEO 2018]

- Si-only doped WG PDs demonstrate sub-band gap detection at high reverse bias.
- Resp and dark current increase with reverse bias: optimize bias!

50 Gb/s all-silicon waveguide photodetectors for photonics integration

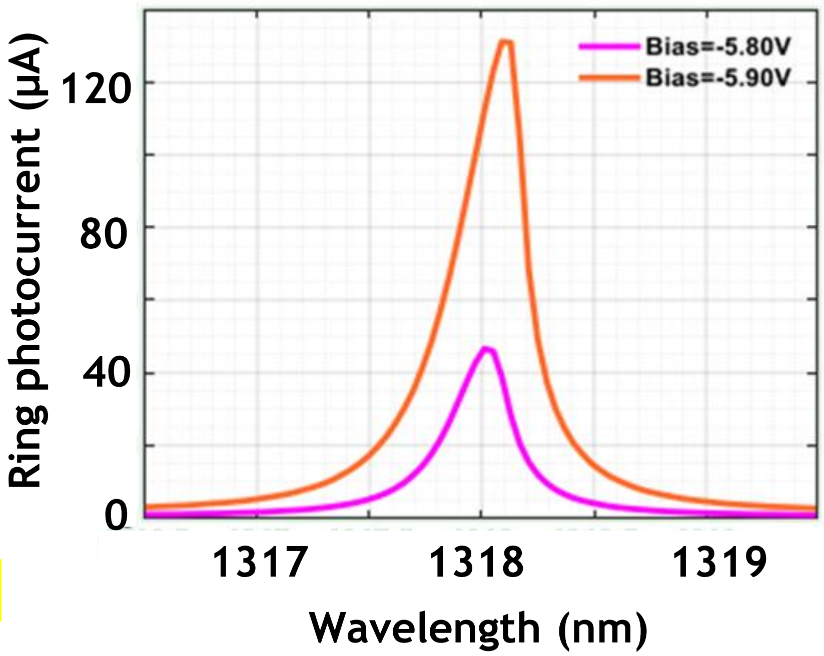
Meer Sakib, Jie Sun, Ranjeet Kumar, Jeffrey Driscoll, and Haisheng Rong

Si Ring-resonator Based Photodiode (RRPD)



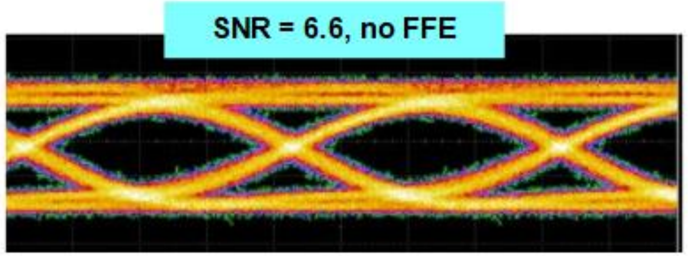
Top view

Ultra-compact



Wavelength-selective

	Ge-PD	Si WG PD	Si RRPD @ 40 pm detuning
Resp (A/W)	0.9 @ -1V *saturated*	0.6 @ -5.8V	0.23 @ -5.8
Terminated B/W (GHz)	40 @ -2V	30 @ -5.8	30 @ -5.8
Dark current (nA)	100 @ -2.5	850 @ -5.8	100 @ -5.8



Si RRPD 50 Gb/s NRZ eye*

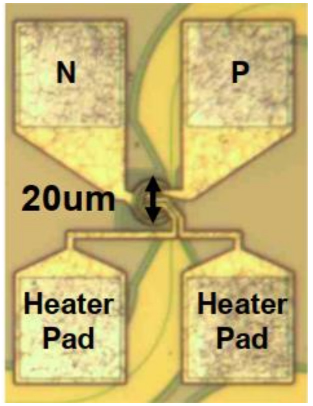
**50 Ω terminated probe* [Intel, OFC 2020]

- Resp and dark current increase with reverse bias: optimize bias!

A 112 Gb/s all-silicon micro-ring photodetector for datacom applications

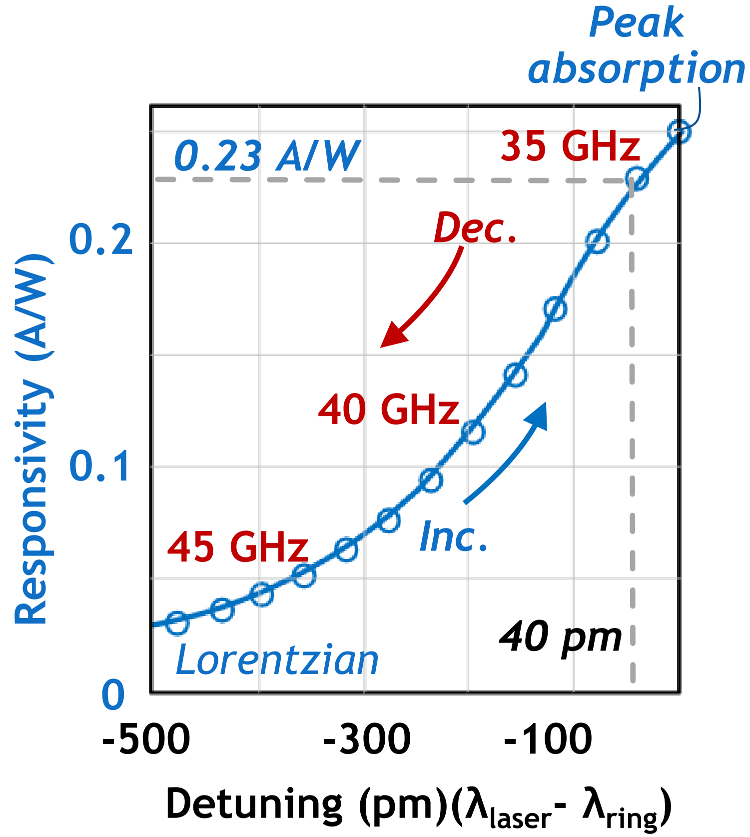
Meer Sakib, Peicheng Liao, Ranjeet Kumar, Duanni Huang, Guan-lin Su, Chaoxuan Ma, and Haisheng Rong

Si Ring-resonator Based Photodiode (RRPD)



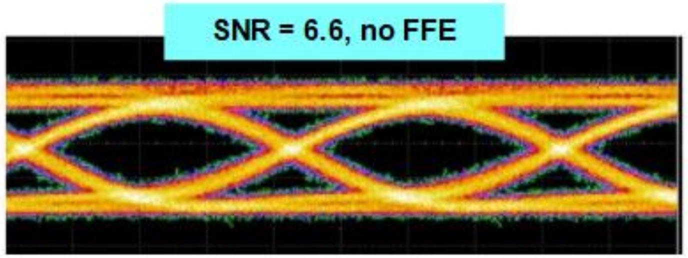
Top view

Ultra-compact



B/W reduces as Resp increases

	Ge-PD	Si WG PD	Si RRPD @ 40 pm detuning
Resp (A/W)	0.9 @ -1V *saturated*	0.6 @ -5.8V	0.23 @ -5.8
Terminated B/W (GHz)	40 @ -2V	30 @ -5.8	30 @ -5.8
Dark current (nA)	100 @ -2.5	850 @ -5.8	100 @ -5.8



Si RRPD 50 Gb/s NRZ eye*

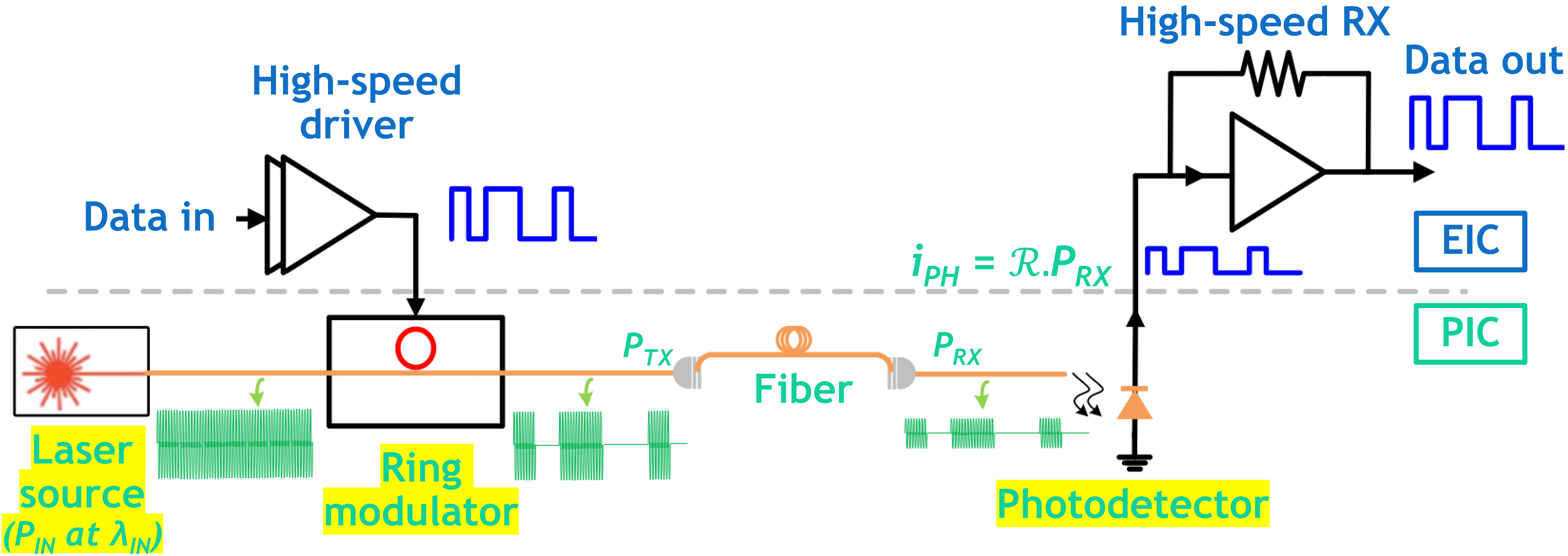
*50 Ω terminated probe [Intel, OFC 2020]

- Resp and B/W trend oppositely with optical bias: optimize detuning!
- Resp and dark current increase with reverse bias: optimize bias!

A 112 Gb/s all-silicon micro-ring photodetector for datacom applications

Meer Sakib, Peicheng Liao, Ranjeet Kumar, Duanni Huang, Guan-lin Su, Chaoxuan Ma, and Haisheng Rong

IMDD Optical Links



Integrated
High power
Clean spectrum

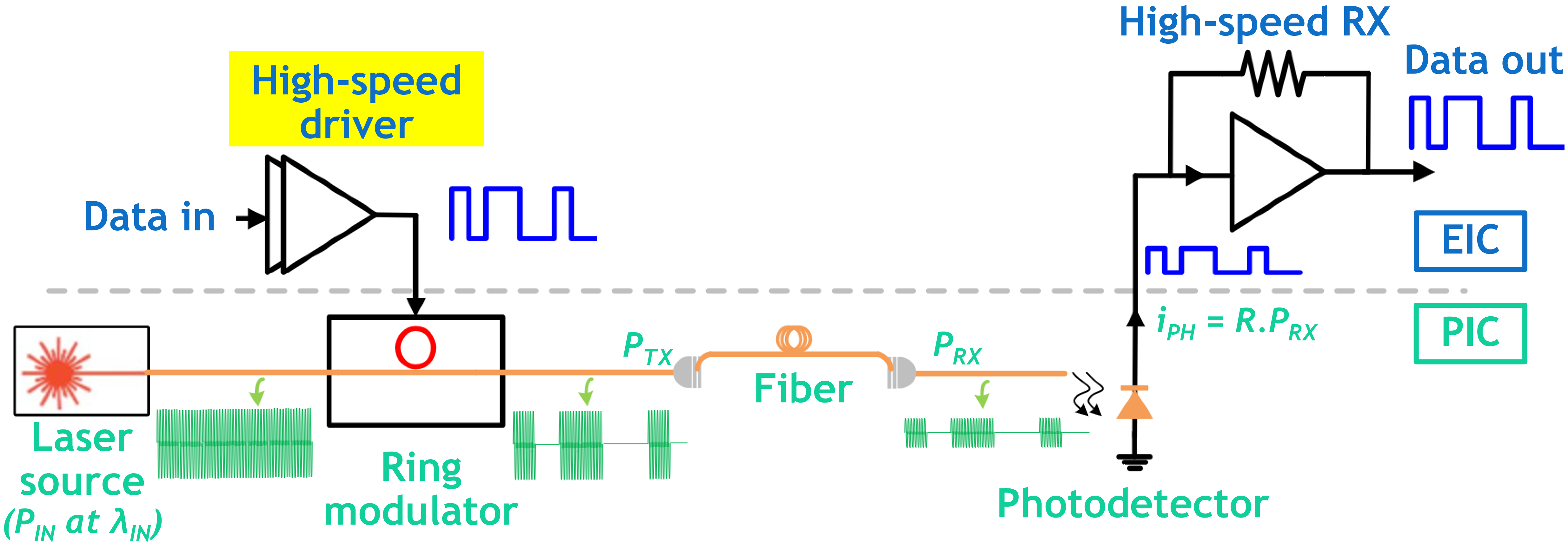
Compact
Low driver swing
High B/W

High B/W and responsivity
Si-only photodiodes

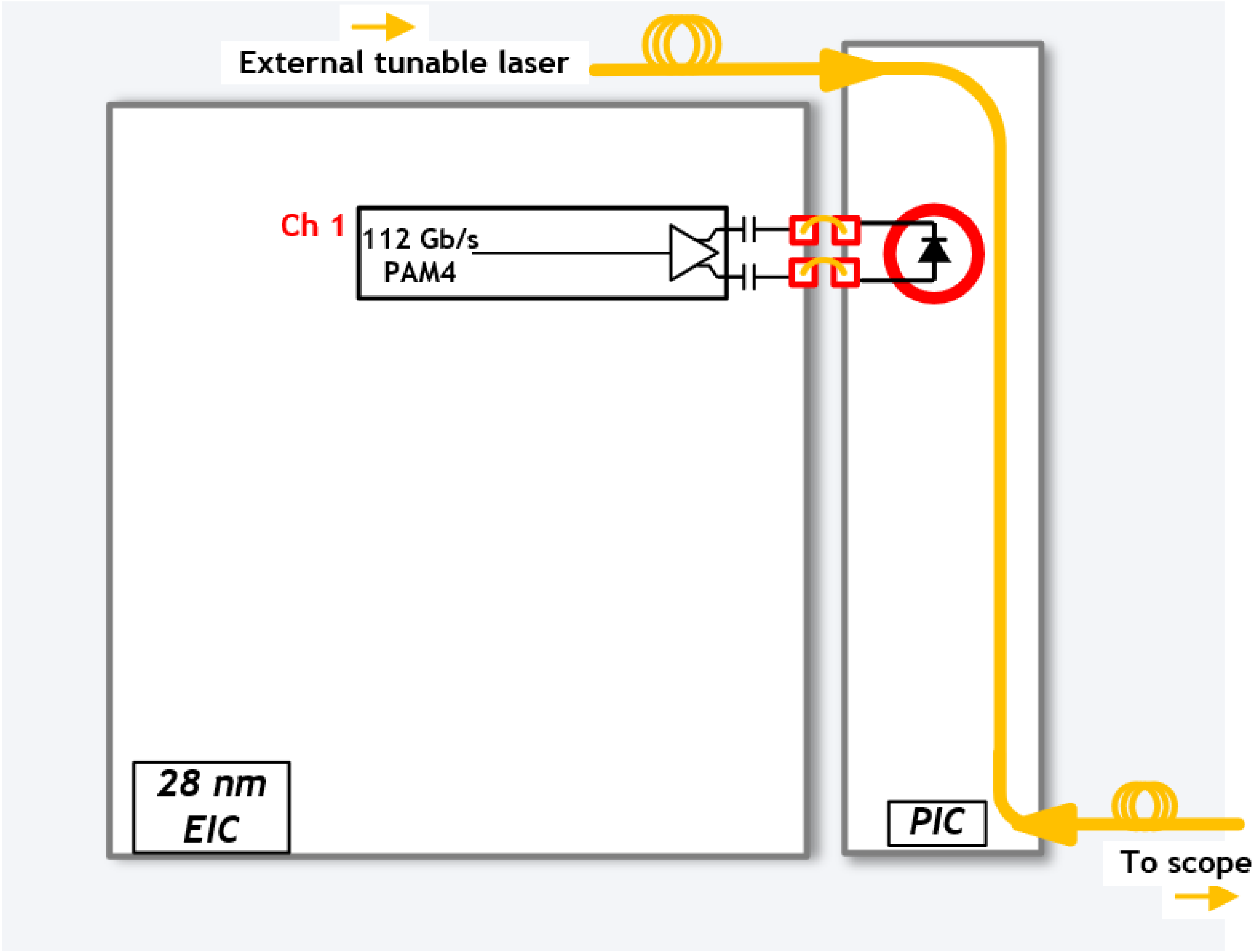
Outline

- SiPh platform for high-speed DCI
- IMDD optical links
- Photonic devices
- <u>CMOS electronics for single-λ links</u>
  - 3-D integrated 112 Gb/s PAM4 CMOS-based OTX with Integrated laser and Modulator
  - 100 Gb/s PAM4 CMOS-based mixed-signal ORX
- Wavelength-division multiplexing
- Future directions and conclusion

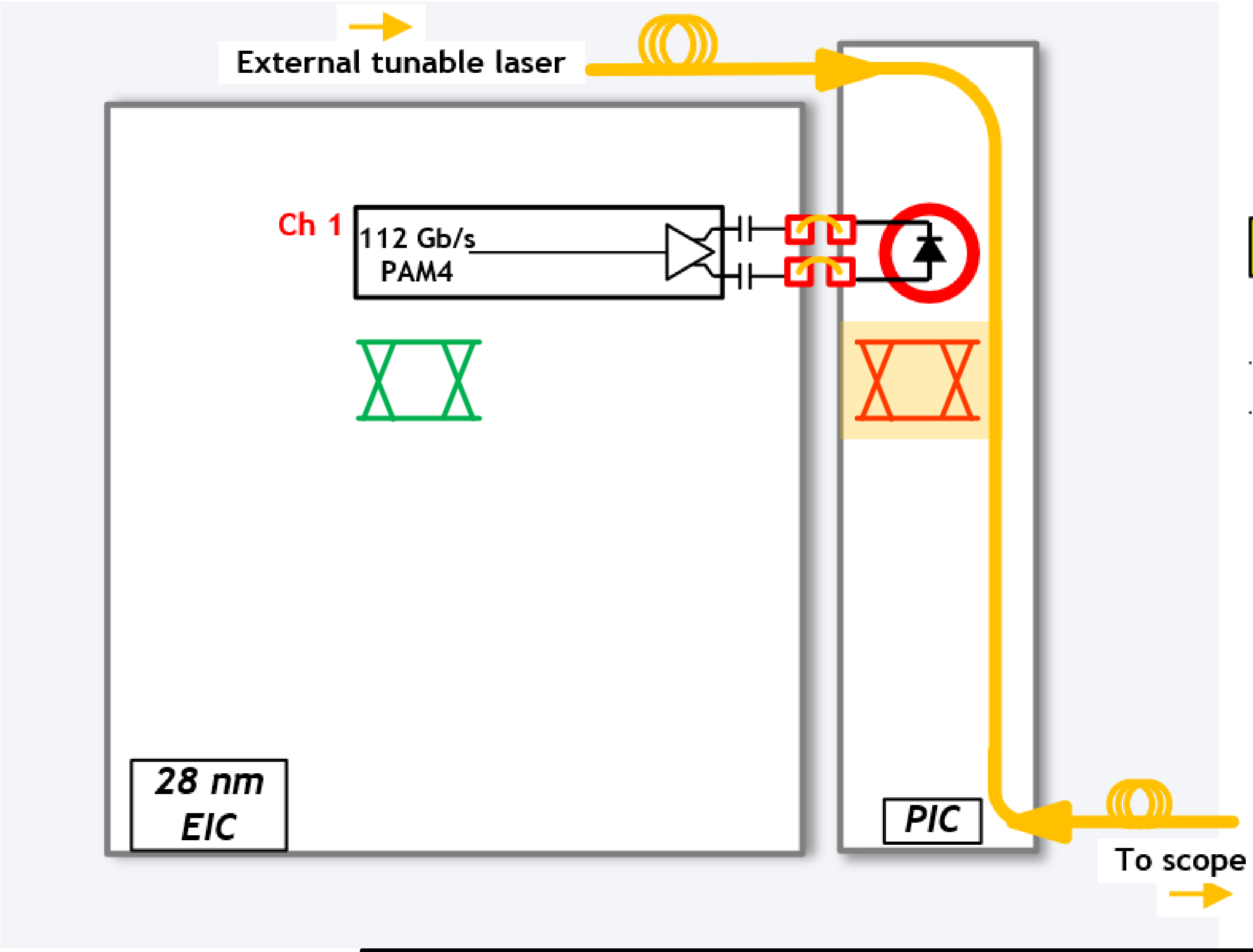
IMDD Optical Links

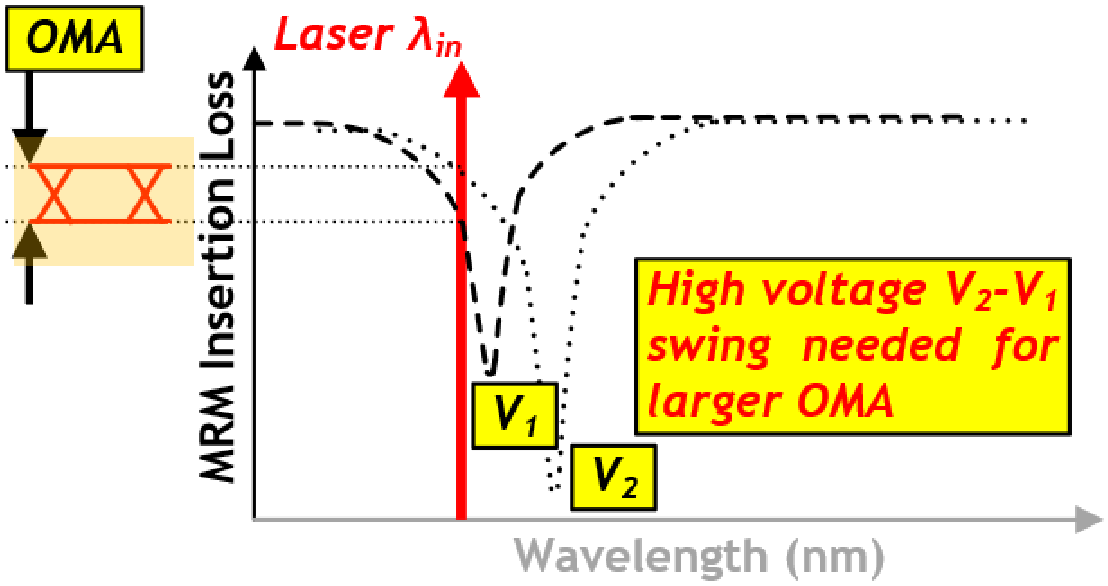


MRM Challenge #1:Electrical Swing



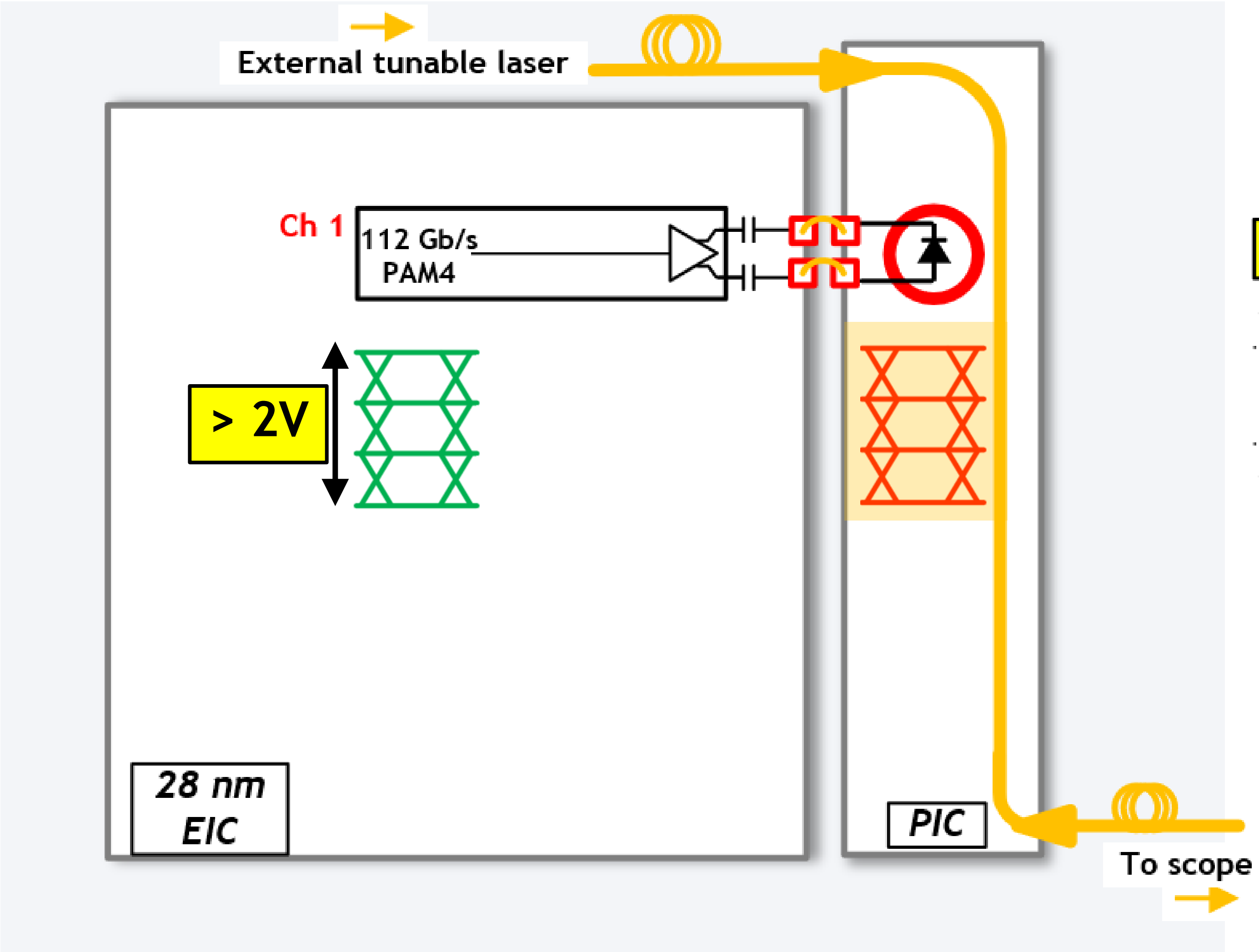
MRM Challenge #1:Electrical Swing

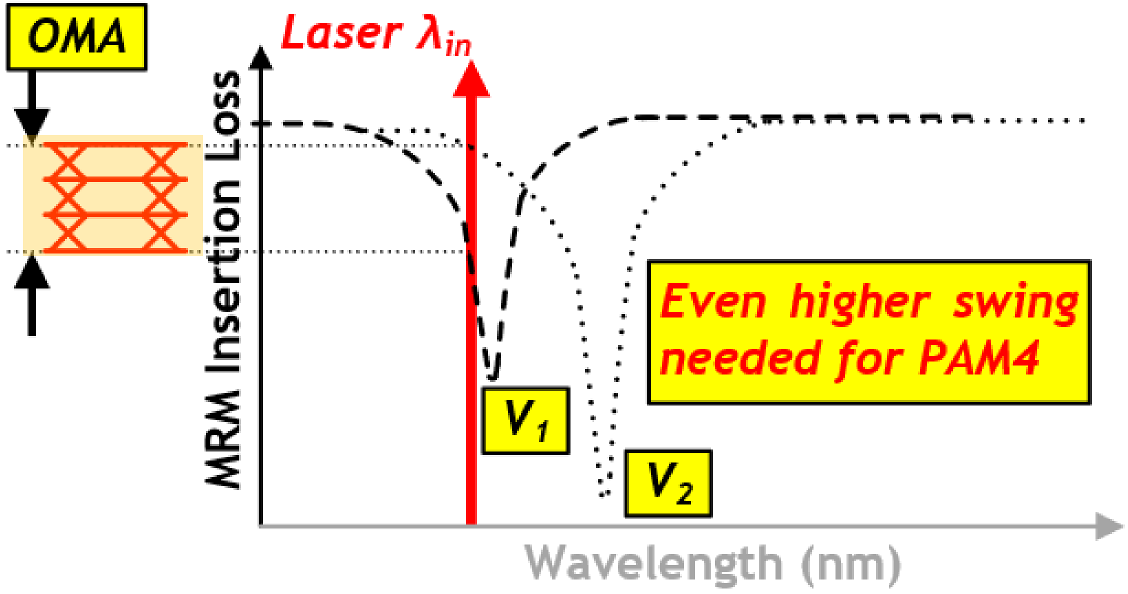




A high-swing driver is required for depletion mode MRM.

