ECEN689: Special Topics in Optical Interconnects Circuits and Systems
Spring 2022

Lecture 11: Ring Resonator Modulator Transmitters

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Announcements

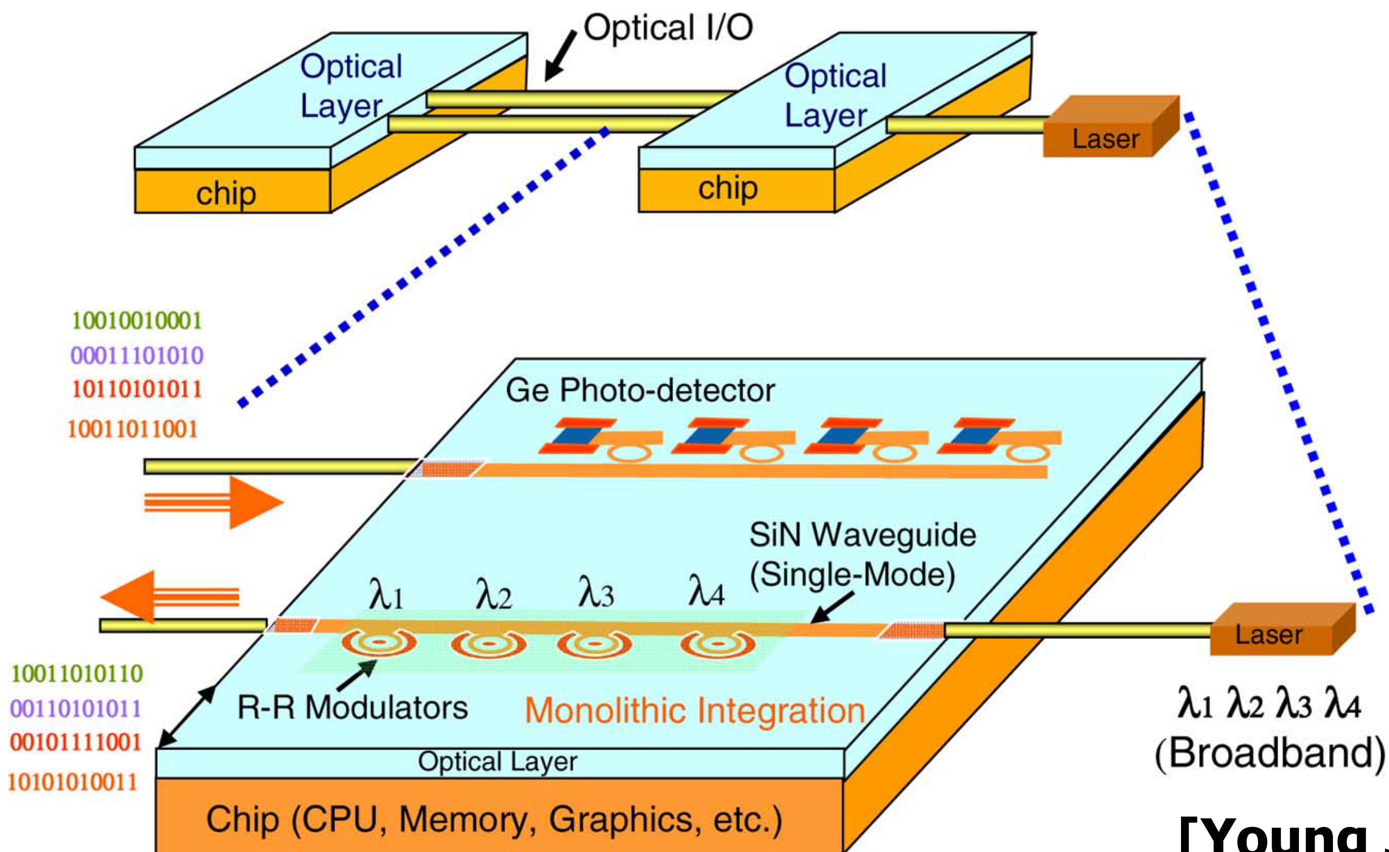
- Homework 3 is due today

- Reading
  - Sackinger Chapter 8

Agenda

- WDM Optical Interconnect Motivation
- Silicon Photonic Modulators
- Carrier-Injection Ring Resonator Modulators
- Carrier-Depletion Ring Resonator Modulators

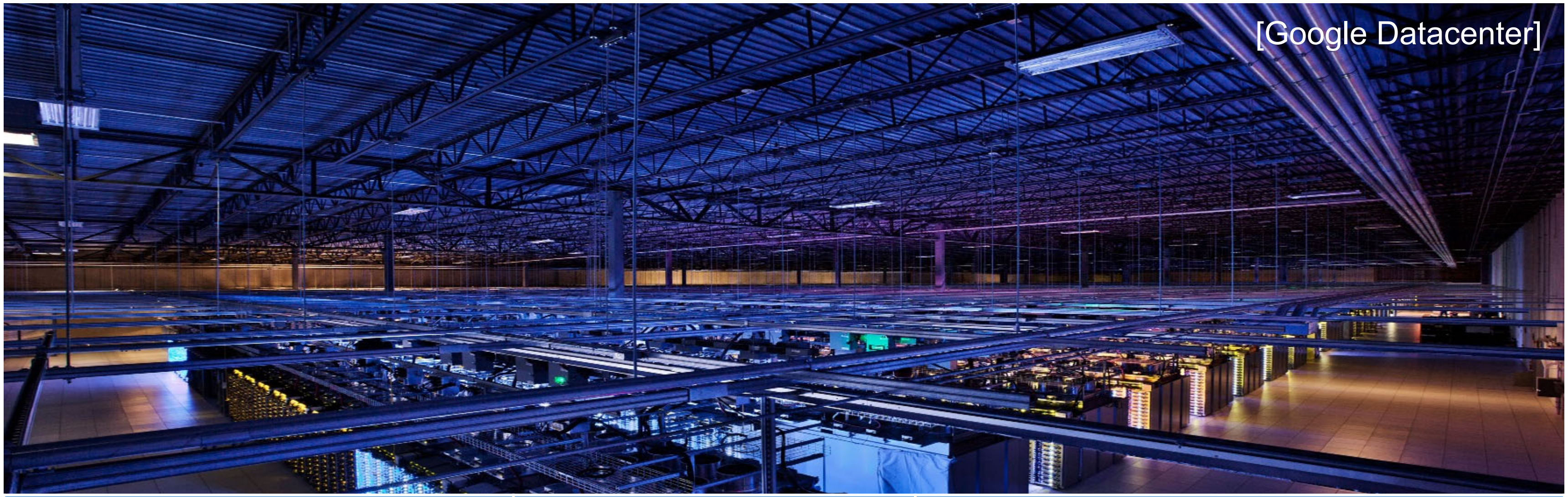
Wavelength-Division Multiplexing (WDM) Optical Interconnects



[Young JSSC 2010]

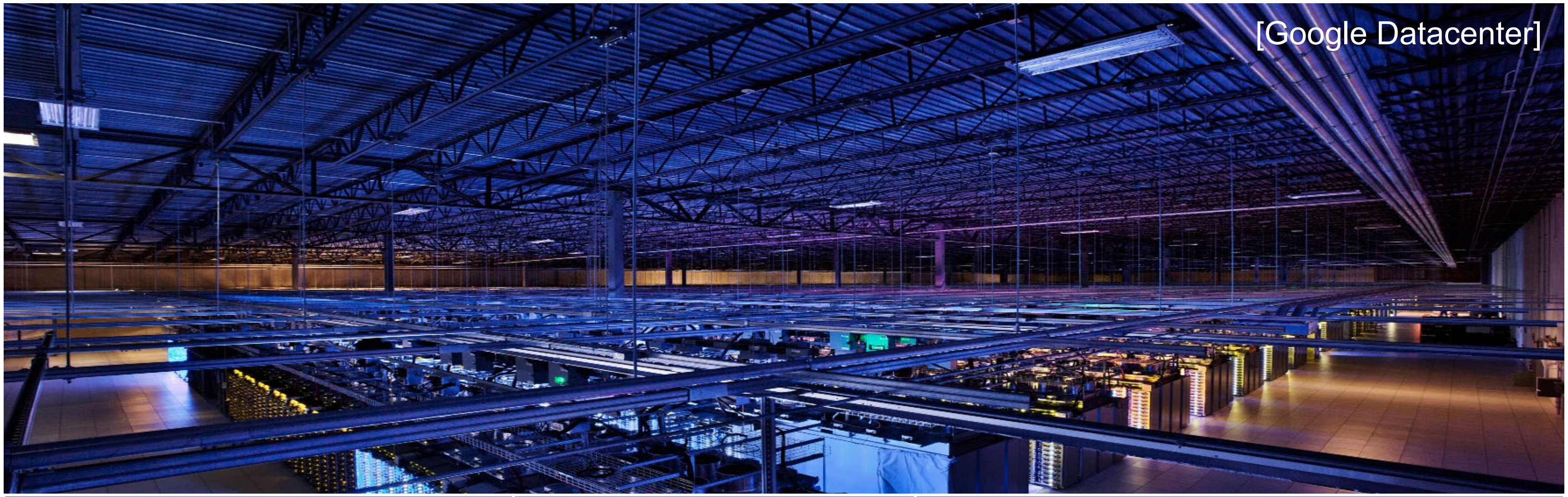
- Optical interconnects remove many channel limitations
- WDM allows for multiple high-bandwidth (10+Gb/s) signals to be packed onto one optical channel

Next-Generation 100G Interconnects



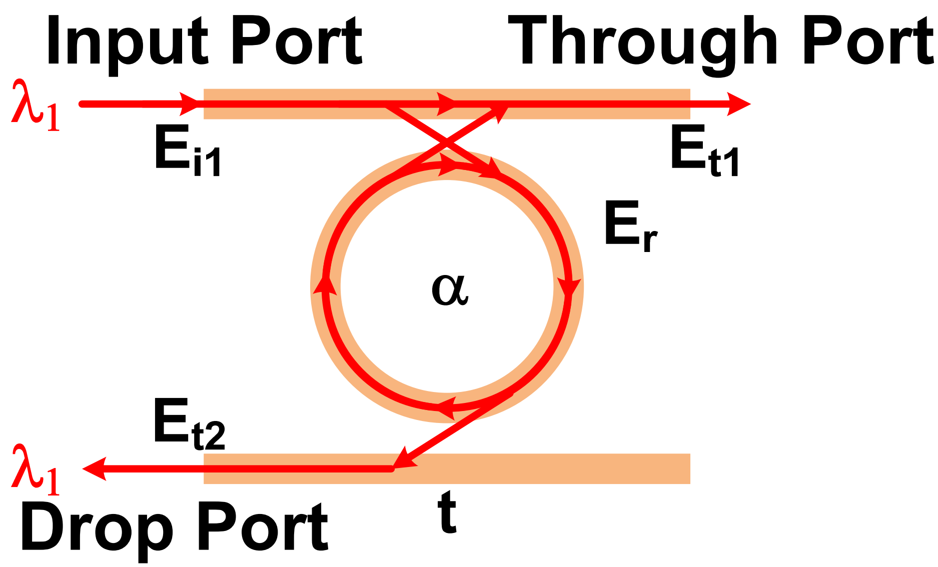
Link Distance	Transceiver Type	# of I/O Ports (25Gb/s NRZ)
0.5m	Electrical	PCB Trace × 4
1m	Electrical	Backplane × 4
10m	Electrical	Cu Cable × 4
100m	VCSEL	MMF × 4
1km	MZI / EAM	SMF × 4
> 10km	MZI / EAM	SMF × 4

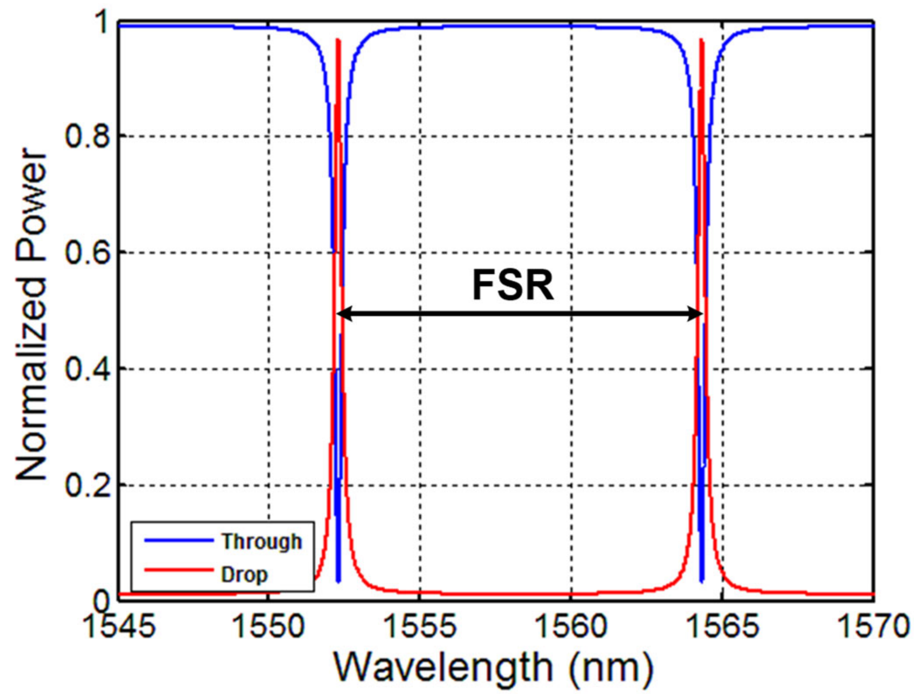
Next-Generation 100G Interconnects



Link Distance	Transceiver Type	# of I/O Ports (25Gb/s NRZ)
0.5m	Electrical	PCB Trace × 4
1m	Electrical	Backplane × 4
10m	Ring Modulator WDM	SMF × 1
100m		
1km		
> 10km		

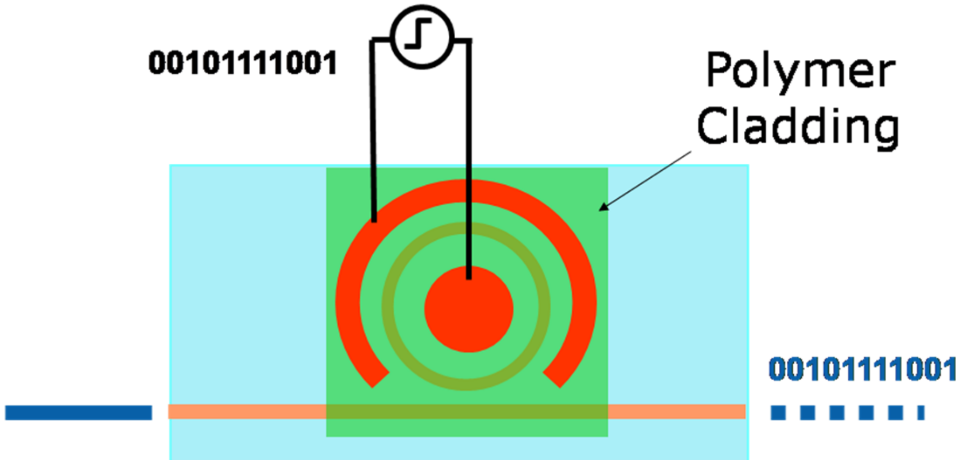
Ring Resonator Filter



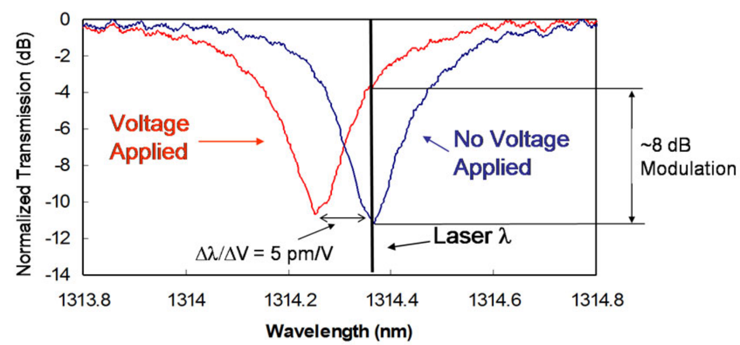


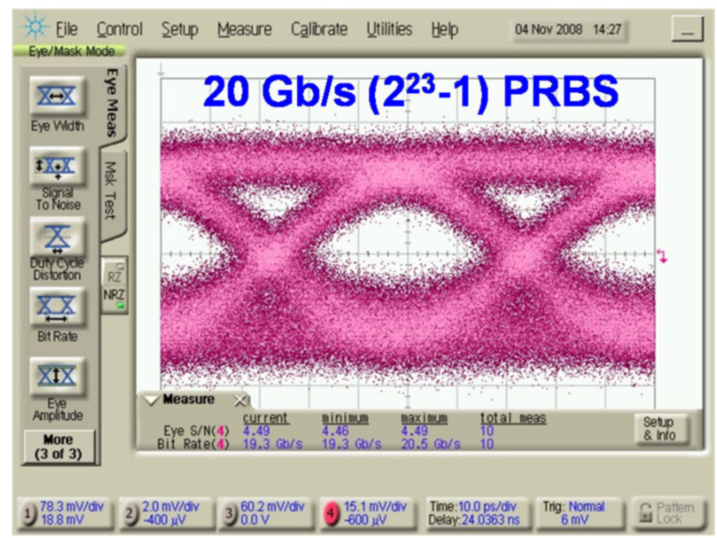
- Ring resonators display a high-*Q* notch filter response at the through port and a band-pass response at the drop port
- This response repeats over a free spectral range (FSR)

Ring-Resonator Modulator (RRM)



High Frequency Modulation

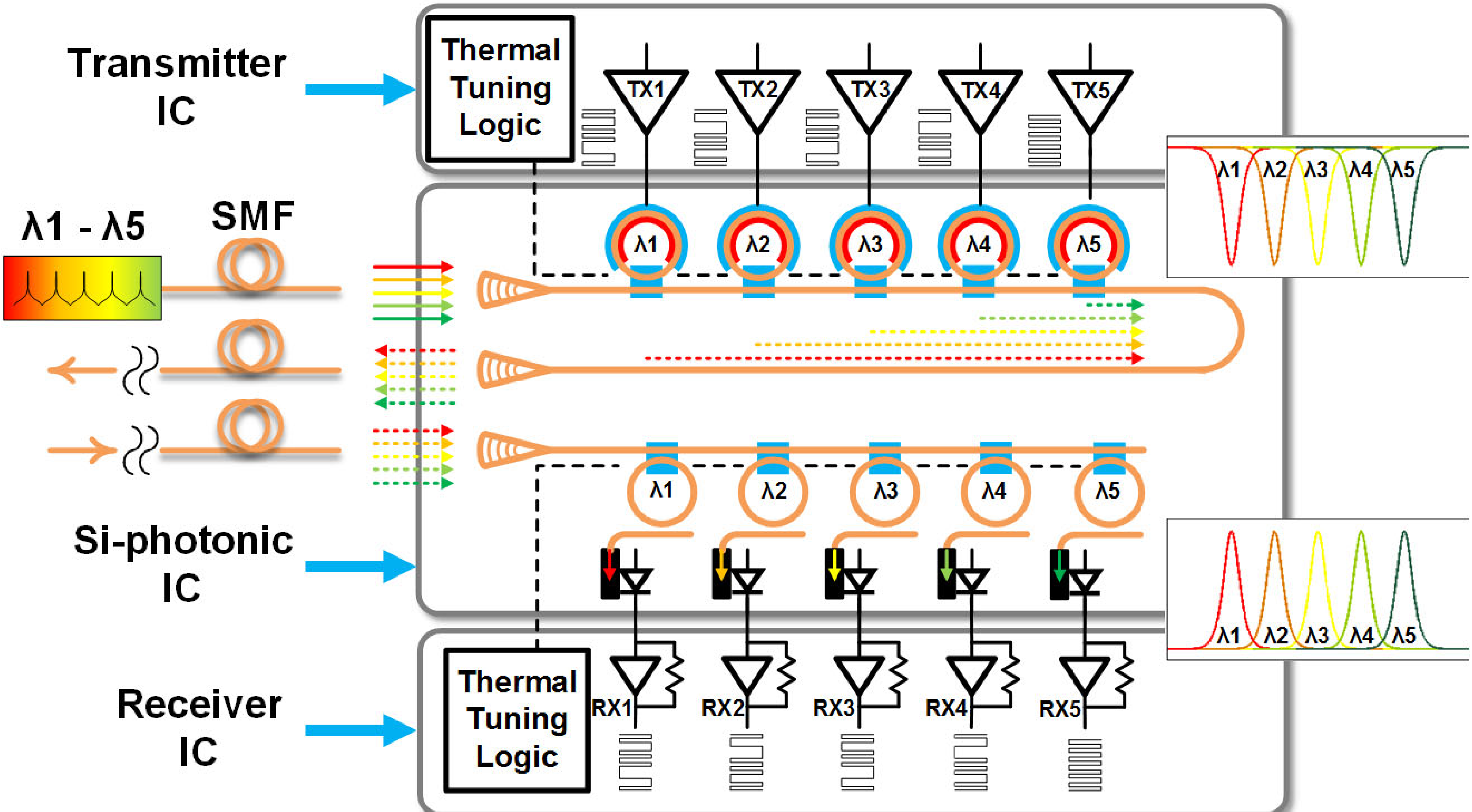




- Refractive devices which modulate by changing the interference light coupled into the ring with the waveguide light
- Devices are relatively small (ring diameters < 20μm) and can be treated as lumped capacitance loads (~10fF)
- Devices can be used in WDM systems to selectively modulate an individual wavelength or as a "drop" filter at receivers

[Young ISSCC 2009]

WDM Photonic Transceiver



- High bandwidth density by combining multi-channels on a single waveguide via wavelength division multiplexing

Agenda

- WDM Optical Interconnect Motivation
- Silicon Photonic Modulators
- Carrier-Injection Ring Resonator Modulators
- Carrier-Depletion Ring Resonator Modulators

Plasma Dispersion Effect

- The change in refractive index and optical absorption coefficient is induced by free carriers in a semiconductor

$$N = n + i\alpha$$

N: complex index of refraction
n: electro-refraction
α: electro-absorption

1550 nm

$$\Delta n_{1.55\mu m} = -8.8\times10^{-22}\,\Delta N_e - 8.5\times10^{-18}\left(\Delta N_h\right)^{0.8}$$

$$\Delta\alpha_{1.55\mu m} = 8.5\times10^{-18}\,\Delta N_e + 6.0\times10^{-18}\,\Delta N_h\ [cm^{-1}]$$

1310 nm

$$\Delta n_{1.31\mu m} = -6.2\times10^{-22}\,\Delta n_e - 6.0\times10^{-18}\left(\Delta n_h\right)^{0.8}$$

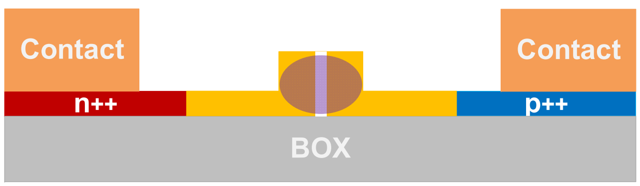
$$\Delta\alpha_{1.31\mu m} = 6.0\times10^{-18}\,\Delta n_e + 4.0\times10^{-18}\,\Delta n_h\ [cm^{-1}]$$

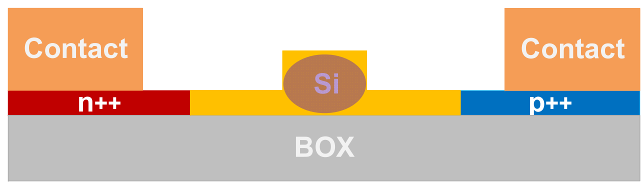
ΔN_e: electrons density
ΔN_h: holes density

Silicon Photonic Modulators

- Carrier Accumulation
- Carrier Injection
- Carrier Depletion

- Electrooptic-polymer modulators have also been developed





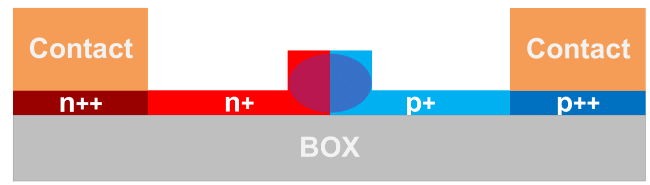
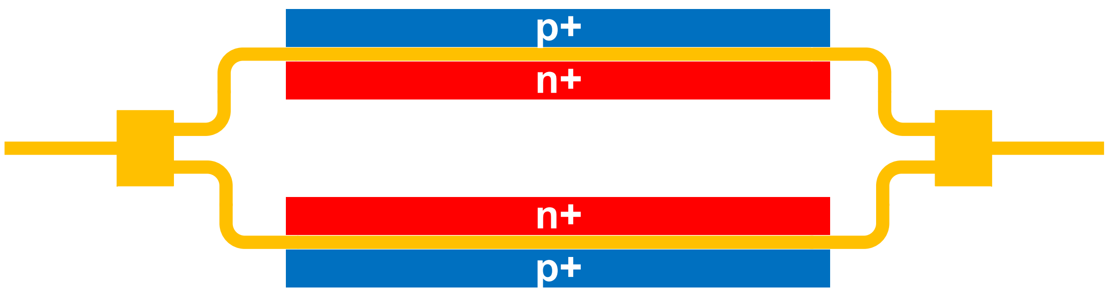


Figure of Merit	Carrier Accumulation	Carrier Injection	Carrier Depletion
Modulation Bandwidth	High +	Low −	High +
Extinction Ratio (ER)	Small −	Large +	Small −
Modulation Efficiency	High +	High +	Low −
Insertion Loss	High −	Low +	High −

MZM vs Microring Modulators

- Mach Zehnder Modulator
- Microring Modulator



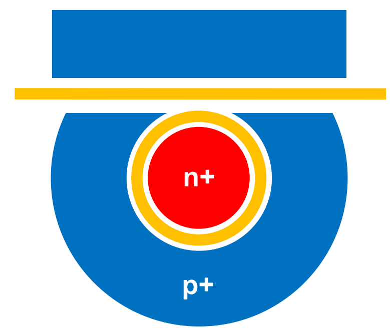
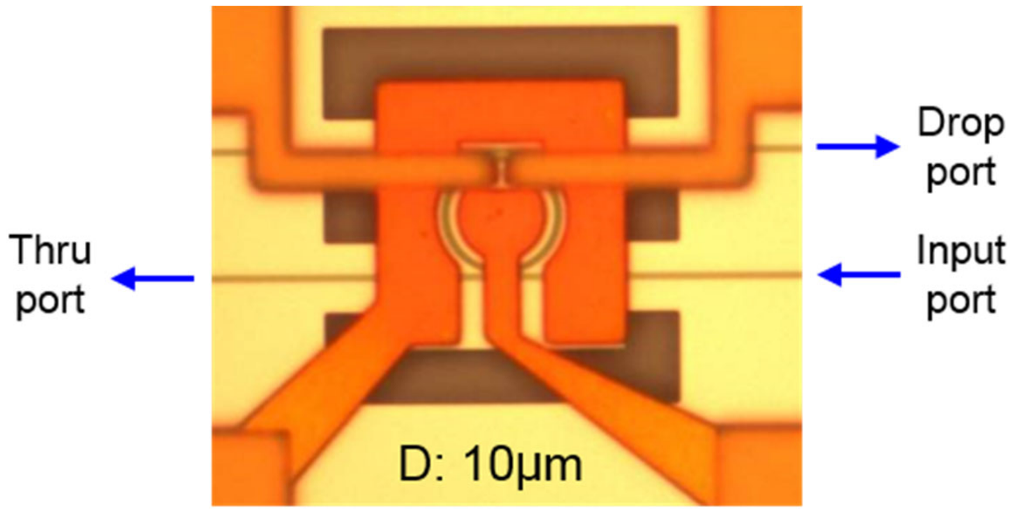


