EE 437/538B: Integrated Systems Capstone/Design of Analog Integrated Circuits and Systems

Lecture 6: Optical TRx (Part 2)

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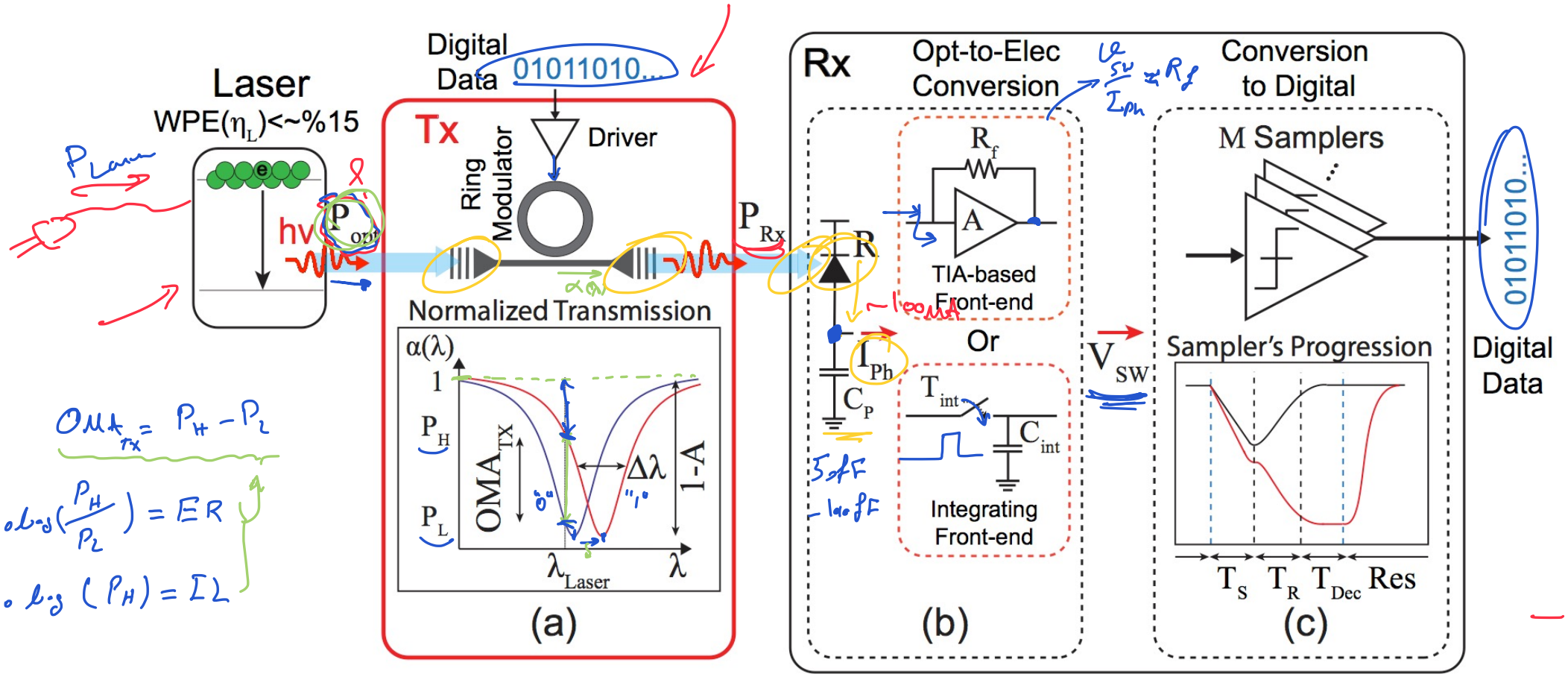
Spring 2022

A Full Photonic Link



$OMA_{TX} = P_H - P_L$

$10\log\left(\frac{P_H}{P_L}\right) = ER$

$10\log(P_H) = IL$

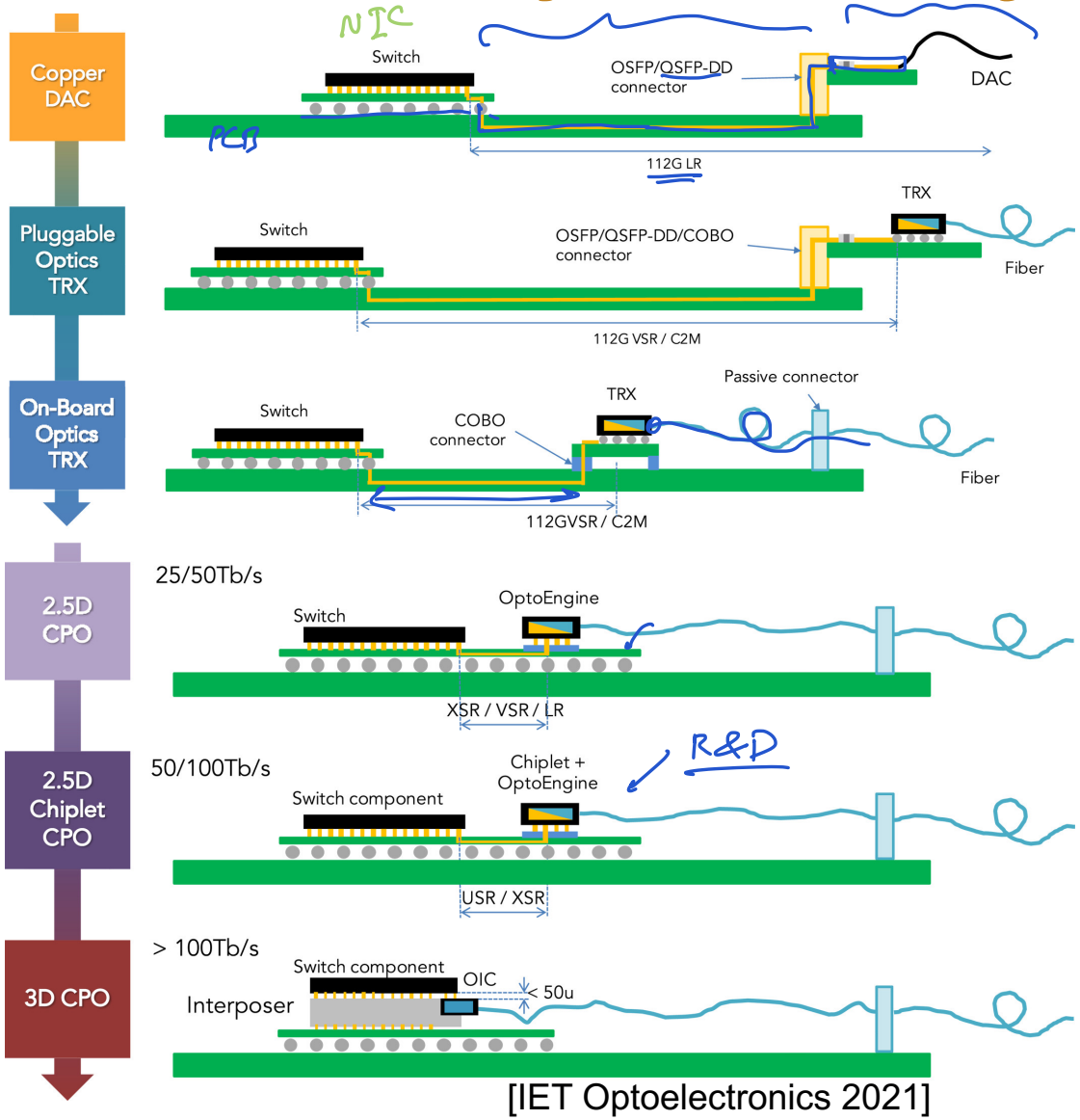
-10 dBm

-20 dBm

- Receiver sensitivity: Min optical power for a certain data-rate & BER ($P_{Rx,in}$)

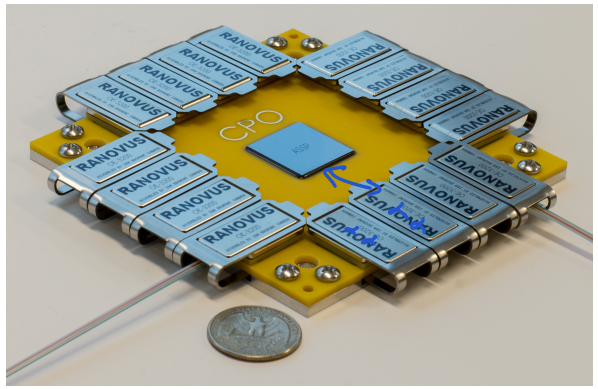
Min OMA @ Rx

Today vs. Near-future E/O Modules



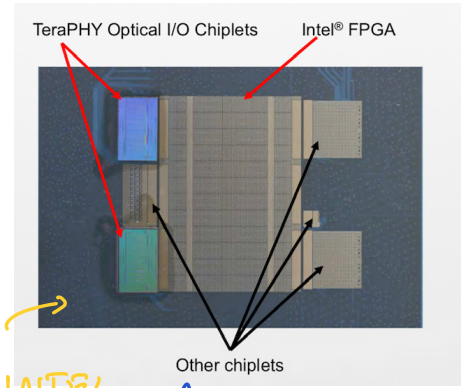
[IET Optoelectronics 2021]

~10pJ/b



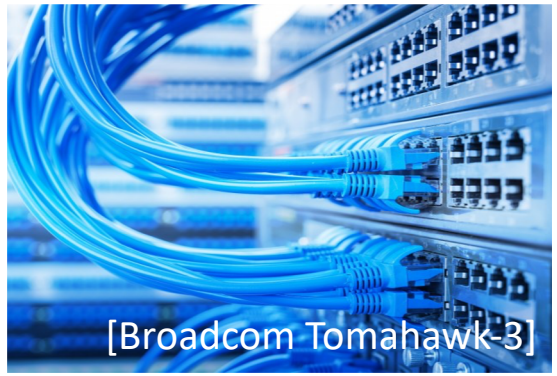
[Ranovus]

~5pJ/b

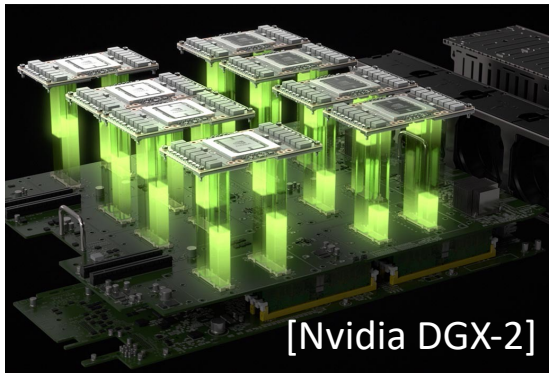


[Ayar Labs]