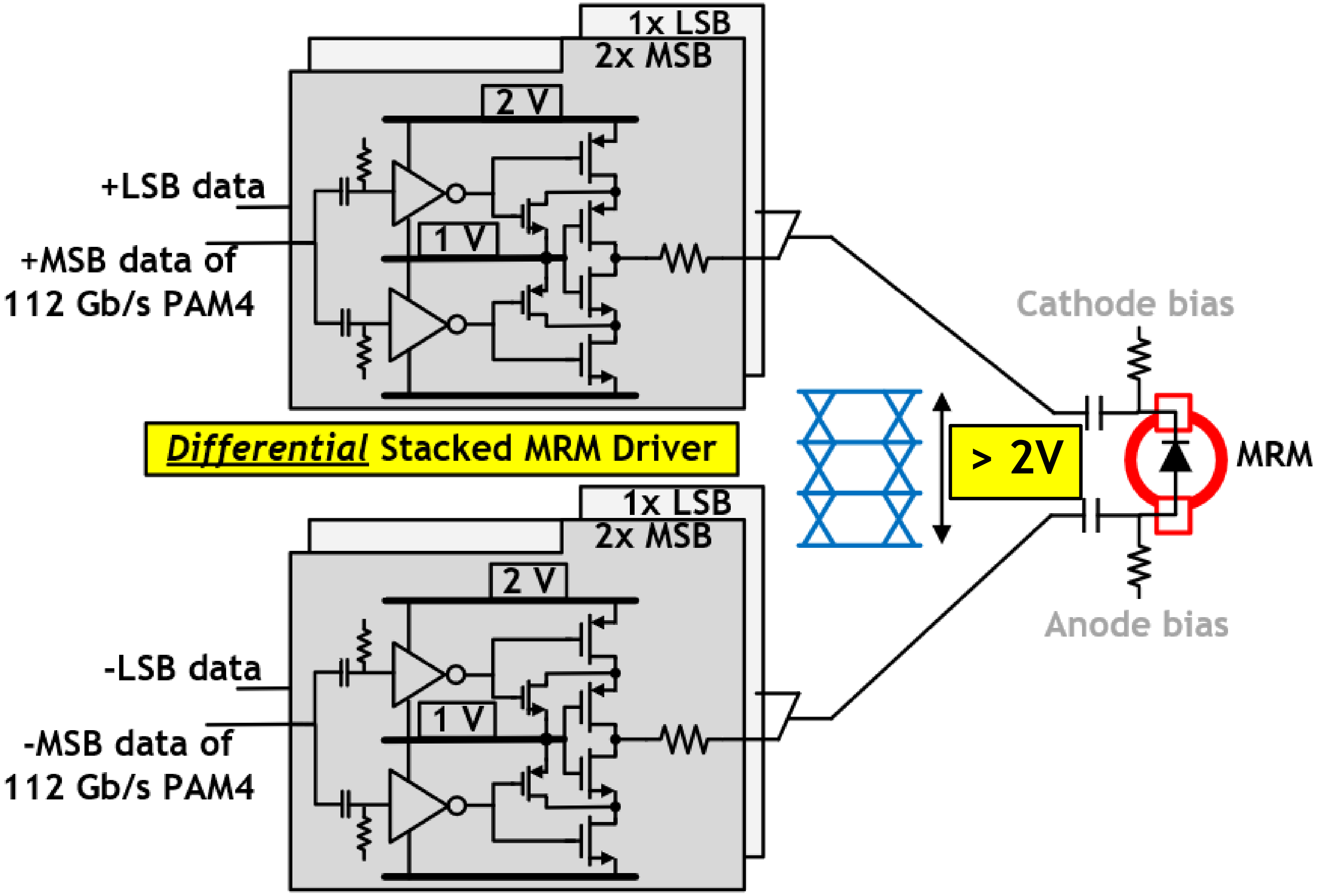
MRM Challenge #1:Electrical Swing





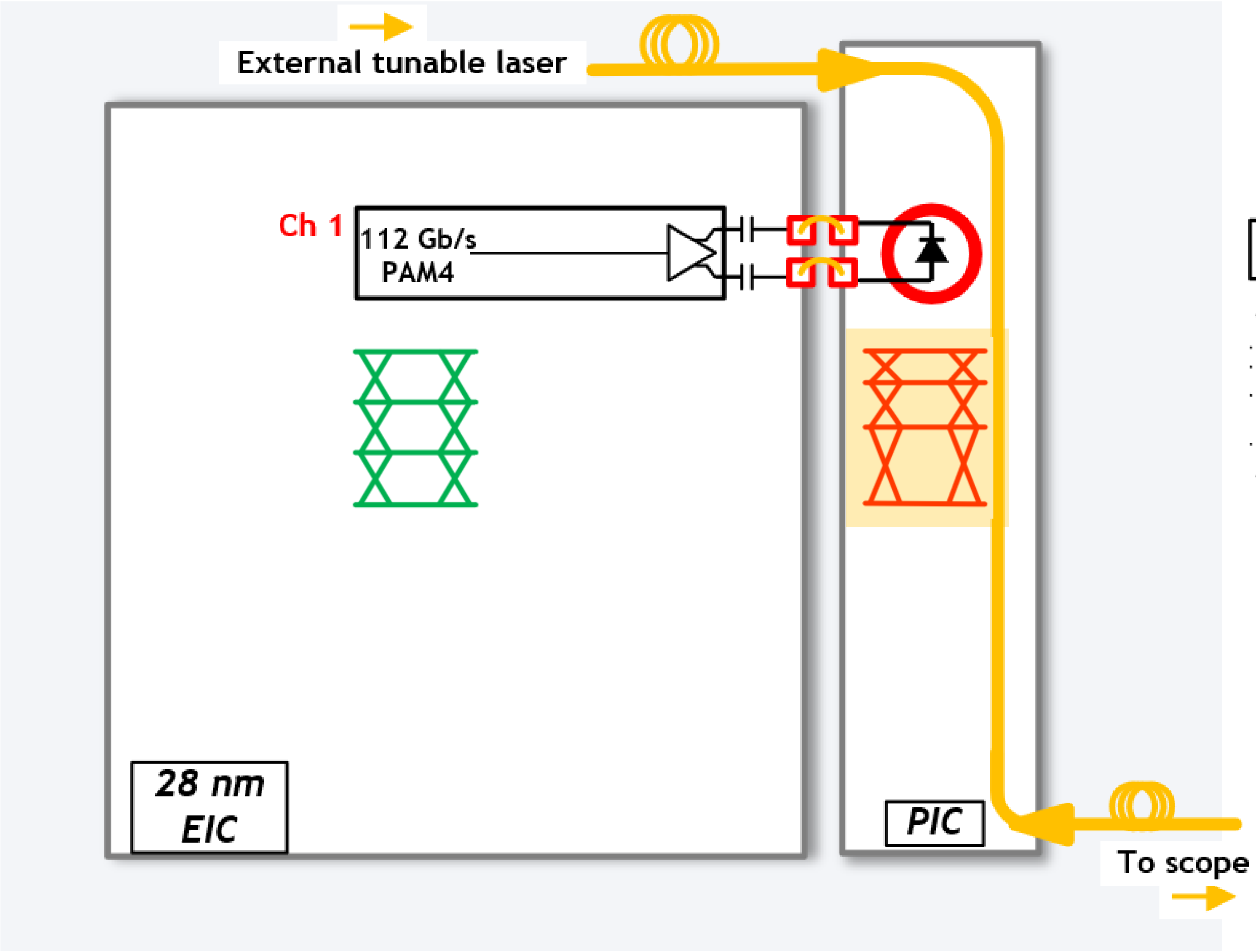
A high-swing driver is required for depletion mode MRM.

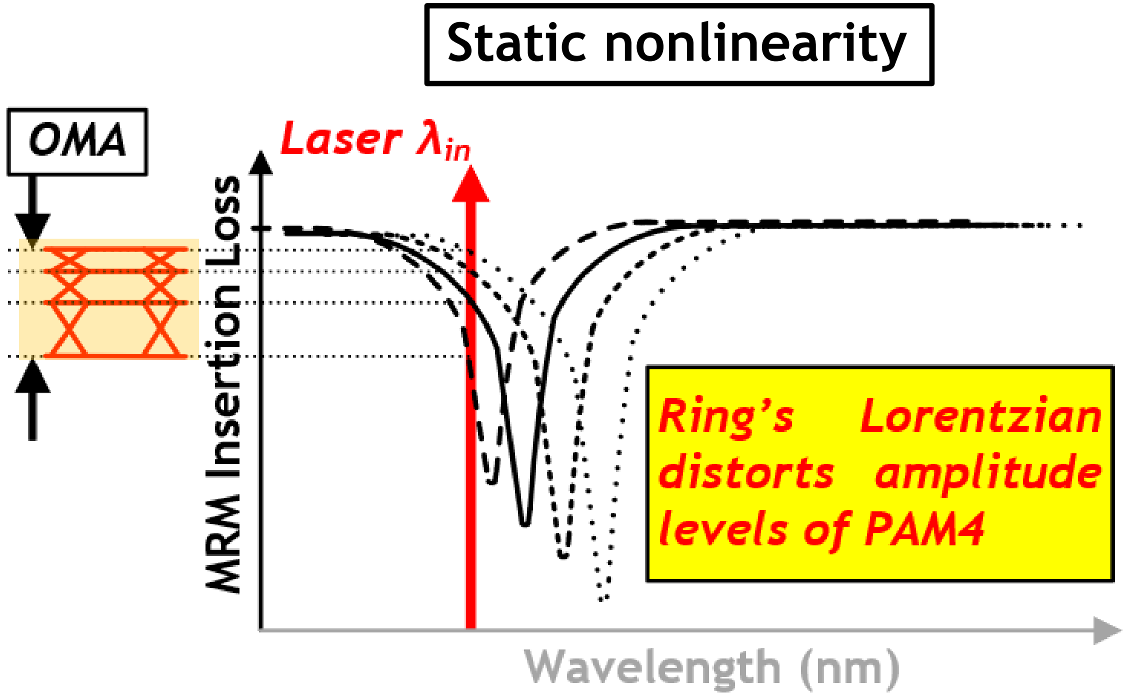
MRM Challenge #1:Electrical Swing



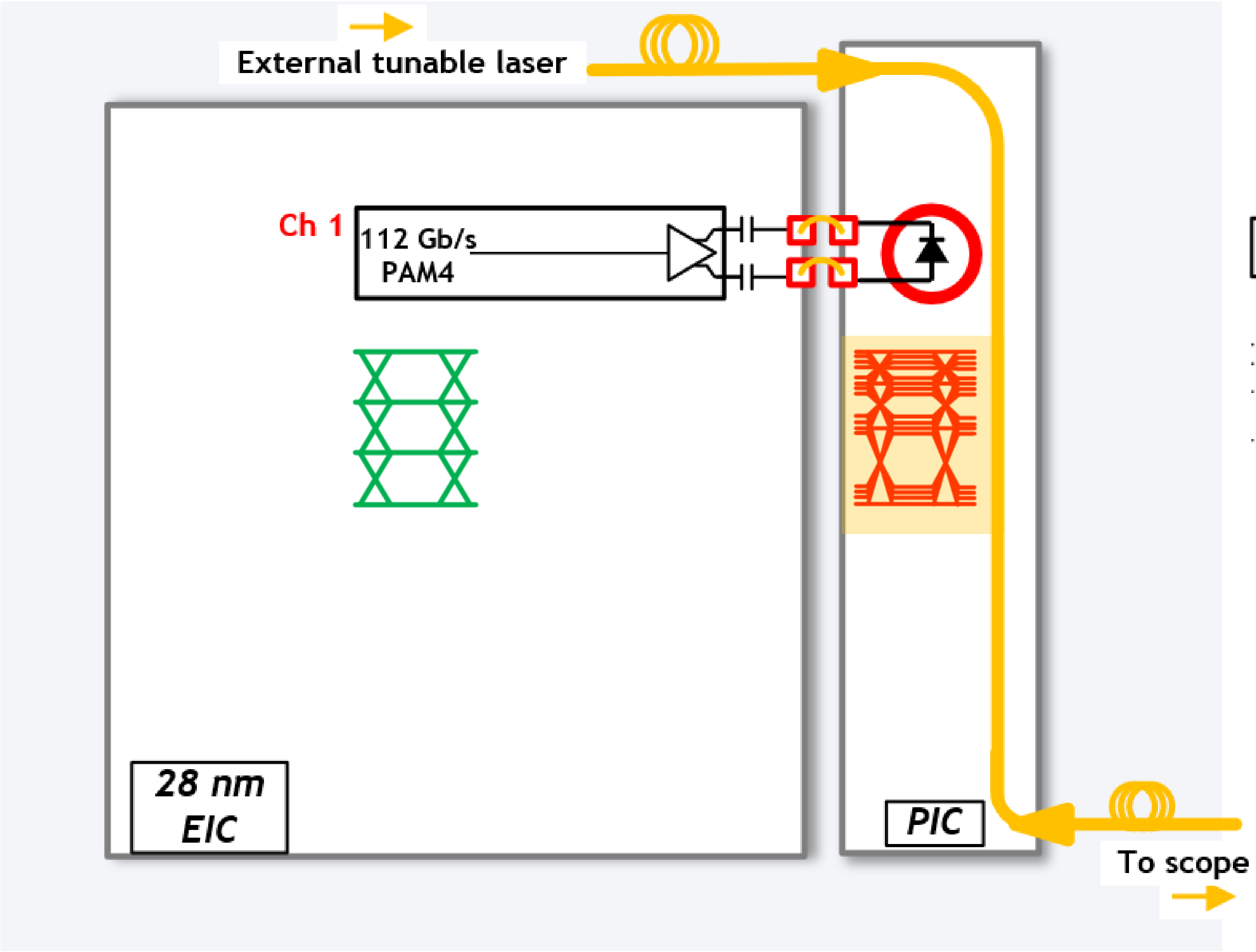
A high-swing driver is required for depletion mode MRM.

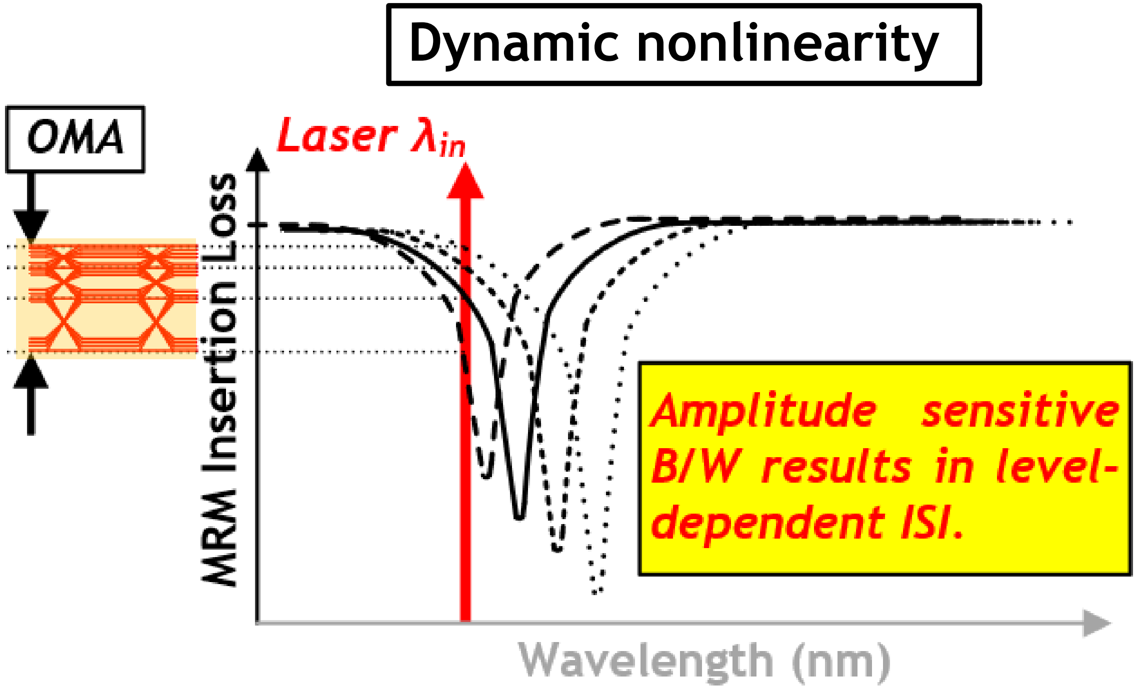
MRM Challenge #2: Optical Nonlinearity



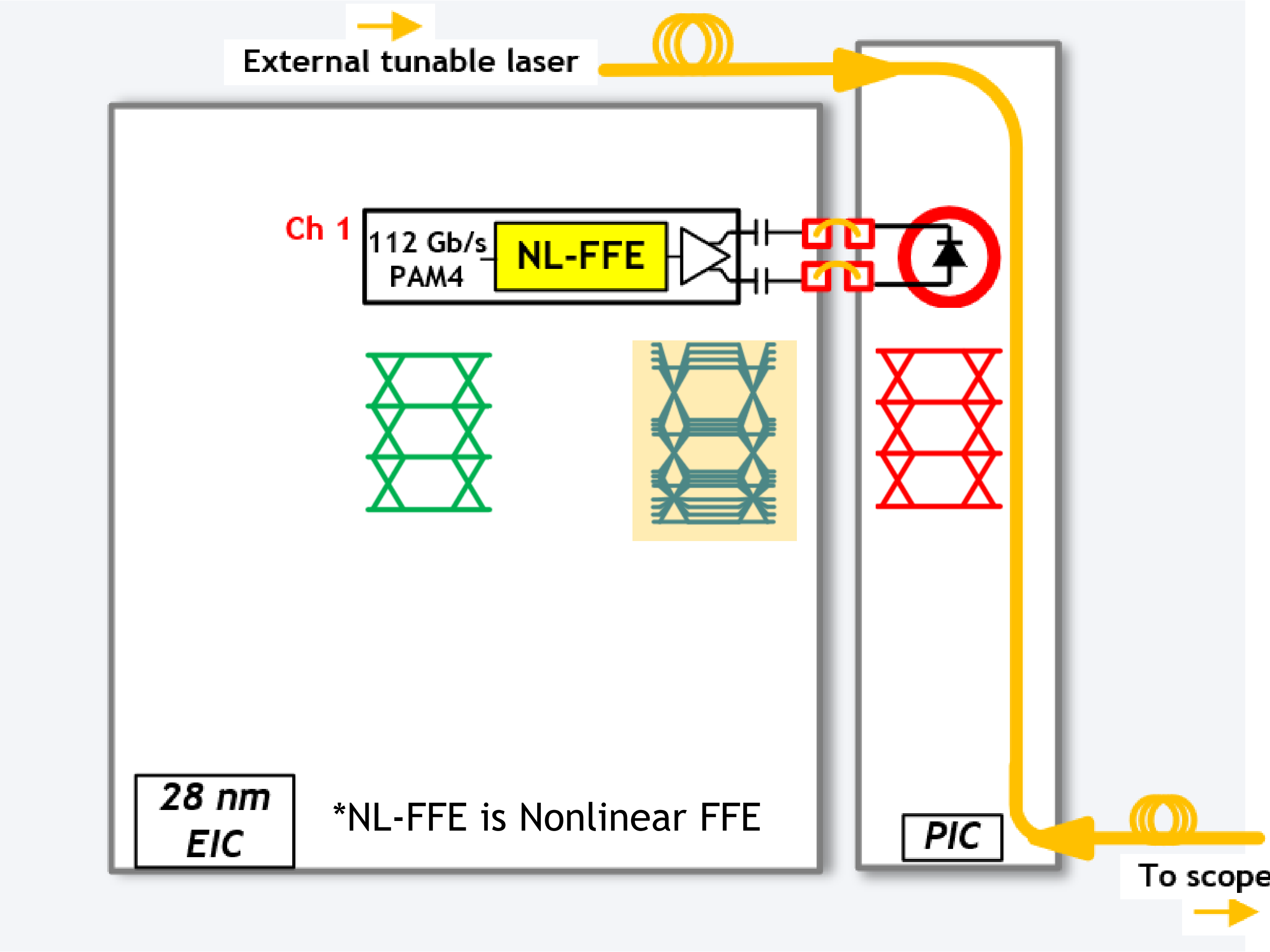


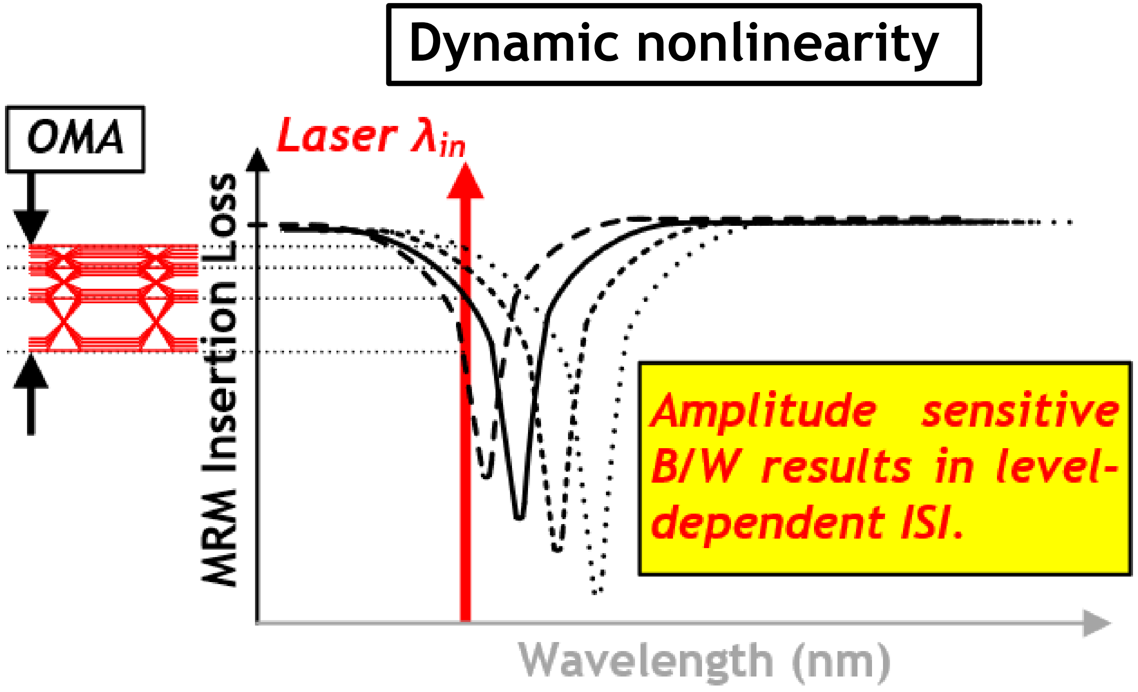
MRM Challenge #2: Optical Nonlinearity





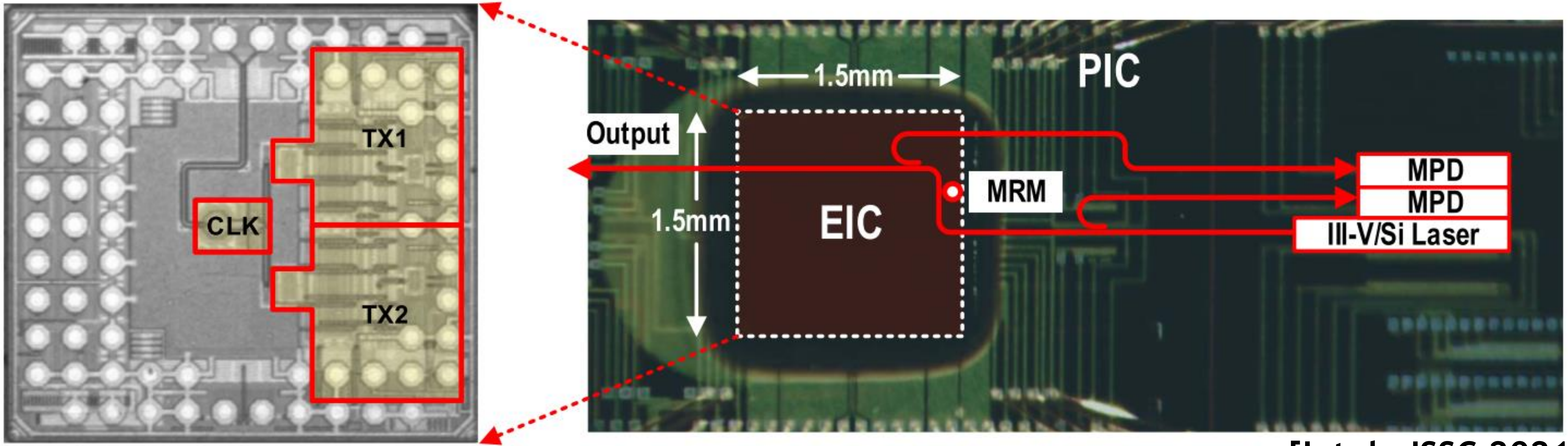
MRM Challenge #2: Optical Nonlinearity





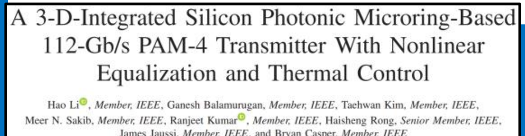
Nonlinear equalization is required to compensate for optical nonlinearity.

Single-λ 112 Gb/s PAM4 OTX



[Intel, JSSC 2021]

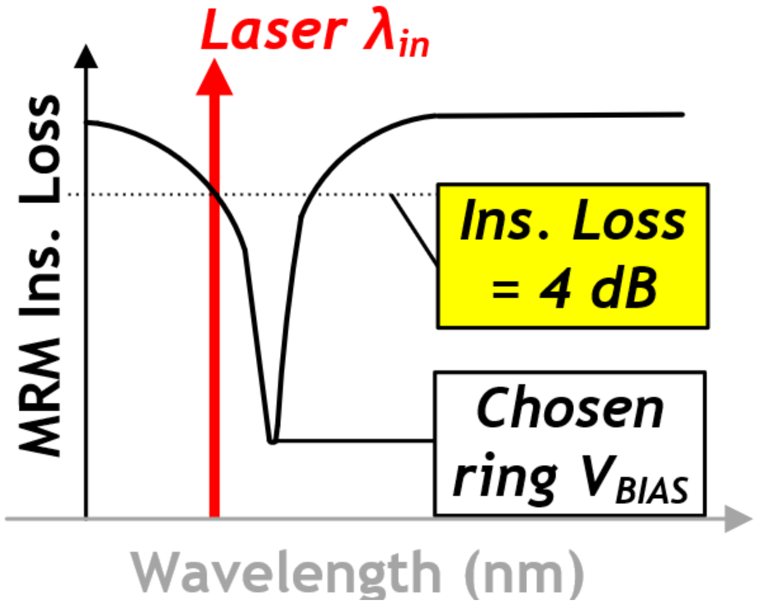
112 Gbps PAM4 OTX in 28nm CMOS was 3-D integrated with
- silicon-photonic MRM and integrated laser
- on-chip MRM thermal control.



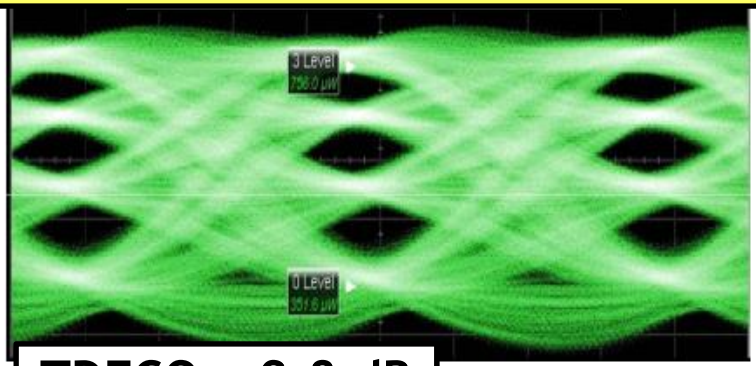
A 3-D-Integrated Silicon Photonic Microring-Based 112-Gb/s PAM-4 Transmitter With Nonlinear Equalization and Thermal Control

Hao Li, *Member, IEEE*, Ganesh Balamurugan, *Member, IEEE*, Taehwan Kim, *Member, IEEE*, Meer N. Sakib, *Member, IEEE*, Ranjeet Kumar, *Member, IEEE*, Haisheng Rong, *Senior Member, IEEE*, James Jaussi, *Member, IEEE*, and Bryan Casper, *Member, IEEE*

Benefit of Enabling NL-FFE PAM4

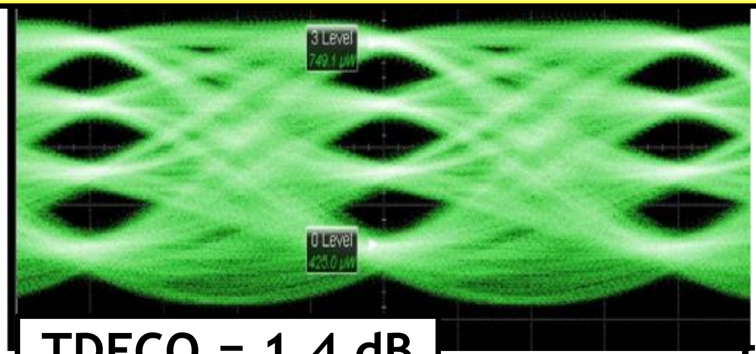


EIC Pre dist./NL-FFE disabled



TDECQ = 2.8 dB

EIC Pre dist./NL-FFE enabled

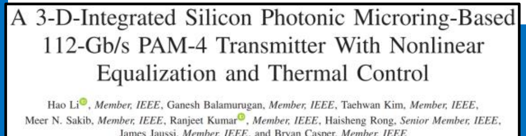


TDECQ = 1.4 dB

[Intel, JSSC 2021]