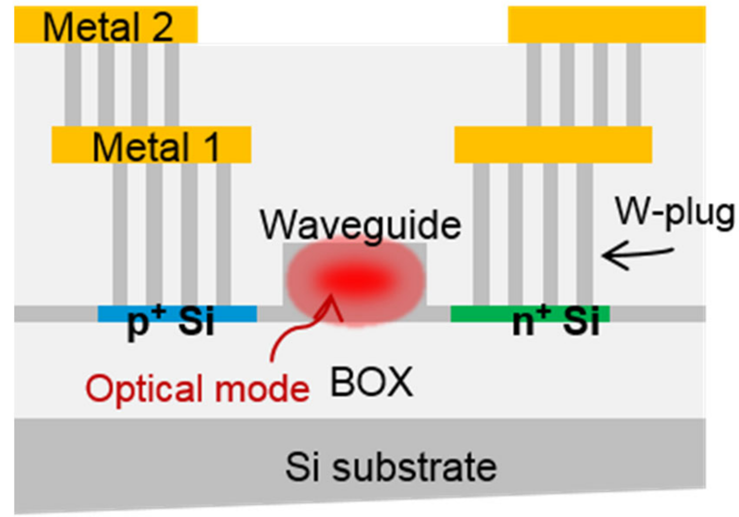
Figure of Merit	Mach Zehnder	Microring
Footprint	Large −	Small +
Extinction Ratio (ER)	Small −	Large +
Insertion Loss	High −	Low +
Wavelength Sensitivity	Low +	High −

Agenda

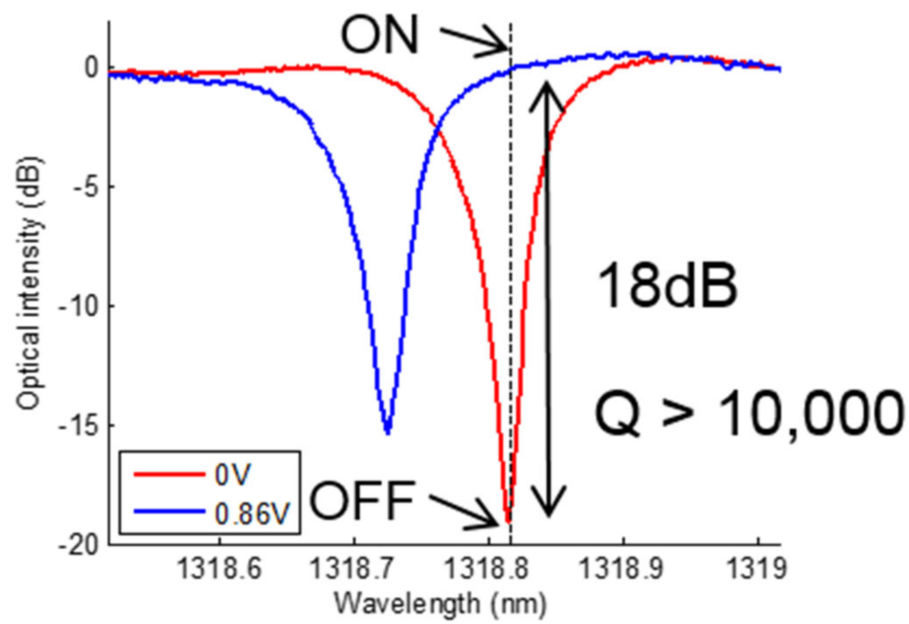
- WDM Optical Interconnect Motivation
- Silicon Photonic Modulators
- Carrier-Injection Ring Resonator Modulators
  - Device Operation and Modeling
  - High-Speed Driver
  - Wavelength Stabilization Loop
- Carrier-Depletion Ring Resonator Modulators

Carrier-Injection Microring Modulator

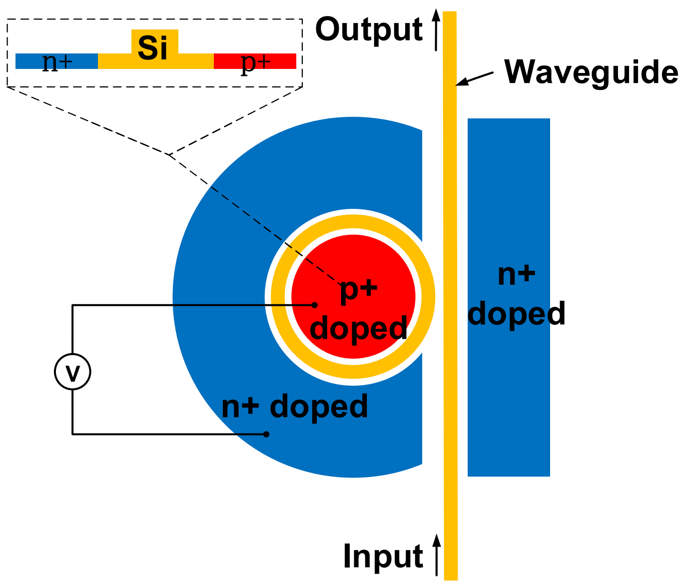




- Ring waveguide is doped as a PIN junction
- Forward-bias voltage injects carriers, changing refractive index for optical modulation via the free carrier plasma dispersion effect

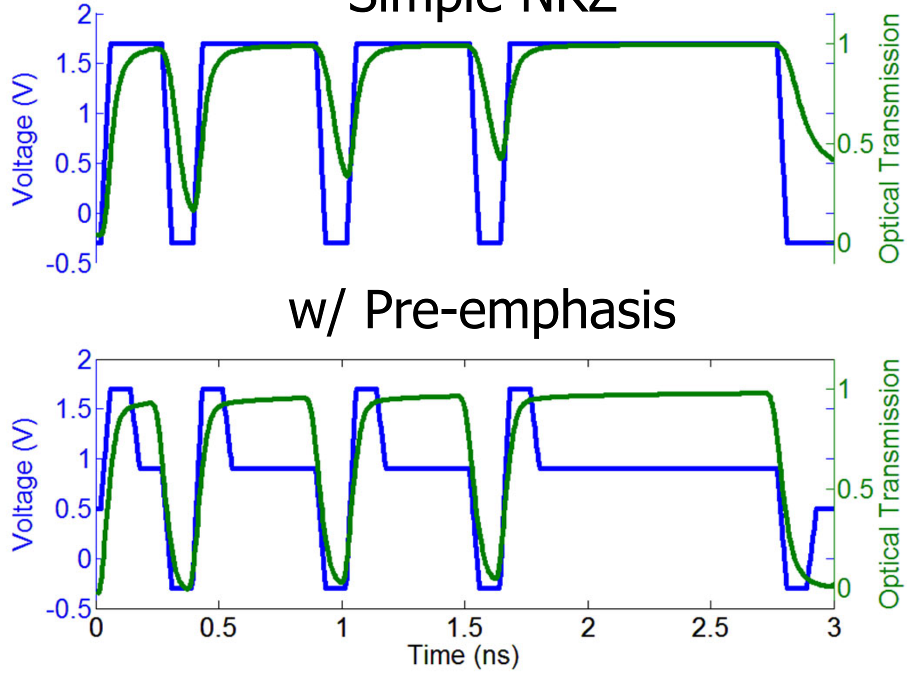


C-I Ring Modulator Speed Limitations

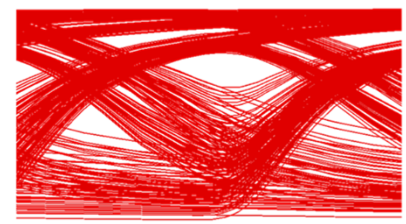


Simple NRZ

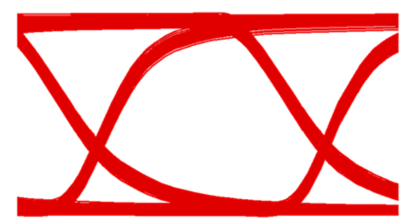
w/ Pre-emphasis



8Gb/s



8Gb/s



- Speed is limited by long minority carrier lifetimes
- Pre-emphasis signaling significantly improves data rates

Carrier-Injection Ring Modulator Modeling

- Previous Related Modeling Work
  - P-I-N diode model (only electrical dynamics) [Strollo TPE 1997]
  - Ring resonator model (only optical dynamics) [Smy JOSA B 2011]
  - Carrier-injection ring modulator model (lack accurate large-signal behavior) [Xu OE 2007, Wu OE 2015]

- Carrier-Injection Ring Modulator Model
  - Capture nonlinear electrical and optical dynamics

[**Binhao Wang**, Cheng Li, Chin-Hui Chen, Kunzhi Yu, Marco Fiorentino, Raymond Beausoleil, and Samuel Palermo, "Compact Verilog-A Modeling of Carrier-Injection Microring Modulators for Optical Interconnect Transceiver Circuitry Design," accepted in Journal of Lightwave Technology]

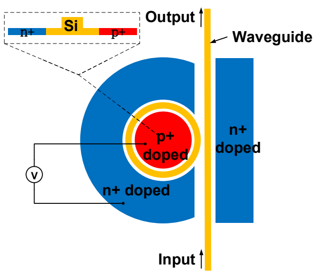
[**Binhao Wang**, Cheng Li, Chin-Hui Chen, Kunzhi Yu, Marco Fiorentino, Raymond Beausoleil, and Samuel Palermo, "Compact Verilog-A Modeling of Silicon Carrier-Injection Ring Modulators," IEEE Optical Interconnects Conference (OIC), 2015]

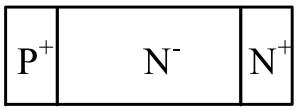
[Cheng Li, Chin-Hui Chen, **Binhao Wang**, Samuel Palermo, Marco Fiorentino, and Raymond Beausoleil, "Design of an Energy-Efficient Silicon Microring Resonator-Based Photonic Transmitter," IEEE Design & Test of Computers, 31, 46-54, 2014]

[Cheng Li, Rui Bai, Ayman Shafik, Ehsan Zhian Tabasy, **Binhao Wang**, Geng Tang, Chao Ma, Chin-Hui Chen, Zhen Peng, Marco Fiorentino, Raymond Beausoleil, Patrick Chiang, and Samuel Palermo, "Silicon Photonic Transceiver Circuits with Microring Resonator Bias-Based Wavelength Stabilization in 65-nm CMOS," IEEE Journal of Solid-State Circuits (JSSC), 49, 1419-1436, 2014]

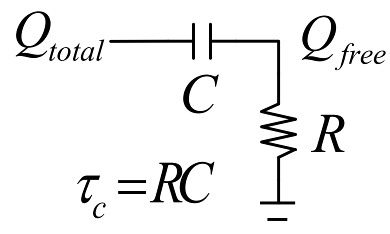
Model Flow Chart

Driving Voltage → p-i-n diode SPICE model → **Current Response**





Current Response → $Q_{total} = \int_0^t I(t)dt/q$ → **Carrier Concentration**

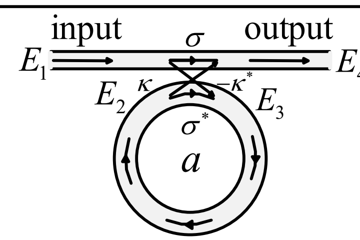


Plasma dispersion effect → **Index and Loss Changes**

$$\Delta n_{1.31\mu m} = -6.2\times10^{-22}\Delta n_e - 6.0\times10^{-18}(\Delta n_h)^{0.8}$$

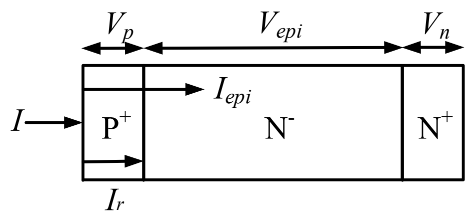
$$\Delta \alpha_{1.31\mu m} = 6.0\times10^{-18}\Delta n_e + 4.0\times10^{-18}\Delta n_h \ [cm^{-1}]$$

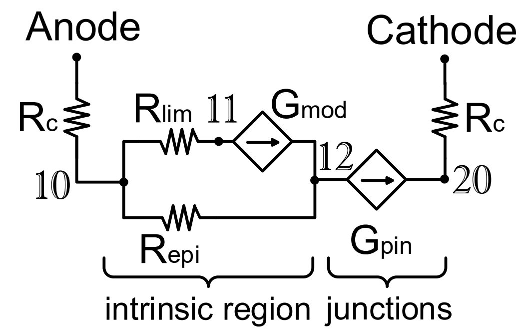
Index and Loss Changes → Dynamic ring resonator model → **Optical Power**

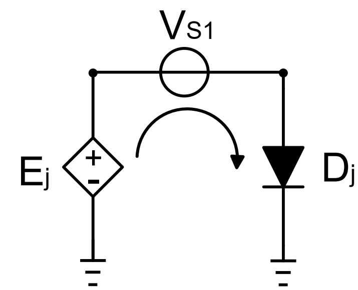


$$T(t) = \frac{E_4(t)}{E_1} = \sigma + \frac{-\kappa^*\kappa}{\sigma^*}\sum_{n=1}^{\infty}\left\{\left[\sigma^* a(t)\right]^n \cdot \exp\left[j\left(\sum_{m=1}^{n}\Phi(t-m\tau)\right)\right]\right\}$$

Electrical Modeling - PIN Dynamics







$$V_{pin} = V_{epi} + V_p + V_n = V_{epi} + V_j$$

$$I = I_{epi} + I_r$$

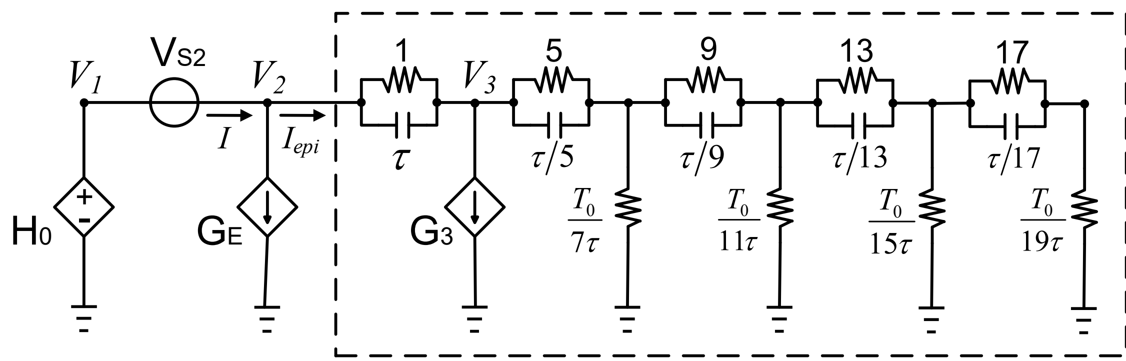
$$V = V_c + V_{epi} + V_j = V_c + V(10,12) + V(12,20)$$

$$G_{mod} = V(11,12)\left[\frac{L_{AM}}{V_M}\cdot V_2 + \frac{1-L_{AM}}{V_M}(V_2 - V_3)\right]$$

$$V_{S1} = 0$$

$$E_j = V_j = V(12,20)$$

$$I(V_{S1}) = q_0/\tau = I_S\left(e^{E_j/NV_T} - 1\right)$$



$$H_0 = I(V_{S1}) = q_0/\tau \quad I = G_{pin} = I_{epi} + G_E$$

$$I_r = G_E = (q_0/\tau)^2 / I_E$$

$$G_3 = V_3 \Bigg/ \left[\frac{T_0}{3\tau}\left(1 - \sqrt{\frac{P_{HI} - V_j}{V_{PT} - R_{SC} I}}\right)^2\right]$$

[Strollo TPE 1997]

- I-V dynamics are based on a moment-matching approximation of the ambipolar diffusion equation

Electrical Modeling - Parameter Extraction

Parameters initialization based on an empirical range

↓

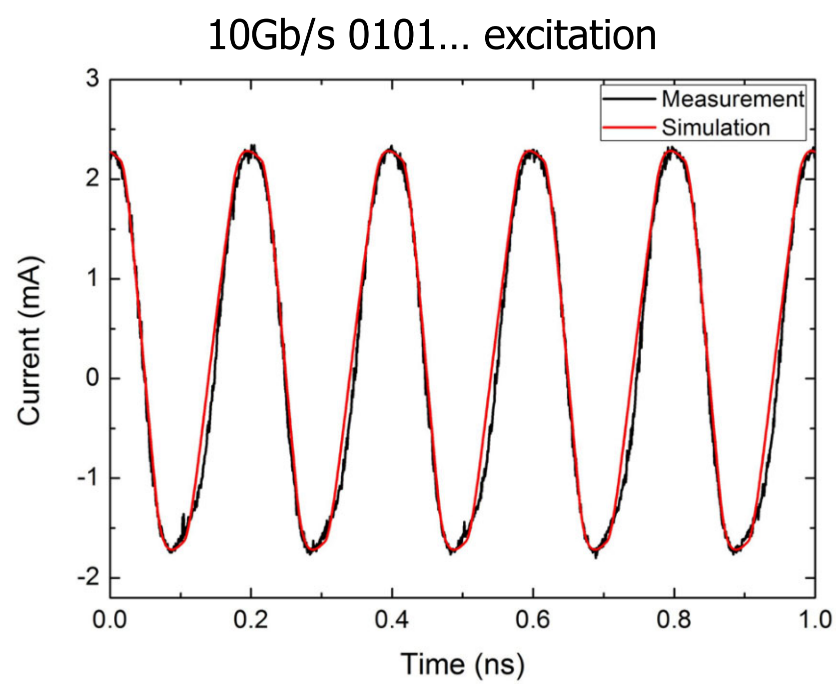
Estimation of R_C, P_{HI}, I_S, N, I_E, V_M, R_{LIM} and R_{EPI} parameters by fitting DC measurement

↓

Estimation of T_0, τ, L_{AM}, V_{PT} and R_{SC} parameters by fitting transient measurement

↓

Delivery of the parameter set



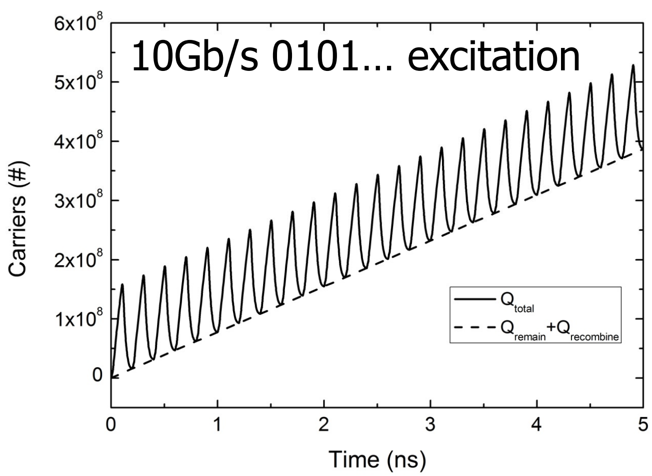
Optical Modeling - Carrier Dynamics

- Carrier Concentration

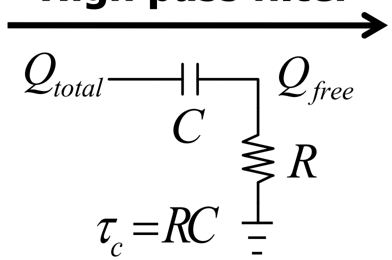
$$Q = \int_0^t I(t)\,dt / q$$

$$I_{total}(t) = I_{free}(t) + I_{remain}(t) + I_{recombine}(t)$$

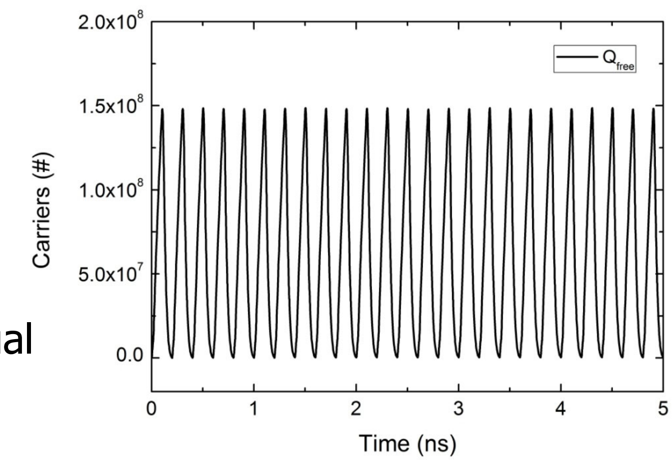
$$Q_{total}(t) = Q_{free}(t) + Q_{remain}(t) + Q_{recombine}(t)$$



High pass filter



The time constant is equal to the carrier lifetime

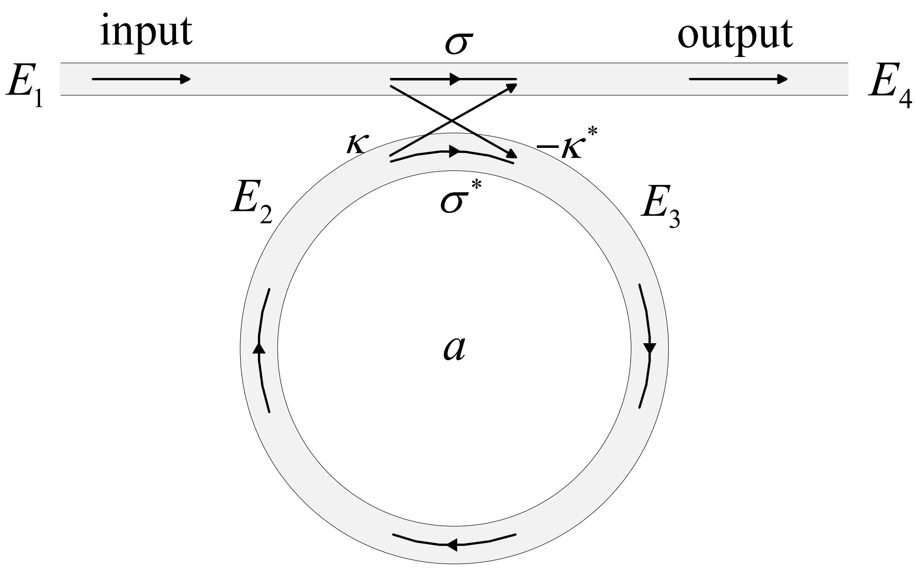


- Index and Loss Changes

$$\Delta n_{1.31\mu m} = -6.2\times 10^{-22}\,\Delta n_e - 6.0\times 10^{-18}\,(\Delta n_h)^{0.8}$$

$$\Delta \alpha_{1.31\mu m} = 6.0\times 10^{-18}\,\Delta n_e + 4.0\times 10^{-18}\,\Delta n_h\ [cm^{-1}]$$

Optical Modeling - Optical Dynamics



$$T(t)=\frac{E_4(t)}{E_1}=\sigma+\frac{-\kappa^*\kappa}{\sigma^*}\sum_{n=1}^{\infty}\left\{\left[\sigma^* a(t)\right]^n\cdot\exp\left[j\left(\sum_{m=1}^{n}\Phi(t-m\tau)\right)\right]\right\}$$

$$T(t)=\sigma+\frac{-\kappa^*\kappa}{\sigma^*}\sum_{n=1}^{\infty}\left\{\left[\sigma^* a(t)\right]^n\cdot\exp\left[jn\Phi(t)\right]\right\}$$

$$=\frac{\sigma-a(t)\cdot\exp\left[j(\Phi(t))\right]}{1-\sigma^* a(t)\cdot\exp\left[j(\Phi(t))\right]}$$

where $\Phi(t)=\frac{2\pi}{\lambda}n_{eff}(t)L$

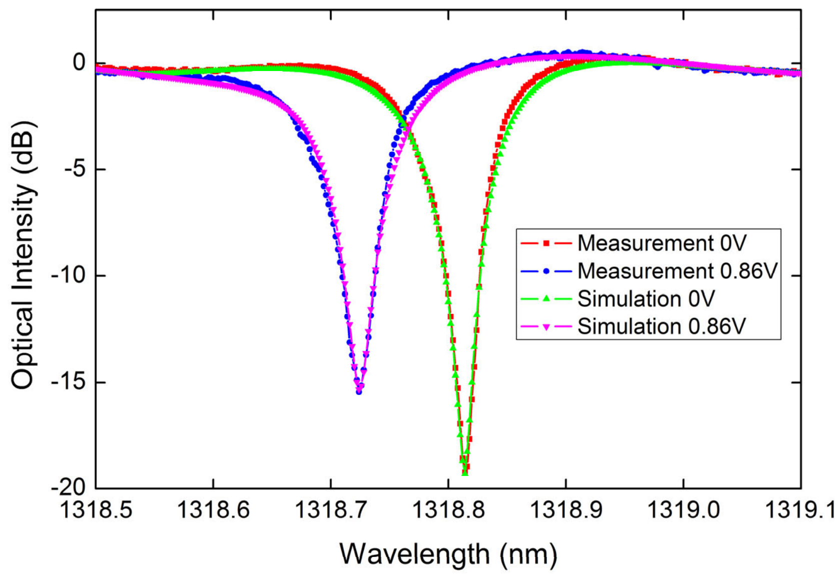
$$\sigma^2+\kappa^2=1$$

[Loannidis OL 1988]

- Consider the ring's cumulative phase shift
- Capture non-linear optical dynamics

Optical Modeling - Optical Dynamics

- Parameter Extraction

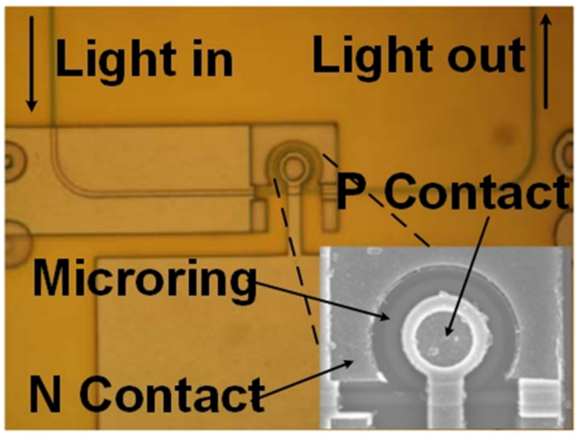


Parameter	Unit	Description	Value
σ	-	Transmission coefficient	0.9944
a	-	Loss coefficient	0.9931
n_{eff}	-	Effective index	2.5188
r	μm	Ring radius	5