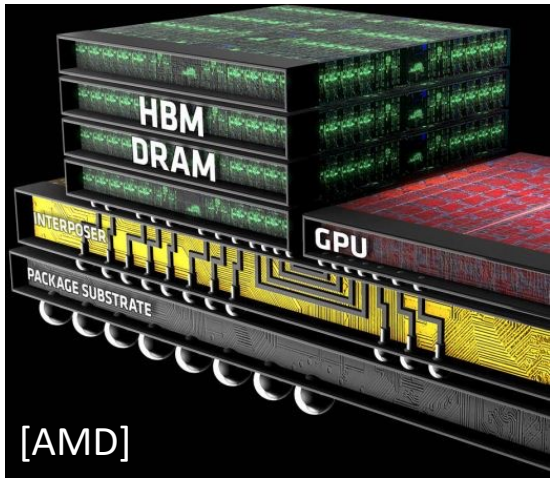
Emerging Needs for Photonics



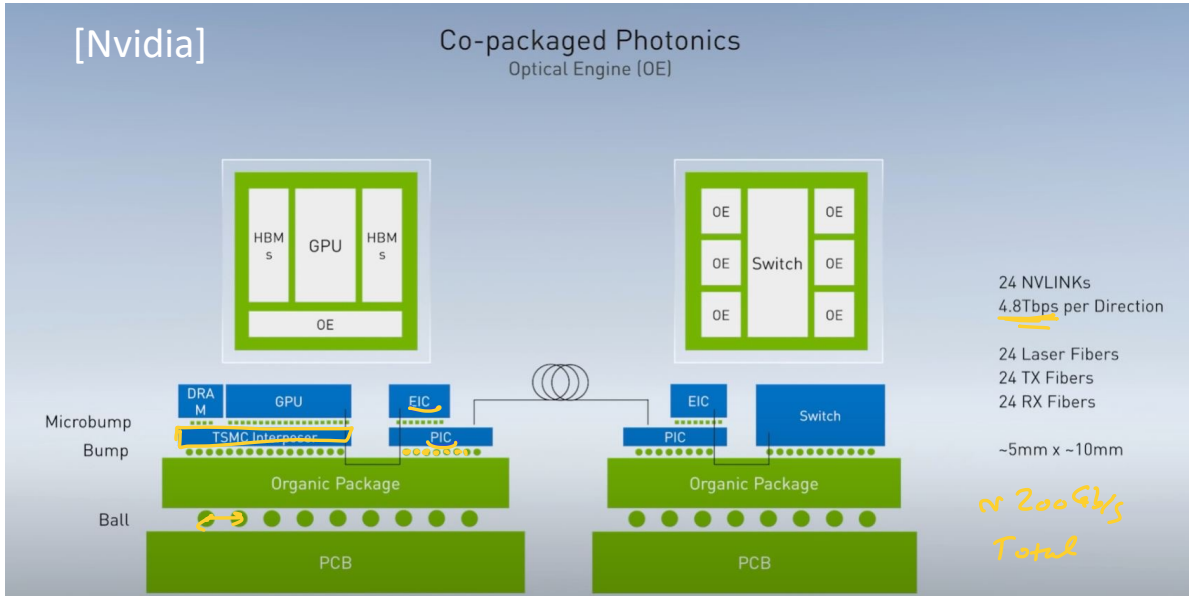
32x400 Gb/s



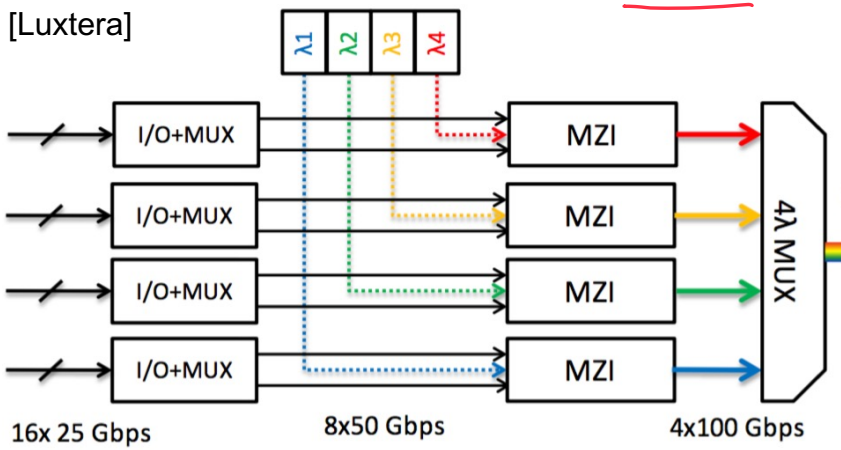
4.8Tb/s

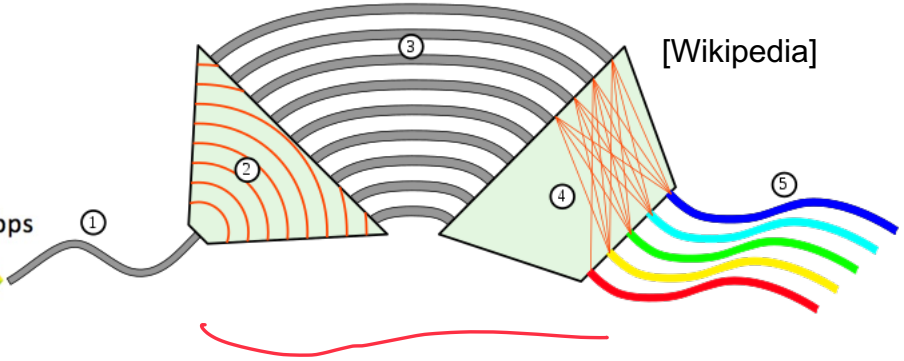


- **Demand for ultra-high data-rates!**
  - Heterogeneity: HBM, …
  - Advanced integration and packaging
- **Time for photonics to join …**
  - Energy-efficiency & High-bandwidth density

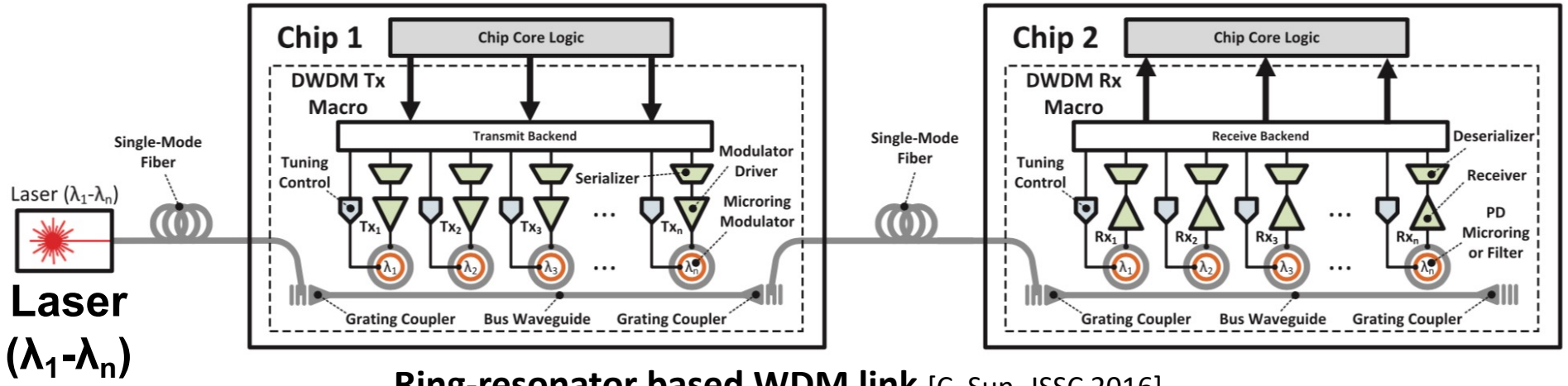


WDM Optical I/O





MZM + AWG MUX **Arrayed Waveguide Grating (AWG) DeMUX**

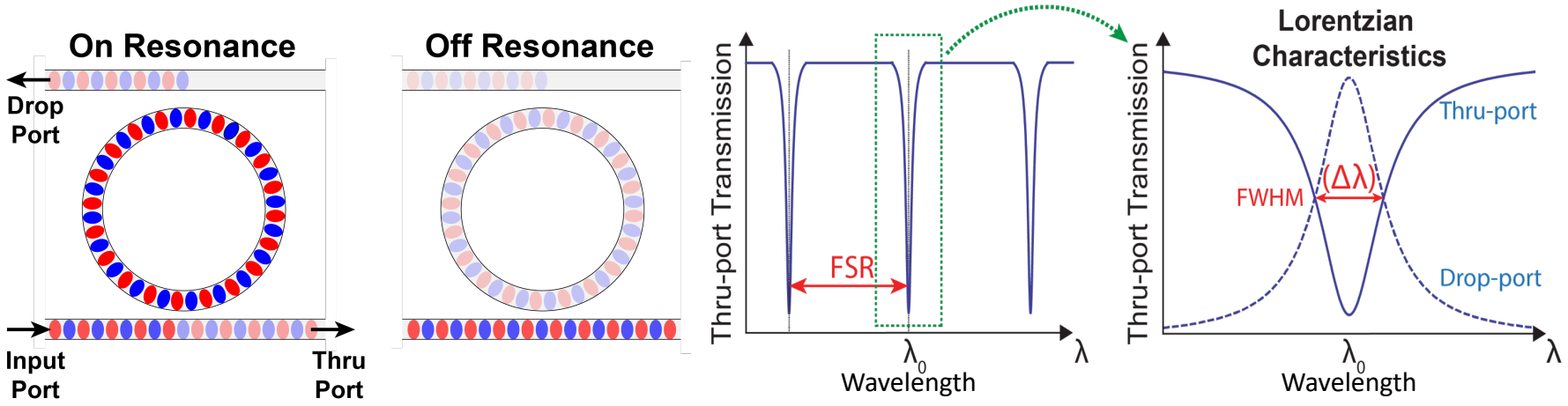


Ring-resonator based WDM link [C. Sun, JSSC 2016]

Important Metrics

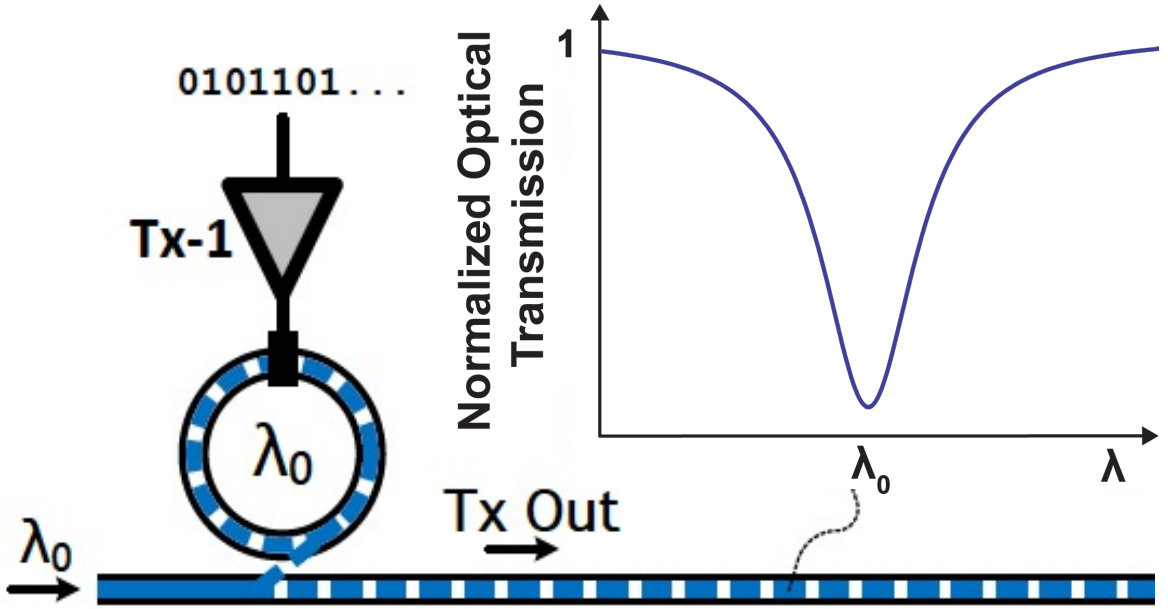
Metric		SiPh TRx [Ayar Labs]	Near Future Needs (<5yr)
Aggregate Data-rate	Tb/s	0.8	>1.6Tb/s (per fiber)
# Wavelengths	#	32	-
Data-rate per channel	Gb/s	25Gb/s	+100Gb/s
Energy-efficiency	pJ/b	5pJ/b	<1pJ/b
Edge BW density	Tb/s/mm		>1Tb/s/mm
Tx Ext. Ratio	db	5	
BER	1E-X	1e-12	
Latency	ns	10ns + 5ns/m	
Cost	$/Gb/s		<0.1$/Gbps

Micro-ring Modulator (MRM)



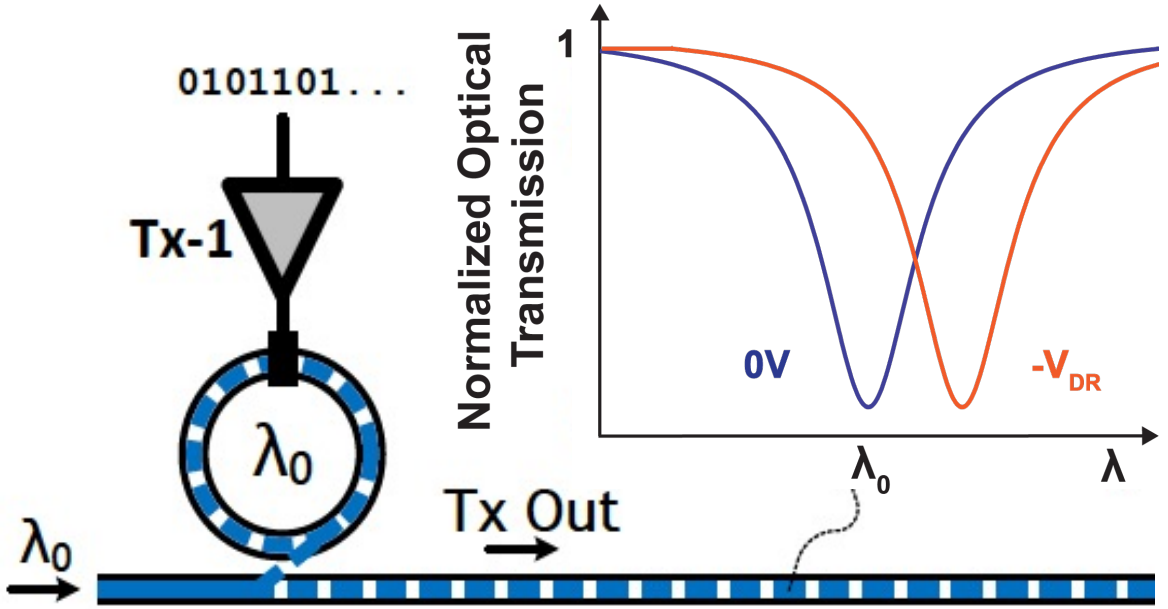
- Resonance wavelength: $\lambda_0 = n_{eff} L/m$, m = 1,2,3,...
  - Q-factor: $Q = \lambda_0 / \Delta\lambda$
- Compact device (radius of 5µm)
  - Energy & area efficient modulator/filter
- Supporting wavelength division multiplexing (WDM)

