

# **EE 437/538B: Integrated Systems**

## **Capstone/Design of Analog Integrated Circuits and Systems**

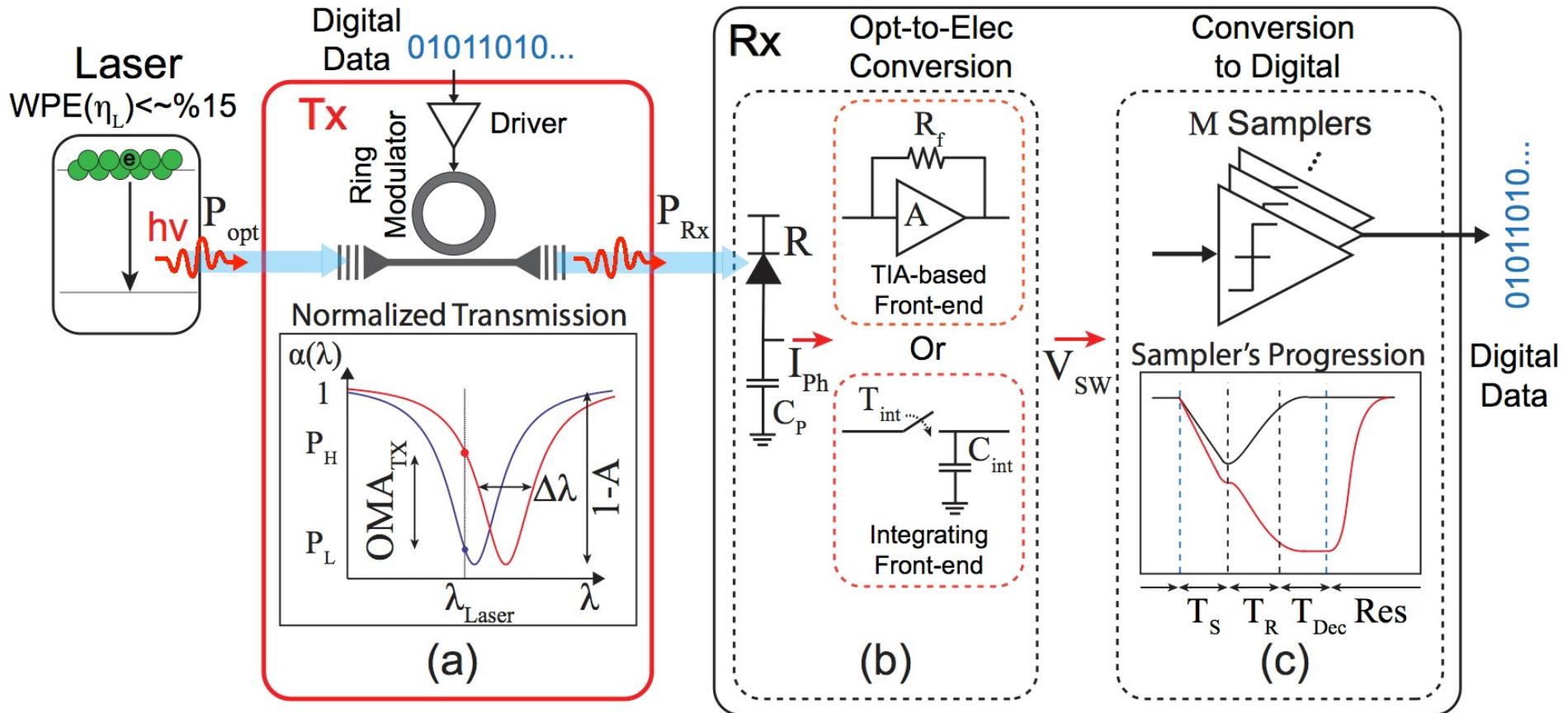
### **Lecture 6: Optical TRx (Part 2)**

Prof. Sajjad Moazeni

[smoazeni@uw.edu](mailto:smoazeni@uw.edu)

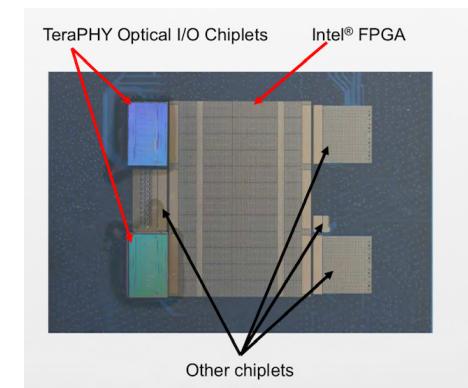
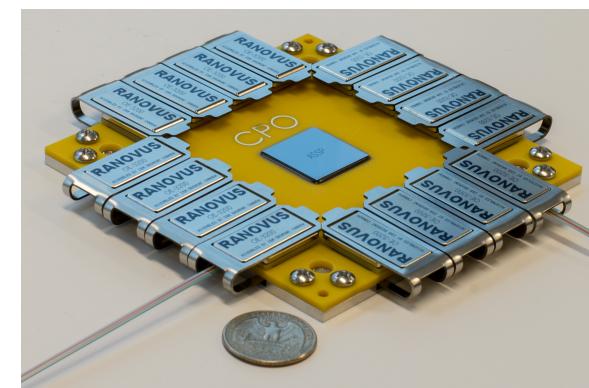
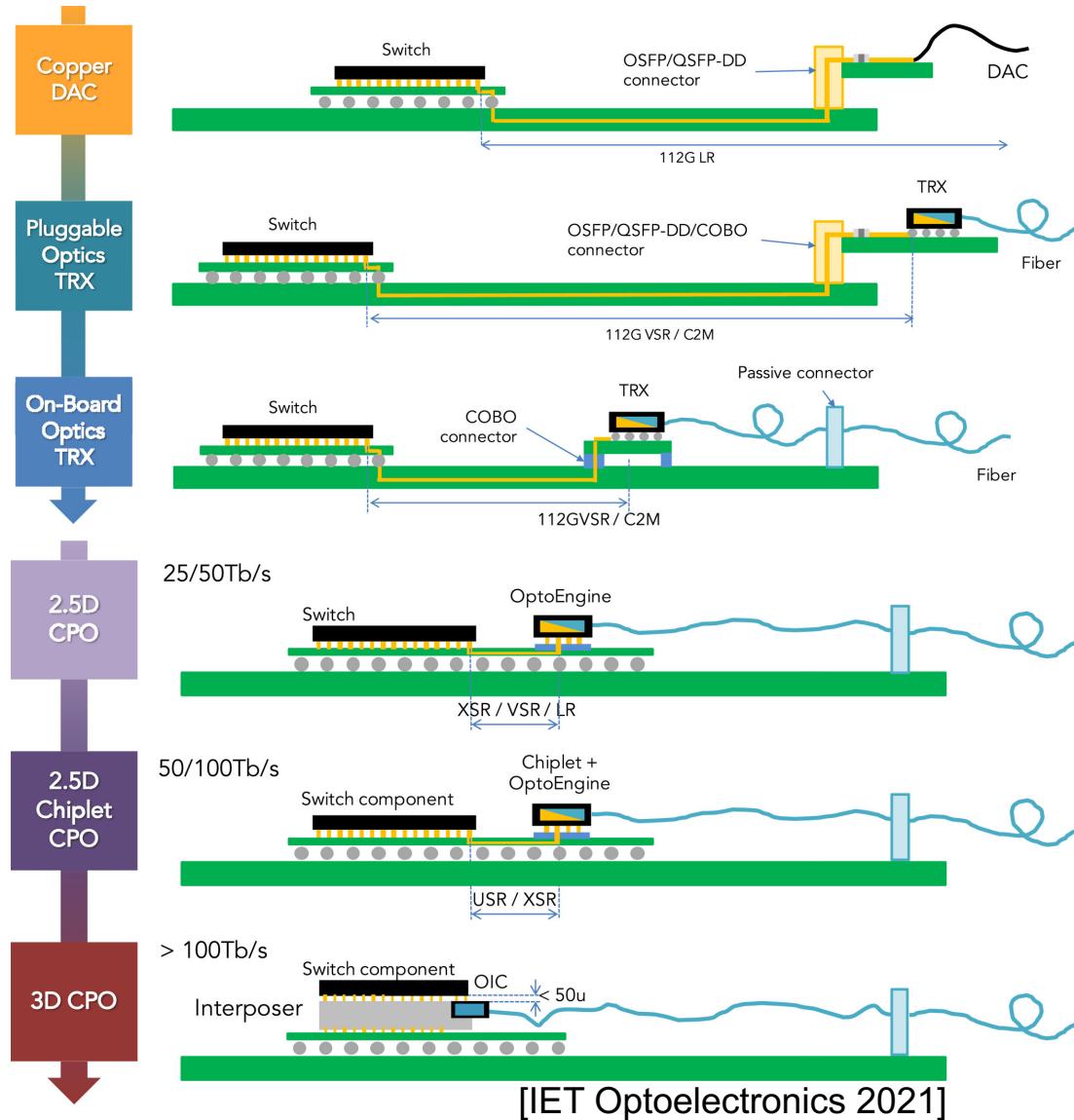
Spring 2022

# A Full Photonic Link

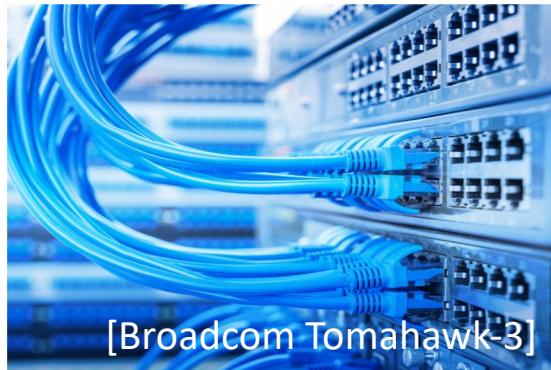


- Receiver sensitivity: Min optical power for a certain data-rate & BER ( $P_{\text{Rx,in}}$ )