- Large extinction ratio (ER) ~20dB
- High modulation efficiency ~560pm/V

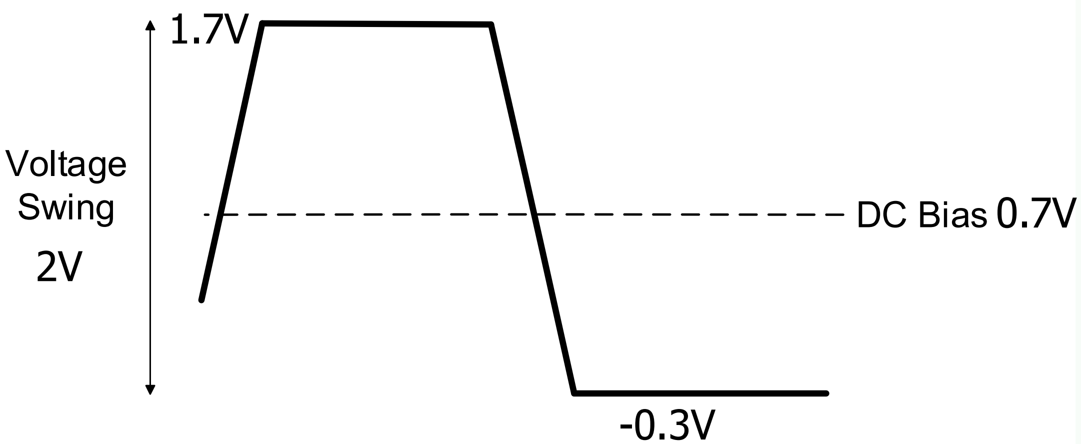
Simple NRZ Signaling

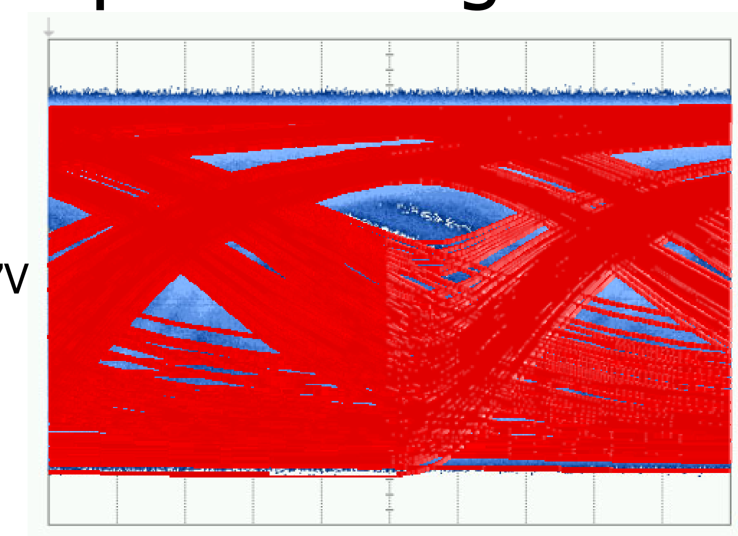
- Ring modulator under test



Parameter	Description
Coupling waveguide	350nm (W), 250nm (H), 50nm (slab)
Ring waveguide	450nm (W), 250nm (H), 50nm (slab)
Gap	250nm
Radius	5um
P+ doping	BF^{2+}, 5e14 cm^{-2}, 10 KeV, Tilt 8°, Twist 27°
N+ doping	As, 5e14 cm^{-2}, 10 KeV, Tilt 8°, Twist 27°

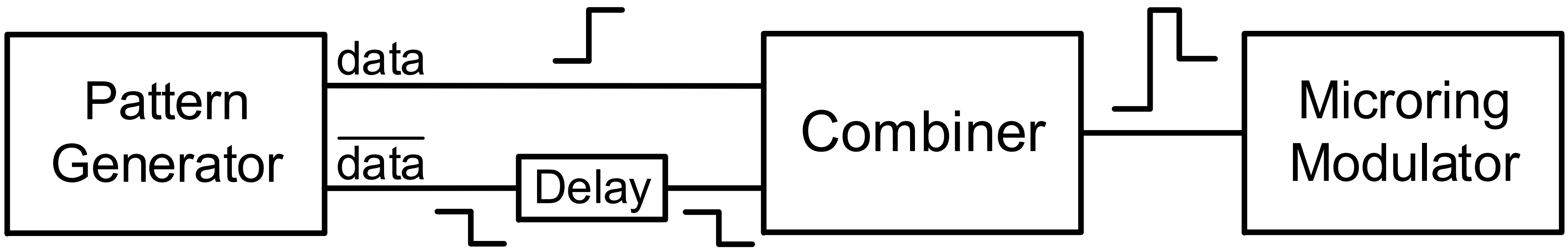
- 8Gb/s eye diagrams with simple NRZ signal





Pre-Emphasis Signaling

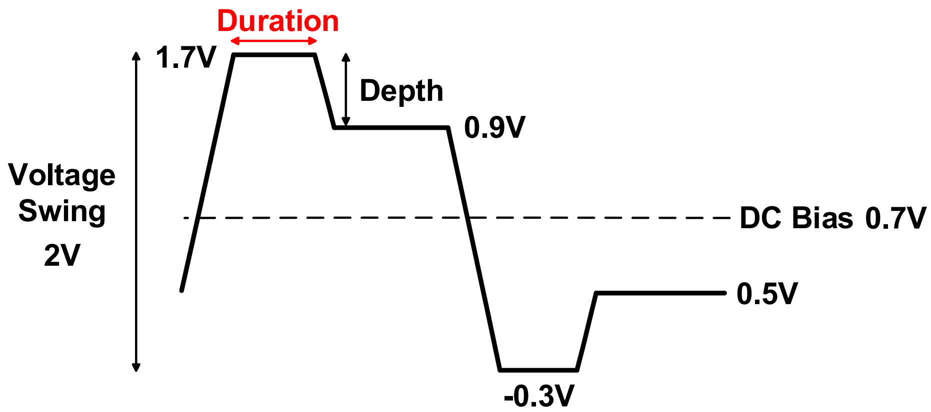
- Pre-emphasis NRZ signal generation



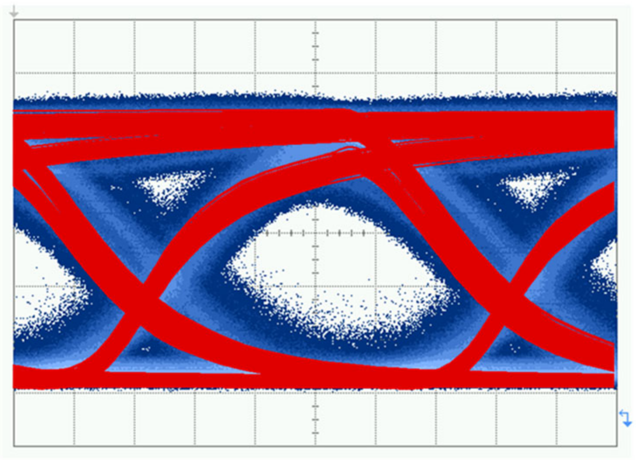
- Proposed model utilized to study the impact of key pre-emphasis parameters
  - Pulse duration
  - Pulse depth
  - DC bias

Pre-Emphasis Optimization - Duration

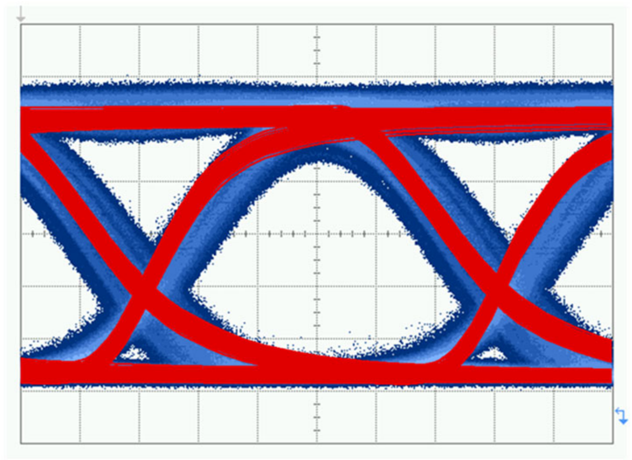
- Pulse Duration
- Pulse Depth = 0.8V
- DC Bias = 0.7V



40ps



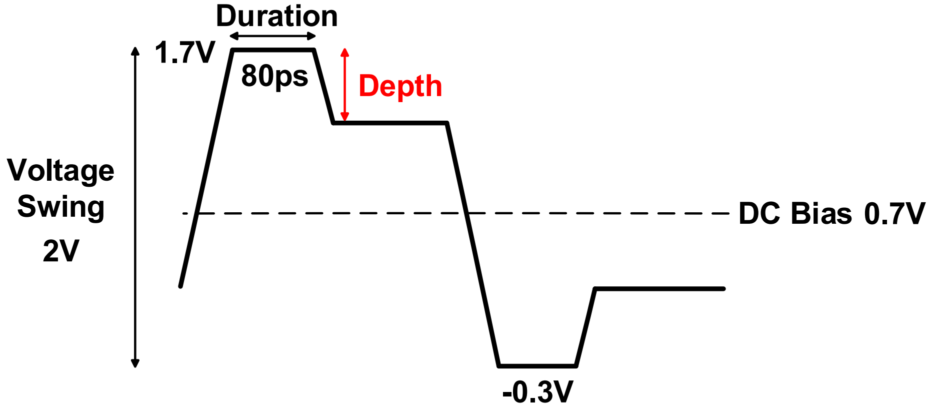
80ps



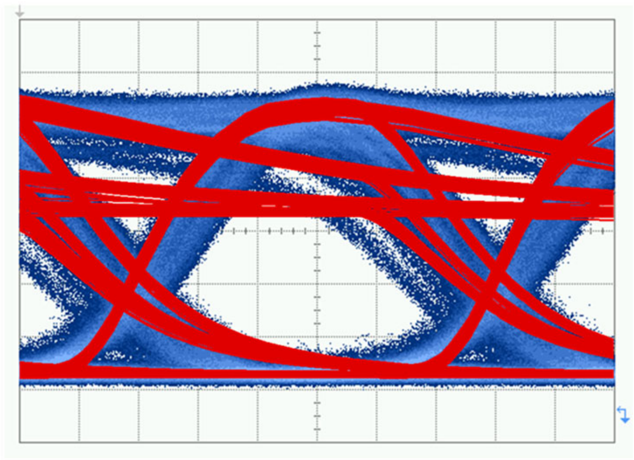
- 40ps pulse duration allows the eye to partially open
- 80ps pulse duration provides optimal eye opening

Pre-Emphasis Optimization - Depth

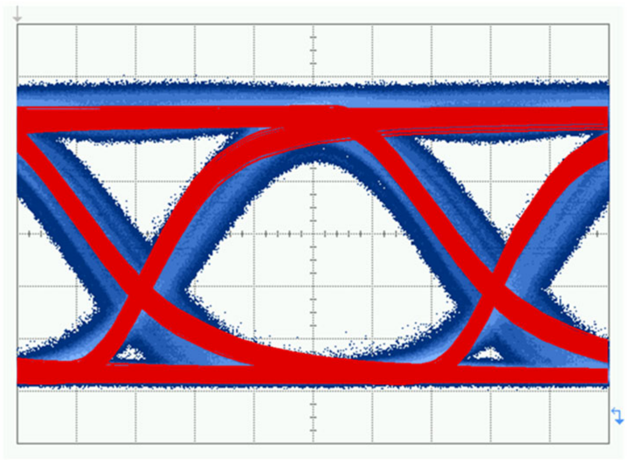
- Pulse Duration = 80ps
- Pulse Depth
- DC Bias = 0.7V



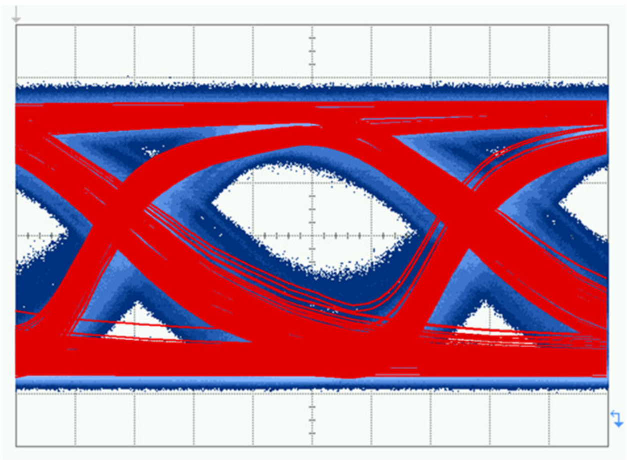
0.9V



0.8V



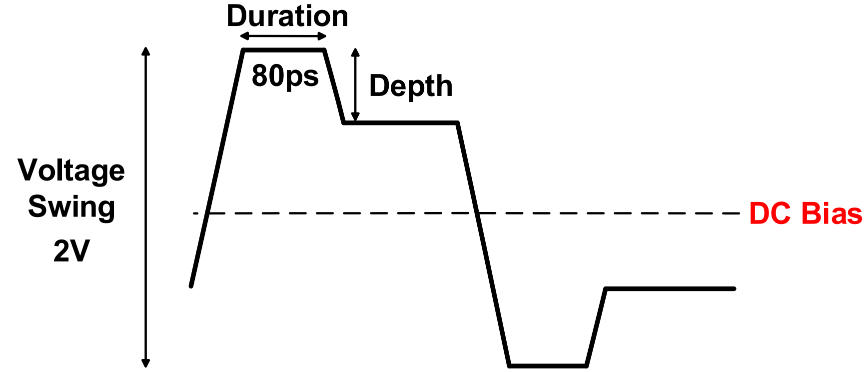
0.7V



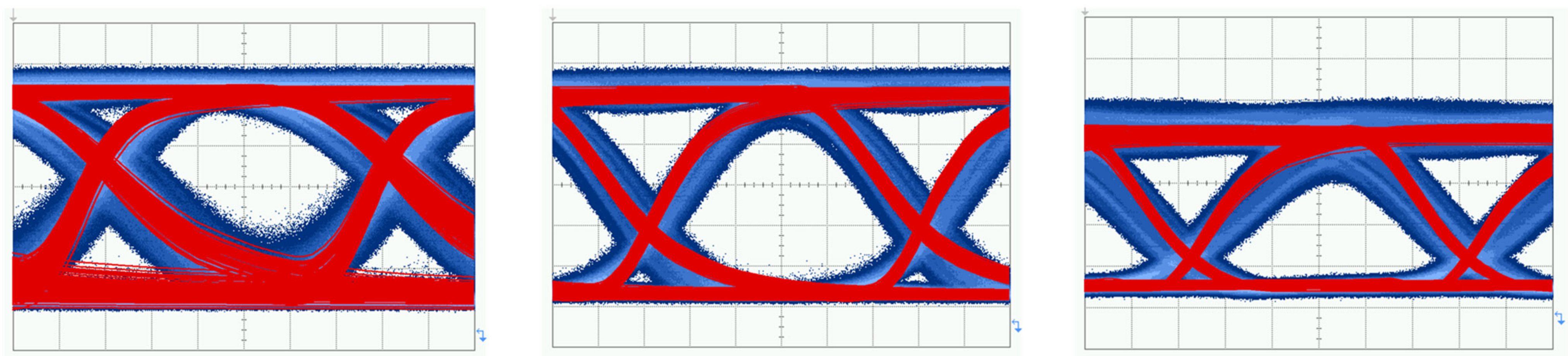
- 0.9V pulse depth results in low amount of charge for logic "1"
- 0.7V pulse depth produces excessive charge for logic "1"

Pre-Emphasis Optimization - DC Bias

- Pulse Duration = 80ps
- Pulse Depth = 0.8 V
- DC Bias

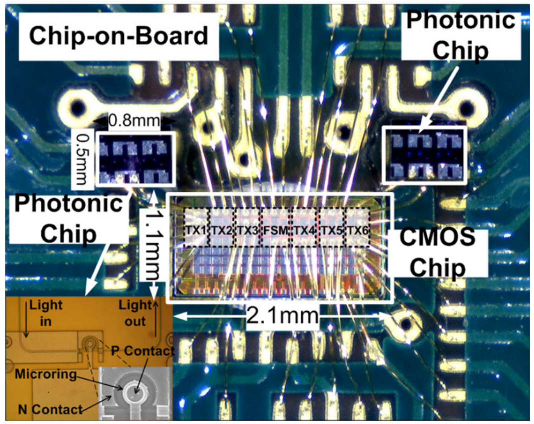


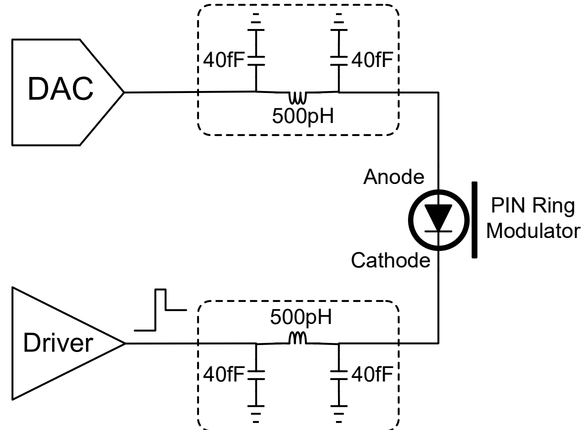
0.75V 0.7V 0.65V

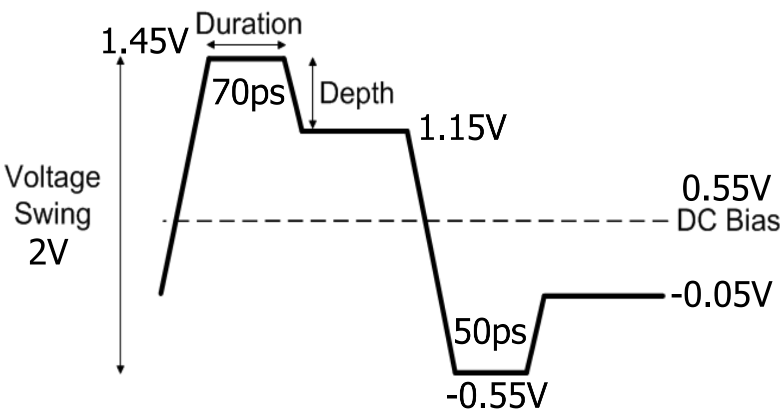


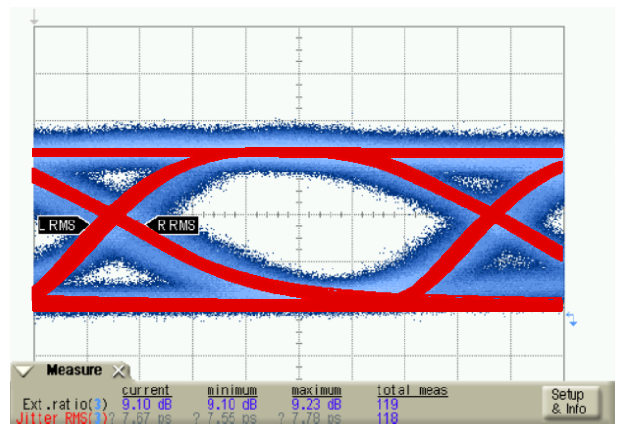
- 0.75V DC bias produces excessive charge for logic “1”
- 0.65V DC bias results in slower carrier injection for logic “1”

Co-Simulation with CMOS Driver



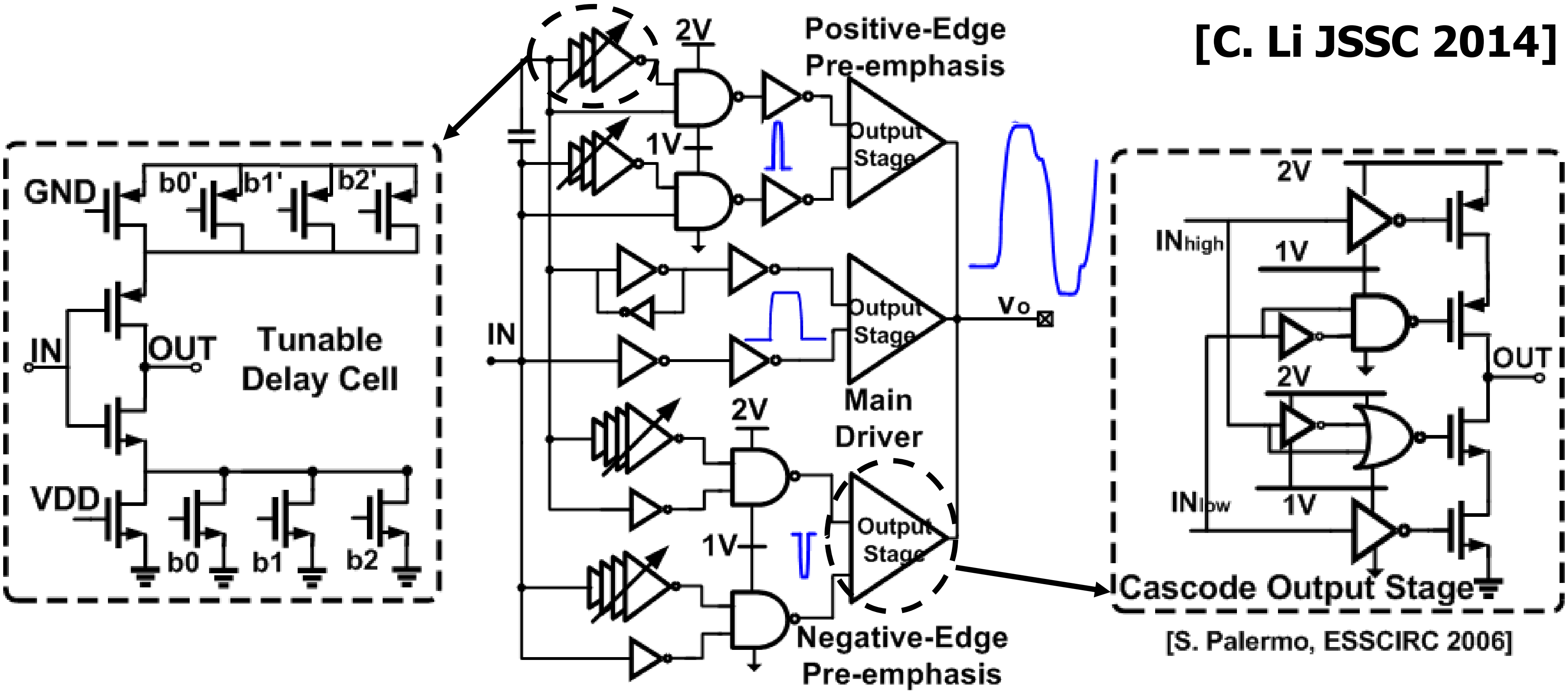






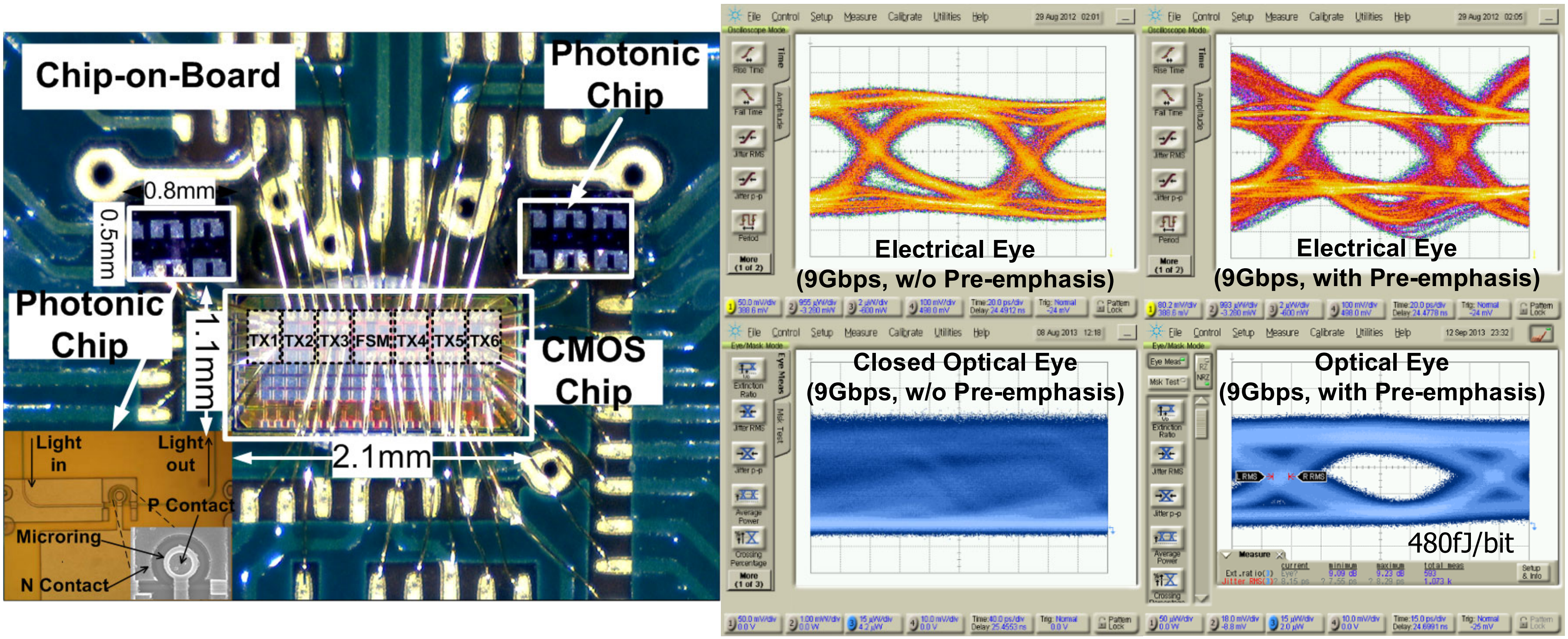
- Hybrid-integrated CMOS and silicon photonics prototype
- Optical transmitter co-simulation schematic
- Asymmetric pulse duration pre-emphasis setting
- 9Gb/s measured and co-simulated eye diagrams

High-Swing Pre-Emphasis Driver



- Dual-edge pre-emphasis with pulse width controlled by tunable delay cells (30ps~60ps)
- Cascode output stage used to meet high modulation swing requirement

Optical Transmitter Assembly

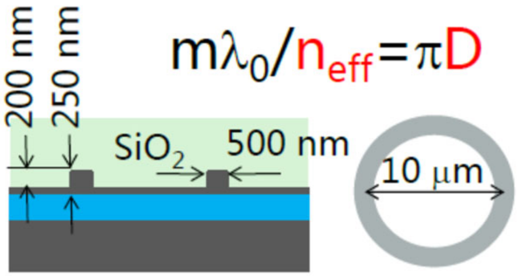


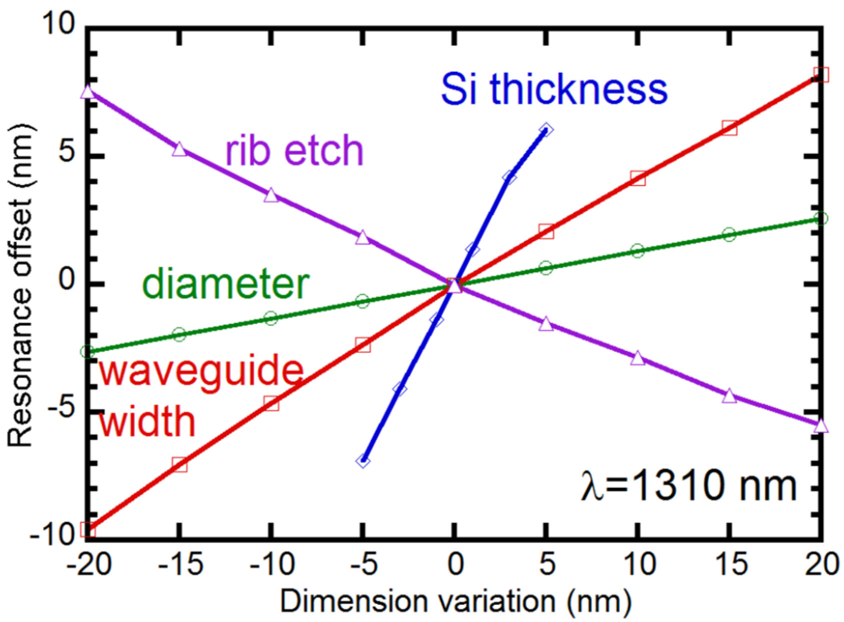
* C. Li et. al. IEEE Design & Test, 2014

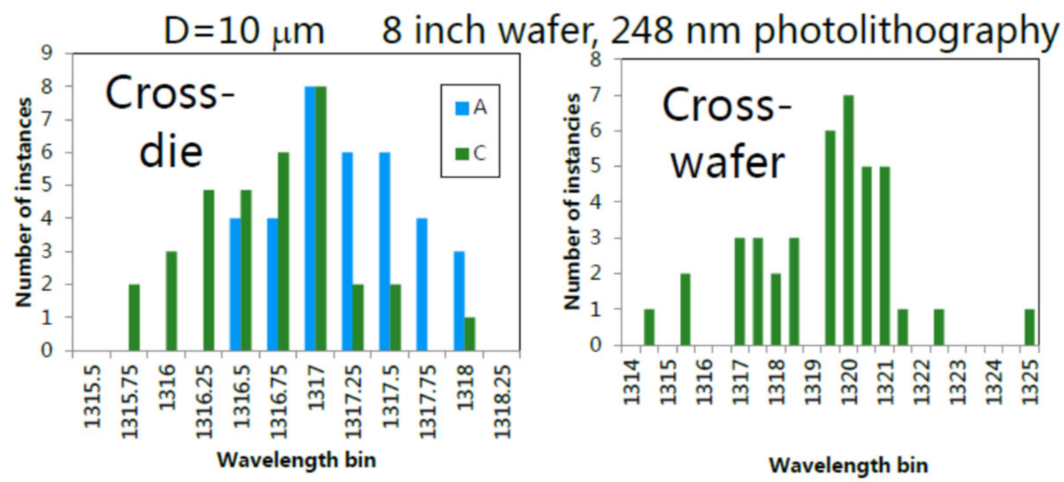
- GP 65nm CMOS 5-channel TX prototype
- 130nm SOI carrier-injection ring resonator modulators

Resonant Wavelength Sensitivity

$m\lambda_0/n_{eff}=\pi D$







Mask A λ_{res}=1317.6 ± 0.4 nm

Mask C λ_{res}=1317.0 ± 0.5 nm

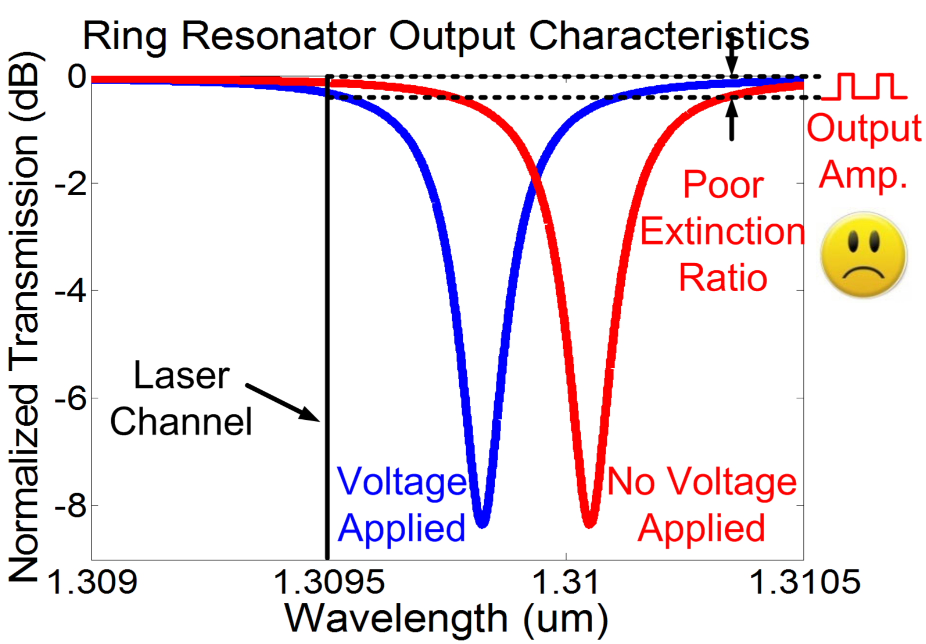
Mask C λ_{res}=1319 ± 2 nm

Zheng, GFP, 2010.