MRM based Optical Links



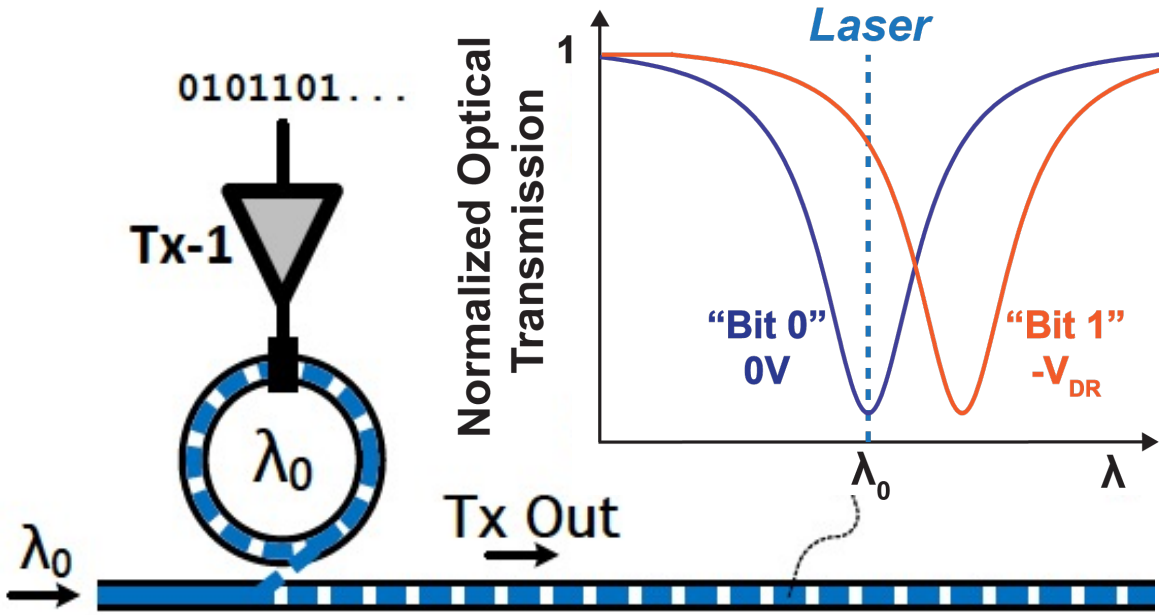
- Modulation Scheme:
  1. Deplete/Inject carriers using PN junctions

MRM based Optical Links



- Modulation Scheme:
  1. Deplete/Inject carriers using PN junctions
  2. Δfree carriers → Δindex of refraction [Carrier-Plasma Effect]

MRM based Optical Links



- Modulation Scheme:
  1. Deplete/Inject carriers using PN junctions
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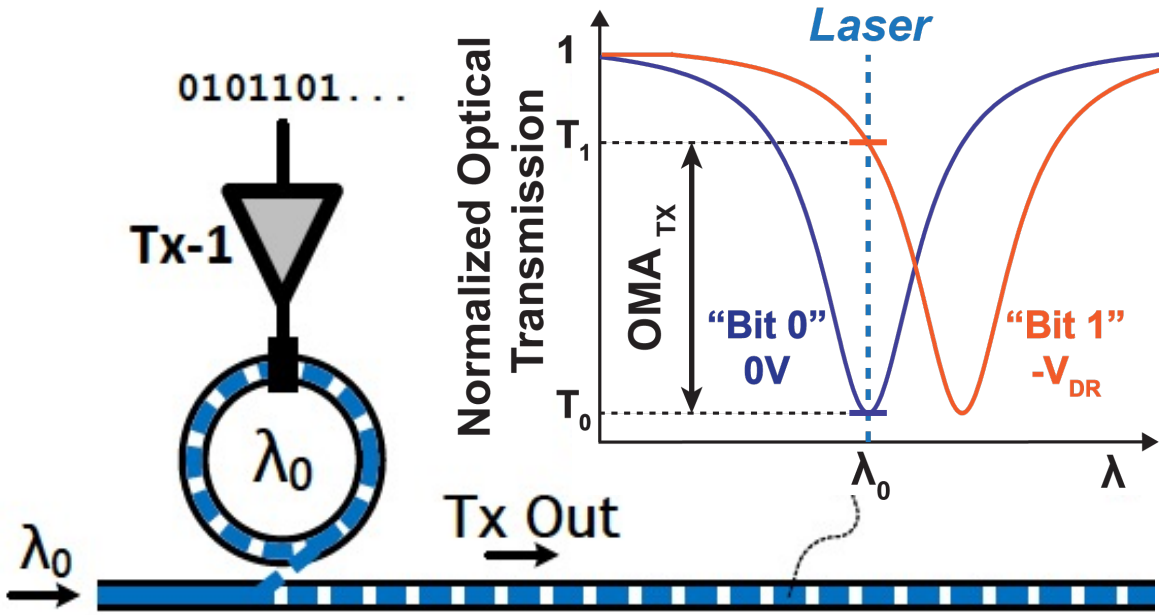
  3. On-Off Keying (OOK) modulation

MRM based Optical Links



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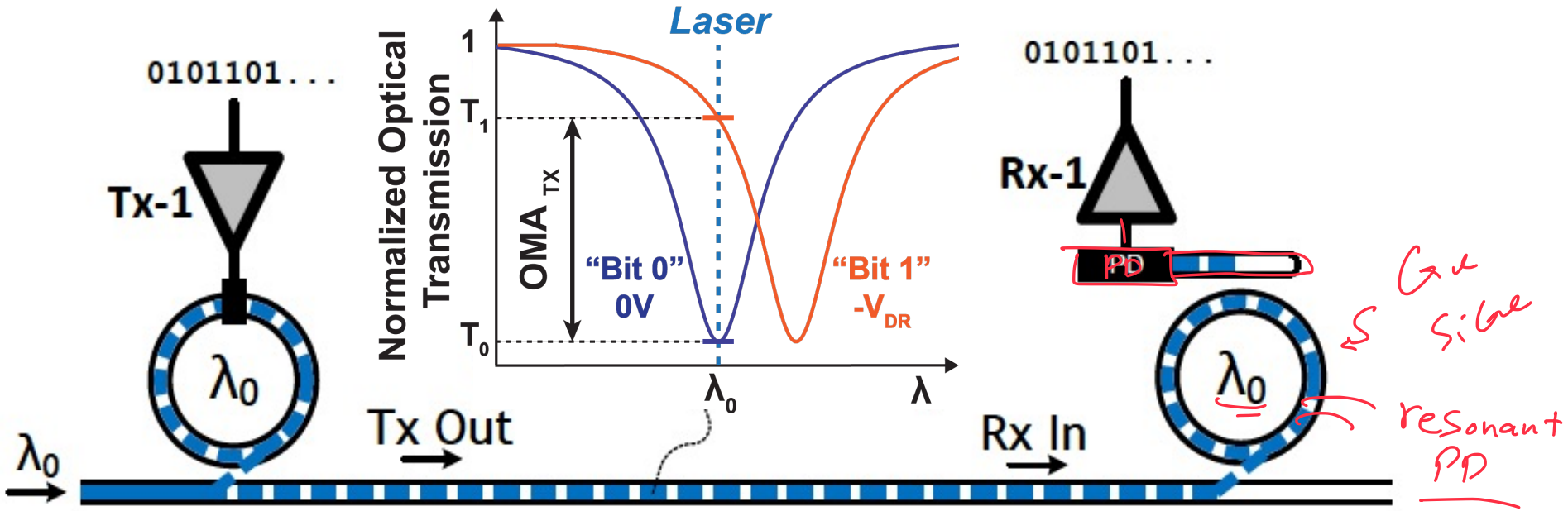
  3. On-Off Keying (OOK) modulation
  *. **OMA**: Optical Modulation Amplitude

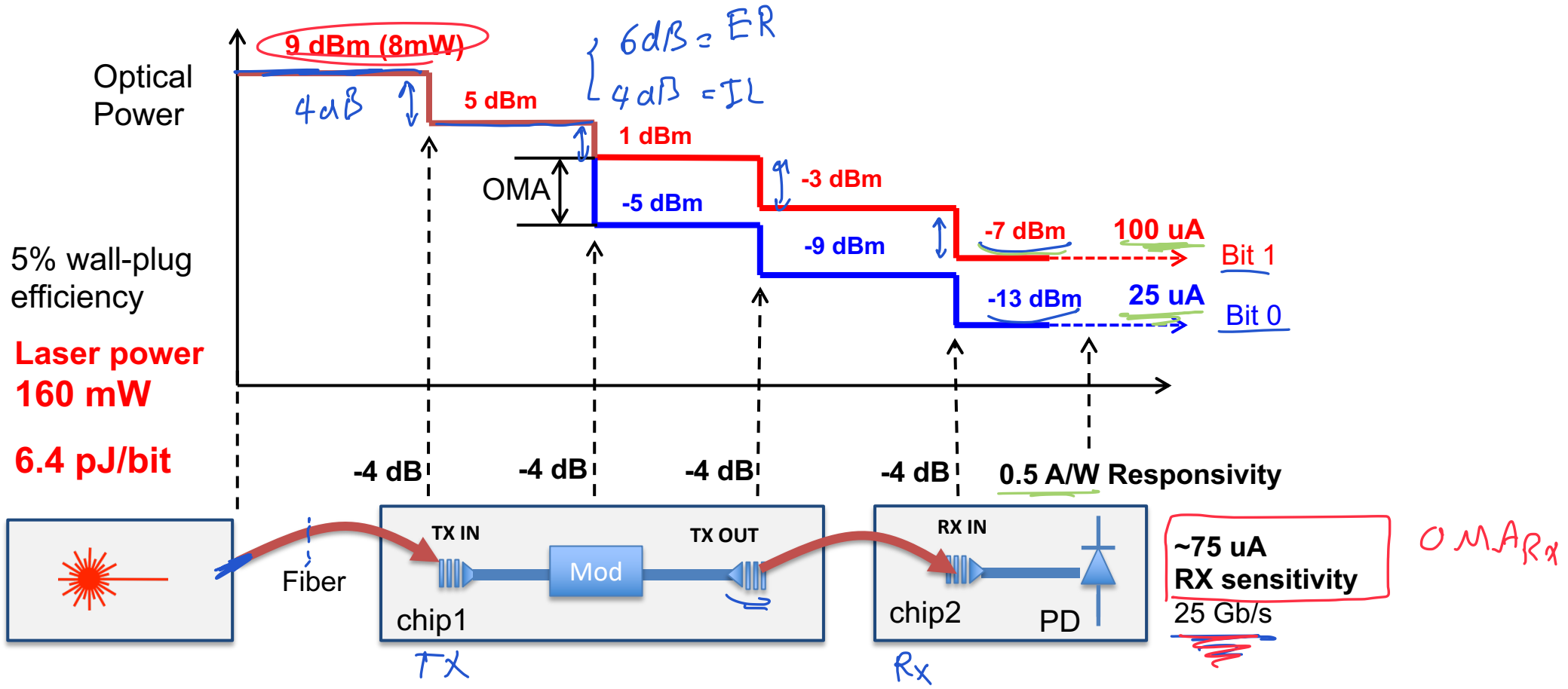
MRM based Optical Links



- Modulation Scheme:
  1. Deplete/Inject carriers using PN junctions
  2. Δfree carriers → Δindex of refraction [Carrier-Plasma Effect]
  3. On-Off Keying (OOK) modulation
  *. **OMA**: Optical Modulation Amplitude

Minimum OMA Required

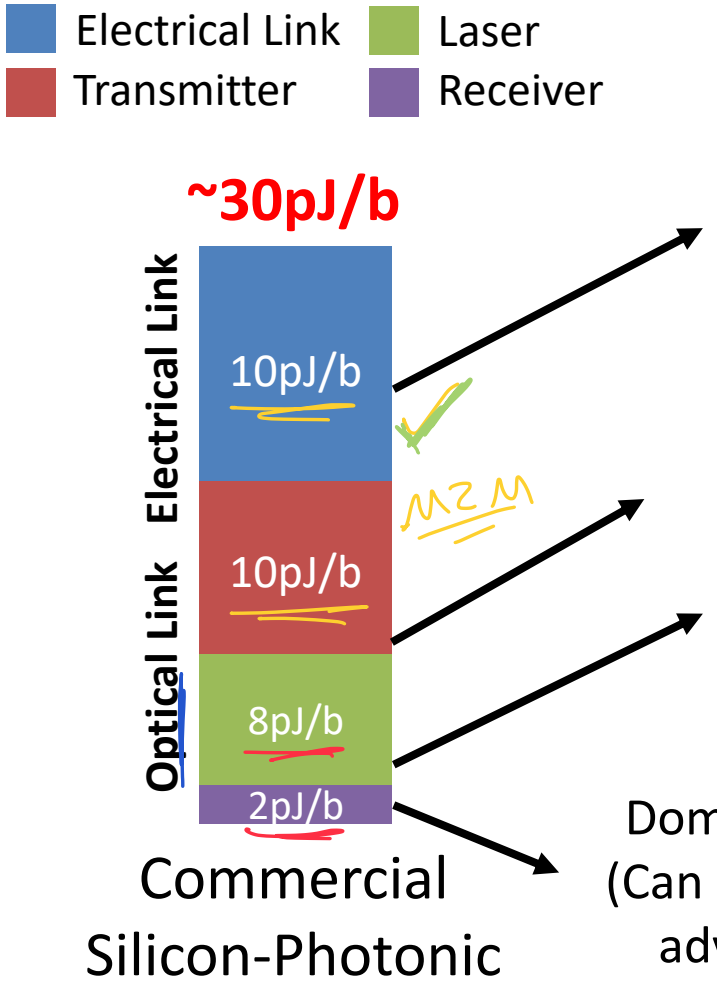
Optical Power Breakdown in an Optical Link

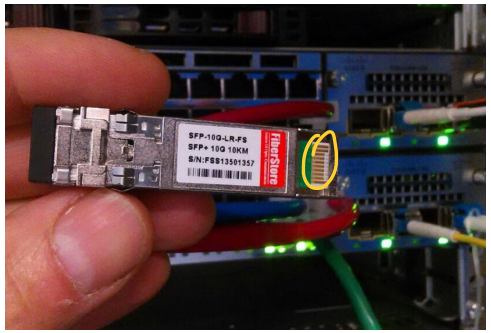


$$E_L = \frac{P_{RX,Min}}{\eta_L \cdot \Gamma_L \cdot OMA_{TX} \cdot DR}$$

energy/bit ← E_L ; η_L ← wall-plug eff ; Γ_L ← total losses : 3 x Grating loss ; $P_{RX,Min}$ → Min P_{opt} ; DR → data_rate