TDECQ metric for PAM4 :
https://www.ieee802.org/3/bs

NL pre-distortion + FFE provide a 1.4 dB improvement in TDECQ at 112 Gb/s PAM4.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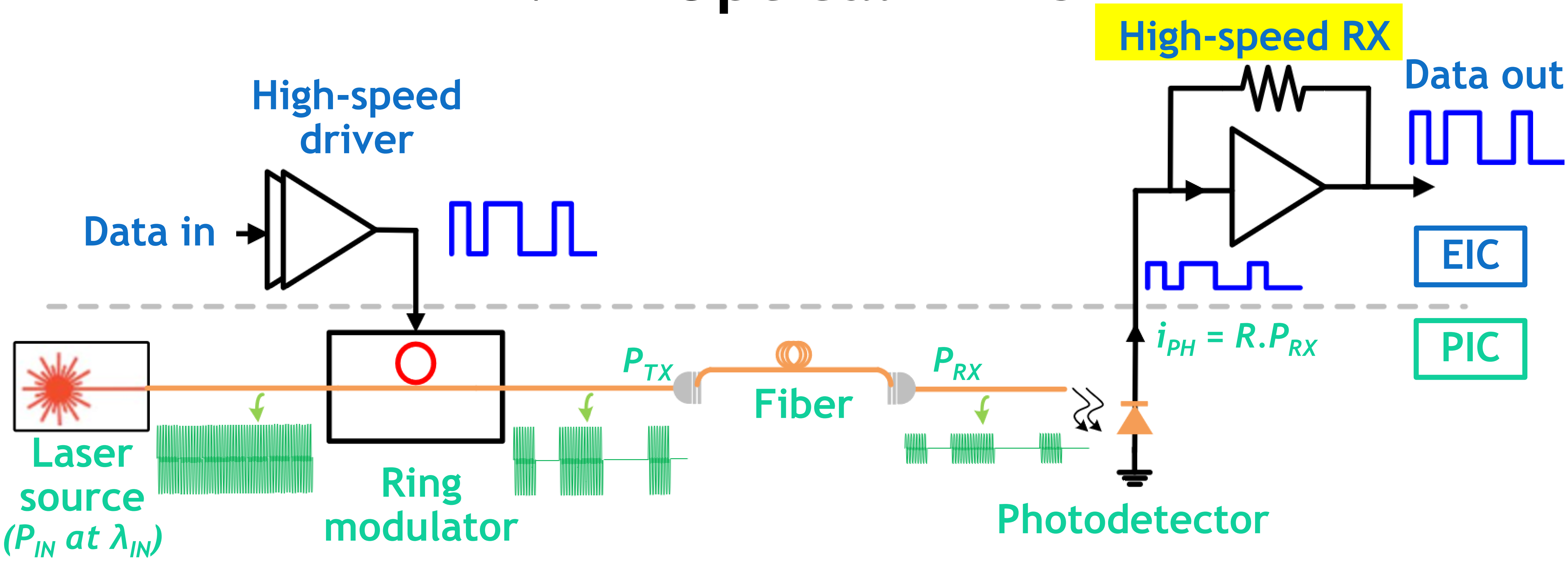
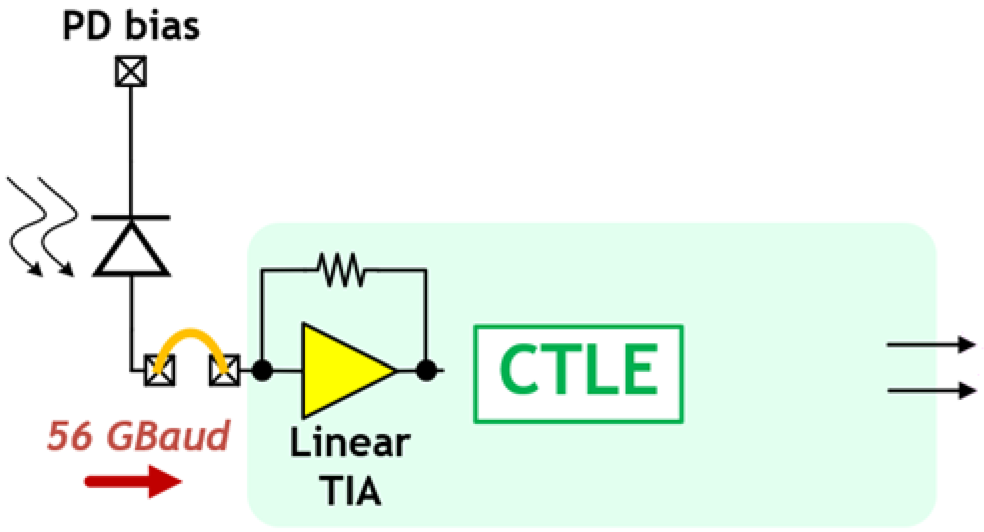
IMDD Optical Links

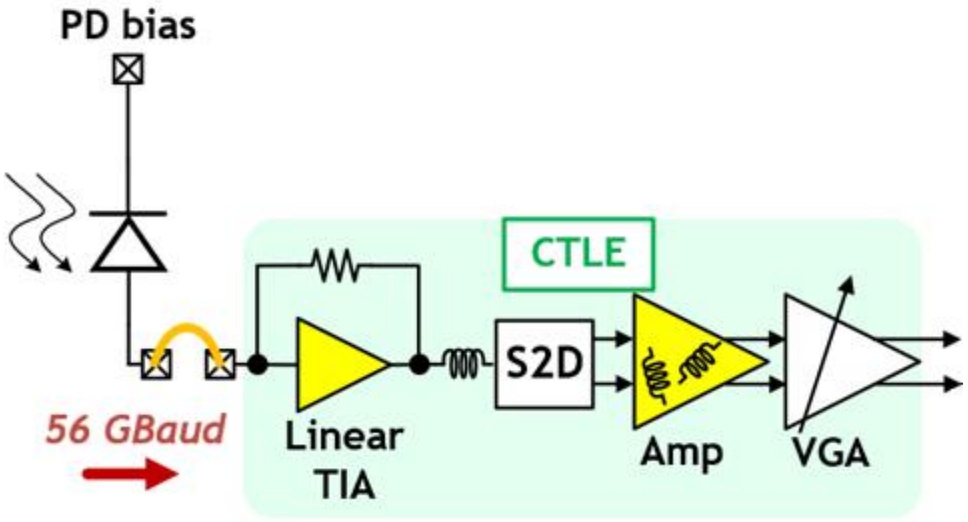


100 Gb/s PAM4 Receiver: TIA



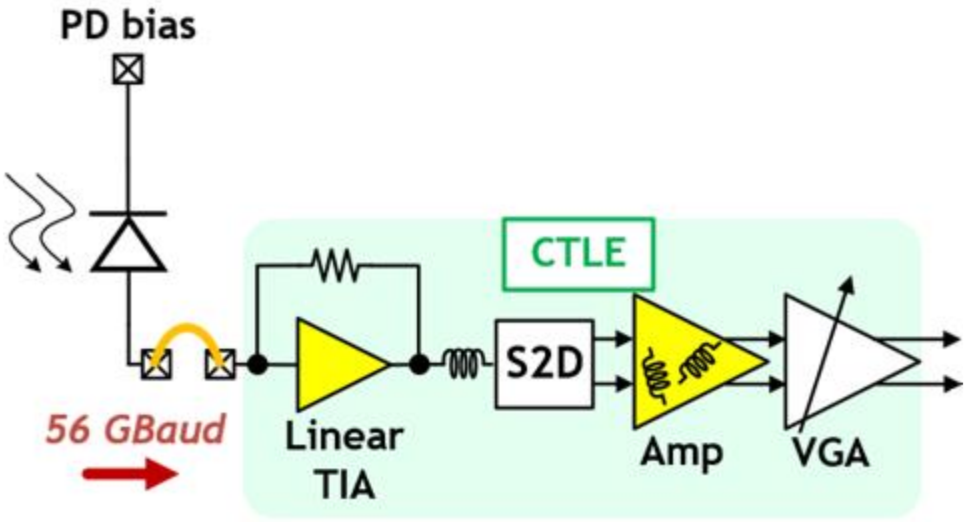
Shunt-TIA topology to overcome bandwidth limitation from input capacitance.

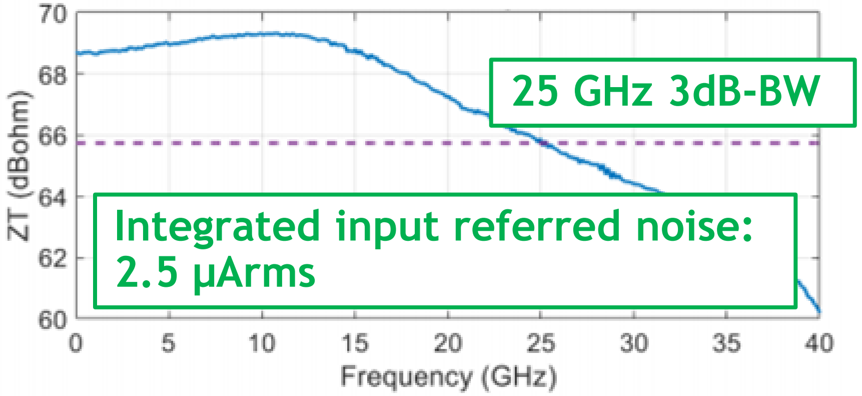
100 Gb/s PAM4 Receiver: CTLE



Continuous time equalization to further improve the front-end bandwidth.

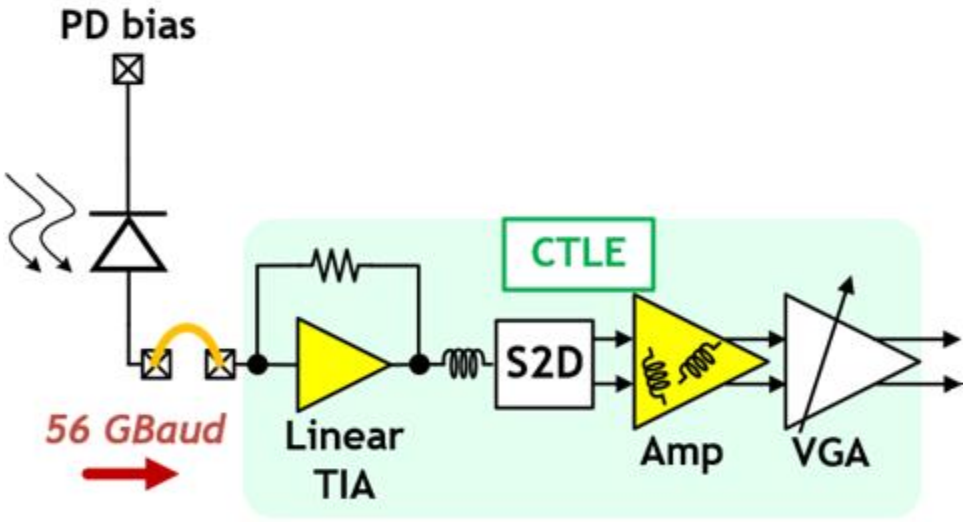
100 Gb/s PAM4 Receiver: Bandwidth vs Noise



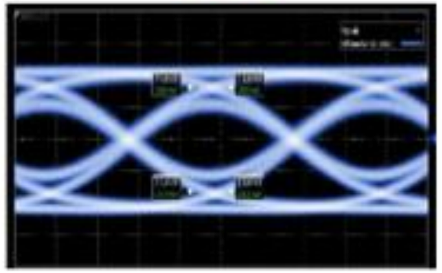


Front-end bandwidth can be traded-off to reduce integrated noise.

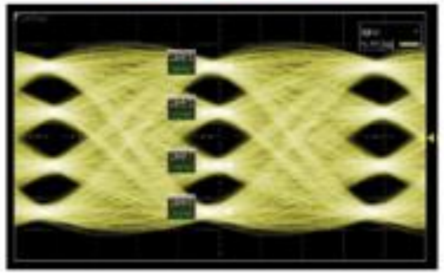
100 Gb/s PAM4 RX: Effect of Low Front-end B/W



53 Gb/s eye NRZ
No EQ

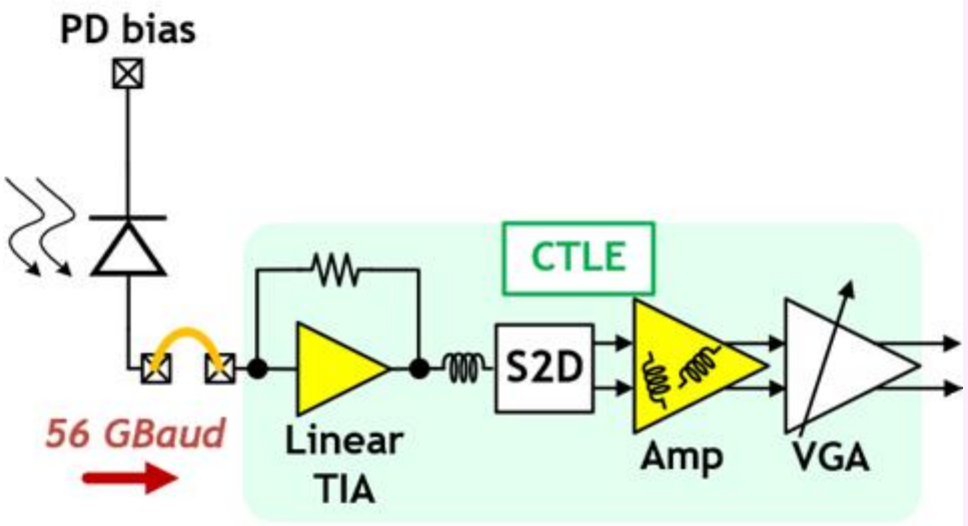


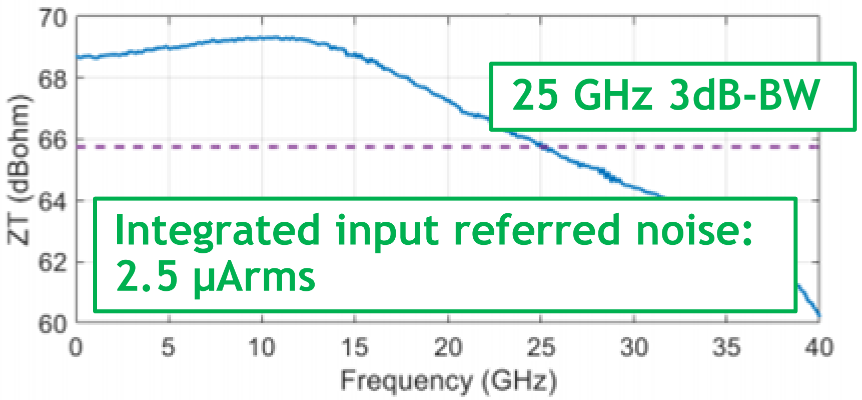
106 Gb/s eye PAM4
With Scope EQ

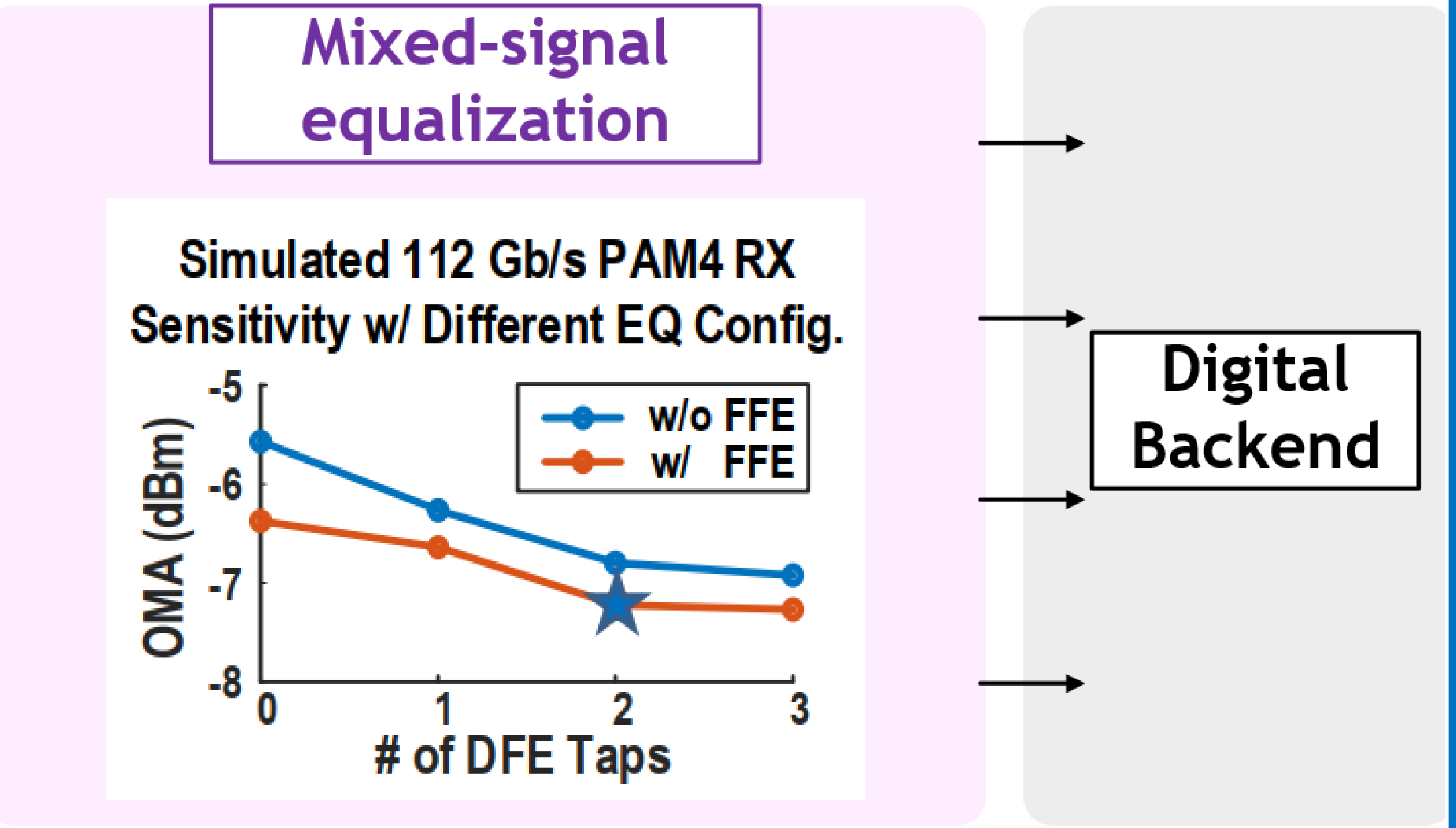


Low bandwidth TIA introduces ISI and needs equalization.

100 Gb/s PAM4 Receiver: Mixed-signal EQ

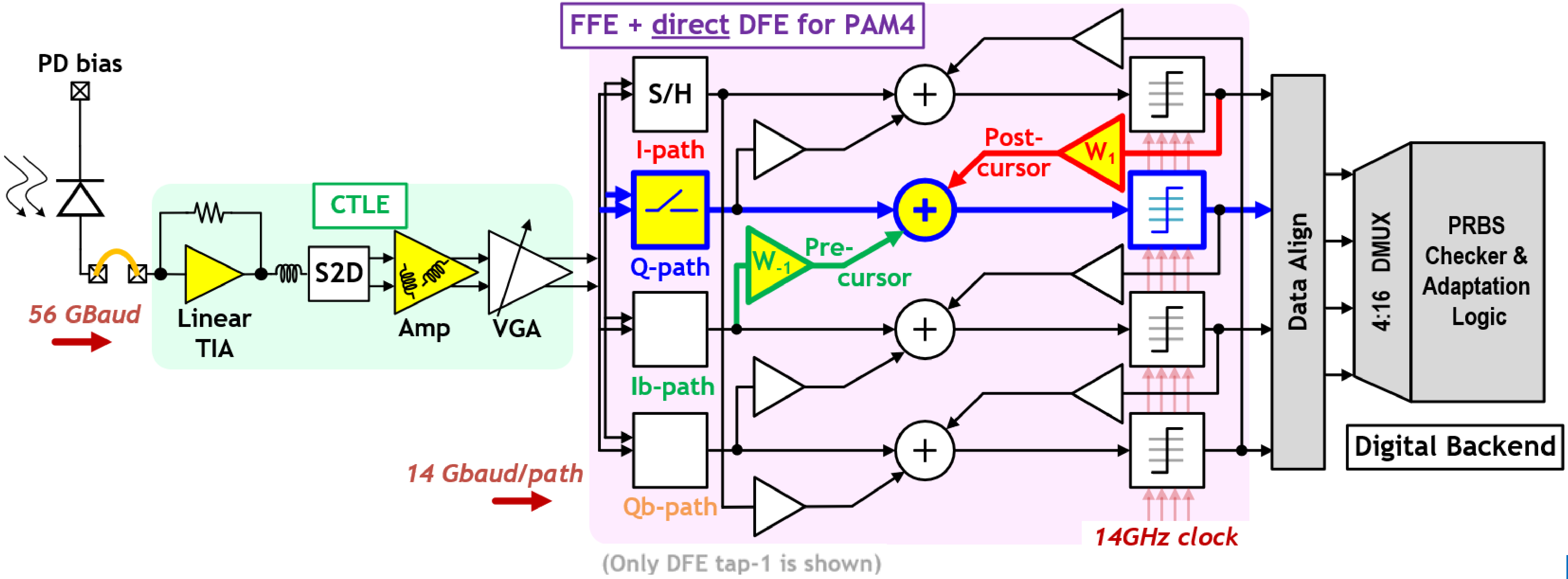






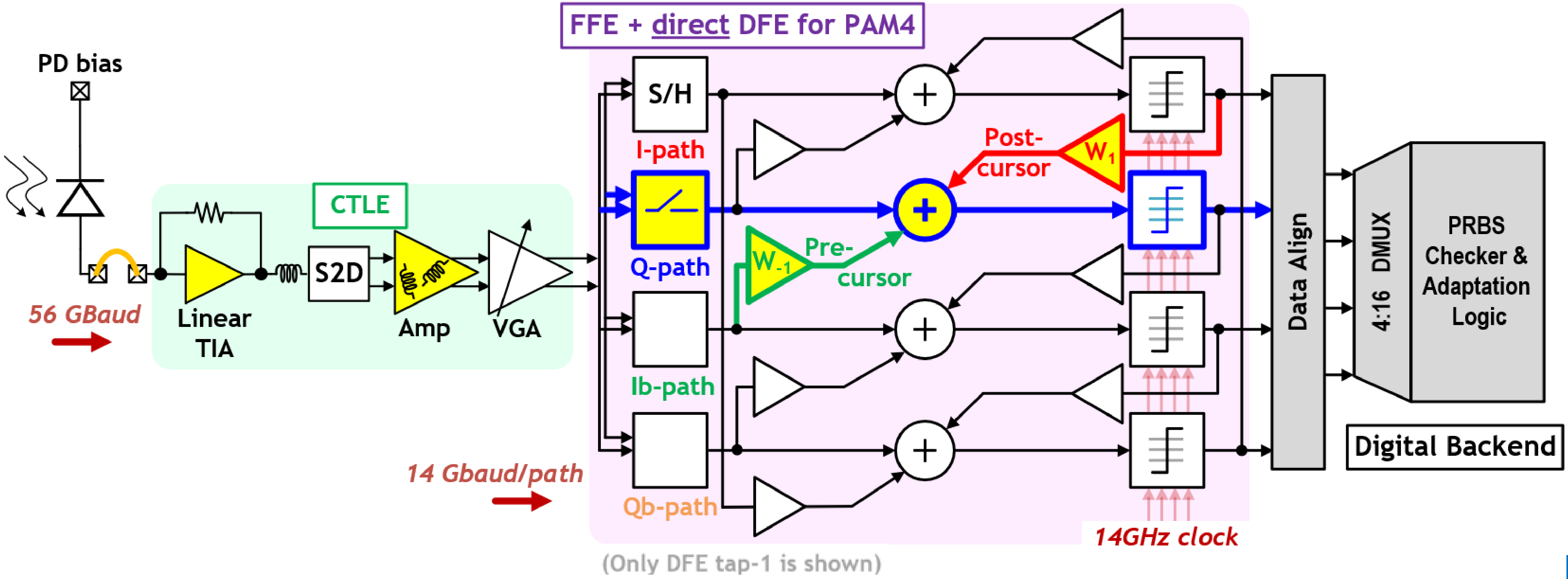
DFE can help compensate low front-end bandwidth without noise enhancement.

100 Gb/s PAM4 RX: Mixed-signal Equalization



On-chip 1-tap FFE for pre-cursor and DFE for post-cursors.

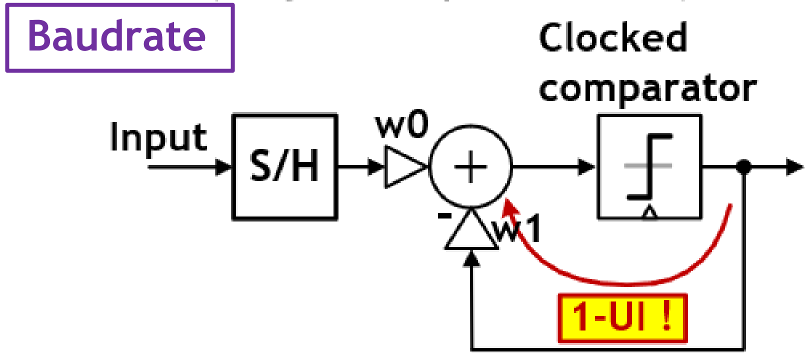
100 Gb/s PAM4 RX: Mixed-signal Equalization

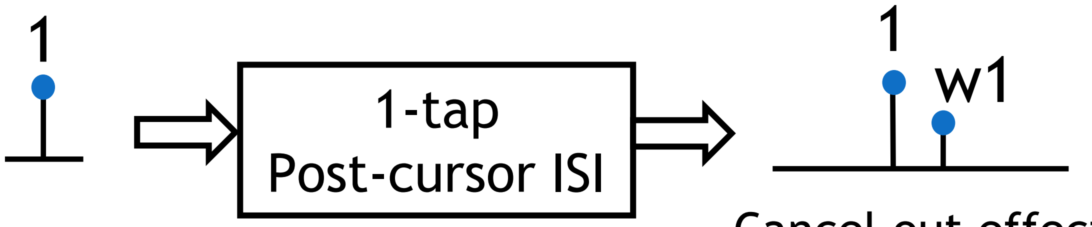


Direct DFE instead of speculative DFE for first post-cursor.

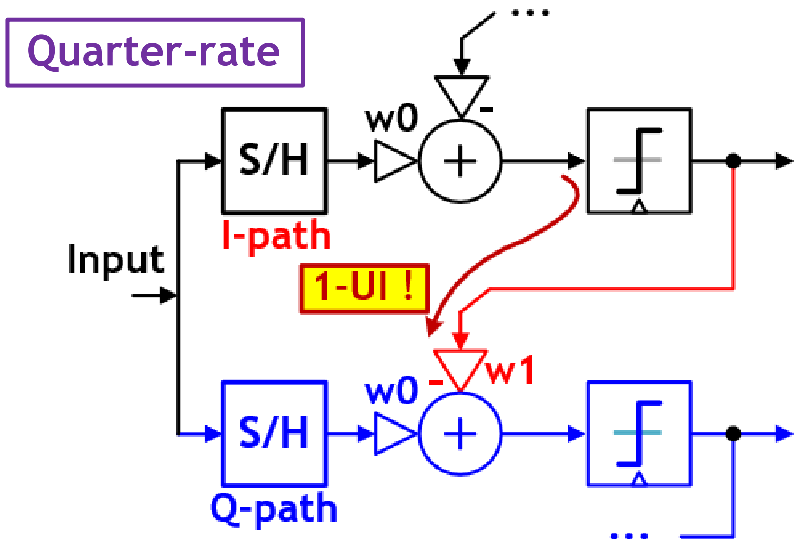
Direct Feedback DFE: Loop Latency

(Only DFE tap-1 is shown)





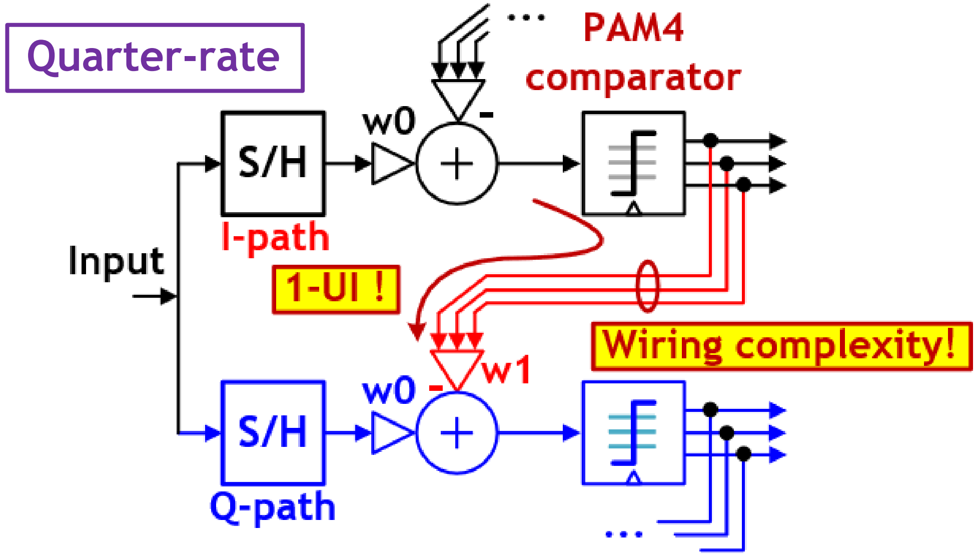
Cancel out effect of w1 on next symbol with DFE



Interleaving does not reduce latency requirements!

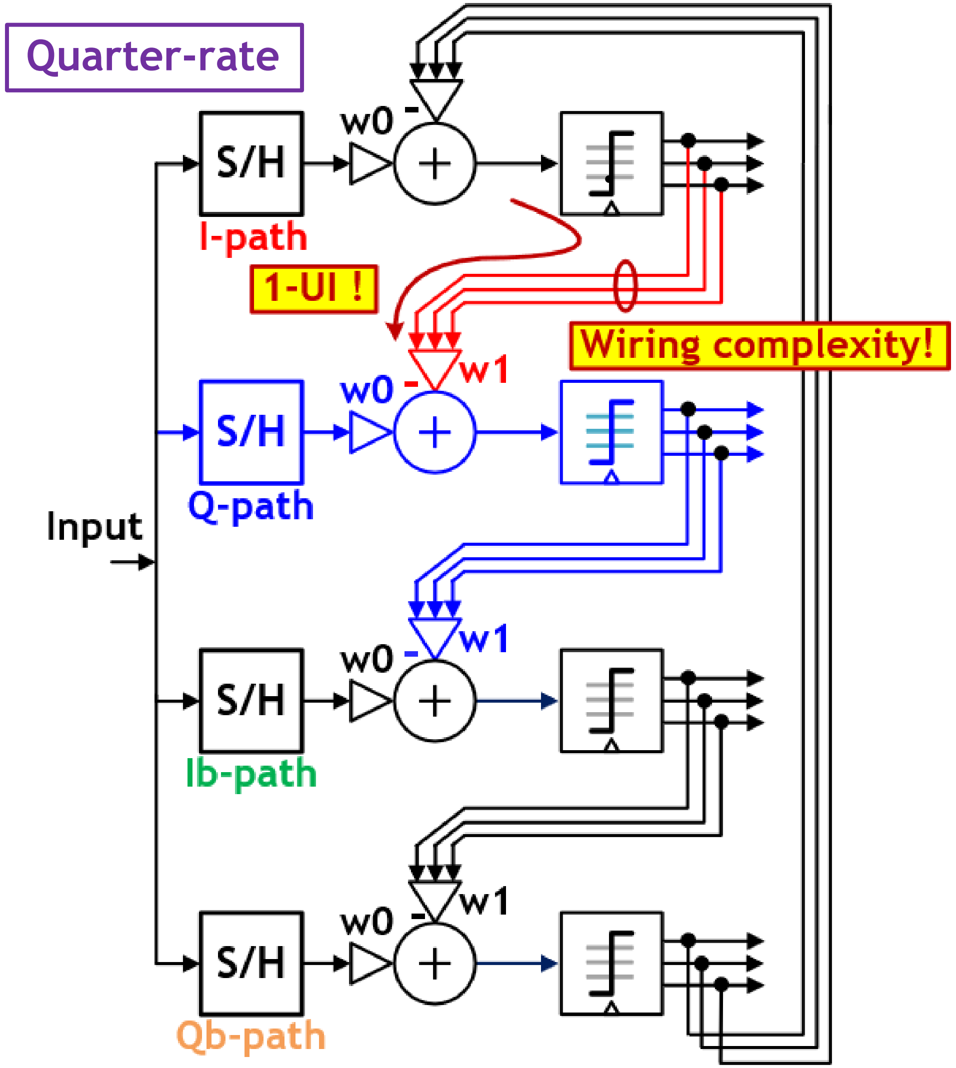
The first-tap post-cursor needs to be closed in one U1.