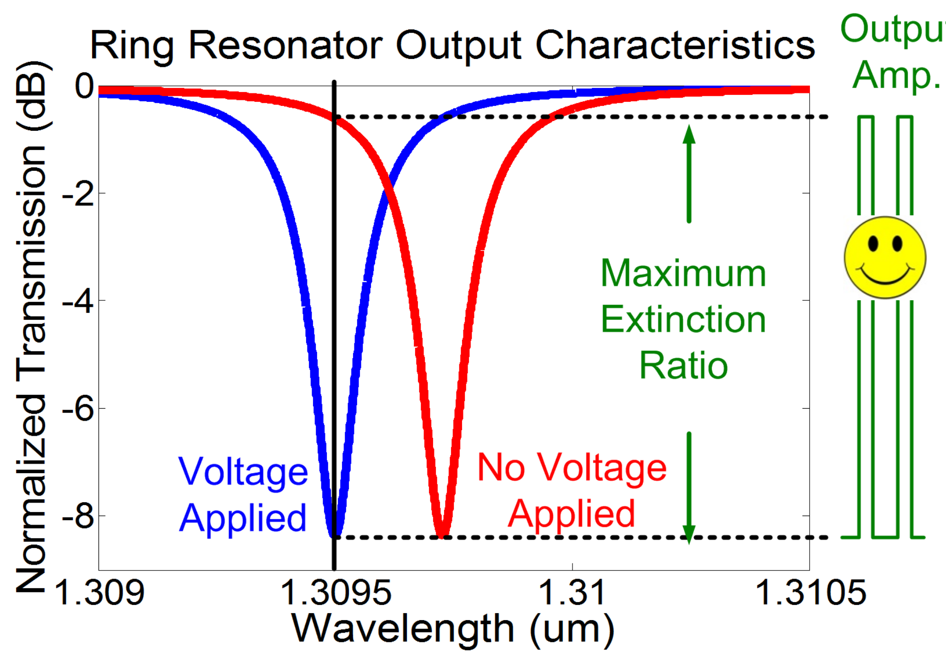
- Ring's resonance wavelength is sensitive to fabrication variations and temperature fluctuations
- Requires tuning schemes to compensate wavelength drifts

Extinction Ratio Impact

- Ring devices resonance wavelength can shift with fabrication and temperature variations
- Tuning schemes necessary to stabilize resonance wavelength

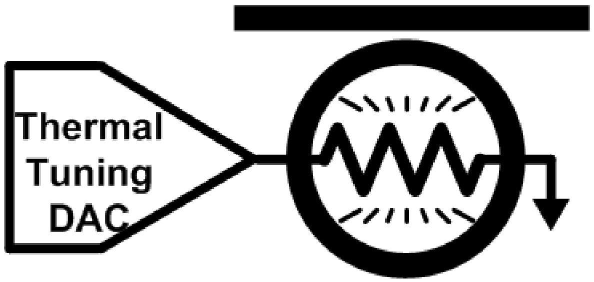


Before Tuning



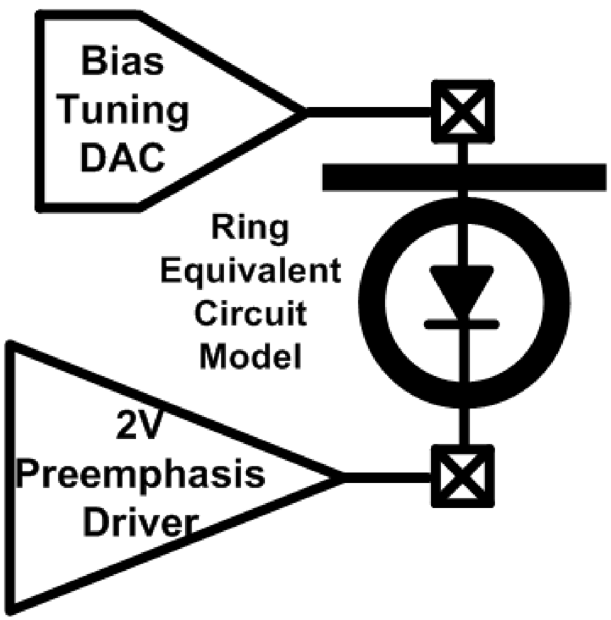
After Tuning

Bias vs Thermal Tuning



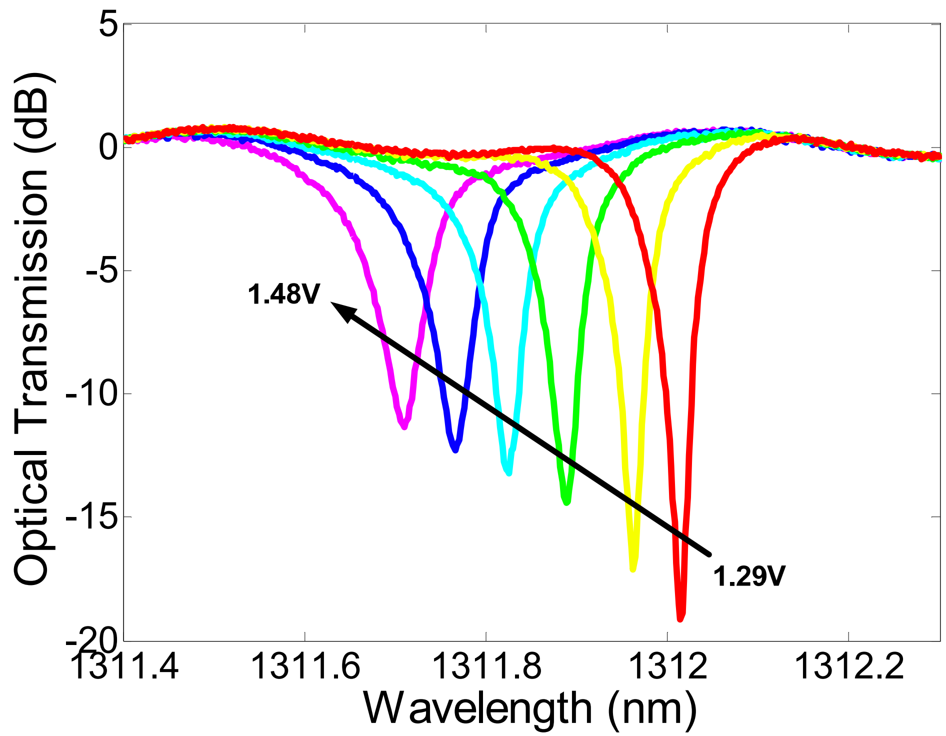
Thermal Tuning

	Bias Tuning	Thermal Tuning
Speed	Fast (~μs) 🙂	Slow (~ms) 🙁
Direction	Blue shift	Red shift
Power	Low 🙂	High 🙁
Range	Narrow 🙁	Wide 🙂

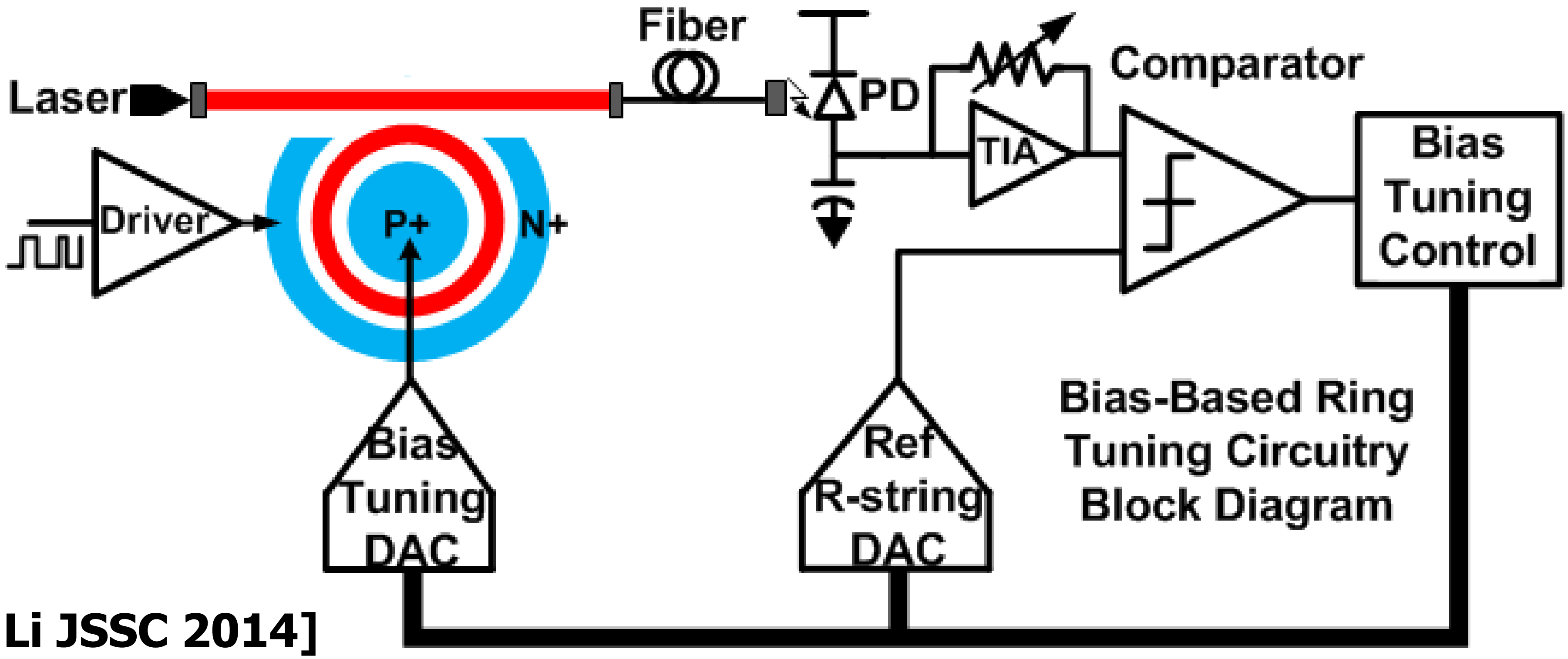


Bias Tuning

Ring Spectrum vs Bias Voltage



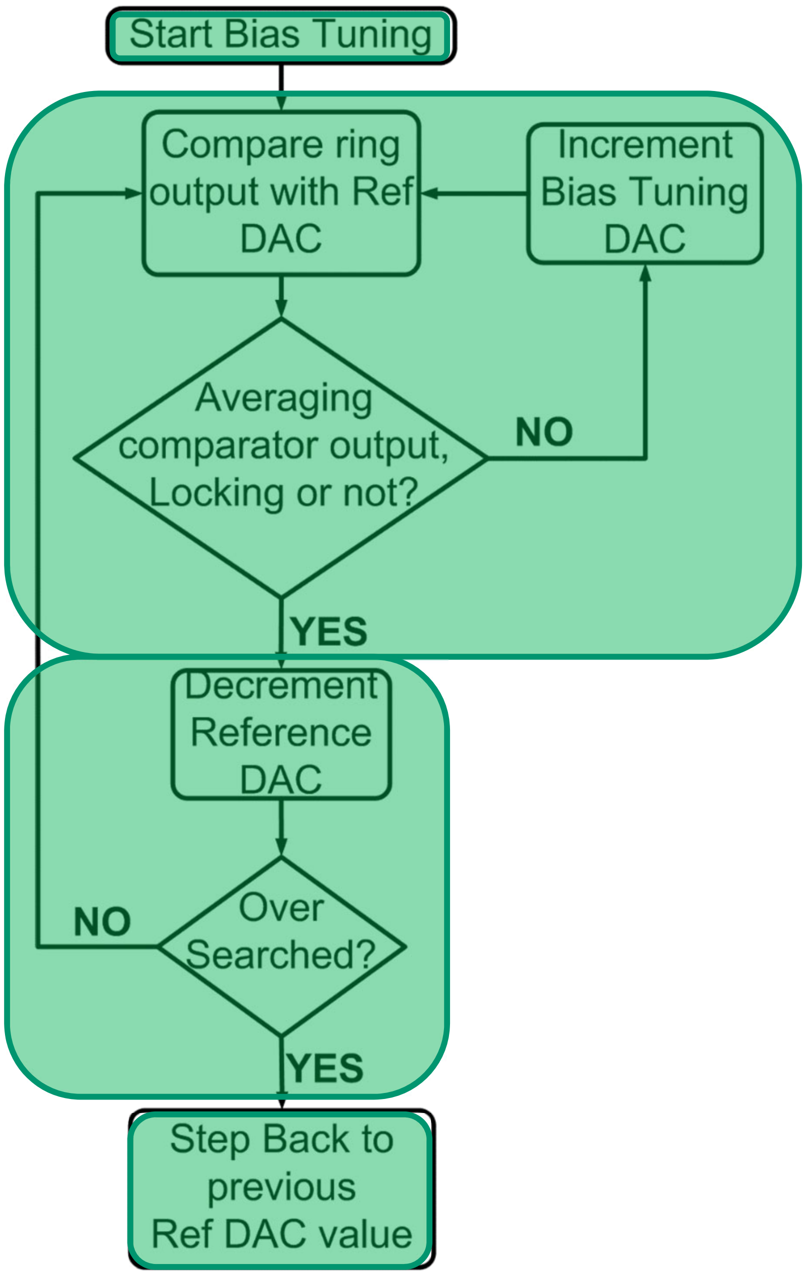
Automatic Tuning Loop

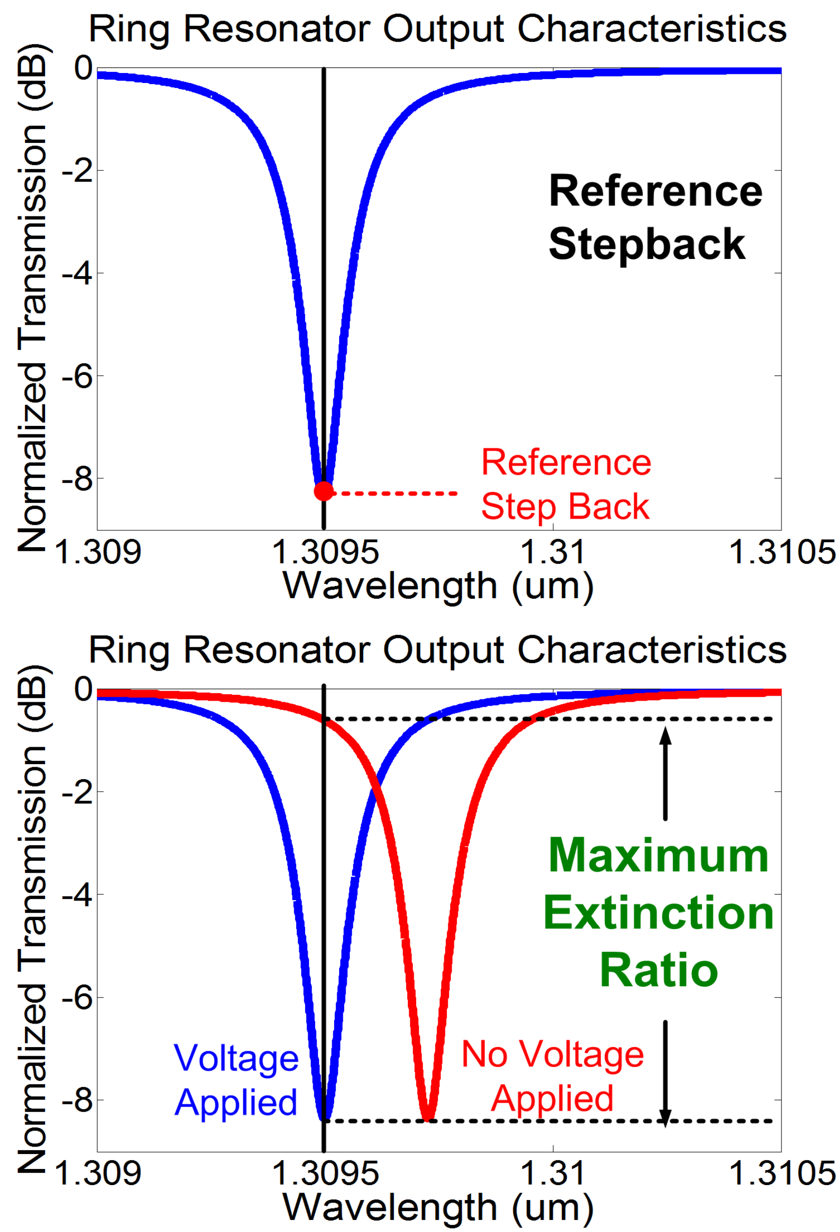


[C. Li JSSC 2014]

- Automatic tuning loop sets ring output power to a DAC-generated reference level corresponding to the ring's resonance point
- Also applicable for thermal tuning

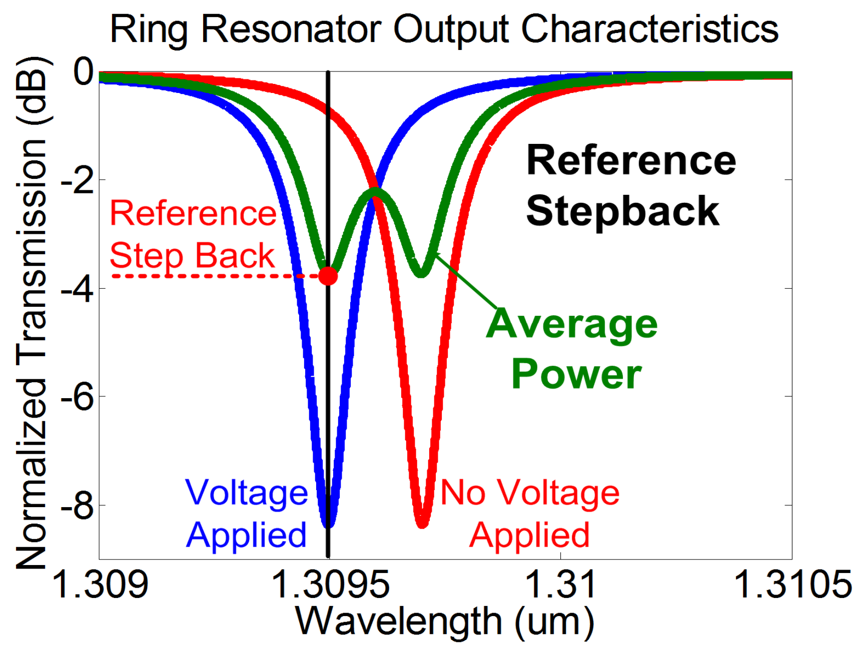
Static Tuning Mode

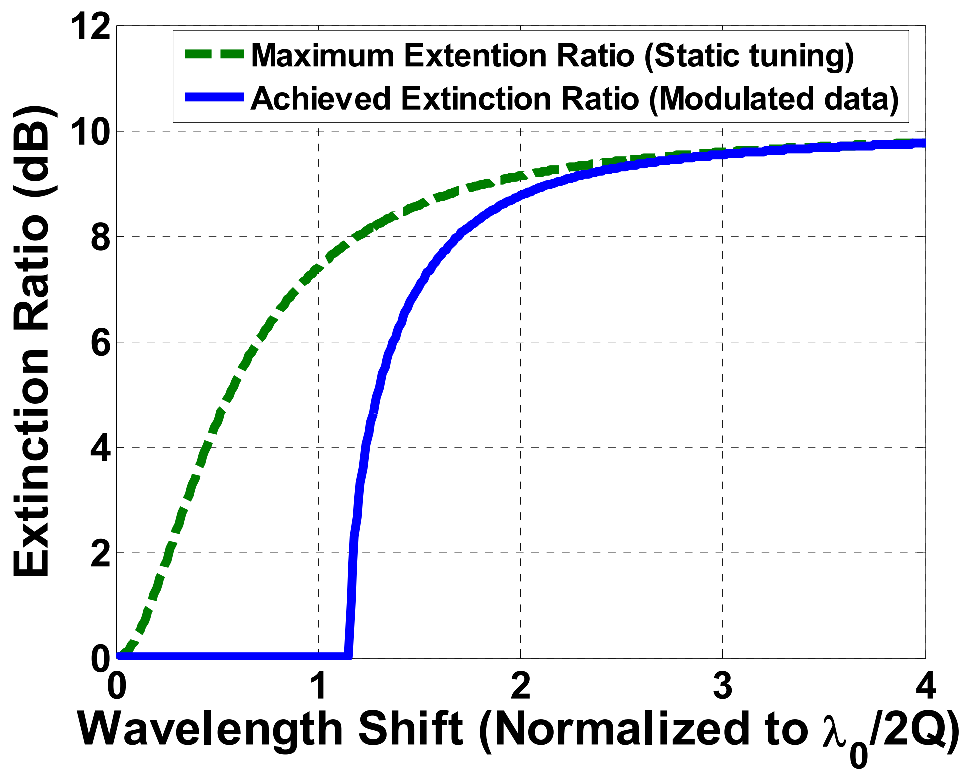


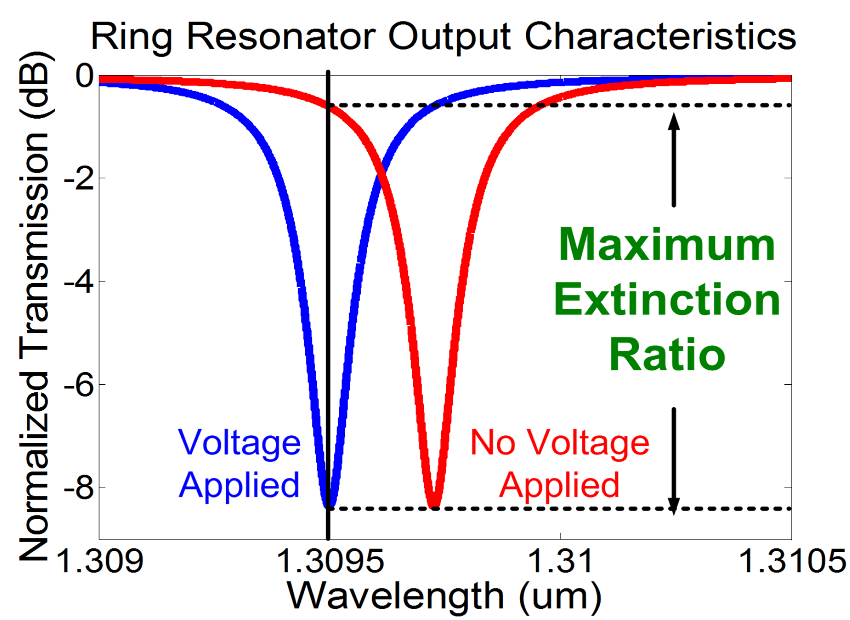


Dynamic Tuning Mode

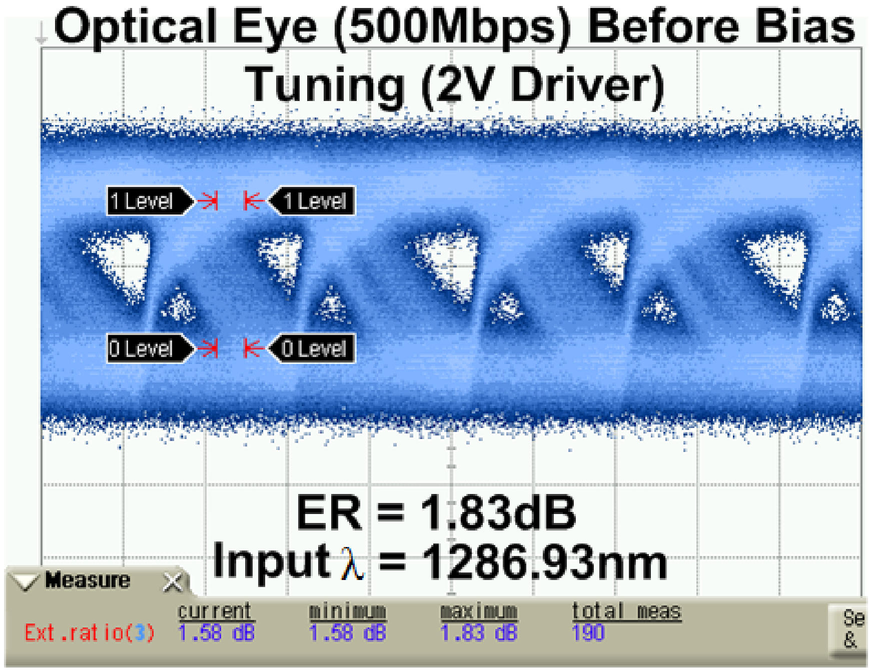
- Lock to average power
- $\Delta \lambda_{shift} \geq FWHM$ to guarantee ER