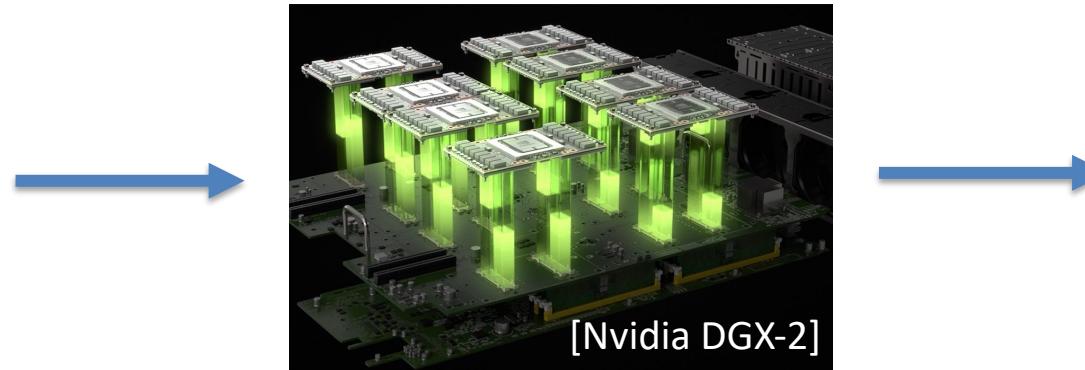
# Today vs. Near-future E/O Modules



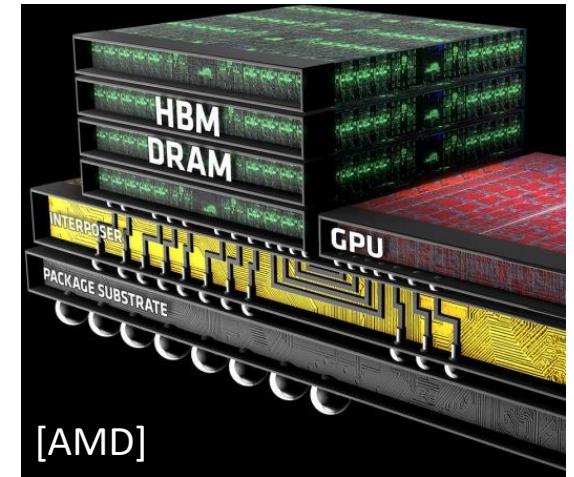
# *Emerging Needs for Photonics*



**32x400 Gb/s**

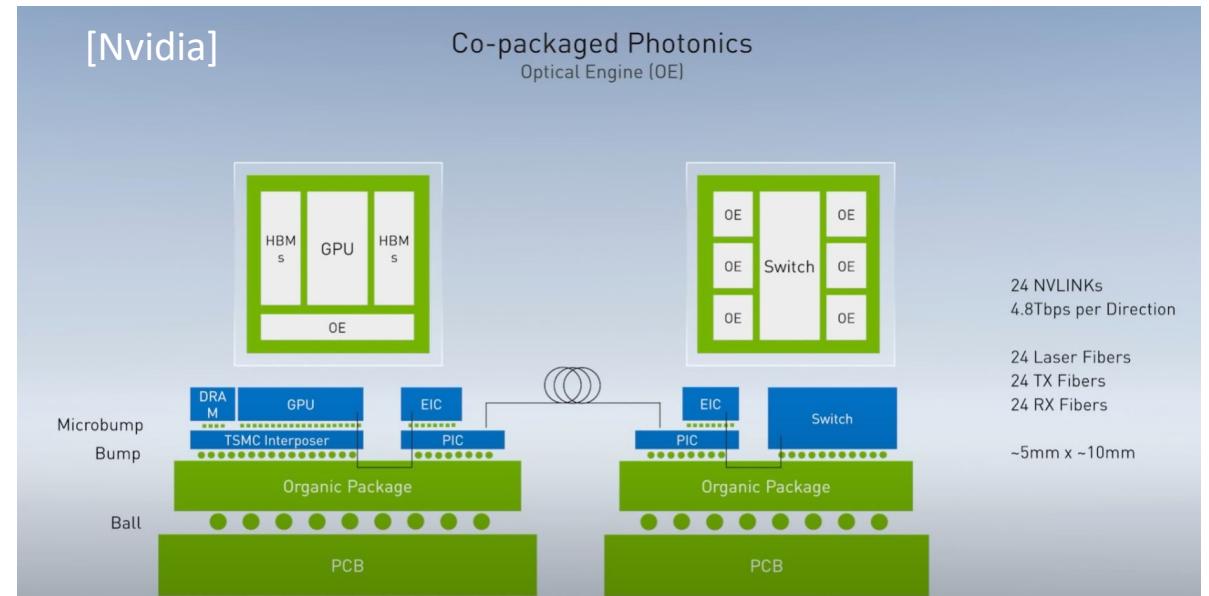


**4.8Tb/s**

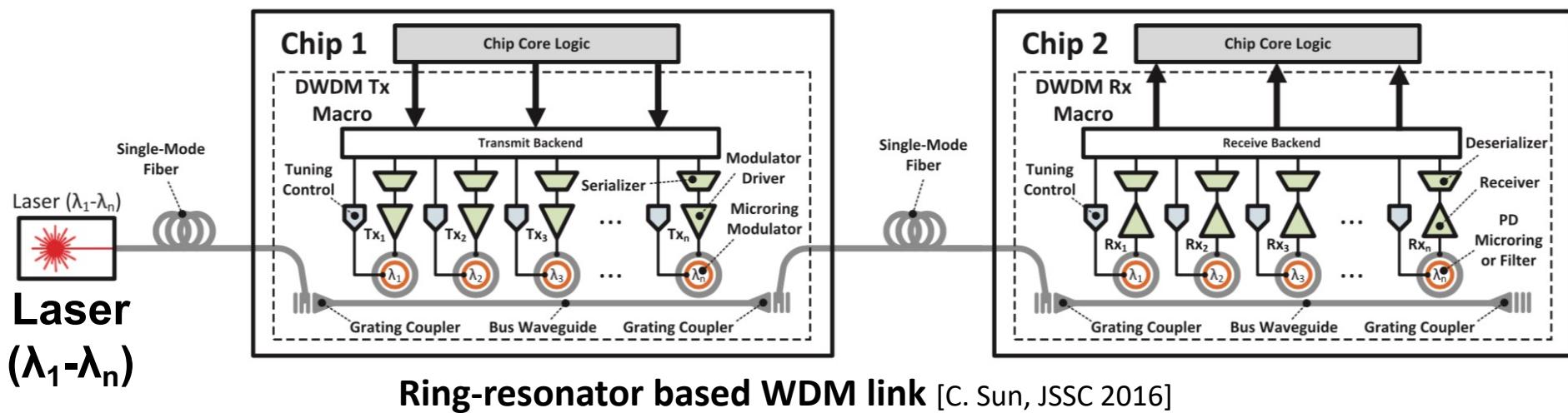
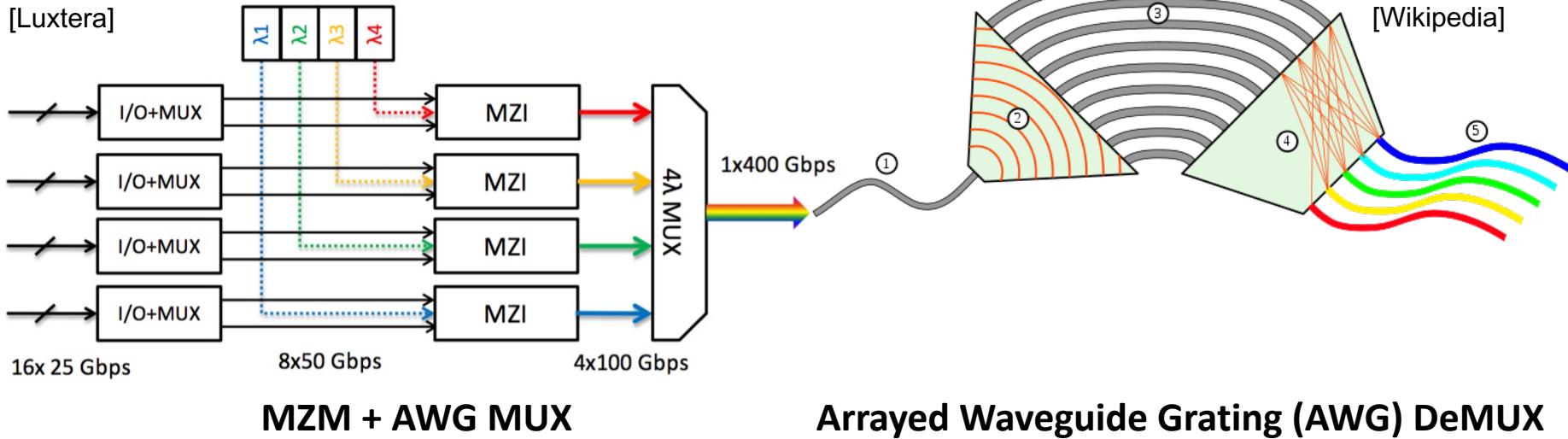


**[AMD]**

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



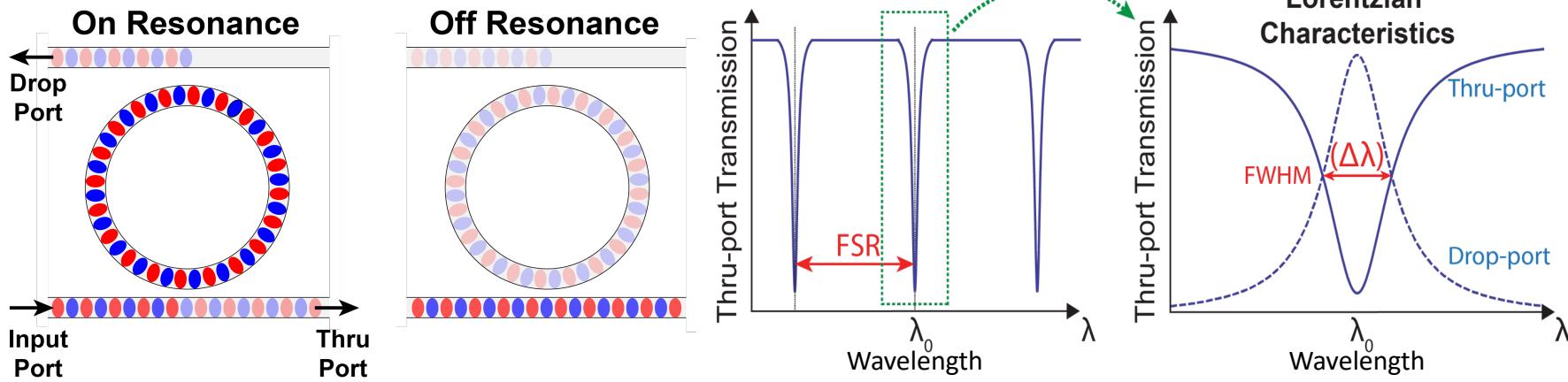
# WDM Optical I/O



# Important Metrics

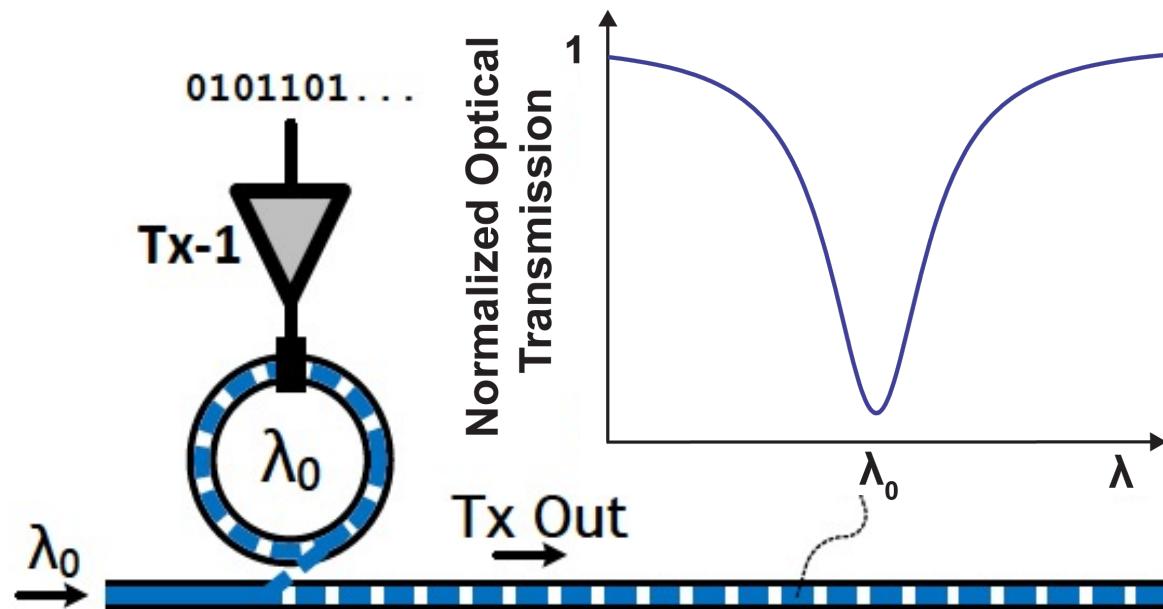
Metric		SiPh TRx [Ayar Labs]	Near Future Needs (<5yr)
Aggregate Data-rate	Tb/s	0.8	>1.6Tb/s (per fiber)
# Wavelengths	#	32	-
Data-rate per channel	Gb/s	25Gb/s	+100Gb/s
Energy-efficiency	pJ/b	5pJ/b	<1pJ/b
Edge BW density	Tb/s/mm		>1Tb/s/mm
Tx Ext. Ratio	db	5	
BER	1E-X	1e-12	
Latency	ns	10ns + 5ns/m	
Cost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

# Micro-ring Modulator (MRM)



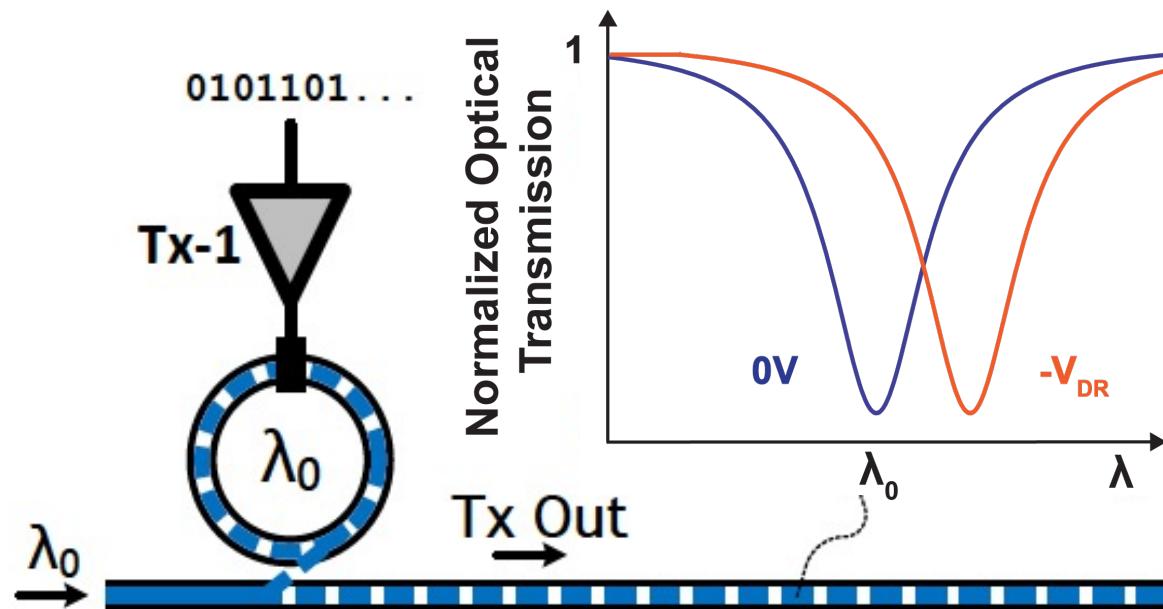
- Resonance wavelength:  $\lambda_0 = n_{\text{eff}} L/m$ ,  $m = 1, 2, 3, \dots$ 
  - Q-factor:  $Q = \lambda_0 / \Delta\lambda$
- Compact device (radius of  $5\mu\text{m}$ )
  - Energy & area efficient modulator/filter
- Supporting wavelength division multiplexing (WDM)