Direct Feedback DFE : Wiring Complexity



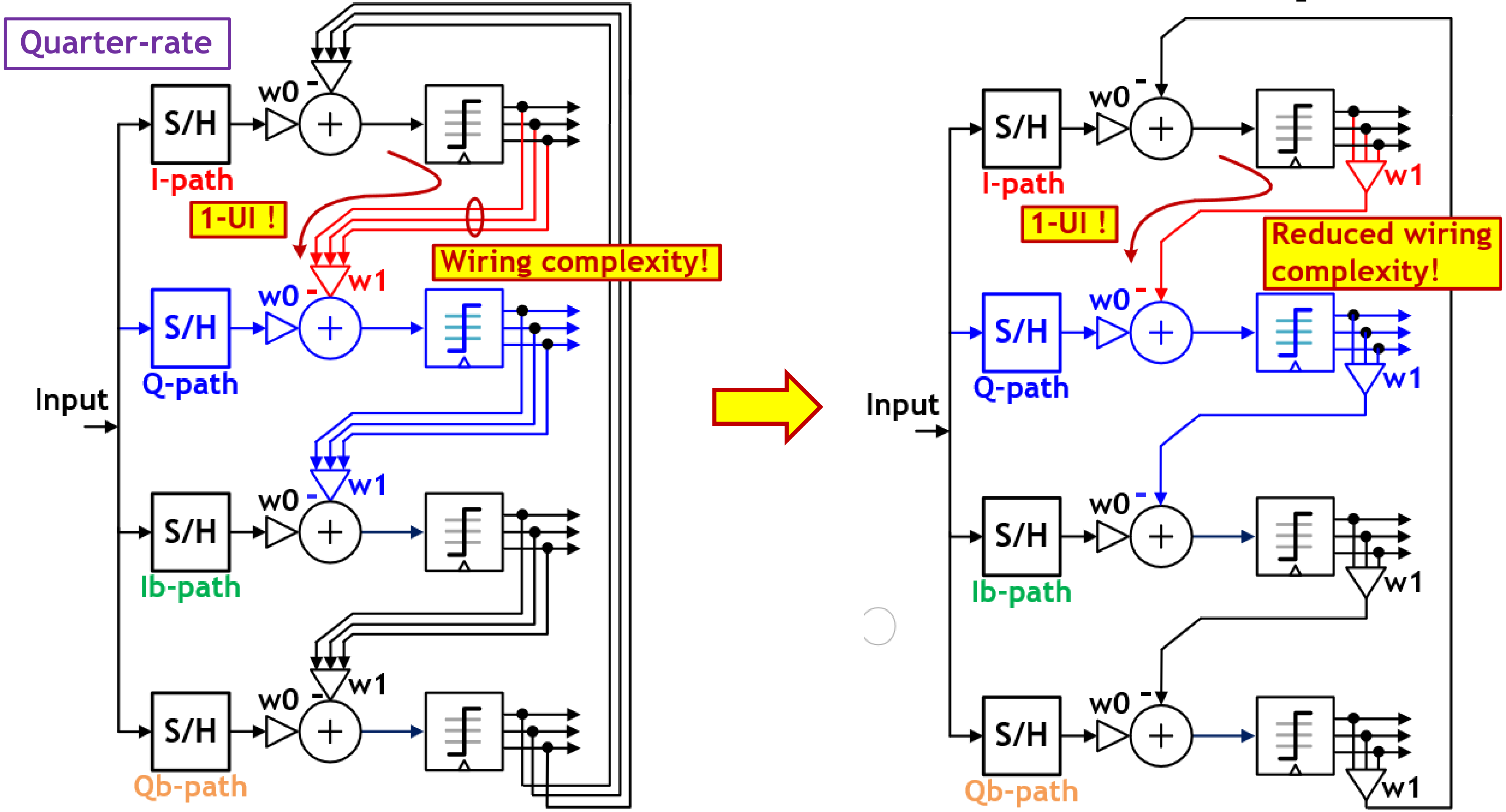
PAM4 wiring complexity for direct DFE increases three times.

Direct Feedback DFE : Wiring Complexity



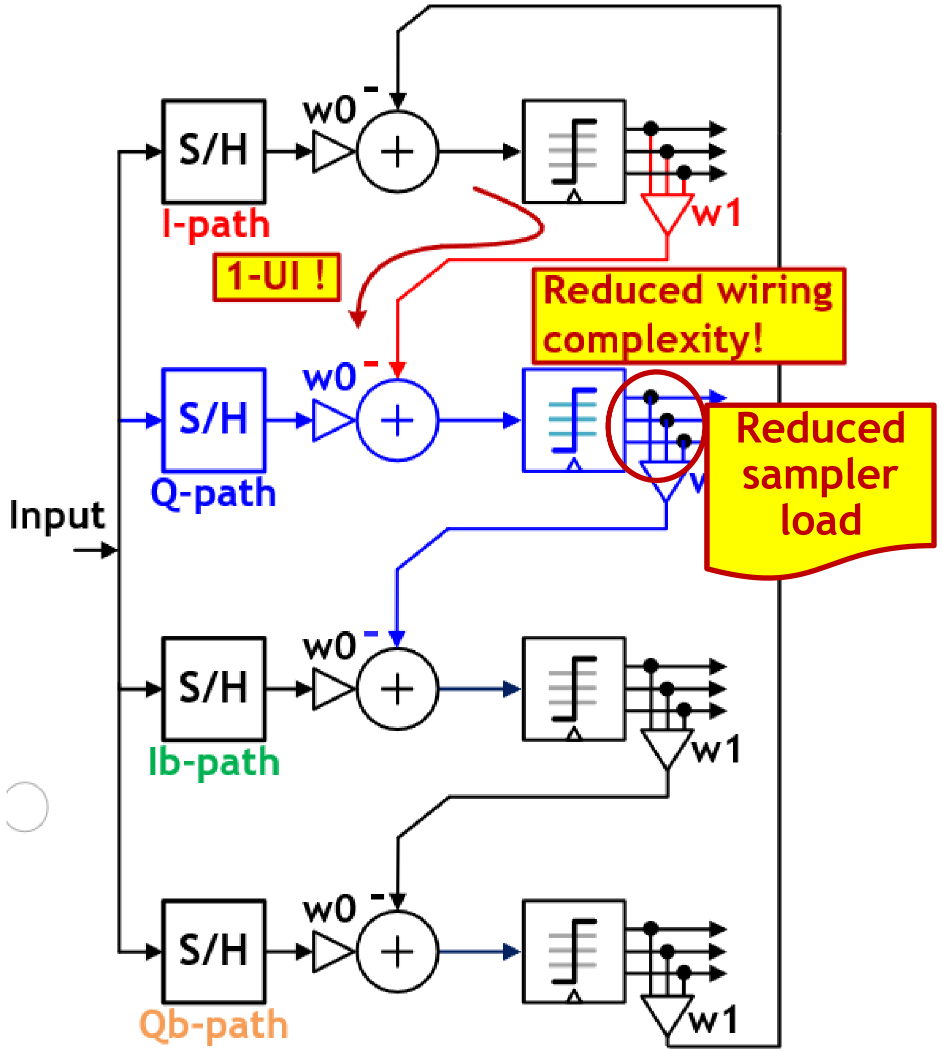
PAM4 wiring complexity for direct DFE increases three times.

Direct Feedback DFE : Reduced Complexity



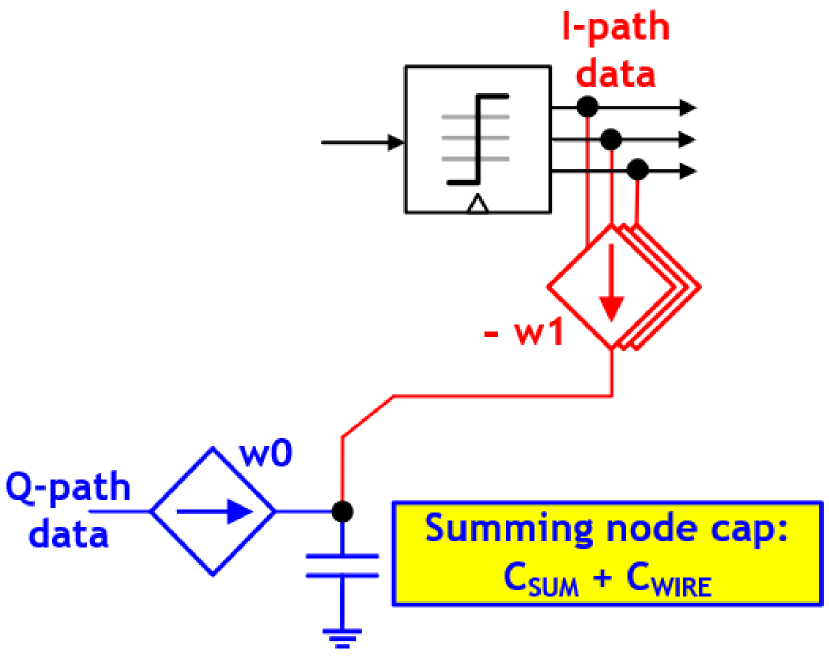
Localizing the V-I conversion to a slice reduces complexity.

Direct Feedback DFE : Improved Slicer Latency

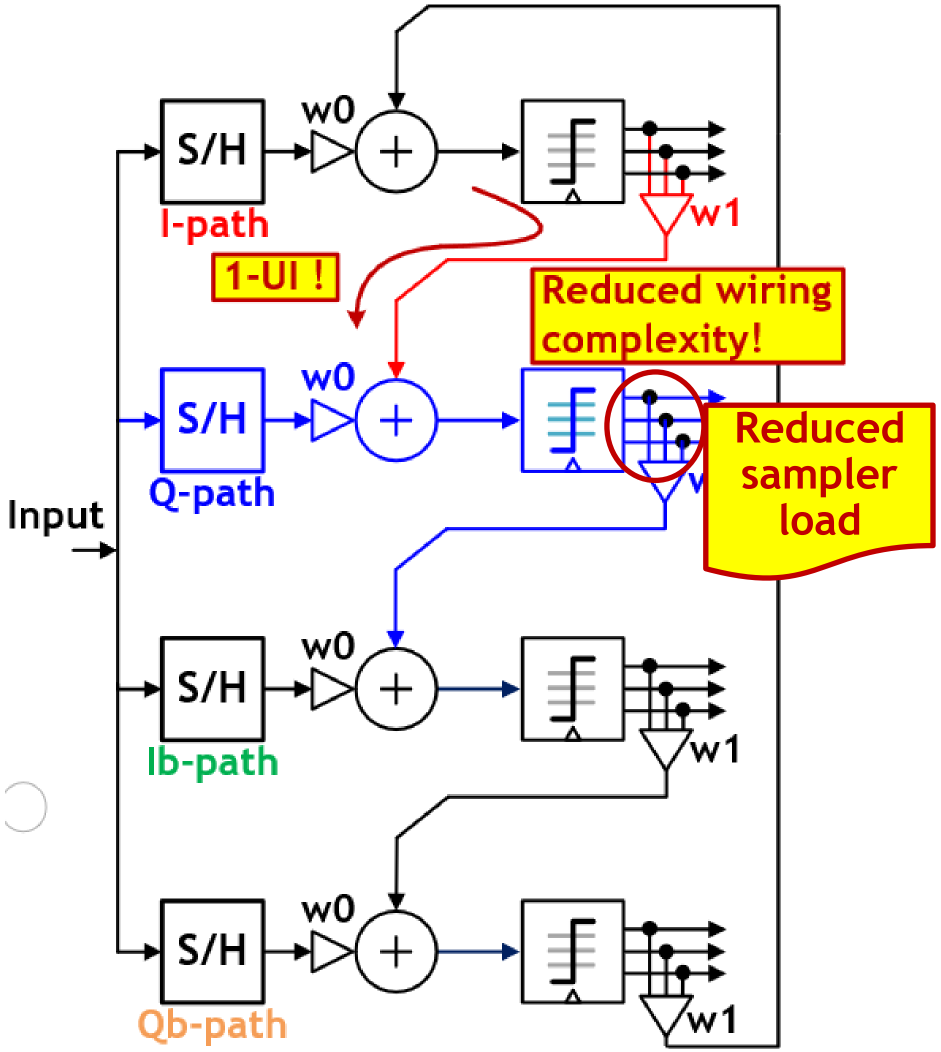


Shorter wiring leads to lower sampler load and improved DFE latency.

Direct Feedback DFE : Integrating Summer Load

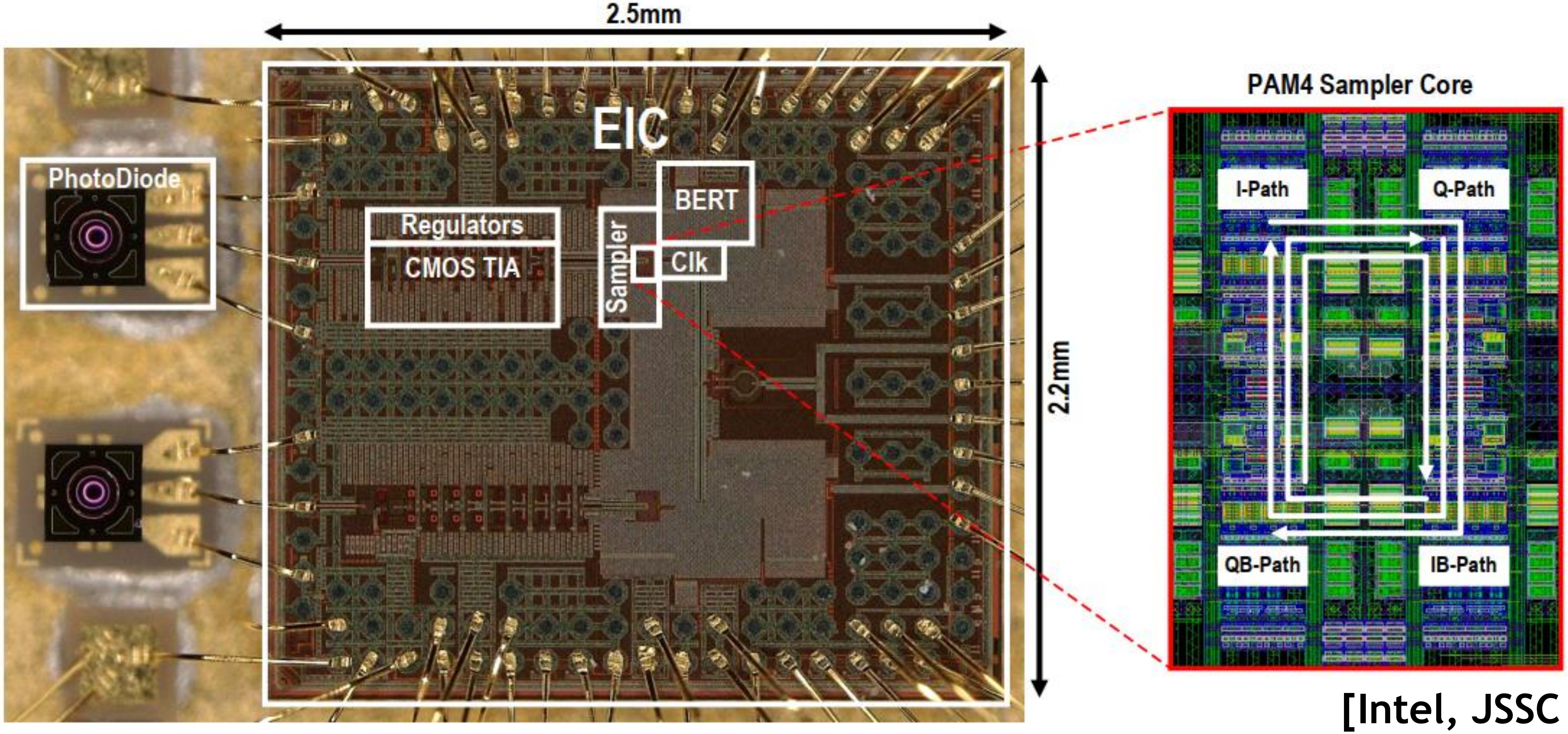


Integrating summer



Wiring capacitance adds to load cap of the ∫ summer improving latency.

28nm CMOS 100 Gb/s PAM4 Mixed-signal RX



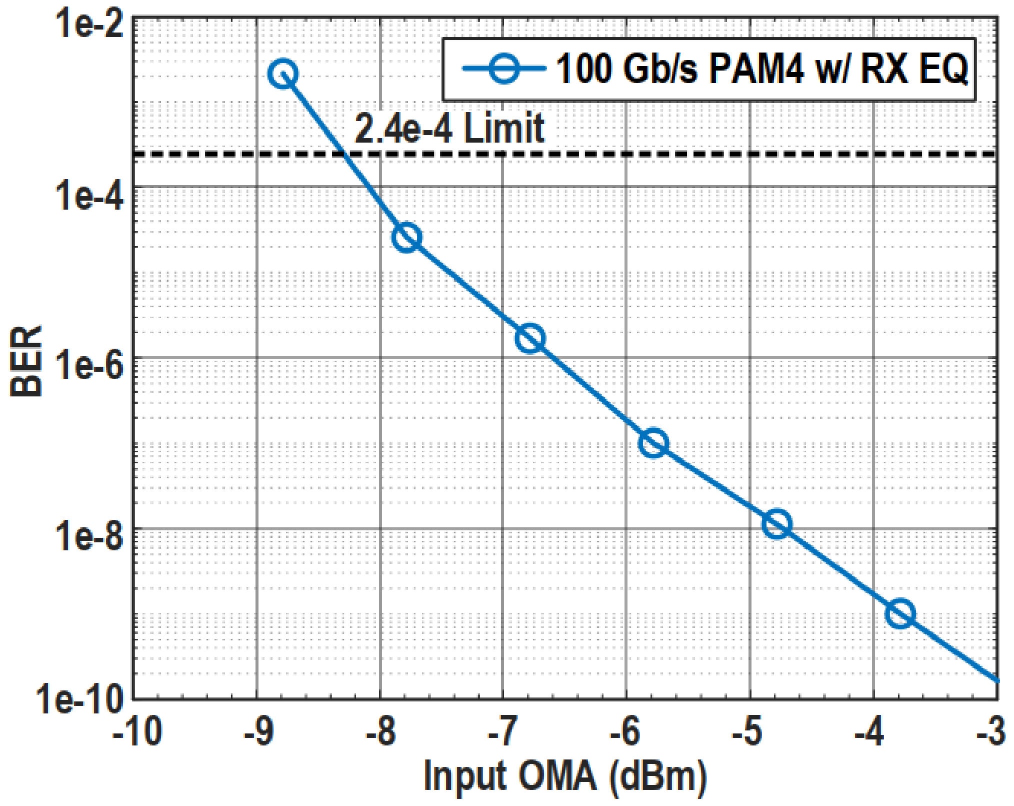
[Intel, JSSC 2021]

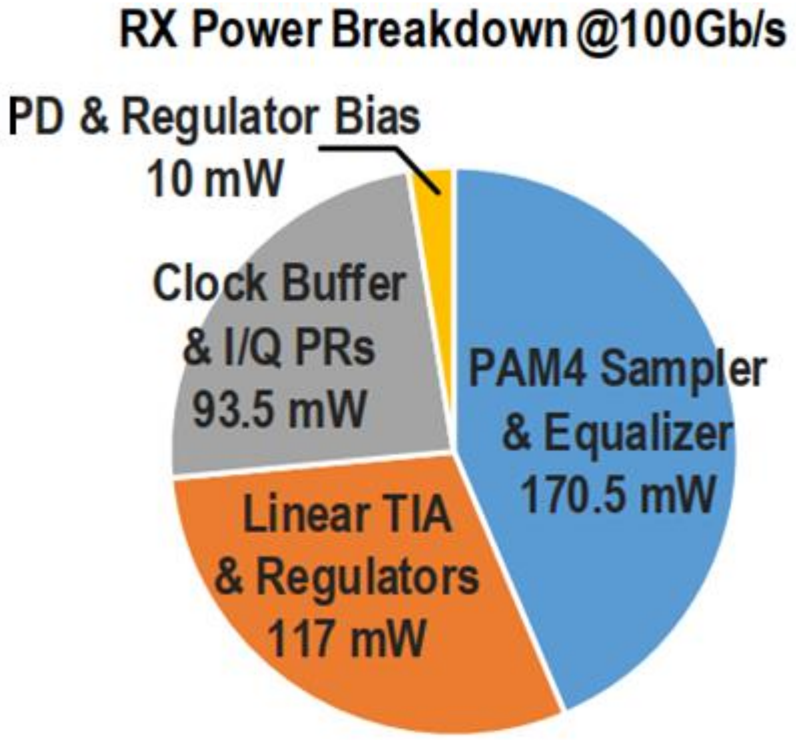
CMOS ORX is bonded with a III-V photodiode with 1A/W responsivity and 35 GHz B/W.

A 100-Gb/s PAM-4 Optical Receiver With 2-Tap FFE and 2-Tap Direct-Feedback DFE in 28-nm CMOS

Hao Li, Member, IEEE, Chun-Ming Hsu, Member, IEEE, Jahnavi Sharma, Member, IEEE, James Jaussi, Member, IEEE, and Ganesh Balamurugan, Member, IEEE

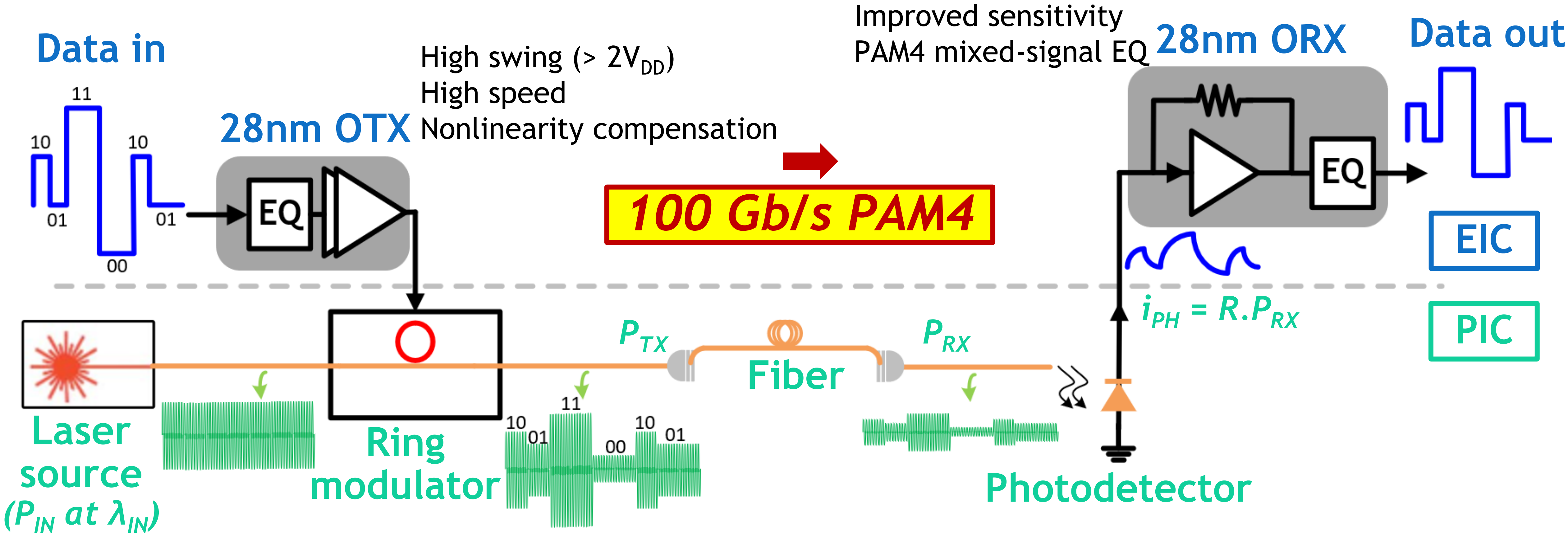
Measured Performance





- First demonstration 100 Gb/s PAM4 mixed-signal CMOS RX.
- ORX has -8.3 dBm sensitivity and 3.9 pJ/bit efficiency.

Single-λ High-Speed Link: Summary



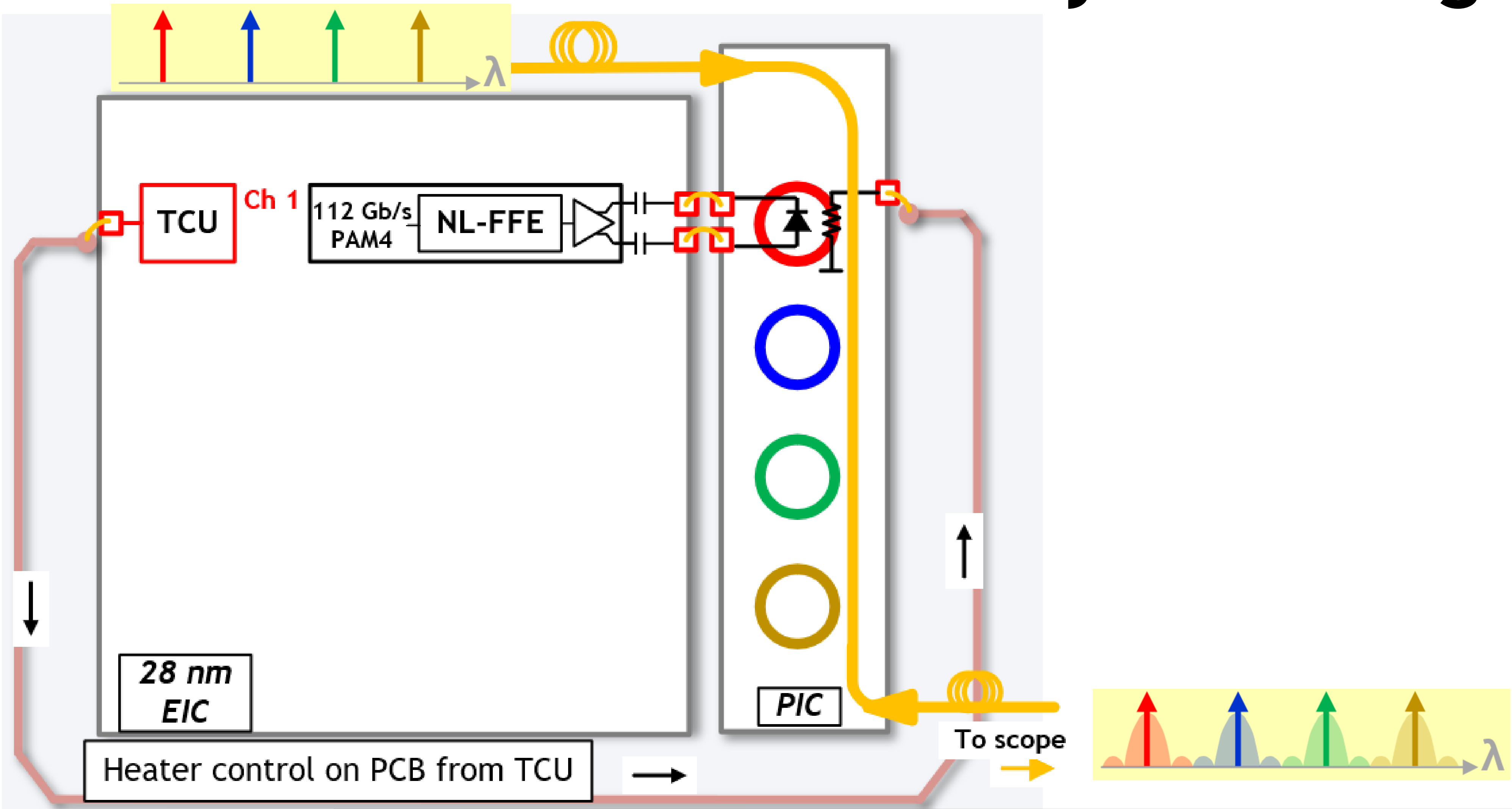
High-speed Single-λ Link

- Multi-level amplitude modulation enables 100 Gb/s per-λ.
- Circuit-level solutions for 100+ Gb/s OTX and ORX in 28 nm CMOS.