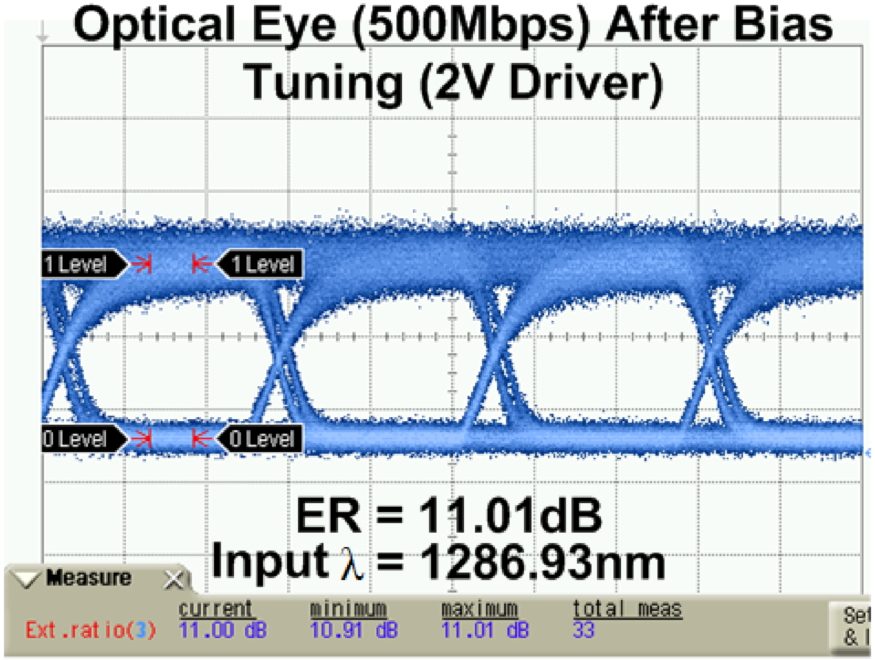






Bias-Based Tuning Measurements





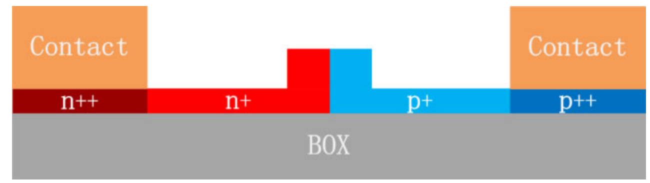
- Extinction ratio dramatically improved after bias-based tuning
- 340μW for a tuning range of 0.28nm

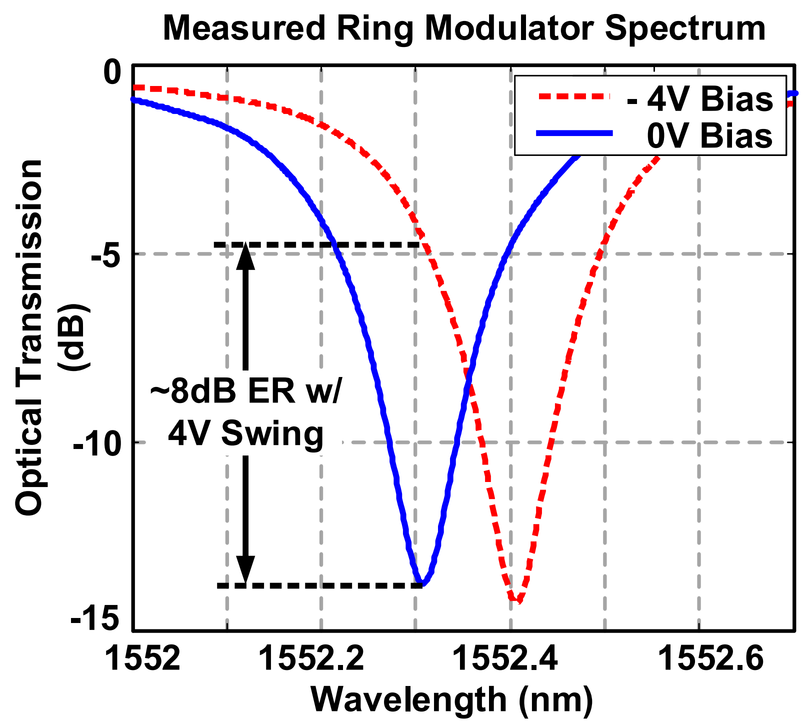
Agenda

- WDM Optical Interconnect Motivation
- Silicon Photonic Modulators
- Carrier-Injection Ring Resonator Modulators
- Carrier-Depletion Ring Resonator Modulators
    - Device Operation and Modeling
    - High-Speed Driver
    - Wavelength Stabilization Loop

Carrier-Depletion Ring Modulator Challenge I: Output Swing & Biasing

	ISSCC 2013	This Work
Ring Type	Injection	Depletion
Doping Profile	PIN	Lateral PN
Q	8000	5000
Tunability (pm/V)	350	25
Data Rate	9Gb/s	25Gb/s
Swing for >7dB ER	< $2V_{pp}$	> $4V_{pp}$

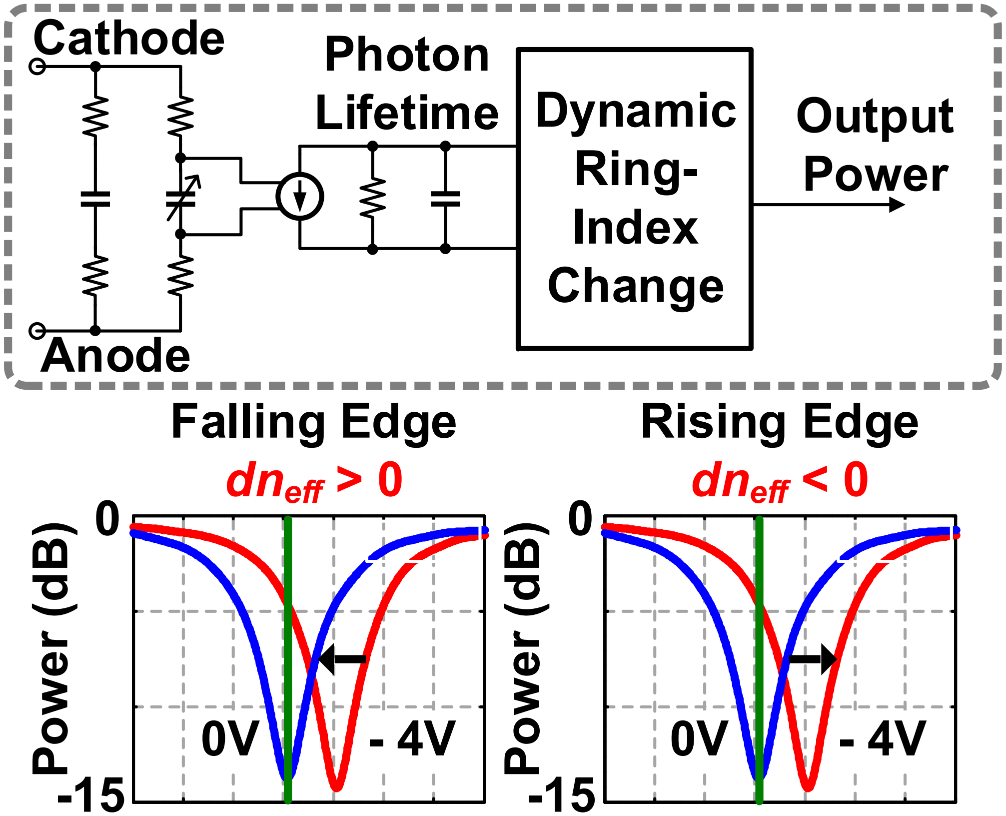




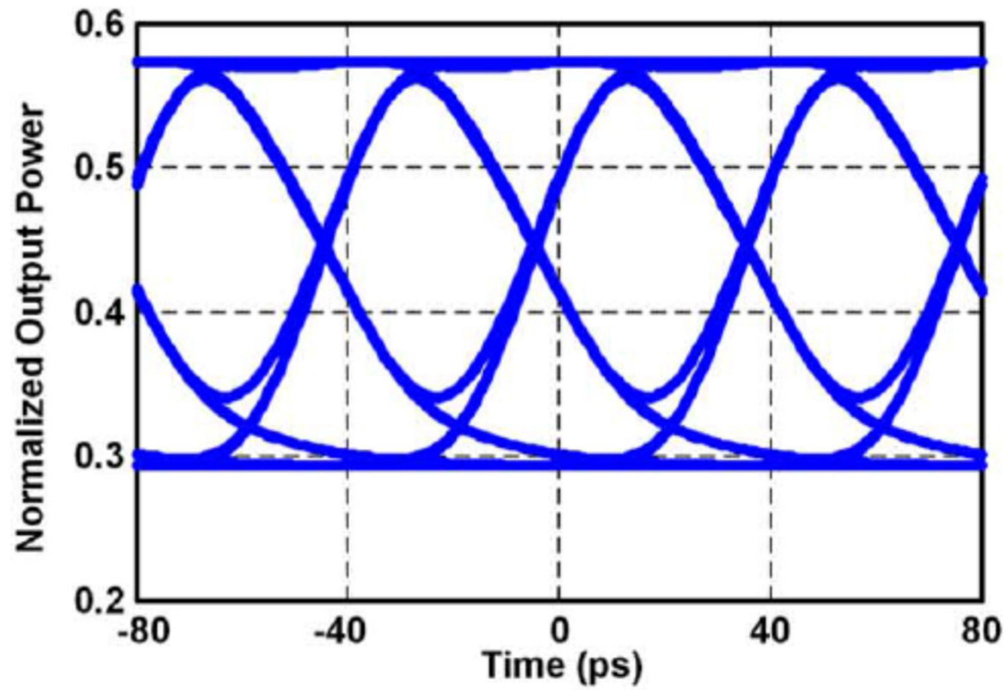
- High-speed depletion-mode ring modulator requires:
  - Large swing: >4V
  - Negative DC-bias: -2V

Carrier-Depletion Ring Modulator Challenge II: Nonlinear Dynamics

Depletion Ring E-O Model



Simulated 25Gb/s Optical Eye Diagram



- Dynamic change of n_{eff} → unequal rise/fall times
- Asymmetric equalization for non-linearity cancellation

Carrier-Depletion Ring Modulator Modeling

- Previous Related Modeling Work
  - Ring resonator model (only optical dynamics) [Smy JOSA B 2011]
  - Carrier-depletion ring modulator model (lack electrical dynamics) [Zhang JSTQE 2010, Buckwalter JSSC 2012, Ban OIC 2015]

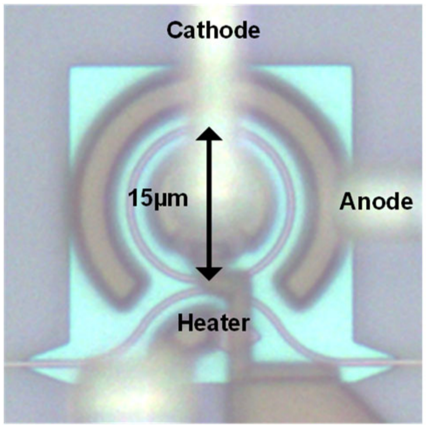
- Carrier-Depletion Ring Modulator Model
  - Capture nonlinear electrical and optical dynamics

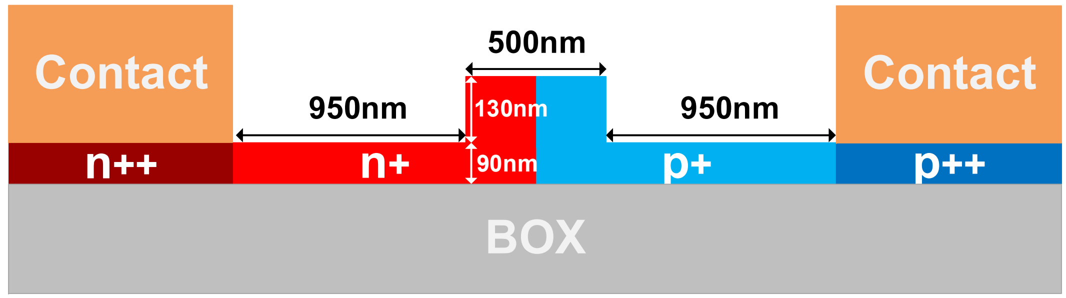
[Ashkan Roashan-Zamir, **Binhao Wang,** Shashank Telaprolu, Kunzhi Yu, Cheng Li, M. Ashkan Seyedi, Marco Fiorentino, Raymond Beausoleil, and Samuel Palermo, "A 40Gb/s PAM4 Silicon Microring Resonator Modulator Transmitter in 65nm CMOS," accepted in IEEE Optical Interconnects Conference (OIC), 2016]

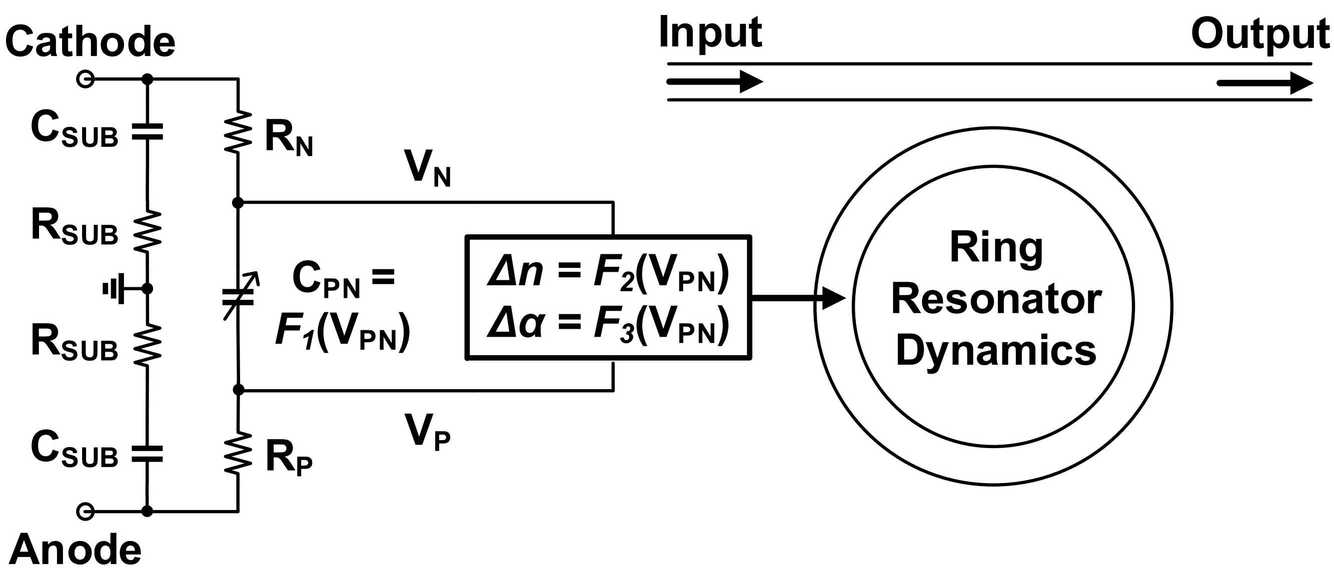
[Hao Li, Zhe Xuan, Cheng Li, Alex Titriku, Kunzhi Yu, **Binhao Wang**, Nan Qi, Ayman Shafik, Marco Fiorentino, Michael Hochberg, Samuel Palermo, and Patrick Yin Chiang, "A 25Gb/s, 4.4V Swing, AC-Coupled Ring Modulator-Based WDM Transmitter with Wavelength Stabilization in 65nm CMOS," IEEE Journal of Solid-State Circuits (JSSC), 50, 3145-3159, 2015]

[Hao Li, Zhe Xuan, Cheng Li, Alex Titriku, Kunzhi Yu, **Binhao Wang**, Nan Qi, Ayman Shafik, Marco Fiorentino, Michael Hochberg, Samuel Palermo, and Patrick Yin Chiang, "A 25Gb/s, 4.4V Swing, AC-Coupled, Si-Photonic Microring Transmitter with 2-Tap Asymmetric FFE and Dynamic Thermal Tuning in 65nm CMOS," IEEE International Solid-State Circuits Conference (ISSCC), 2015]

Carrier-Depletion Ring Modulator Model

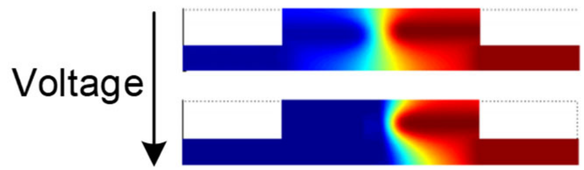


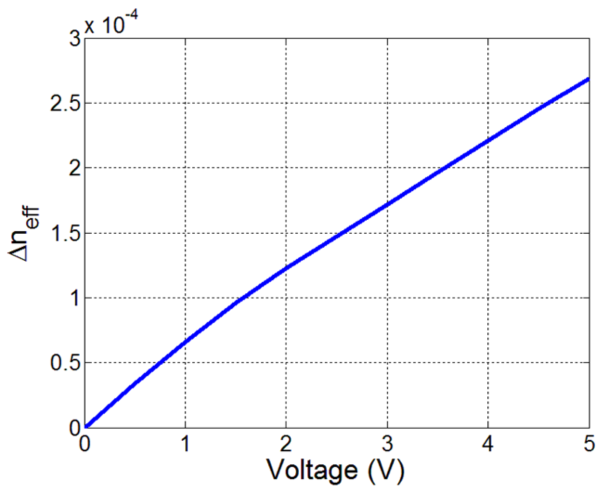


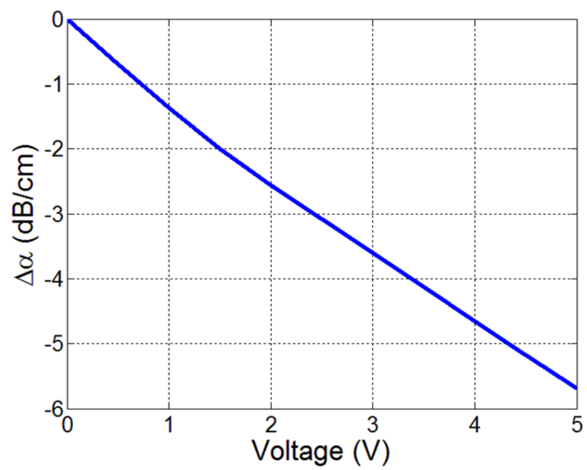


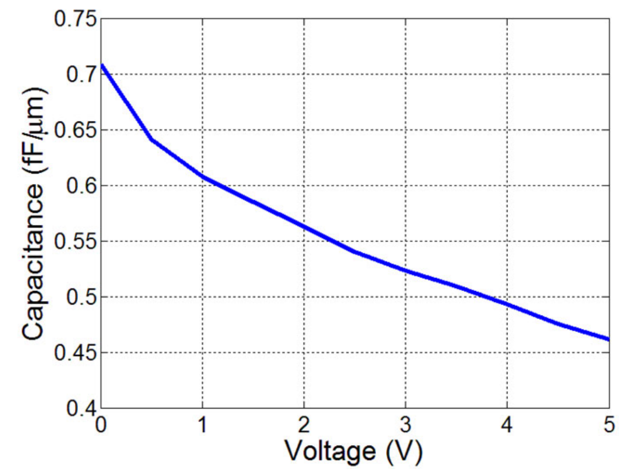
Electrical Modeling - Parameter Extraction

- Lumerical







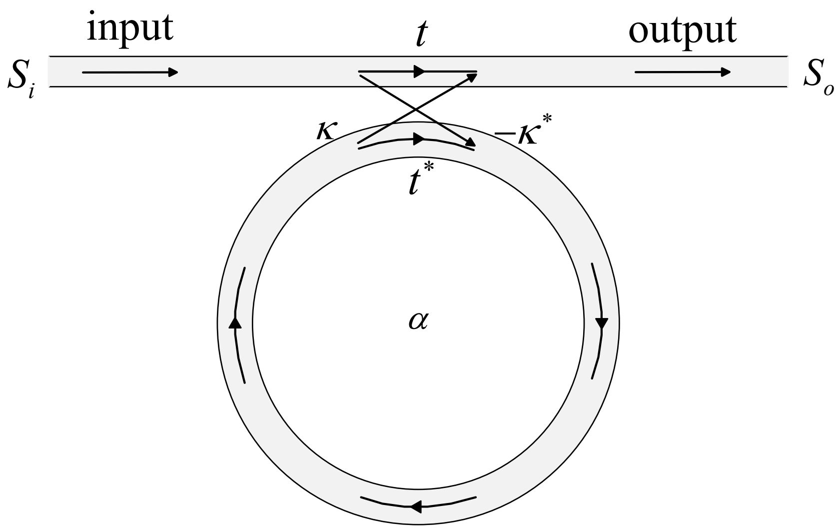


- Polynomial Curve Fitting

$$f\left(V\right) = a_0 + a_1 V + a_2 V^2 + a_3 V^3 + a_4 V^4$$

Parameter	Unit	a_0	a_1	a_2	a_3	a_4
Δn_{eff}	-	-4.3×10^{-7}	7.3×10^{-5}	8.0×10^{-6}	1.1×10^{-6}	5.2×10^{-8}
$\Delta\alpha$	dB/cm	0.01	1.5	0.17	-2.3×10^{-2}	1.0×10^{-3}
C	fF/μm	0.71	-0.14	5.5×10^{-2}	-1.2×10^{-2}	1.0×10^{-3}

Optical Modeling - Optical Dynamics



$$\frac{\partial A}{\partial t} = \left(2\pi cj \left(\frac{1}{\lambda} - \frac{1}{\lambda_0} \right) - \frac{1}{\tau} \right) A + j\mu S_i$$

$$S_o = S_i + j\mu A$$

where $1/\tau = 1/\tau_c + 1/\tau_l$

$$\mu^2 = \kappa^2 v_g / 2\pi R = 2/\tau_c$$

$$\tau_l = 1 / \left(v_g e^{2\pi R(\alpha_0 + 0.75\Delta\alpha)} \right)$$

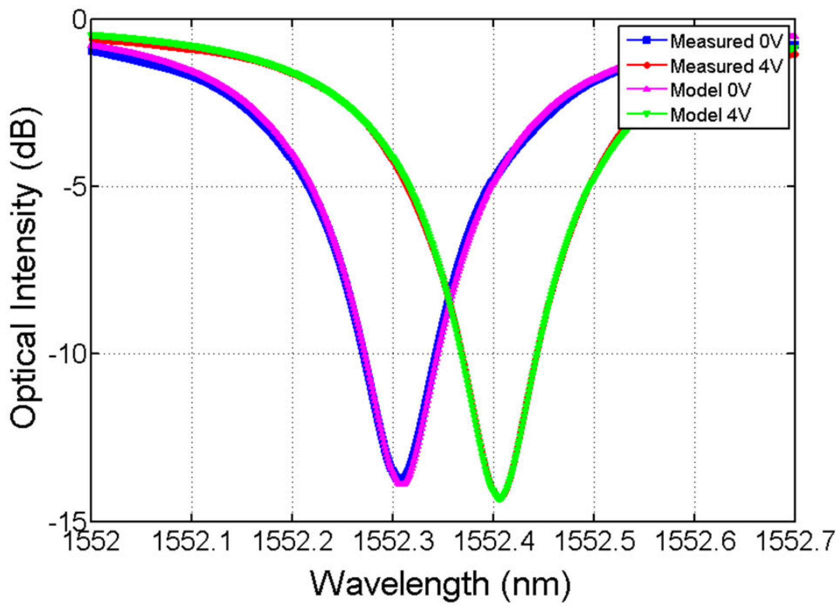
$$2\pi(n_0 + \Delta n) R = m\lambda_0$$

[Little JLT 1997]

- Capture non-linear optical dynamics
- Require less memory and computation time

Optical Modeling - Optical Dynamics

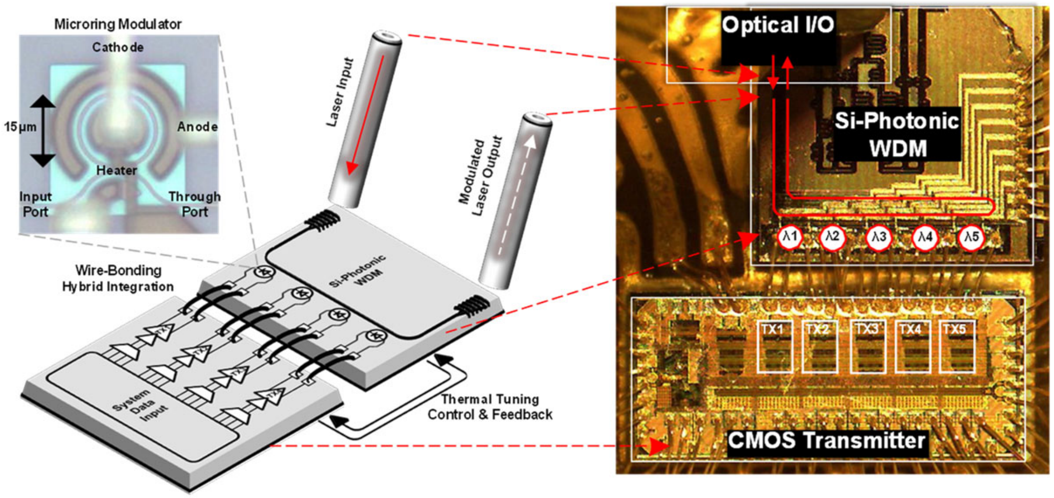
- Parameter Extraction

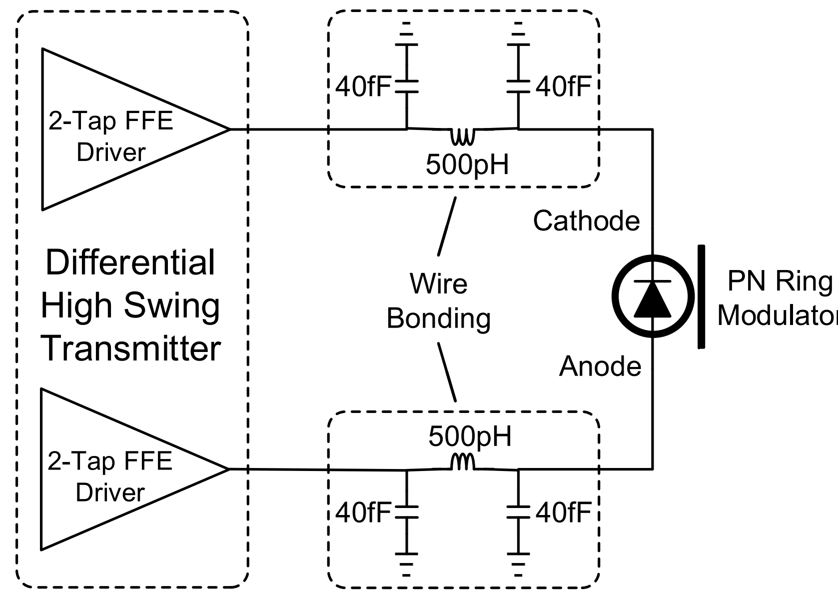


Parameter	Unit	Description	Value
τ	ps	Amplitude decay time	9.07
κ	-	Coupling ratio	0.188
m	-	Mode number	28
r	µm	Ring radius	7.5