Energy-efficiency of Photonic Links

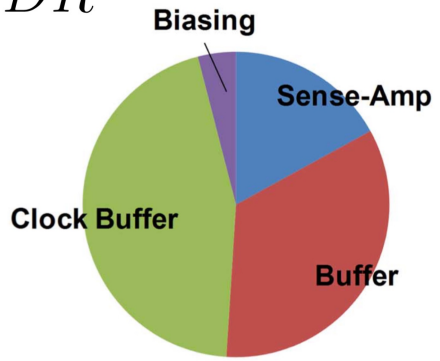




Modulator driver + SerDes + Clocking + …

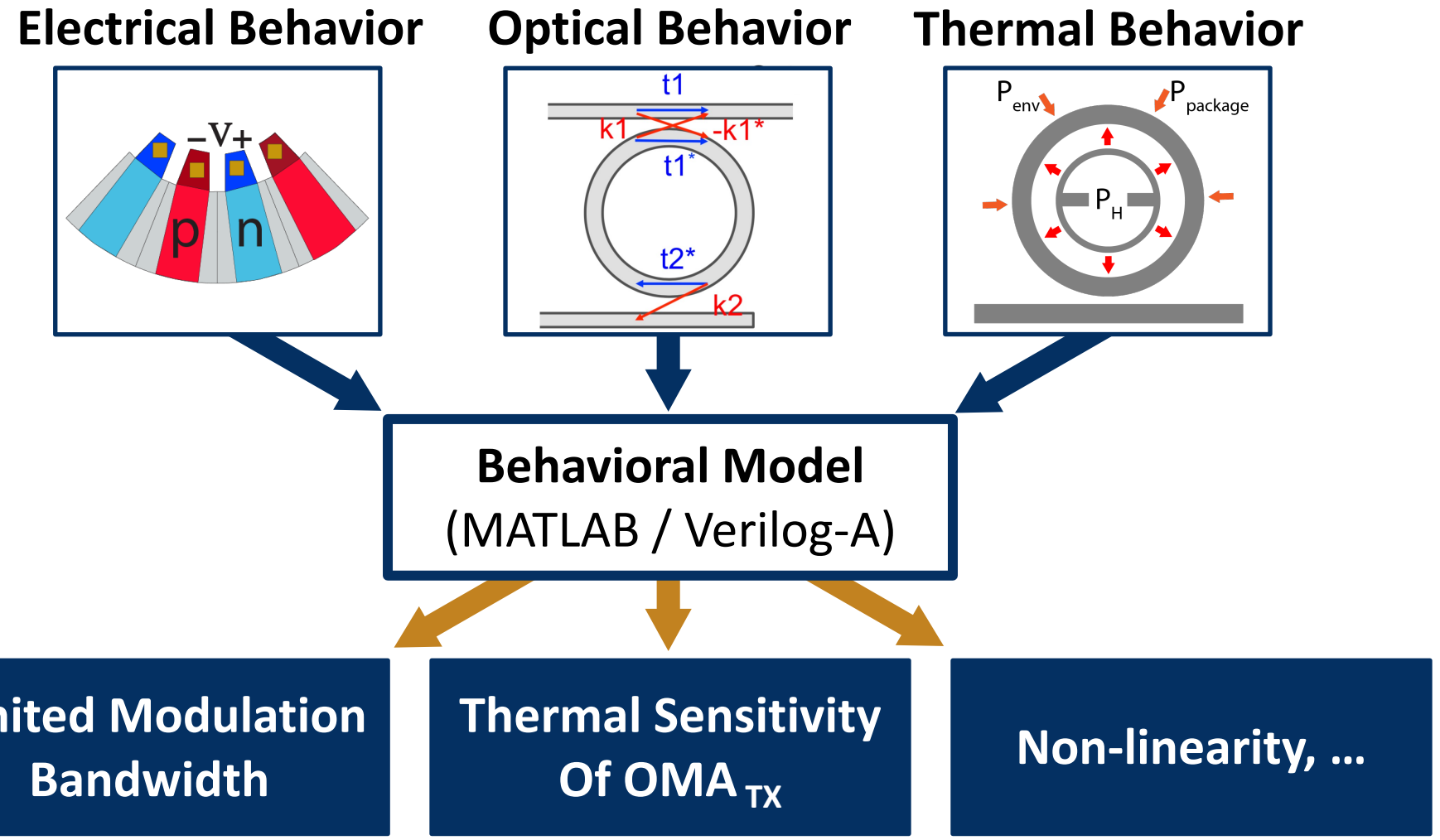
$$E_L = \frac{P_{RX,Min}}{\eta_L \cdot \Gamma_L \cdot OMA_{TX} \cdot DR}$$

Dominated by electrical blocks (Can be improved by using more advanced CMOS processes)



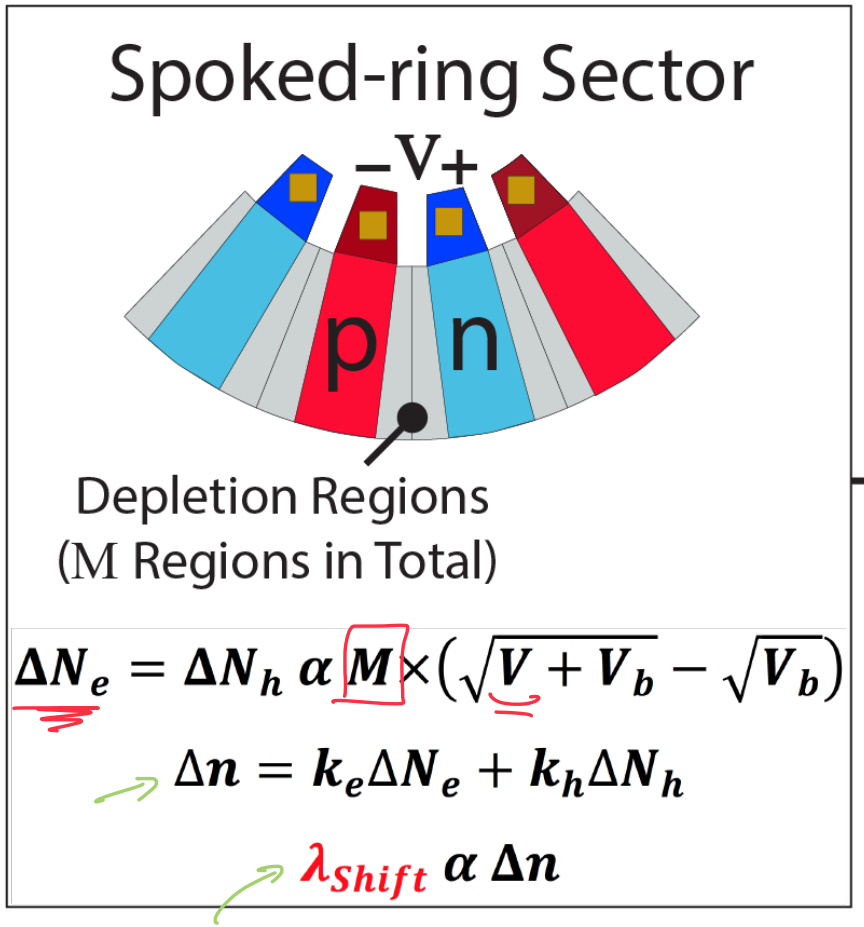
[M. Nazari, JSSC13]

Pushing to Higher Data-rates



[Moazeni *et al.*, JSSC 17]

Behavioral Modeling

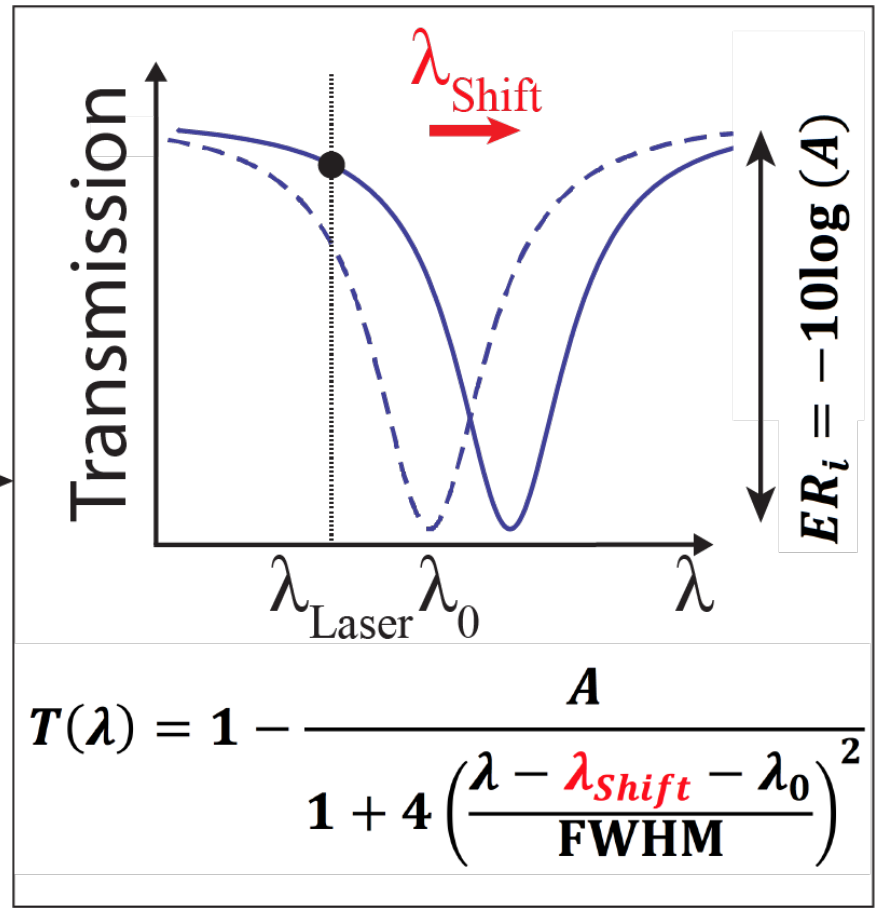


$$\Delta N_e = \Delta N_h \, \alpha \, M \times \left(\sqrt{V + V_b} - \sqrt{V_b}\right)$$

$$\Delta n = k_e \Delta N_e + k_h \Delta N_h$$

$$\lambda_{Shift} \, \alpha \, \Delta n$$

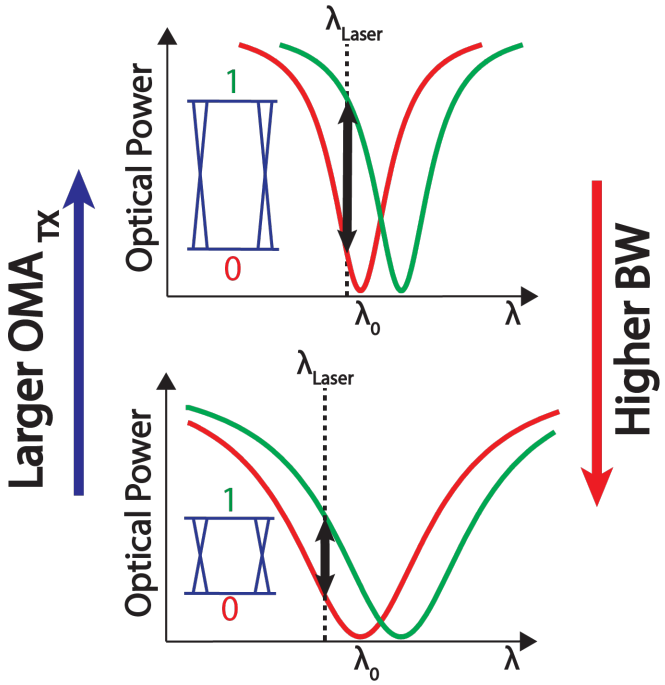
λ_{Shift}

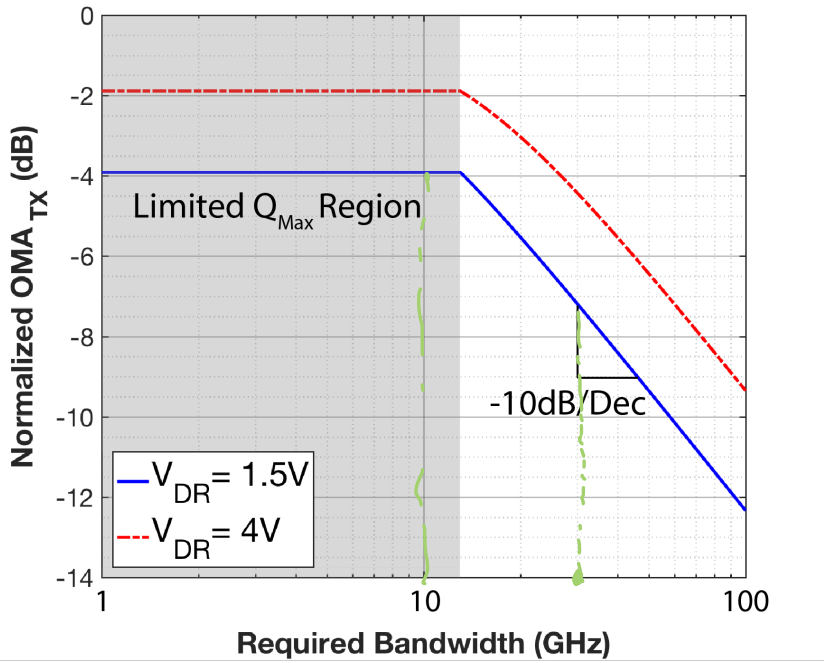


$$T(\lambda) = 1 - \frac{A}{1 + 4\left(\frac{\lambda - \lambda_{Shift} - \lambda_0}{FWHM}\right)^2}$$