Outline

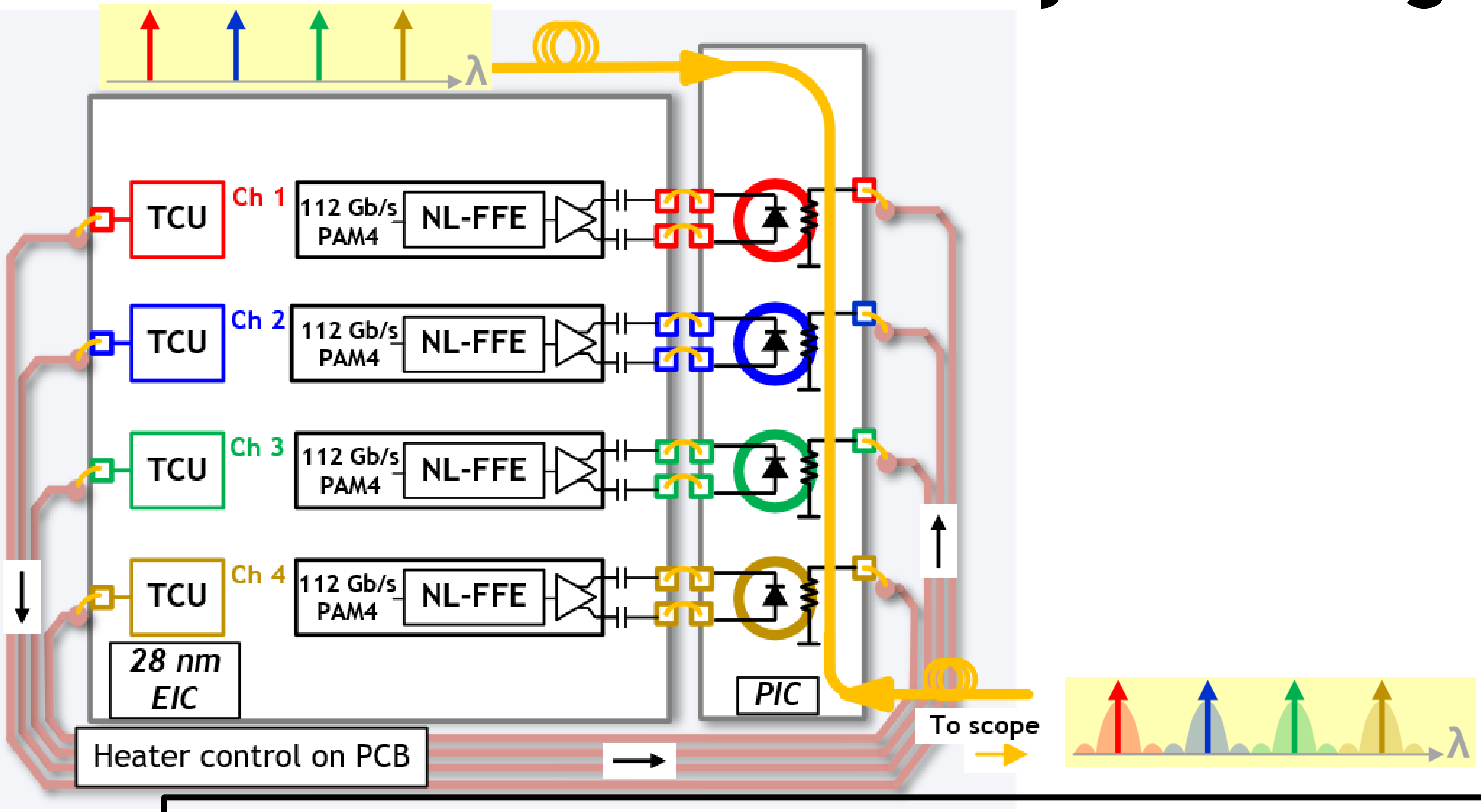
- SiPh platform for high-speed DCI
- IMDD optical links
- Photonic devices
- CMOS electronics for single-λ links
- **Wavelength-division multiplexing**
  - **4-λ × 112 Gb/s PAM4 OTX**
  - Compact thermal control in WDM links
  - 4-λ × 50 Gb/s NRZ optical link
- Future directions and conclusion

Four-lane WDM O-band Hybrid-integrated TX



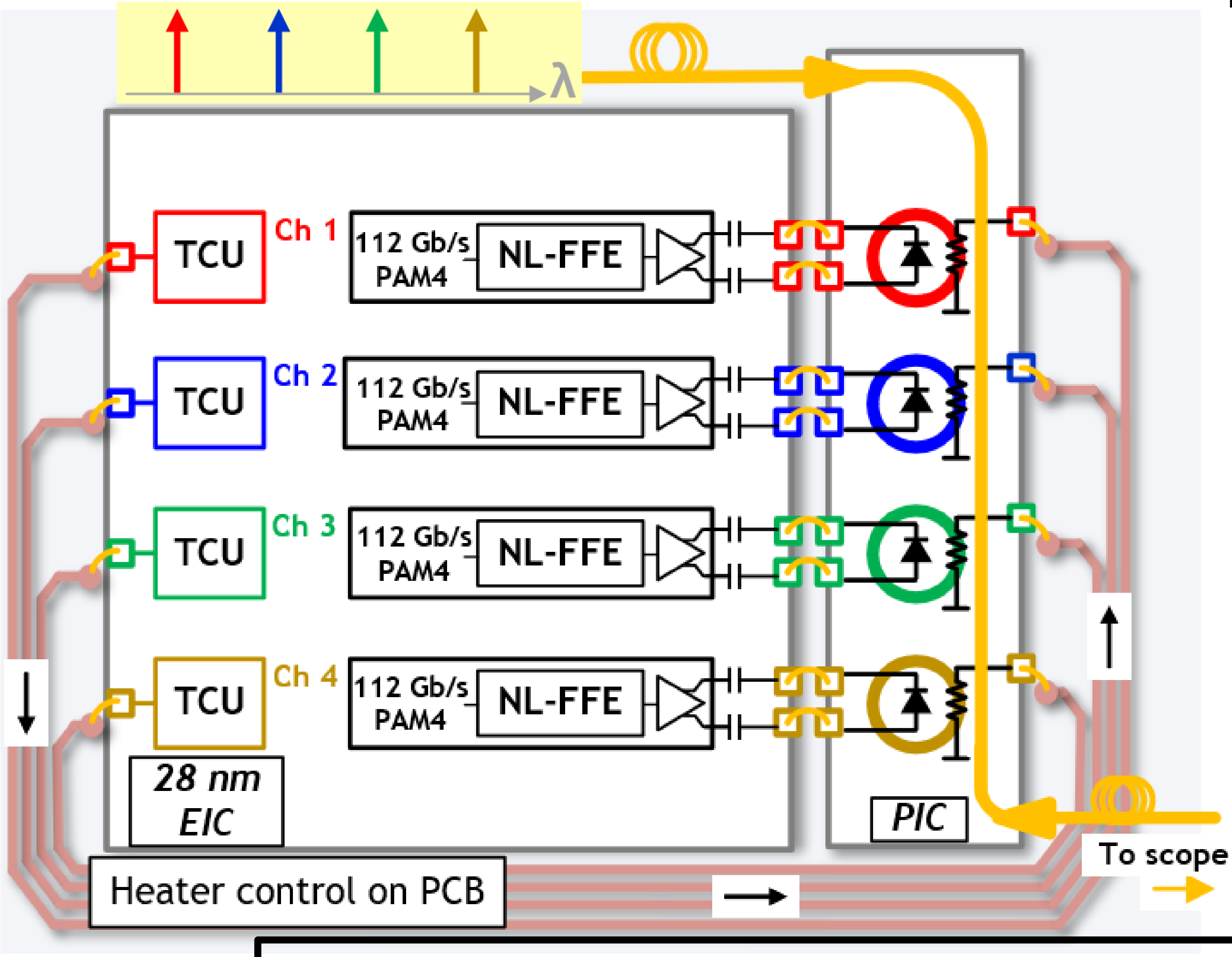
WDM can dramatically increase per-fiber data rates.

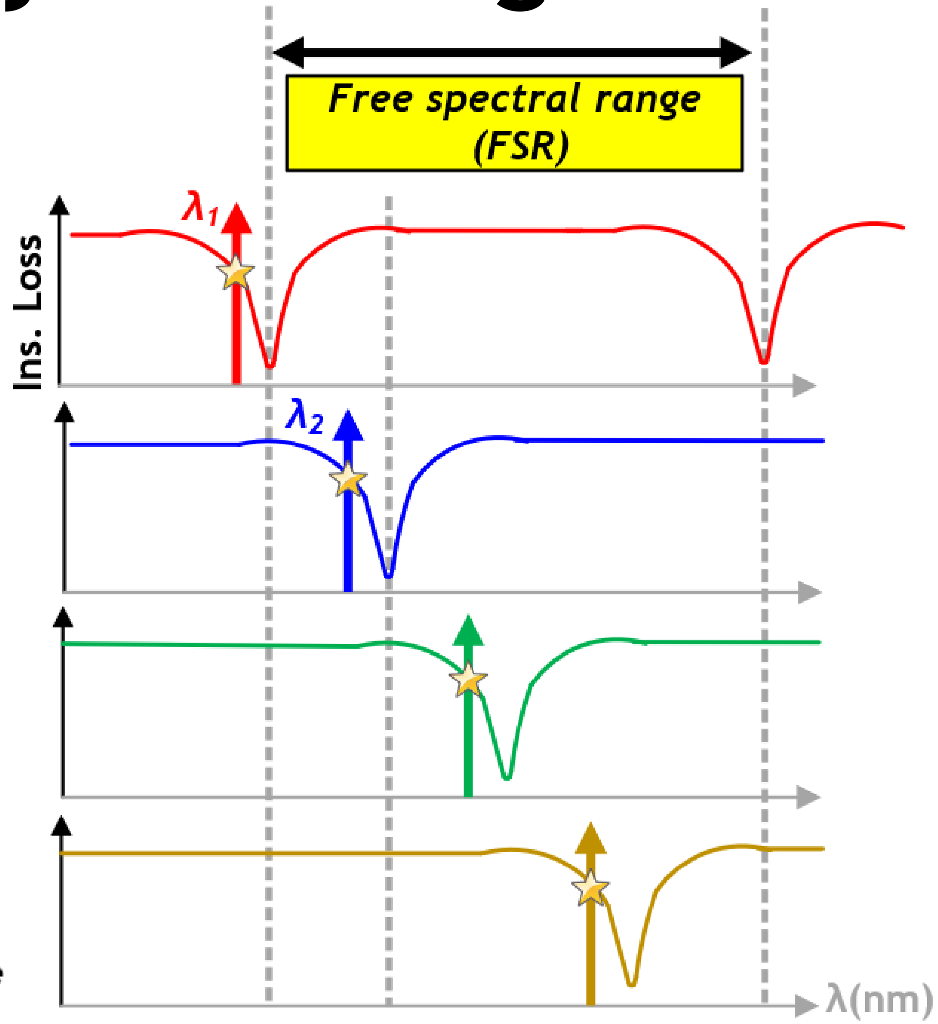
Four-lane WDM O-band Hybrid-integrated TX



Four-lane O-band WDM TX with 112 Gb/s/λ enabled through MRMs.

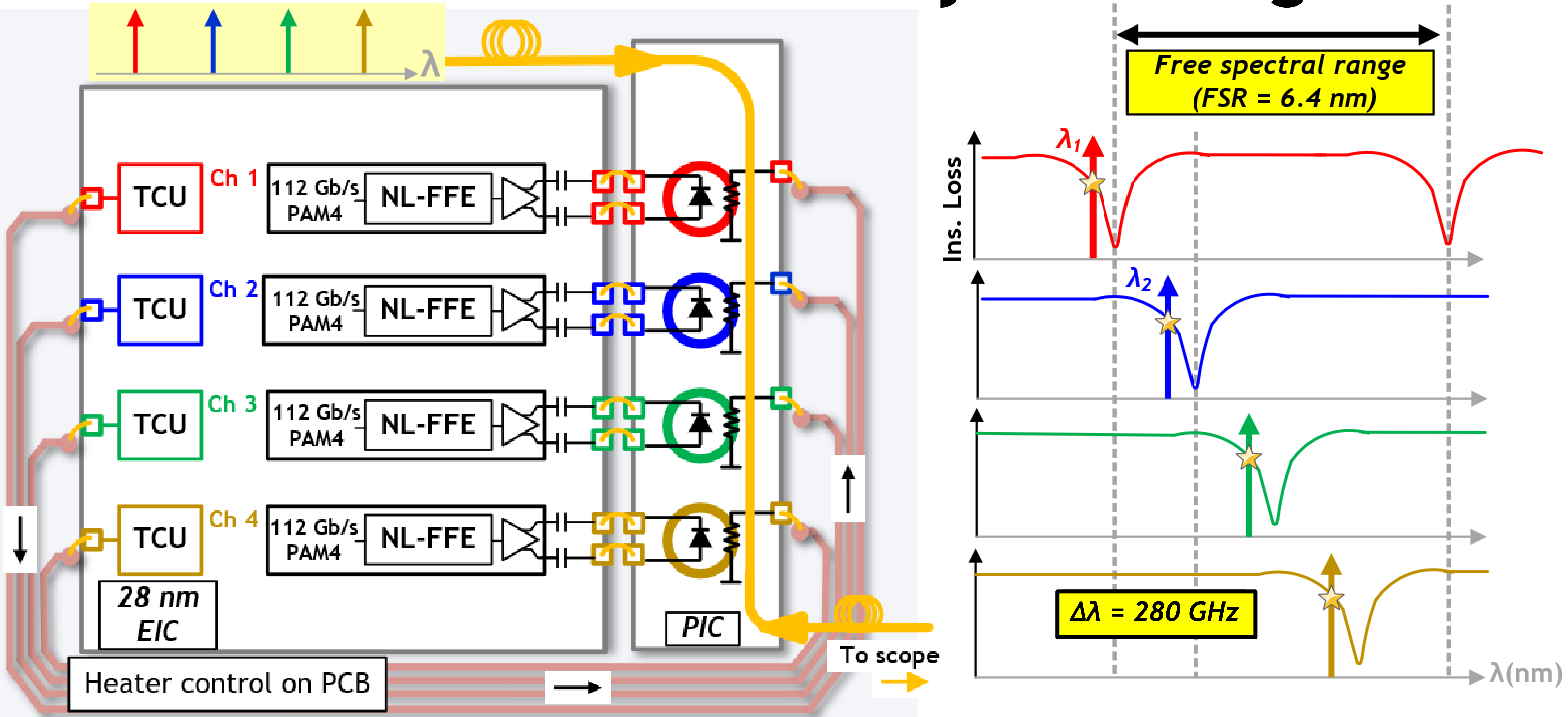
Four-lane WDM O-band Hybrid-integrated TX





MRMs provide optical multiplexing due to their resonant nature.

Four-lane WDM O-band Hybrid-integrated TX



Four-lane O-band MRM-based WDM OTX with 112 Gb/s/λ and 280 GHz λ-spacing.

Optical Modulators: WDM Application

	Driver swing	Modulator B/W	Thermal sensitivity	Area	WDM
MZM	High	High	Low	High	Separate (de)mux needed
EAM	Low	High	Low	Low	Separate (de)mux needed
MRM	Low	High (improved)	High (temp control)	Very low	Ring resonance is WDM (de)mux

Why MRMs?

- **low swing, high-bandwidth and compact modulator for integrated SiPh.**
- **(de)multiplexing functionality for WDM without hardware overhead.**

MRM WDM Challenge #1 : Crosstalk

- ***Crosstalk analysis:***

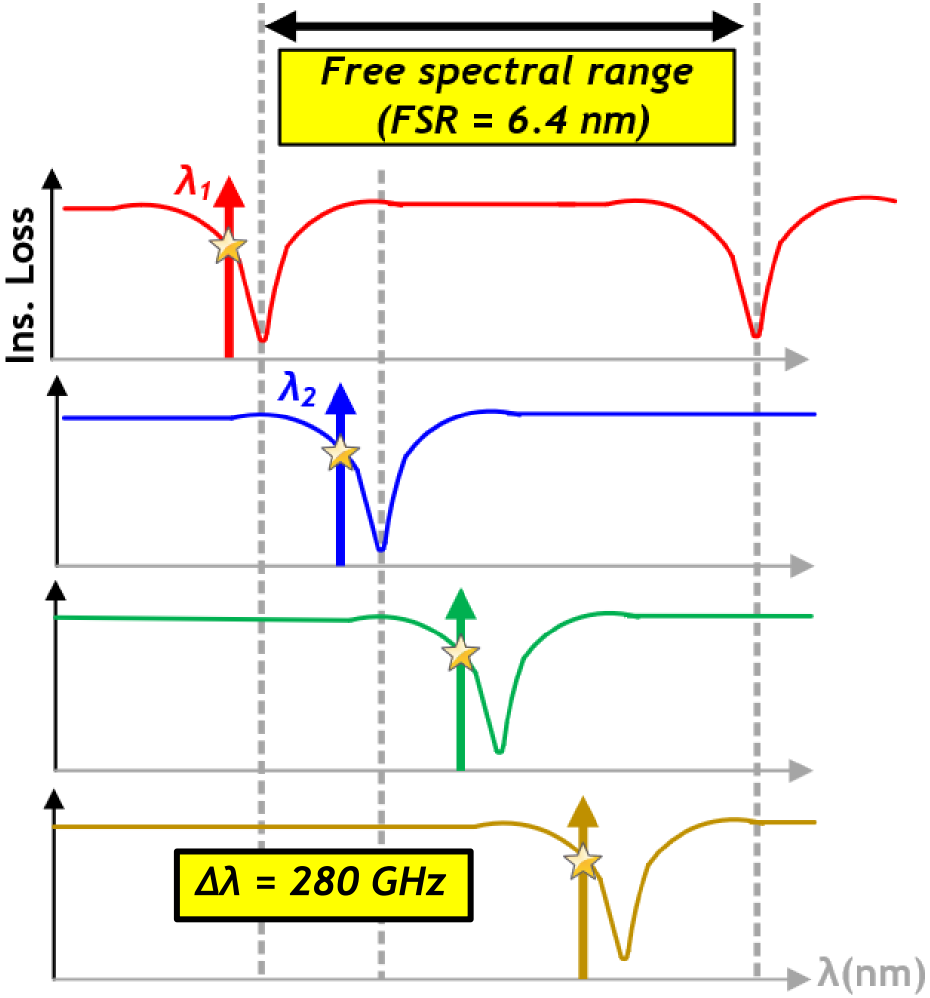
  Effect of TX / RX ring QF

  Role of photodiode nonlinearity

  [Intel, JSSC: VLSI special issue]

Silicon Photonic Microring-based 4 × 112 Gb/s WDM Transmitter with Photocurrent-based Thermal Control in 28nm CMOS

Jahnavi Sharma, *Member, IEEE*, Zhe Xuan, *Member, IEEE*, Hao Li, *Member, IEEE*, Taehwan Kim, *Member, IEEE*, Ranjeet Kumar, *Member, IEEE*, Meer Sakib, *Member, IEEE*, Chun-Ming Hsu, *Member, IEEE*, Chaoxuan Ma, *Member, IEEE*, Haisheng Rong, *Fellow, IEEE*, Ganesh Balamurugan, *Member, IEEE*, and James Jaussi, *Member, IEEE*



- **Channel crosstalk limits Δλ and # of wavelengths packed per ring FSR.**

MRM WDM Challenge #1 : Crosstalk

- ***Crosstalk analysis:***

  Effect of TX / RX ring QF

  Role of photodiode nonlinearity

  [Intel, JSSC: VLSI special issue]

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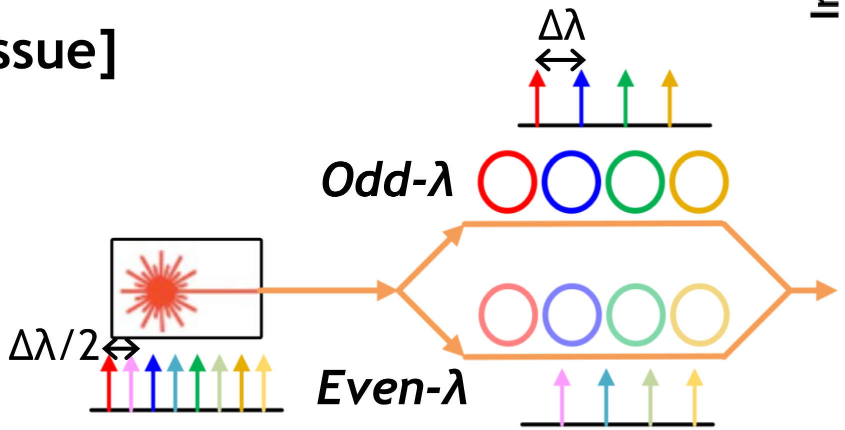
- ***Super FSR:***

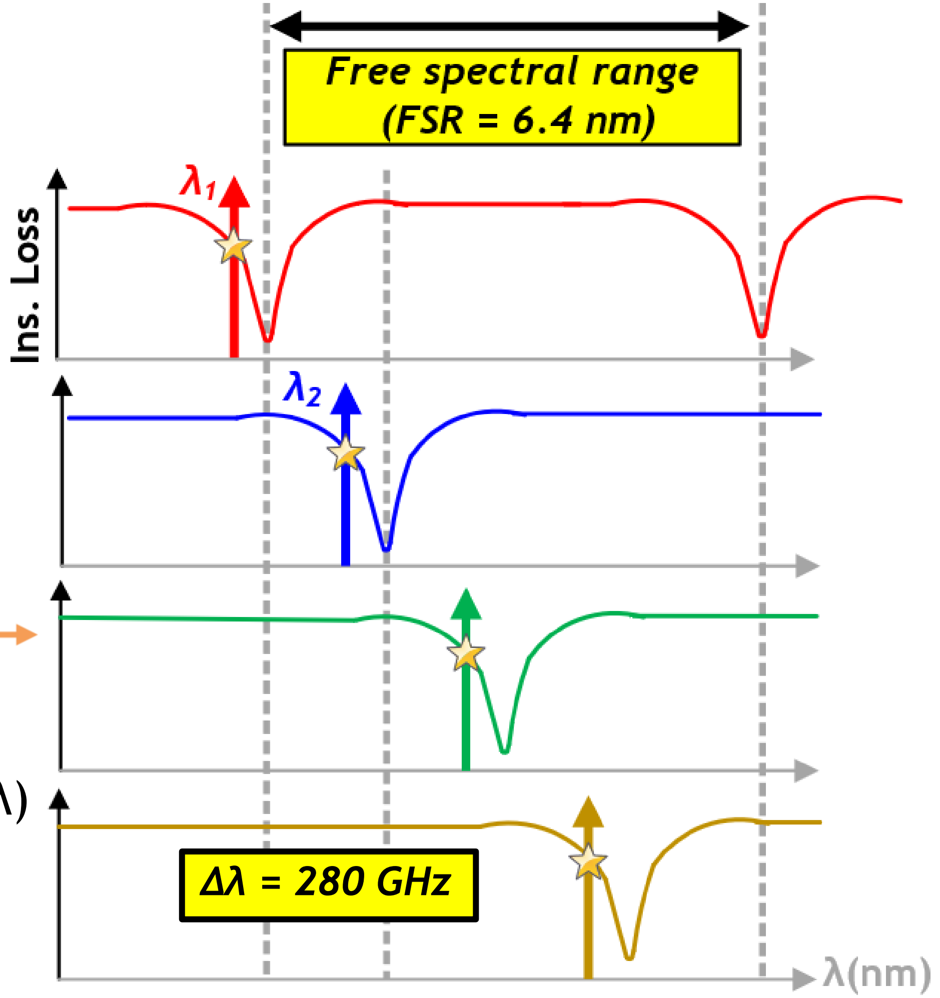
  Ultra-dense carriers muxed

  on rings in different buses

  [Columbia, ArXiv 2021]



(Example: 2x carriers for fixed Δλ)



Integrated Kerr frequency comb-driven silicon photonic transmitter

Anthony Rizzo[1,†], Asher Novick[1,†], Vignesh Gopal[1,†], Bok Young Kim[2], Xingchen Ji[1], Stuart Daudlin[1], Yoshitomo Okawachi[2], Qixiang Cheng[1,3], Michal Lipson[1], Alexander L. Gaeta[1,2], and Keren Bergman[1,*]

- **Channel crosstalk limits Δλ and # of wavelengths packed per ring FSR.**
- **Super-FSR can aggressively increase number of channels beyond FSR/Δλ.**

MRM WDM Challenge #2: Scalable Thermal Control

	Driver swing	Modulator B/W	Thermal sensitivity	Area	WDM
MZM	High	High	Low	High	Separate (de)mux needed
EAM	Low	High	Low	Low	Separate (de)mux needed
MRM	Low	High (improved)	High (temp control)	Very low	Ring resonance is WDM (de)mux

Develop scalable thermal control solution for MRM scalable to WDM applications.

A sub-400 fJ/bit thermal tuner for optical resonant ring modulators in 40 nm CMOS

Philip Amberg, Eric Chang, Frankie Liu, Jon Lexau, Xuezhe Zheng, Guoliang Li, Ivan Shubin, John E. Cunningham, Ashok V. Krishnamoorthy and Ron Ho

[Oracle, ASSCC 2012]

A 45 nm CMOS-SOI Monolithic Photonics Platform With Bit-Statistics-Based Resonant Microring Thermal Tuning

Chen Sun, *Member, IEEE*, Mark Wade, Michael Georgas, Sen Lin, Luca Alloatti, Benjamin Moss, Rajesh Kumar, Amir H. Atabaki, Fabio Pavanello, Jeffrey M. Shainline, Jason S. Orcutt, Rajeev J. Ram, *Fellow, IEEE*, Miloš Popović, *Member, IEEE*, and Vladimir Stojanović, *Member, IEEE*

[Berk/U Colorado/MIT, JSSC 2016]

Wavelength Locking of a Si Ring Modulator Using an Integrated Drop-Port OMA Monitoring Circuit

Saurabh Agarwal, Mark Ingels, *Member, IEEE*, Marianna Pantouvaki, *Member, IEEE*, Michiel Steyaert, *Fellow, IEEE*, Philippe Absil, and Joris Van Campenhout, *Member, IEEE*

[IMEC/KU Leuven, JSSC 2016]

A 3-D-Integrated Silicon Photonic Microring-Based 112-Gb/s PAM-4 Transmitter With Nonlinear Equalization and Thermal Control

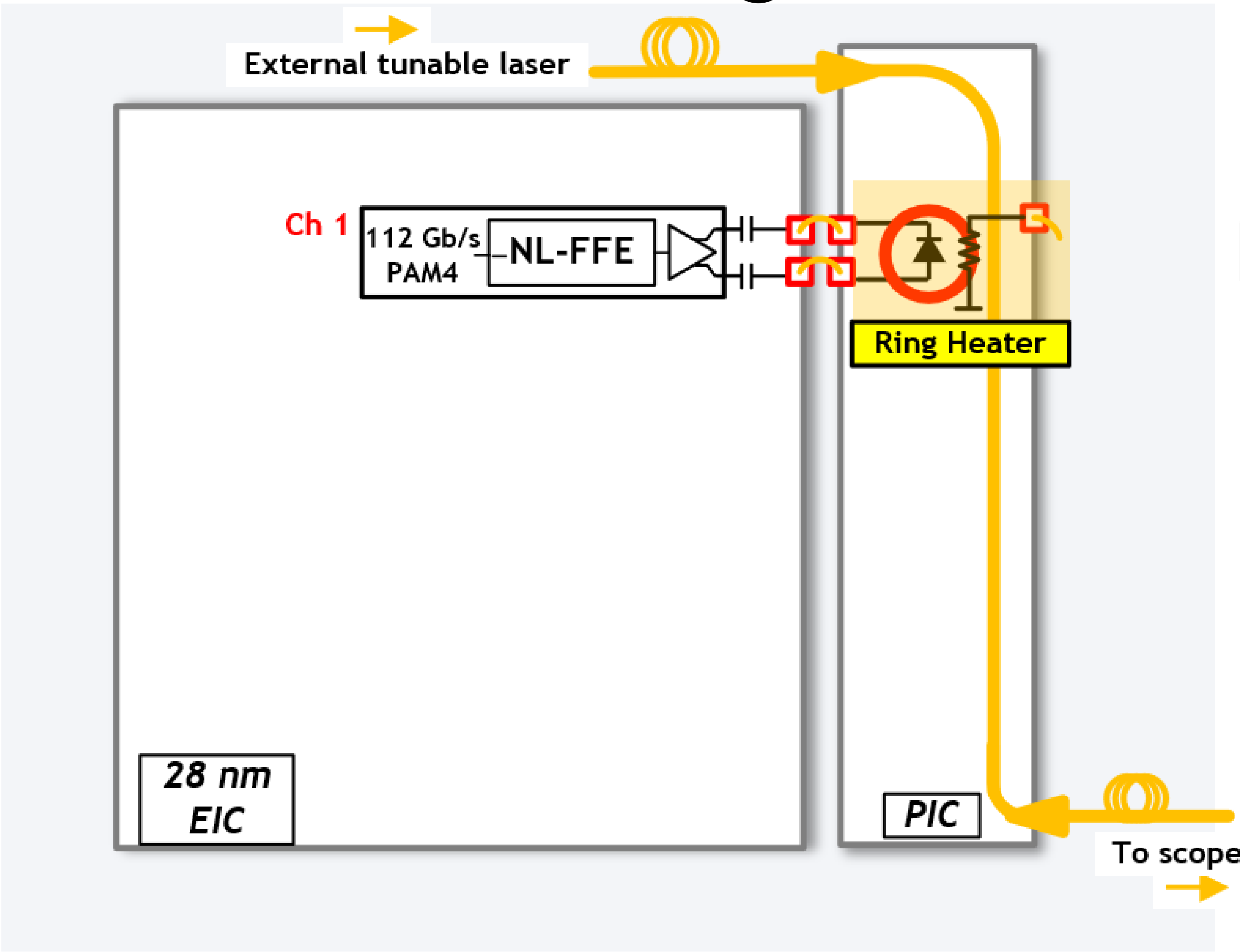
Hao Li, *Member, IEEE*, Ganesh Balamurugan, *Member, IEEE*, Taehwan Kim, *Member, IEEE*, Meer N. Sakib, *Member, IEEE*, Ranjeet Kumar, *Member, IEEE*, Haisheng Rong, *Senior Member, IEEE*, James Jaussi, *Member, IEEE*, and Bryan Casper, *Member, IEEE*

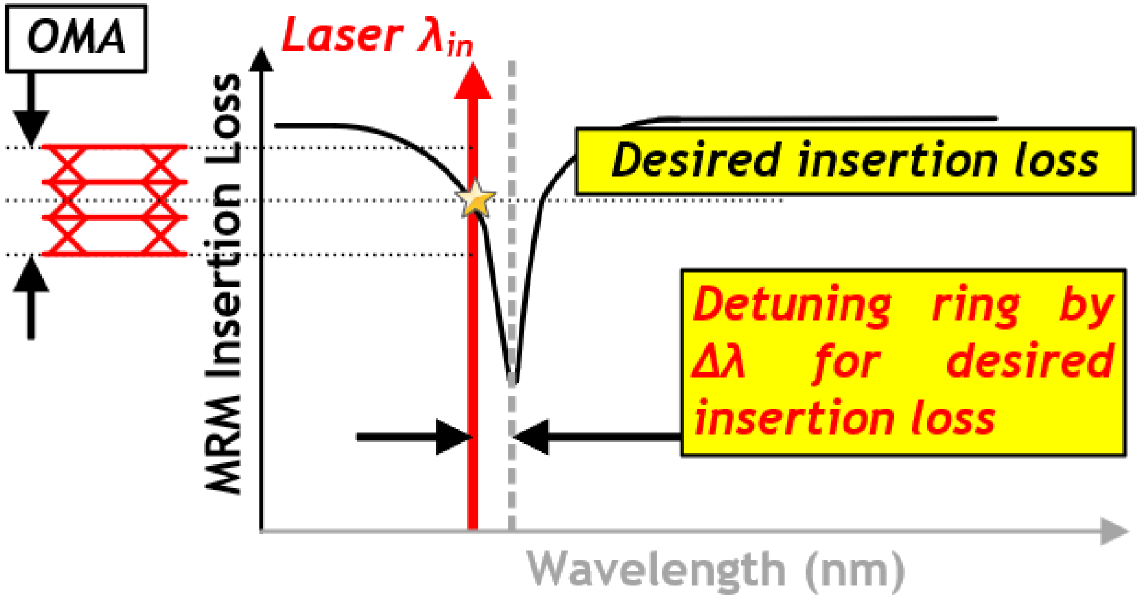
[Intel, JSSC 2021]