- Extinction ratio (ER) ~10dB
- Modulation efficiency ~25pm/V

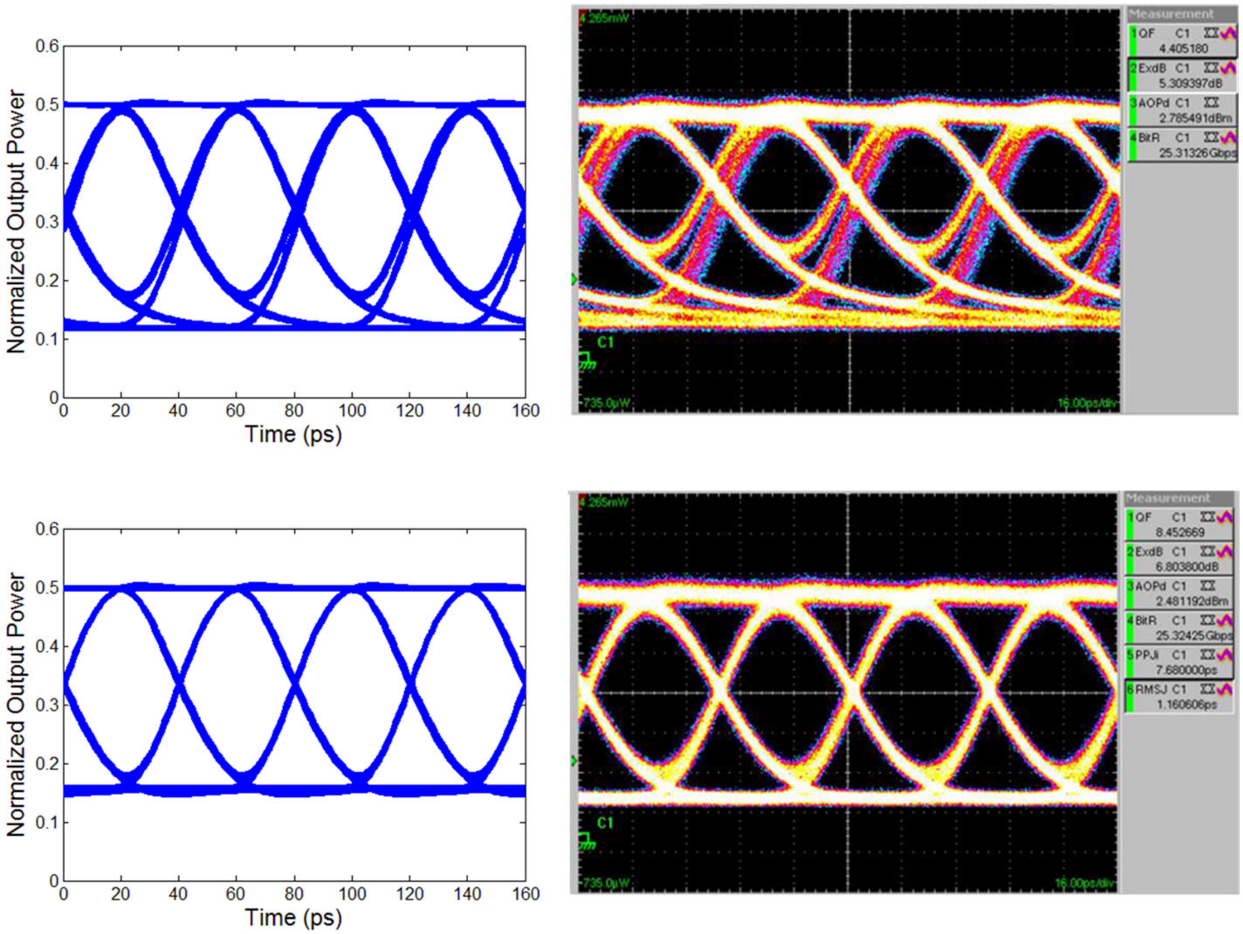
Co-Simulation with CMOS Driver





- Optical transmitter prototype assembly
- Optical transmitter co-simulation schematic

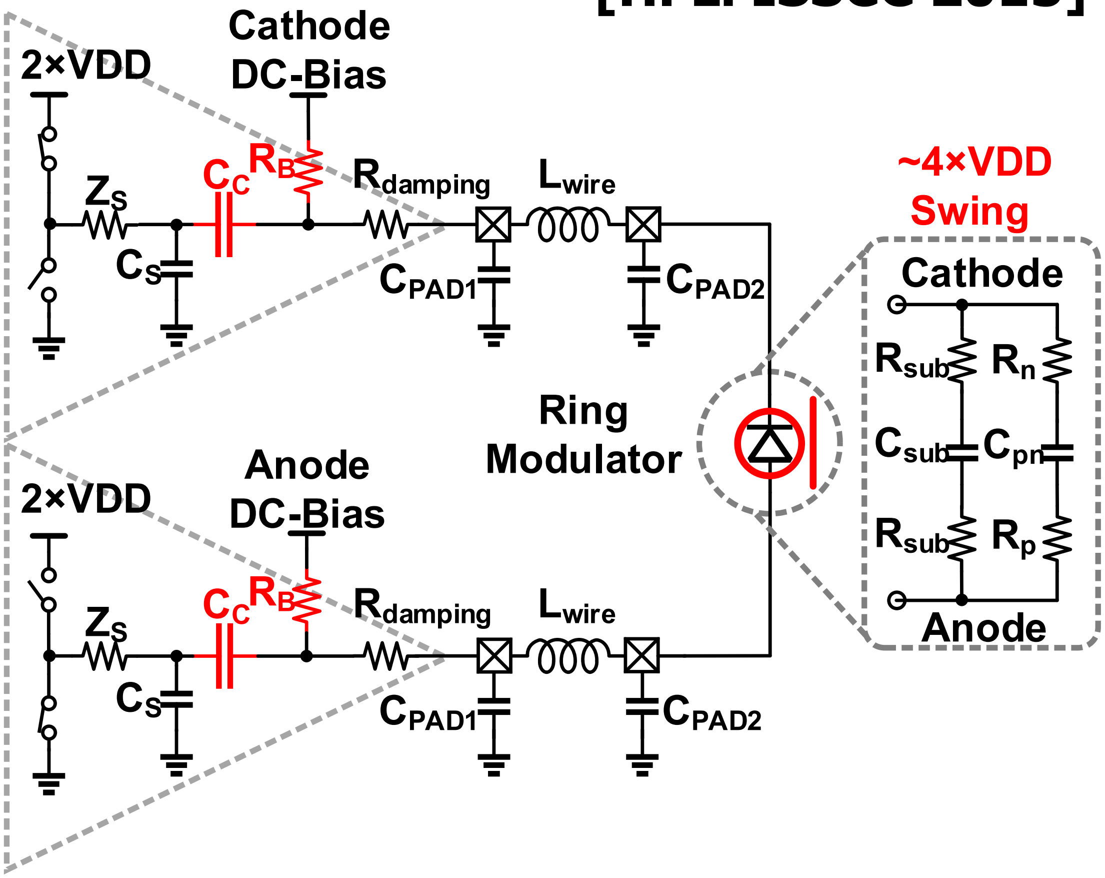
Measured and Co-Simulated 25Gb/s Eye Diagrams



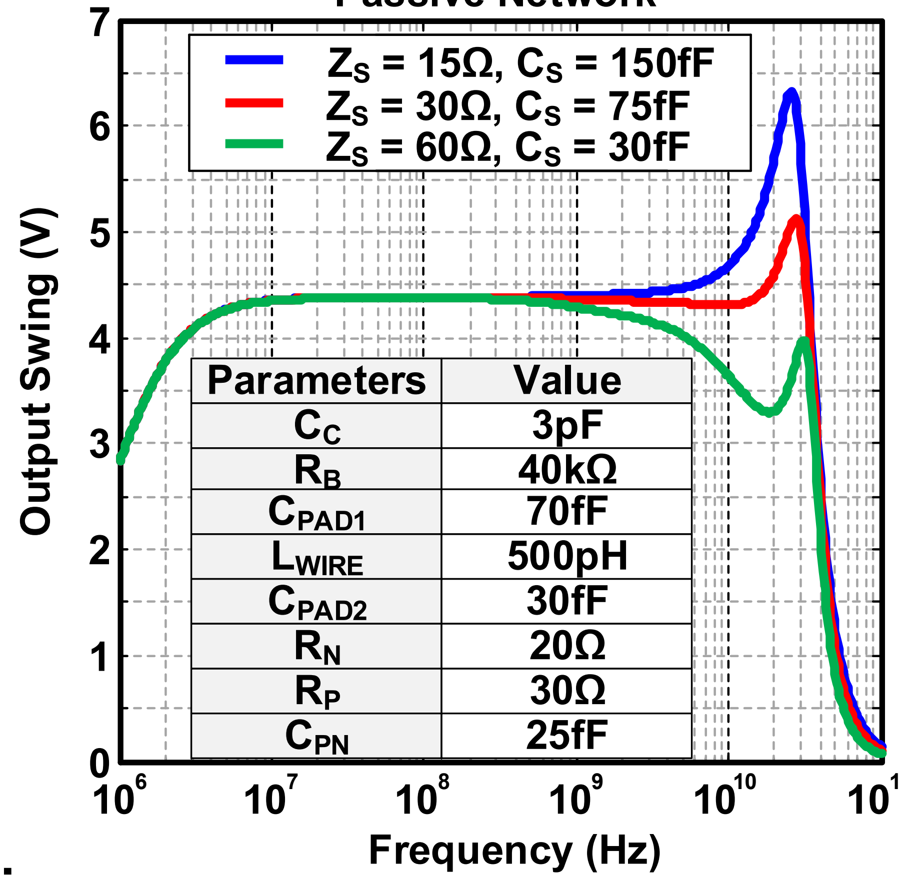
- Asymmetrical ISI is due to the device nonlinearity
- It is compensated by an optimized nonlinear equalizer

Proposed AC-Coupled Differential Driver

[H. Li ISSCC 2015]



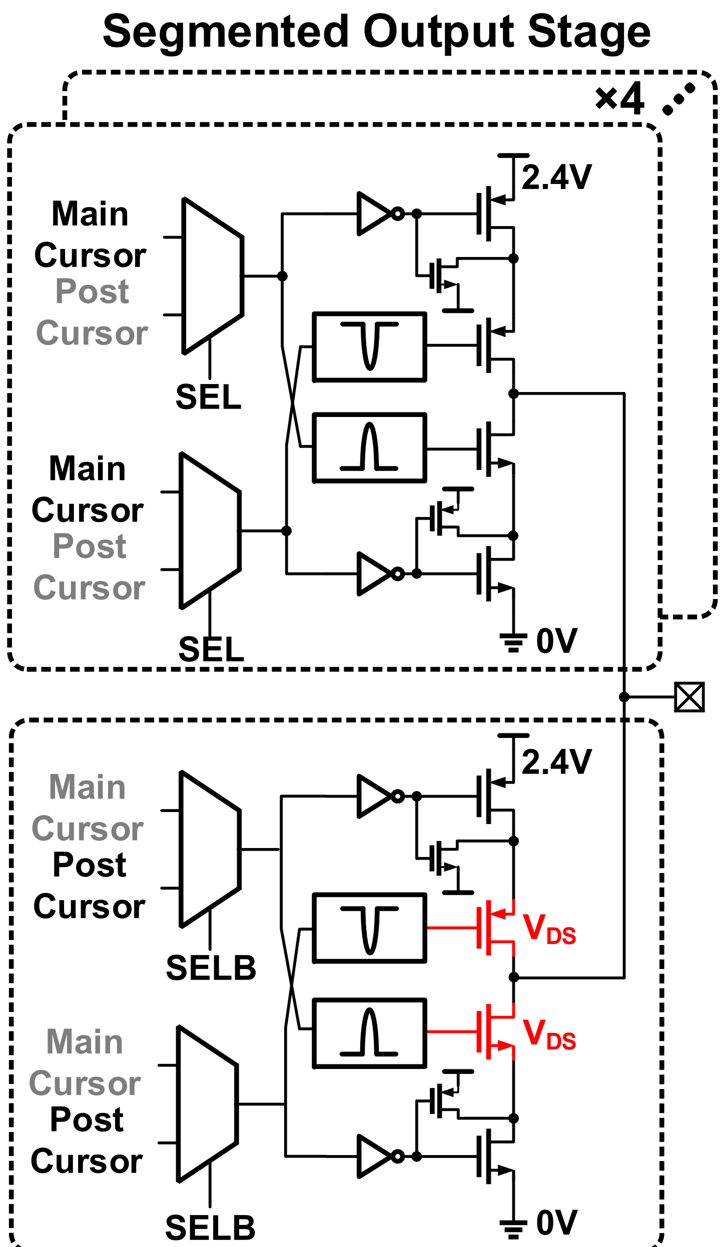
Simulated AC-Response of Output Passive Network



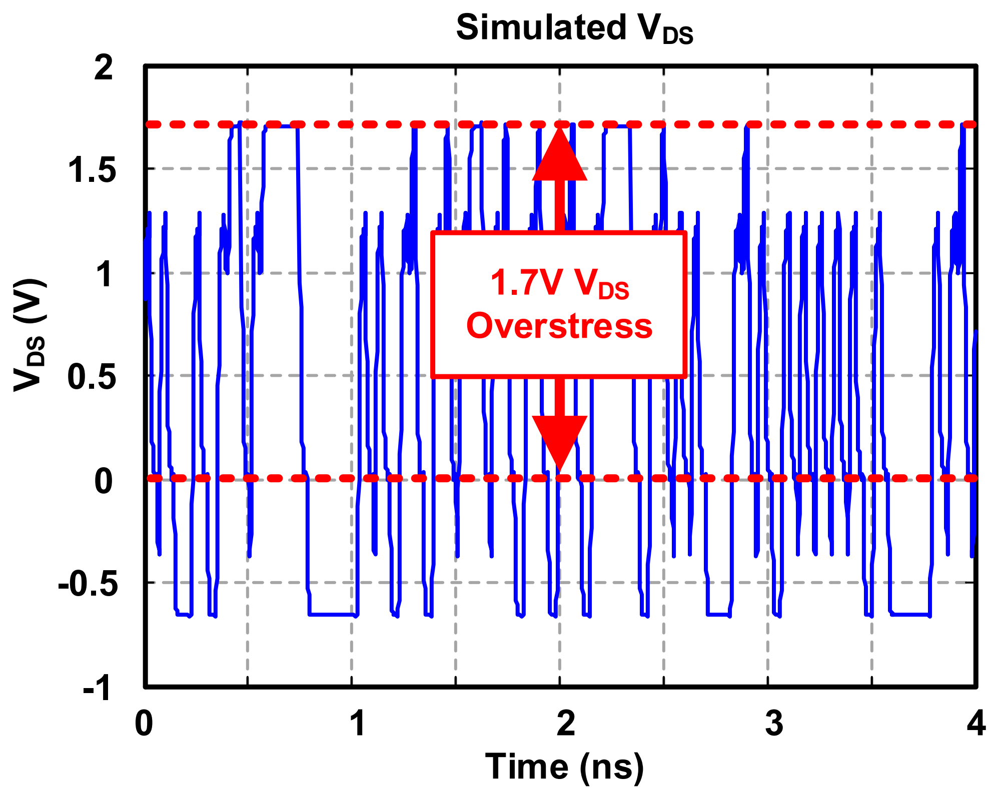
Parameters	Value
C_C	3pF
R_B	40kΩ
C_{PAD1}	70fF
L_{WIRE}	500pH
C_{PAD2}	30fF
R_N	20Ω
R_P	30Ω
C_{PN}	25fF

- C_C = 3pF → 4.4V differential swing
- Z_S < 30Ω to minimize low-pass attenuation
- High-pass cut-off: < 10MHz

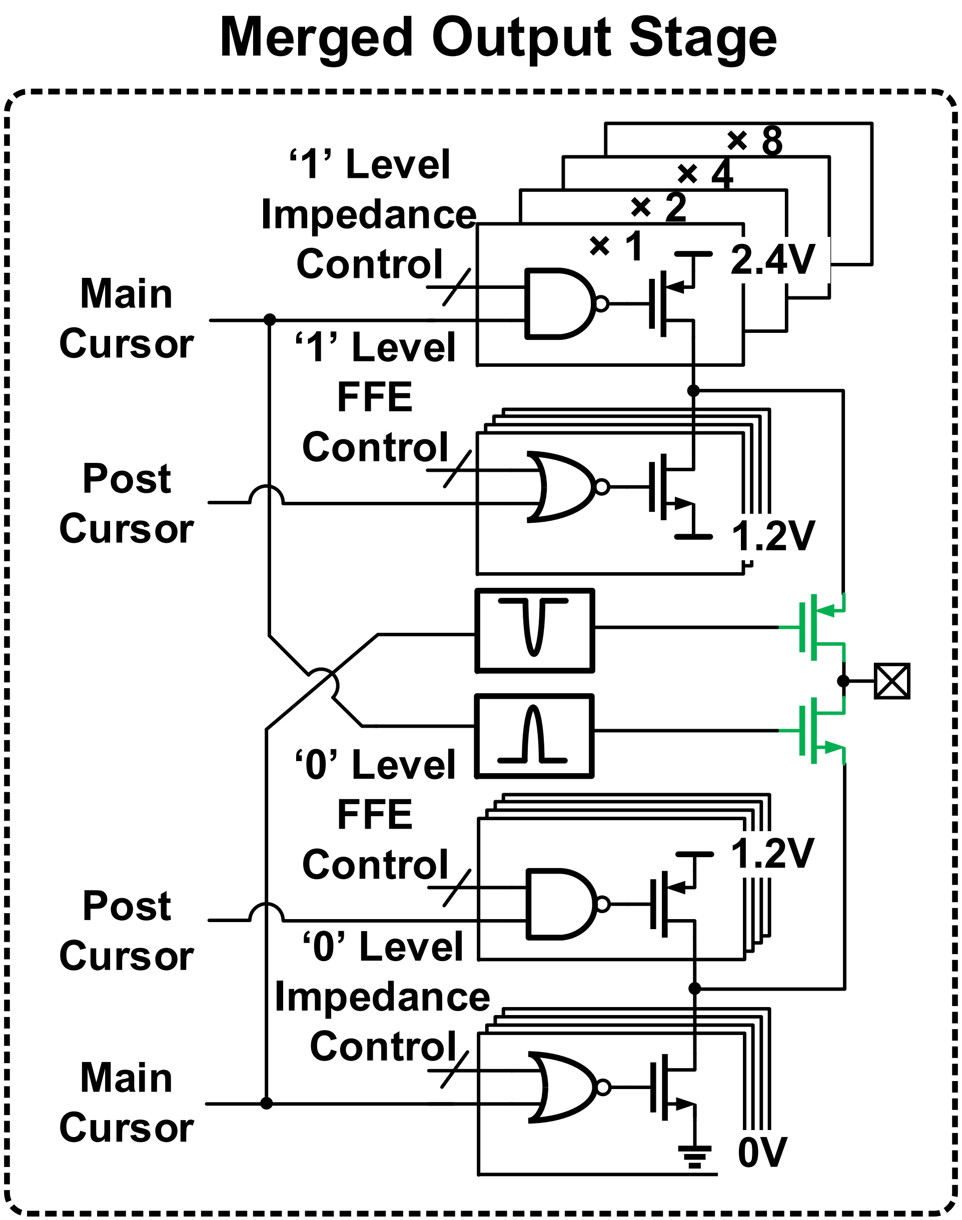
Conventional Segmented Output Driver



- Cascode transistors suffer V_{DS} overstress
- Large parasitic capacitance due to segmented design

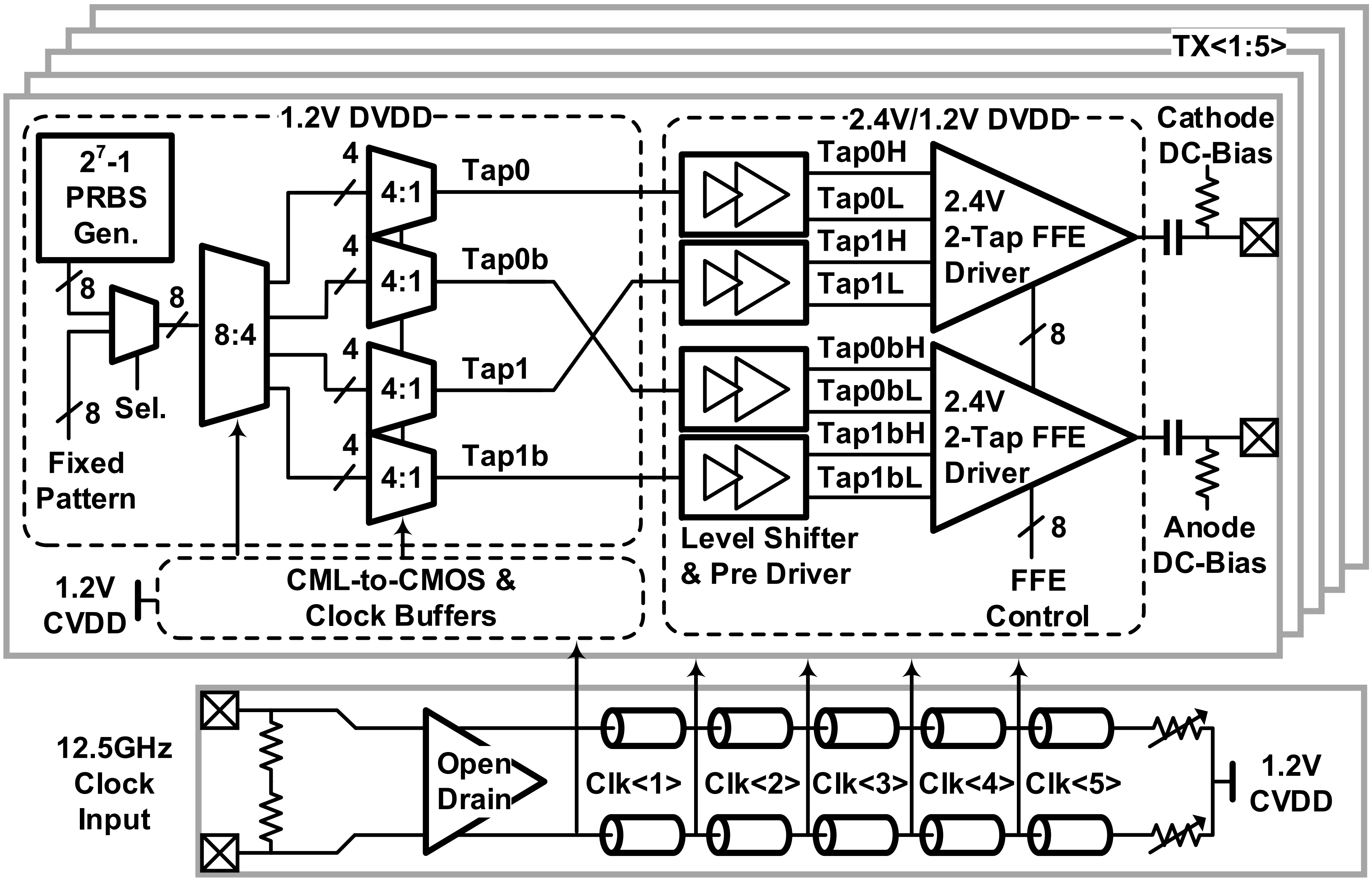


Proposed 2-Tap FFE Output Driver

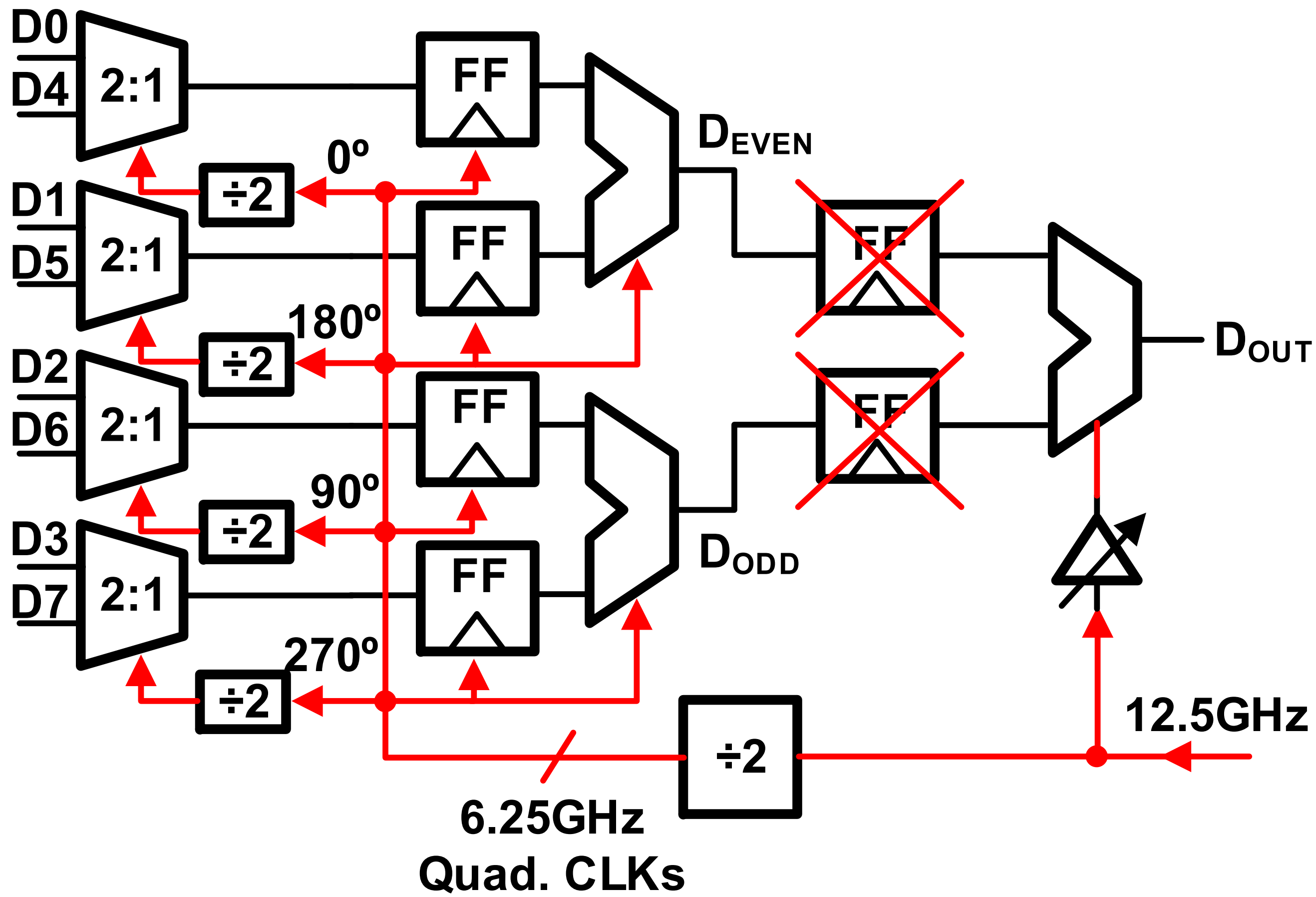


- Merged cascode transistors
- No V_{DS} overstress
- Reduced parasitics and area
- Independent '1'-Level and '0'-Level FFE coefficients