# *MRM based Optical Links*



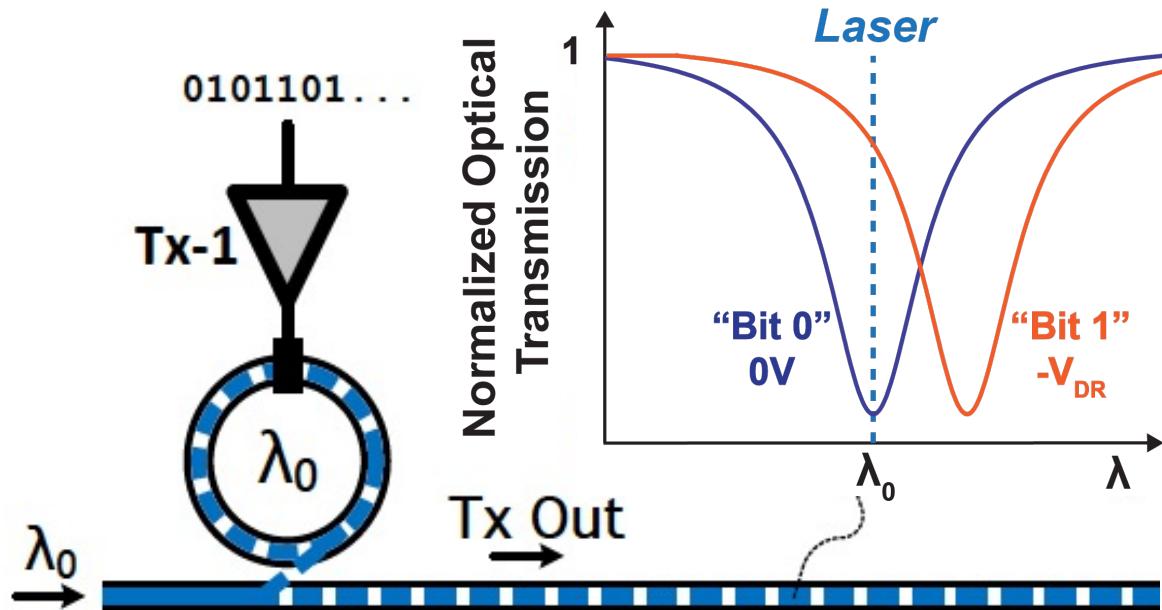
- Modulation Scheme:
  1. Deplete/Inject carriers using PN junctions

# *MRM based Optical Links*



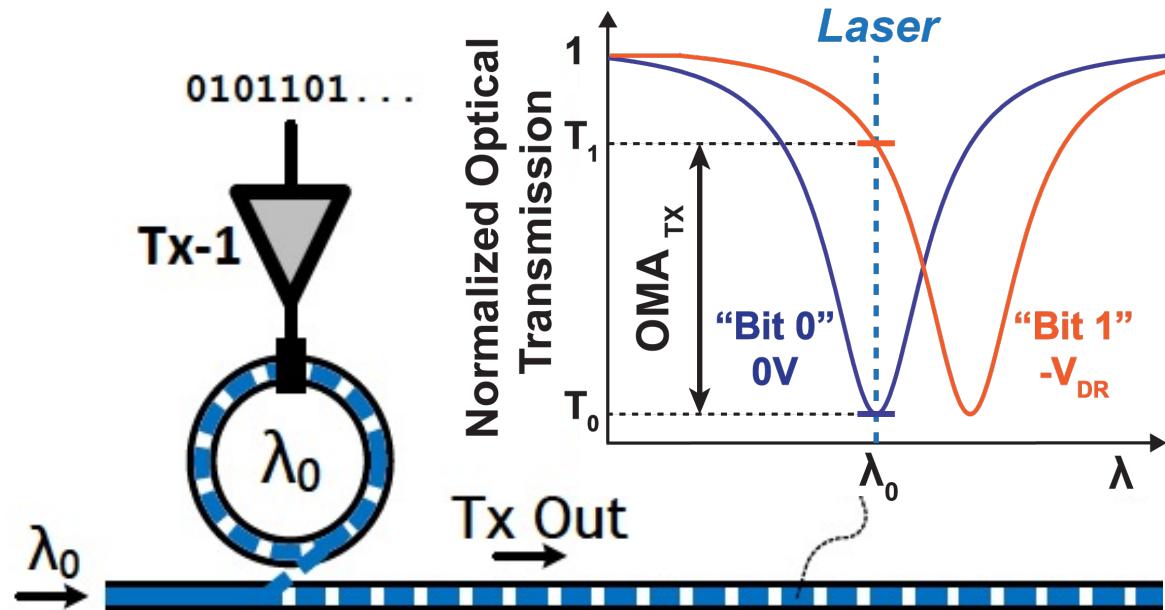
- Modulation Scheme:
  1. Deplete/Inject carriers using PN junctions
  2. Δfree carriers → Δindex of refraction [Carrier-Plasma Effect]

# MRM based Optical Links



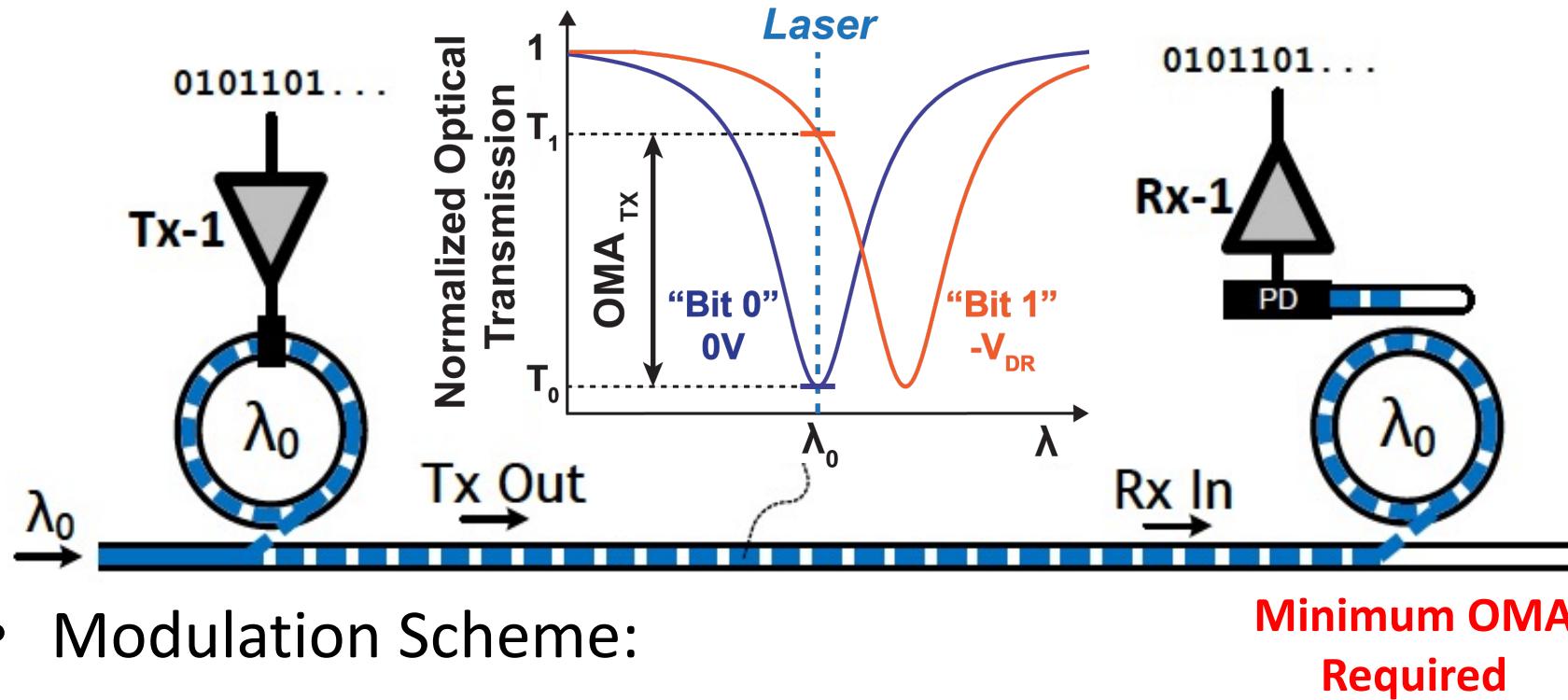
- Modulation Scheme:
  1. Deplete/Inject carriers using PN junctions
  2.  $\Delta$ free carriers  $\rightarrow \Delta$ index of refraction [Carrier-Plasma Effect]
  3. On-Off Keying (OOK) modulation

# MRM based Optical Links



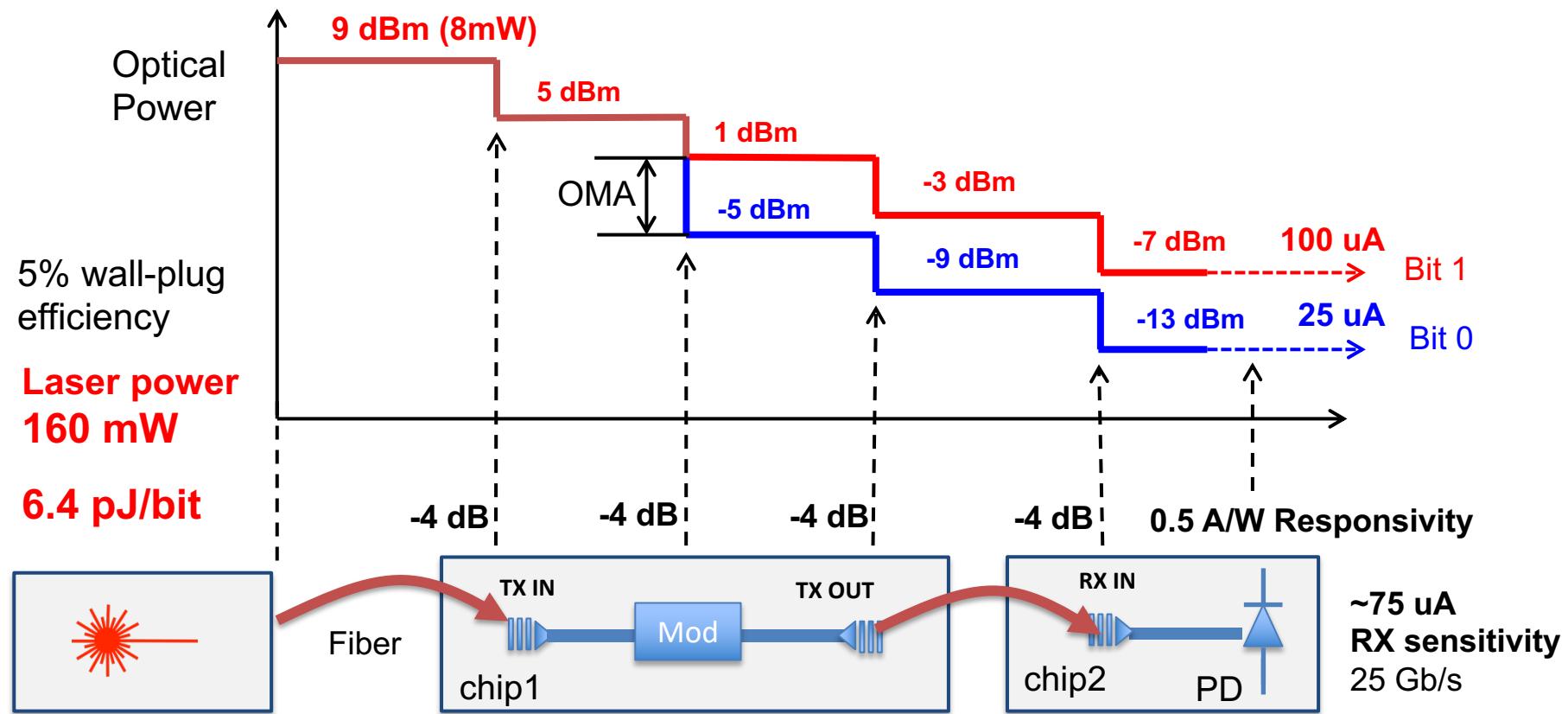
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  1. Deplete/Inject carriers using PN junctions
  2.  $\Delta$ free carriers  $\rightarrow \Delta$ index of refraction [Carrier-Plasma Effect]
  3. On-Off Keying (OOK) modulation
- \*. **OMA:** Optical Modulation Amplitude