MRM Transmitter Challenges

1. **Limited Modulation Bandwidth:** Trade-off between bandwidth & OMA_{TX}





Smaller OMA_{TX} → Larger transmitter & laser energy

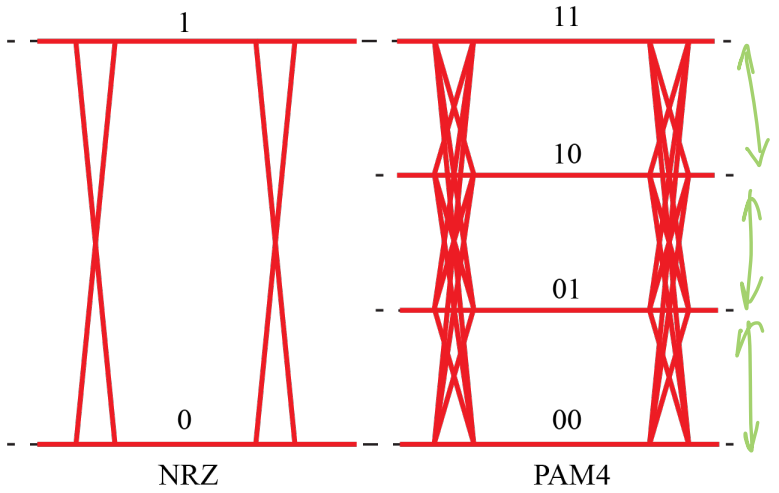
[Moazeni *et al.*, JSSC 17]

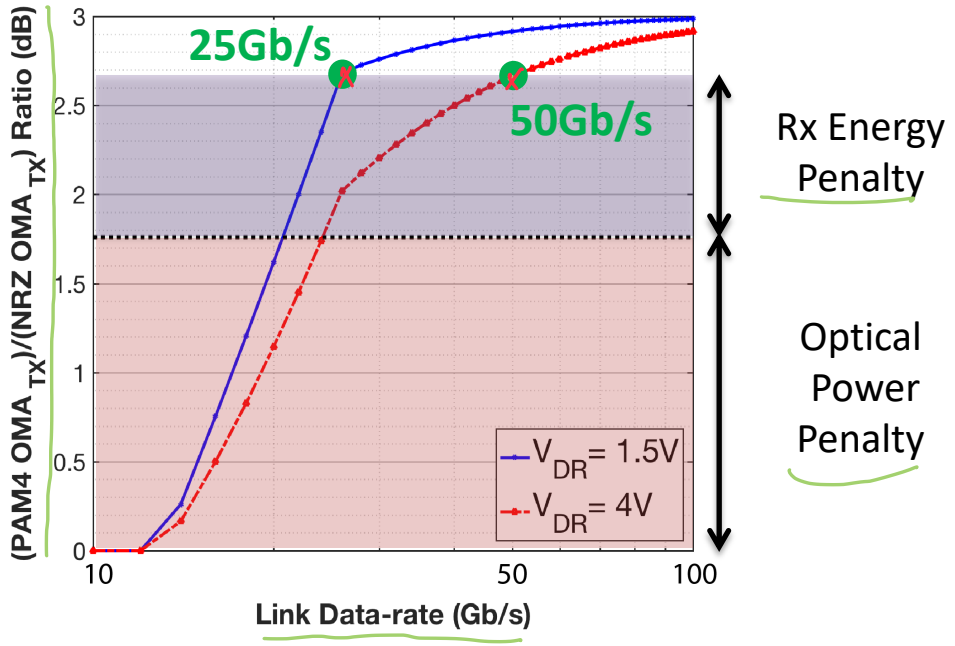
MRM Transmitter Challenges

1. **Limited Modulation Bandwidth:** PN junctions' RC-bandwidth limitation

Increasing spectral efficiency by higher order modulation

(PAM4, 2x Data-rate/Same BW)



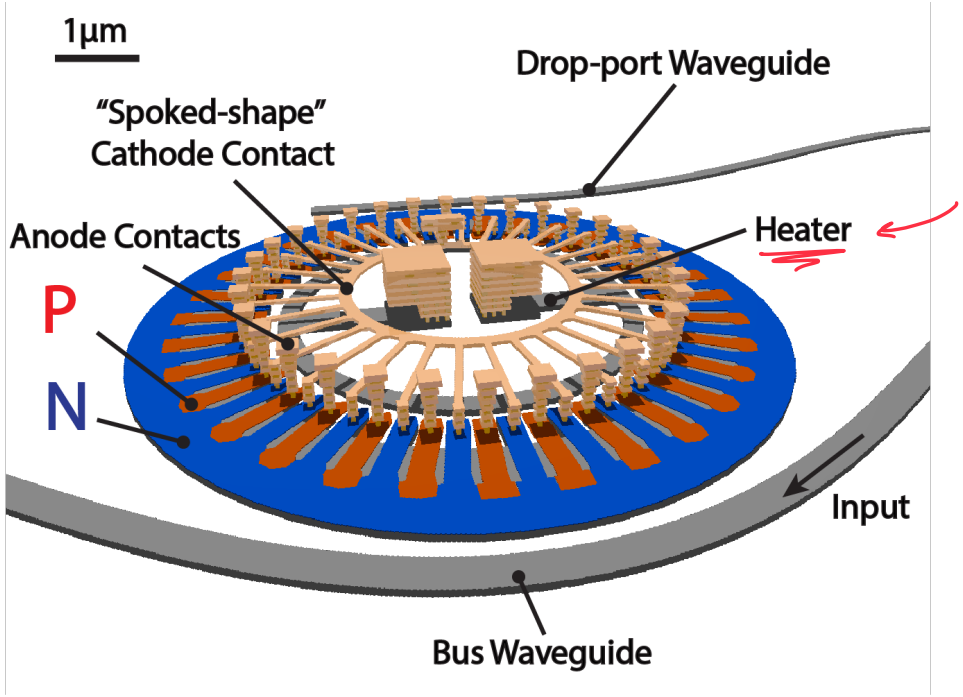


How to generate multi-level optical intensities efficiently?

[Moazeni *et al.*, JSSC 17]

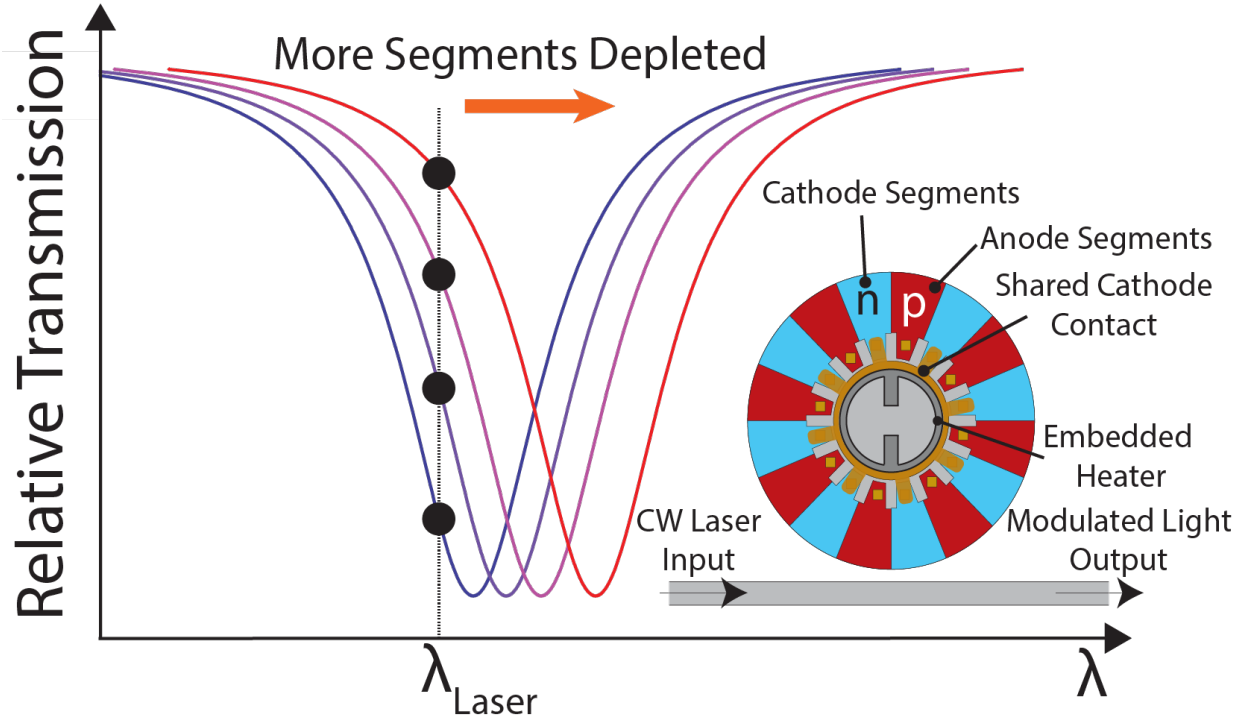
MRM in Zero-change Platforms

- Using Source/Drain doping implants for PN regions
- Interleaved planar PN junctions
- Embedded heater for thermal tuning



[Moazeni *et al.*, JSSC 17]

Optical Digital-to-Analog Convertor (DAC)



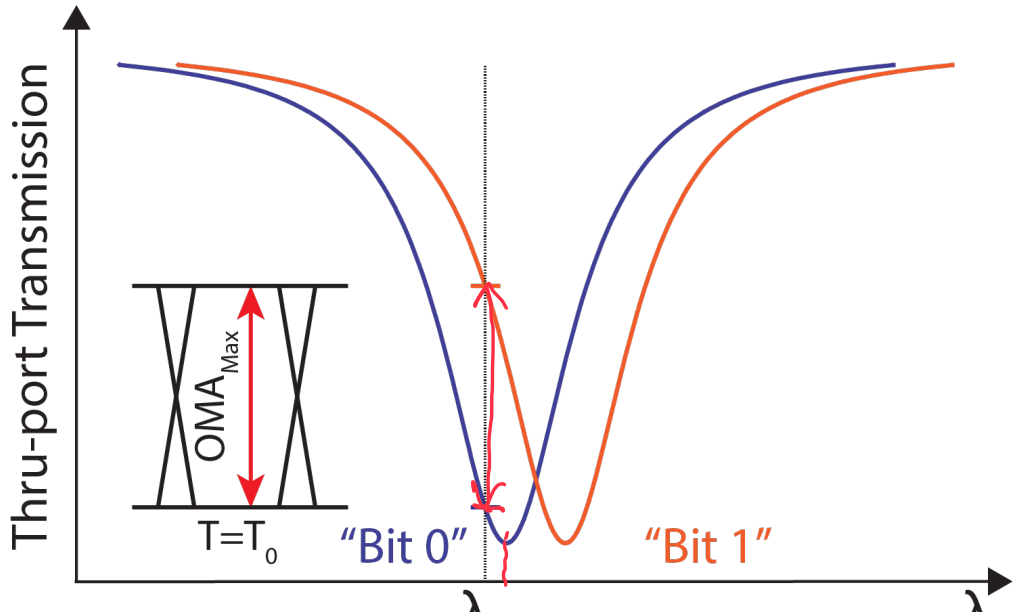
- Drive each segment independently
- Control resonance by depleting a portion of segments
- 64 P + 64 N regions ➔ 6b Optical DAC

[Moazeni *et al.*, ISSCC/JSSC 17]

MRM Transmitter Challenges

2. Thermal Sensitivity of OMA_{TX}

– Temperature variation sources: Circuits, Optical power inside the ring, …



[Moazeni *et al.*, JSSC 17]

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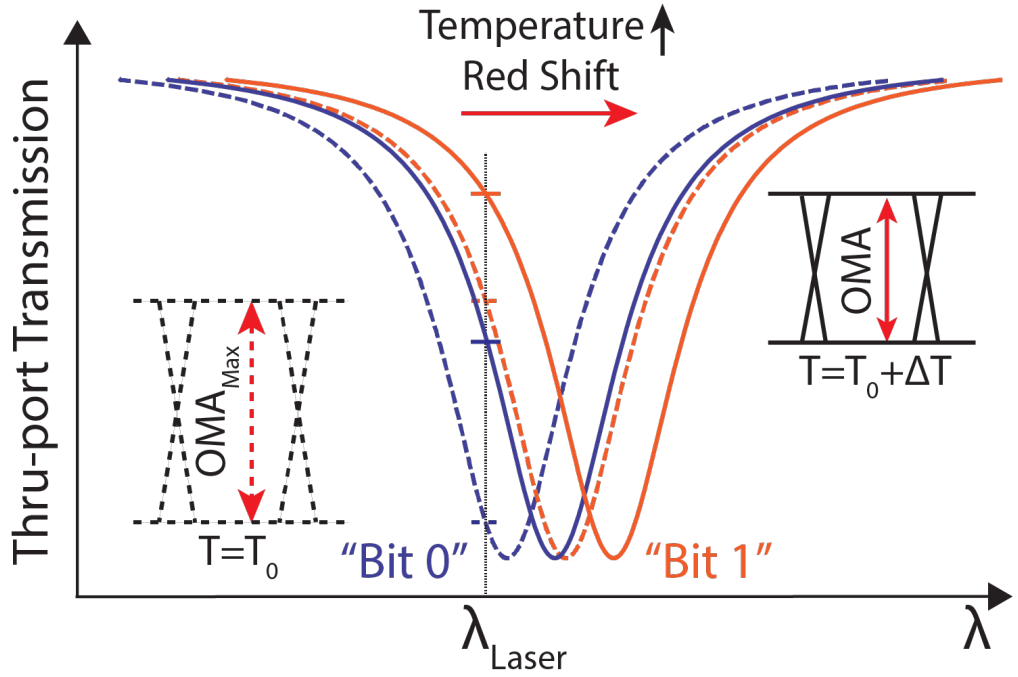