Outline

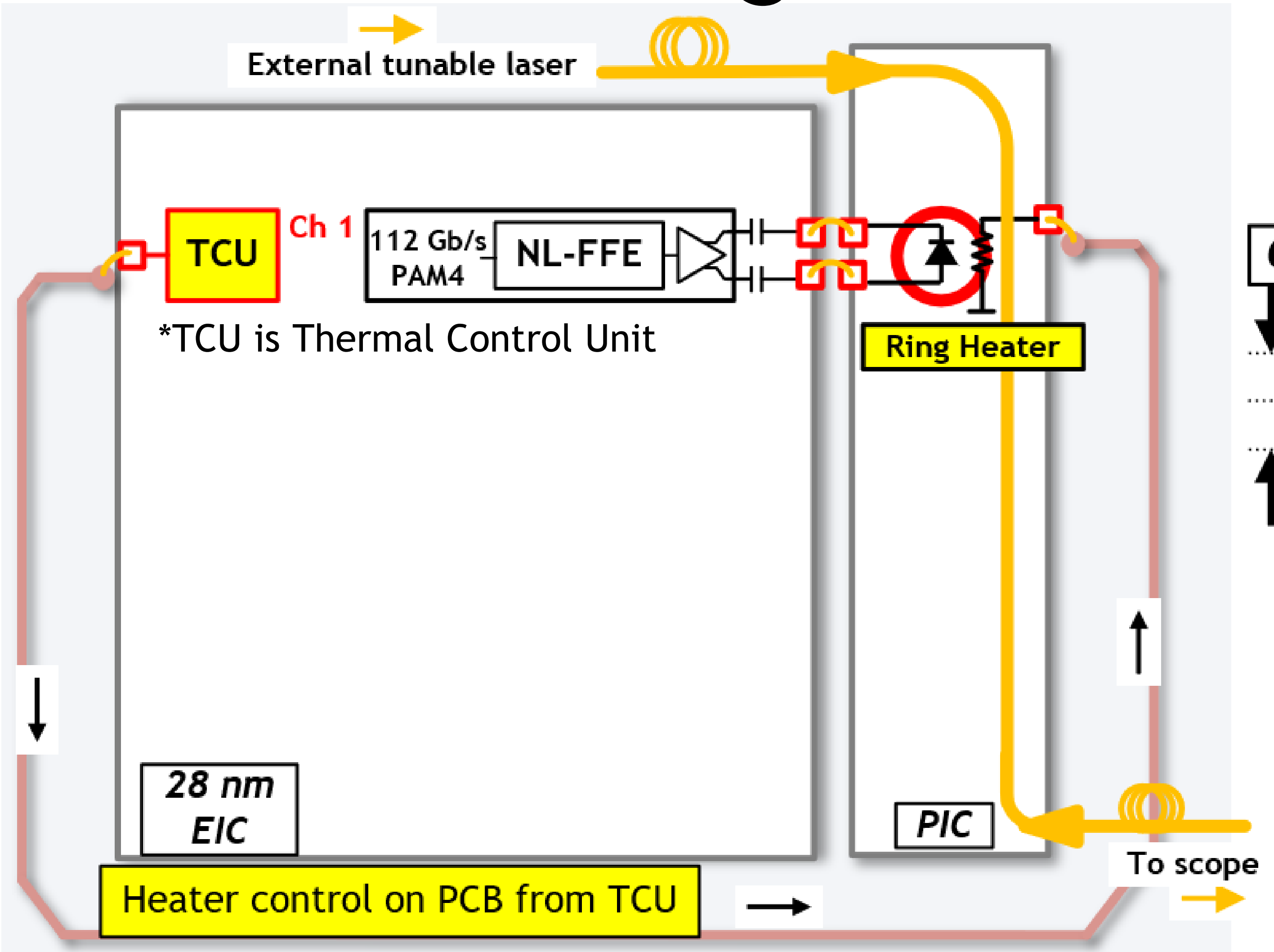
- SiPh platform for high-speed DCI
- IMDD optical links
- Photonic devices
- CMOS electronics for single-λ links
- **Wavelength-division multiplexing**
  - 4-λ × 112 Gb/s PAM4 OTX
  - **Compact thermal control in WDM links**
  - 4-λ × 50 Gb/s NRZ optical link
- Future directions and conclusion

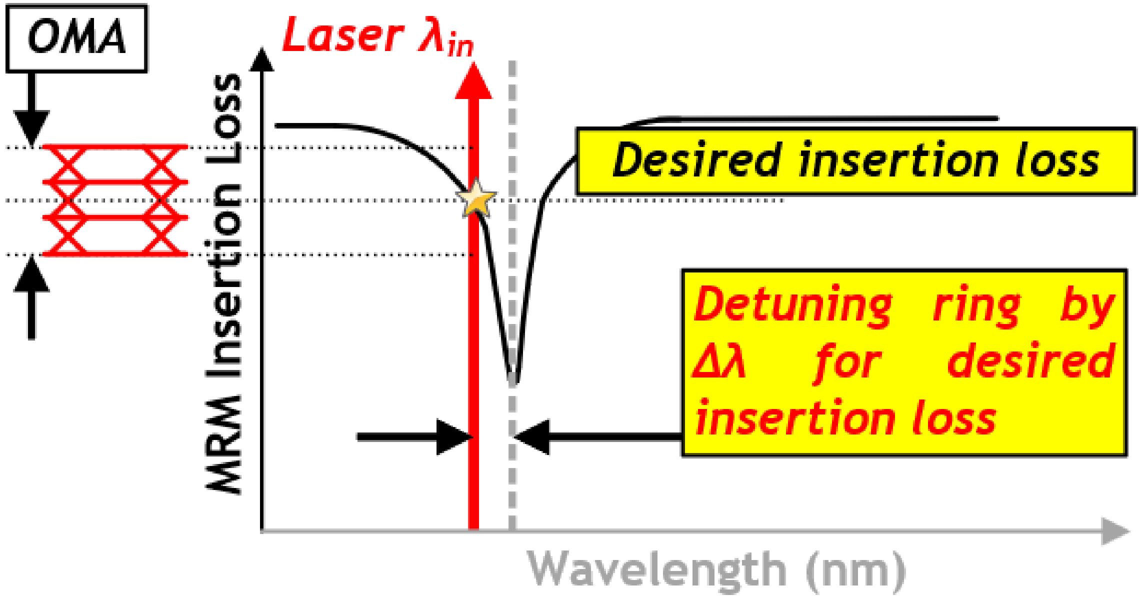
MRM Challenge : Process Var/Thermal Drift





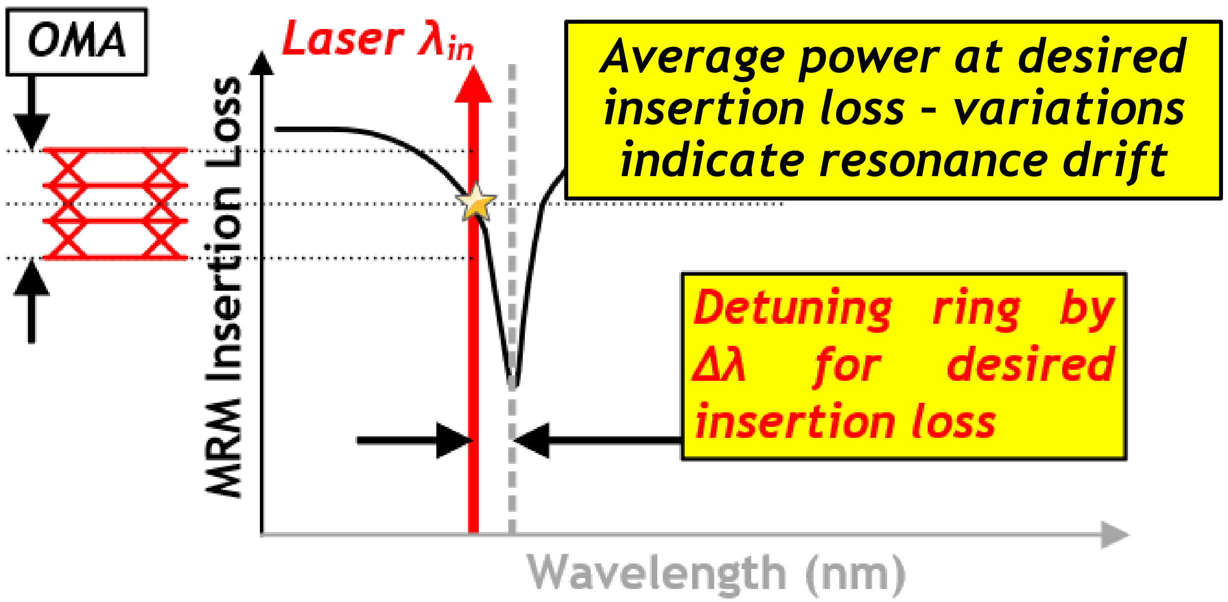
MRM Challenge : Process Var/Thermal Drift

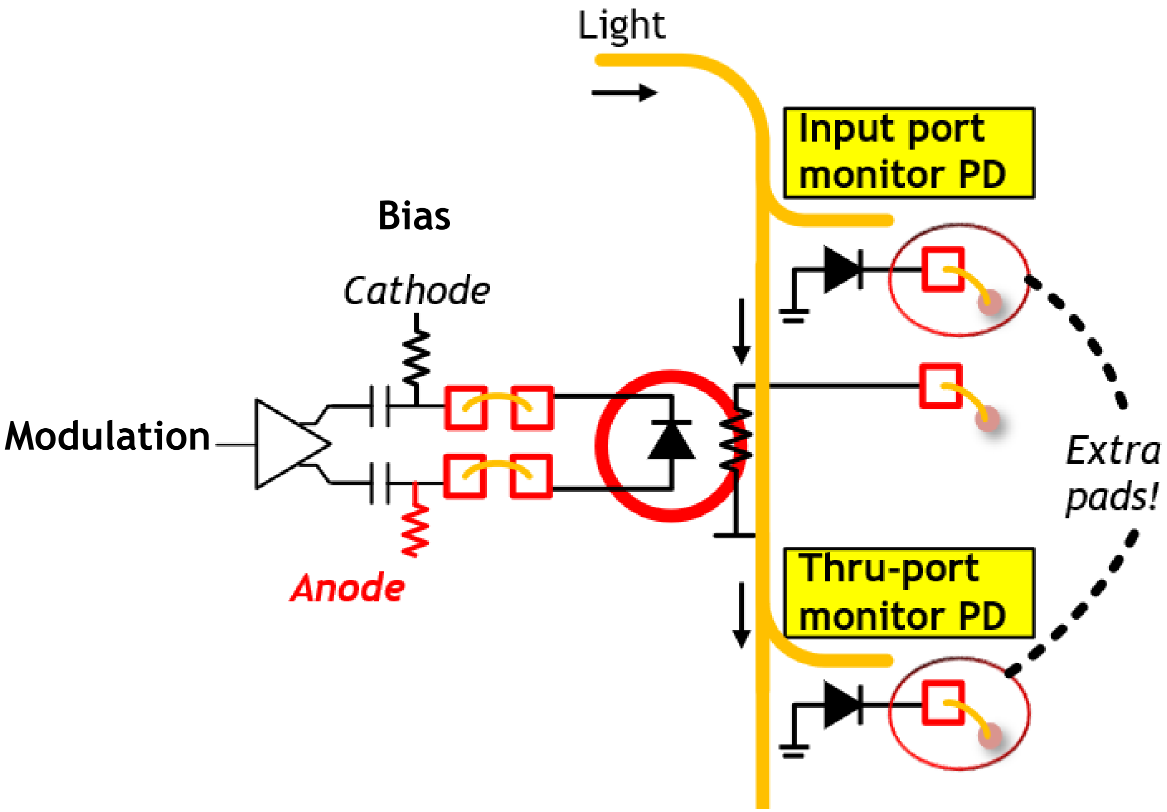




Thermal control unit (TCU) adjusts ring detuning across process and temperature.

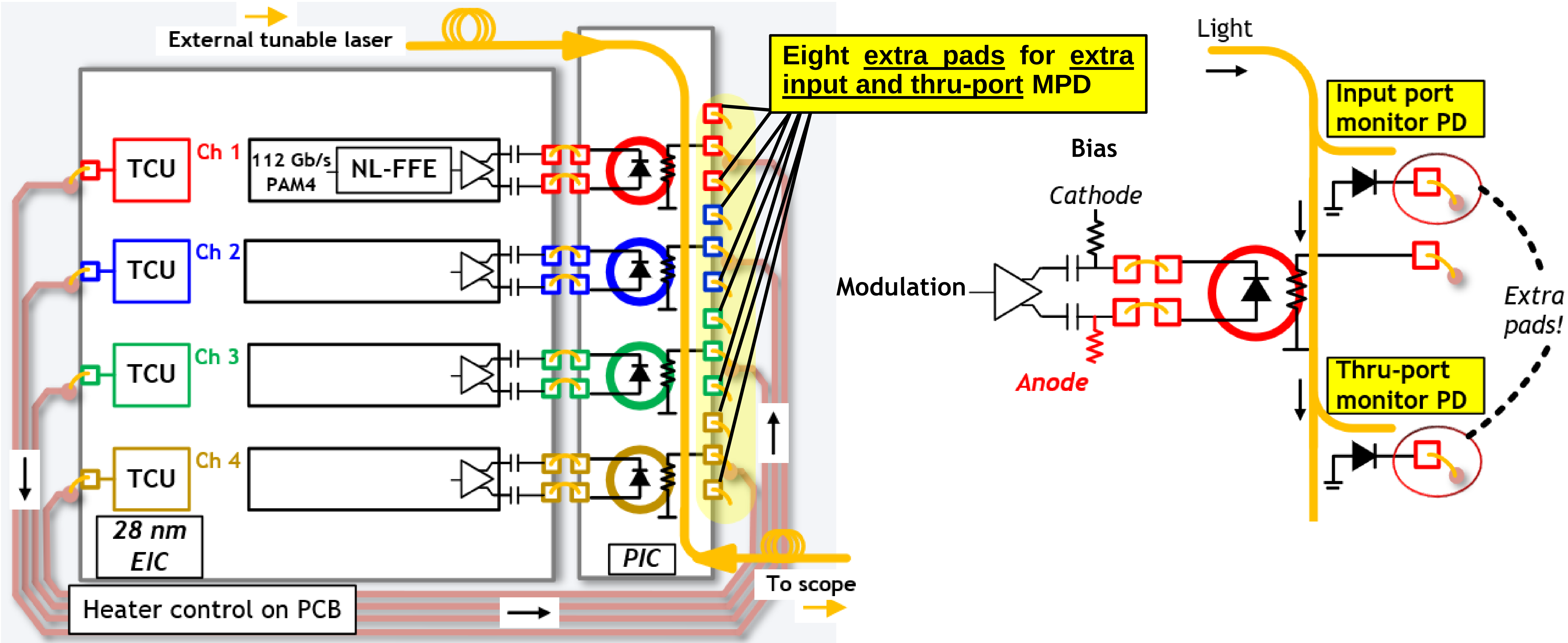
Hybrid WDM: Scalable Thermal Control





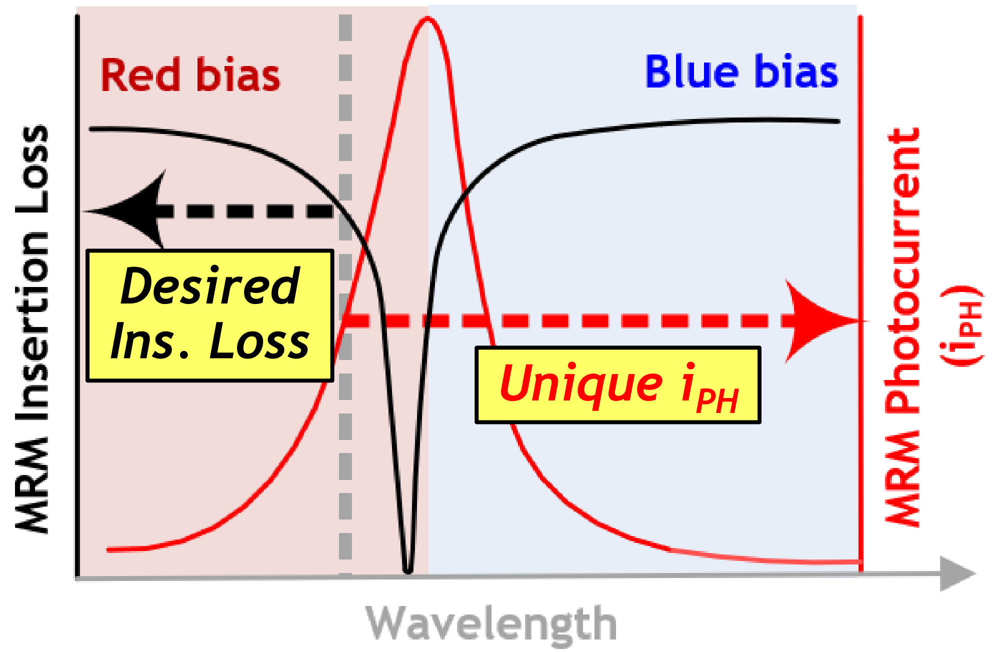
Two sensors: detect the ring's lock point and normalize any input power fluctuation.

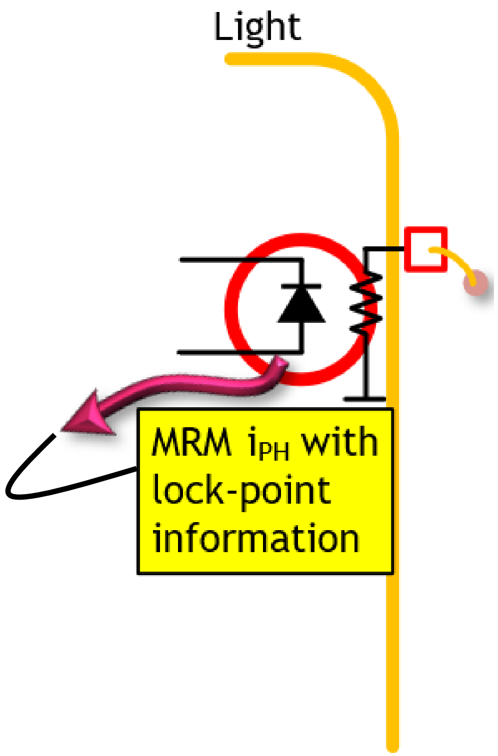
Hybrid WDM: # Interfaces for Thermal Control



Thermal sensors (thru/drop+input port monitors) add *two* EO interfaces *per* ring.

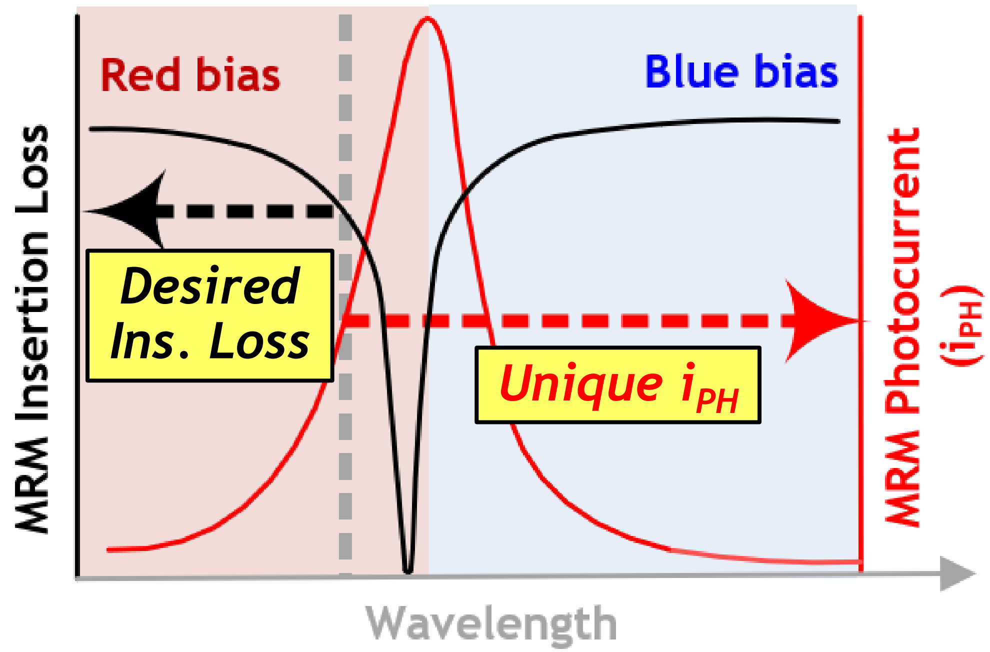
Compact Thermal Control : MRM as Sensor

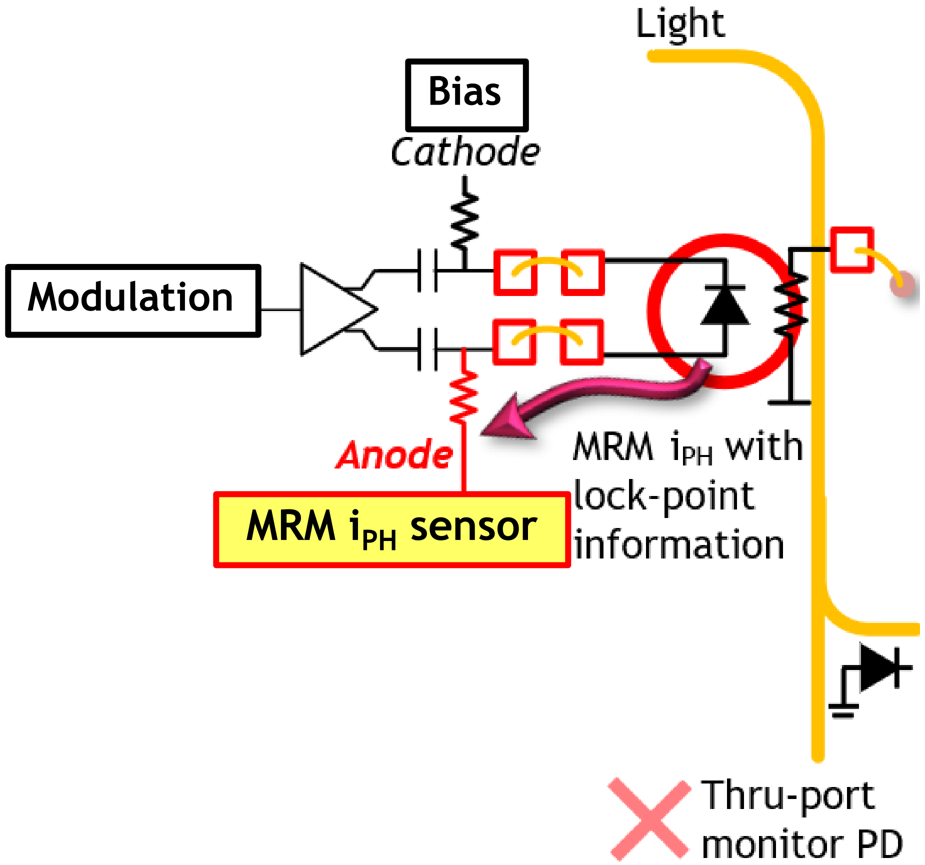




Reverse-biased MRM is a PD that can be a thermal sensor for its absorbed power.

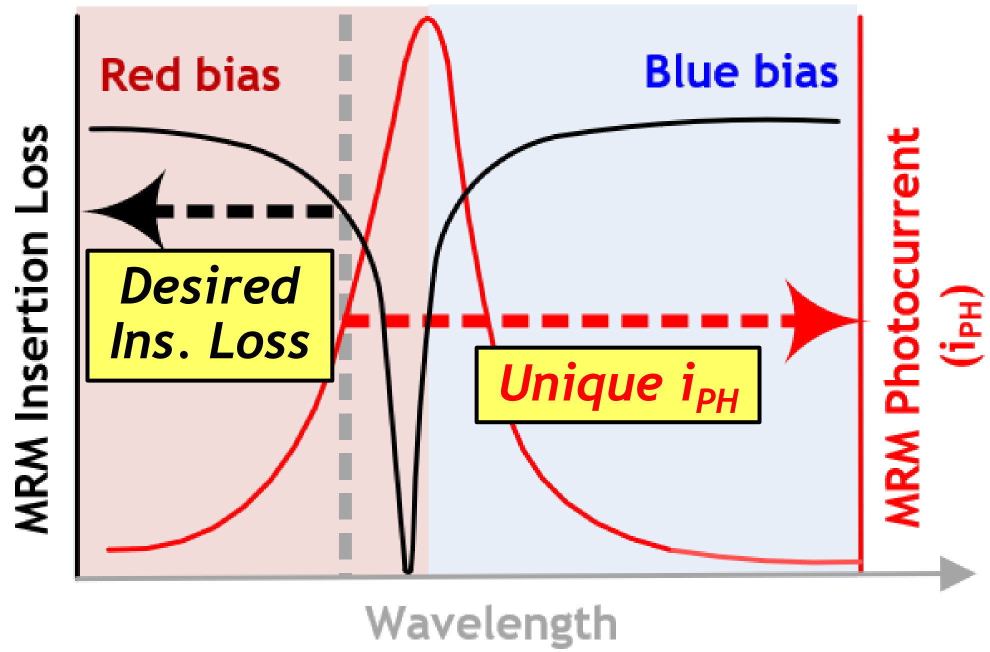
Compact Thermal Control : MRM as Sensor

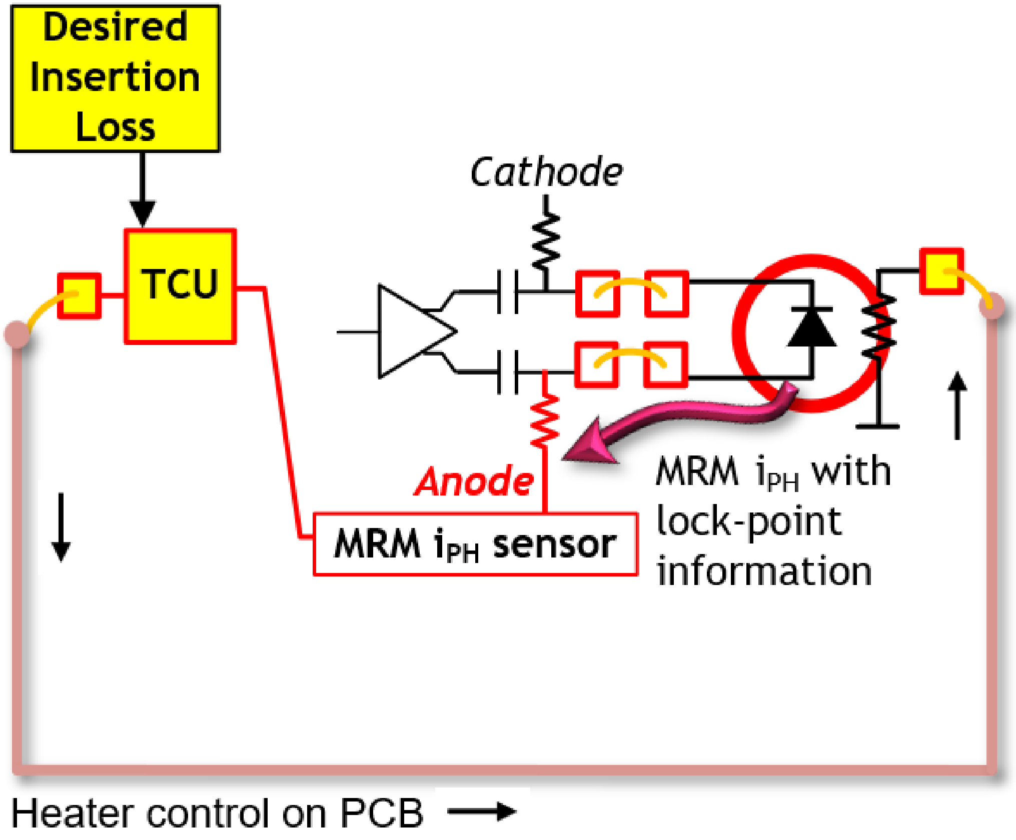




MRM photocurrent is available at the diode nodes without additional interfaces.