# MRM based Optical Links



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

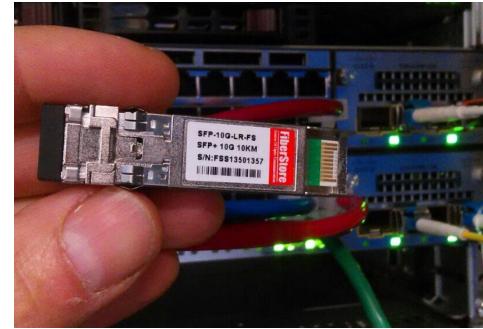
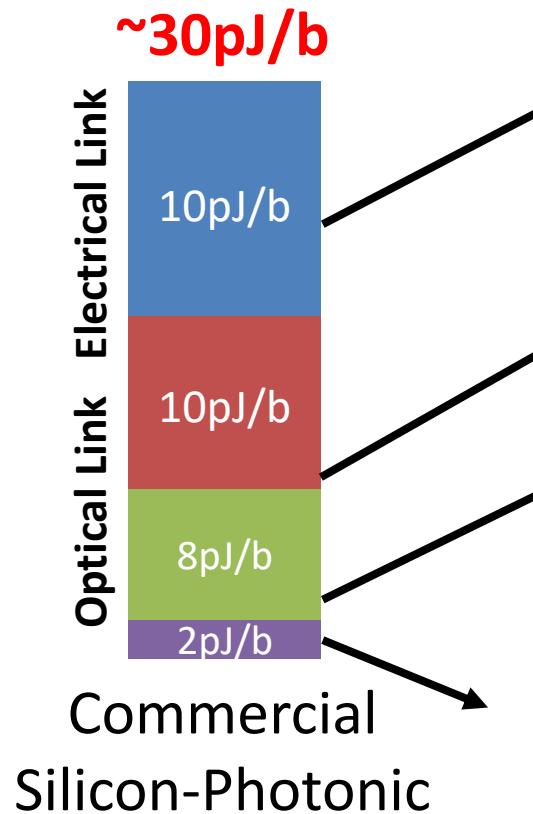
# Optical Power Breakdown in an Optical Link



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

# *Energy-efficiency of Photonic Links*

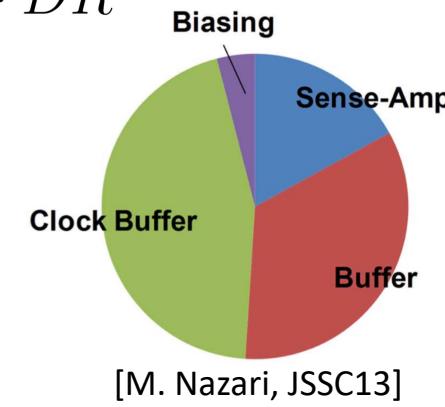
■ Electrical Link   ■ Laser  
■ Transmitter   ■ Receiver



Modulator driver + SerDes +  
Clocking + ...

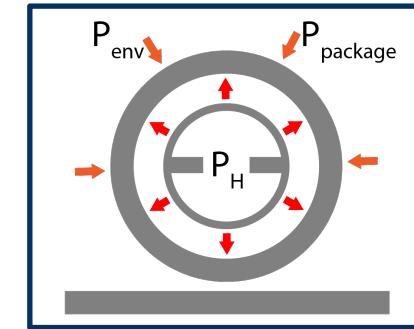
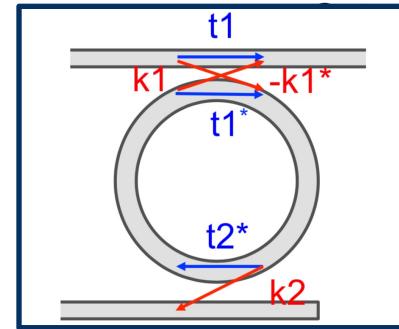
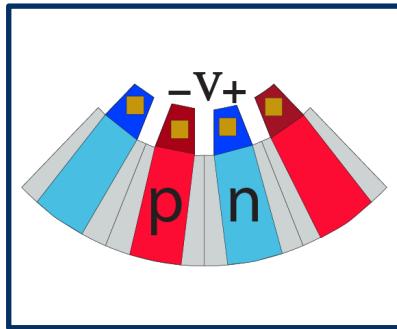
$$E_L = \frac{P_{RX,Min}}{\eta_L \cdot \Gamma_L \cdot OMA_{TX} \cdot DR}$$

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



# *Pushing to Higher Data-rates*

## Electrical Behavior      Optical Behavior      Thermal Behavior



**Behavioral Model**  
(MATLAB / Verilog-A)

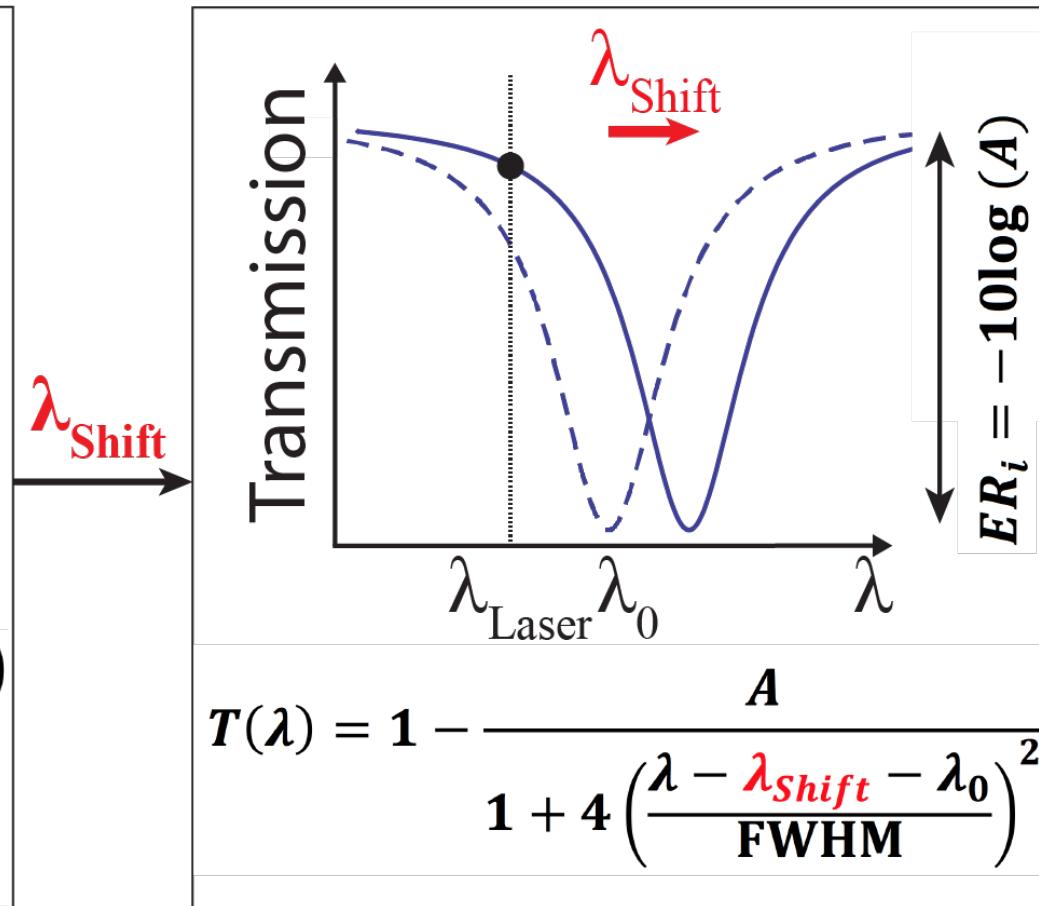
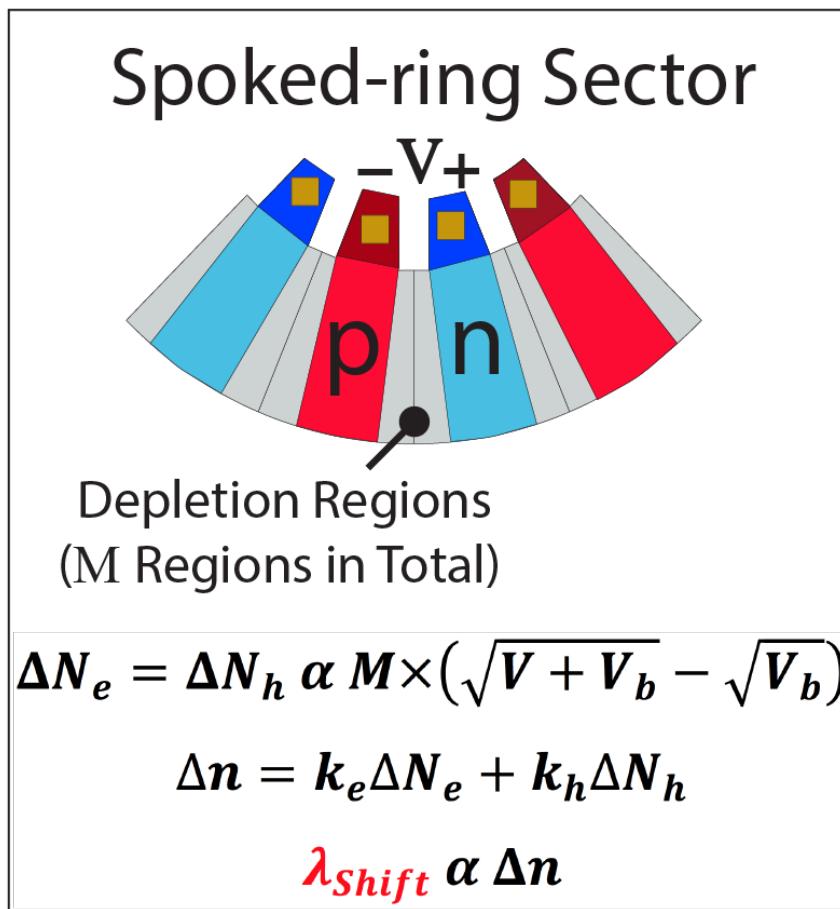
Limited Modulation  
Bandwidth

Thermal Sensitivity  
Of OMA<sub>TX</sub>

Non-linearity, ...

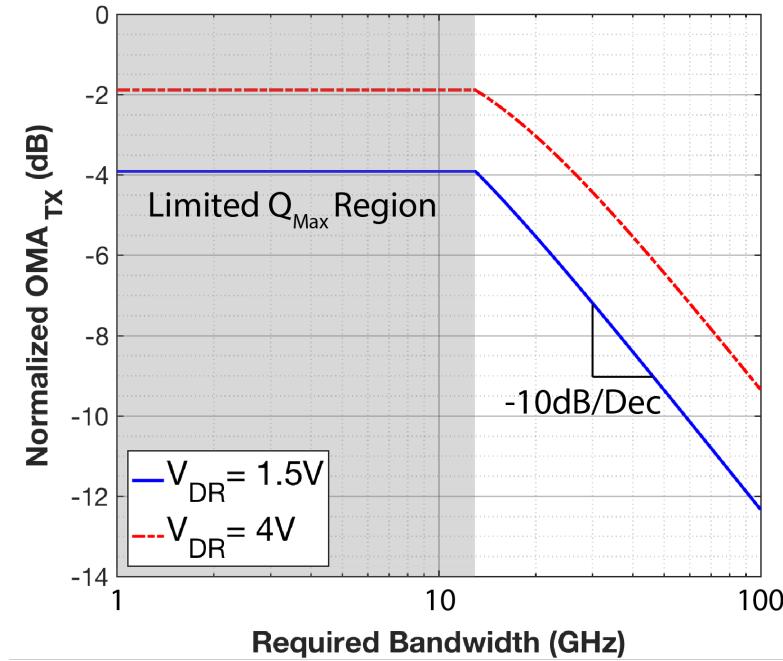
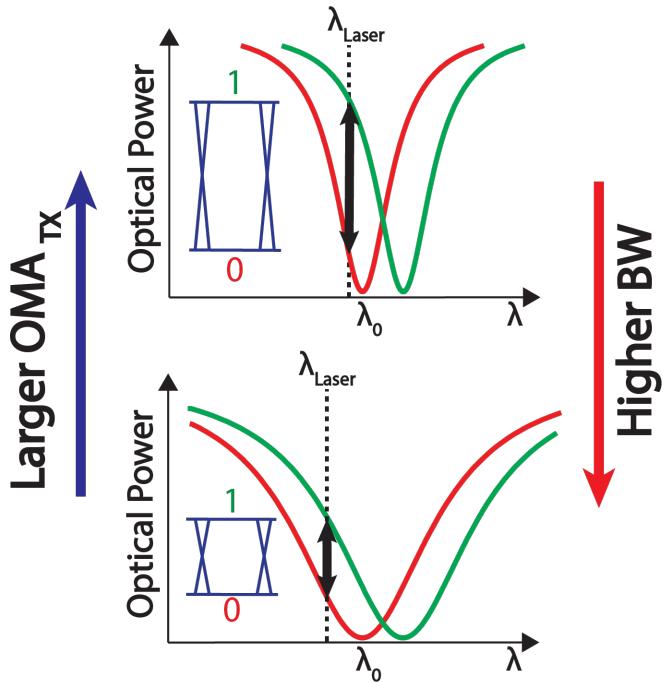
[Moazeni *et al.*, JSSC 17]