[Moazeni *et al.*, JSSC 17]

MRM Transmitter Challenges

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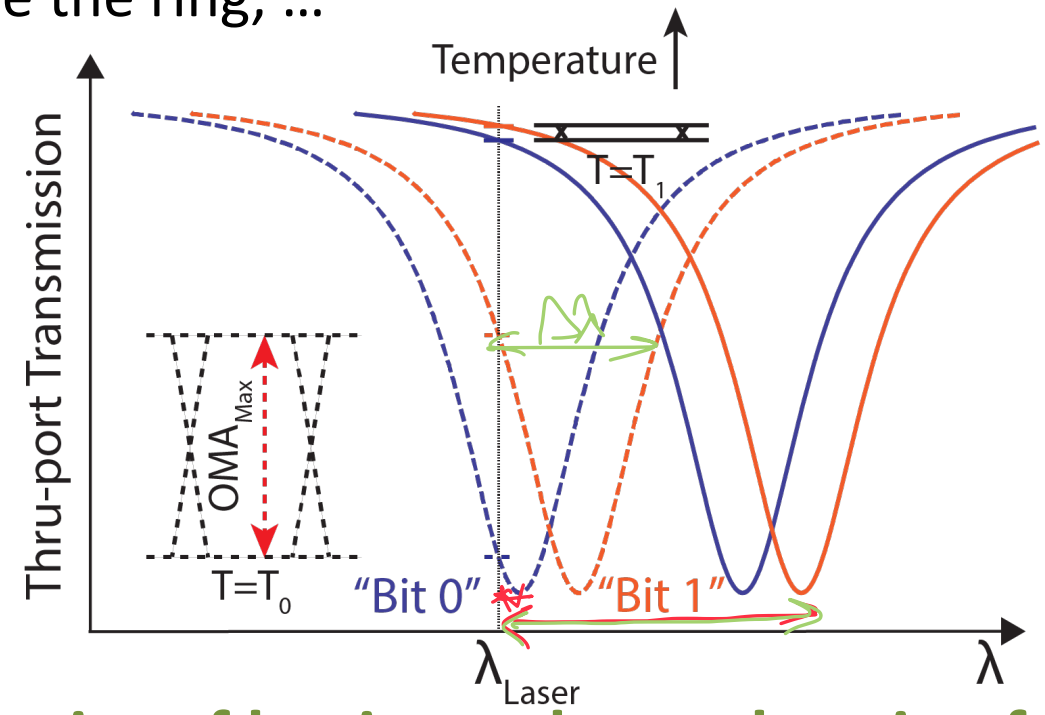
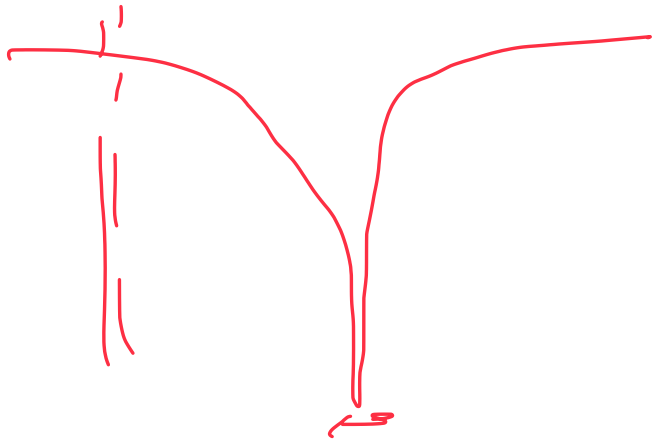




Necessity of having a thermal tuning feedback

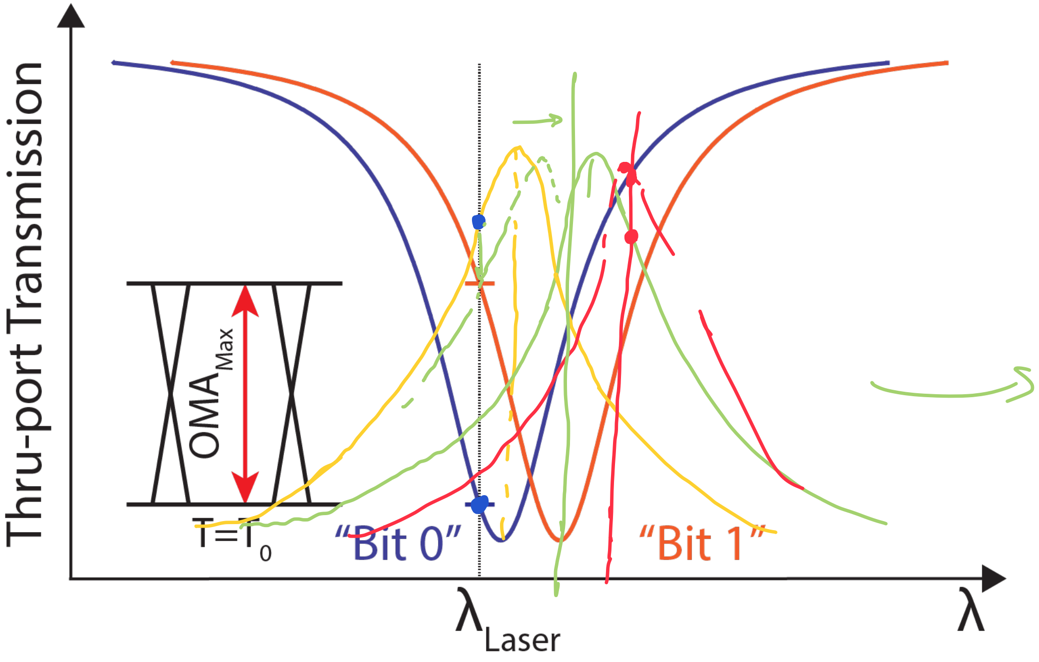
[Moazeni *et al.*, JSSC 17]

Thermal Stability

- Why are we biasing the ring resonance on the right side of the laser?

↑ Opt. inside the ring → $\Delta T > 0$ → $\Delta \lambda_{res} > 0$ → Opt. inside the ring ↓ → neg. fb

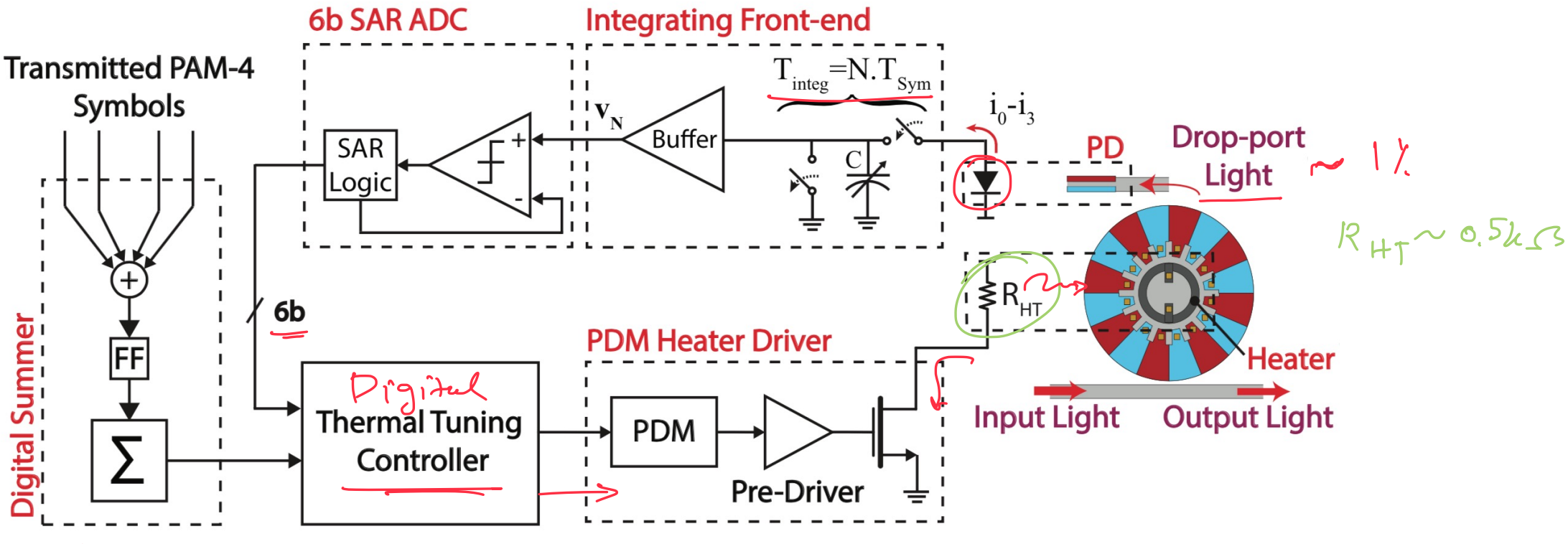
Self-heating



→ positive fb → notch neg. = losses

Chen Sun, MIT thesis

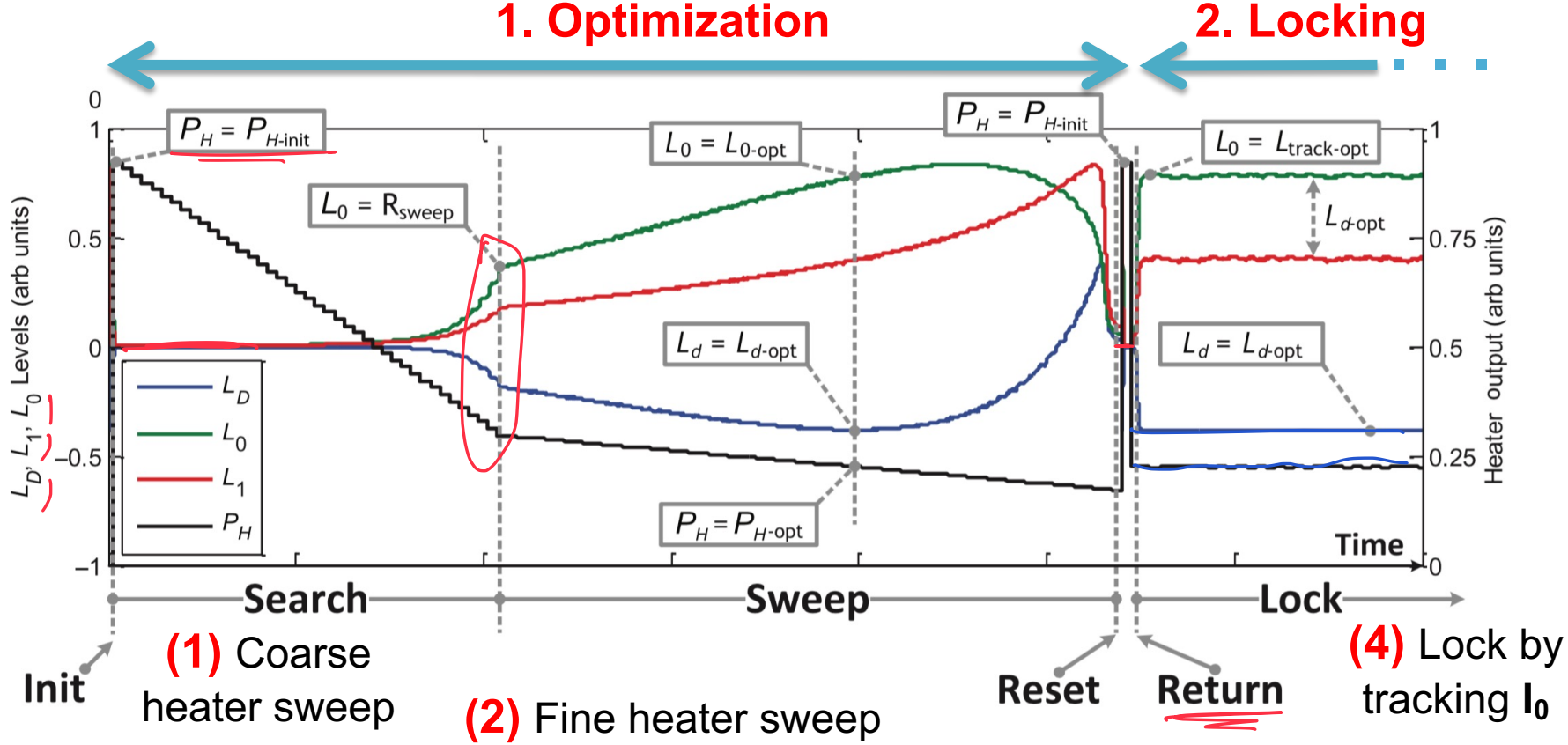
Thermal Tuning for PAM4



- Sense optical power & Adjust heater strength
- Finds and tracks the optimized ring resonance

[Moazeni *et al.*, JSSC 17]