Compact Thermal Control : TCU Feedback Loop

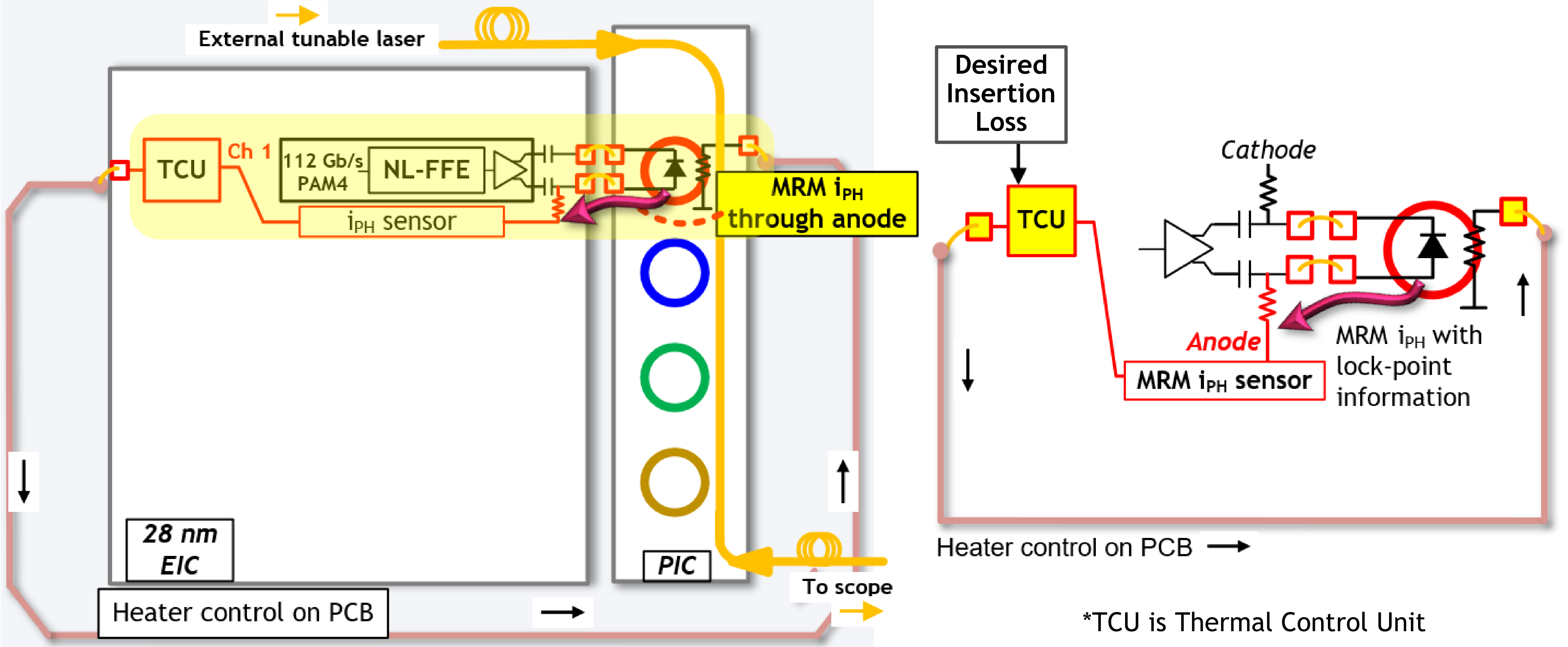




*TCU is Thermal Control Unit

TCU tunes the ring heater based on MRM i_{PH} and desired insertion loss.

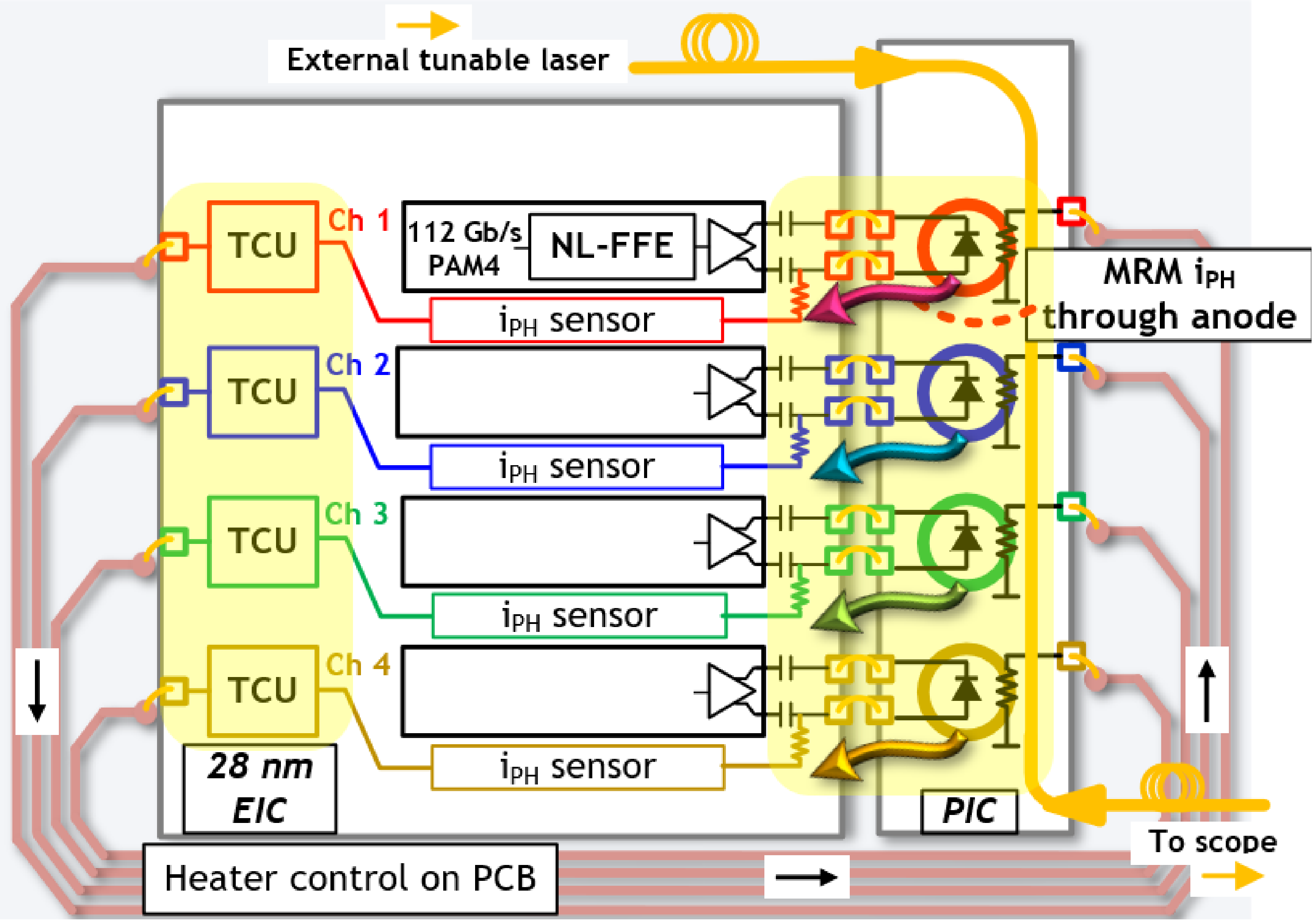
Compact Thermal Control : TCU Feedback Loop

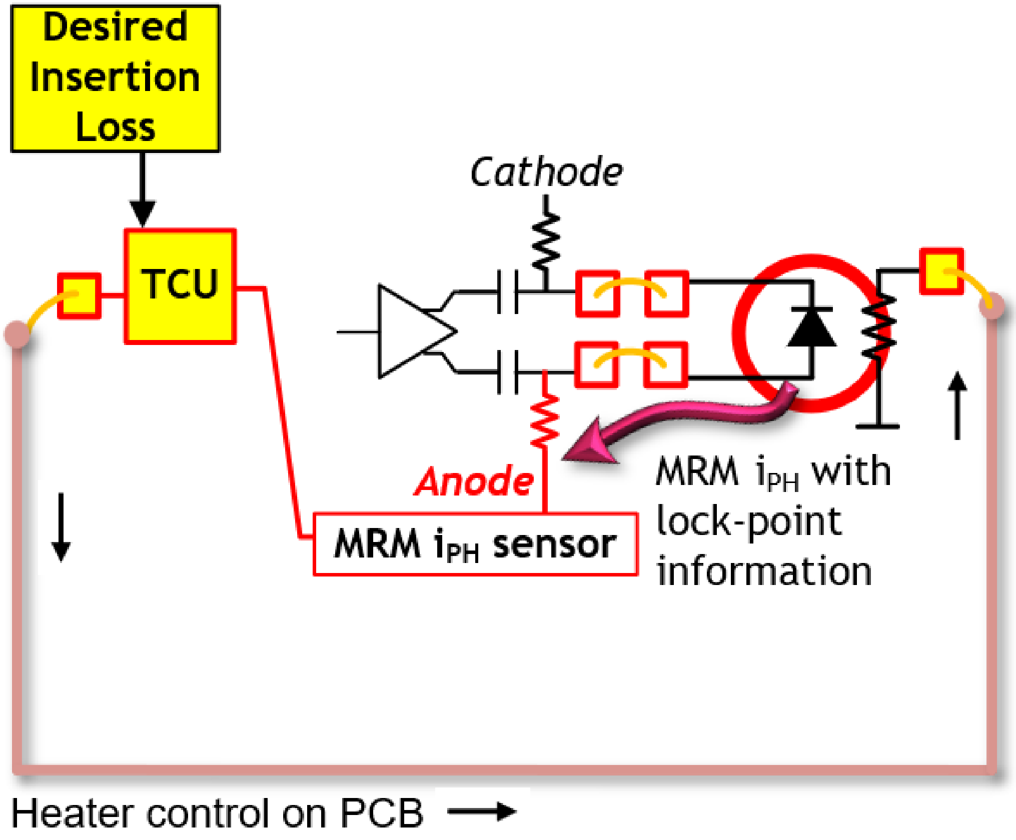


*TCU is Thermal Control Unit

TCU tunes the ring heater based on MRM i_{PH} and desired insertion loss.

Compact Thermal Control : WDM Scalability

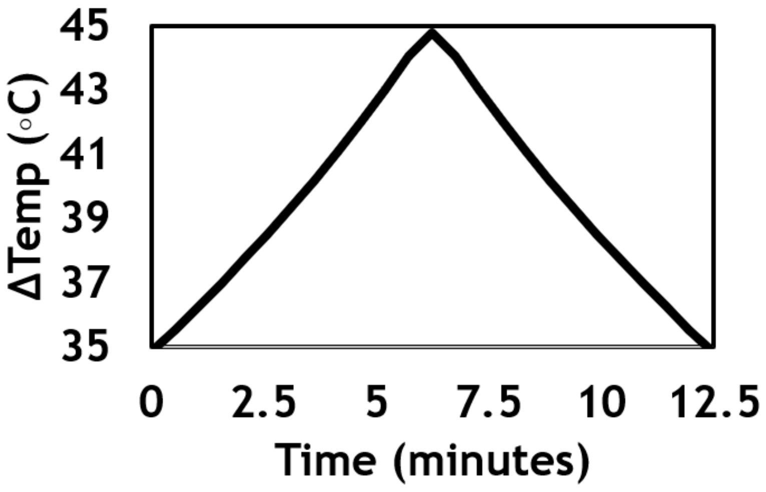




*TCU is Thermal Control Unit

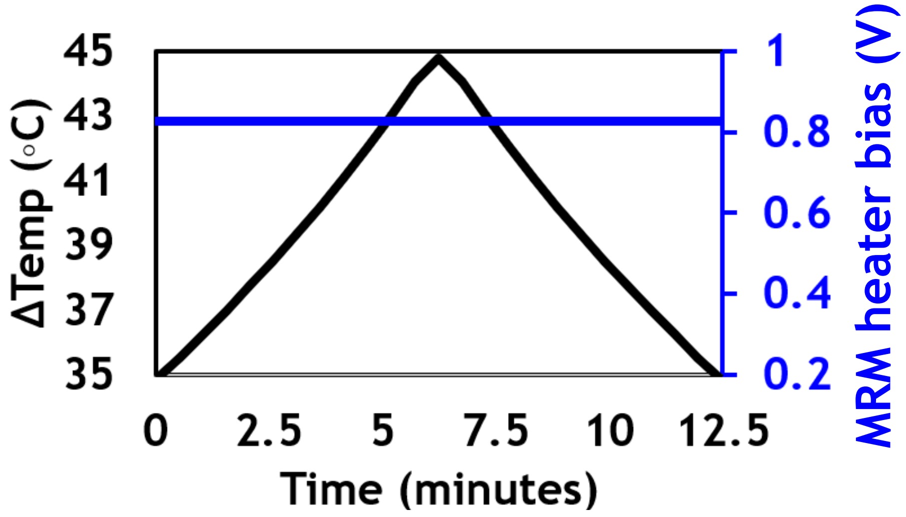
Compact scheme based on MRM photocurrent as a thermal sensor suitable for WDM.

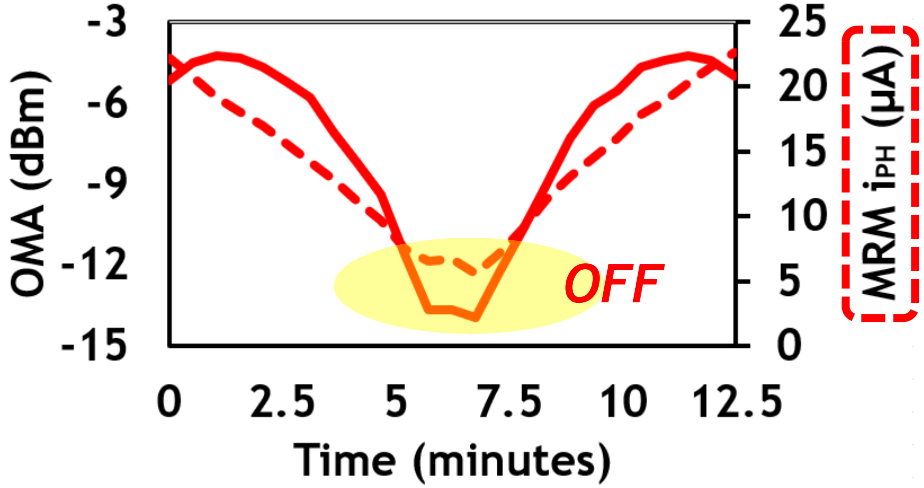
Thermal Measurement : Temperature Ramp



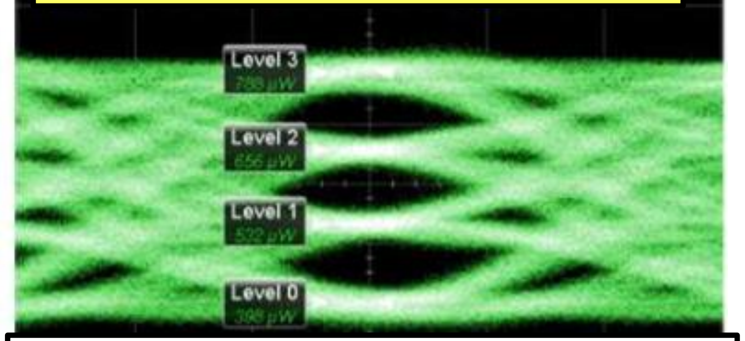
Thermal control scheme is verified by a temperature ramp.

Thermal Measurement Results: TCU OFF





112 Gbps PAM4 @ 35◦C

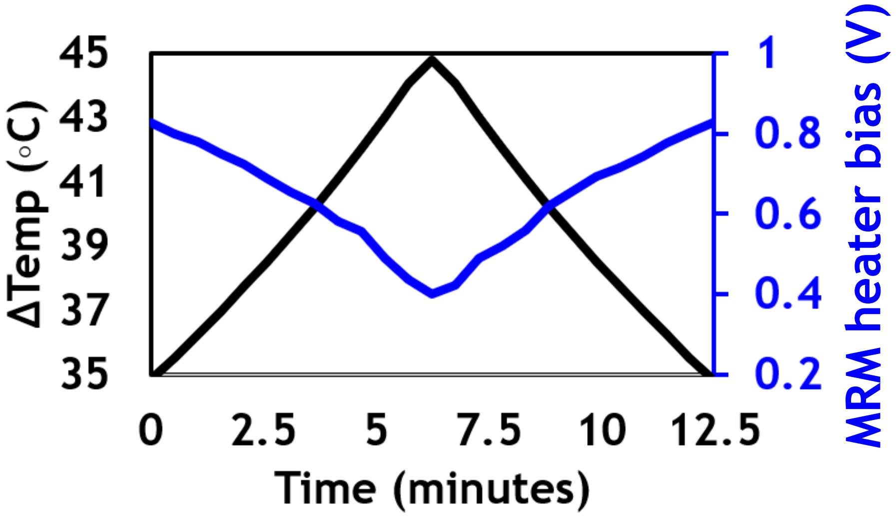


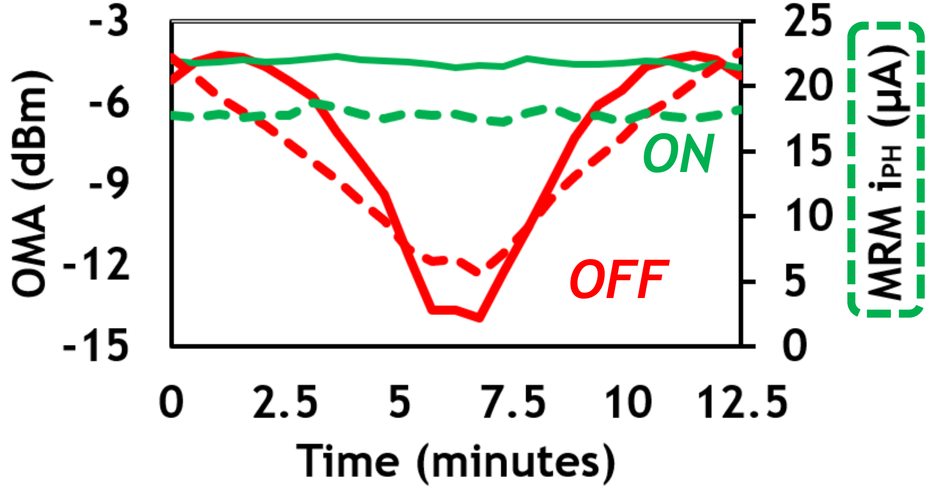
TDECQ = 0.63 dB, ER = 2.7 dB

Closed eye at 45 deg C

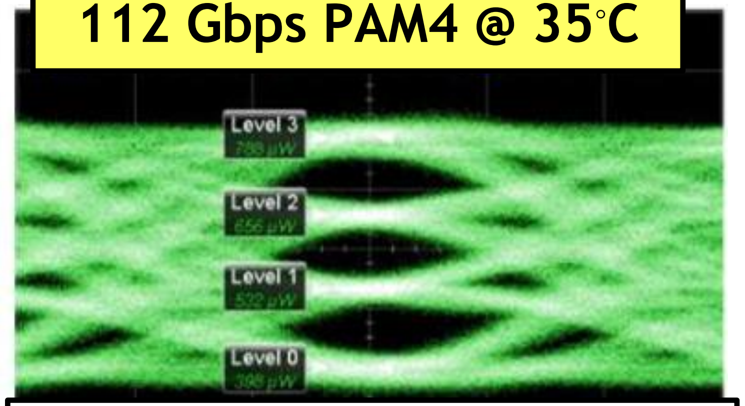
With the thermal controller OFF, the eye closes under a temperature ramp.

Thermal Measurement Results: TCU ON



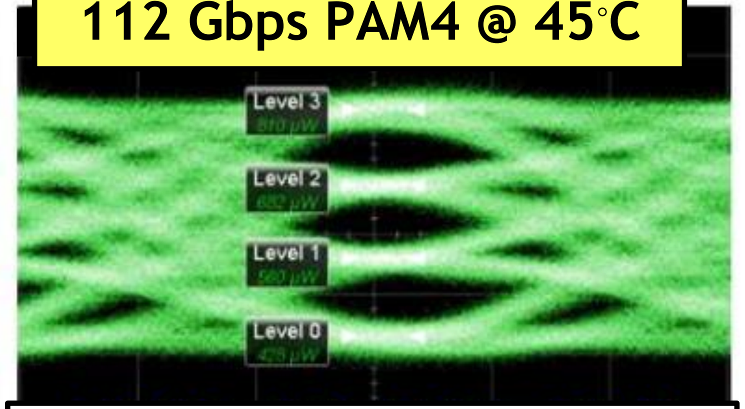


112 Gbps PAM4 @ 35°C



TDECQ = 0.63 dB, ER = 2.7 dB

112 Gbps PAM4 @ 45°C

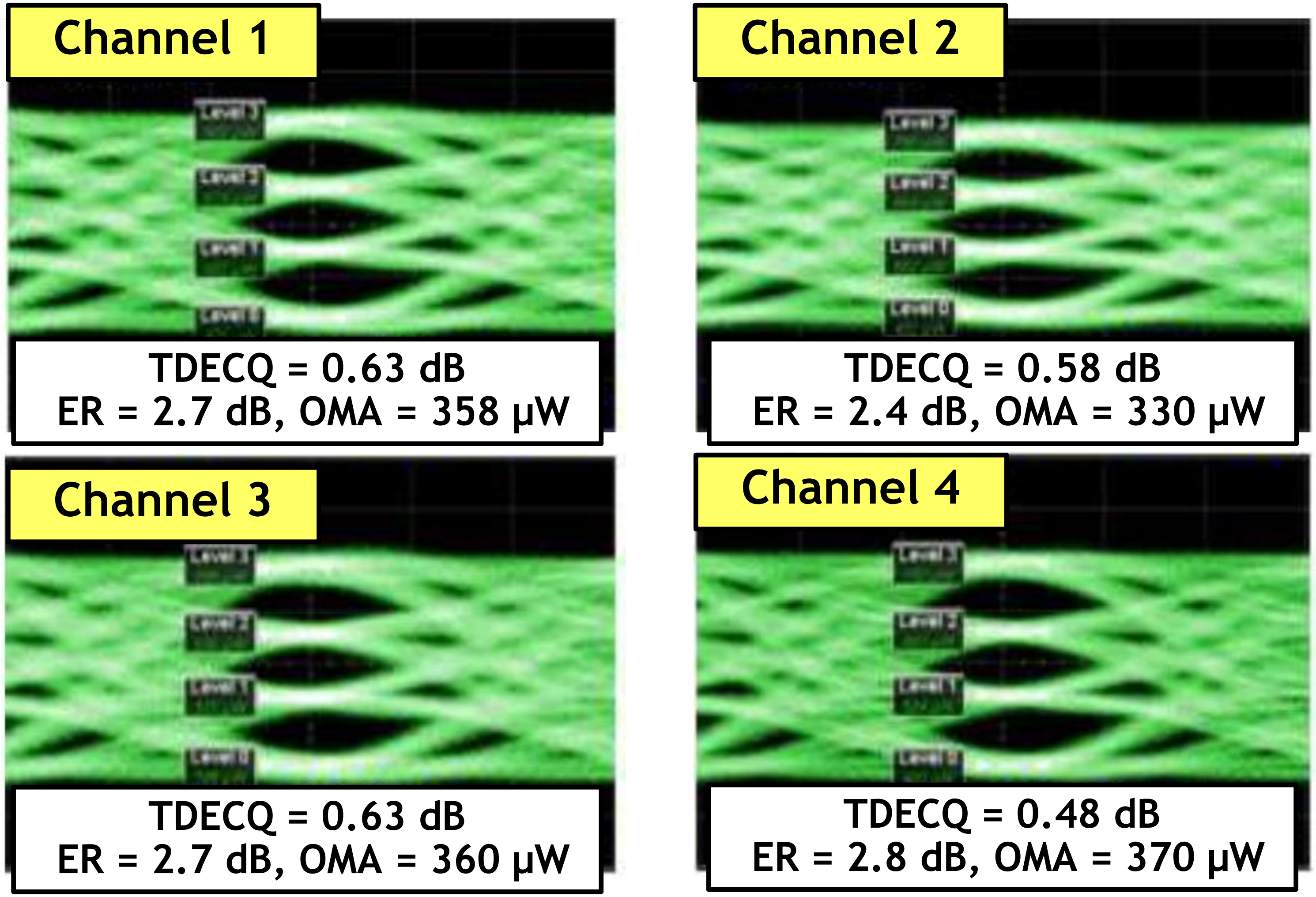


TDECQ = 0.66 dB, ER = 2.6 dB

[Intel, VLSI 2021]

With the thermal controller ON, OMA is maintained with temperature ramp.

OTX-only Measurement: 4-λ × 112 Gb/s PAM4



[Intel, VLSI 2021]

Per-channel 112 Gbps PAM4 eye with > 330 uW OMA and < 0.65 dB TDECQ.

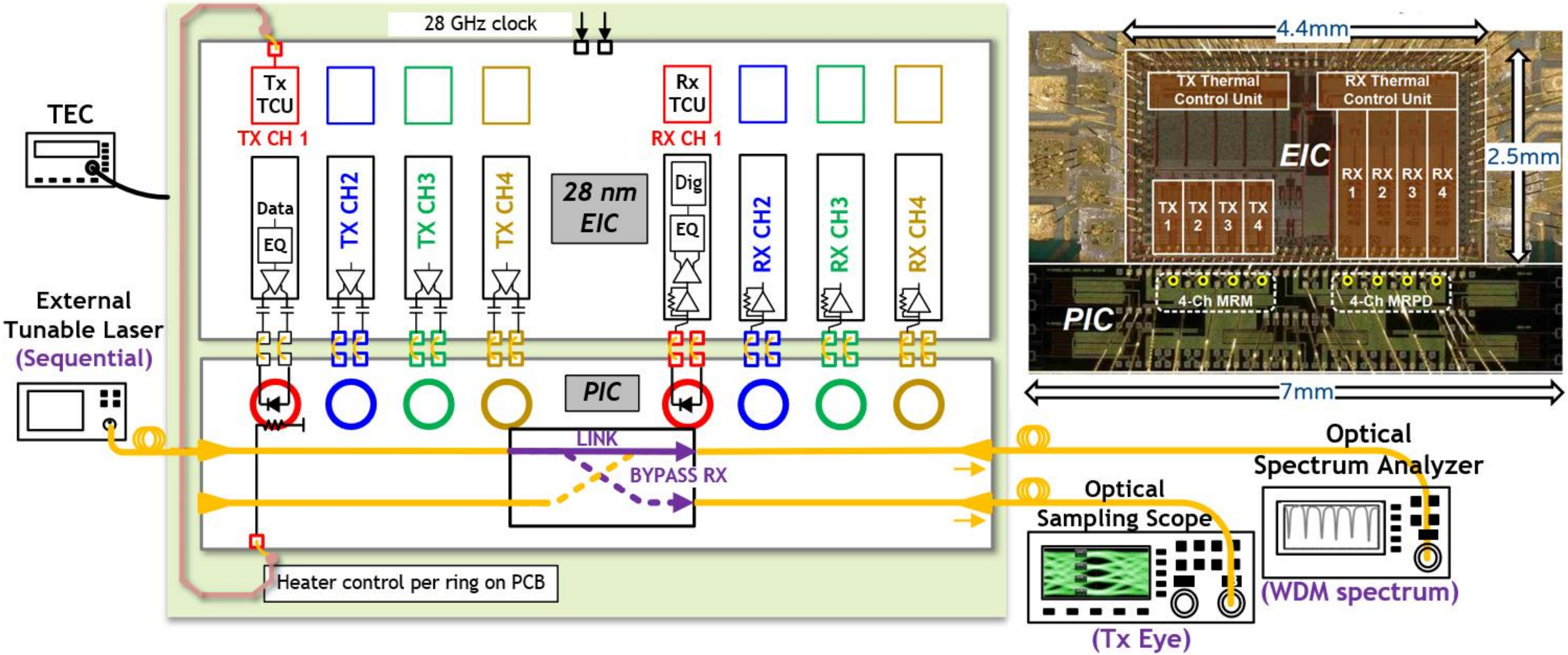
Silicon Photonic Micro-Ring Modulator-based 4 x 112 Gb/s O-band WDM Transmitter with Ring Photocurrent-based Thermal Control in 28nm CMOS

Jahnavi Sharma*, Hao Li*, Zhe Xuan, Ranjeet Kumar, Chun-Ming Hsu, Meer Sakib, Peicheng Liao, Haisheng Rong, James Jaussi, and Ganesh Balamurugan

Outline

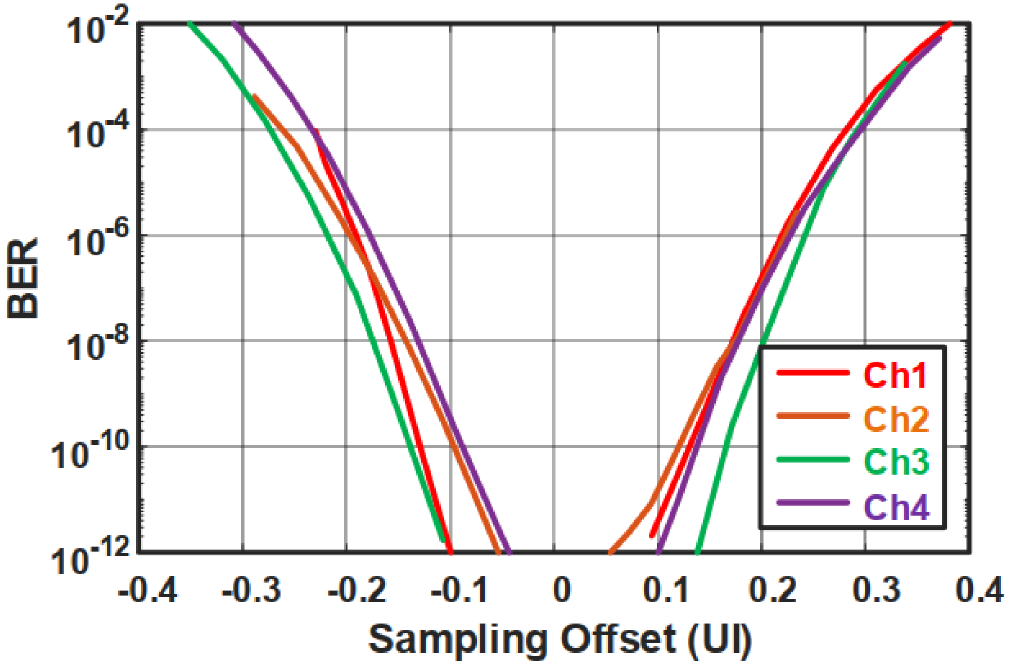
- SiPh platform for high-speed DCI
- Photonic devices
- CMOS electronics for single-λ links
- **Wavelength-division multiplexing**
  - 4-λ × 112 Gb/s PAM4 OTX
  - Compact thermal control in WDM links
  - **4-λ × 50 Gb/s NRZ optical link**
- Future directions and conclusion

4-λ O-band WDM Optical Transceiver

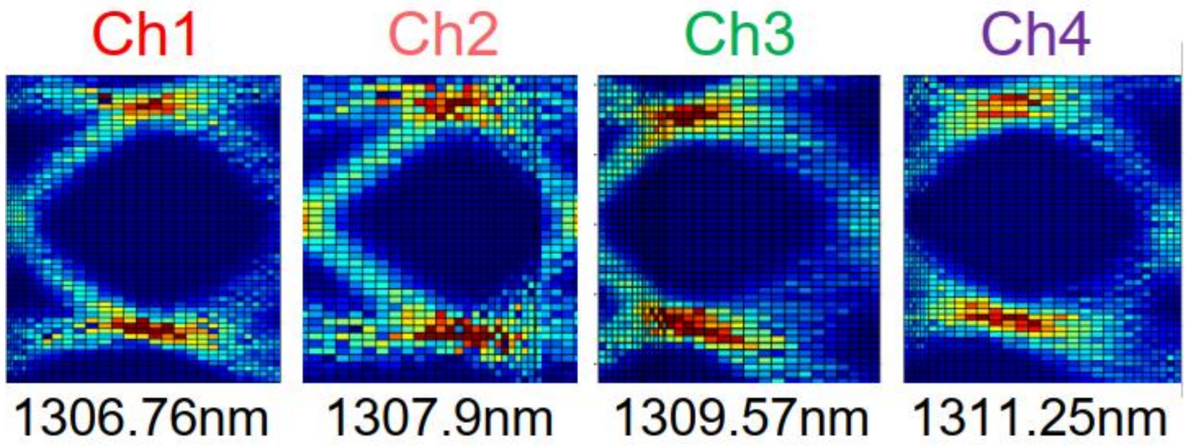


4-λ OTRX in 28nm CMOS with integrated thermal control for TX and RX rings.