Transmitter Architecture

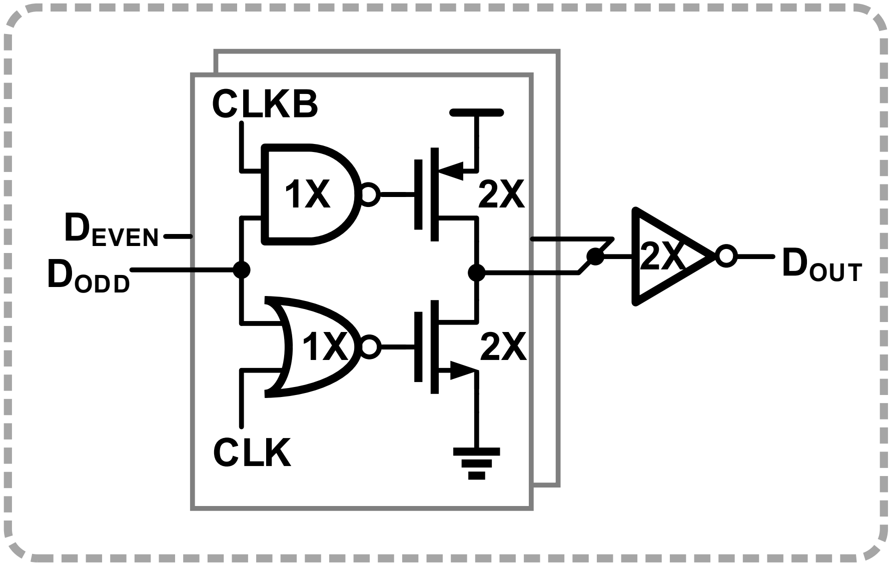


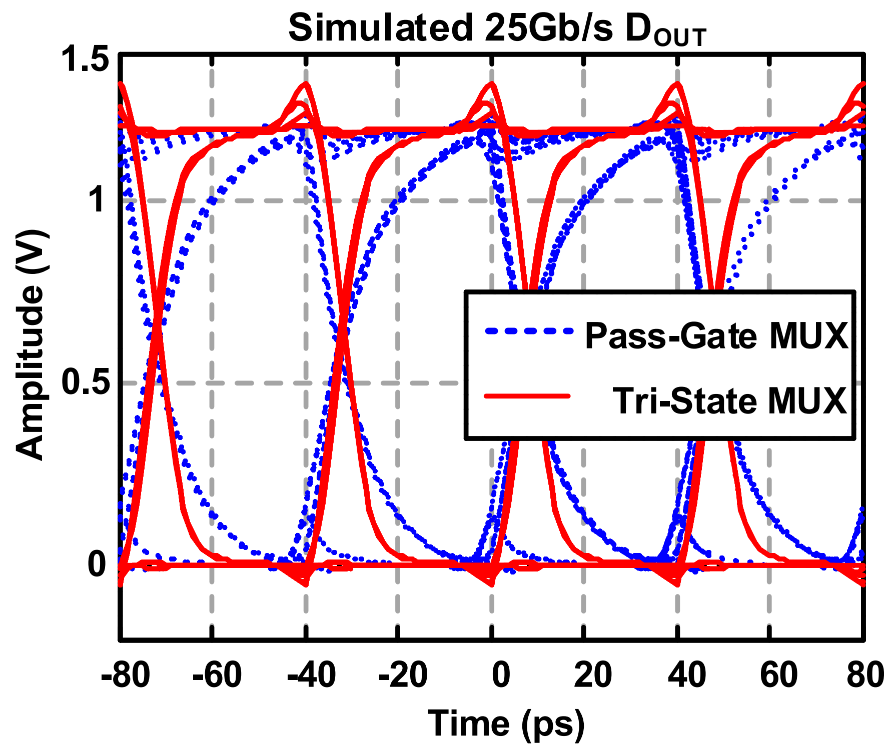
25Gb/s 8:1 CMOS Serializer



- Quadrature quarter-rate architecture eliminates high-speed retiming before final 2:1 MUX

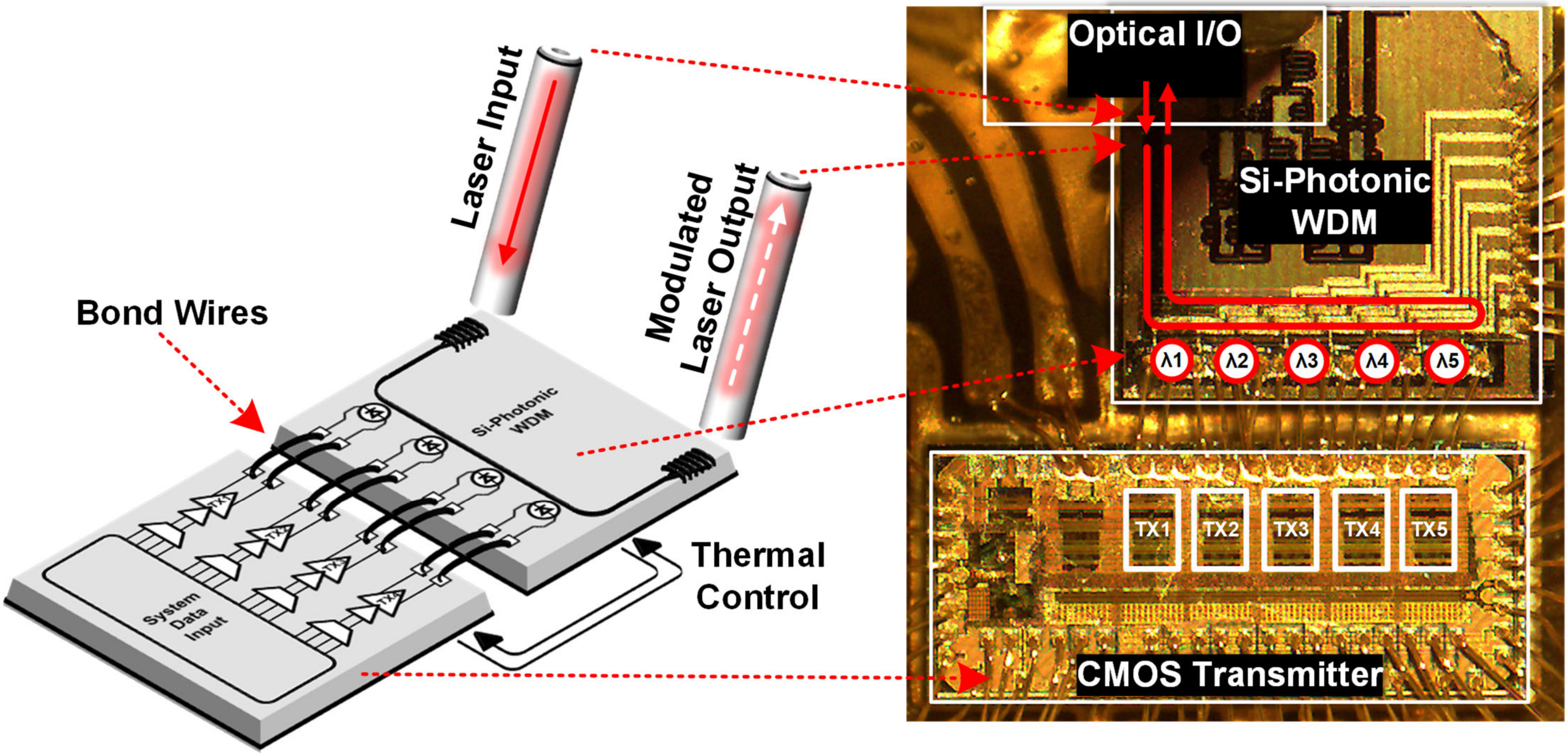
25Gb/s 8:1 CMOS Serializer





- Tri-state inverter-based 2:1 MUX for fast edge rate

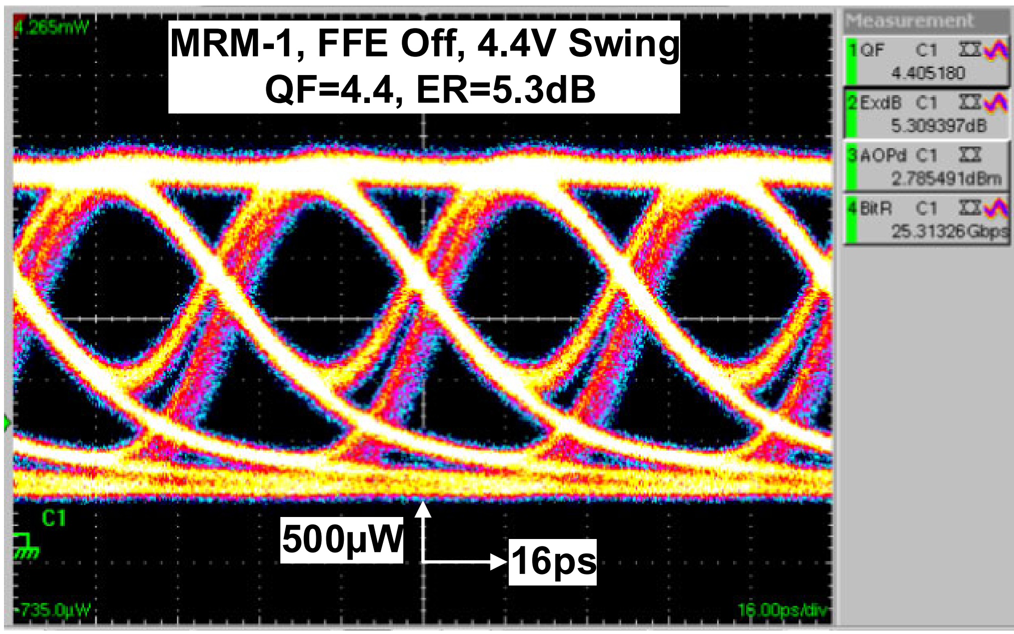
Heterogeneous Integration



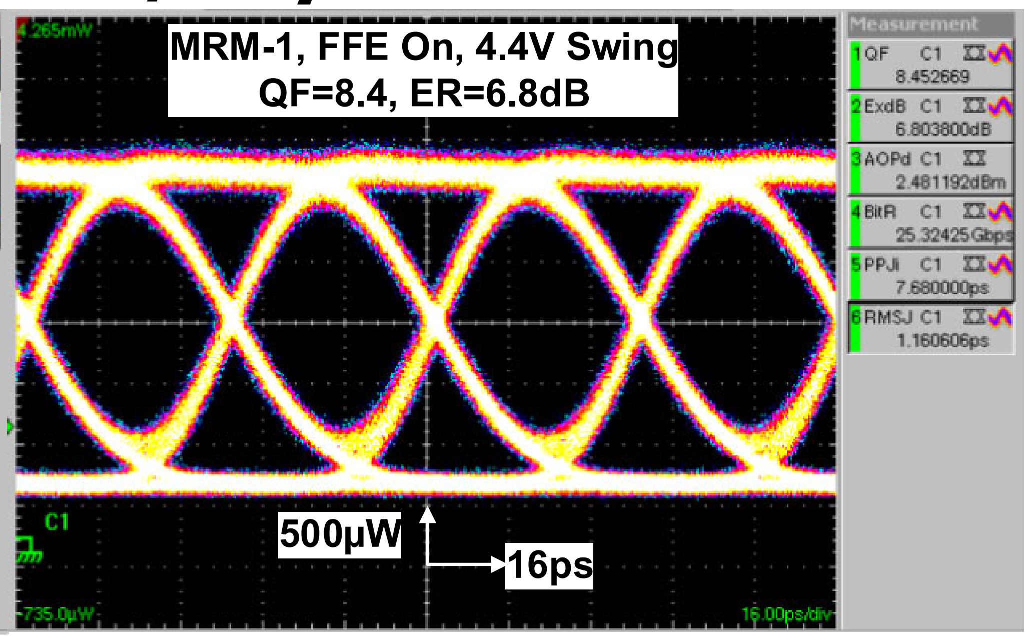
- Hybrid CMOS-Photonic packaging (<0.5mm bond-wires)
- Stable optical coupling using vertically-attached fibers

25Gb/s Optical Measurement

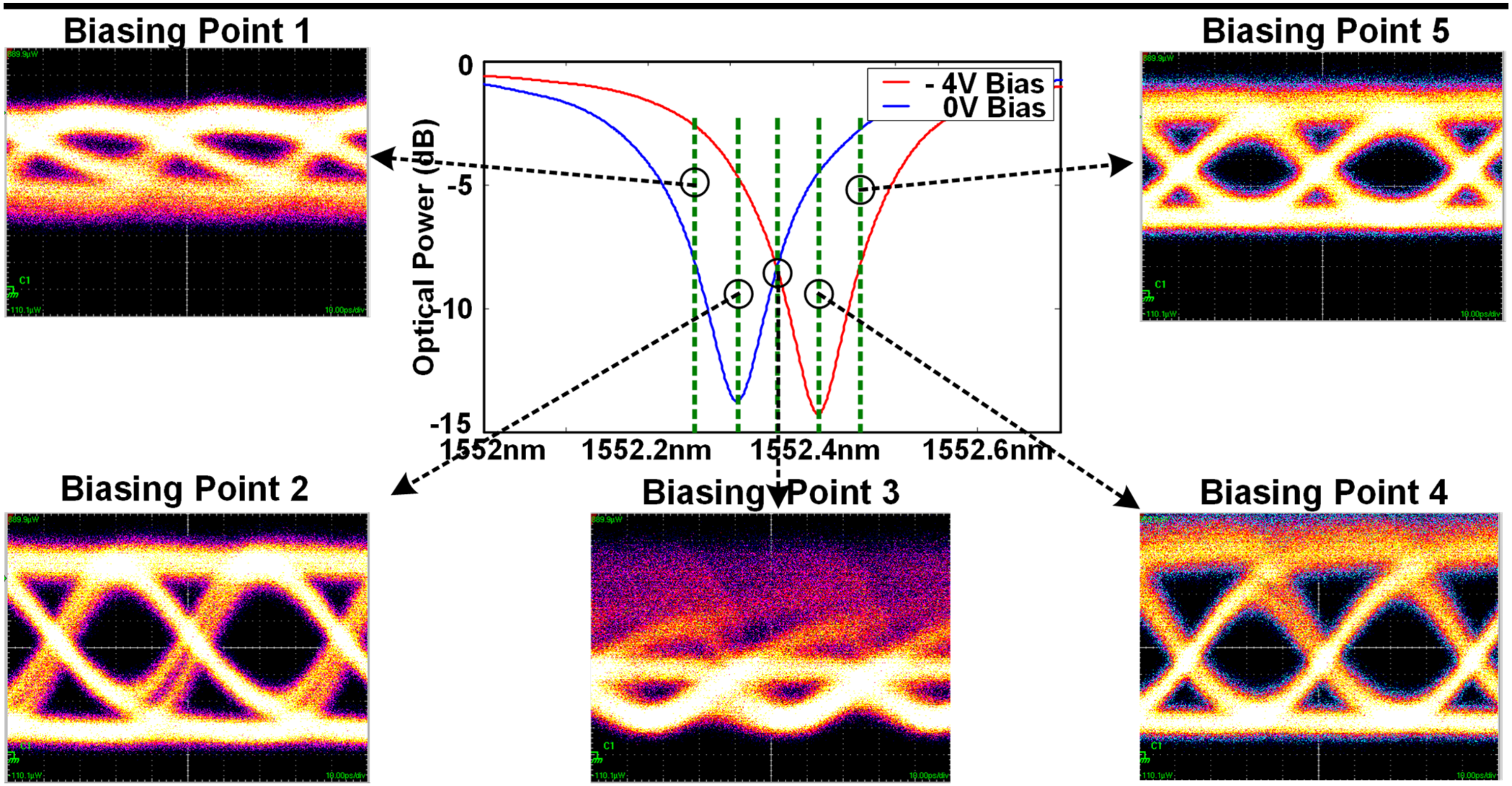
Test Channel 1
w/o FFE



Test Channel 1
w/ Asymmetric FFE

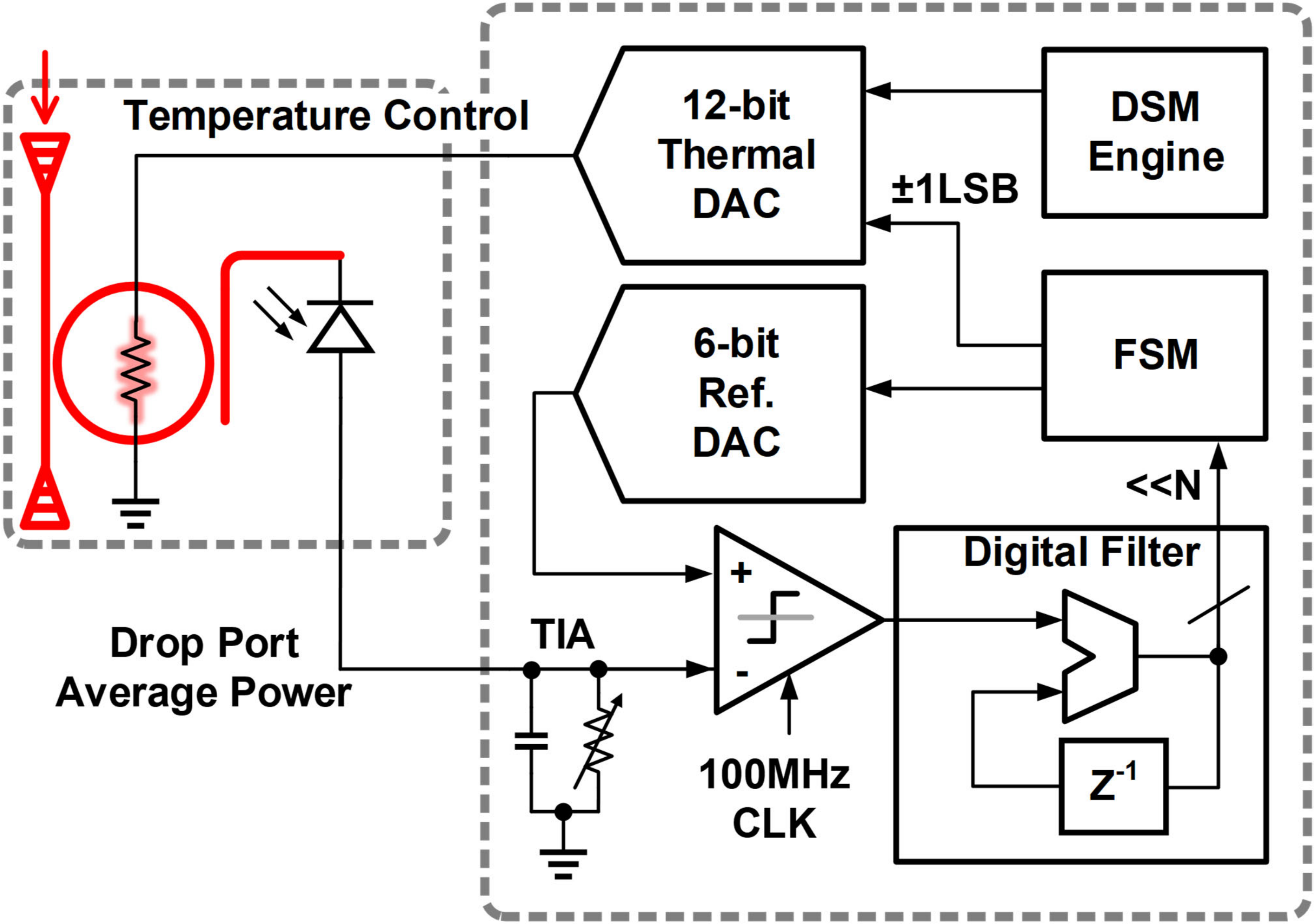


Challenge III: Wavelength Stability

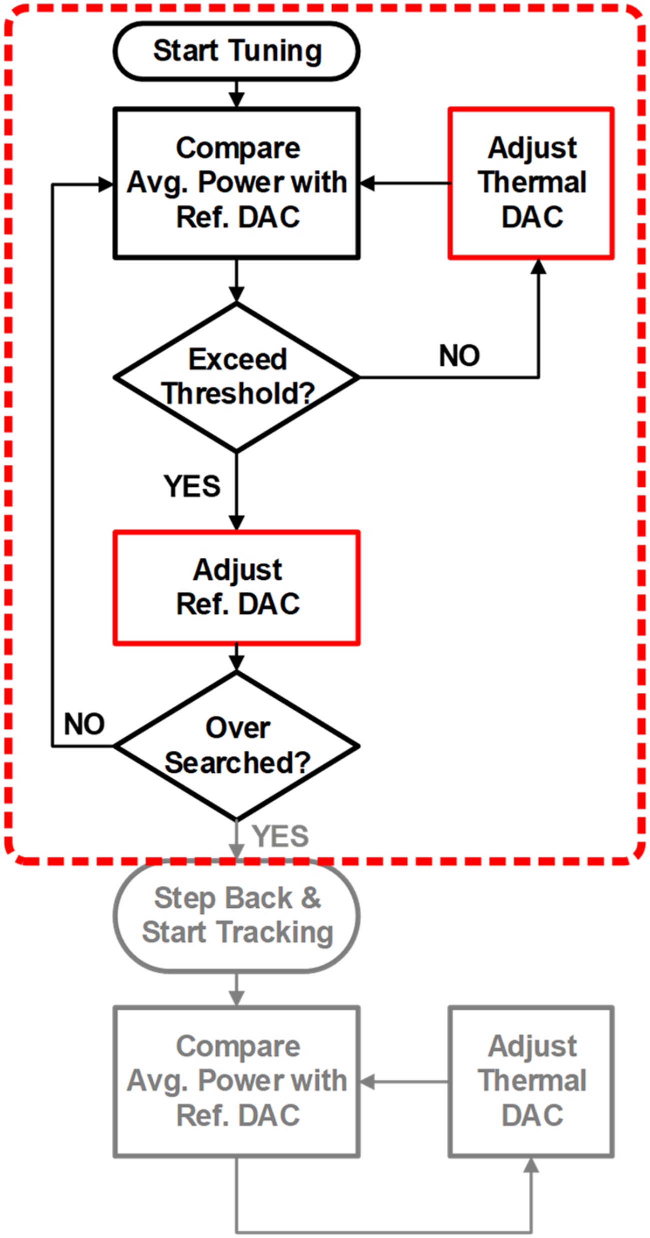


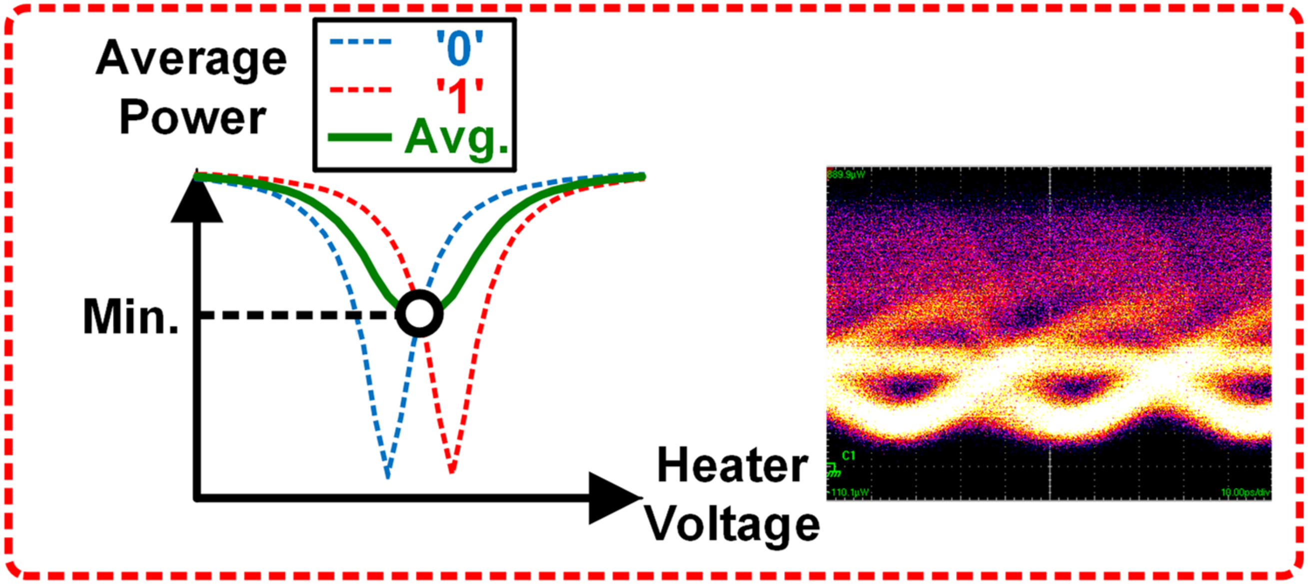
- Modulation efficiency depends strongly on wavelength
- ER degradation due to temperature fluctuation
- Closed-loop control is necessary for robust operation