# Behavioral Modeling



# MRM Transmitter Challenges

## 1. Limited Modulation Bandwidth: Trade-off between bandwidth & OMA<sub>TX</sub>

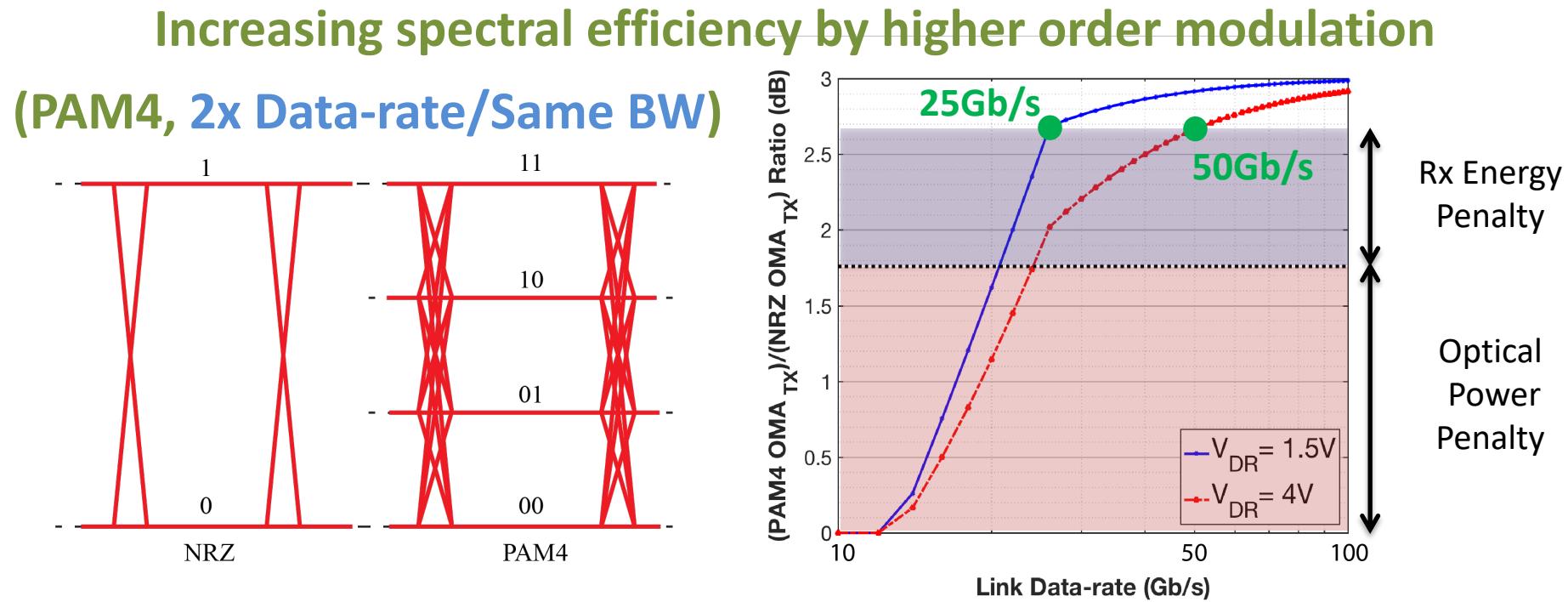


**Smaller OMA<sub>TX</sub> → Larger transmitter & laser energy**

[Moazeni *et al.*, JSSC 17]

# MRM Transmitter Challenges

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

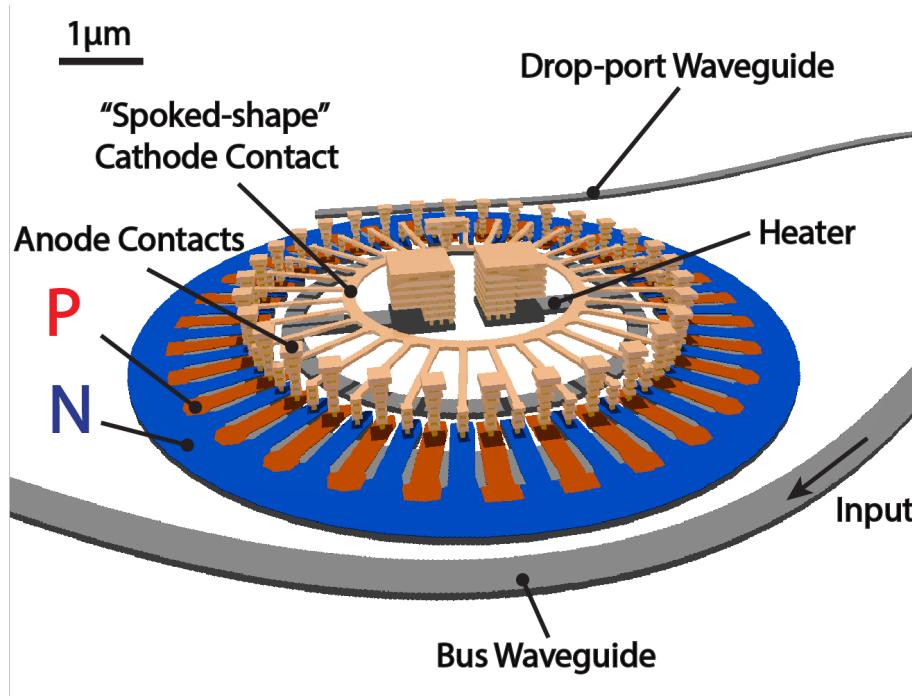


**How to generate multi-level optical intensities efficiently?**

[Moazeni *et al.*, JSSC 17]

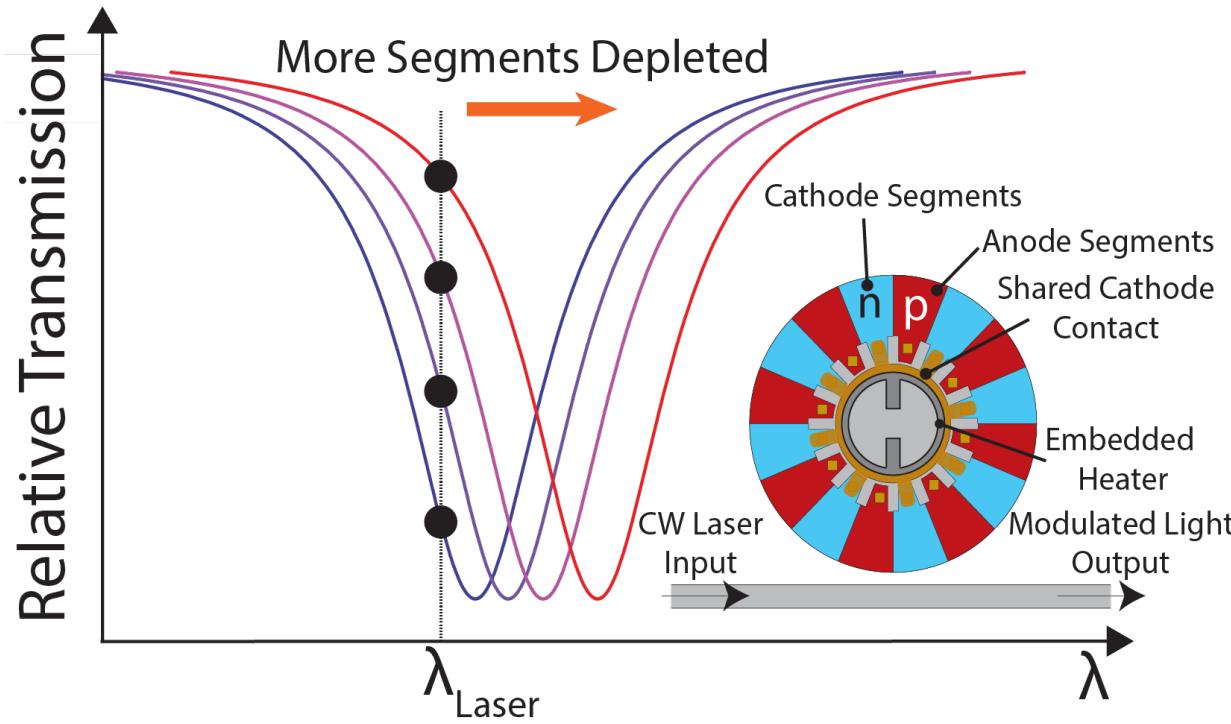
# *MRM in Zero-change Platforms*

- 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)



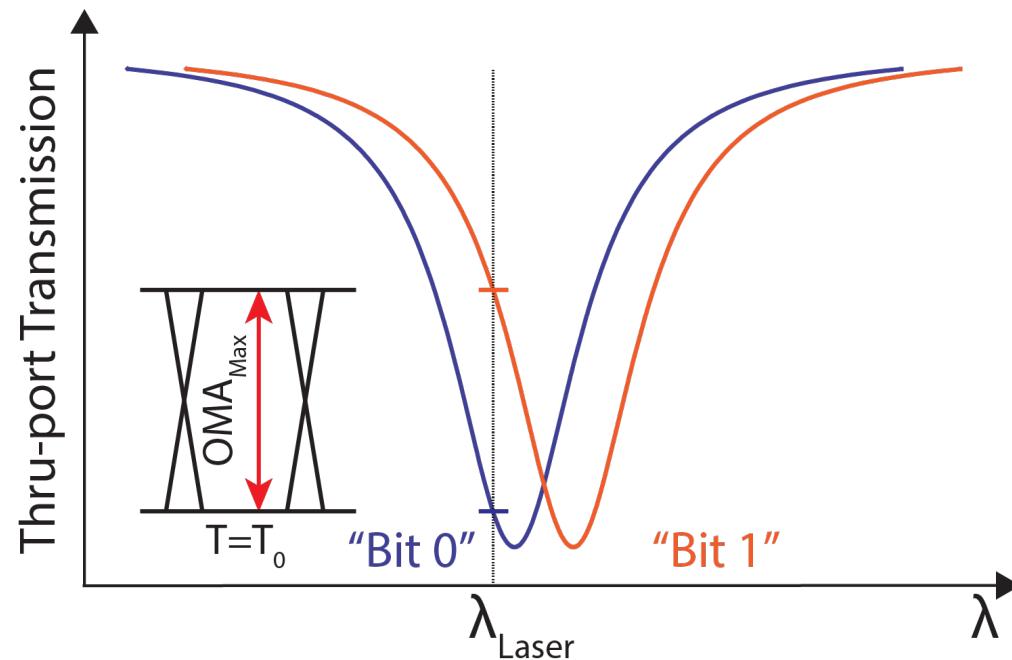
- Drive each segment independently
- Control resonance by depleting a portion of segments
- 64 P + 64 N regions → 6b Optical DAC

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

# MRM Transmitter Challenges

## 2. Thermal Sensitivity of OMA<sub>TX</sub>

- Temperature variation sources: Circuits, Optical power inside the ring, ...