Optical Link Measurement: 4-λ × 50 Gb/s NRZ



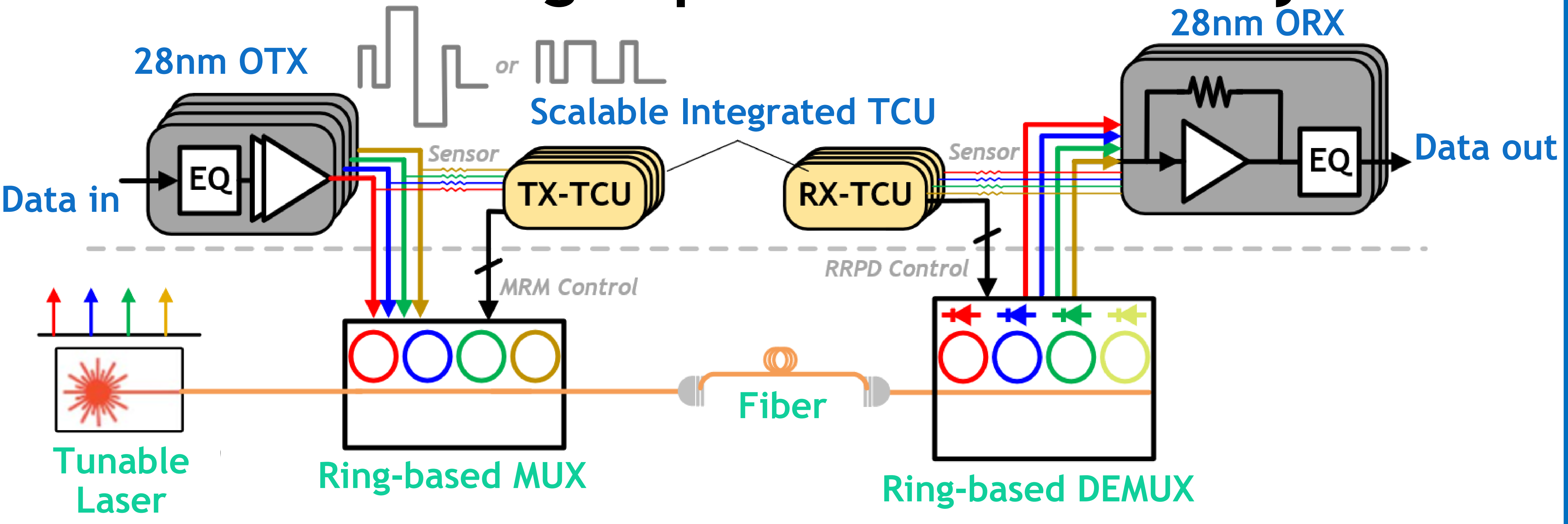
50 Gb/s NRZ On-chip eye plots



[Intel, ECOC 2021]

- BER better than 10e-12 for all four channels with equalization enabled.
- Error-free operation for > 10 minutes with Tx+Rx thermal control enabled.

Multi-λ High-Speed Link: Summary



Ring-based Wavelength-Division Multiplexing

- Scalable thermal-control solutions
- 4-λ × 112 Gb/s PAM4 OTX
- 4-λ × 50 Gb/s NRZ optical link

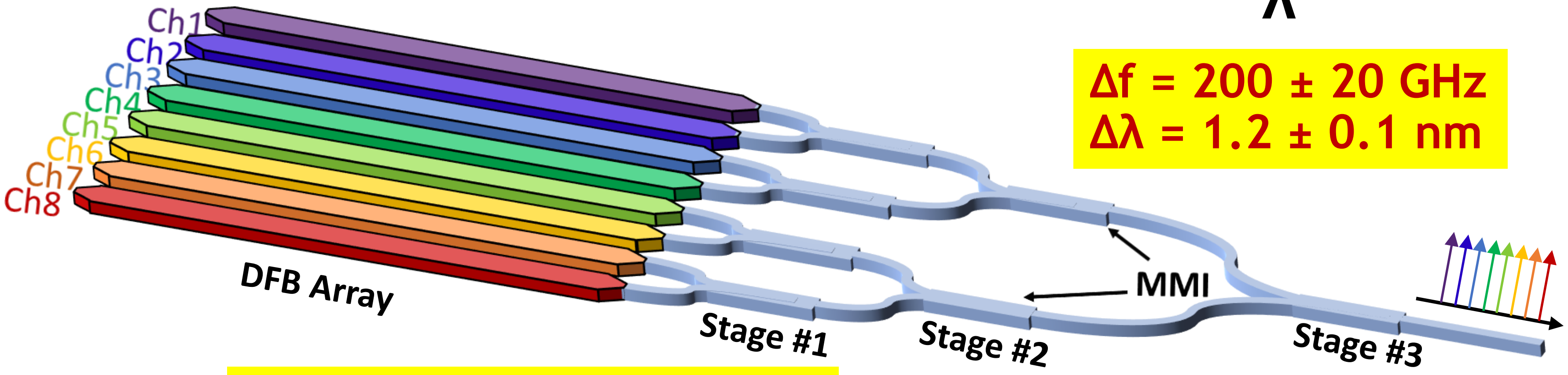
Outline

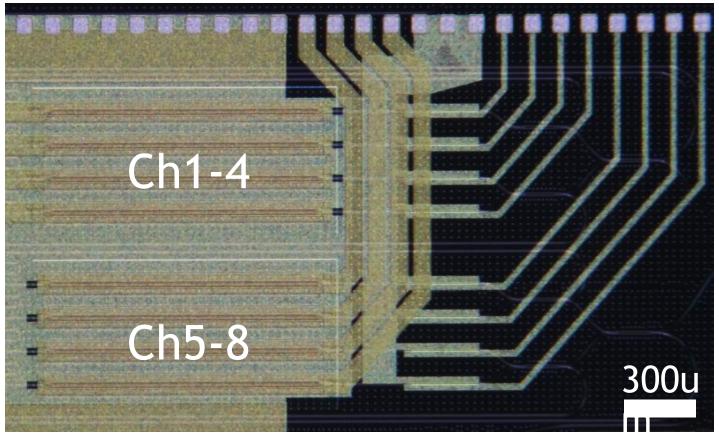
- SiPh platform for high-speed interconnects
- Photonic devices
- CMOS electronics for single-λ links
- Wavelength-division multiplexing
- **Future directions: WDM source, Polarization-Multiplexing, Packaging**
- Conclusion

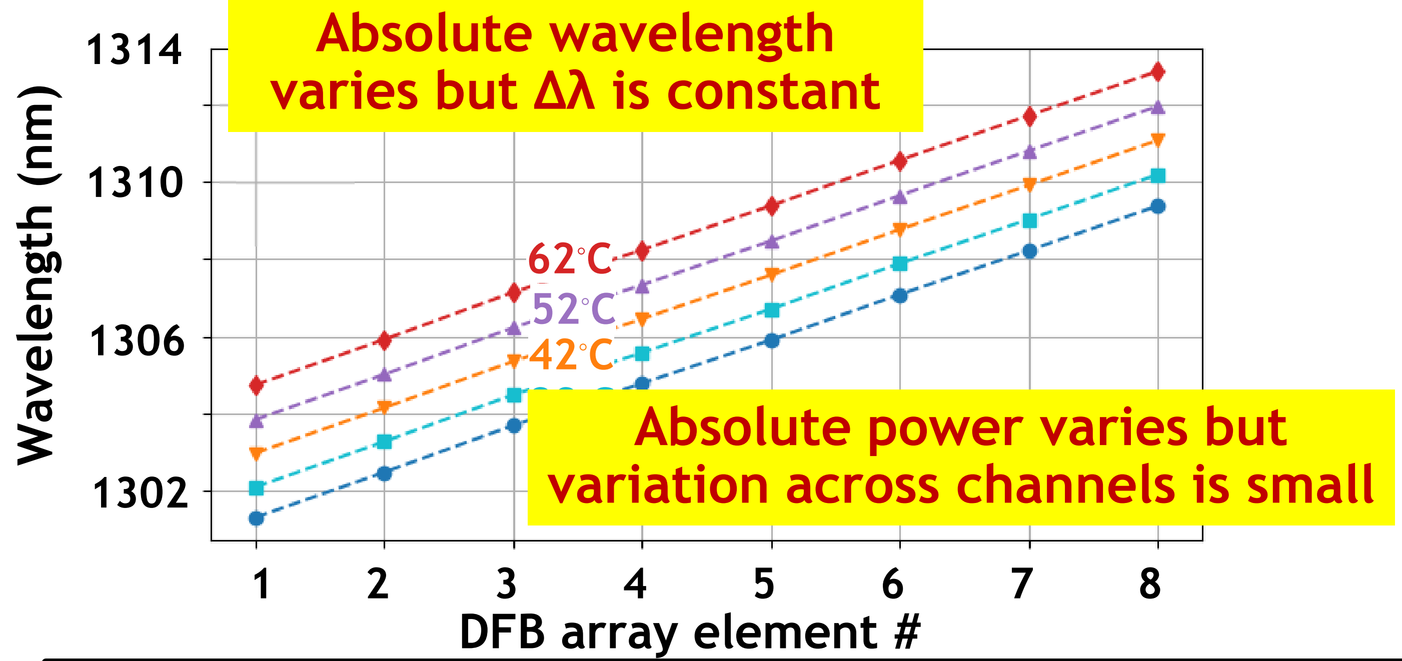
8-λ Laser: ΔP_λ vs ΔT

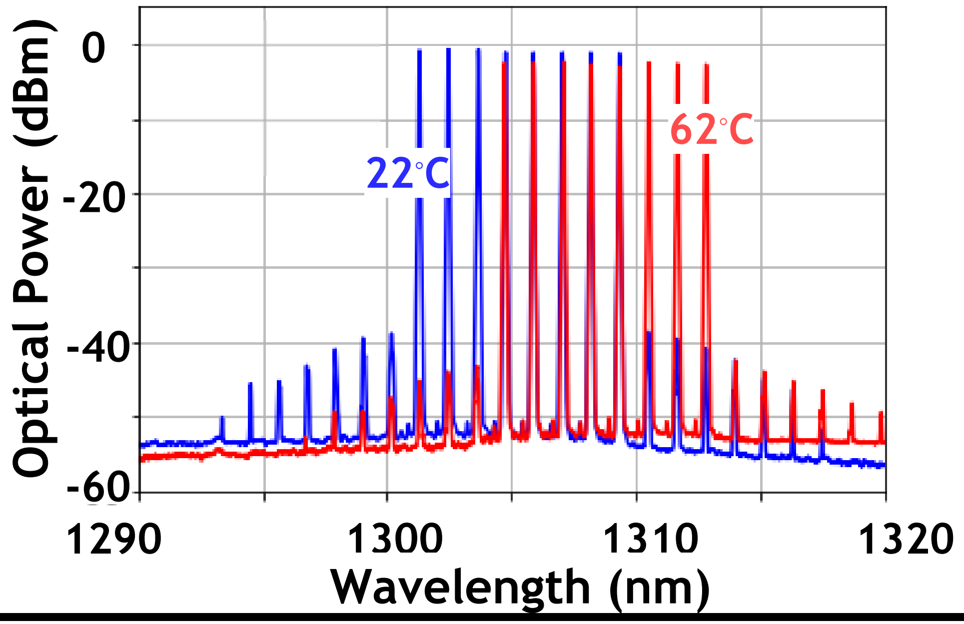
[Intel, ISLC 2021]

Δf = 200 ± 20 GHz
$\Delta\lambda$ = 1.2 ± 0.1 nm







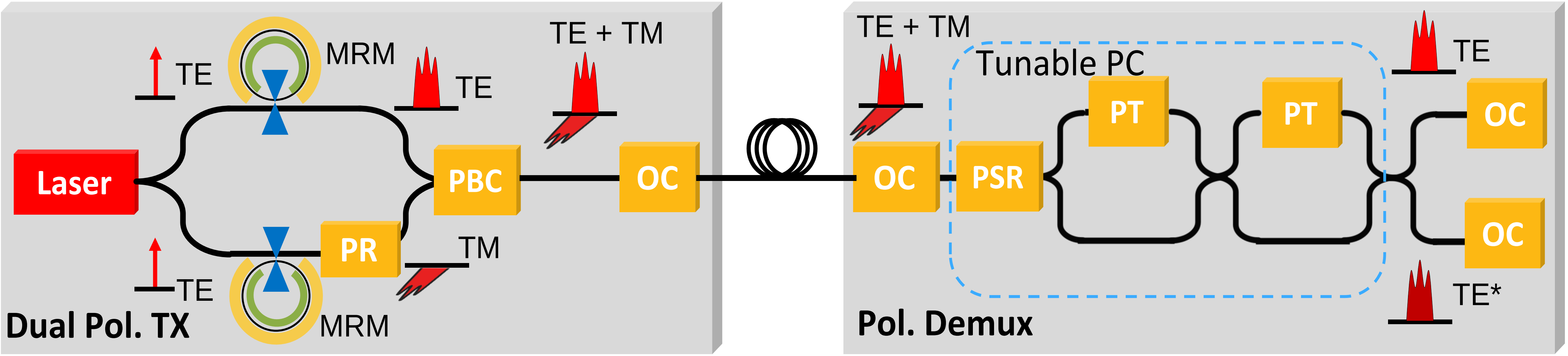


Power variation between WDM channels remains small for different temperatures.

8-channel hybrid III-V/silicon DFB laser array with highly uniform 200 GHz spacing and power

Duanni Huang*, Ranjeet Kumar*, Xinru Wu, Kimchau N. Nguyen, Guan-Lin Su, Meer Sakib, Chaoxuan Ma, John Heck, Haisheng Rong*

Scaling Data Rate: Polarization Multiplexed Links



[Intel, OFC 2021]

TE/TM: transverse electric/magnetic; MRM: micro-ring modulator; PR: polarization rotator; PBC: polarization beam combiner; PSR: polarization splitter and rotator; OC: optical coupler; PT; phase tuner. PC: polarization control

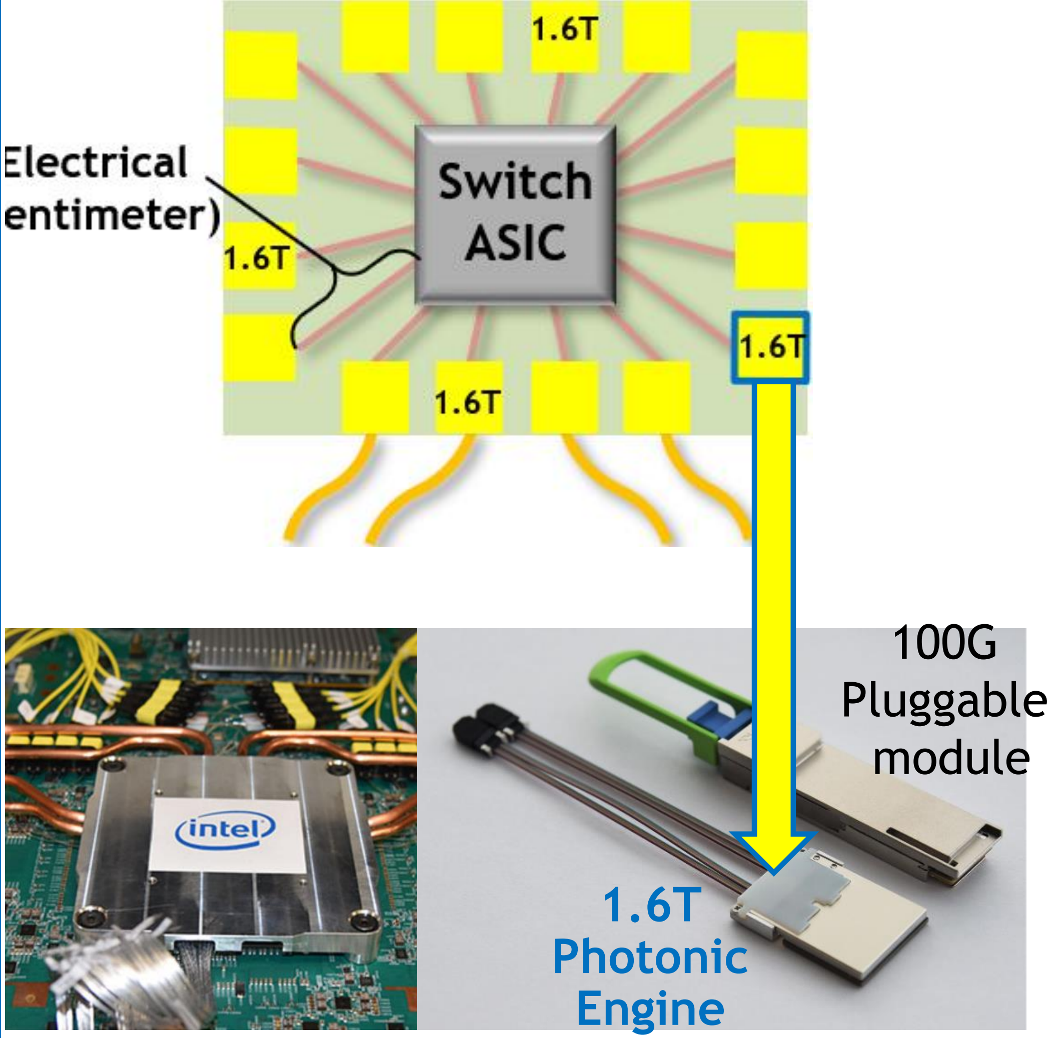
Polarization multiplexing can help double the per-fiber data rate.

A 260 Gb/s/λ PDM link with silicon photonic dual-polarization transmitter and polarization demultiplexer

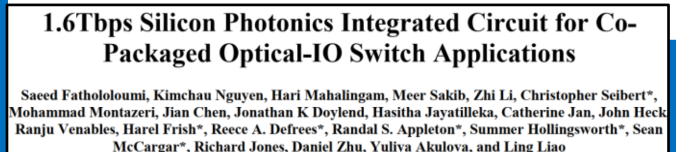
Peicheng Liao, Meer Sakib, Duanni Huang, Ranjeet Kumar, Xinru Wu, Chaoxuan Ma, Guan-Lin Su, and Haisheng Rong

Packaging for CPO

2020 demo



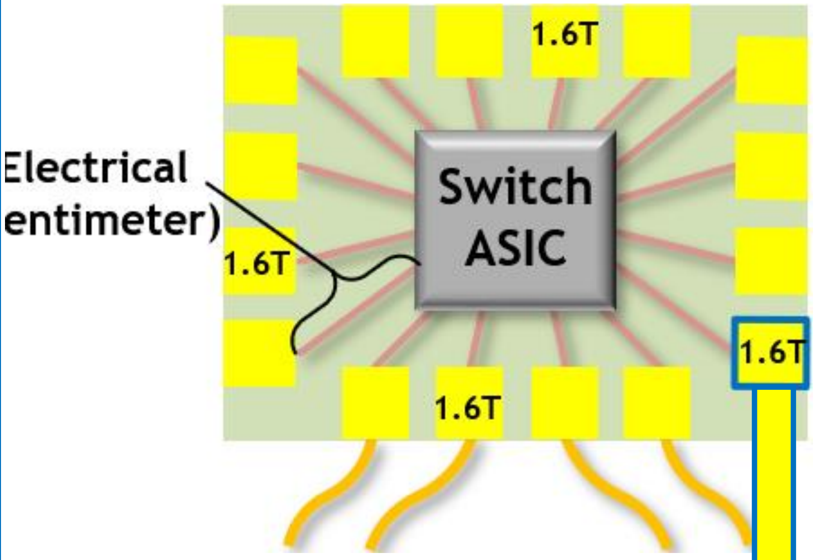
[Intel, OFC 2020]


1.6Tbps Silicon Photonics Integrated Circuit for Co-Packaged Optical-IO Switch Applications

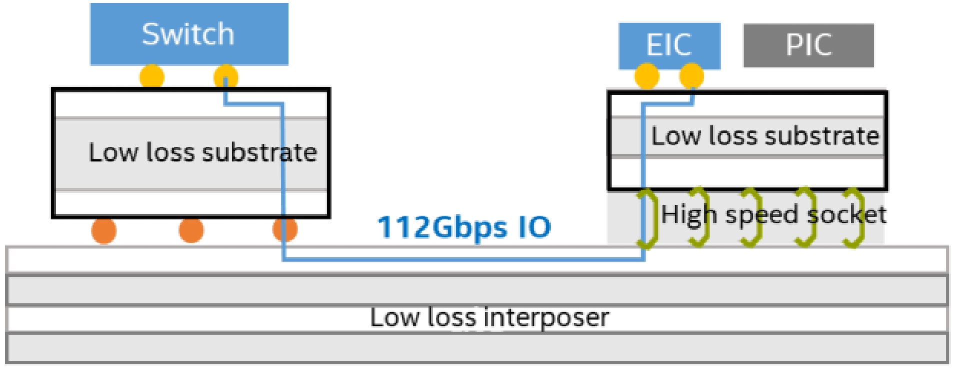
Saeed Fathololoumi, Kimchau Nguyen, Hari Mahalingam, Meer Sakib, Zhi Li, Christopher Seibert*, Mohammad Montazeri, Jian Chen, Jonathan K Doylend, Hasitha Jayatilleka, Catherine Jan, John Heck, Ranju Venables, Harel Frish*, Reece A. Defrees*, Randal S. Appleton*, Summer Hollingsworth*, Sean McCargar*, Richard Jones, Daniel Zhu, Yuliya Akulova, and Ling Liao

Packaging for CPO: Challenges

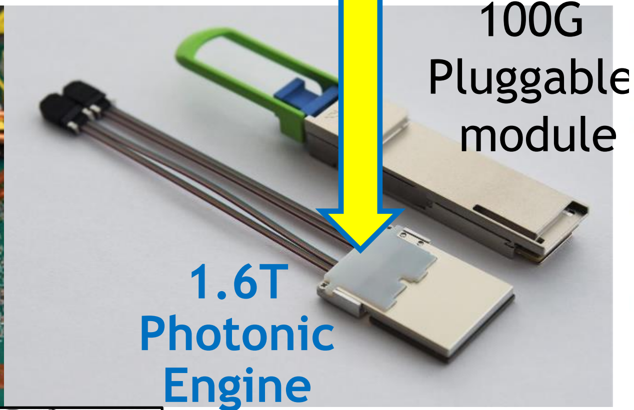
2020 demo

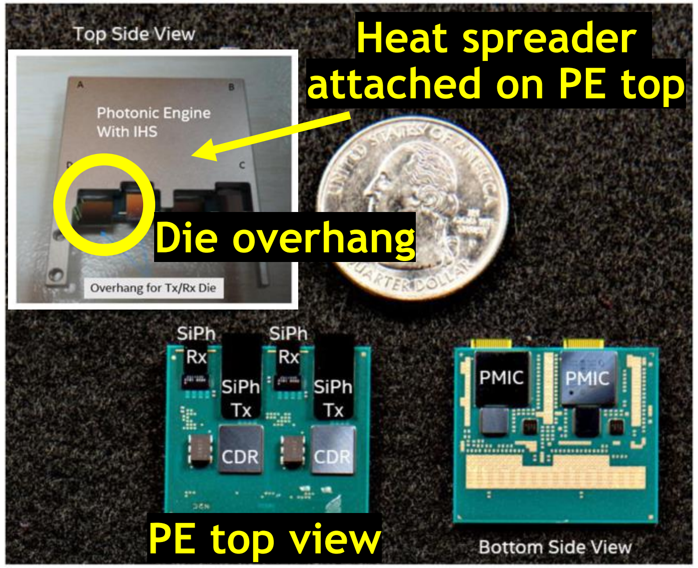


[Intel, JLT 2021]

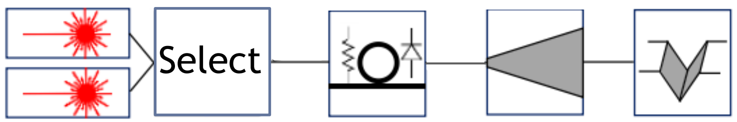


High-speed XSR electrical link





Thermal management



Fiber Attach
- Alignment
- Robustness

SSC: Spot-Size Converter

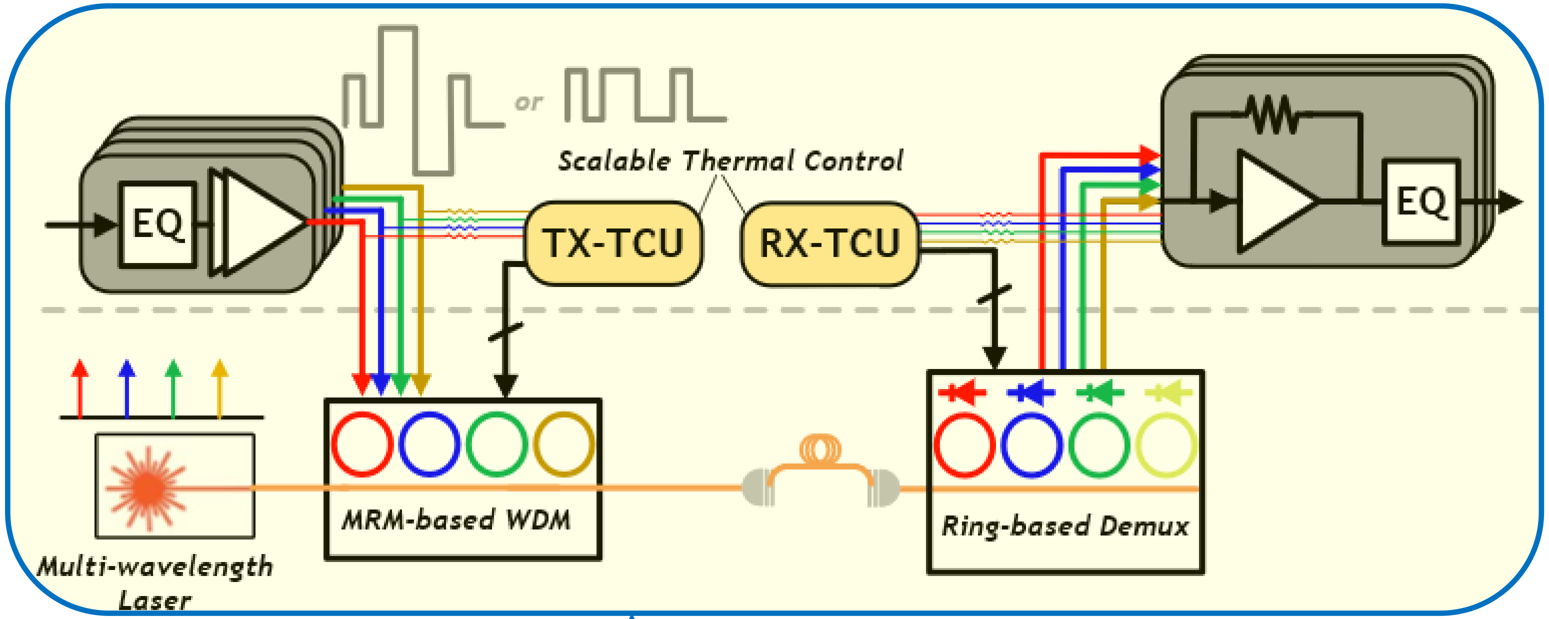
Co-Packaged Photonics for High Performance Computing: Status, Challenges and Opportunities

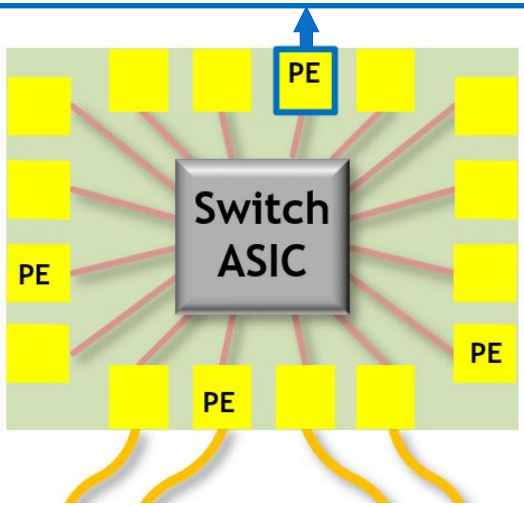
Ravi Mahajan, *Fellow IEEE*, Xiaoqian Li *Member IEEE*, Joshua Fryman *Senior Member IEEE*, Zhichao Zhang *Senior Member IEEE*, Srikant Nekkanty, Pooya Tadayon, James Jaussi *Member IEEE*, Sergey Shumarayev, Ankur Agrawal *Senior Member IEEE*, Susheel Jadhav, Kumar Abhishek Singh *Member IEEE*, Andrew Alduino *Member IEEE*, Sushrutha Gujjula, Chia-Pin Chiu *Member IEEE*, Thomas Nordstog *Member IEEE*, Kaveh Hosseini, Sandeep Sane, Nitin Deshpande, Kemal Aygün *Senior Member IEEE*, Arnab Sarkar, Priyanka Dobriyal *Member IEEE*, Suresh Pothukuchi *Member IEEE*, Vanessa Pogue, David Hui

Outline

- SiPh platform for high-speed interconnects
- Photonic devices
- CMOS electronics for single-λ links
- Wavelength-division multiplexing
- Future directions
- **Conclusion**

Co-packaged SiPh for High-speed Interconnects





Optical building blocks for IMDD

Integrated Lasers, Modulators and Detectors

Pushing IMDD data rates

- Single-λ links with PAM4 modulation

  CMOS OTRX to enable 100+ Gb/s per-λ
- Wavelength-Division Multiplexing
  - Scalable thermal-control solutions
  - 4-λ × 112 Gb/s PAM4 OTX
  - 4-λ × 50 Gb/s NRZ optical link
  - Multi-wavelength integrated laser source
- Future directions: Polarization-Multiplexing

Packaging challenges for CPO