Average Power Thermal Stabilization

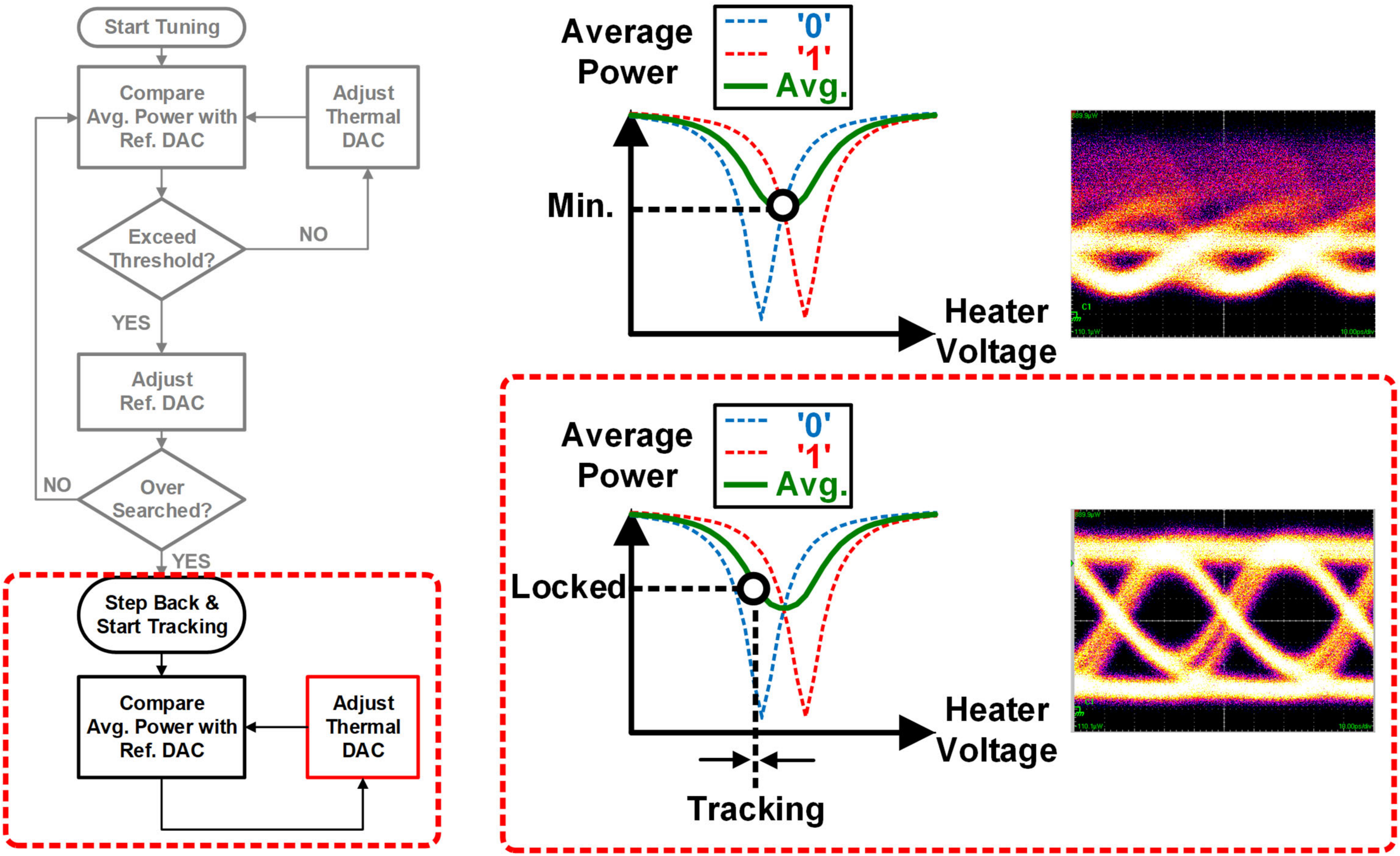


Thermal Tuning Algorithm

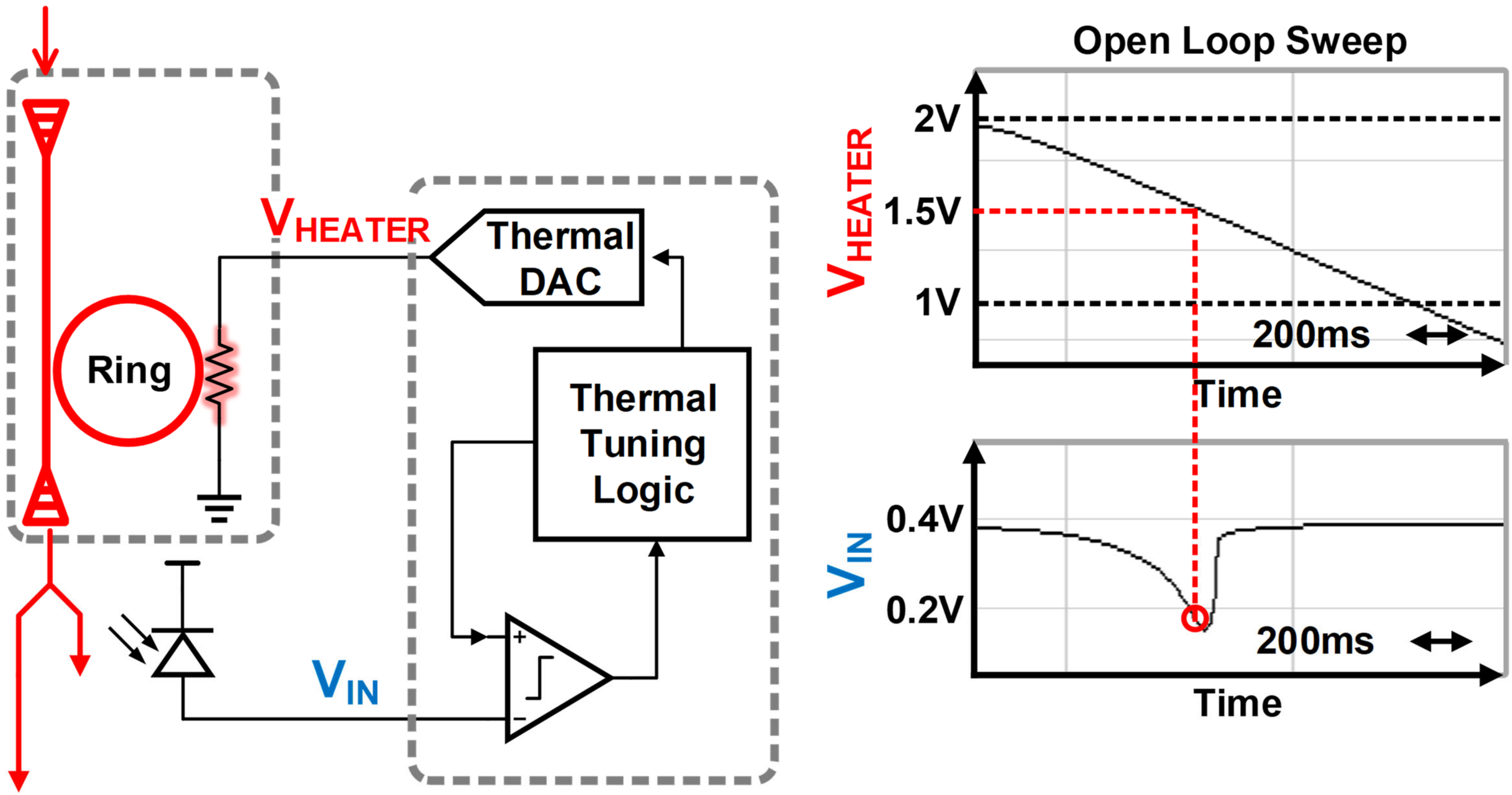




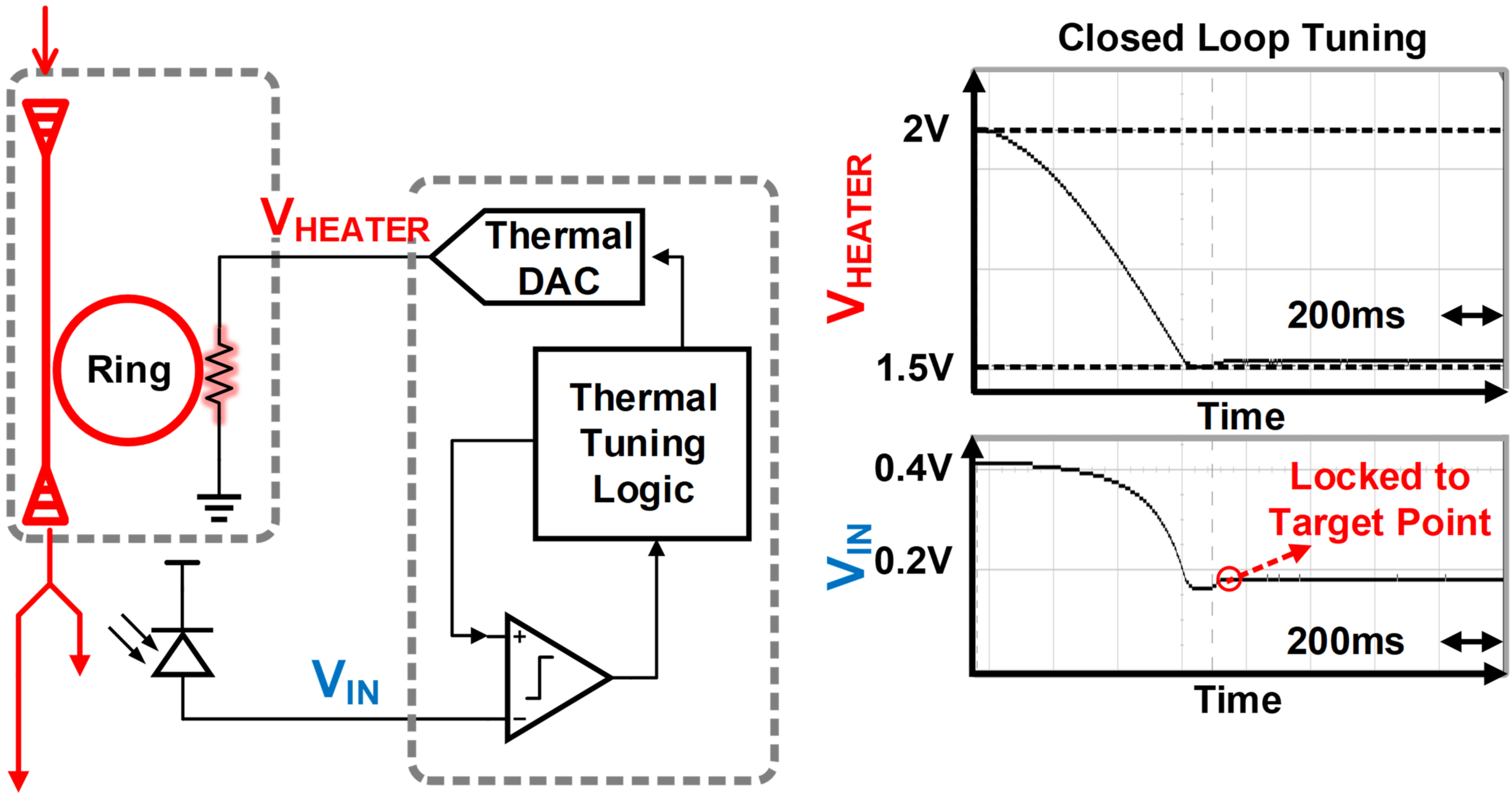
Thermal Tuning Algorithm



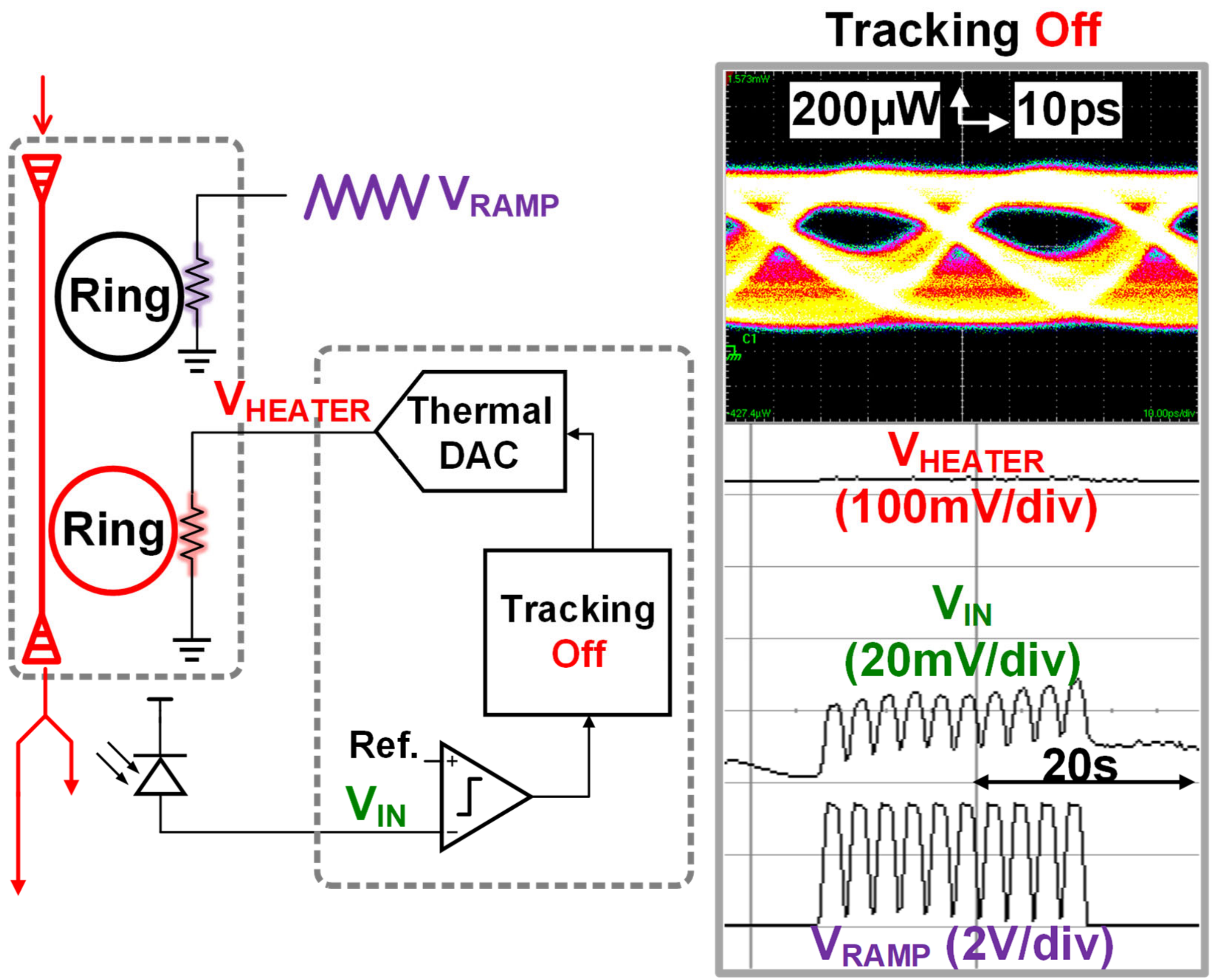
Thermal Tuning Test



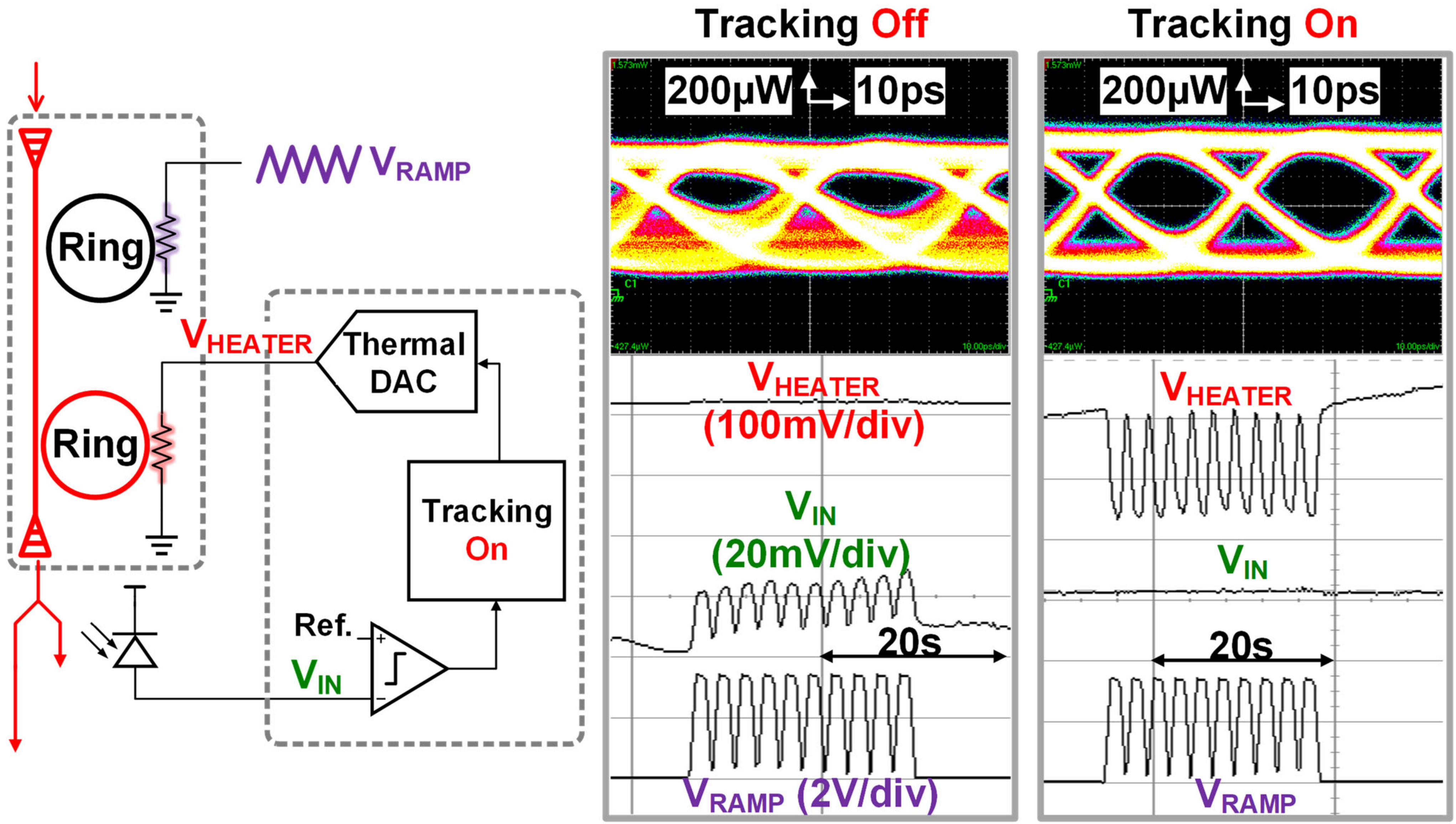
Thermal Tuning Test



Dynamic Thermal Tracking Test



Dynamic Thermal Tracking Test

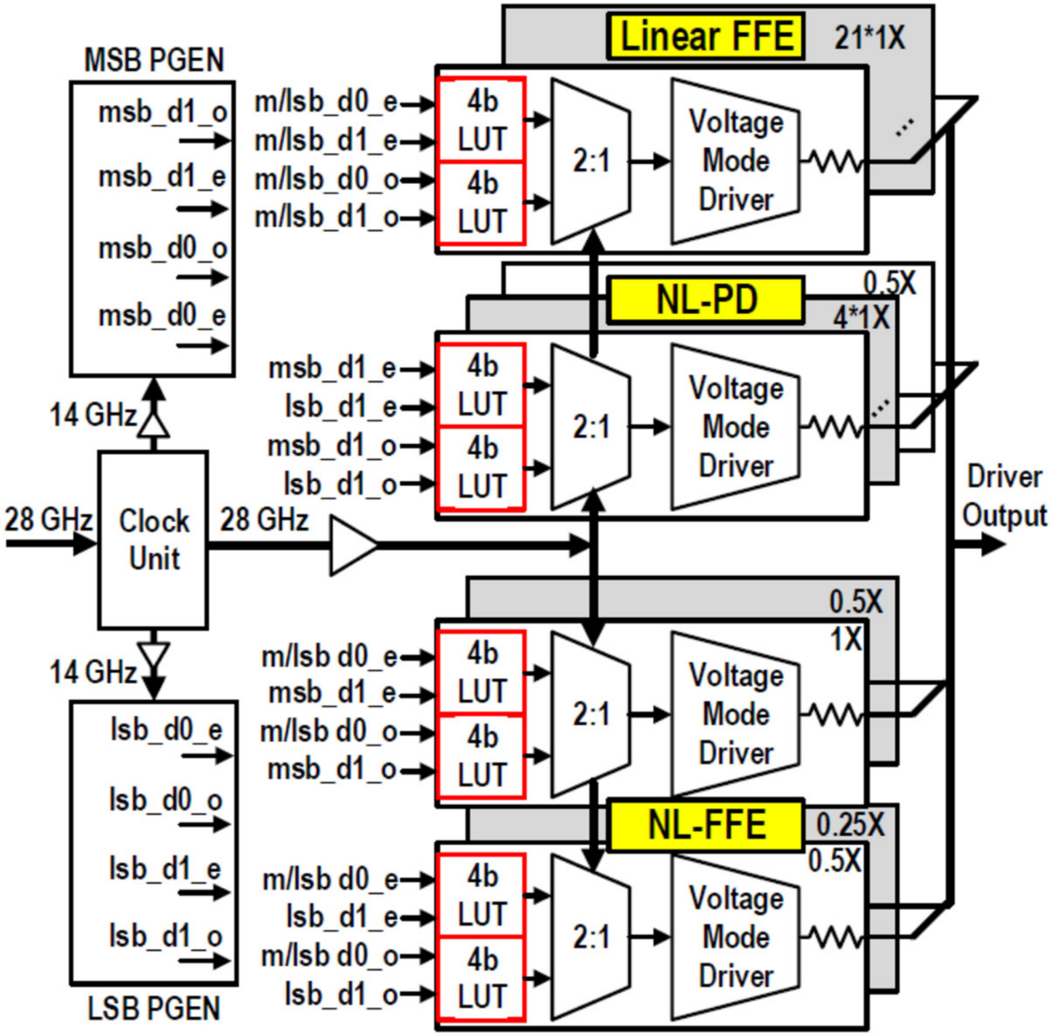


TX Performance Comparison

	Liu JSSC2012	Li ISSCC2013	Moss ISSCC2013	Buckwalter JSSC2012	This Work
Technology	40nm CMOS	65nm CMOS	45nm SOI	130nm SOI	65nm CMOS
Data Rate	10Gb/s	5Gb/s	2.5Gb/s	25Gb/s	25Gb/s
Integration	Flip Chip	Wire Bonding	Monolithic	Monolithic	Wire Bonding
MRM Type	Depletion	Injection	Injection	Depletion	Depletion
MRM Q	~15000	~8000	~4000	~13000	~5000
Supply	1V, 2V	1V, 2V	1.1V, 1.5V	+1.5V, -1.5V	1.2V, 2.4V
Channels	8	6	1	1	5
EQ	N/A	2-Tap FFE	2-Tap FFE	2-Tap FFE	2-Tap FFE
Swing	$2V_{pp}$	$2V_{pp}$	$1.5V_{pp}$	$2.4V_{pp\text{-}diff}$	$4.4V_{pp\text{-}diff}$
ER	7dB	12.7dB	3dB	6.5dB	7dB
MRM Stabilization	Static Thermal	Static Bias	N/A	N/A	Dynamic Thermal
Transmitter Power	*1.35mW	4.04mW	*3.07mW	*207mW	113.5mW

* w/o Serialization and Clocking

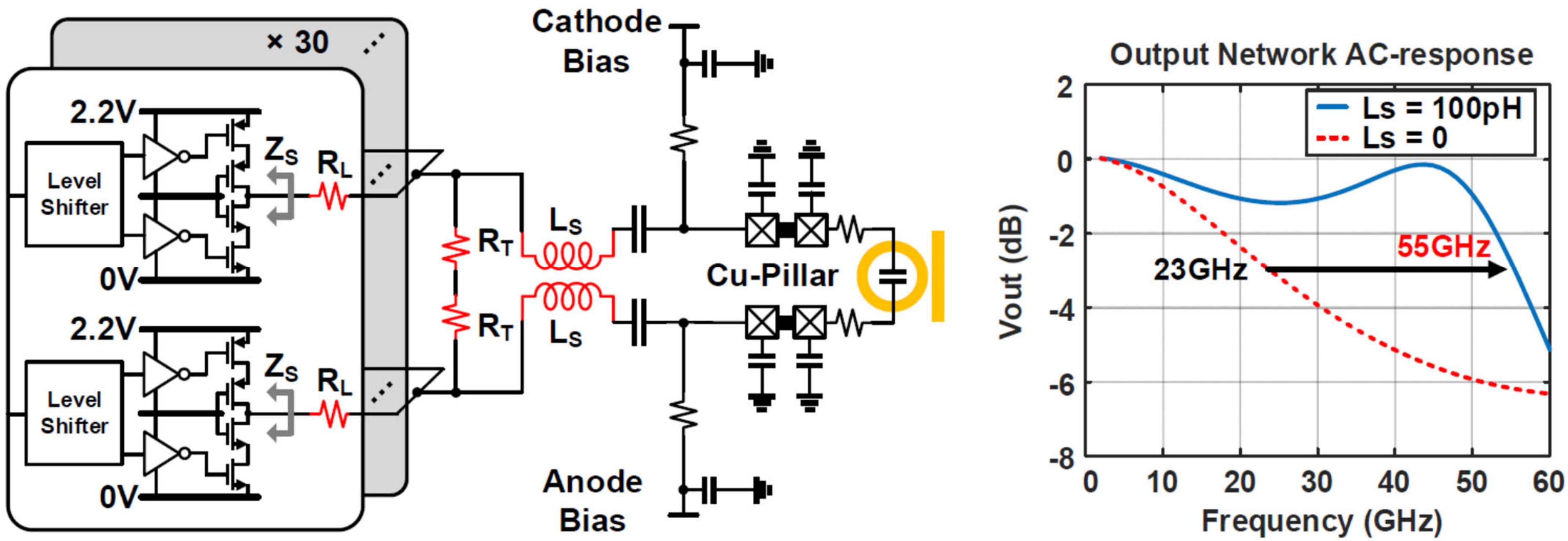
112Gb/s PAM4 Transmitter



[Li ISSCC 2020]

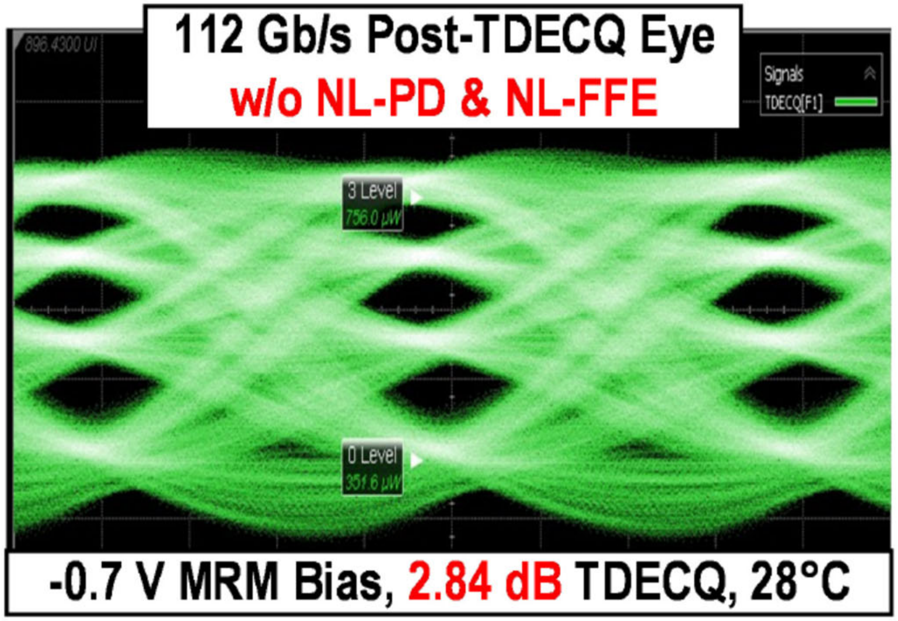
- Look-up table (LUT) DAC-based output stage
- 2-tap linear FFE (21X slices)
- Non-linear static pre-distortion (4.5X slices)
- Nonlinear 2-tap FFE (2.25X slices)

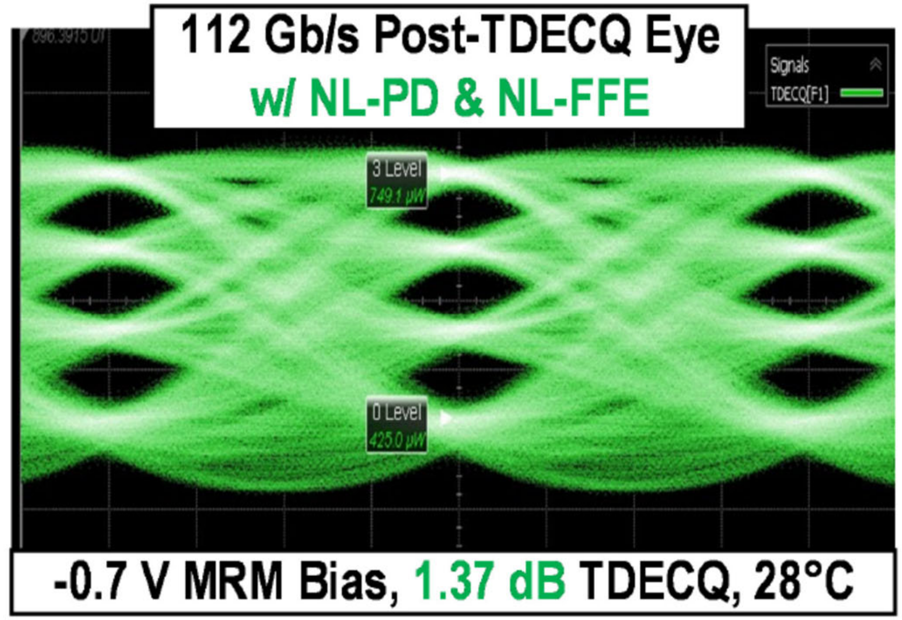
112Gb/s DAC Output



- Differential cascade output driver w/ level shifted pre-drivers
- Per-slice series R_L and lumped shunt R_T improve linearity at the cost of reduced output swing ($3V_{ppd}$)
- Series peaking inductor provides significant bandwidth extension

112Gb/s PAM4 Eye Diagrams





- Utilizing only linear FFE results in significant eye skew and poor TDECQ
- Enabling the non-linear pre-distortion and FFE aligns the 3 eyes and improves TDECQ by ~1.5dB

Next Time

- Laser Sources