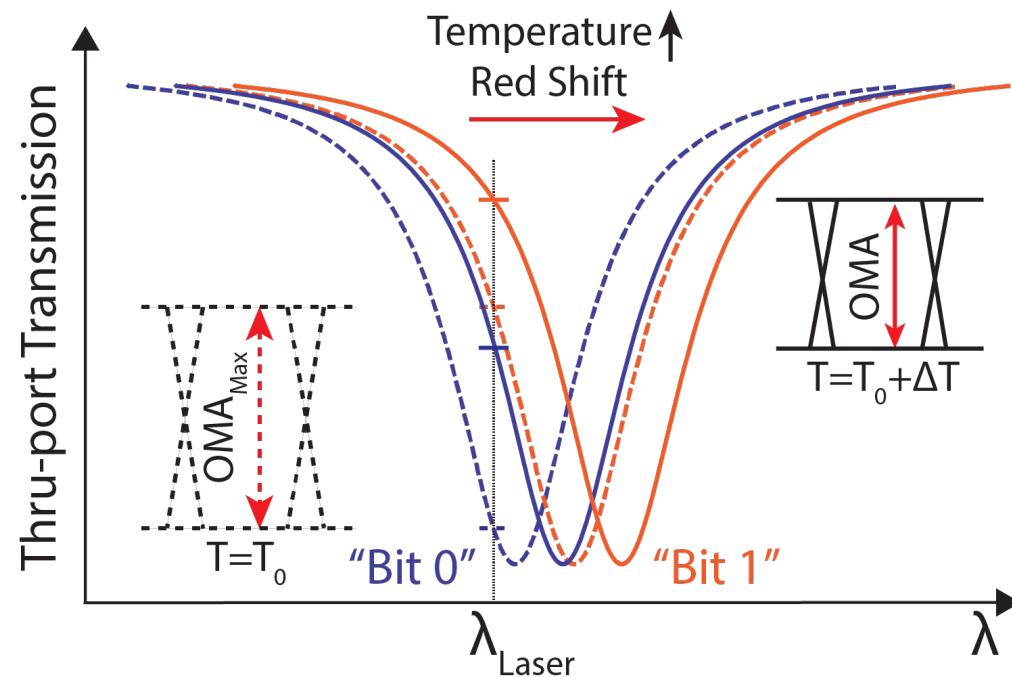


[Moazeni *et al.*, JSSC 17]

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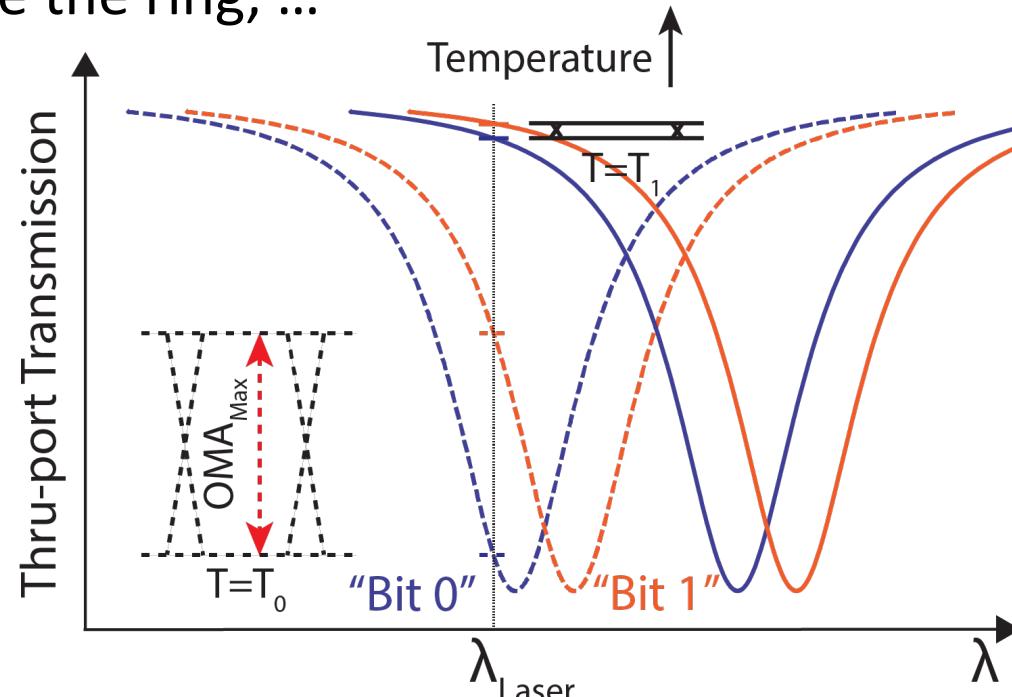


[Moazeni *et al.*, JSSC 17]

# MRM Transmitter Challenges

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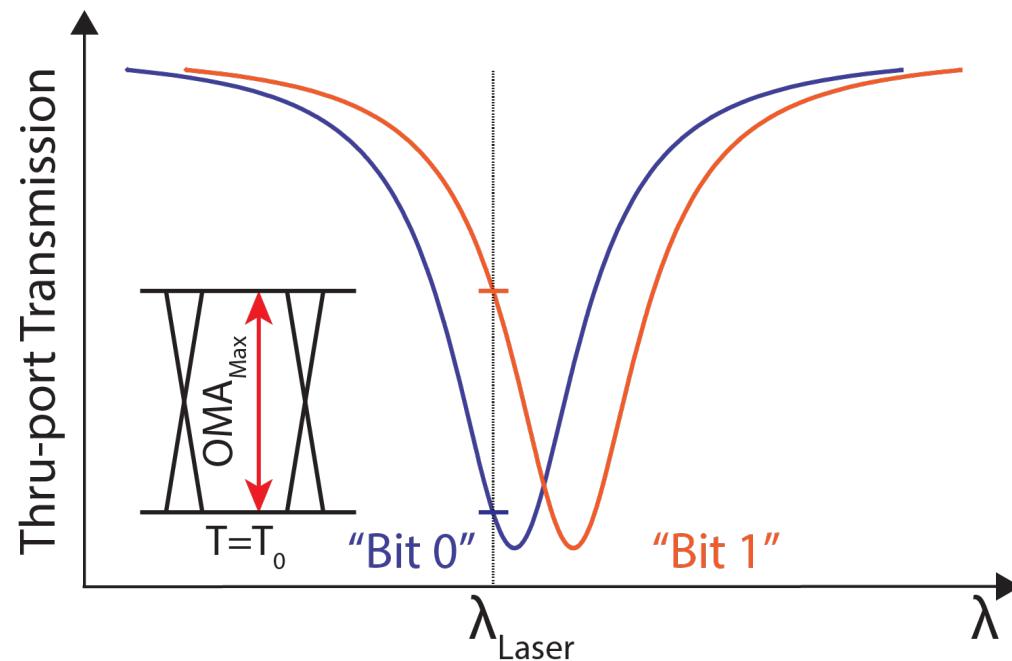


Necessity of having a thermal tuning feedback

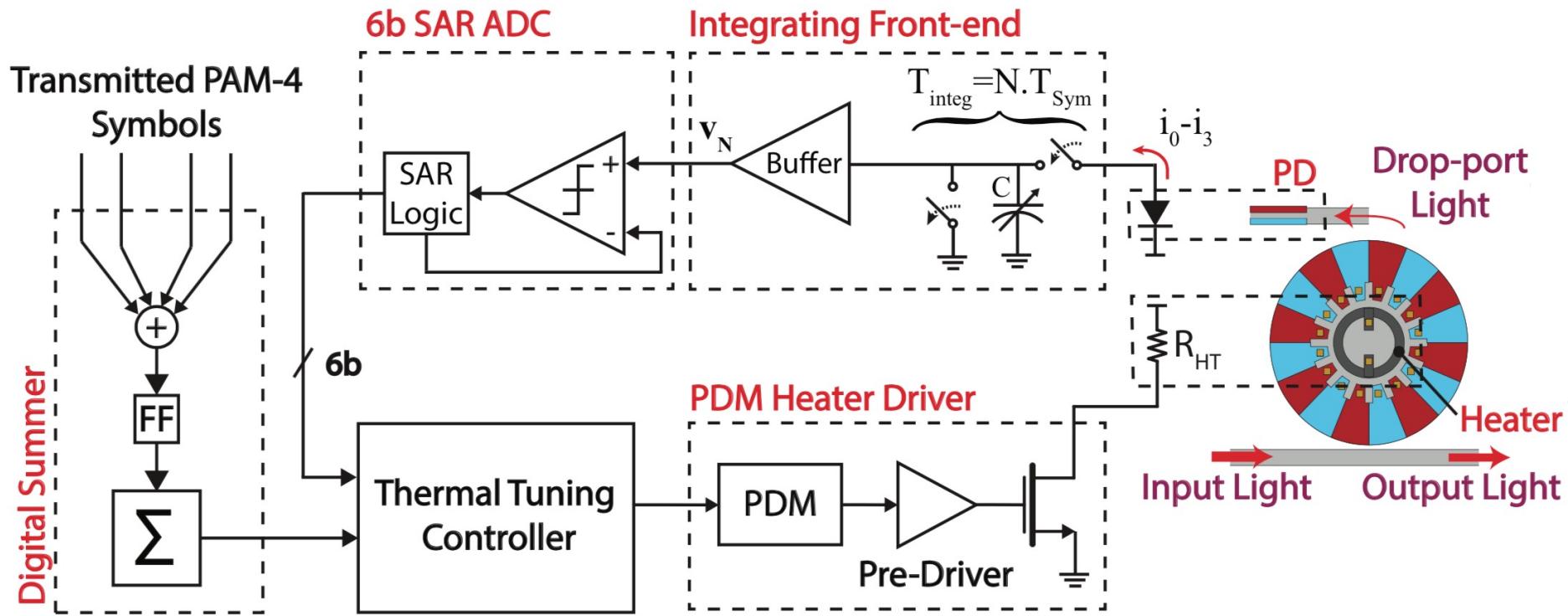
[Moazeni *et al.*, JSSC 17]