Thermal Tuning Algorithm



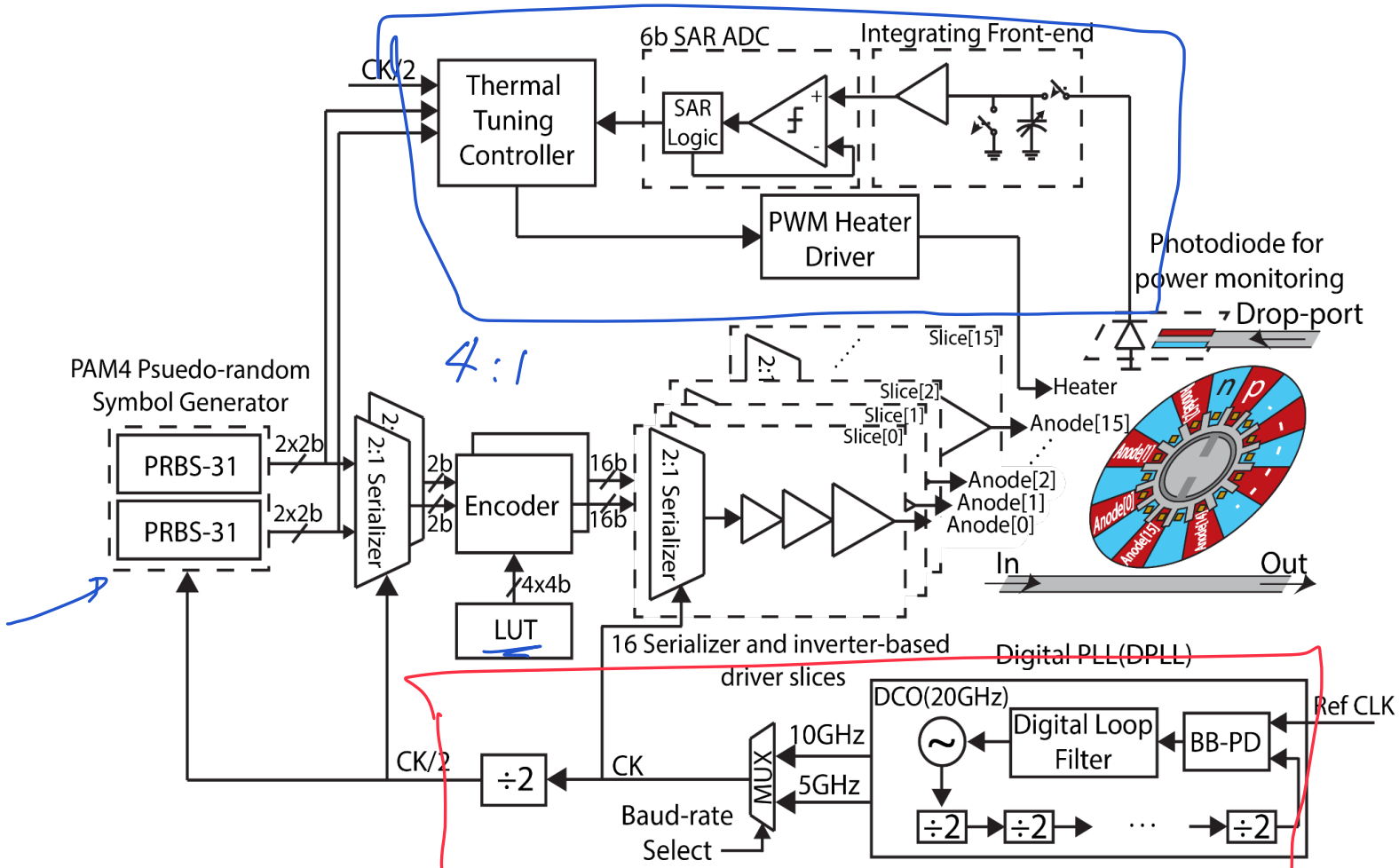
(1) Coarse heater sweep

(2) Fine heater sweep & save P_H where I_d is maximized

(3) Restart heater to optimal $\mathbf{P_H}$

(4) Lock by tracking $\mathbf{I_0}$

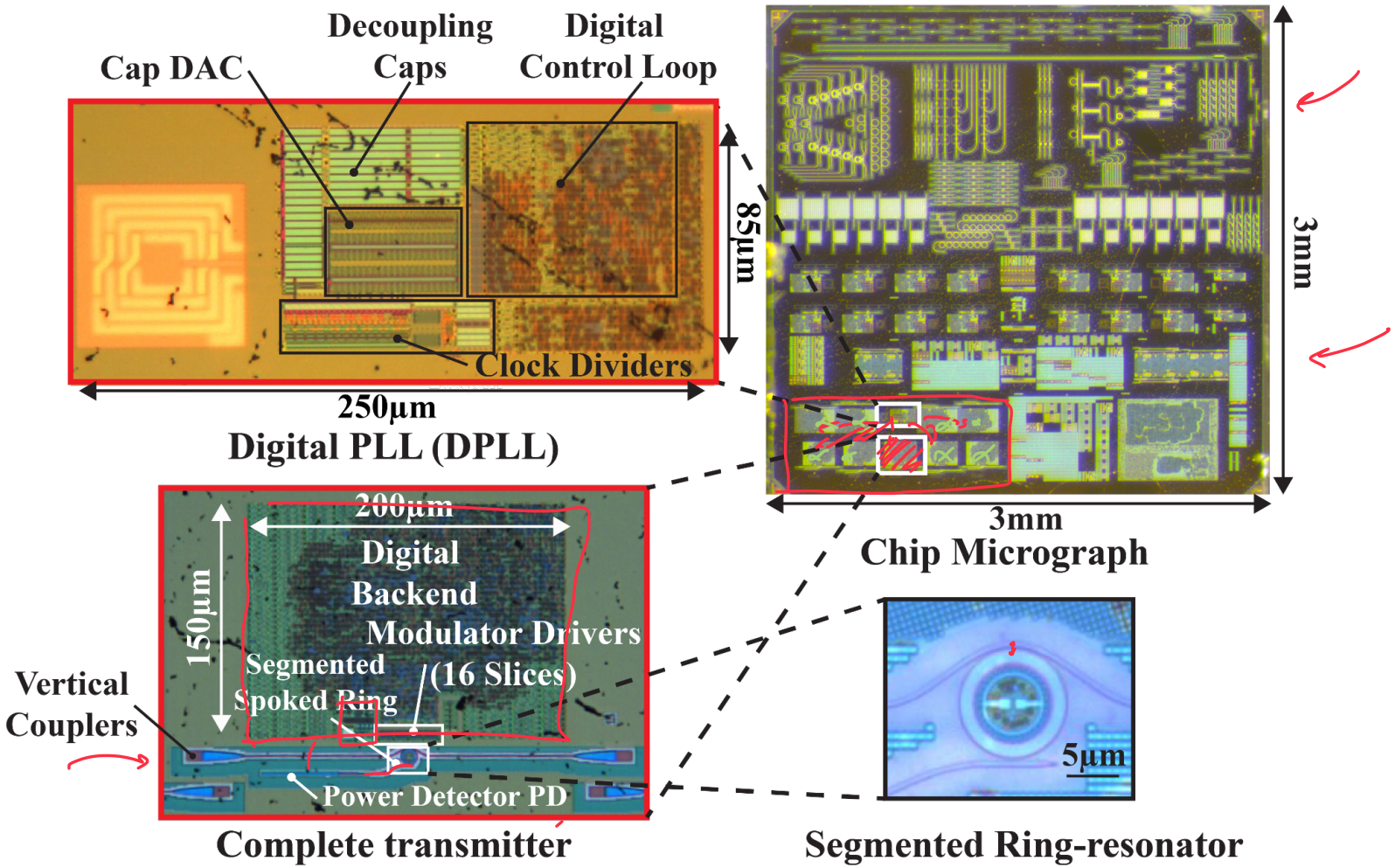
Full Transmitter Architecture



Direct Digital-to-Optical Conversion

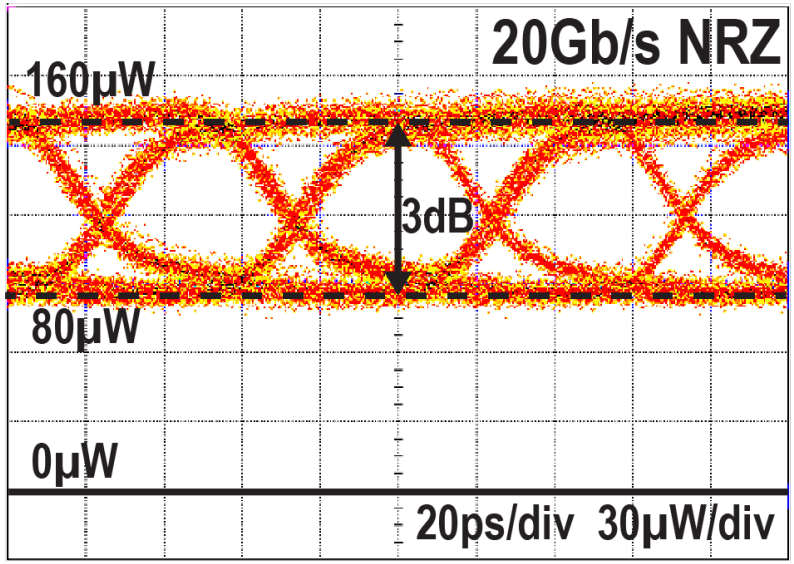
[Moazeni *et al.*, ISSCC/JSSC 17]

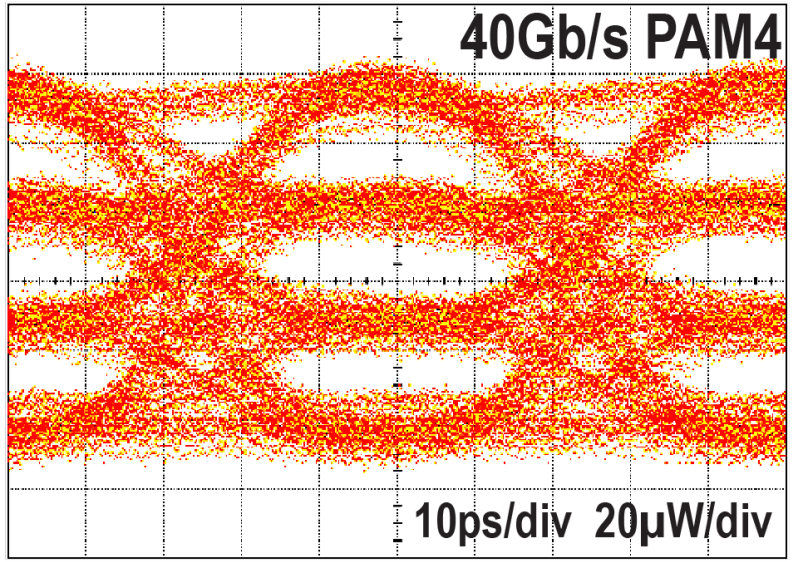
Transmitter Micrographs



[Moazeni *et al.*, ISSCC/JSSC 17]

Transmitter Performance





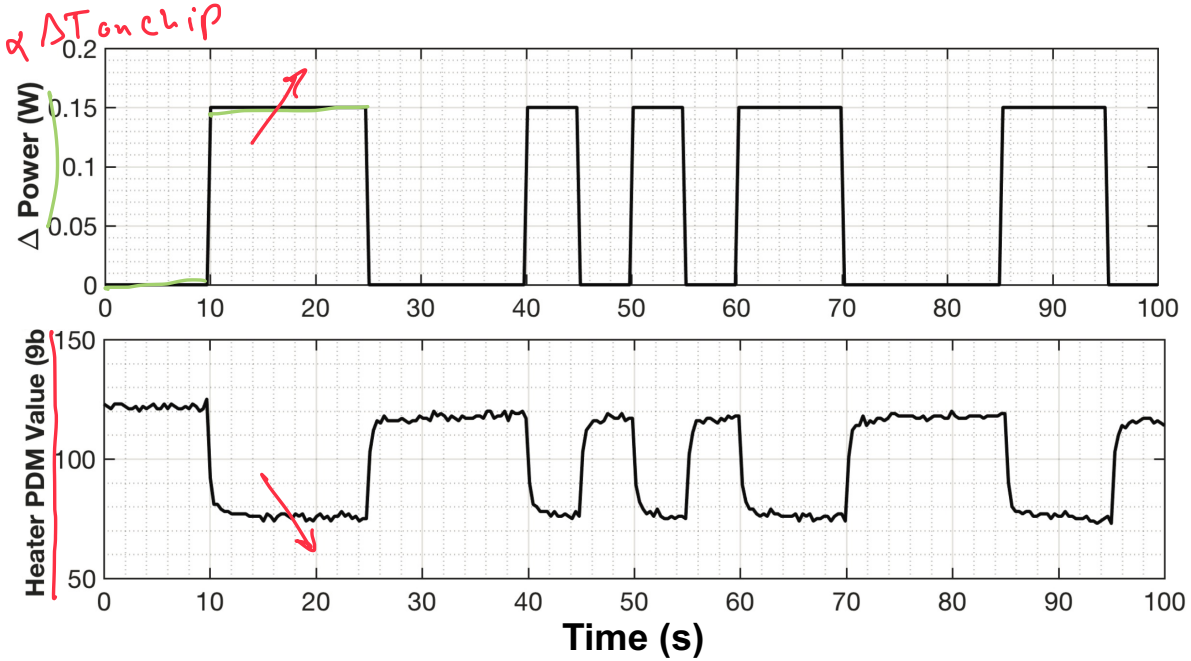
- **42fJ/b** driver energy efficiency
- **3.6Tb/s/mm²** modulator and driver BW density
- Suitable approach for co-integration with processor, memory, …

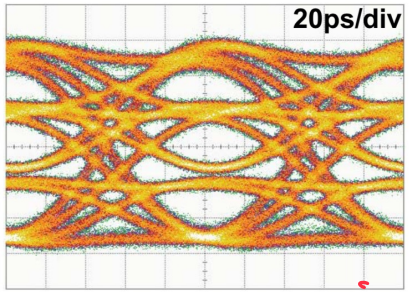
[Moazeni *et al.*, ISSCC/JSSC 17]