# *Thermal Stability*

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



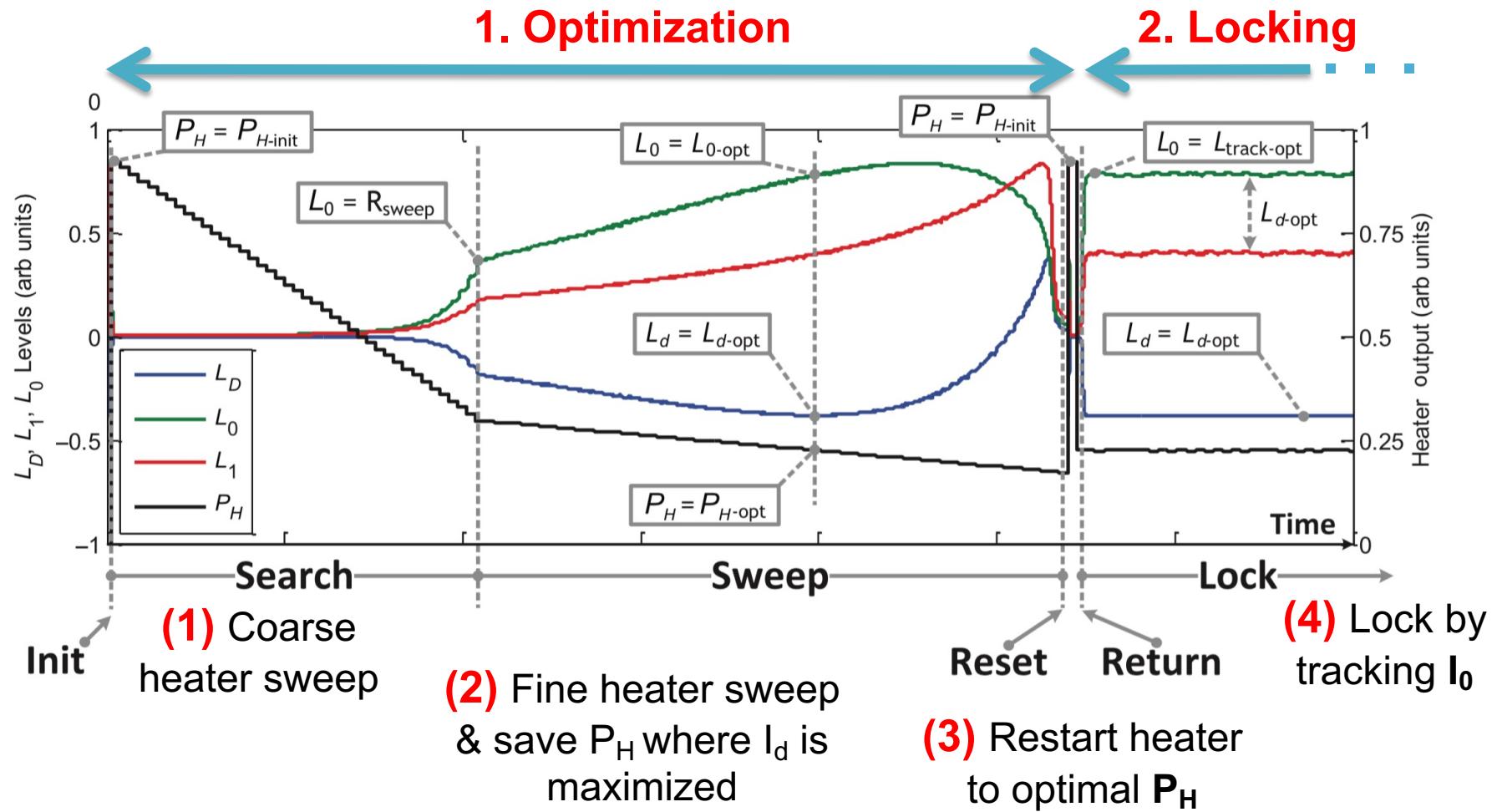
# Thermal Tuning for PAM4



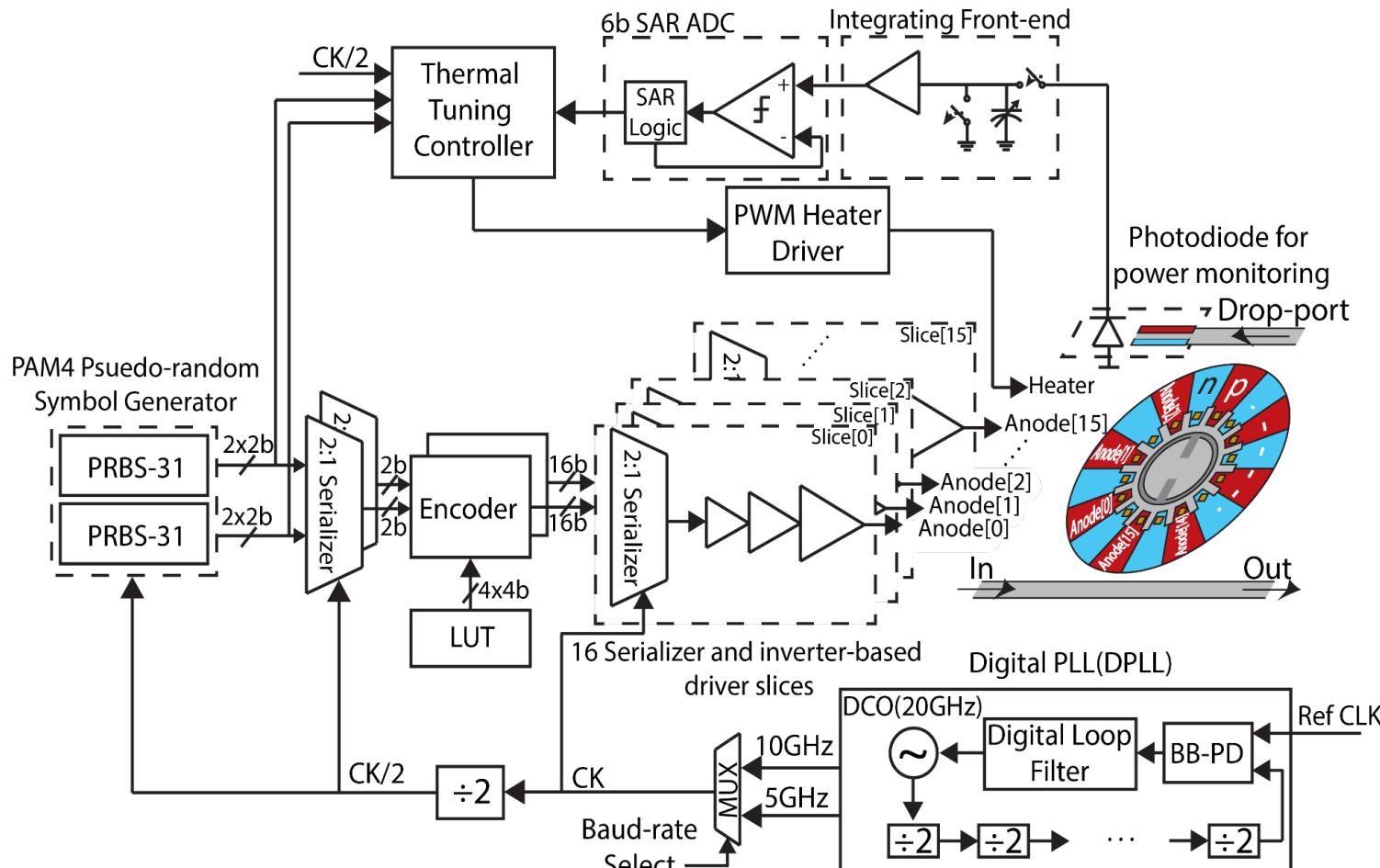
- Sense optical power & Adjust heater strength
- Finds and tracks the optimized ring resonance

[Moazeni *et al.*, JSSC 17]

# Thermal Tuning Algorithm



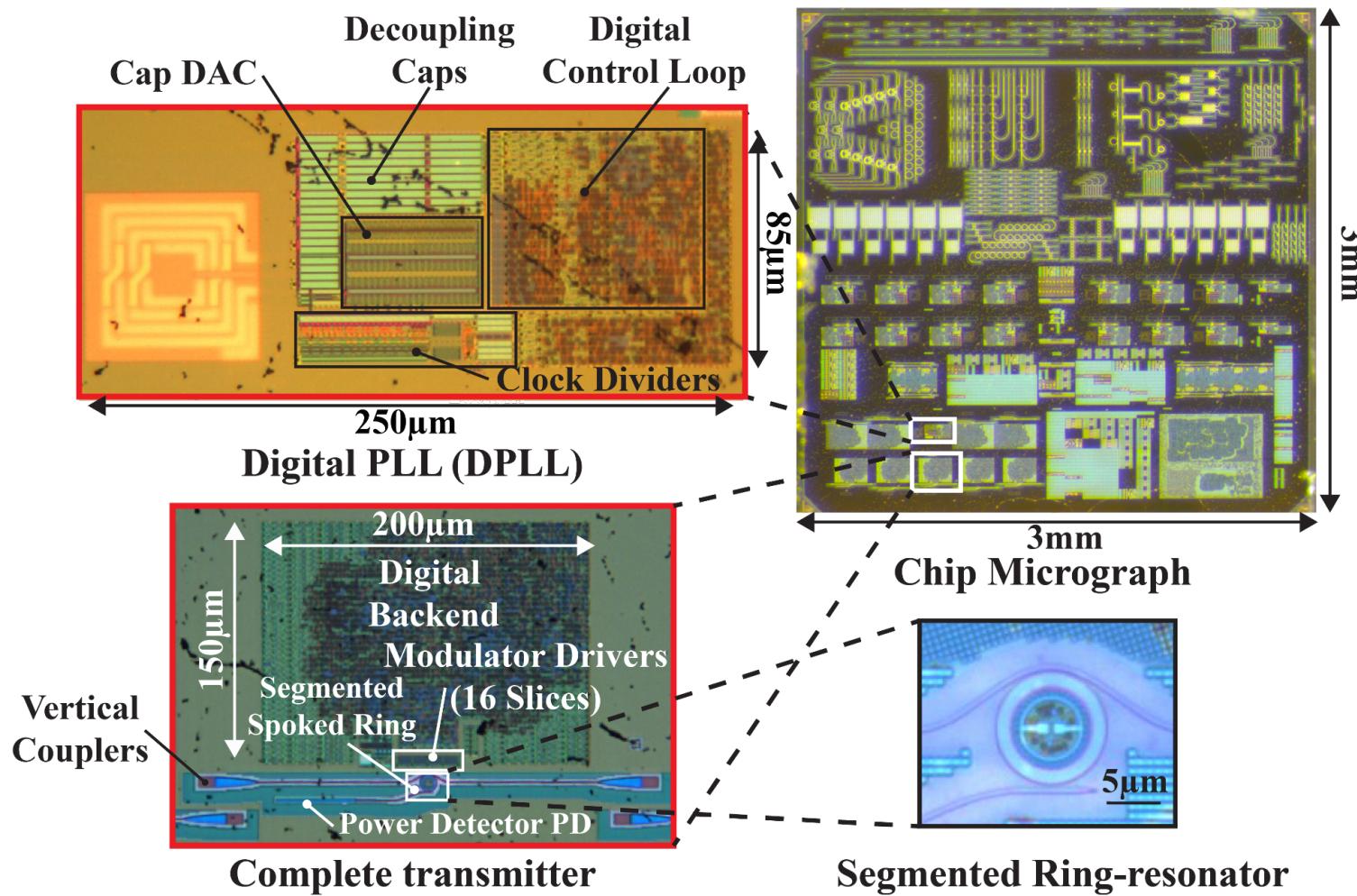
# Full Transmitter Architecture



Direct Digital-to-Optical Conversion

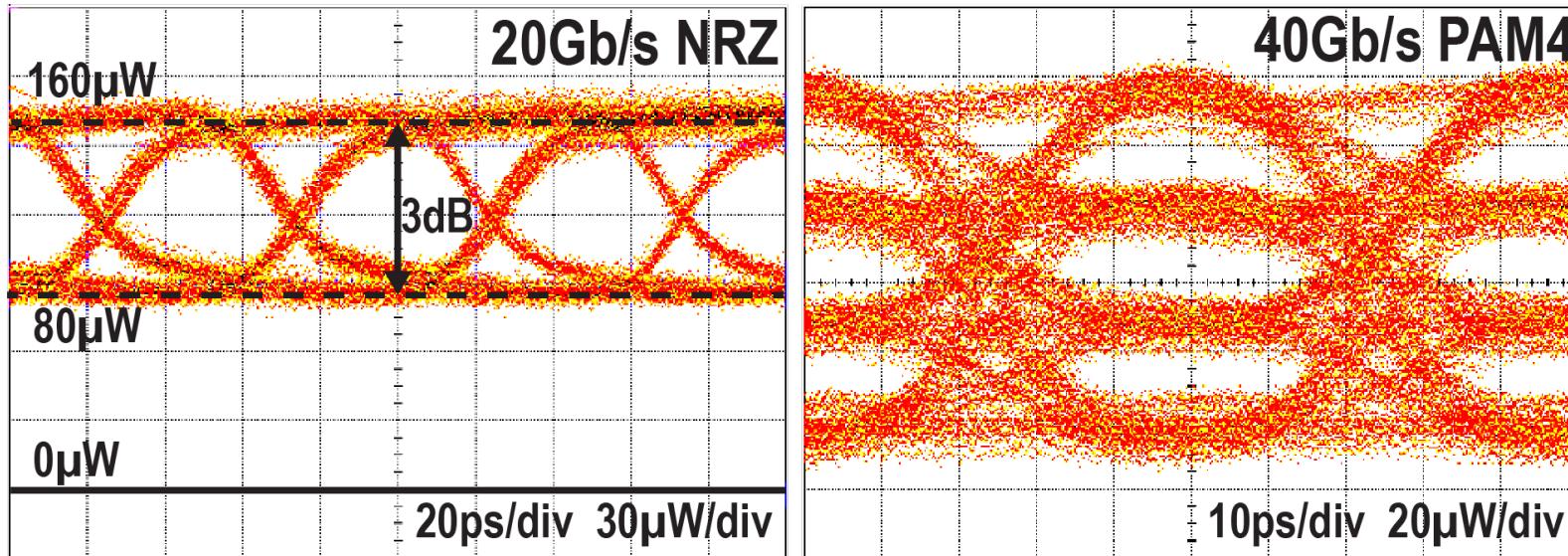
[Moazeni et al., ISSCC/JSSC 17]

# Transmitter Micrographs



[Moazeni et al., ISSCC/JSSC 17]

# Transmitter Performance



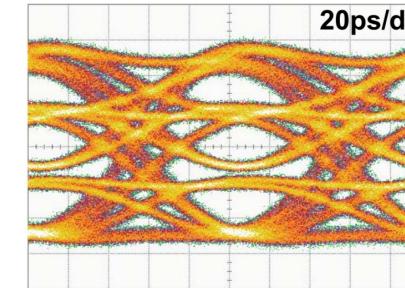
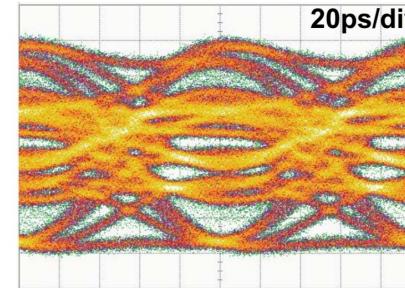
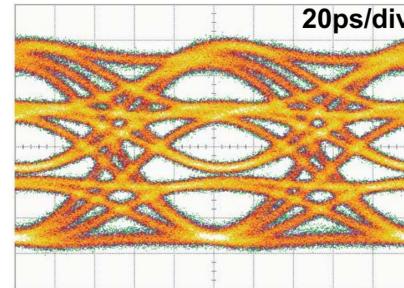
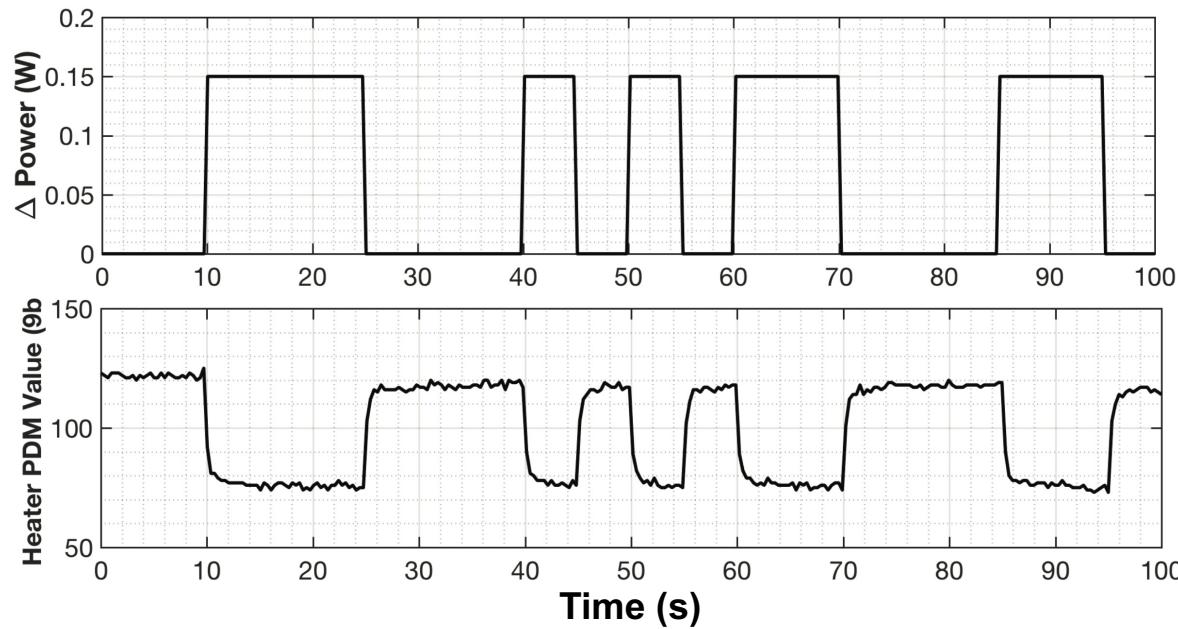
- **42fJ/b** driver energy efficiency
- **3.6Tb/s/mm<sup>2</sup>** modulator and driver BW density
- Suitable approach for co-integration with processor, memory, ...