Thermal Stress Test

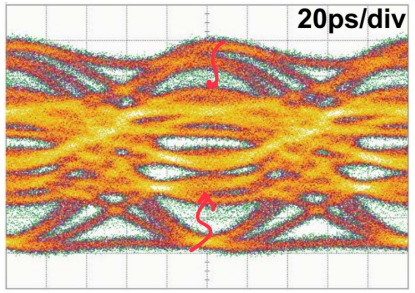
Thermal Perturbations Pattern

Heater Strength

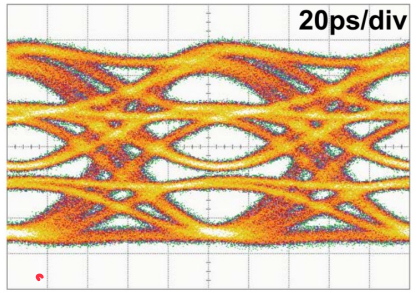




Thermal Stress ***OFF***
Thermal Tuner ***OFF***



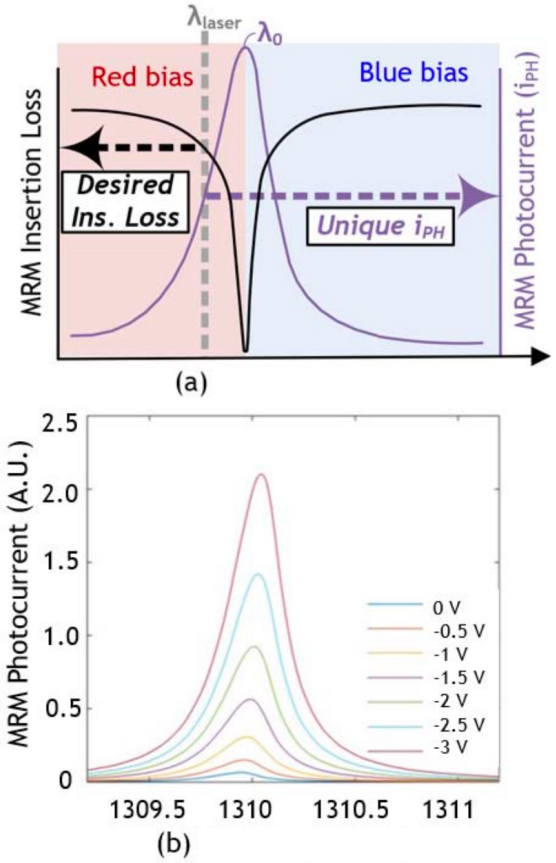
Thermal Stress ***ON***
Thermal Tuner ***OFF***

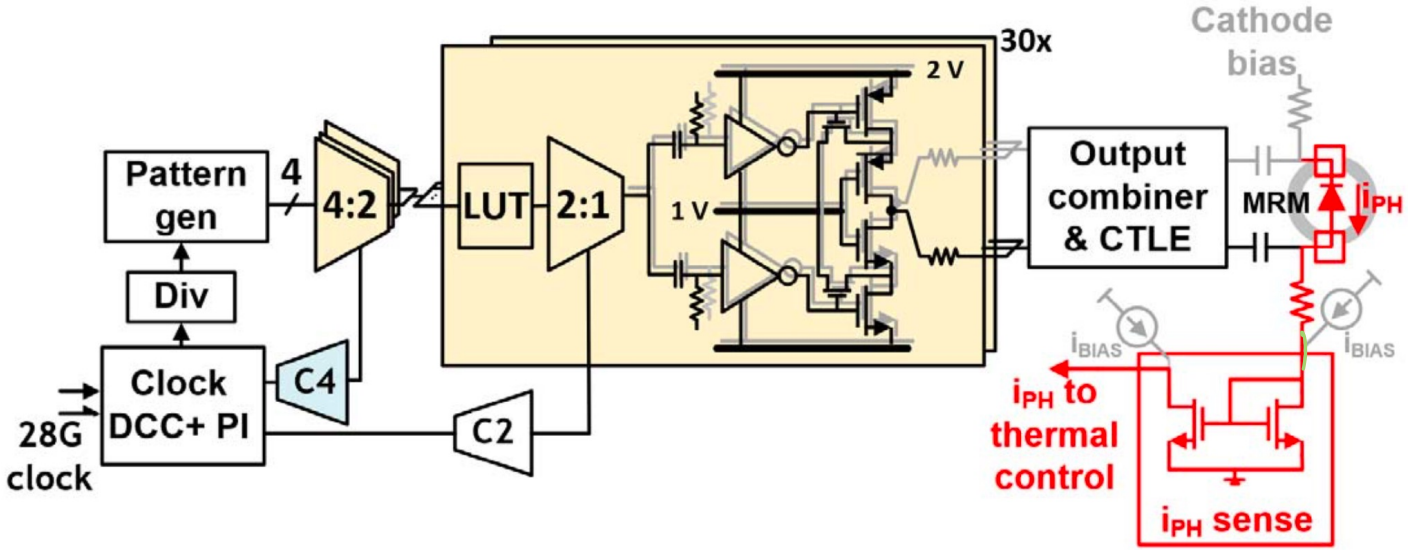


Thermal Stress ***ON***
Thermal Tuner ***ON***

[Moazeni *et al.*, JSSC 17]

Other Thermal Tuning Schemes





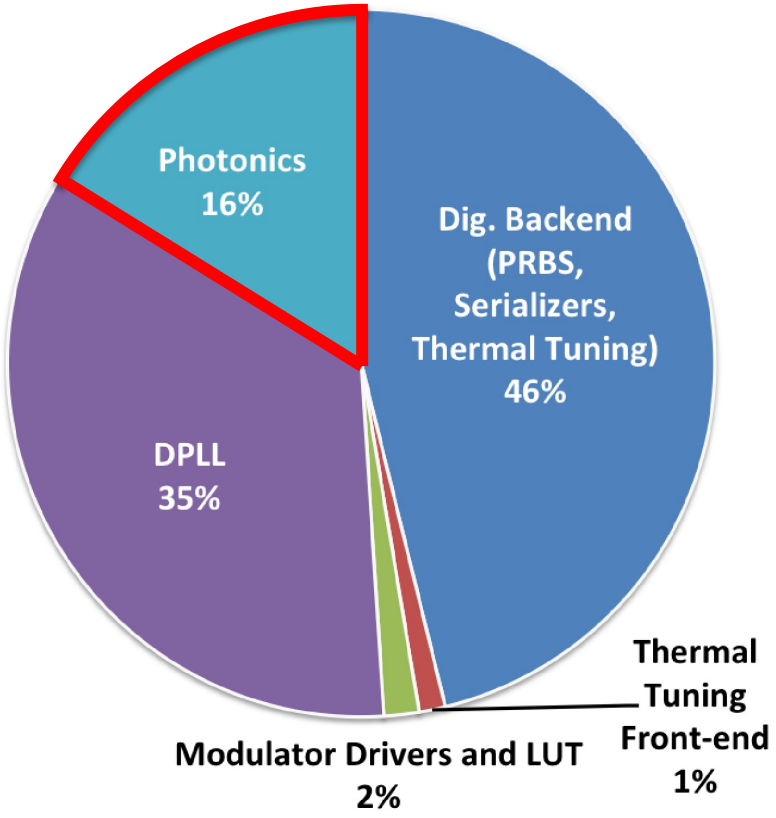
* Sense Opt. inside the ring

* Sense temp. the ring

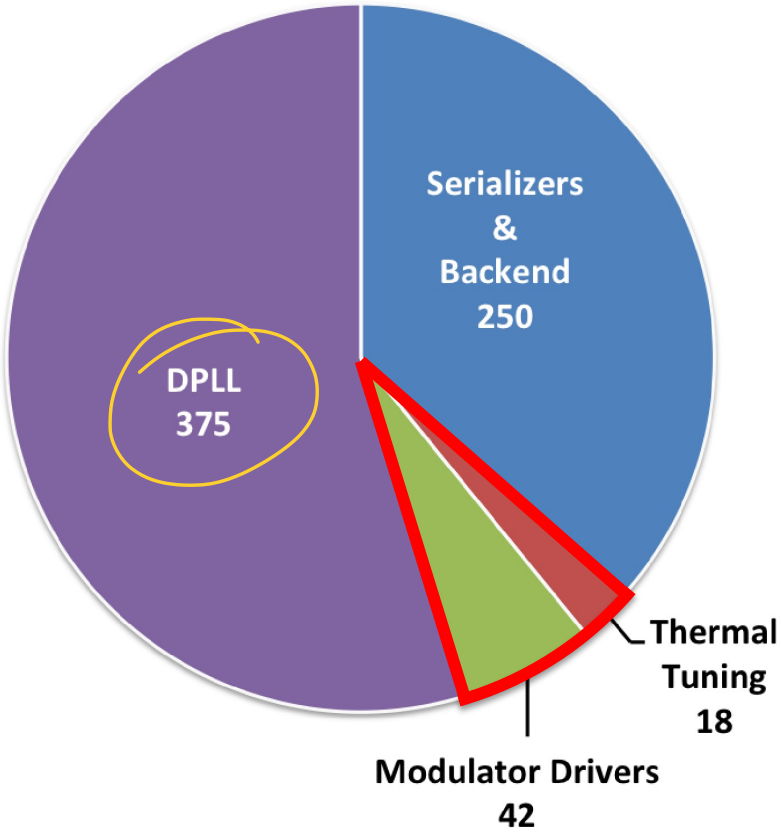
Ref: Silicon Photonic Microring-Based 4 × 112 Gb/s WDM Transmitter With Photocurrent-Based Thermal Control in 28-nm CMOS (JSSC 2022)

Area/Energy Breakdown

Area Breakdown
Total Transmitter Area = 0.06 mm²



Energy Breakdown (in fJ/b)
Total Transmitter Energy = 685fJ/b



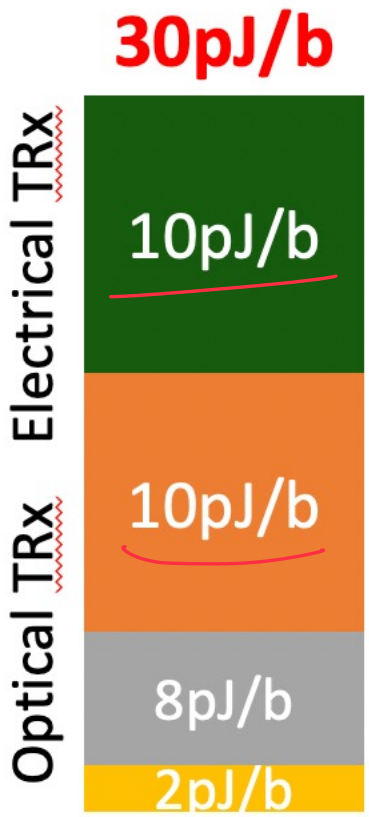
[Moazeni *et al.*, ISSCC/JSSC 17]

PAM4 Tx Performance Summary

Reference	Wu ISSCC 13	Xiong OI 15	Roshan-Zamir OI 16	Intel ISSCC 20	Moazeni ISSCC 17
Integration	Hybrid	Monolithic	Hybrid	Hybrid/3D	Monolithic
CMOS Technology	40nm	90nm	65nm	22nm	45nm
Modulator	MZM	MZM	MRM	MRM	MRM
Driver Supply (V)	1	1.1	2.4	4	1.55
ER/IL (dB)	-	6.3/5	7/5		3/5.5
PAM4 Data-rate (Gb/s)	20	56	40	100	40
Modulator and Driver Energy Efficiency (pJ/b)	0.29	4.8	3.04	6	**0.042**
Modulator and Driver BW Density (Tb/s/mm^2)	0.053	0.036	0.5		**3.6**

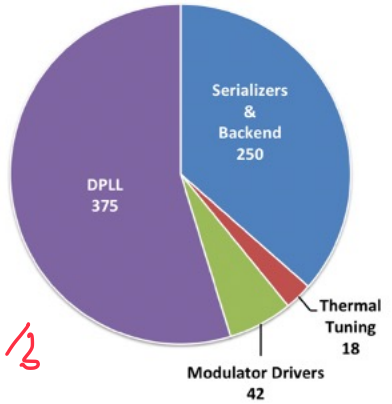
[Moazeni, ISSCC/JSSC 17]

Next-generation Co-packaged Optics

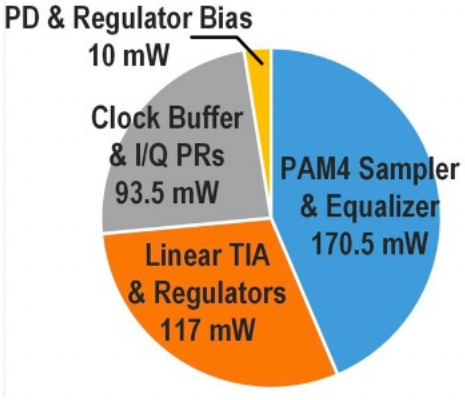


Electrical Link
Transmitter
Laser
Receiver

40Gb/s PAM-4 Tx (0.5pJ/b)
[Moazeni *et al.*, ISSCC17]



100Gb/s PAM-4 Rx (3.9pJ/b)
[Li *et al.*, ISSCC21]



7.5x

4pJ/b

>4x

Sub-pJ/b

Commercial Pluggable Silicon-Photonic (SiPh)
< 100Gb/s/mm

Co-packaged (45nm) Monolithic SiPh
> 0.5Tb/s/mm

Monolithic Photonics in Sub-10nm (?)
Multi-Tb/s/mm

Packaging & Test Setup