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

# Thermal Stress Test

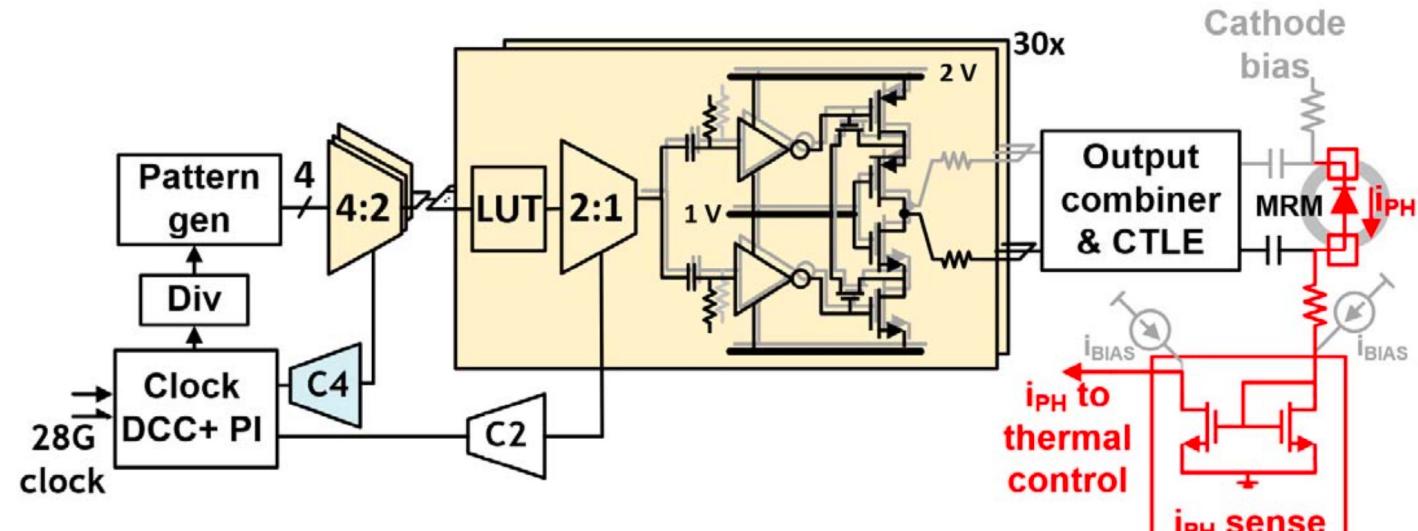
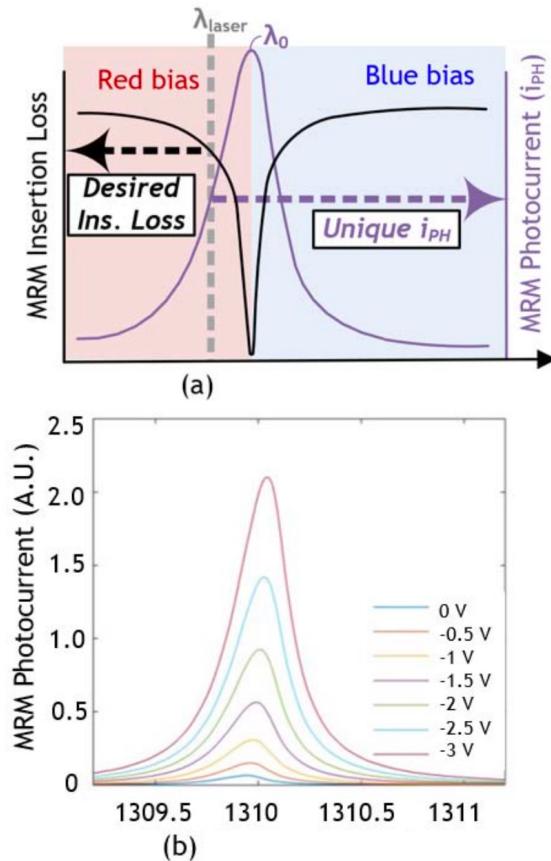
Thermal  
Perturbations  
Pattern

Heater  
Strength



[Moazeni *et al.*, JSSC 17]

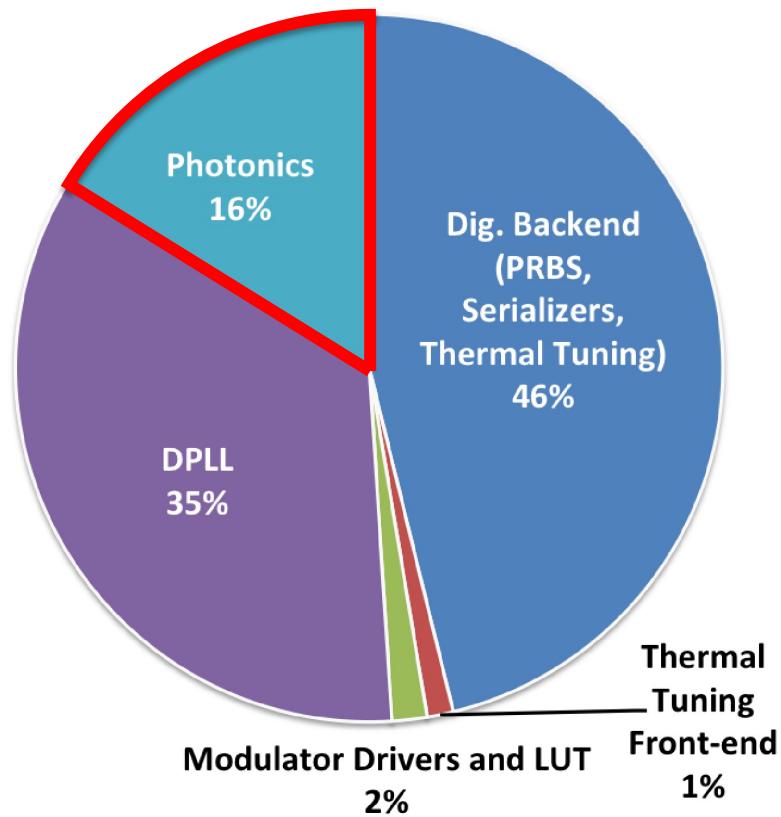
# Other Thermal Tuning Schemes



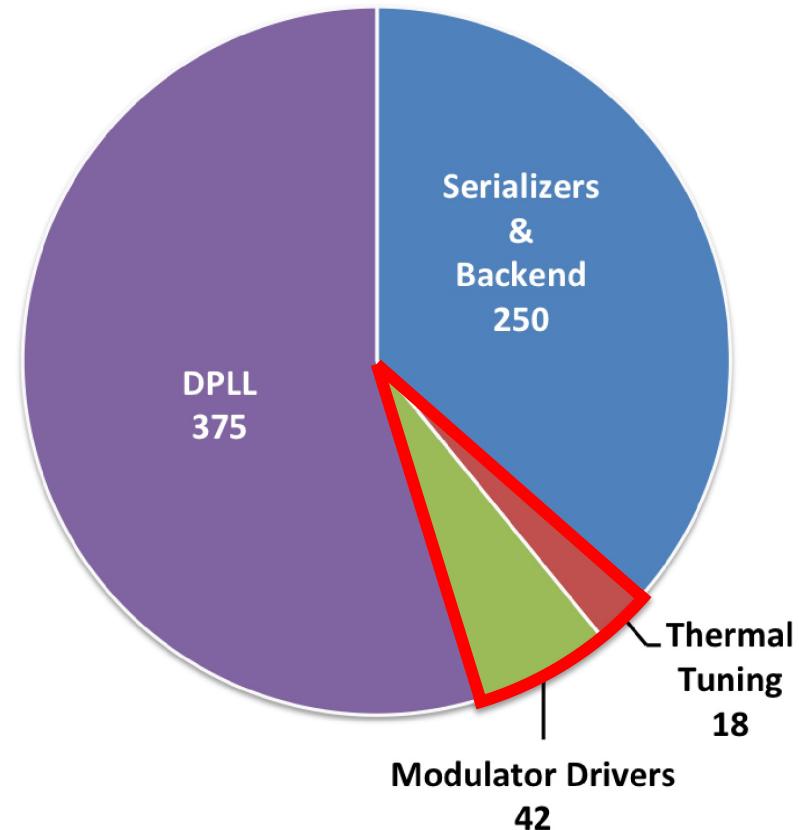
Ref: Silicon Photonic Microring-Based  $4 \times 112$  Gb/s WDM Transmitter With Photocurrent-Based Thermal Control in 28-nm CMOS (JSSC 2022)

# *Area/Energy Breakdown*

**Area Breakdown**  
Total Transmitter Area =  $0.06 \text{ mm}^2$



**Energy Breakdown (in fJ/b)**  
Total Transmitter Energy =  $685 \text{ fJ/b}$



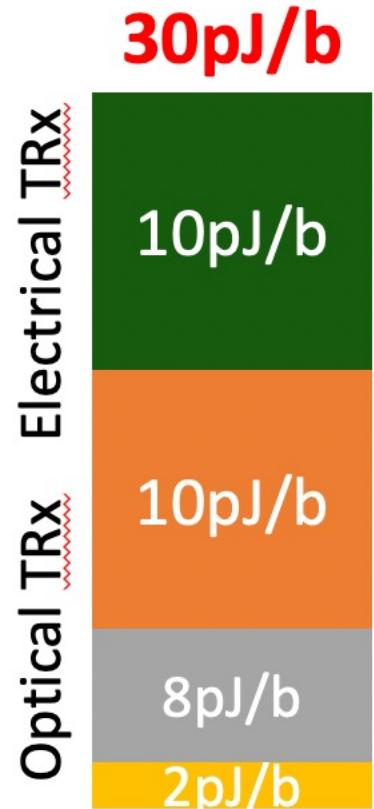
[Moazeni et al., ISSCC/JSSC 17]

# PAM4 Tx Performance Summary

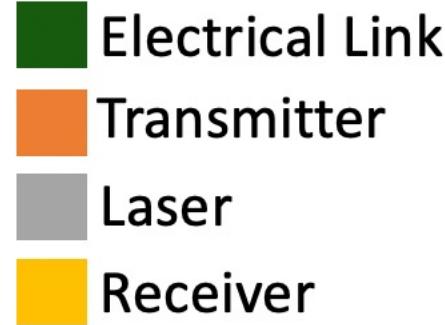
Reference	Wu ISSCC 13	Xiong OI 15	Roshan-Zamir OI 16	Intel ISSCC 20	Moazeni ISSCC 17
Integration	Hybrid	Monolithic	Hybrid	Hybrid/3D	Monolithic
CMOS Technology	40nm	90nm	65nm	22nm	45nm
Modulator	MZM	MZM	MRM	MRM	MRM
Driver Supply (V)	1	1.1	2.4	4	1.55
ER/IL (dB)	-	6.3/5	7/5		3/5.5
PAM4 Data-rate (Gb/s)	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 <sup>2</sup> )	0.053	0.036	0.5		3.6

[Moazeni, ISSCC/JSSC 17]

# Next-generation Co-packaged Optics



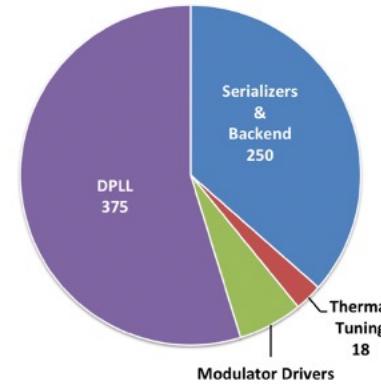
**Commercial Pluggable  
Silicon-Photonic (SiPh)**  
< 100Gb/s/mm



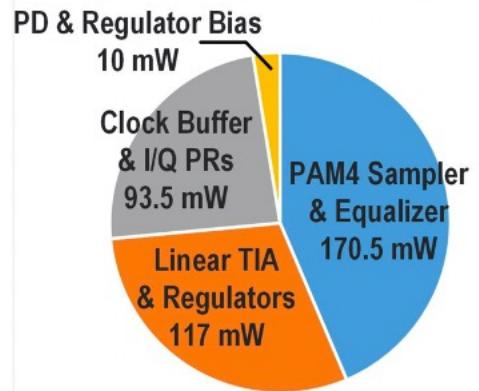
**7.5x**

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

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



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



**Sub-pJ/b**

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

# Packaging & Test Setup

